RIVER STUDIES

AND RECOMMENDATIONS ON IMPROVEMENT OF

NIGER AND BENUE

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NIGER AND BENUE

BY

NEDECO

NETHERLANDS ENGINEERING CONSULTANTS

THE HAGUE

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«NEDECO»

NETHERLANDS ENGINEERING CONSULTANTS

167C/6661 The Hague, February 7th, 1959

Sir,

We have pleasure in submitting herewith the Report on the Investigation of the Niger and Benue Rivers, for consideration by the Government of the Federation of Nigeria.

Our Special Mission, consisting of twelve expert engineers stationed in Nigeria during three years, has made a comprehensive study of these two rivers and examined the possibilities of improving the shipping conditions.

The elaboration of the study and the preparation of the Report have been completed in Holland in collaboration with a panel of specialists including:

Professor J.Th. Thijsse, Professor of Hydraulics, Delft Technological University; Director Hydraulics Laboratory;
Professor P.Ph. Jansen, Directing Senior Engineer in charge of the Delta Works, Rijkswaterstaat, The Hague; Professor of Hydraulic Engineering, Delft Technological University;
J.B. Schijf, Chief Engineer, Central Research Division, Rijkswaterstaat, The Hague; and
Professor L. van Bendegom, Professor of Hydraulic Engineering, Delft Technological University.

We feel that, apart from the required general information on the regime and navigability of the rivers, the Report provides a justified and workable programme of successive improvements to the shipping conditions.

We shall, of course, follow with great interest the actions taken by your Government in connection with our recommendations.

In conclusion, we should like to take this opportunity to express our sincere appreciation of the assistance we received from all with whom we came in contact during the execution of our study and investigation, and for the courtesy which has been shown to us at all times.

We have the honour to be, Sir,

Yours faithfully,

E.W.H. Clason,
Managing Director, NEDECO

H.C. Frijlink, O.B.E.
Chief Engineer, Niger and Benue Investigation.

To: The Permanent Secretary,
Federal Ministry of Transport,
L a g o s.
Nigeria.

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PREFACE

The Government of the Federation of Nigeria commissioned the Netherlands Engineering Consultants NEDECO to study the conditions obtaining in the Niger and Benue Rivers with the object of determining how shipping conditions on the rivers can be most effectively improved. As this Report makes clear, the Consultants found themselves obliged in the course of their investigation to consider matters which, though having a direct bearing on the development of inland water transport, are not strictly concerned with the technical problems of river regulation and river management. In particular, the Consultants learned at an early stage that three conditions should be fulfilled if the maximum benefit is to be gained from the development of the magnificent river system with which Nigeria is endowed by Nature.

In the first place, the Federal Government's efforts to develop the inland waterways will in due course call for comparable efforts by private enterprise to take advantage of the improved conditions provided by Government.

Secondly, the Federal Government has included in the Economic Programme 1955—62 plans for training-works to be constructed at the Escravos entrance to the Niger Delta. Quite apart from the benefits which this project will confer on the ports of the Western Delta, the project must also be regarded as the essential first step in any programme for a major expansion of transport in the creeks and rivers. This type of transport can serve areas the development of which has hitherto been hampered by the lack of modern means of communication, resulting in excessively high transport costs.

Finally, in the course of their investigations the Consultants worked in close co-operation with the French authorities engaged on similar studies. Conferences were held, both for the exchange of information and for the discussion of common problems, and on occasion these meetings were held under the Chairmanship of the Honourable the Minister of Transport, now the Prime Minister of the Federation. It is most desirable that this co-operation should continue. In the words of the Prime Minister, when addressing the conference at The Hague in May 1956: "Rivers have no respect for political frontiers. They are the common property of many peoples and, if they are to be harnessed to the service of mankind, it is essential that we should continue to consult together, to exchange information and to discuss our problems."

Strictly speaking, these questions are matters of policy for the consideration of the Federal Government, not for the Netherlands Engineering Consultants. Nevertheless, their importance is such that these three points are developed further and reference to them, either directly or by implication, is frequent in this Report.

PART I

INTRODUCTION AND SUMMARY

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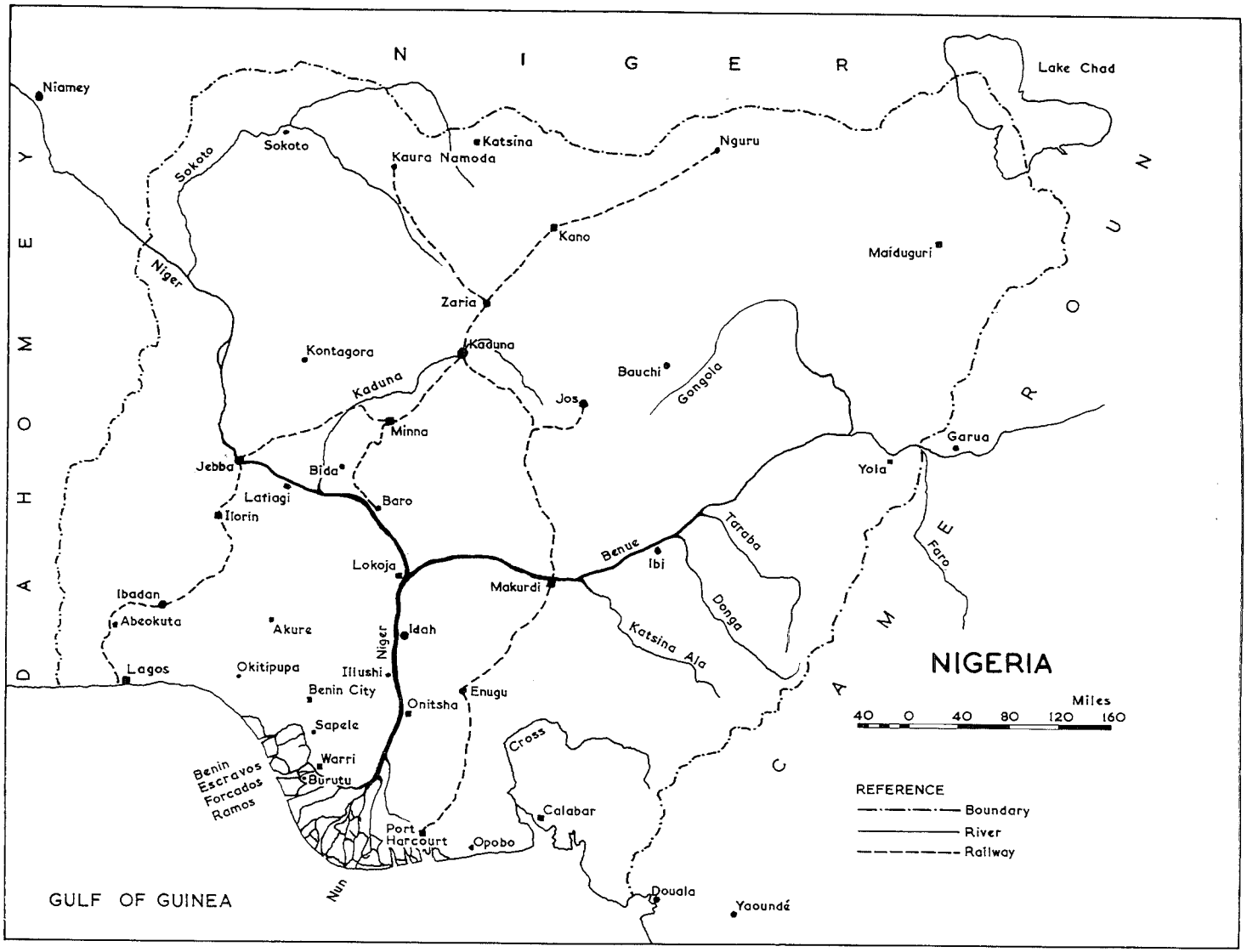

NIGERIA
N I G E R
DAHOMEY
CAMEROUN
Niamey
Sokoto
Katsina
Kaura Namoda
Nguru
Lake Chad
Kano
Maiduguri
Zaria
Kontagora
Kaduna
Bauchi
Gongola
Jos
Minna
Garua
Yola
Jebba
Bida
Baro
Latiagi
Ilorin
Benue
Ibi
Taraba
Faro
Lokoja
Makurdi
Donga
Ibadan
Abeokuta
Akure
Idah
Katsina Ala
Lagos
Okitipupa
Illushi
Benin City
Enugu
Onitsha
Sapele
Warri
Burutu
Benin
Escravos
Forcados
Ramos
Cross
Calabar
Port Harcourt
Opobo
Nun
Douala
Yaoundé
GULF OF GUINEA
Miles
40 0 40 80 120 160
REFERENCE
Boundary
River
Railway

CHAPTER 1

INTRODUCTION

1.1. HISTORY OF THE INVESTIGATION

1.1.1. Western Niger Delta investigation

Access from the sea to the Benin Ports (Burutu, Sapele and Warri) has given much cause for concern since about 1930. These ports, in particular Burutu and Warri, form the link with inland navigation on the extensive Niger and Benue system, which provides a waterway reaching about a thousand miles into the continent of Africa.

Early in this century the port of Burutu was established on an island in the Western Niger Delta. Forcados Estuary was at that time the best entrance to the Benin ports; ships drawing some 20 feet could then easily cross the Bar. Since the survey of 1899, however, the Bar has gradually deteriorated and from 1934 draughts had been limited to about 12 feet. In 1938 it was decided to open the Escravos Estuary for sea-going shipping. Though only slightly deeper, the channel across Escravos Bar is in a better position than the Forcados Channel, being more or less in the direction of the prevailing wind and swell. But draughts of ships are still limited to 13'6" or 14' at high water on the Bar.

After a preliminary reconnaissance by Professor P. Ph. Jansen of NEDECO, made in 1952, an agreement was signed by representatives of the Government of Nigeria and of NEDECO on September 16, 1953, which stated

> "that NEDECO will carry out a general study and investigation of conditions obtaining in the Niger River Delta with the object of determining how access to the ports of Burutu, Warri and Sapele can be most effectively ensured and maintained, and fully inform and advise the Government in writing accordingly".

Preparations for the Western Delta Investigation were already in an advanced stage at that time, and one year later the staff of NEDECO in Nigeria, consisting of 6 expatriate engineers, an expatriate administrative officer and 17 Nigerian technical assistants, draughtsmen, clerks, etc., had completed the field-work for the Investigation.

Late in 1954 the Report on the Western Niger Delta Investigation ([1] was submitted to the Government of Nigeria. In addition to giving detailed descriptions of the Western Delta area, that Report included studies of the past and present processes of delta building and coast formations, in particular along the entire western flank of the Delta, the tidal regime of the Ramos, Forcados, Escravos and Benin Estuaries, and the hydrological and morphological characteristics of the undivided Niger at the apex of the Delta, its branches within that Delta and the interconnecting creeks.

It was recommended in that Report to construct a breakwater with a length of 4.5 miles

([1] NEDECO, 1954. GEN. 23

at Escravos Entrance and to dredge in the lee of this breakwater a channel to a depth of 20 feet below Chart Datum.

A scale-model investigation, necessary to determine the correct alignment of that breakwater, was carried out at the Delft Hydraulic Laboratory in 1956—58. Contract documents for the Escravos works were prepared by Messrs. Coode & Partners and tenders were submitted by a number of contractors in October, 1958. It is expected that the execution will commence in 1959.

1.1.2. Preliminary investigation of Niger and Benue Rivers

Soon after the Western Delta Investigation was started in 1953, preparations were made for a study of the possibility of improving the shipping conditions on the Niger and Benue Rivers. A Preliminary Investigation was judged useful before any large-scale survey was entered into, and for this purpose Mr. L. van Bendegom, Chief Engineer of the Netherlands Government Waterways Department, visited Nigeria from December 1953 to March 1954.

The object of that preliminary investigation could be formulated in the following two questions: (i) the feasibility from a technical point of view, without unreasonable expense, of an improvement of the Niger downstream from Baro and of the Benue downstream from Garua; and (ii) the nature and extent of the problems involved and the programme for a detailed investigation in case of a positive answer to the first question.

As regards the first question, the preliminary investigation led to the conclusion that improvements on both rivers would be technically feasible, but that a much more detailed investigation would have to be carried out before the extent and the cost of the necessary works, in particular those on the Benue, could be etablished.

Concerning the second question, a succinct analysis of the problems and an outline of an investigation programme were submitted in a report to the Government of Nigeria, dated May 1954.

1.1.3. Terms of reference of the Niger and Benue investigation

An agreement on the full-scale investigation of the Niger and Benue Rivers was signed by representatives of the Government of the Federation of Nigeria and of NEDECO on August 21, 1954. The present Report deals with the results of this investigation.

The Terms of Reference have been set out in Clause 1 (a) of that Agreement as follows:

"NEDECO will carry out a general study and investigation of conditions obtaining in the Niger and Benue system with the object of determining how the shipping conditions on these rivers can be most effectively improved, and fully inform and advise the Government in writing accordingly.

"The said general study shall as far as practicable be directed to the following matters:
(i) "discovering the characteristic nature and behaviour of the component parts and the entirety of the river system, aiming to constitute a foundation on which projects for the improvement might be based;
(ii) "the composition by means of an aerial survey, supplemented by terrestrial measurements and soundings, of a complete series of sufficiently accurate river maps covering the entire length of the river system downstream from Baro and Garua;
(iii) "discovering sufficient information concerning the regime of the rivers, necessitating observations of flow discharges, water-levels, slopes, rainfall, evaporation, transportation of bed-load and sediments in suspension, etc., and establishing the relations between these elements as well as their dependence from the seasonal cycle and variations therein and possibly other outside factors;
(iv) "study of the vagaries of channel configuration and depths and investigate a number of crucial localities, such as junctions, shoals, projecting rocks, etc.; and

(v) "an enquiry into the feasibility of outlined projects including, as circumstances direct, geologic observations and hydraulic model investigations and into the possible methods of construction and the suitability of locally found materials".

1.2. INTERIM REPORTS

1.2.1. Interim Report, June 1956

In Clause 1 (f) of the Agreement mentioned in the preceding paragraph, it was stated that "NEDECO will submit to the Government from time to time such reports on the progress of the study and investigation as the Government may require".

In June 1956, a little over a year after the field investigations had commenced, a first Interim Report was issued to provide information on the progress made and on the possible development, so that the Government might consider further action to be taken in developing the rivers. In that Report, the results of the first measuring campaigns were given, together with a description of the organisation that had been built up for the survey, and a summary of the various activities.

A description was further given of the navigation and navigability of the rivers, as well as a provisional selection of methods that might be considered for improving the rivers.

Particular reference was made to the proposed establishment of an Inland Waterways Department (Sessional Paper no. 7 of 1956) and it was hoped that the Interim Report might provide a basis for the planning of the full department.

Lastly, the programme for the 1956/1957 measuring campaigns was explained. The Proceedings of two Conferences with the Cameroun agencies were appended to the Report, with a translation of the conclusions of the preliminary annual report of Electricité de France (the Cameroun consultants) on the navigability of the Cameroun part of the Benue.

1.2.2. Interim Report Channel Patrols, December 1956

In the course of the first year of the investigation it had already become apparent that shipping might greatly benefit by a system of channel marking, consisting of buoys and beacons. While experiments for such a buoyage were being initiated on a section of the Niger, a special study was made of the possible organisation and equipment of the service that would be responsible for positioning and maintaining the channel markers.

In the December 1956 Report it was discussed in detail how a better use could be made of the existing navigable channel. For that purpose, the existing situation with regard to maps, pilots, buoys and channels was surveyed, whilst a preliminary choice was made for the marking of the Niger and Benue channels.

1.2.3. Interim Report, July 1957

This Report, issued two years after the Investigation was started, contained information on the progress made in the various items and in particular on:

(i) the hydrological data that had been collected;
(ii) the observations regarding the navigation;
(iii) the means of guiding this navigation; and
(iv) the possible improvements of the rivers.

Item (i) was thought to be of interest to other departments within and outside Nigeria, as requests were frequently made by various interested parties for water-levels or discharges, etc.

Reference (ii), the analysis of the navigation seasons of the Benue and the Niger in 1956/57

proved instructive in explaining the characteristics and the problems of shipping and the causes of the delays experienced.

As to (iii), an experimental buoyage system had been introduced by NEDECO on a section of the Niger. The Interim Report described that experiment and arrived at some conclusions regarding a similar experiment to be undertaken on the Benue, and on a continuation of that navigation service during the following Niger season.

Lastly (ref. (iv)), progress was reported on the study of the possibilities of permanent improvements on the Niger and Benue navigability, which showed the trend of the possible development.

Recommendations were given on the establishment of a number of permanent river gauges and on the organisation of their readings.

As a result of a study and reconnaissance of the upper section of the Niger within French West Africa, it could be stated in the 1957 Interim Report that the French dam and irrigation works near Sansanding (Soudan) have so far had no deteriorating effect on the Niger below Baro.

As in 1956, full agreement with the Cameroun agencies investigating the Benue could be reported. The proceedings of another conference with the Cameroun authorities and consultants were appended to the Report.

1.2.4. Interim Report Buoyage Vessels, February 1958

In July 1957 it was agreed that NEDECO should prepare and submit to the Director of the Inland Waterways Department a report and sketches of possible designs of Channel Patrol and Buoyage vessels. The buoyage experiments on the Niger and Benue, and comparison with channel patrol work in other countries, had provided information about the organisation of a Nigerian Channel Patrol Service, and had enabled a programme of requirements for buoyage vessels to match this organisation to be drawn up.

The Report gave a brief outline of the Channel Patrol Service and a number of remarks about buoyage vessels, followed by a more detailed discussion of the proposed service and a summarised programme of requirements for the vessels with several sketches of alternative designs. After further explanation, a design has been recommended.

1.2.5. Related reports

a. *Onitsha Bridge*

In November 1955 the Federal Ministry of Transport in Nigeria made enquiries whether NEDECO were prepared to undertake an investigation into the possibility of constructing a bridge across the Niger in the neighbourhood of Onitsha.

This enquiry resulted in the signing of the Agreement of March 2, 1956, between representatives of the Government of the Federation of Nigeria and of NEDECO.

Under that agreement, NEDECO assumed the responsibility for obtaining all necessary surveys, levels, soundings and borings and making such investigations and enquiries as would be necessary for the purpose of submitting a Report which would inform the Government on the practicability of constructing a bridge across the River Niger not more than five miles from Onitsha and also suggesting the most suitable site therefore, bearing in mind the requirements of river navigation.

Particularly with respect to this latter point, it seemed natural that, having already been entrusted with the Niger and Benue studies with the object of determining how shipping conditions on these rivers can most effectively be improved, NEDECO should also consider any other solutions for river crossing that could contribute to that end.

The consideration of such solutions has been included in the Onitsha Bridge Report. In

particular, the possibilities of constructing a dam connecting both banks of the Niger have been gone into. Such a dam might serve for an improvement of the navigability of the Lower Niger as well as for the generation of electricity. It was concluded from the preliminary considerations that dam building would seem feasible here, but in connection with other purposes only. No recommendations were made with regard to such an ambitious multi-purpose solution as a means of bank connection by road.

A high-level 8-span truss bridge flanked by 4-span plate girder bridges at a site south of Onitsha was finally recommended as most suitable to serve as a basis for further consideration. With regard to navigation, this bridge would offer a clear height of at least 74 feet during highest flood, beneath a main span of at least 400 feet width between the piers. The construction of this bridge will commence in 1959.

Some of the geological data which has been assembled in pursuance of the Onitsha Bridge Investigation has been used in the Chapters on Geology and Valley Narrowings of the present Report.

b. *Idah Bank Erosion*

In September 1956 the Ministry of Works, Northern Region, asked NEDECO to investigate the bank erosion at the Niger port of Idah and to advise on the design of a bank protection that would offer possibilities for the loading and discharging of river vessels. On November 26 of the same year, a Provisional Report was submitted to the authorities, containing a discussion of the bank erosion and its probable trend. Recommendations were made on a series of measures to be carried out as circumstances would require, including a proper alignment of the slope, the construction of a jetty, provision of a pontoon and ultimately the construction of a wharf.

1.3. FINAL REPORT

1.3.1. Purpose

The present Report is, of course, written in the first place in compliance with Clause 1 of the Terms of Reference, namely, to inform and advise the Government on the results of the study and on the question how the shipping conditions on the Niger and Benue River system can be most effectively improved.

There appeared to be a lack of comprehensive descriptions of the many aspects of these rivers. The excellent work of NIEHOFF ([1 must be considered out-dated, and the report of REFFAY ([2 deals mainly with the Niger in French West Africa. Information on the Niger and Benue Rivers is required for many purposes, and especially during the present stage of general development. Therefore in the present Report an effort has been made towards such a full description, although it is realised that not all aspects of a 3,000-mile long river system can be described in one book. This description is mainly based on observations and measurements during the three-years' field investigation of the NEDECO team; where such observations were not available, a compilation has been made from various outside data.

In view of the establishment and recommended expansion of the Hydrological Branch of the Inland Waterways Department, it was considered useful to elaborate on the sections dealing with the explanation of the characteristics of the Niger and Benue Rivers, and the possible river-engineering works, so that this Report might serve as a text-book to trainees for that Branch.

It has further been tried to provide an insight into the navigation and navigability of the main river, as such information may be of use to those interested in river transport and in the general transport facilities.

([1 NIEHOFF, 1917. GEO. 32
([2 REFFAY, 1948. HYD. 9

1.3.2. Sub-division

The present Report is divided into six Parts, indicated by Roman numerals I to VI. For numbering the Chapters, Sections, Paragraphs as well as the Diagrams and Photographs, the decimal system has been used, so that for instance I, 2.3.4-5 indicates the fifth Diagram of Paragraph 4, Section 3, Chapter 2 of Part I.

The use of small print indicates that the reading of those lines is not directly essential for an understanding of the remainder of that paragraph.

The following chapters of this Part give a summary of the original NEDECO studies and their results as contained in the Report, without summarising the information obtained from other sources.

This is followed by a description of the actual investigation, its staff, the planning, the instruments that were used, etc. (Part II).

Part III deals with the Rivers, explaining their hydrological and morphological regime and describing the other characteristics.

Part IV provides information on transport, navigation and navigability, whilst Part V summarises the defects of the shipping conditions.

Finally, Part VI gives a discussion of the various possibilities for improving the navigability, resulting in a recommended programme of improvements.

A glossary of technical expressions and a list of symbols and units have been included in the Report. It should be noted that an effort has been made to use both metric and British units for all data and calculations. Only where this would be too cumbersome, such as in Tables and in lengthy calculations, has a single system been used, but care has been taken to present final data always in both systems.

General maps of West Africa and of Nigeria are inserted inside the back cover of this Report.

Lastly, a List of References is appended, which has been sub-divided into five sections: General, (GEN), Morphology (MOR), Hydrology (HYD), Geology (GEO) and Transport (TRP). Reference is made to the contents of these lists by giving in a foot-note the name of the author, the year of issue and the list and number of reference.

It should perhaps be explained that as the various members of the NEDECO team have each endeavoured to be as complete as possible in their evaluation of the situation and possible remedies, there has in some cases been a certain repetition of facts or ideas.

In the compilation of this Report, such repetition or duplication was deliberately retained. As this Report will in some respects serve as a guide-book for those who will be responsible for the future development of the Niger-Benue system, it has been felt essential for each chapter to be complete in itself, largely irrespective of what has been said in the other chapters.

1.4. INTERNATIONAL CONSULTATION

1.4.1. Reconnaissance of the Niger in French West Africa (see III, 1.2.4. and 2.3.1 and IV, 3.3)

Little information was available on the regime of the Niger upstream from Nigeria, and of the conditions obtaining in that section of the River. But as this upstream section naturally has an important influence on the navigability of the Nigerian part of the Niger, it was judged useful to make an investigation of the Niger in French West Africa and to visit the various agencies concerned with hydrology and navigation in this area.

A Report on that reconnaissance, which was made by two NEDECO Engineers in February

and March 1957, was appended to the Interim Report of July 1957. The visit included the towns of Niamey, Gao, Diré, Mopti, Sansanding, Ségou, Koulikoro and Bamako along the Niger. Several sections of the river were inspected by launch, whilst the remainder between Niamey and Bamako were inspected by air. Finally, discussions were held at the Public Works Headquarters at Dakar. The Report included notes on the discussions and survey trips, a discussion of the various existing river projects, and calculations on the influence of these French projects on the discharge of the Niger in Nigeria.

This information has been used for compiling several sections of the present Report. In addition, a valuable contact has been made between the agencies in Nigeria and in French West Africa dealing with the River Niger, a contact which has made it possible to issue long-term predictions of the river-stages in Nigeria.

1.4.2. Conferences on the Benue in the Cameroun

The Cameroun Government in 1950 initiated studies of the section of the Benue River within that territory. There has been a close and efficient cooperation between the Cameroun authorities and consultants dealing with the hydrology and navigability of the Benue on the one side, and the Nigerian authorities and their consultants on the other.

A number of conferences were held on the common subjects of Benue navigation studies and river investigation. The first was held in Yaoundé in March 1954, followed by several other official meetings at Lagos, Paris, Duala, and The Hague. Unofficial discussions took place at Garua, Yola and Lokoja, completed by various meetings on the rivers.

These contacts have resulted in a combined effort as regards the field investigations, where the French investigation extended into Nigeria as far as the Gamadio Flats whilst the NEDECO survey extended into Cameroun territory as far as Garua. Complete agreement was reached on the technical features of the rivers as well as on the possibilities for an improvement.

Another result of this contact is the combined navigation bulletin which is issued during the Benue season, including both predictions of Cameroun origin and stages and depths of Nigerian origin.

The Cameroun investigation was concluded in 1957 and the Final Report of the French consultants on the regime and navigability of the Benue was completed in 1958. Reference to that Report has been made at the appropriate places in the present Report.

1.5. FURTHER INVESTIGATIONS

1.5.1. Jebba Investigation

The Electricity Corporation of Nigeria, facing an increasing demand for power, has been considering the further development of generating possibilities, and early in 1958 a preliminary investigation was initiated into the feasibility of a hydro-power project on the Niger in the vicinity of Jebba.

Realising the advantages of a multi-purpose project which would also offer benefits to navigation and agriculture as well as flood protection, this assignment grew into a joint commission to Messrs. Balfour, Beatty & Co., Ltd. and NEDECO to investigate the feasibility of such a multi-purpose project.

The field observations were commenced in March 1958, and continued throughout the year. The joint report was due by the end of 1958.

1.5.2. Eastern Delta Investigation

The 1953/1954 investigation of the Western Niger Delta dealt with the access to the ports of Sapele, Warri and Burutu and therefore only that part of the Niger Delta was studied and surveyed which lies to the west of Bomadi Creek. The latter creek was included in the investigation, as well as the Ramos, Forcados, Escravos and Benin Estuaries. The coast was reconnoitred from the Nun River Estuary (Akassa area) westward.

In view of the many problems and possibilities of the Niger Delta, it was only natural that the Federal Government was anxious to have a hydrological survey and investigation also of the remaining part and to consider such a survey as a sequel to the Niger and Benue Investigation.

In March 1958 an Agreement was signed between representatives of the Government of the Federation of Nigeria and of NEDECO whereby it was agreed that NEDECO would:

(i) "carry out general studies and investigation of conditions in the Eastern Niger River Delta, an area limited by the water-sheds of Bomadi Creek and Kwa Ibo River, these waters themselves excluded, with the object of extending the general scientific knowledge of the hydrological regime of the Delta, and fully inform and advise the Government in writing accordingly. The said general study shall as far as practicable be directed to the following matters:
the flow of fresh water run-off through rivers, creeks, and estuaries to the sea;
the tidal movements through estuaries and creeks;
the distribution of sediments from the rivers through the Delta;
the nature of winds, waves, currents and tides along the coast;
the resulting sand transportation along the coast; and
the shapes and changes of beaches and bars".

(ii) "acquire more information about conditions prevailing in the access routes from the sea to the ports of Port Harcourt, Opobo and Akassa, and the natural or artificial developments of these routes; study the intra-coastal links from the Western Delta ports via Akassa to Port Harcourt and Opobo; and investigate connections between the Niger River system and the above ports".

Fieldwork for this investigation was commenced early in November 1958 by a staff of four expatriate engineers and ten Nigerian technical and clerical assistants. The report is expected towards the end of 1960.

CHAPTER 2

STUDIES

2.1. DESCRIPTION OF THE RIVERS

2.1.1. The Niger (see III, 2.3.1)

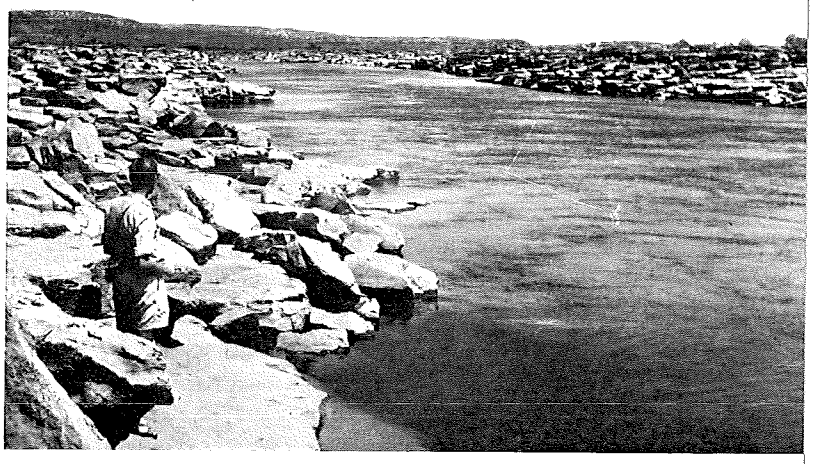
The Niger rises in the mountains of Sierra Leone (see Map A inside back cover) on the Futa Jalon Highlands, only 150 miles from the Atlantic Ocean, but as its source is on the landward side of this mountainous ridge, the river runs off in a north-easterly direction towards the centre of the Western Soudan depression.

Up to Kouroussa (2,307 miles from the outlet into the Atlantic Ocean) the river is obstructed by many small rapids and the average slope amounts to 20×10^{-5}, i.e., just over a foot per mile.

From Siguiri (Mile 2,209) downwards, the river-bed becomes sandy and has an alluvial flood-plain about one mile wide.

Direct downstream from Bamako (Mile 2,081), the second largest town on the whole Niger, there is a section of 40 miles with two major rapids (Photograph 2.1.1-1, i.e., III, 2.3.1-5).

At Koulikoro (Mile 2,041) the terminus of the railway-line from Dakar, the river again



PHOTOGRAPH 2.1.1-1

The Niger between Bamako and Koulikoro at low water

PHOTOGRAPH 2.1.1-2

The Port of Baro

becomes navigable and can be used for shipping over a distance of more than 800 miles. Near Sansanding (Mile 1,918) a 2,650 feet long dam has been built in the Niger for irrigation purposes.

The river next enters the swamp area which is the remainder of an old Interior Delta, where the slope of the river decreases from 5×10^{-5} to 1×10^{-5}. Much Niger water is lost here, due to infiltration and evaporation, and at Diré (Mile 1,574) only 35 % of the annual discharge of the Niger is left.

The Niger continues to flow from Timbuctu (Mile 1,528) downward in an area of sandy ridges and swamps, until a rocky ridge obstructs its course near Tosay (Mile 1,341). The river then flows in a south-easterly direction through a semi-desert area with hardly any rainfall, but near the Nigerian border the rainfall increases again. Between Labbenzenga (Mile 1,149) and Tillabéry (Mile 1,068) naviagtion is hardly possible owing to the presence of rapids. Below this valley narrowing the river becomes navigable again for a distance of over 300 miles. The high-water bed is one or two miles wide, bordered by table-mountains with their tops about 200 feet above river-level.

Below Kirtachi (Mile 930) the course of the Niger is disturbed by a rocky interference, and the river zig-zags with a few minor rapids through the so-called "Double V".

After another section with wide flood-plain and flattopped mountains, the aspect of the Niger changes when the hills begin to close in. Between Yelwa (Mile 688) and Jebba (Mile 556) (1

(1 see Map B inside back cover

the river is narrow with a rocky bed, and several series of rapids occur. Downstream from Jebba the river is navigable as far as the sea, flowing through broad and shallow valleys five to ten miles wide with extensive fertile swampy plains on each side and many islands within the river.

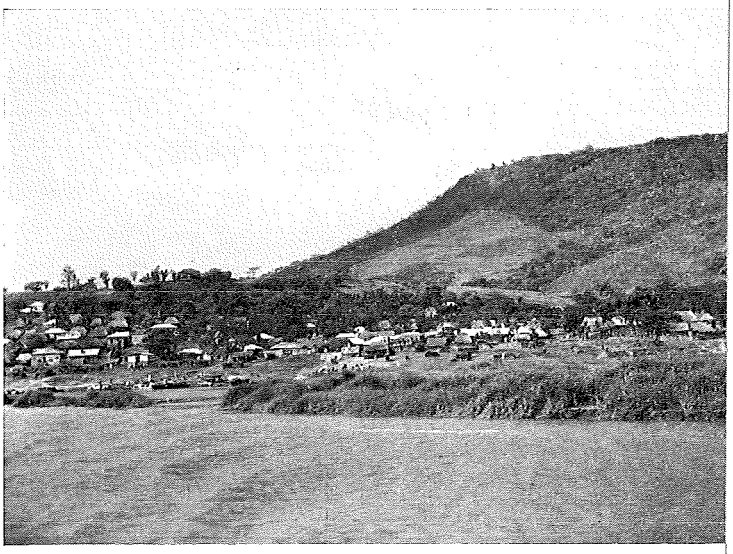
Before Baro is reached the river turns south-east; on the left a few flat-topped hills are to be seen. Baro (Mile 434) is the railhead of the line from Kano and plays an important role in the evacuation of the groundnut crop from the Northern Region and, in fact is one of the most important ports on the Niger (Photograph 2.1.1-2, i.e., III, 2.3.1-19).

Some miles downstream from Baro the table-mountains also appear on the right bank and at places the flat-topped hills still rise up over considerable distances in all their ancient grandeur, with precipitous slopes on each side. More frequently, however, the escarpments are rounded off and eroded by lateral valleys, while at times they recede to a distance and leave between themselves and the river a more or less extensive plain with here and there a flat-topped remnant of the once continuous plateau. For more than 20 miles the Niger flows between the broken walls of what once was a magnificent river gorge two miles wide in the ancient peneplain.

At Lokoja (Mile 362) the Niger is joined from the east by its largest tributary, the Benue (see 2.1.2), which about doubles the annual discharge of the river. Downstream from Lokoja the hills close in rapidly and the channel becomes narrow and rocky. Lofty granite domes and rounded hills separated by wooded valleys rise up on each bank and this part of the Niger, from Ogbo to Itobe, is considered the most picturesque section of its lower course.

The few rocks which protrude into the shipping channel are marked by buoys, and as the combined eroding forces of the Niger and Benue have been strong enough to cut a deep channel into the rocks of the Basement Complex, the currents are only a little swifter than in the other parts of the river, so that navigation through the so-called Rocky Section of the Niger is comparatively easy.

After a short stretch where the river flows through its own alluvium, the Niger narrows again at Idah (Mile 310) and flows between sandstone cliffs, which pass into stretches of wooded rising ground.



PHOTOGRAPH 2.1.1-3

Mount Patti and the native town of Lokoja

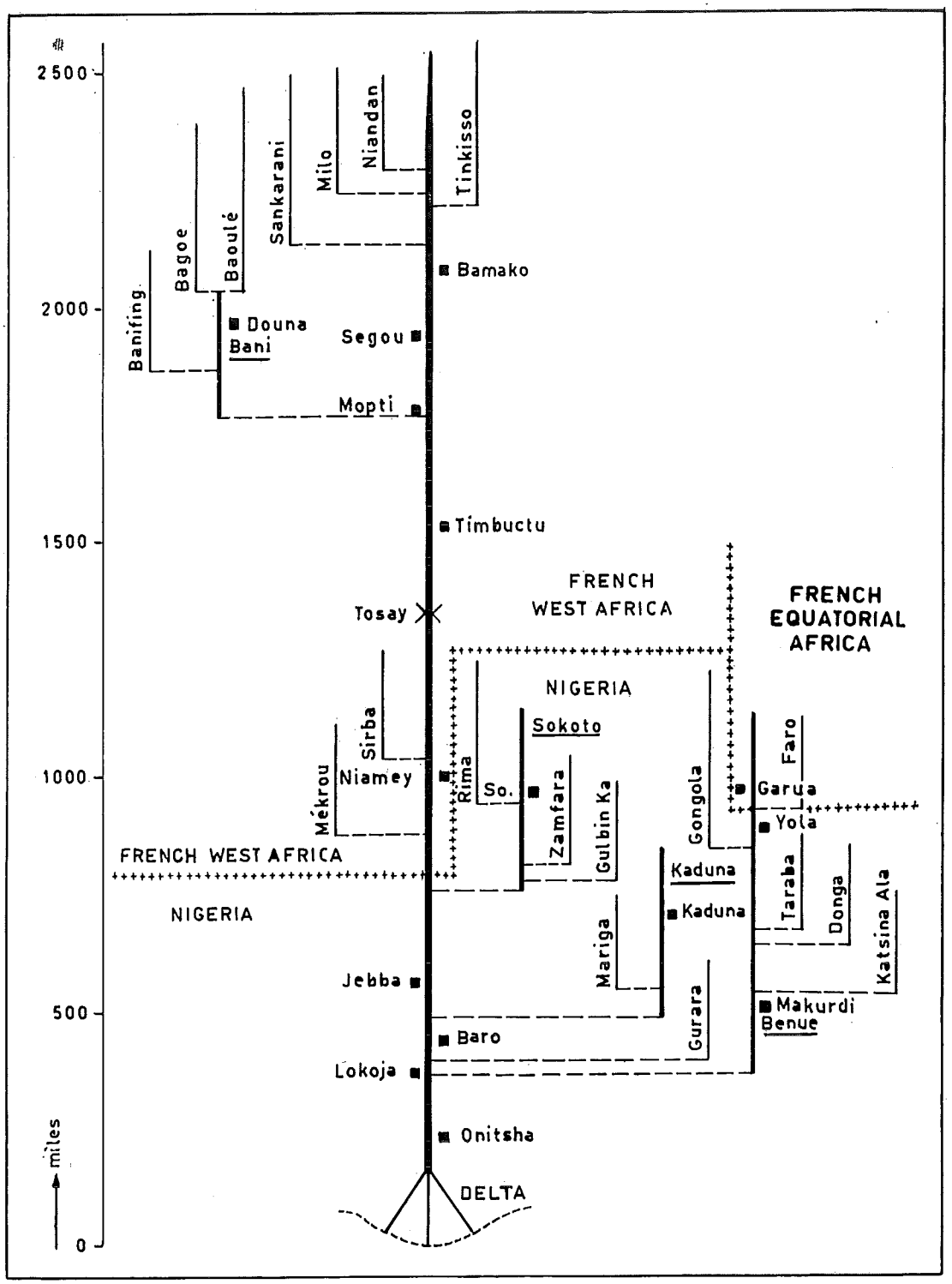


DIAGRAM 2.1.1-4

The Niger and its main tributaries

The Niger below Idah is bordered on the right bank at a distance by gently-sloped low hills. On the left bank a 20-mile wide plain of alluvium, tapering towards the valley-narrowing near Onitsha, stretches as far as the course of the Anambra River. After the river leaves the Rocky Section, the banks are for the greater part sandy and covered with rather dense vegetation. Many villages and small towns are found along this part of the river, which flows with a fairly uniform slope of 8.5×10^{-5} through a one-mile wide river-bed. Numerous sand-banks which emerge from the river as soon as the water-level falls some 5 to 10 feet below its H.W.-stage, tower above the river during the low-water season when shipping, although with some restrictions, is still possible because of the Black Flood phenomenon (see III, 4.5.4).

At Onitsha (Mile 232) which is the largest town along the Niger, with a very important and large market, the river-valley narrows for the last time.

After passing the last rocky obstruction and still heading due south, the Niger flows in its own alluvial deposits, and finally bifurcates in many branches and reaches the ocean, into which it has built out a vast delta.

The drainage area of the Niger amounts to 430,000 sq. miles; it is drained by many affluents and in Diagram 2.1.1-4 (i.e., III, 2.3.1-1) an outline is given of the most important Niger

TABLE 2.1.1—5

MILEAGE OF VARIOUS TOWNS ALONG THE NIGER AND ITS MAIN TRIBUTARIES

NIGER	2,550 miles
Escravos	0
Burutu	40
Warri	44
Siama	88
Patani	130
Aboh	177
Onitsha	232
Illushi	272
Idah	310
Itobe	332
Lokoja	362
Budon	399
Baro	434
Jebba	556
Bussa	642
Yelwa	688
Frontier	790
Malanville	811
Say	955
Niamey	995
Tillabery	1,068
Labbenzenga	1,149
Ansongo	1,211
Gao	1,270
Tosay	1,341
Timbuctu	1,528
Diré	1,574
Mopti	1,765
Sansanding	1,918
Ségou	1,940
Koulikoro	2,041
Bamako	2,081
Siguiri	2,209
Kouroussa	2,307
Source	2,550

BANI	700 miles
Mopti	1,765
Douna	1,963
Source	2,465
SOKOTO	**390 miles**
Confluence	753
Birnin Kebbi	860
Sokoto	884
Source	1,143
KADUNA	**360 miles**
Confluence	485
Zunguru	565
Kaduna	705
Source	845
BENUE	**810 miles**
Lokoja	362
Umaisha	401
Bagana	434
Loko	454
Makurdi	510
Abinsi	528
Ibi	614
Kwatta Nanido	712
Lau	778
Gamadio	815
Numan	846
Yola	888
Wuro Boki	916
Frontier	926
Garua	972
Riao	1,008
Lagdo	1,011
Source	1,172

FARO	235 miles
Confluence	926
Beka	950
Safai	983
Source	1,160
GONGOLA	**380 miles**
Confluence	846
Bare	855
Shellem	877
Dadinkowa	935
Nafada	1,001
Source	1,226
TARABA	**200 miles**
Confluence	672
Gassol	691
Beli	753
Source	872
DONGA	**210 miles**
Confluence	636
Nyankwala	649
Donga	686
Source	846
KATSINA ALA	**215 miles**
Confluence	536
Sevav	570
Katsina Ala	610
Source	751

tributaries. Table 2.1.1-5 (i.e., III, 2.3.1-3) shows the mileage (counted from the navigation outlet of the Niger into the sea) of various major towns or gauge-stations on the banks of the Niger system.

Of the total length of 2,550 miles of the main river, about 75 %, or 1,930 miles, are useful for commercial shipping, divided into four navigable stretches (Diagram 2.1.1-6, i.e., III, 1.2.4-1).

2.1.2. The Benue (see III, 2.3.2)

The Benue, by far the largest tributary of the Niger, rises in the French Camerouns on the Adamawa Plateau at about 4,400 feet above sea-level. In its drainage area the average annual rainfall varies from 120″ in the upper reaches of the Katsina Ala River to 35″ in the middle course of the Gongola River.

Over the first 20 miles the river falls 2,500 feet, and during the next 90 miles another 1,200 feet, leaving for the remaining 700 miles to the Niger Confluence a fall of only 570 feet.

Between Yola (Mile 888, mileage from Escravos Estuary) and Wuro Boki (Mile 916) and at Makurdi (Mile 510) the river flows through sandstone rocks, but even at those places the bottom of the former rock valley is buried under many feet of sand deposits.

For 80 % of its length the Benue is a typical alluvial river, the greater part of which is of a somewhat braided type, with broad and fertile flood-plains on each side.

At Mile 972 high land takes the place of the flood-plains. Here the North-South road crosses the river, whilst on the embankment of Garua river-tows evacuate produce of the French Camerouns.

Downstream from Garua the slope of the Benue decreases to 13×10^{-5} at high water. The river, here often called the Garua Creek, meanders through a flood-plain and forms a fairly good shipping route. The river-bed and the banks consist of sand and clayish material, but locally rock outcrops are visible. The flood-plain, about 2 miles wide between Mile 972 and Mile 942, widens to 6 miles at the Faro Confluence (Mile 926).

The large quantities of sand brought down into the Benue by the Faro River are the cause of the completely different aspect downstream of the confluence (see Photograph III, 2.3.2-1). As the slope of the river below the confluence (25×10^{-5} at high water) is not sufficient to transport all the sand from the Faro and the Garua Creek, sand deposits slowly raise the valley-floor downstream from the Faro Confluence and this is the cause of the gentle slope of the Garua Creek. If the Garua Creek had a steeper slope, its depth would have been less, so although the Faro sand causes trouble for navigation on the Wuro Boki Flats, it also acts indirectly in creating a reasonably deep fairway from the confluence to Garua.

At Dasin Hausa sandstone rocks on the south side of the river approach the Bagele Hills (north of the Benue) close enough to form the defile which is considered a dam-site of a possible Yola reservoir (see Diagram VI, 8.5.1-1). From Mile 904 to Mile 897 the Bagele Hills and the hills of Dasin Hausa, Dasin Pagan and Njobolyo border the river. The Bagele Hills are wooded, in contrast to the more cultivated country south of the Benue, where only scattered trees and shrub survive.

Yola, or rather Jimeta which is the name of the town at the riverside at Mile 888, is after Makurdi the most important Nigerian port on the Benue. The rocky shore at Jimeta (left bank) and also at Dalmare (right bank) prevent erosion of the embankment.

The river between Yola and Numan (Miles 888—846) shows in its general aspect: sand-banks, fairly straight high-water shores and one or two meandering channels mostly with islands in between and flood-plains covered with grass, brushwood and scattered trees.

Opposite Numan the Gongola flows into the Benue; it is the main Benue tributary from

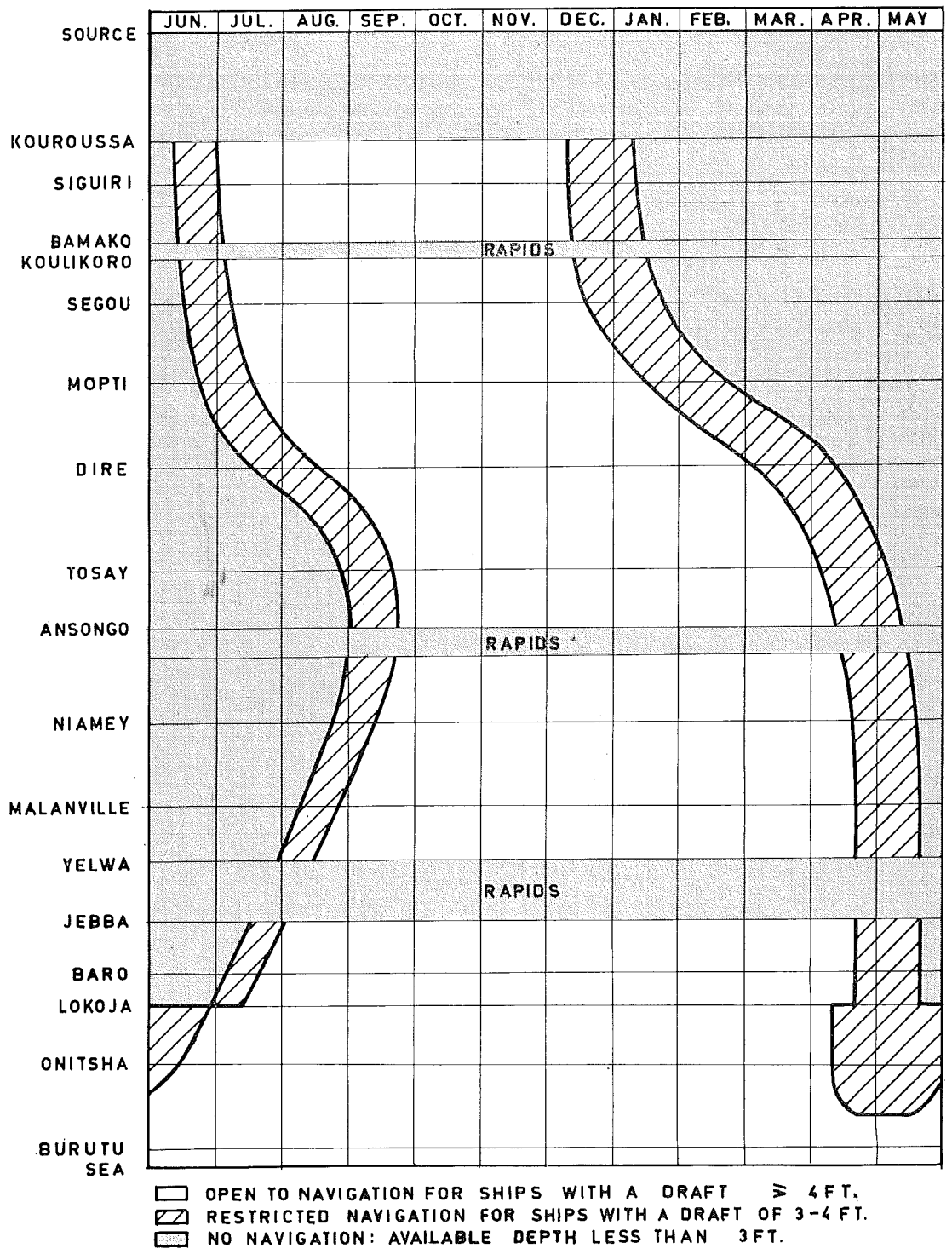


DIAGRAM 2.1.1.-6

Navigability of the Niger

the north. Numan lies on the left bank on high ground and its riverside just beyond the rock outcrop at Mile 846½ would be excellent for port installations.

The Kabawa Flats, and in fact the whole river stretch from Numan to Lau, are difficult to navigate. Rapidly-changing shoals often delay ships that either run aground or have to wait for a rise. The Gamadio Flats (around Mile 818) are, together with the Wuro Boki Flats (Mile 922), the most notorious places on the Benue. The Gamadio Flats are described in detail in III, 6.5.3.

The north bank of the Benue is fairly straight from Numan to Lau, with the exception of the ten-mile stretch between Gamadio and Tungaladan.

PHOTOGRAPH 2.1.2-1

Confluence of Benue and Taraba

The foothills of the rugged Lamurde and Kwoni Hills, clearly visible from the Benue, border the flood-plains on the northern side. These mountains are also referred to as the Muri Hills. South of the river, at Mile 882, a small volcano (600 feet high) leaps to the eye. On the south side the valley slowly rises to higher land, and in the distance the Lankoviri Hills (Fumbina Mountains) are visible.

The tributaries of the Benue, even the larger ones such as the Katsina Ala, Donga and Taraba, enter the Benue unobtrusively.

The Taraba forms a fluviatile delta where it enters the Benue. The main channel flows into the Benue at Mile 672, (see Photograph 2.1.2-1, i.e., III, 2.3.2-7) and secondary branches debouche at Miles 670 and 643. Older courses had their junction at Miles 685 and 652.

One or two miles below the Taraba Confluence flats occur; these would have been a hindrance to navigation if the narrow deep creek along the left bank had not been there. Not only here but on many other places on the Benue and Niger these secondary channels are preferable to the main channel. This creek, from Mile 671 to Mile 667, is often called the Taraba Creek. It is a branch of the Benue, but it carries almost exclusively water from the tributary. There is a sharp distinction between Benue water and Taraba water, the latter being much clearer and darker, containing less silt. Not until many miles downstream from the confluence is the water of the two rivers completely mixed.

The Benue below the Donga Confluence is 50 % wider than above the Taraba Confluence, whereas its depth is roughly the same. The average slope decreases from 15×10^{-5} to 13×10^{-5} which is maintained down to Lokoja.

The Katsina Ala is the last large tributary of the Benue. From here until the confluence with the Niger, the Benue undergoes no major changes in slope, discharge, sand or vegetation. Upto a few miles beyond Abinsi (Mile 528) the rivers winds round large islands, yet the least available depth is about the same as downstream of Makurdi.

At Makurdi sandstone hills force the river into a bed 2,200 feet wide, where the only bridge across the Benue has been built. The riverside at Makurdi south bank is over a length of more than a mile suitable for the loading and unloading of barges.

Downstream from Makurdi the Akpanaja Flats (Miles 502—506) have been regarded as troublesome to navigation. Although they indeed belong to the shallowest parts of the river between Lokoja and Makurdi, the Benue Bar at the Niger-Benue Confluence in its present natural state determines the opening of the season in most years.

Passing Umaisha towards Mozum (Mile 400) the table-mountains, a common feature of

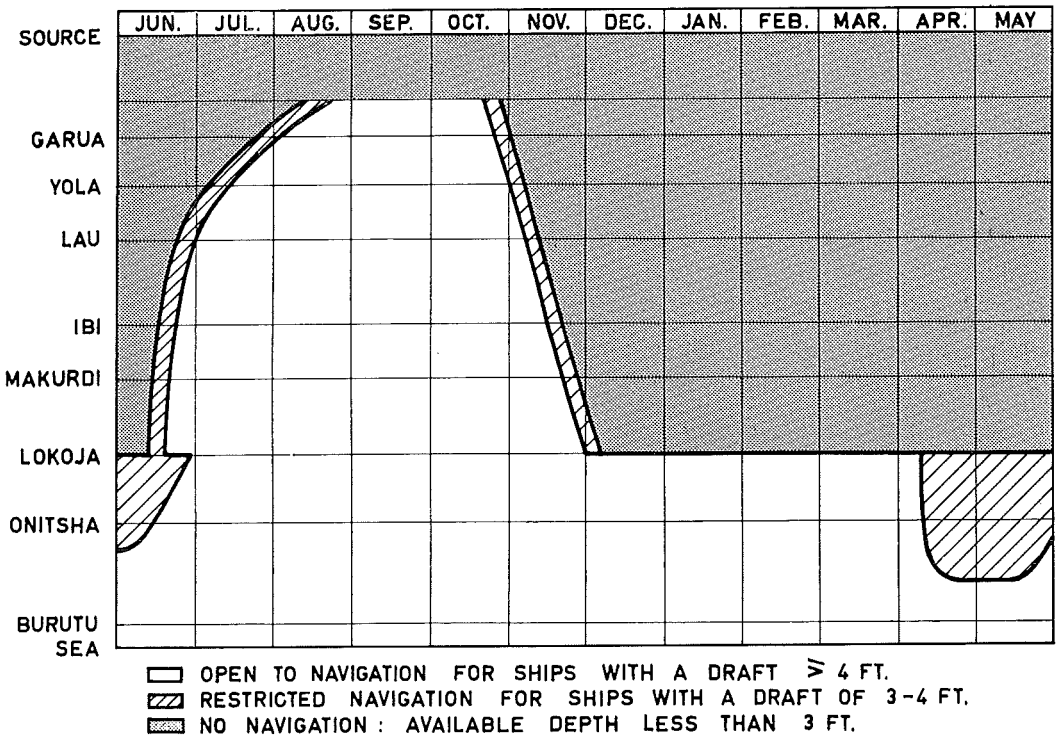


DIAGRAM 2.1.2-2

Navigability of the Benue

the Niger Valley, become visible. And 810 miles from its source, in annual run-off comparable with the Niger above Lokoja, the Benue debouches into the Niger.

The Benue is seasonally navigable from Garua downwards, as illustrated by Diagram 2.1.2-2 (i.e., III, 1.2.4-2).

2.2. GEOLOGY OF THE RIVER-BASINS

2.2.1. Evolution of the Niger and Benue

An outline has been given of the geology of Nigeria, based upon reports and publications prepared by the Geological Survey Department. It may be summed up as follows:

In a great part of the country rocks of the Basement Complex crop out, consisting of metamorphic and plutonic rocks. Among these the Younger Granites, which contain tinstone and other minerals, are of considerable economic interest. Sedimentary formations of the Cretaceous and Tertiary ages occur along the Lower Niger Valley and along the Benue Valley, often covering the older basement rocks to a very considerable thickness. During the late Tertiary, periods of peneplanisation and accumulation alternated with periods of uplifting and erosion. In the last part of the geological history, during the Quaternary, in several areas movements of subsidence alternated with upheaval, while the same period was also characterised by variations of the climate and of the sealevel. The outcome has been the present landscape of Nigeria with wide valleys, ridges, plateaux, inselbergs and a few small volcanoes scattered over a relatively level country and with a huge delta built up by the Niger River protruding into the ocean.

The studies made at the site of a proposed bridge and at several valley narrowings have provided new and hitherto unpublished geological data which shed some more light on the evolution of the main drainage system of the country.

The most important of these new observations concerns the presence of a buried valley floor under the entire length of the river-beds of the Benue River on Nigerian territory and of the Lower Niger River. The existence of a thick alluvial fill on the valley bottom has a direct bearing on any projected work across the rivers, for bridges as well as dams. By correlating the origin of the now buried valleys with a low sea-level contemporaneous with a Quaternary pluvial period, and their aggradation as a result of an interpluvial high sea-level, and furthermore taking into consideration the genetical relation existing between several soil types (such as laterites and wind-blown sand) and the climate, it has been possible to date tentatively the various terraces and stages of valley formation observed during the study or recorded by other authors from the Upper Benue and Upper Niger areas and to condense them into a chronological table.

Thus it has become clear that the modern Niger and Benue river systems were established at some time during the Quaternary, possibly during the Kamasian/Kanjerian Pluvial. The Niger drainage basin then included the Southern Tilemsi, Azaouak and other now almost entirely degradated Saharian valleys, while the Benue was temporarily joined by the Logone River. The Upper Niger River, however, which formerly flowed into the Senegal Valley and in a later period debouched into the Araouane Basin, only became part of the Lower Niger drainage system during the Gamblian Pluvial. The complicated geological history of the Niger and Benue areas, which in some aspects is completely different, and the ensuing variations in flow and sediment of these rivers, explain several of their special features.

2.2.2. The modern valleys

The morphological and geological features of the country are of considerable importance from an agricultural point of view. In the Gongola Valley valuable soils occur, and the area

is one of the most productive regions of the Benue drainage basin. Along the Benue River and its tributaries draining the Jos Plateau, along the Lower Taraba, Katsina Ala and Donga Rivers as well as along the Niger from Jebba to Lokoja and along the Lower Kaduna River, fadama areas occur, suitable for rice-growing. Other parts of the Benue Valley, as well as the Niger Valley, do not play an important part in the country's agricultural economy.

Report and papers prepared by the Geological Survey Department describing the mineral deposits of the country show that a further exploitation of these natural resources will not have a major influence upon shipping on the Niger and Benue Rivers. Only the ironstone deposits situated around the Niger-Benue Confluence, if their mining would become economically justified in the future, would for transportation depend on shipping. The sites near Jakura and Makurdi, where cement manufacturing has been projected, are situated near the main rivers where shipping facilities for fuel and for the finished products are available.

In view of the proposed civil engineering works, a survey has been made of the occurrence of natural building materials in Nigeria. Rock and stone for construction purposes and concrete manufacture are found only in the so-called "Rocky Section" of the Lower Niger between Idah and Lokoja and along the Upper Niger between Jebba and Yelwa. Sand occurs everywhere along the main rivers in very considerable quantities. Gravel has been observed in minor quantities in the Benue Valley and in the Lower Niger Valley. Large quantities of gravel of good quality might be expected to occur in the upper reaches of the Benue tributaries, the Nasarawa and Akwanga areas and the Cameroun Mountain area. Gravel is found also in large quantities in the Niger Valley between Jebba and Yelwa.

The Report discusses the geology of valley narrowings at Lagdo, Cossi, Benue Rocky Section above Yola, Makurdi (all in the Benue Valley), Dadin Kowa, Kombo, Kiri-Bobore (all three in the Gongola Valley), Dalli (in the Taraba Valley), and Awuru, Jebba, Niger Rocky Section between Lokoja and Idah, and Onitsha (all four situated in the Niger Valley). A field reconnaissance has been carried out at Benue Rocky Section, at Makurdi, along the Gongola River, along the Taraba River, at Jebba, along the Niger Rocky Section and at Onitsha. Reconnaissance drilling has been carried out upstream of Yola and, for a bridge project, at Onitsha.

The merits of the various rocks for the construction of dams are explained in III, 3. At every site, with the possible exception of the Awuru defile, a considerable thickness of pervious alluvial deposits is expected to lie underneath the present river-bed. At Lagdo, Cossi, Dalli, Awuru and Niger Rocky Section rocks of the Basement Complex (granites, gneisses, etc.) form the sides of the valley. At Jebba the defile is bordered by quartzites; at the Benue Rocky Section, Makurdi, the three Gongola narrowings and Onitsha the sides of the valleys consist of sandstones. At a number of sites faulting and gentle folding is apparent. Moreover, volcanic activity has been observed to have taken place in the past at a few of the sites studied (Kiri-Bobore and the Benue Rocky Section upstream of Yola).

2.3. HYDROLOGY OF THE RIVERS

2.3.1. Water-levels (see III, 4.2)

For the purpose of collecting more detailed data NEDECO has since 1955 extended the existing system of gauges by installing new gauges on the Niger below Jebba and on the Benue and its most important tributaries within Nigerian territory.

Primary gauges were maintained by NEDECO at the following stations up to the end of the investigations and were handed over to the Nigerian Government in April 1958:

on the Niger: Jebba, Egwamama, Budon, Shintaku, Idah and Isara-Aboh;
on the Benue: Wuro Boki, Yola, Numan, Lau, Angwan Taru, Ibi, Makurdi, Loko and Umaisha;
on the Gongola: Dadin Kowa and Bare;
on the Taraba: Beli and Gassol;
on the Donga: Donga and Nyankwola; and
on the Katsina Ala: Katsina Ala and Sevav.

The gauges at Baro, Lokoja and Onitsha on the Niger have always been maintained, firstly by the Nigeria Marine Department and afterwards by the Inland Waterways Department.

The elevation of each gauge is known relative to benchmarks erected on the shore, so that damaged or washed-away gauges can be replaced in their original positions.

The result of a Geodetic Leveling, executed on behalf of the NEDECO Niger and Benue Investigation by the Federal Survey Department, became known in the course of 1957. By means of this levelling the elevation relative to Mean Sea Level could be given of the benchmark

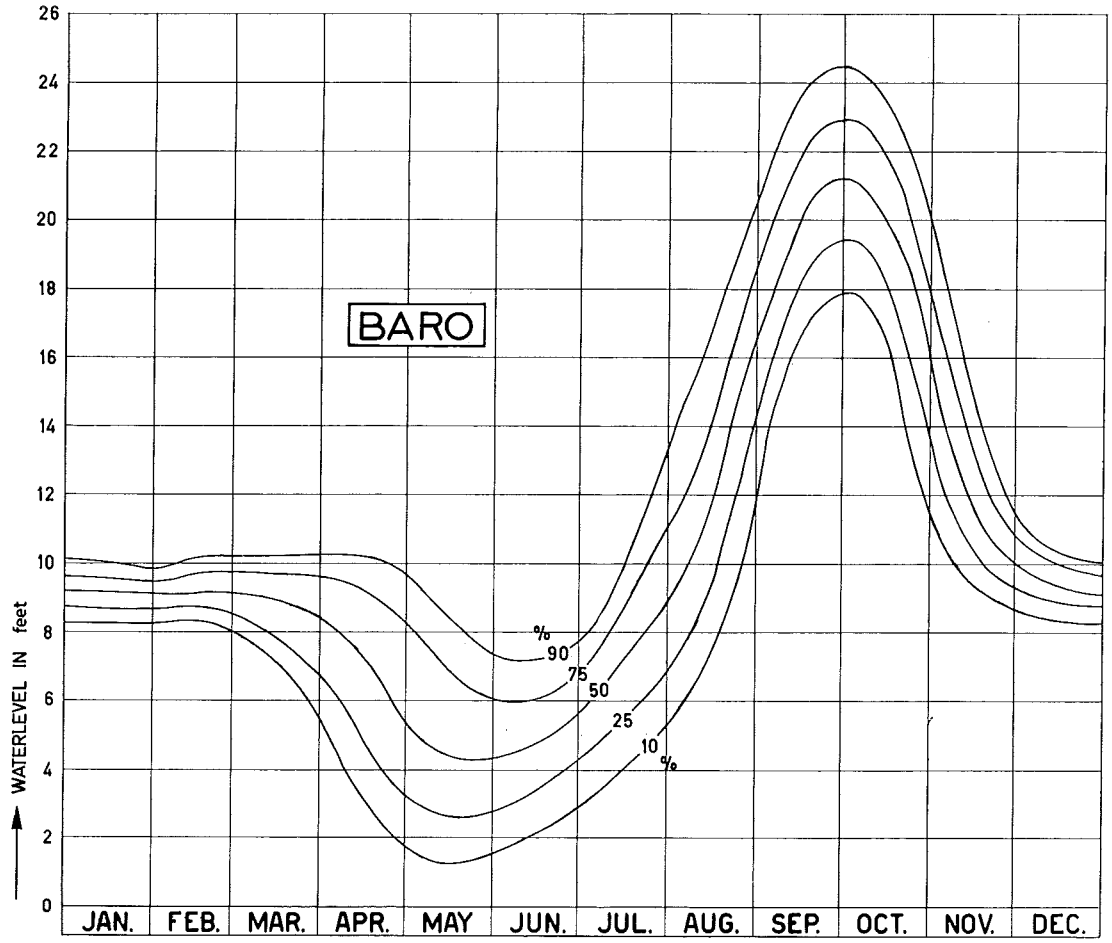


DIAGRAM 2.3.1-1

Frequencies of river-stages at Baro for a fixed day

and thus of the datums, of most of the primary gauges in the Niger-Benue Basin within Nigeria.

A register of water-level records was kept up-to-date at NEDECO Headquarters in Lokoja and was handed over to the Inland Waterways Department in April 1958.

The curve obtained by plotting water-level observations of a river-gauge against the time on which they were taken is called a water-level hydrograph. The hydrographs reproduced in III, 4.2.2. show clearly that there is a remarkable seasonal variation in river-stages.

This is also illustrated by the frequency curves of the water-levels (III, 4.2.3). From these diagrams can be read for every day of the year which water-level has not been reached during a certain part (in %) of the period over which records are available.

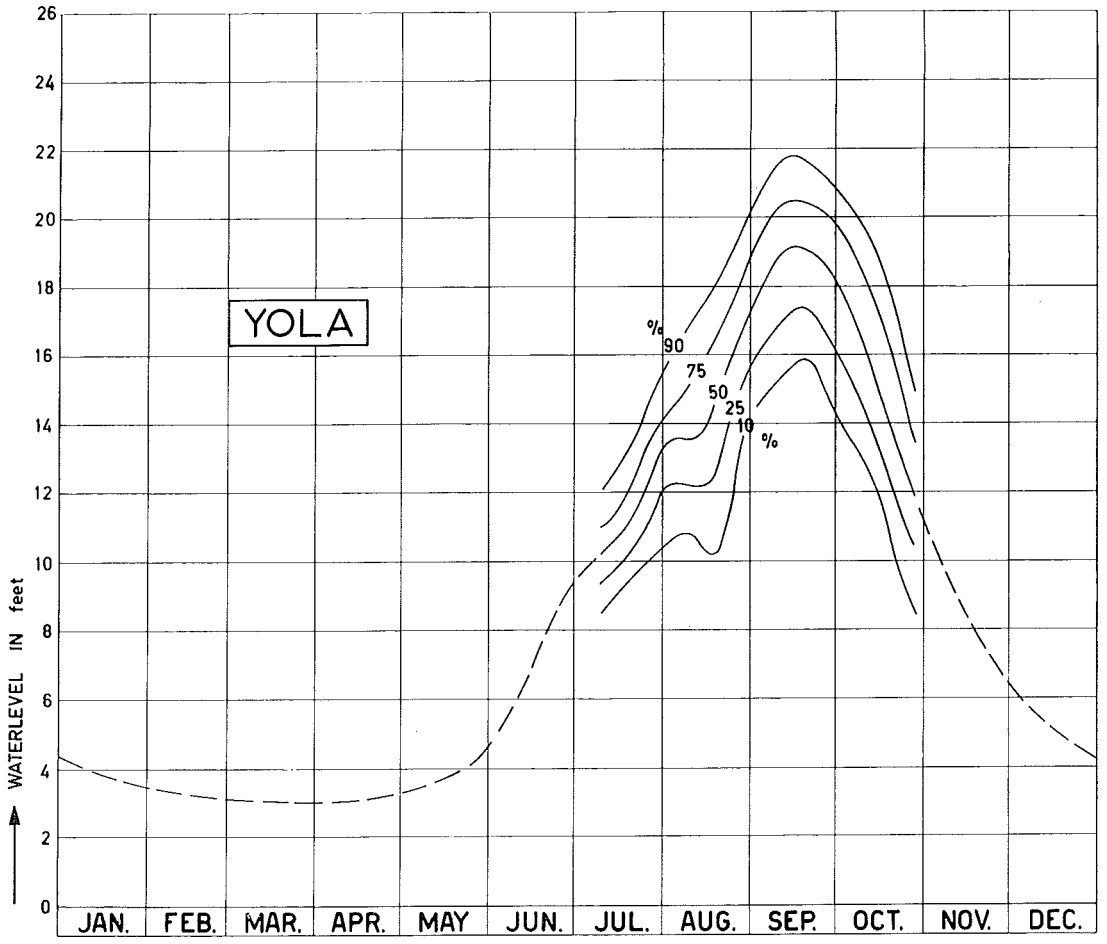


DIAGRAM 2.3.1-2

Frequencies of river-stages at Yola for a fixed day

Along the Upper Niger, from Jebba to Baro (Diagram 2.3.1-1) the water-levels are rising due to the local rains from July to early October, when the annual peak-level is reached. The river then falls until December, when the fall is balanced by the second flood which has travelled from the headwater area in French West Africa after having been retarded in the swamp area south-west of Timbuctu. This Black Flood (as it is called because its waters are clearer than those of the silt-laden local White Flood) results in a period of sustained water-levels until March or April, when there is a further fall, continuing until June.

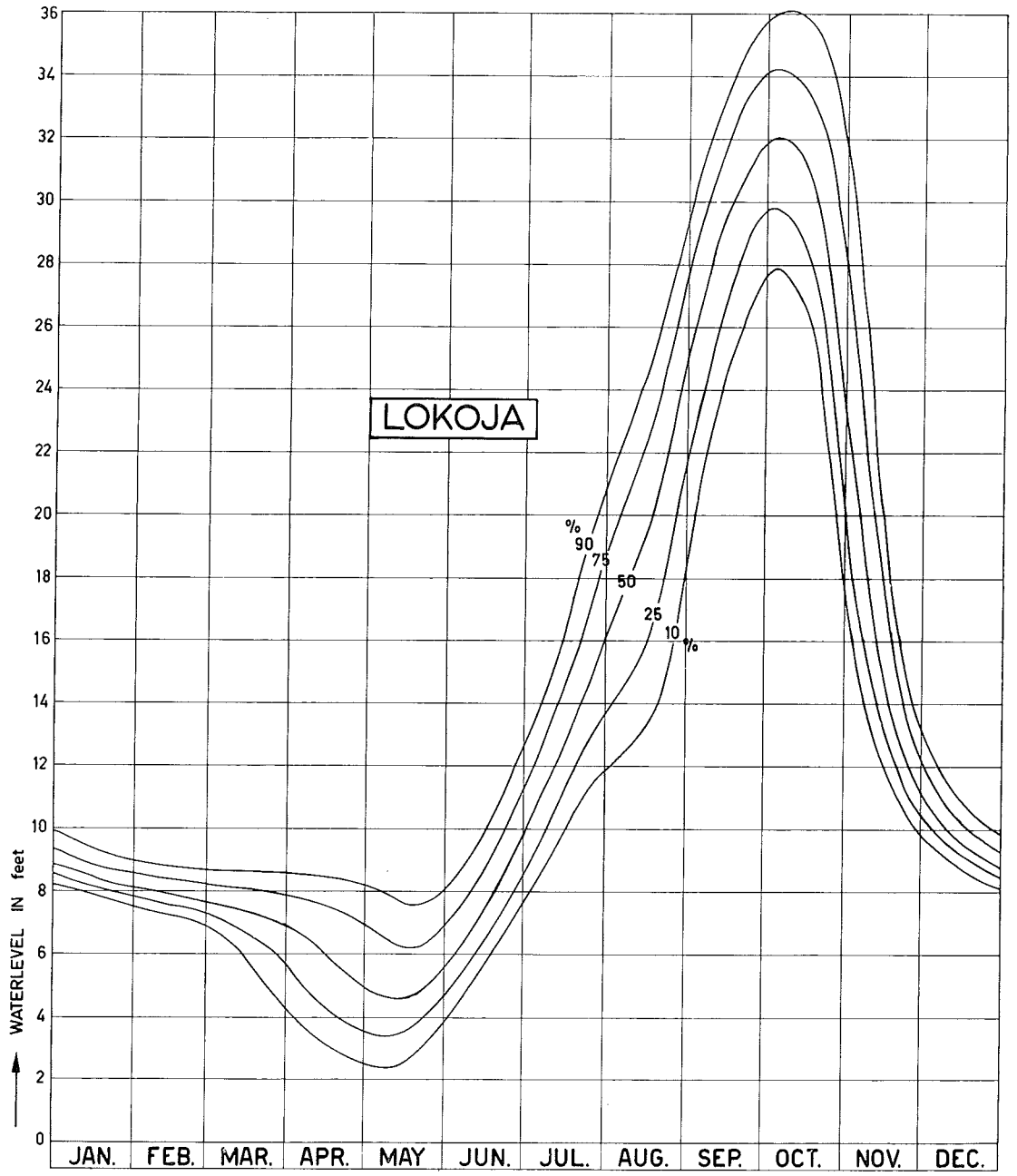


DIAGRAM 2.3.1-3

Frequencies of river-stages at Lokoja for a fixed day

On the Benue (Diagram 2.3.1-2, i.e., III, 4.2.3-2), stages are rising from May to October, although the hydrographs are not going upwards smoothly. During July of August there may be a temporary fall.

Along the Lower Niger (Diagram 2.3.1-3, i.e., III, 4.2.3-5), the influence of the Benue is noticeable, as the continued Benue fall is superimposed on the Black Flood, and the Benue rise causes the Lower Niger water-levels to rise from May or June onwards.

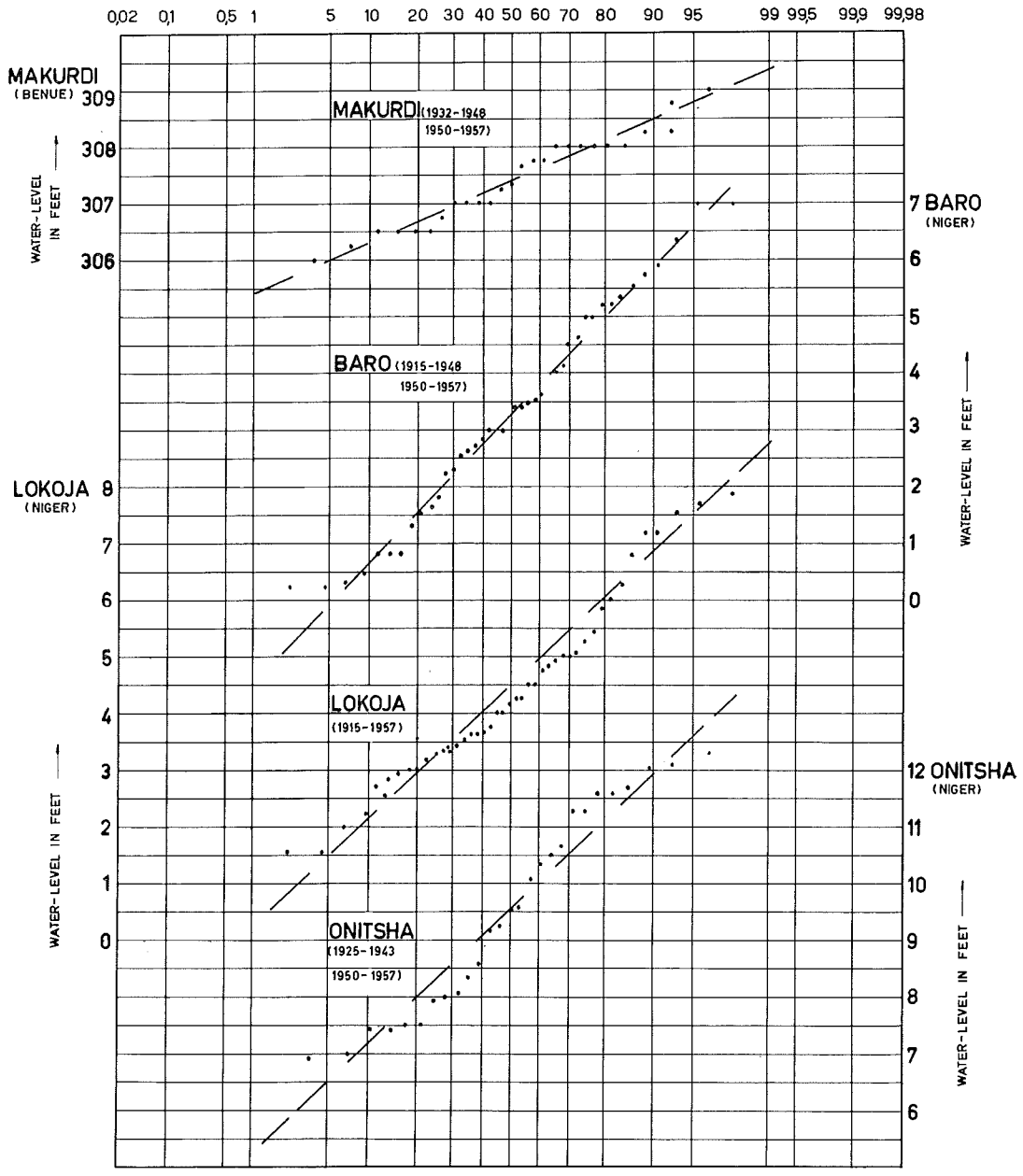


DIAGRAM 2.3.1-4

Frequencies of annual lowest water-levels along Niger and Benue

The general trend of the hydrographs of the Benue tributaries is the same as for the Benue, with the exception of the Gongola (Dadin Kowa and Bare), where river-stages show their maximum during August or September.

The annual maximum and minimum water-levels for a number of stations along the Niger and Benue Rivers have been plotted on normal probability paper for those periods in which reliable records were available, as shown, for instance, on Diagram 2.3.1-4 (i.e., III, 4.2.4-4). From these graphs it can be seen whether the highest and the lowest river-stages of a particular

year have been exceptional or not. Moreover, these data are of importance for the design of quays or flood-walls.

A certain relation exists between the readings of a gauge at the upstream end of a river-section and those of a gauge at the downstream end, when the lateral inflow into that river-section is negligible with regard to the river-discharges. A definite time-lag will then occur between a reading at the upstream gauge and the corresponding reading at the downstream gauge, a lag which is equal to the time required by a flood-wave to travel from the one gauge to the other. These relations and time-lags have been computed in III, 4.2.7.

To compare soundings made at various river-stages, they must be reduced to the same datum. In the beginning of this Investigation, the reduction-planes were chosen arbitrarily (Table 2.3.1-5, i.e., III, 4.2.8-1) and termed Low River Level or L.R.L., which has been used throughout this Report. But with the help of the data now available, it is recommended to define a new L.R.L. as being a plane connecting those readings at the various gauges along the river below which navigation with a draught exceeding 5 feet is generally not possible. These gauge readings are indicated in Columns 3 and 6 of Table 2.3.1-5.

TABLE , 2.3.1—5

DATUMS OF SOUNDINGS

BENUE			NIGER		
1	2	3	4	5	6
STATION	gauge reading corresponding to reduction-plane used during 1955—1957	gauge reading corresponding to proposed reduction-plane	STATION	gauge reading corresponding to reduction-plane (L.R.L.) used during 1955—1957	gauge reading corresponding to proposed reduction-plane
Wuro Boki	11′ 6″	12′	Baro	11′	9′
Yola	11′ 2″	12′	Lokoja	9′	8′
Numan	8′ 10″	11′	Idah	0′ 6″	0′
Gamadio	15′	— (1	Onitsha	13′	12′
Lau	15′ 6″	17′	Aboh	2′	1′
Ibi	17′ 8″	13′ (1			
Makurdi	313′	312′ (1			

(1 it is advised to reconsider these figures

2.3.2. Slopes (see III, 4.2.5)

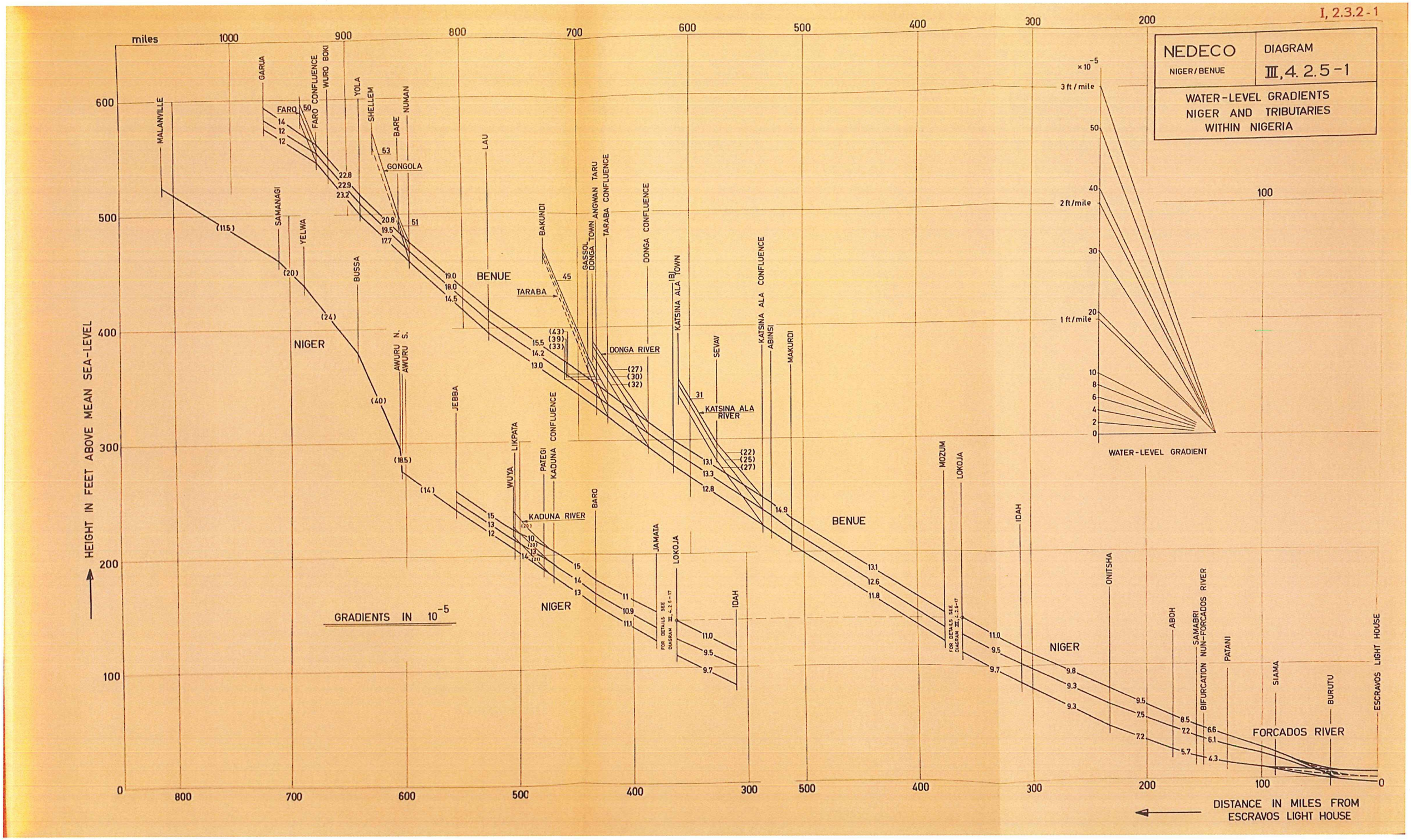
The slope or water-level gradient of a river is shown by plotting comparable water-levels with respect to a horizontal reference-plane (Mean Sea-Level) against the longitudinal axis of the river. This has been done in Diagram 2.3.2-1 (i.e., III, 4.2.5-1) for high, medium and low stages.

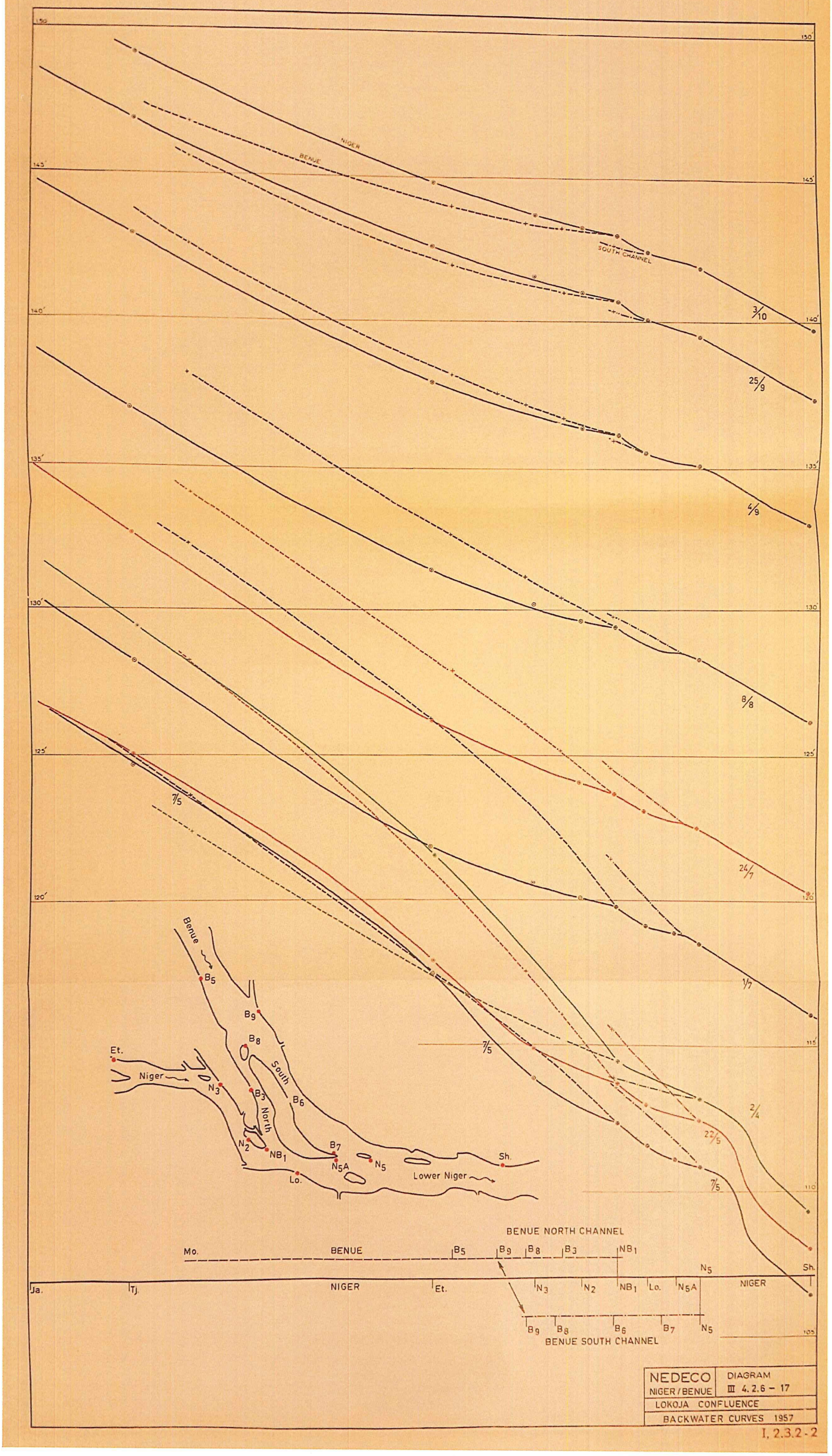
The slopes may be expressed as dimensionless quantities obtained by dividing the drop of the water-level by the river length over which this drop takes place, commonly in units of 10^{-5} (equal to 0.053 feet per mile). These quantities are written along the water-levels in the Diagram, being averages over fairly long river-stretches.

I, 2.3.2 - 1

NEDECO	DIAGRAM
NIGER / BENUE	III, 4. 2. 5 - 1

WATER-LEVEL GRADIENTS
NIGER AND TRIBUTARIES
WITHIN NIGERIA




150
145
140
135
130
125
120
115
110
105
NIGER
BENUE
SOUTH CHANNEL
3/10
25/9
4/9
8/8
7/5
24/7
1/7
7/5
2/4
22/5
7/5
Benue
B5
B9
B8
B3
B6
B7
N5
N5A
NB1
N2
N3
Et.
Niger
South
North
Lo.
Sh.
Lower Niger
BENUE NORTH CHANNEL
Mo.
BENUE
B5
B9
B8
B3
NB1
N5
Sh.
Ja.
Tj.
NIGER
Et.
N3
N2
NB1
Lo.
N5A
NIGER
B9
B8
B6
B7
N5
BENUE SOUTH CHANNEL
NEDECO
NIGER / BENUE
DIAGRAM
III 4.2.6 – 17
LOKOJA CONFLUENCE
BACKWATER CURVES 1957
I, 2.3.2-2

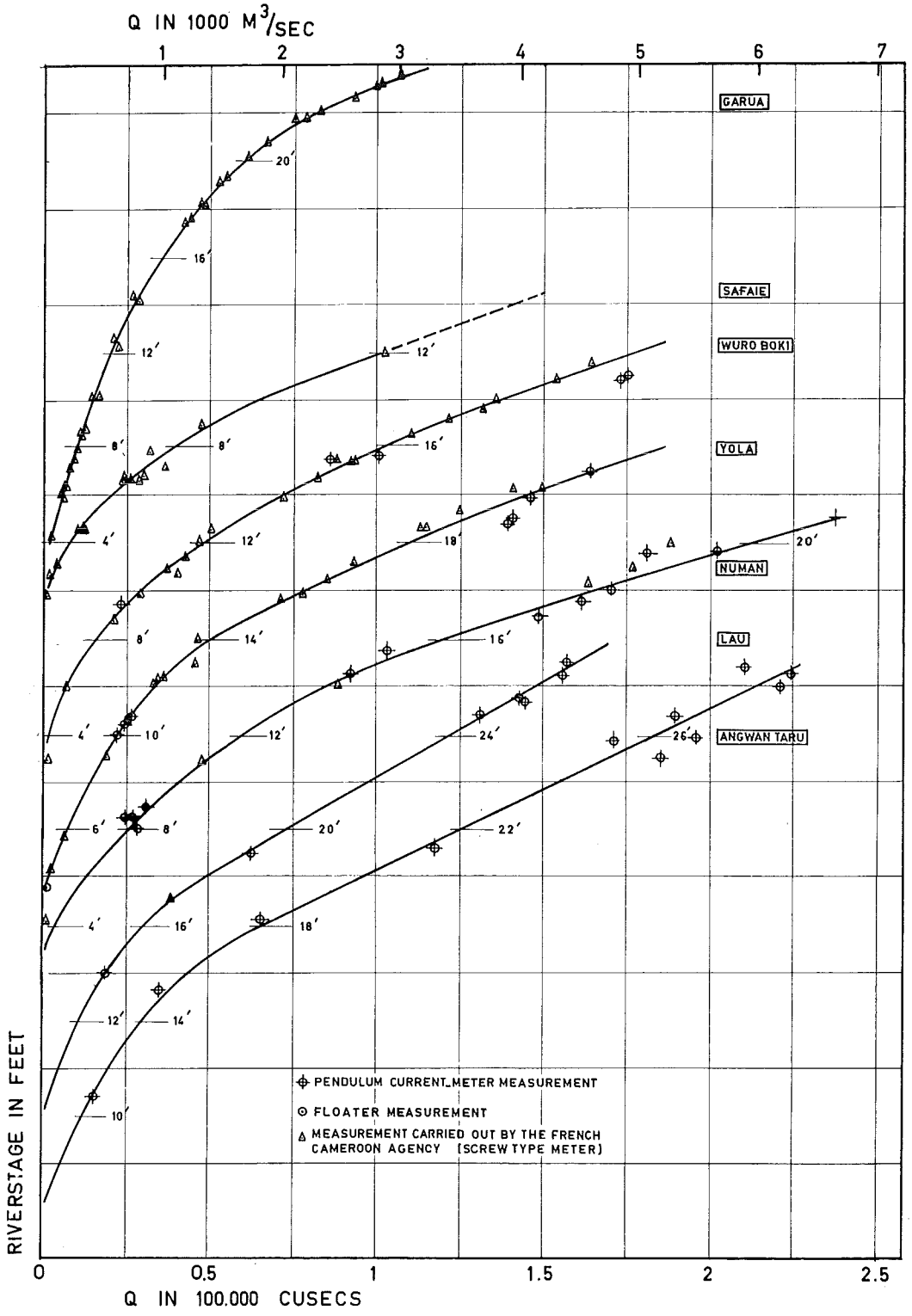


DIAGRAM 2.3.3-1

Discharge rating curves for Benue above Ibi

Slopes near a confluence of two rivers depend on the discharges arriving from both rivers. The water-level at and below the confluence is determined by the combined discharge, but for some distance upstream from the point of confluence there is a mutual influence of the two rivers, resulting in raise or draw-down (backstage).

Diagram 2.3.2-2 (i.e., III, 4.2.6-17) shows the successive backwater curves in 1957 of the water-levels around the Niger/Benue Confluence.

2.3.3. Discharges (see III, 4.3)

Throughout the three-years' investigation, river discharges have been measured at over twenty selected stations along the main rivers and their tributaries. By relating every measured discharge to the river-stage as read during the measurement at a gauge in the neighbourhood of the measuring-site, stage-discharge relation curves, or rating curves, have been obtained for a number of stations within Nigeria. Diagram 2.3.3-1 (i.e., III, 4.3.2-1) shows some of these rating curves as constructed for the Upper Benue.

Making use of these rating curves, the water-level frequency curves as mentioned in 2.3.1 can be converted into discharge frequency curves. The rating curves of 1955—1957, the only ones available, had for this purpose to be applied on water-level records dating as far back as 1914, a method which introduces some uncertainties as conditions determining the rating curve may have changed in the course of time. One of the resulting frequency curves is shown on Diagram 2.3.3-2 (i.e., III, 4.3.4-2).

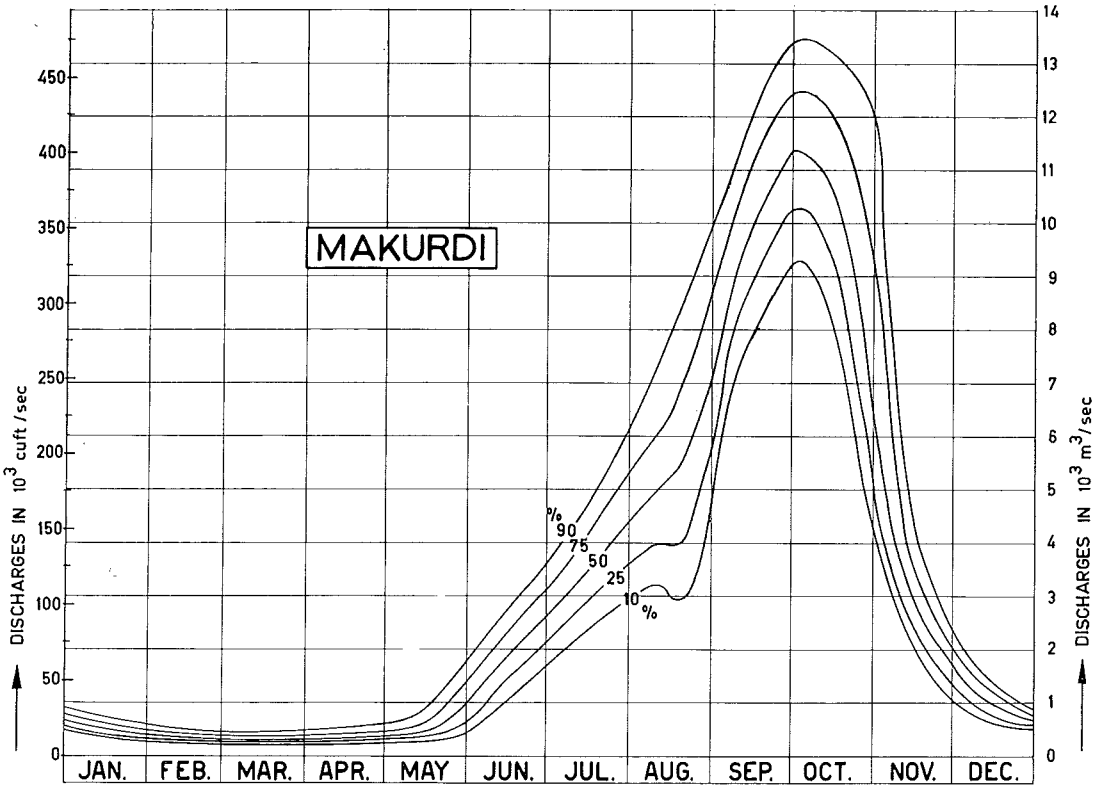


DIAGRAM 2.3.3-2

Frequencies of discharges at Makurdi for a fixed day

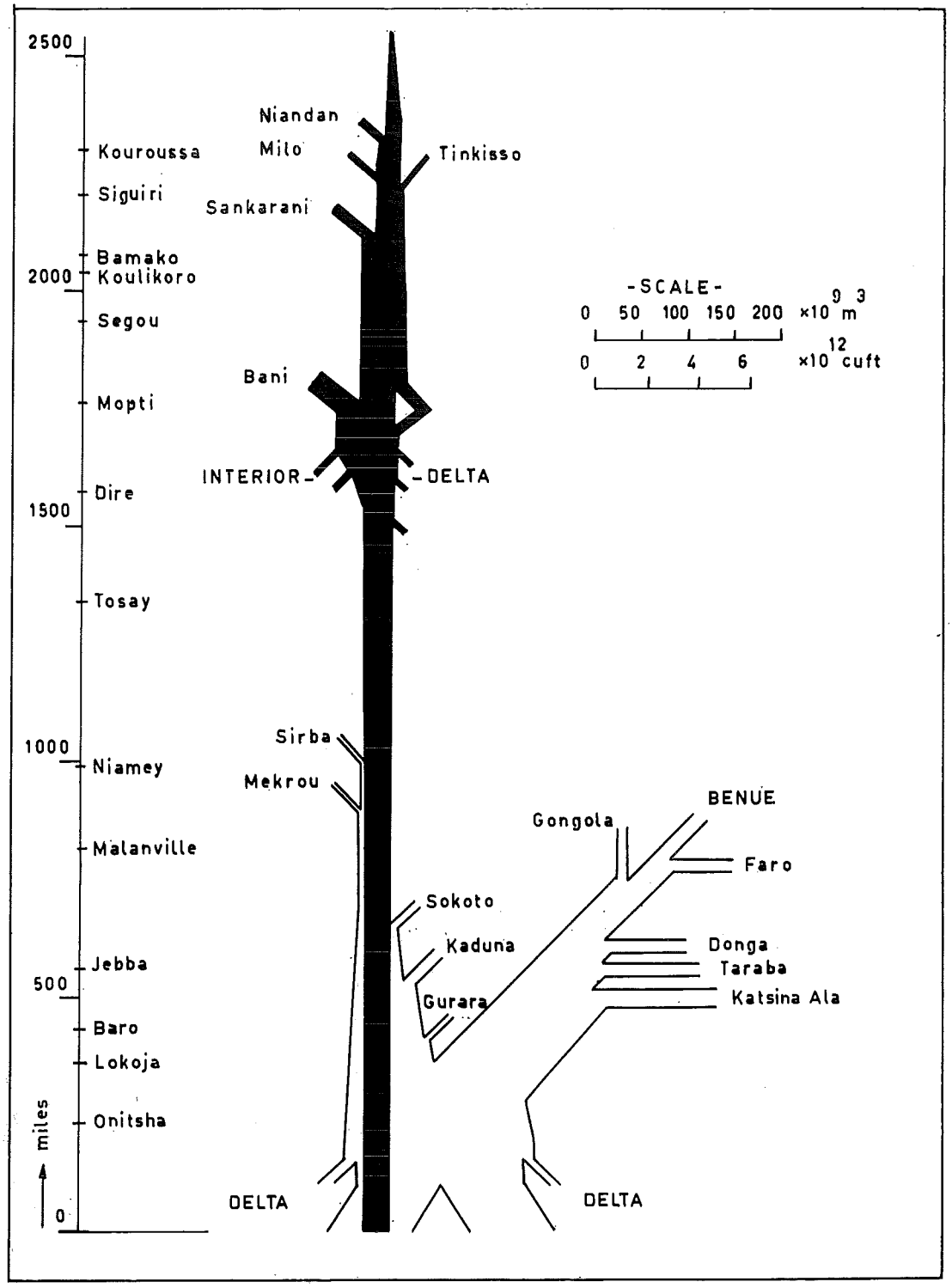


DIAGRAM 2.3.3-3

Schematic representation of the annual discharges of the Niger system

The average yearly water-discharges of the entire Niger/Benue system have been represented in Diagram 2.3.3-3 (i.e., III, 2.3.1-23) where the width of the rivers is a measure of their discharge.

For a clear picture of the range of the year-averages of the discharge, these have been plotted on probability paper, in which the discharge axis has a logarithmic scale whilst the horizontal axis shows the frequency of occurrence of average yearly discharges (Diagram 2.3.3-4, i.e., III, 4.3.5-5).

The average discharges as well as the specific discharges (i.e., the run-off per unit of time and per unit of area) have been compiled in Table III, 4.3.6-3.

The part of a hydrograph after the crest of a flood-wave has passed is called the recession curve. River-stages fall because the amount of water entering the river decreases, which, in its turn, is caused by a decrease of rain. By analysing the actual recession curves of a number of flood-waves for a particular station, it is possible to establish an ideal curve which would occur if, after the crest of a flood-wave has passed, no precipitation has fallen on the basin. Such recession curves have been established for Baro, Yola and Makurdi (III, 4.3.7); they are of importance for making post-flood predictions of least occurring stages or discharges.

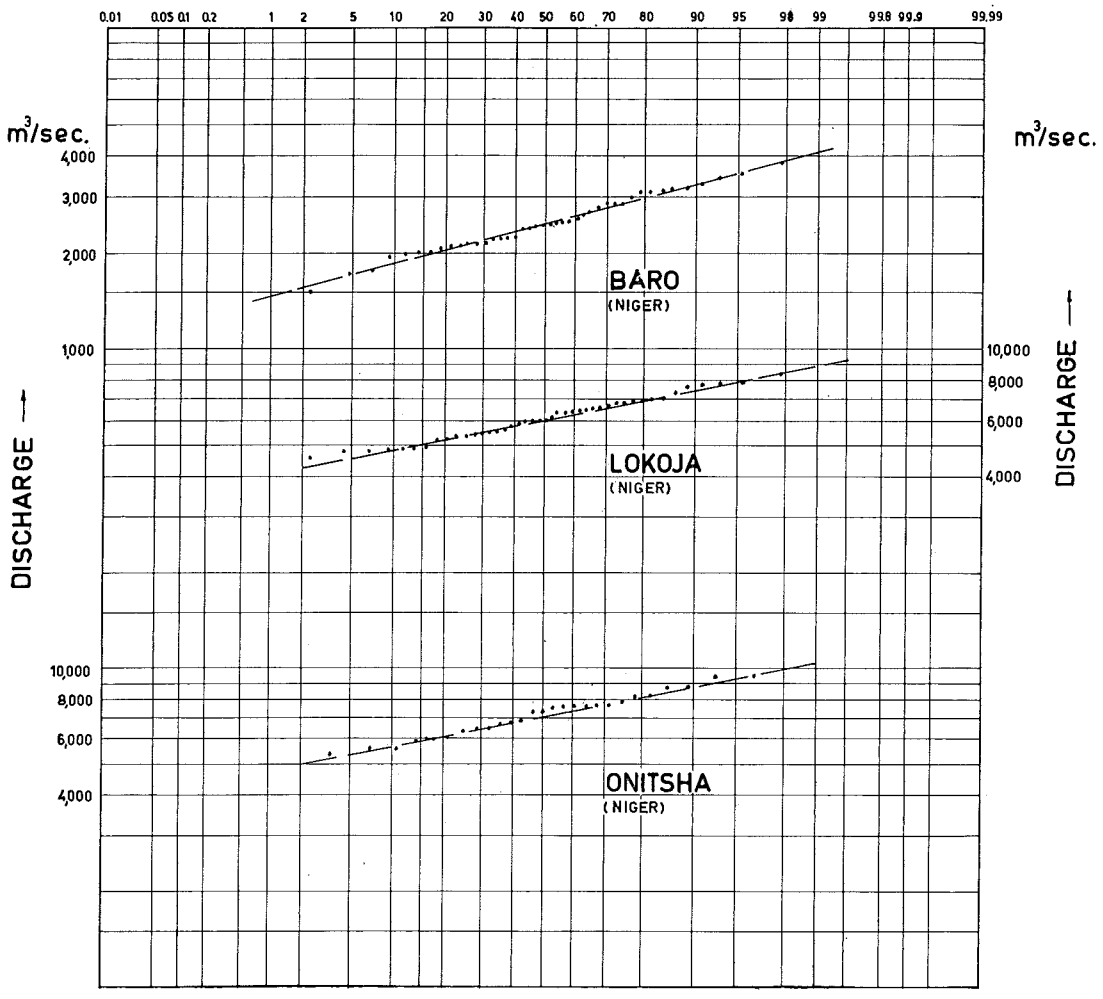


DIAGRAM 2.3.3-4

Frequencies of year-averages of the discharge along the Niger

WATER VAPOUR IN THE ATMOSPHERE

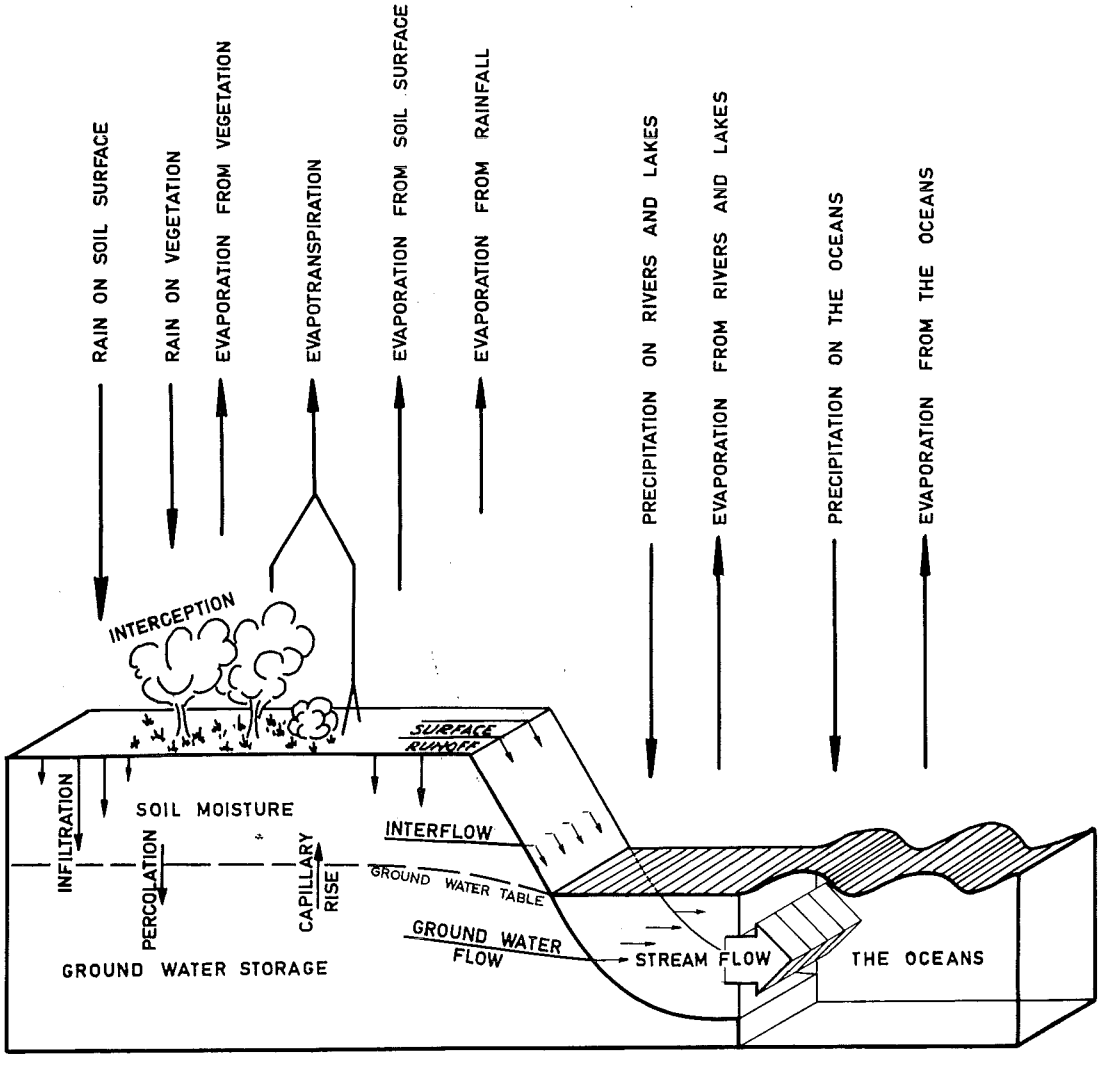


DIAGRAM 2.3.4-1

Simplified scheme of the hydrological cycle

Special studies have been made of the distribution of the discharges around islands and at other bifurcations (III, 4.3.8).

2.3.4. Hydrological cycle (see III, 4.5.1)

The general circulation of water from the sea to the atmosphere, to the ground and back to the sea again is called the hydrological cycle. A simplified scheme of it is given in Diagram 2.3.4-1 (i.e., III, 4.5.1-1).

Under certain circumstances a part of the water vapour in the air will condense and may cause precipitation on the surface of the earth; in West Africa the most important part of this precipitation is in the form of rainfall.

The available rainfall data in Nigeria have been described and elaborated by NEDECO (III, 4.1); moreover, some additional rain-gauges have been positioned in the course of the Investigation.

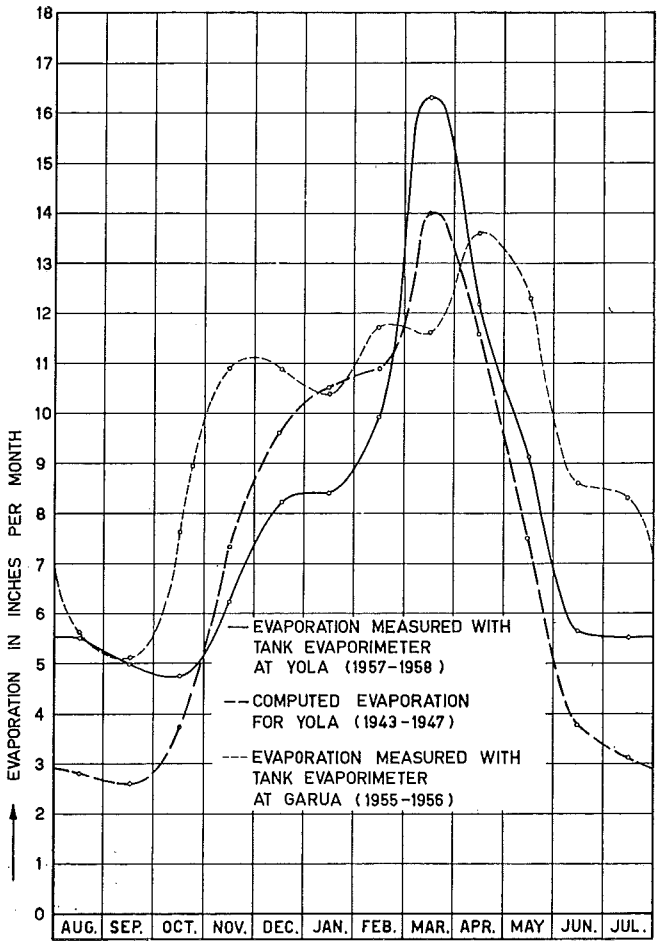


DIAGRAM 2.3.4-2

Tank evaporation at Yola and Garua

Few data were available on evaporation and evapotranspiration in Nigeria, although recently the British West African Meteorological Services have installed a number of tank evaporimeters. The amount of evaporation is of special interest in the vicinity of Yola, in view of the planned reservoir in this area. Tank measurements and computations with Dalton's formula have yielded results which are shown in Diagram 2.3.4-2 (i.e., III, 4.4.2-3). From this it could be derived that the yearly evaporation from a lake near Yola will be between 65 and 70 inches.

A certain amount of water is stored in the river channels, on the flood-plains and in the ground below the ground-water table. The effect of valley storage on the propagation of floods is discussed in III, 4.5.2. Although more data will be necessary than are now available for a computation of the ground-water storage to be made, it is estimated that between 10 and 15 % of the yearly Benue discharge finds its origin in ground-water storage. An equal amount originates in the returning valley storage.

From various considerations the following equation for a river basin can be set up:

$$P = E + \Delta S + R$$

in which:

P = precipitation on the basin during a time Δt,
E = evapotranspiration + evaporation during a time interval Δt,
S = storage, which is the quantity of water contained by the soil and the rivers,
ΔS = change in storage before and after Δt, and
R = run-off during the time Δt.

P can be computed from rainfall measured during Δt at a number of stations spread over the basin. This can be done, for example, by drawing isohyets. R can be obtained by measuring the discharge at the lower end of the basin. If the hydrological year is chosen as the unit of time over which the above equation has to be solved, then the change in storage can be taken as zero.

It is then possible to compute the run-off coefficients of the river basins, defined as the ratio of the year run-off (R) from that basin to the amount of precipitation (P) over the basin during

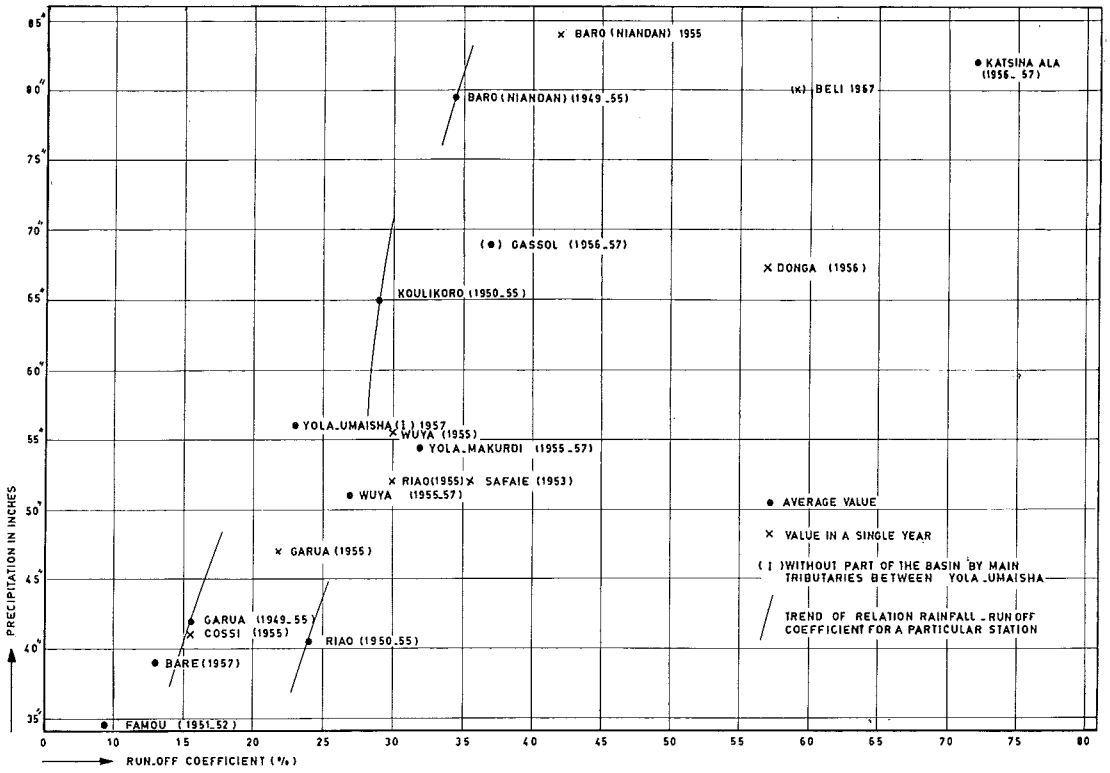


DIAGRAM 2.3.4-3

Run-off coefficient as a function of the precipitation

the same period. Diagram 2.3.4-3 (i.e., III, 4.5.3-2) shows run-off coefficients for several parts of the Niger-Benue Basin, plotted against the appertaining precipitation.

2.3.5. Discharge relations (see III, 4.5.4)

Making use of considerations set out in Chapter III, 4, which are summarised in the preceding Paragraphs of this Section, a general picture of the connections and interrelations between the discharges downstream and those upstream — the time-lag taken into account — has been obtained.

Diagram 2.3.5.-1 (i.e., III, 4.5.4-1) gives the discharge relations of the Niger-Benue Basin within Nigeria. Two dashlines in this diagram follow the propagation and increase of discharges, one starting from Yola on June 14, 1957 and from Jebba on June 19, 1957, which join at Lokoja and finally reach Aboh on June 26, 1957, and the other starting from Wuro Boki on August 24, 1957 and from Jebba on August 27, 1957, which reach Aboh on September 13, 1957.

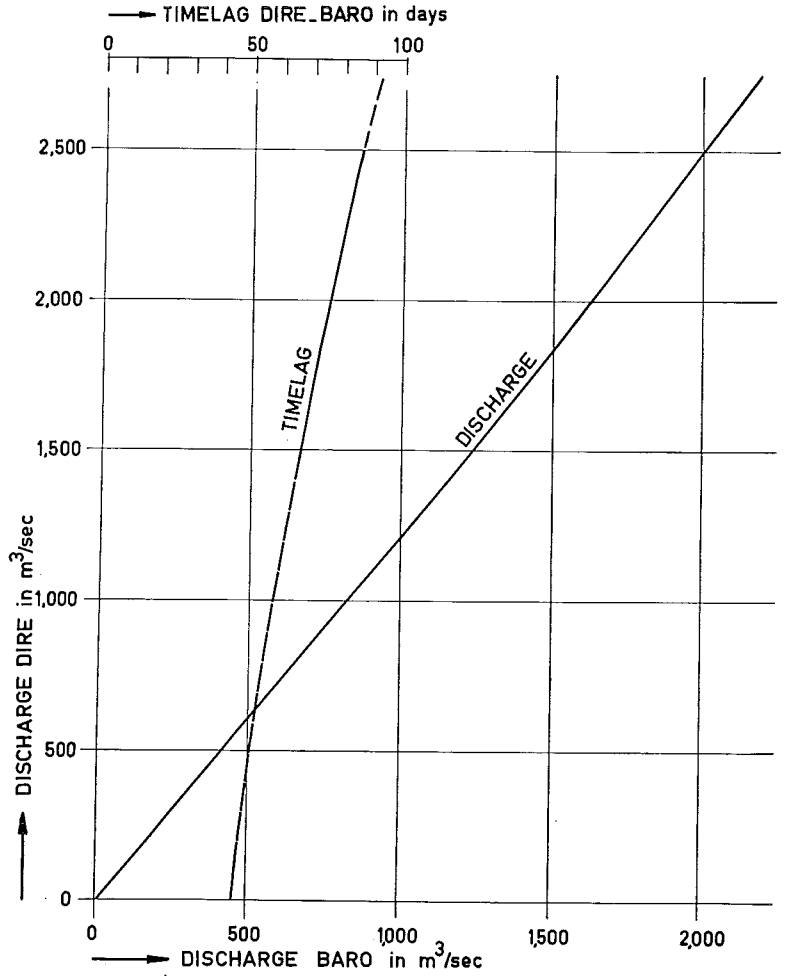


DIAGRAM 2.3.5-2

Relation curve and time-lag of discharges between Dire and Baro

The importance of this diagram, apart from reconstructing the propagation of flood-waves, is that it forms a basis for predictions of water-levels and discharges. This possibility is considered in more detail in VI, 3.7.

Discharge relations upstream from Wuro Boki have been established by the French Cameroun investigators.

The discharges of the Niger in its middle course near Timbuctu bear a close relation to those of the Black Flood in Nigeria (as already mentioned in 2.3.1). In view of its importance for navigation in Nigeria, the behaviour of the Black Flood has been studied.

Diagram 2.3.5-2 (i.e., III, 4.5.4-10) shows the resulting relation curve and time-lag of discharges at Diré (near Timbuctu) and Baro. This result has been used in VI, 3.6.2. as a basis for long-term stage predictions of the Black Flood.

2.4. MORPHOLOGY OF THE RIVER-BED

2.4.1. Sand discharges (see Chapter III, 5)

The river morphology describes the regime of materials composing and flowing through the alluvial bed as well as the formation and deformation of that bed.

These materials are under a collective name called sediments; they are the weather products from the drainage basin and are carried downward by the flow. Broadly speaking, the weathering and the transport of sediments from higher to lower elevations is the constant levelling process of Nature under the forces of sun-energy and gravity. Qualitative and quantitative knowledge of the mechanism of sediment transport is essential for an insight into bed-formation and deformation as well as into the expected results of artificial intervention in the regime of the river.

RECEIVED	19-7-'57	SIEVE OPENING	WEIGHT REMAINING ON SIEVE	% REMAINING ON SIEVE	% PASSING THROUGH SIEVE.
DRIED	2-8-'57				
DISH Nº	3	11.2	0	0	100
SIEVE	5-8-'57	5.6	1.5	1.2	98.8
L.N. - ANWAM 1-7-'57 position III 180 m from L.O. B.TMA.		2.8	6.1	4.7	95.3
		1.4	20.3	15.8	84.2
		0.6	45.7	35.6	64.4
		0.3	98.2	76.5	23.5
		0.15	127.0	98.8	1.2
		0.105	128.2	99.8	0.2
		0.09	128.3	99.9	0.1
		0.075	128.4	99.9	0.1
		0.06	128.5	100	0
		less	128.5	100	0
		TOTAL	128.5	100	

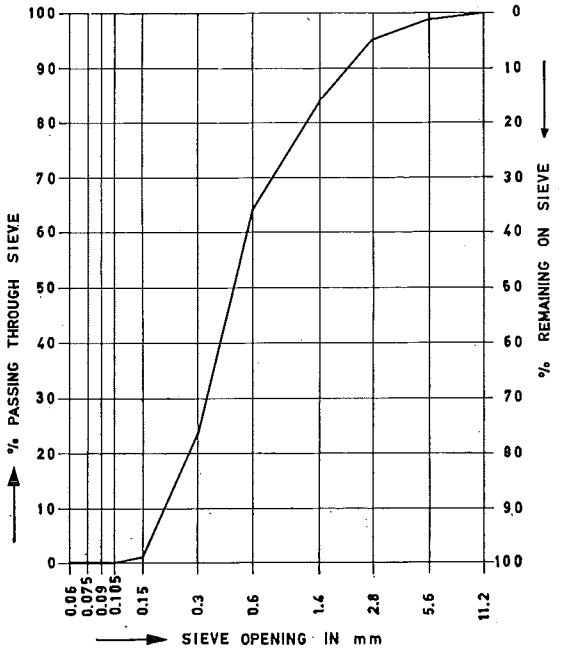


DIAGRAM 2.4.1-1

Example of analysis of a sediment sample

Measurements of sediment transport in rivers are of recent date and have as yet not been extensively taken. In the Netherlands the "Delft Bottles" (DF) and the bed-load transport meter "Arnhem" (BTMA), as described in II, 3.5, were developed for sediment transport measurements, and have been used in Nigeria during the investigation. They are designed for the measurements of different kinds of transport, i.e., bed-load, determined by the BTMA in the first 4 inches from the bottom; saltation-load, measured with the DF_2 from 4 inches to 16 inches from the bottom; and suspended load, measured with the DF_1 from 16 inches from the bottom to the surface. Samples of non-moving particles can be taken from the bottom and the banks. All are sieved to determine grain-sizes (Diagram 2.4.1-1, i.e., III, 5.1.1-1).

Sand measurements have been taken in the most important stations where observations on water discharge have been made. The sand caught was sieved and the characteristic values of

TABLE 2.4.1 - 2

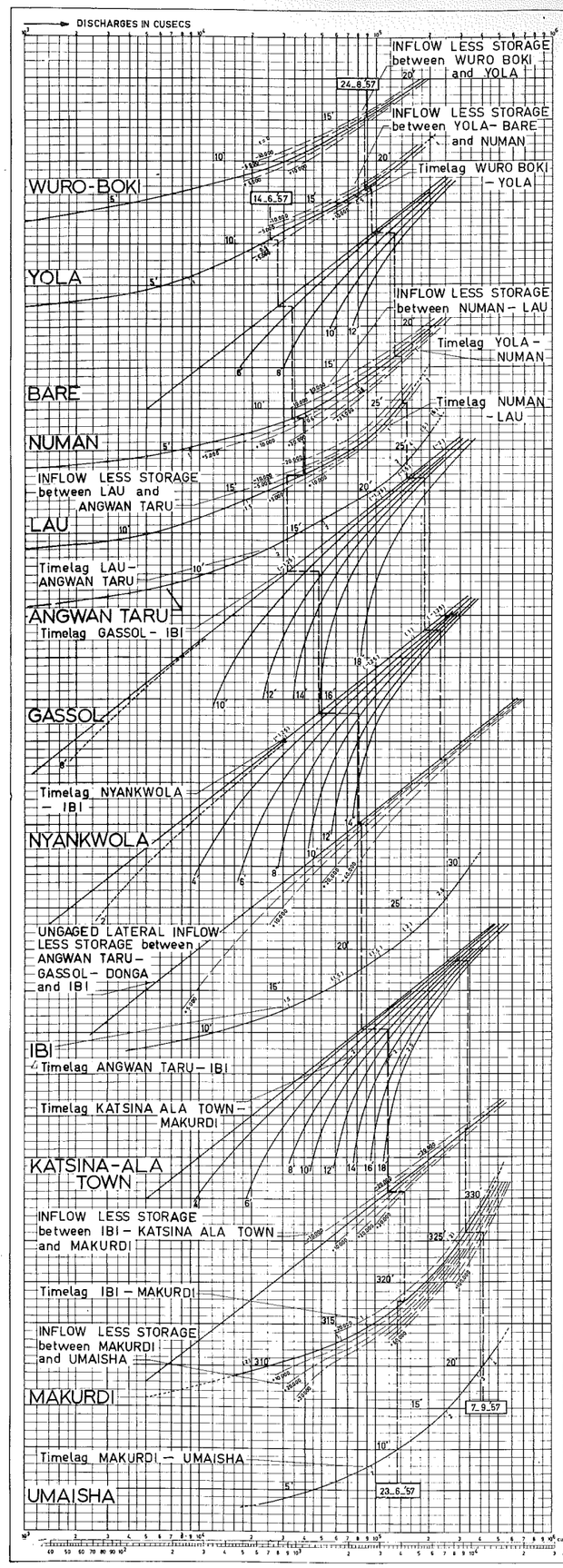
AVERAGE GRAINSIZES OF CATCH BY BTMA AND DF

figures in mm

STATION	BTMA			DF_2			DF_1		
	d_{50}	d_{60}	d_{90}	d_{50}	d_{60}	d_{90}	d_{50}	d_{60}	d_{90}
Benue									
Yola	0.66	0.80	2.3	0.32	0.39	0.71	0.21	0.23	0.42
Numan	0.56	0.71	2.2	0.30	0.36	1,4	0.22	0.24	0.42
Gamadio	0.53	0.66	2.1	0.32	0.39	0.93	0.14	0.17	0.29
Ibi	0.85	1.05	3.0	0.41	0.58	1.5	0.18	0.21	0.49
Makurdi	1.04	1.22	4.3	0.63	0.80	1.7	0.22	0.23	0.69
Upper Niger									
Pategi	0.54	0.62	1.3	0.28	0.30	0.56	0.18	0.20	0.37
Baro	0.52	0.62	1.6	0.23	0.27	0.55	0.21	0.24	0.40
Lower Niger									
Shintaku	0.78	1.0	3.3	0.23	0.27	0.75	0.15	0.17	0.31
Idah	0.67	0.72	2.0	0.22	0.25	0.48	0.15	0.17	0.29
Onitsha	0.52	0.60	1.8	0.20	0.23	0.43	0.13	0.15	0.25
Aboh	0.49	0.54	1.1	0.15	0.16	0.31	0.11	0.12	0.18
Gongola									
Bilachi	0.81	1.1	3.7	0.36	0.43	1.1	0.16	0.20	0.39
Faro									
Kossel	0.75	0.95	2.8	0.55	0.68	1.9	0.16	0.19	0.34
Taraba									
Sendirdi	0.82	1.0	3.1	0.68	0.87	2.3	0.21	0.25	0.46
Donga									
Nyankwola	0.88	1.1	2.2	0.42	0.51	0.8	0.13	0.15	0.23
K'Ala									
Confluence	0.85	1.0	2.7	0.50	0.55	1.7	0.27	0.32	0.77

1 mm = 0.04 inch

the sieve-curves determined (Table 2.4.1-2, i.e., III, 5.1.2-6). The same applies to bottom samples taken all along the Niger and Benue (Diagram 2.4.1-3, i.e., III, 5.1.2-4). The characteristic sieving values are essential for the application of formulae. Grain-sizes will decrease in the



WURO - BOKI mile 916
Area Drainage Basin between WURO - BOKI and YOLA: 900 sqmiles

YOLA - BENUE mile 888.2
Area Drainage Basin between YOLA - BARE and NUMAN : 3,100 sqmiles

BARE - GONGOLA mile 852
Drainage Area : 21,500 sqmiles Timelag BARE - NUMAN about 2 hours

NUMAN - BENUE mile 846.3
Area Drainage Basin between NUMAN and LAU : 3,600 sqmiles

LAU - BENUE mile 777.5
Area Drainage Basin between LAU and ANGWAN TARU : 9,900 sqmiles

ANGWAN TARU - BENUE mile 682.6
Drainage Area : 79,500 sqmiles

GASSOL - TARABA mile 690
Drainage Area : 8,240 sqmiles
Timelag GASSOL - IBI depends on IBI discharge

NYANKWOLA - DONGA R. mile 650
Drainage Area : 7,650 sqmiles
Timelag NYANKWOLA depends on IBI discharge

Area Drainage Basin between ANGWAN TARU - GASSOL - NYANKWOLA and IBI : 4,100 sqmiles

IBI - BENUE mile 614
Drainage Area : 99,500 sqmiles

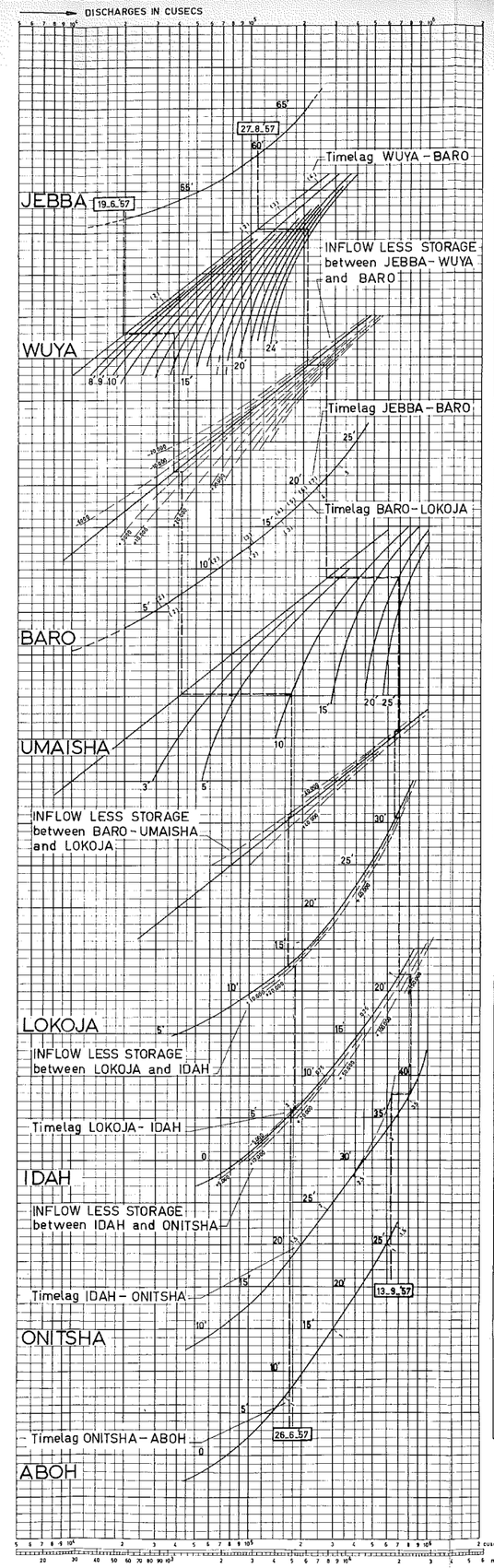
KATSINA-ALA TOWN - KATSINA-ALA R.
Drainage Area : 6,450 sqmiles

Area Drainage Basin between IBI - KATSINA-ALA TOWN and MAKURDI : 11 500 sq.miles

MAKURDI - BENUE mile 511.6 (Railway Gauge)
Drainage Area : 117,500 sqmiles
Area Drainage Basin between MAKURDI and UMAISHA : 11,400 sqmiles

UMAISHA - BENUE mile 400.6
Drainage Area : 128,900 sqmiles

TIMELAG in DAYS
STORAGE less INFLOW in cuft / sec.



JEBBA - NIGER mile 556

WUYA - KADUNA RIVER mile 515
Drainage Area 25,300 sqmiles Timelag WUYA - BARO depends on BARO discharge

Area Drainage Basin between JEBBA, WUYA and BARO 12,700 sqmiles

BARO - NIGER mile 434

UMAISHA - BENUE mile 400.6
Drainage Area 128,900 sqmiles Timelag UMAISHA - LOKOJA about half a day

Area Drainage Basin between BARO, UMAISHA and LOKOJA 9,100 sqmiles

LOKOJA - NIGER mile 362
Area Drainage Basin between LOKOJA and IDAH : 3,000 sqmiles

IDAH - NIGER mile 310
Area Drainage Basin between IDAH and ONITSHA : 7,000 sqmiles

ONITSHA - NIGER mile 232
During river stages higher than 28' ONITSHA gauge, a part of the NIGER discharge flows towards the ORASHI and ASE river.

Lateral inflow between ONITSHA and ABOH is negligable

TIMELAG in DAYS
STORAGE less INFLOW in cuft / sec.

I, 2.3.5 - 1

NEDECO NIGER/BENUE	DIAGRAM III, 4.5.4 - 1
DISCHARGE RELATIONS NIGER-BENUE BASIN WITHIN NIGERIA	

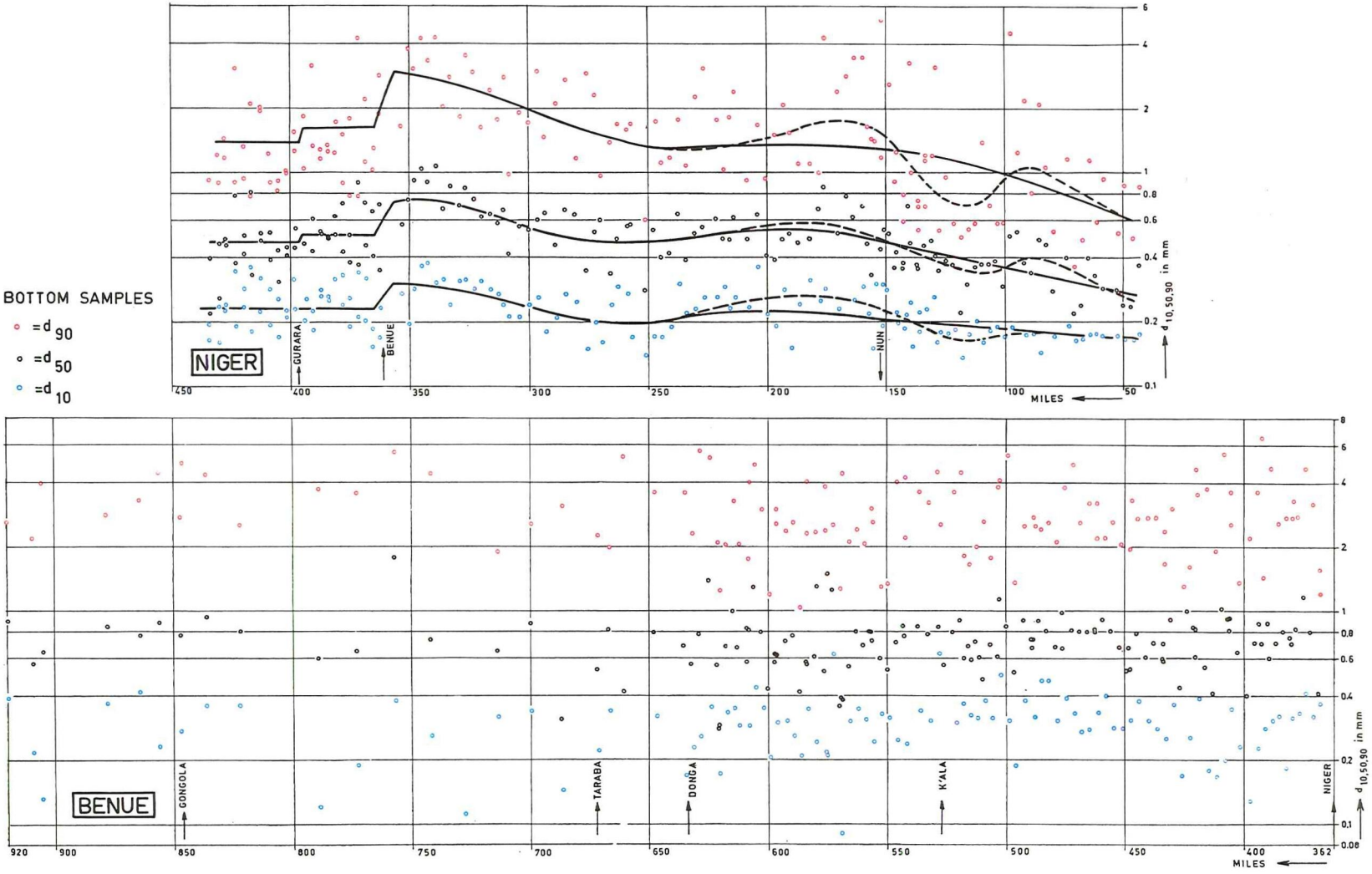


DIAGRAM 2.4.1-3

Observations of grain-size of bottom sand in Niger and Benue

lower section of the river as a result of friction and weathering and also due to the exchange of grains between valley and river-bed.

The mineral composition of some samples has been examined in the Delft University Mining Laboratory (Table III, 5.1.3-1). The main distinction in mineral composition between Niger sands and Benue sands consists of the presence of metamorphic minerals in the former and of volcanic minerals in the latter. The Niger upstream from Lokoja and its most important affluents show considerable outcrops of Basement Rock in their drainage area, whereas the Benue and several of its tributaries drain areas where much basic volcanic rock exists.

For a long time efforts have been made to catch sand-transport in formulae for the obvious reason of minimising efforts to obtain necessary data or to forecast development and changes in sand-transport before artificial encroachment on the regime is carried out. This has to a certain extent been successful. With the basic characteristics of the rivers, KALINSKE, MEYER-PETER and MULLER, and EINSTEIN have described mathematical formulae for the sand-transporting capacity in rivers. All three lead to similar results with only minor differences (see Diagram III, 5.2.1-1). The measurements in the Niger and Benue appeared to follow the formula of MEYER-PETER and MULLER satisfactorily and as this formula is easily applicable it is used throughout this Report.

It is generally accepted that in an alluvial river the actual sand-transport (bed-load plus saltation-load) is always equal to the transporting capacity. A too small sediment-load would immediately involve local erosion from the bottom or the banks, and a too heavy sediment-load would cause deposition. The flow will never be unsatiated with sediments, and variation in transporting capacity will immediately result in scour or deposition.

The measurements of sand-transport by NEDECO are summed up in Diagram 2.4.1-4, i.e., III, 5.2.2-1, where they are plotted in relation to the water-discharges. It has been calculated that the formula of MEYER-PETER and MULLER

$$s = 6.5\, d^{\frac{3}{2}} \sqrt{\Delta g} \left[\frac{\mu a i}{\Delta d} - 0.047 \right]^{\frac{3}{2}}$$

describes the measurements best. The value of the coefficient 6.5 is in the original formula 8, derived for Europe. It is believed that this deviation for the Nigerian rivers is caused by the higher water temperatures in these tropical rivers.

Total year transports of bed-load are given in Table 2.4.1-5, i.e., III, 5.2.3-1, for various stations, which can either be graphically computed from the actual measurements or be computed with the formula (for past years with the aid of the present stage-discharge relation, when the stages in those years are known). Care should be taken in drawing conclusions from a comparison of the figures of a single year. Sand-transport is a slow phenomenon; the magnitude varies from year to year and from place to place. However, continued measurements and the search for relations between the observed or calculated sand-transport and other characteristics of the river will eventually lead to a clearer insight and discoveries into the phenomena of the river which are at present hidden by the complex nature and the slow motion of one year in the long ages of history.

Finally, it must be remarked that the flow of sand in the river-bed should have some influence on the bed-formation and in particular on the cross-section in the river-bed. As has already been discussed, there exists a relation between sand and water discharges. Since the water discharge varies seasonally, the sand discharge does the same, and any morphological consideration on the behaviour of the river-bed is made very complex by this variation of this basic magnitude; while a constant flow, that would shape the cross-section of the river-bed as adapted to the discharges of water and sand, would involve a rather simple mechanism on bed-formation.

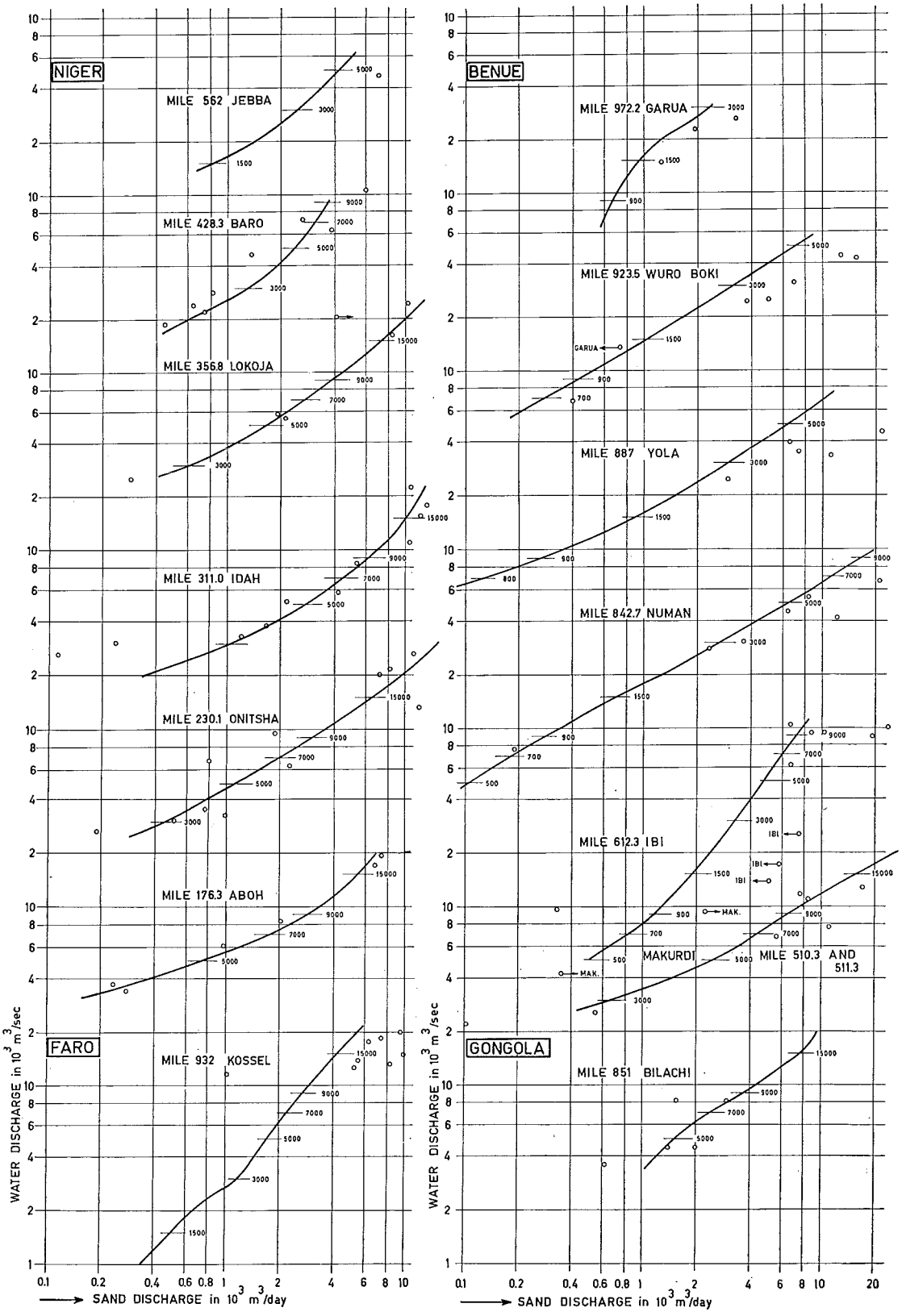


DIAGRAM 2.4.1-4

Relation curves for discharge of water and sand on the Niger and Benue

From this idea the conception of Dominant Discharge has been born. It has not appeared possible to determine a certain discharge that, constantly and continuously flowing, would produce a river-bed similar to the actual bed under varying discharges. But such a discharge can indeed be found when, of all the various characteristics of the river-bed, one is taken into consideration, for instance, the depth (III, 6.1.1 and III, 5.2.4). This is of importance in connection with the regime changes (for instance, occurring at discharge regulation), as such a regime change will alter the Dominant Discharge and thus the shape of the cross-section.

TABLE 2.4.1 - 5

YEAR TRANSPORTS OF BED-LOAD (in 10^6 m^3)

Station	1956	1957	AVERAGE YEAR	
			transport	period
Niger				
Baro	0.29	0.44	0.31	1914—1957
Shintaku	0.72	1.2	0.88	1915—1956
Idah	1.1	1.6		
Onitsha	0.76	1.3	1.0	1925—1957
Aboh	0.45	0.75		
Samabri	0.70	1.1	1	1919—1949*)
Benue				
Garua	0.10	0.10		
Wuro Boki	0.23	0.27		
Yola	0.20	0.28	0.20	1934—1957
Numan	0.29	0.36		
Ibi	0.71	0.93		
Makurdi	0.57	0.86	0.61	1932—1957
Faro				
Gassol	0.40	0.50		
Gongola				
Bilachi	0.34	0.24		

*) From information, given in the report on the Western Niger Delta, NEDECO, 1954

2.4.2. Suspension discharges

The sand discharge in bed-load (including saltation-load) has a great influence on the actual river-bed. Besides this, the river-flow is loaded with suspended load, i.e., particles of smaller size than the bed-load particles, which do not jump over small distances or roll over the river-bed but remain in suspension over long distances. There cannot be given a sharp boundary between the two kinds of transport. It is clear that suspension must be some function of turbulence and velocity of water, for no suspended load exists in a lake with stagnant water. However, it has not yet been possible to derive a mathematical law for suspended load as for bed-load. Owing to the general aspect of decreasing slope, velocity and turbulence in downstream direction of the river (see III, 2.5), there might be a tendency to deposition of suspended particles while going downstream. This means a transfer from suspension into bed-load, and such is the effect of suspended load upon the characteristics of the river-bed.

The greater part of the suspended load is carried off to the sea or is deposited on the flood-plains, and no major influence on the actual river-bed is probable. As the transport cannot be calculated from the basic river data, measurements are necessary, and these were carried out with the Delft Bottle DF_1 as described under II, 3.5 (see Diagram 2.4.2-1, i.e., III, 5.3.1-1).

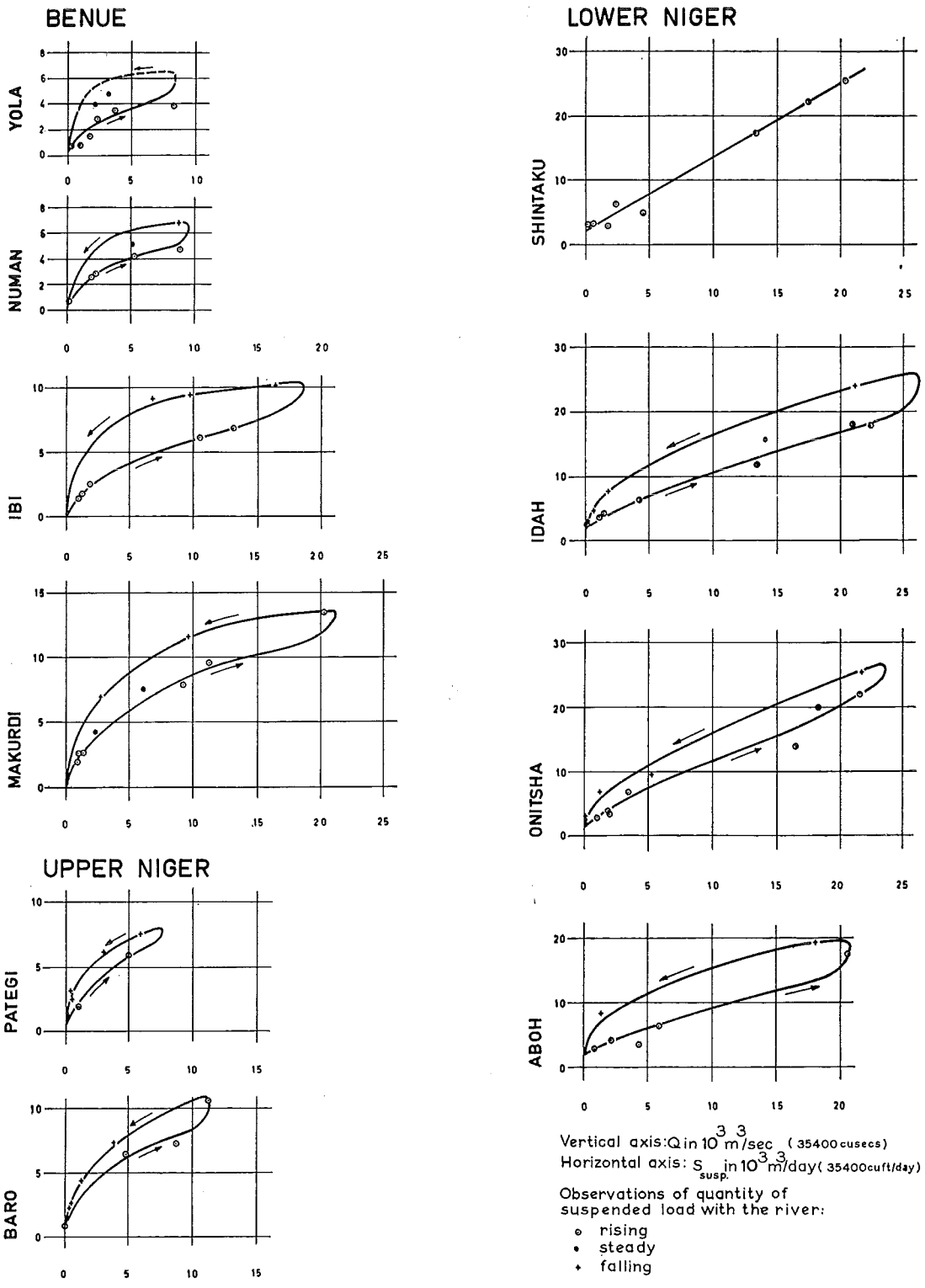


DIAGRAM 2.4.2-1

Relation between suspension and water discharge

TABLE 2.4.2 - 2

OBSERVATIONS OF SILT CONCENTRATION ON NIGER AND BENUE

TOWN	MILE	DATE	Q m³/sec		SILT CONCENTRATION			
					left	middle	right	average
NIGER								
Jebba	562	11.10.56	4,400	s	*30*	*125*	*90*	**80**
Likpata	509	10.10.56	4,400	s	*45*	*50*	*50*	**50**
Pategi	480	11.10.56	5,900	s	*220*	*100*	*15*	**110**
Pategi	480	27.11.56	2,000	s	60	45	60	**60**
Egwamama	428	27.11.57	2,100	s	60	70	70	**70**
Gwachinko	428	11.10.56	6,000	s	*45*	*20*	*100*	**60**
Gwachinko	428	28.11.57	2,800	s	100		70	**90**
Kelebe	389	7. 8.57	4,000	s	*900*	*450*	*180*	**510**
Kelebe	389	8.11.57	4,900	s	*110*	*45*	*30*	**80**
Lokoja-up	362.5	17. 4.58	1,970	s	80	130	200	**140**
Lokoja-up	362.5	24. 4.58	2,050	s	160	190	200	**180**
Lokoja-up	362.5	9. 5.58	1,910	s	140	130	140	**140**
Lokoja-up	362.5	23. 5.58	1,330	s	130	150	90	**120**
Confluence	358.5	17. 4.58	2,150	s	105	230	90	**140**
Confluence	358.5	24. 4.58	2,220	s	90	190	160	**150**
Confluence	358.5	9. 5.58	2,180	s	100	160	110	**120**
Lokoja-down	358	23. 5.68	1,920	s	120	140	110	**120**
Shintaku	357	28.11.57	6,140	s	80	120	110	**100**
Idah	310	29.11.57	6.220	s	50	120	90	**90**
Idah	310	22. 1.58	2,980	s	50	50	50	**50**
Idah	310	1. 5.58	2,380	s	160	150	110	**140**
Anwam	244	18. 1.58	2,960	s	60		60	**60**
Anwam	244	18. 1.58		s	70		70	**70**
Onitsha	231	30. 4.58	2,510	s	160	170	110	**150**
Aboh	178	28. 4.58	2,530	s	120	130	120	**120**
KADUNA								
Nupeko	483	9.10.56	1,900	s		*600*		**600**
GURARA								
Gerinya	400	11.10.55		s		*3,300*		**3,300**
ORASHI								
—		21.11.57		s		*80*		**80**

TOWN	MILE	DATE	Q m³/sec		SILT CONCENTRATION			
					left	middle	right	average
BENUE								
Jimeta	894	19. 9.57	2,920	s	350	290	330	
				m	310	*110*	*200*	
				b	280	420	330	
				a	**310**	**355**	**330**	**330**
Jimeta	884	26. 9.57	3,240	s	290	260	*170*	
				m	*110*	330	*100*	
				b	270	350	330	
				a	**280**	**310**	**330**	**310**
Jimeta	884	22.10.57	2,210	s	270	280	*65*	
				m	220	250	*110*	
				b	230	350	390	
				a	**240**	**295**	**390**	**310**
Jimeta	884	23.10.57	2,040	s	190	330	210	
				m	280	310	230	
				b	250	*110*	150	
				a	**260**	**320**	**195**	**260**
Numan	846	24.10.57	2,240	s	160	140	840	
				m	190	250		
				b	*170*	250		
				a	**175**	**215**	**840**	**410**
Numan	846	31.10.57	1,510	s	260	*140*	300	
				m	*80*	320	*160*	
				b	270	*130*	690	
				a	**265**	**320**	**445**	**340**
Lau	777	3.11.57	1,630	s	*280*	*110*	*160*	
				m	*160*	*180*	330	
				b	350	330	*170*	
				a	**350**	**330**	**330**	**340**
—	647	6.11.57	2,530	s		90	*40*	
				m		190	260	
				b		150	250	
				a		**145**	**255**	**200**
Ibi	614	20.10.56	8,200	s	*100*	*160*	*160*	**140**
Ibi	614	6.11.57	5,110	s	200	210	230	
				m	150	220	260	
				b	110	160	250	
				a	**155**	**200**	**245**	**200**
Makurdi	511.6	9.11.57	6,130	s	110	310	220	
				m	120	270	250	
				b	60	280	280	
				a	**95**	**285**	**250**	**210**
Akpanaya	502	22.10.56		s		*200*		**200**
Umaisha	400	10.11.57	8,200	s	70	160	200	
				m	80	190	190	
				b	90	220	165	
				a	**80**	**190**	**185**	**150**
Lokoja	N. 364.8	17. 4.58	180	s	85	85	60	**80**
Lokoja	S. 364.8	17. 4.58		s	110	110	105	**110**
Lokoja	N. 364.8	24. 4.58	170	s	70	90	90	**80**
Lokoja	S. 364.8	24. 4.58		s	80	60	70	**70**

TOWN	MILE	DATE	Q m³/sec		SILT CONCENTRATION			
					left	middle	right	average
GONGOLA								
Dadinkowa	935	7.11.57	100	s	580	680	1150	
				m	470	1040	840	
				b	940	900	630	
				a	**665**	**875**	**875**	**810**
Kombo	897	6.11.57	100	s	640	760	650	
				m	970	780	780	
				b	600	700	430	
				a	**735**	**745**	**620**	**700**
Confluence	848	1.11.57	120	s	400	500	*250*	
				m	380	*160*	460	
				b	*190*	*140*	500	
				a	**390**	**500**	**480**	**460**
TARABA								
Beli	753	30.10.57	730	s	70	150		
				m	100			
				b	90	80		
				a	**85**	**115**		**100**
Gassol	691	7. 8.57	850	s	*200*	*46*	*185*	**140**
Confluence	673	5.11.57	940	s	*160*	220	280	
				m	110	190	80	
				b	130	250	230	
				a	**120**	**220**	**195**	**180**
DONGA								
Nyakura	649	19.10.56	1,200	s	*130*	*200*	*120*	**150**
—		8. 8.57	1,230	s	*80*	*80*	*80*	**80**
—		21. 9.57	1,560	s		*150*		**150**
Confluence	637	6.11.57	1,130	s	220	*180*	105	
				m	*170*	240	200	
				b	420	*250*	*100*	
				a	**320**	**240**	**155**	**240**
KATSINA ALA								
Sevav	570	12.10.56	2,100	s	*110*	*210*	*180*	**170**
Confluence	538	29. 7.57	1,420	s	*80*	*80*	*80*	**80**
Confluence	538	7.11.57	1,607	s	110	110	90	
				m	90	100	70	
				b	80	90	80	
				a	**95**	**100**	**80**	**90**

s = surface-sample
m = middle-sample
b = bottom-sample
a = average

Not caught in the DF_1 is the sediment of such small grain-size that it does not settle but is carried out of the instrument together with the water. Such sediment is called "wash-load" or silt, and it never settles in a normal river-stretch but may be only deposited on the natural levees and the flood-plain, where vegetation may hold it. There it affects the composition of the banks and therefore indirectly the erodibility, which indeed is an important factor in the behaviour of the river. The remainder of the wash-load or silt is carried off into the sea, where it settles as the main delta-building material (see III, 2.4). Wash-load is mainly composed of silt and clay and possibly also of a very small quantity of fine sand. The amount of wash-load in the water depends only on the supply into the river from outside. As it cannot be measured by the DF_1, the method of measuring the concentration of sand and silt particles in the water

TABLE 2.4.2 - 3

Silt concentration in various rivers of the world

RIVER	COUNTRY	Place of sampling or calculation	SILT CONCENTRATION *) kg/m³		
			max.	yearly average	min.
King Ho (trib. of Wei Ho)	China	Changchiaschau	300	150	
Rio Puerco (trib. of Rio Grande del Norte)	U.S.A.			144	
Yungting (trib. of Hai)	China	San Che Tien	557		
Wei Ho (trib. of Hwang Ho)	China		540		
Hwang Ho	China	Shenhsien	460	44	1.1
Great Fish River	South-Africa	Lake Arthur		33.5	
Isser	Algerie	Tablat		20.0	
Sundays River	South-Africa	Lake Mentz		18.5	
Rio Grande del Norte	U.S.A.	Butte		17.0	
Colorado	U.S.A.	Grand Cañon		11.7	
Missouri (trib. of Mississippi)	U.S.A.	Kansas City		2.97	
Kosi (trib. of Ganges)	Nepal	Chatra		2.86	
Nile	Egypt			1.97	
Yang Tze	China	Chihkiang	5.61	1.86	0.015
Tigris	Iraq	Bagdad		1.57	
Durante	France			1.50	
Ganges	India	Faracca	1.0		0.05
Amazon	Brazil			0.8	
Irrawaddy	Burma	Prome		0.57	
Mississippi	U.S.A.	Robertsville		0.41	
Po	Italy	Ponte Lagoscuro		0.28	
Ohio (trib. of Mississippi)	U.S.A.			0.20	
Mekong	Cambodja	Kratie	0.3	0.16	
Parana	Argentine	Corrientes		0.15	
Rhône	France	Lyon		0.15	
Danube	Hungary	Budapest		0.14	
Danube	Austria	Vienna		0.10	
Congo	Central-Africa			0.04	
Rhine	Netherlands	Nijmegen		0.04	
Benue	Nigeria	various places	0.4		0.06
Niger	Nigeria	various places	0.5		0.06

*) Results obtained mainly from calculation; only occasionally from actual observation of silt concentration. Calculation is possible f.i. by considering the total amount of silt deposited yearly in reservoirs in connection with the total annual water discharge.

Figures for this table are extracted from ECAFE: flood control series no 1, 1950.
PARDÉ: Sur les valeurs de la turbidité des rivières, 1952.

has been carried out by drying and weighing or with the aid of a turbidimeter (Table 2.4.2-2, i.e., III, 5.3.2-3). It then appears that suspended load is practically all wash-load. Also, it appears from a comparison with other rivers that the Niger and Benue do not discharge large amounts of silt (see Table 2.4.2-3, i.e., III, 5.3.2-1). This is of great importance with respect to the decrease of reservoir capacity by deposition. Table 2.4.2-4 (i.e., III, 5.3.3-1) summarises the yearly transport of sediments as a result of calculations.

The three groups of transport — bed-load, suspended load and wash-load — have great differences in origin and mechanism as well as in effect upon the river and the river-bed. The bed-load is determinant for the behaviour of the river-bed. As the rivers are alluvial, the quantity of bed-load always equals the transporting capacity. Extra supply of sand means deposition and ultimately an increase of river-slope; reduced supply will, on the contrary, cause scour and decrease of slope. The bed-load is, however, only a small quantity of the total transport, the bulk being wash-load, which is mainly responsible for the building up of the alluvial valley and

TABLE 2.4.2 - 4

YEAR TRANSPORTS OF SEDIMENT ON NIGER AND BENUE

STATION	YEAR	BED-LOAD (incl. salt. load)			SUSPENDED LOAD			WASH-LOAD			TOTAL	
		10^6 m³	10^6 cuft	% of total	10^6 m³	10^6 cuft	% of total	10^6 m³	10^6 cuft	% of total	10^6 m³	10^6 cuft
Upper Niger												
Baro	1956	0.29	10	8	0.29	10	8	3	100	84	3.6	120
	1957	0.44	16	7	0.82	29	13	5	180	80	6.3	220
	average 1915—1957	0.31	11	6½	0.55	19	11	4	140	82½	4.9	170
Benue												
Yola	1956	0.20	6.9	6	0.17	6.0	5	3.0	110	89	3.3	120
	1957	0.28	10	6	0.24	8.5	5	4.2	150	89	4.7	170
	average 1934—1957	0.20	7.2	6	0.17	6.0	5	3.0	110	89	3.3	120
Makurdi	1956	0.57	21	5	0.87	31	8	9.5	340	87	11	390
	1957	0.86	31	5½	1.3	47	9	13	470	85½	15	540
	average 1932—1957	0.61	22	5	0.95	34	8	10	370	87	12	420
Lower Niger												
Shintaku	1956	0.72	26	5	1.0	36	7	*13*	*460*	88	*15*	*520*
	1957	1.2	42	5½	1.8	65	9	*18*	*640*	85½	*21*	*750*
	average 1915—1957	0.88	31	5	1.3	46	8	*15*	*530*	87	*17*	*610*
Onitsha	1956	0.76	27	5	1.2	44	8	*14*	*500*	87	*16*	*570*
	1957	1.3	47	6	2.2	79	10	*19*	*670*	84	*22*	*800*
	average 1925—1957	1.0	36	5½	1.7	59	9	*16*	*570*	85½	*19*	*660*

the delta, and which is important for the rate of decrease in reservoir capacity when discharge regulation is applied as an improvement of the river. These three phenomena will be a slow process compared with many other rivers, as the suspended load concentration in Niger and Benue water appeared to be relatively small.

In Section III, 5.4, particular phenomena of the bed morphology have been described. Important is the scour-criterion which is mathematically derived from the formulae for discharges of water and sand. The result is that under certain simplified conditions scour occurs when ba^{α} decreases in consecutive cross-sections, whereas deposition takes place when ba^{α} increases, b being the width of the flow-line, a the depth in the flow-line and α a coefficient, which depends on the quantity of sand-transport per unit width and which varies between 1 for no sand-transport and 1.5 for very large sand-transport.

Further, the distinction between local and through transport is described, both of which form the total resulting transports of many local transports of sand in the turbulent water. This local and through transport is of great importance for the understanding of channel formation in bends and of the almost uniform distribution of depth over crossings, as it is related to the curvature of the flow-lines. Moreover, this local and through transport gives a deeper insight into the causes of meandering.

The formation and propagation of the bed-ripples are discussed in III, 5.4.3. This remains a very intricate problem. The major part of the sand-transport along the bottom occurs through the movement of bed-ripples although, of course, each particle moves and not the ripple as a whole. Waves — as the ripples can be seen — occur always in Nature when two media of different density and composition brush past each other. Model tests and existing theories have been discussed, whilst NEDECO made observations on the behaviour of ripples in the Niger. It appeared that during high water and the subsequent higher water-velocities, ripples grow in size. There was a marked retardation in the adaptation of the river to the actual flow, resulting in fair-sized ripples which sometimes hampered shipping considerably when the water-level had dropped and the ripples were still high.

The study of sand-banks showed that they develop and exist where circumstances for deposition are favourable, i.e., always where ba^{α} increases and often where flow-lines diverge. This occurs in general in the inner bends opposite the outer bends where deep channels exist.

The propagation of sand-banks is certainly faster than could be expected from the sand moving over the sand-bank and the deposition of this sand just behind the sand-bank. So the explanation of this must be sought in the cross-exchange of sand during high water, which is pronounced by the sudden change in bed-shape, resulting in horizontal sand-laden eddies which move large quantities of sand from the downstream end of the channel to the area just below the sand-bank. In this way both sand-banks and channels move more quickly forward than could be expected from the normal sand-transport.

Finally, the accumulation of sand near tributaries is discussed. The causes of this effect should be sought in the temporary or lasting domination of the sand and water regime of one of the joining rivers onto the joint river.

2.4.3. Meanders and islands

a. *Meanders* (III, 6.2.1)

Meandering is an essential part of alluvial river behaviour. At first sight, there are rivers that do not appear to meander, although a closer investigation always reveals the oscillating

nature. The cause of meandering springs from the natural oscillation of particles moving downstream under the action of gravity. Under perfect condition, such as symmetrical channel, uniform material, etc., the discharge would be expected to flow in a straight course down the line of steepest slope. However, the slightest departure from symmetry or variation in erodibility of the banks will cause an increased flow on one side of the channel and a departure from the straight flow. This is then the introduction of an oscillation which is along the course of the river regularly strengthened or weakened.

The oscillation is everywhere present as the disturbance from the perfect symmetrical conditions is everywhere present. The shape, however, in which the banks and bed of the river appears is threefold:

(i) a braided section: several oscillating channels existing next to one another between the banks.

(ii) a reach: a section in the river with practically straight banks and a single oscillating channel; and

(iii) a meander section: a single oscillating channel with banks oscillating in the same pattern as the channel.

The choice between merely oscillating and meandering seems to be determined by the boundary conditions, amongst which are slope, discharge, bed-load, grain-size of bank and bed material and erodibility of the banks. In III, 6.2.1 these various factors are discussed, and although the coherence of these river characteristics and the bed-shape cannot yet be clearly indicated, some observations and speculations are useful when contemplating the regulation of the river.

Shortly summarised it can be said:

(i) Rivers with gentle slopes are inclined sooner to develop a meander pattern than rivers with steep slopes which are more inclined to shaped braided beds. A sudden decrease in slope, however, may result in a deterioration of the bed as a result of loss in sand-transporting capacity and the consequent deposition.

(ii) A small discharge seems easier to develop a meandering than a large discharge. The seasonal varying discharges complicate this. Each significant group of water-stages may provoke its own meander pattern, but in reality there is of course a mutual influence between these patterns. It should be noted that there is a strong indication that, with all other factors remaining constant, a larger discharge implies a wider but not a deeper bed (see III, 6.1.1). It is likely that the occurrence of a single channel depends on the attraction of the banks. Since in wide channels this attraction will be relatively smaller, high discharges with wider beds are inclined to get a braided character.

Regulation will decrease the higher and increase the lower discharges and as much as possible create a constant discharge. As the high discharges determine the width for the greater part, it is thus expected that, as a result of regulation, river-beds will become narrower and will be more inclined to form a meander pattern. Further, as a result of the constant discharge, the adverse effect of two meander patterns not in phase will not occur.

(iii) In principle the bed-load is always equal to the sand-transporting capacity and is then a function of the slope, discharge and grain-size, so that indirectly bed-load is discussed under these variables. There remains, however, the circumstance when the transporting capacity is greater or smaller than the load. A sudden decrease in transporting capacity as a result of a sudden decrease in slope will subsequently give deposition and may lead to a degraded river, as already

has been discussed. Another point is the conclusion of FRIEDKIN ([1] that meandering results primarily from local bank erosion and consequent local overloading and deposition by the river of the heavier sediments, which move along the bed. In other words, the non-equality of transporting capacity and actual load caused by the erosion of the banks is an indispensable condition for river-meandering.

(iv) The grain-size of the bed and bank material will definitely influence the shape of the bed and meanders, as well was the choice between braiding and meandering. However, the absence of sufficiently systematically grouped data and the lack of a theoretical basis makes any opinion about this influence too speculative. In this connection, MATTHES ([2] may be quoted: "Bed-resistance is controlled by the character of the materials composing the alluvium, more particularly by its resistance to erosion. Grain-sizes, specific gravity, cohesion, and the roughness of the channel are important factors. Grain-sizes may range from cobblestones in headwater alluvium to fine sands and silts in the lower reaches of large rivers, but a cobblestone alluvium produces as definite a meander-pattern as does one composed of sand."

(v) Once meanders have been formed, the erodibility of banks allows the meander pattern to deform constantly and has its influence on the equilibrium of such a pattern. Whether or not a natural cut-off will occur does not necessarily depend on the presence of rocks, clay or other erosion-resistant material. Such a cut-off may also develop in more or less homogeneous material, but from observations of many rivers in the world and from laboratory experiments the impression is gained that this is more likely in small sloping rivers than in rivers with a larger slope. The valley slope itself causes the meander pattern to propagate downward.

b. *Islands* (III, 6.2.2)

Islands are considered to be disturbances in a natural unbraided river. Several circumstances may stimulate the formation and durability of islands. The surveys and studies on the Niger and Benue have led to the assumption that the basic sources, essential to and eventually leading to the formation of islands, may possibly be simplified into the two following conditions:

(i) local variation in bank resistance against erosion; and

(ii) varying water-levels (discharges).

The varying bank resistance will lead to the stronger erosion of the weaker parts of the river-banks, disturbing the alignment of the banks. Under such conditions the formation of islands is possible, as has been tentatively described in III, 6.2.2 and is represented in Diagram III, 6.2.2-1. Normally islands are constantly attacked at the upstream end and grow at the downstream end. When they grow too long, they often "drip-off" at the downstream end.

Where there is a varying water-level and a uniform resistance of the banks against erision, it may be presumed that in general the resistance of the banks against scour is more than that of the bed. When the river is in spate, it tends to enlarge its cross-section initially by deepening but finally by widening. During this process the cross-section of the bed may show a channel along each shore. In a subsequent period of lower water-levels the river will decrease its too wide cross-section first by accretion and then by narrowing of the bed. This accretion, combined with the fall of water-levels, may cause the mid-river sand-bank to dry up. Favourable conditions for vegetation on such sand-banks, combined with the accretion of cohesive materials (fine sand and clay), may protect the newly-formed island from destruction in the seasonal high water.

([1] FRIEDKIN, 1945. MOR. 9
([2] MATTHES, 1947. MOR. 22

These high waters may then even assist in the heightening of the sand-banks and further widen the original banks. Such a cycle has been illustrated in Diagram III, 6.2.2-2.

At the same time, islands are threatened with destruction by the attack of flowing water, which is in general on top, frontal and/or sideways. Sometimes this is compensated by the accretion at the downstream end of the island, but conditions can also be unfavourable there, and then degradation or "drip-off" may occur. Sideways attack is often strong when the original banks have become so wide that they eventually rest in erosion resistant material. Also flow conditions can be such that one of the channels re-silts when the flow has preference for the other channel.

The whole mechanism of islands is so complex that only with the aid of long-time records can more be understood of their behaviour. Specially air photography at regular intervals will help this understanding.

The circumstances for the existence and formation of islands in the Niger and Benue Rivers seem to be favourable, as follows from the very great number of islands in this river (Table 2.4.3-1). Variations in erosion resistance as well as in water-levels are appreciable. It is noticeable that the formation of an island with a length many times the meander-length often causes difficulties to navigation, whilst it should be mentioned that where a regular meander pattern exists, channels are stable and island formation is rare.

TABLE 2.4.3 - 1

NUMBER OF ISLANDS IN VARIOUS RIVER-STRETCHES

Stretch	River	Miles	Number of islands per 100 miles
Jebba — Raba	Niger	564—545	115
Raba — Budon	Niger	545—395	65
Budon — Lokoja	Niger	395—360	100
Lokoja — Aboh	Niger	360—177	43
Aboh — Patani	Niger	177—130	30
Garua Creek	Benue	980—925	only appreciable between Miles 955—960
Faro — Lau	Benue	925—775	77
Lau — Tunga	Benue	775—575	60
Tunga — Abinsi	Benue	575—535	40
Abinsi — Lokoja	Benue	535—360	65

2.4.4. Cross-sections (see III, 6.1)

An approach has been made towards a calculation of the size of the cross-section of a hypothetical rectilinear river, under the assumption that the river is alluvial, flowing through its own sediment and capable of building up or eroding its shores, so that both the width and the depth are determined by the river characteristics and not restricted by outside conditions.

If the river characteristics remain constant over a certain stretch (i.e., a steady and uniform flow of water and sediment) it can be reasoned that then also the slope of the water-level and of the river-bed will be rectilinear. This straight slope is minimum when the river is in equilibrium, that is, when the steady discharge and sediment load are carried through without being affected.

An implication of the condition of the minimum slope is that the transport of sediment on the river-stretch is at a maximum. For any other (larger) value of the slope the corresponding size of the cross-section would cause a smaller transport of sand.

This condition can be summarised as follows:

Of a straight alluvial river-stretch in equilibrium, the slope is the least possible slope at which the incoming load can be transported downstream, and the cross-section then enables a transport of sediment which is, for that slope, the maximum possible amount.

In combination with the discharge formula of DE CHEZY and with one of the bed-load formulae, this leads to the following result:

In a straight alluvial river with erodible banks and bed, with a rectangular-shaped cross-section and with uniform flow, the relationship between the equilibrium slope (i) and the depth (a) is:

$$\frac{\Delta d}{a i} = \alpha$$

where d = the average diameter of the sediment-grains;
Δ = the relative density of the sediment in water; and
α = a coefficient, being approximately constant.

It follows from calculations with data of the Niger and Benue that the value of α is in the region of 1.5.

In the case of a non-steady flow, a river tends to maintain its width constantly adapted to the varying discharge, and tends to keep its depth constant. But quick sequences of high water and low water cause little variation in width of the river because the shores can hardly be expected to follow, for instance, seasonal variations. However, after a series of wet years the cross-section at bankfull stages will be adapted to the higher discharges and will consequently be wider than after a series of dry years. It will be clear that the worst shipping conditions occur in a dry year that is preceded by a series of wet years (wide and shallow cross-sections).

In fact, any characteristic of the river-bed, such as its width, depth, or bank-height, is subject to deformation by each separate group of discharges. The magnitude of this influence is determined by its duration and force, and the complete range and sequence of discharges determines the characteristic. It is impossible to envisage a single steady discharge that would shape a river-bed with all characteristics similar to those that result from a superposition of the influences of the varying discharges. But for each single characteristic it will be possible to define a certain discharge that is dominant for the origin and nature of that characteristic: for instance, the width of the bed between the shores is determined by the bankfull discharge.

It has been possible to calculate dominant discharges with respect to the bed-level for the Niger and Benue, a level which should be identical both with the dominant discharge and with the seasonal range of discharges; in the latter case the average of the varying bed-levels should be taken. These dominant discharges are important for the design of bed-regulation works. It appears that the Benue has a well-defined dominant discharge near high water, whilst the Niger has essentially two dominant discharges, one in the region of the long middle-water discharges resulting from the Black Flood, and the other near the short but forceful high water.

The above considerations about cross-sections in a straight river give a first approximation of the actual river-bed. The cross-section in a bend has also been discussed in the present Report, and it has appeared possible to calculate an equilibrium profile in a continuous bend, under certain simplifying assumptions.

The flow-pattern in a bend, too, can be calculated. The well-known result is a helicoidal secondary current: together with the normal downstream direction of the flow there is a spiral flow, directed outward along the surface and inward along the bed; at the concave bank the flow is directed downward and along the convex bank upward.

There is also a tendency towards a spiral flow in straight sections, as a result of the rotation of the earth. This motion, which results from the Coriolis acceleration, has been calculated and in spite of the low latitudes its influence on the flow could not be entirely neglected.

Every bend must be limited in length, and on the other hand a completely straight channel cannot be stable over an appreciable length, as occasional disturbances will result in curved flow-lines with spiral flow and, in consequence, meandering. A natural channel consists of alternating bends, linked by a transition consisting of a more or less straight alignment.

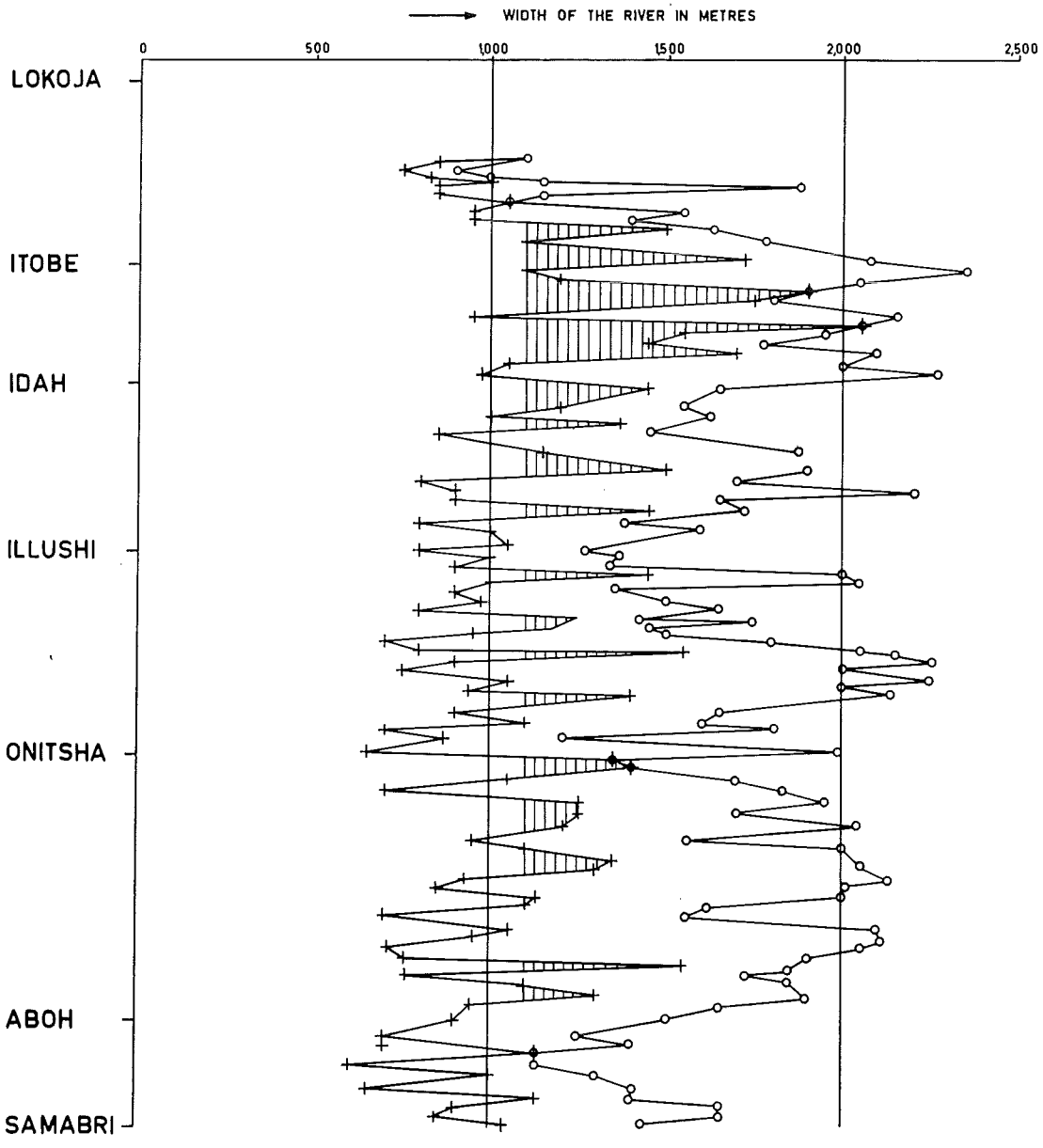


DIAGRAM 2.4.4 - 1

Widths along the lower Niger at bankfull stage and at Low River Level

In the bends the capacity of the discharge is mainly concentrated in the deep outer-bend. In the calculation of the cross-section, the spiral-flow dominates and other morphological factors such as the law of maximum sand-transport do not play a major role. In the transitional crossings the curvature decreases, and with it the influence of the spiral flow. Theoretically, the channel will become wider and shallower and approach the equilibrium depth of a straight channel, but before this equilibrium is reached a counter-curve has made itself felt, concentrating the flow again. So the depth at the crossing will in general be smaller than the average depth but still be larger than the theoretical equilibrium depth of a straight river.

In the reach-type of river-bed, which is normal for the greater part of the Niger and Benue, the high-water banks are fairly straight, with a channel meandering between sandy shoals. This system of shoals and channels propagates downward, so that a bend may be located where a few years before a straight channel formed the transition between two opposite bends. These bends and their straight transitions are therefore related in width, as they both are situated between the same parallel banks of the major river-bed. This relation, however, has not been expressed in mathematical terms.

Lastly, some characteristics of the cross-sections of the Niger and the Benue have been produced, such as the width, the frequency-distribution of the depths, and the quantity $a^{\frac{3}{2}}b$ which is of importance for the discharge capacity.

In Diagram 2.4.4-1 (i.e., III, 6.1.6-1) the widths of series of cross-sections, as sounded during the H.W.-period and at L.R.L. have been plotted.

2.4.5. Longitudinal sections

Cross-sections (see 2.4.4. and III, 6.1) are separately studied in relation with the sand and water regime of the river. In longitudinal direction the cross-sections ranging side by side show also a certain mechanism through a period, caused by the hydrographic variations in such a period. The seasonally and yearly variations in the discharges of both sand and water have a distinct effect on the bottom height at each point of each cross-section. To describe this for each point is not possible, as the local conditions differ widely from point to point. Moreover, the bottom height over large parts of each cross-section is of no interest to shipping. Therefore, specially, the actual behaviour of channels and deepest spots on crossings have been studied. The connection between the deepest parts of successive cross-sections is called the talweg, and the behaviour of this talweg and its position is in the first instance of importance for the navigation.

The talweg, deep in the bends and shallow on the crossing, is an undulating line on which the smaller waves-lines of the sand ripples are superimposed. The talweg section will be used when determining:

(i) the maximum depth in any cross-section;
(ii) the distribution of the maximum depths over a certain river-stretch and the quality and quantity of the shallow places; and
(iii) the least available depth (L.A.D.) of a river-stretch.

Diagram 2.4.5-1, i.e., III, 6.4.1-1, shows a talweg profile of the Niger as derived from soundings. The depth from point to point varies considerably along the talweg. The depth is also varying with the different discharges through the year, which is clearly illustrated by a hydrograph combined with the bottom height in Diagram 2.4.5-2, i.e., III, 6.4.2-6. This last diagram is given for a point in the talweg on a crossing. Such a point has a maximum talweg height between all lower-lying points of the talweg when compared with a reduction plane, (f.i., the water surface), and is therefore of special interest to navigation as it has a minimum available

depth. It is remarkable, however, that the bottom in such a point reacts on the discharges (in the diagram given as water-levels) and in such a way that this bottom is respectively lower and higher with low and high water. This reaction of the bottom on the different discharges (water-levels) starts immediately when discharges change, but takes some time to be established. As the discharges may vary constantly, there is always a certain time-lag between the occurrence of a discharge and the adaption of the bottom to this discharge or the actual change of stage and the resulting change of bed-formation. The total difference in bottom height on crossings may be upto four feet on the Niger and even reach 6 to 8 feet on the Benue. The reason for this difference between the Niger and Benue must probably be sought in the greater high-water/low-water ratio of the Benue, as the whole phenomenon is caused by the varying discharges. Although not measured in the deep channels — as it was not important in relation to the navigability of the rivers — it is likely, as declared by other observers, that the reverse will happen in channels. The channels deepen by scouring during high water and silt during low water. Observations and computations make it likely that the scouring in the channel during high water mainly occurs at the downstream end of a channel and silting mainly happens at the upstream end of a channel. At the lower ends of the channels, where they change in a crossing, the cross-exchange of sand is pronounced during high water by the rather sudden change in bed-shape resulting in horizontal eddies across the river loaded with sand. During low water the flow over a crossing is strongly deviated from the course of the banks, and the scoured material from the crossing is brought in the upper end of the channel (see Photograph 2.4.5-3, i.e., III, 6.4.2-2).

The phenomena of scouring and silting, which on the crossing are of highest importance to shipping, are greatly complicated by the fact that the bottom configuration moves between the banks. This means that scouring and silting in a point are not only dependent on the hydrograph but also on the actual location of the point. For instance, the shallowest spot in the talweg on a crossing is in its elevation not only dependent on the hydrograph but also on the movement of the crossing between the banks as the boundary conditions change. Such a change of boundary conditions occurs, for example, when the crossing moves from a narrow river-stretch into a wider river-stretch.

Important are the preliminary conclusions which could be drawn from the observations made on the talweg through the Niger and Benue and especially on the talweg over the crossings. They can be summarised for the Niger as:

(i) The average crossing is over 6 feet deep at Low River Level (L.R.L.), and the crossings with less than 6 feet L.A.D. at L.R.L.-stage are few in number and generally found below a bifurcation or where the river-bed is wide, perhaps as a result of easily erodible banks.

(ii) The restrictive crossings hamper navigation after the rapid drop of water-levels, in November and December when rain has stopped. The Black Flood (see III, 2.3.1) arrives in December and stabilises river-levels at about L.R.L. Just after the drop in water-levels, and before scour on the crossings starts to take effect, the worst shipping conditions occur and the L.A.D. on the restrictive crossing will be between 4′ and 4′6″. Dependent on scour and an occasional raise of 3—6 inches in the Black Flood during January and February, the L.A.D.'s may increase by $\frac{1}{2}$—1 foot.

(iii) When in March or in April the Black Flood ends, water-levels drop rapidly and scour will occur on an increasing number of crossings. As this drop may be 4 feet or more, L.A.D. may fall to 2′ to 2′6″ on the restrictive crossing, even while a scour of 2—3 feet of the bed is not unusual. Navigation then has to stop or will be restricted to the section of the Niger below Onitsha.

(iv) During the observation period 1956—1958 the Black Flood discharges on the Niger

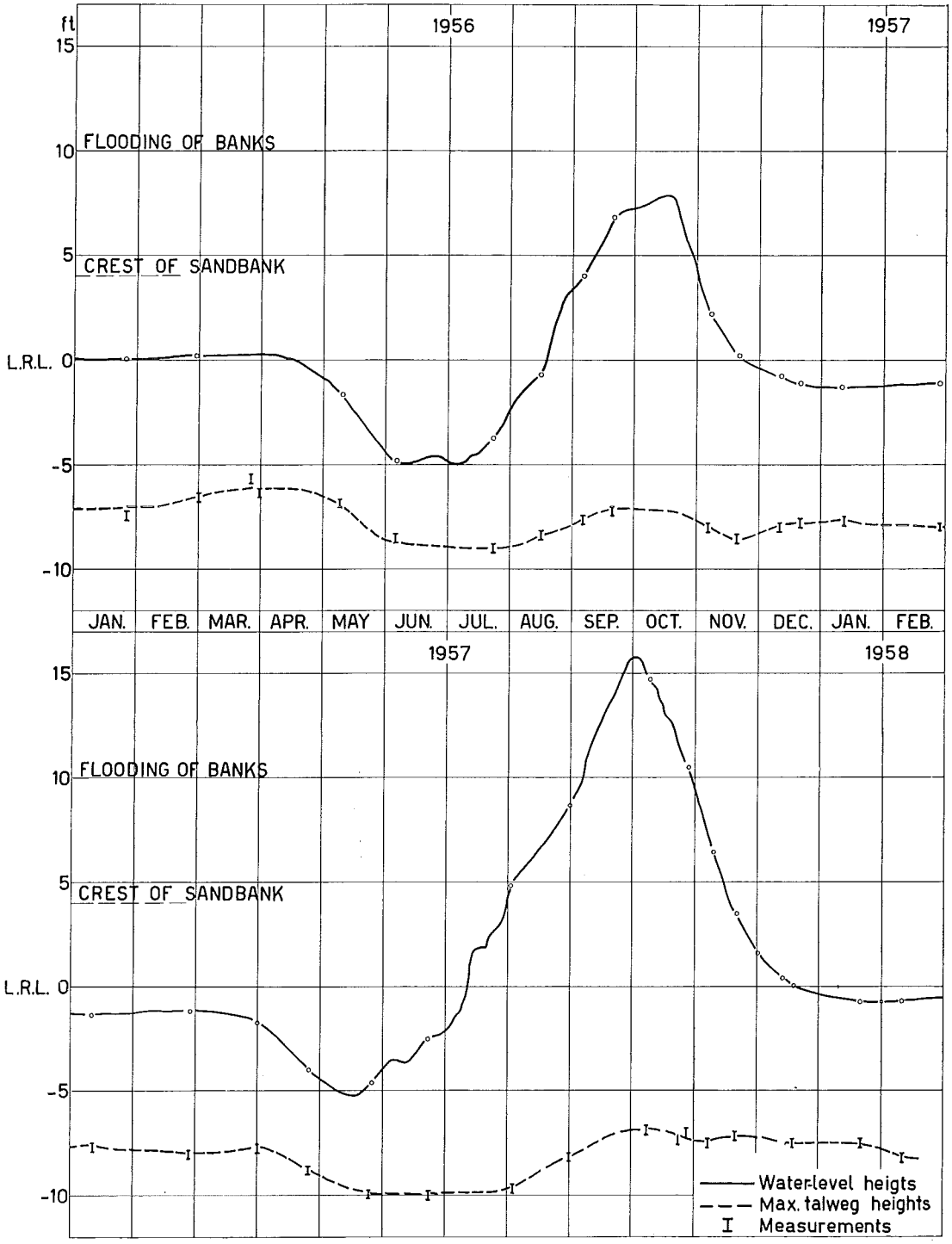
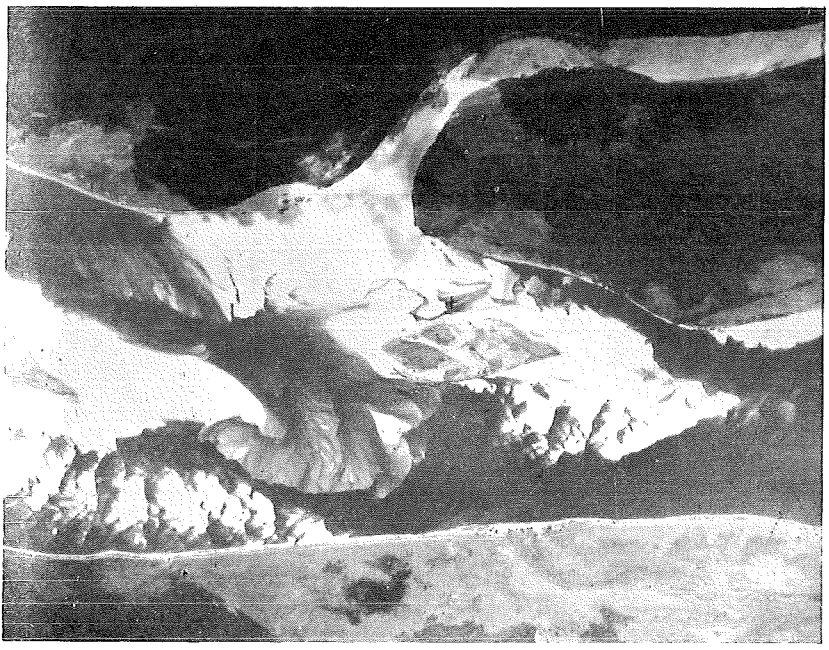


DIAGRAM 2.4.5 - 2

Talweg depths and water-levels on the Kelebe crossing (Niger, Mile 389)



PHOTOGRAPH 2.4.5 - 3

Flow over a crossing delivering a trumpet of sand into the deep channel downstream

have always been above the average in height as well as in length. An average discharge of the Black Flood will bring water-levels during January and February approximately 1'6" below L.R.L. A restrictive depth of 4 feet in December, improving to not over 4'6" during January and February, may well be expected in an average year, and the end of the Black Flood will then be at the end of March or early April.

(v) The number of crossings that must be dredged to gain 1 foot more available depth during the steady Black Flood is limited to some 8 or 10. The fall in discharge and water-level at the end of the Black Flood is so large that no further results can be expected from continued dredging at the end of the Black Flood in April.

For the Benue the mechanism of shoaling and scouring is in principle the same as on the Niger, although it may be more pronounced as a result of the larger high-water/low-water ratio on the Benue than on the Niger. As there is no Black Flood which stabilises the water-levels during a part of the dry season, the Benue is only navigable in the rainy season. Navigation is practically restricted by the L.A.D. on the Gamadio and Wuro Boki Flats, and these are dependent on the discharge and vary in the navigation season from 3'6" to 8' or 9'. Below Lau navigation is possible with more draught, but the flats in the entrance of the Benue restrict the moment when the Benue can be entered. At the end of the rainy season water-levels drop sharply and continue to do so until the Benue is no longer navigable, a process which may happen in a fortnight. The result of such a sharp decrease in discharge to a very small discharge is that no possibilities exist of lengthening the Benue season by dredging.

2.5. NAVIGABILITY

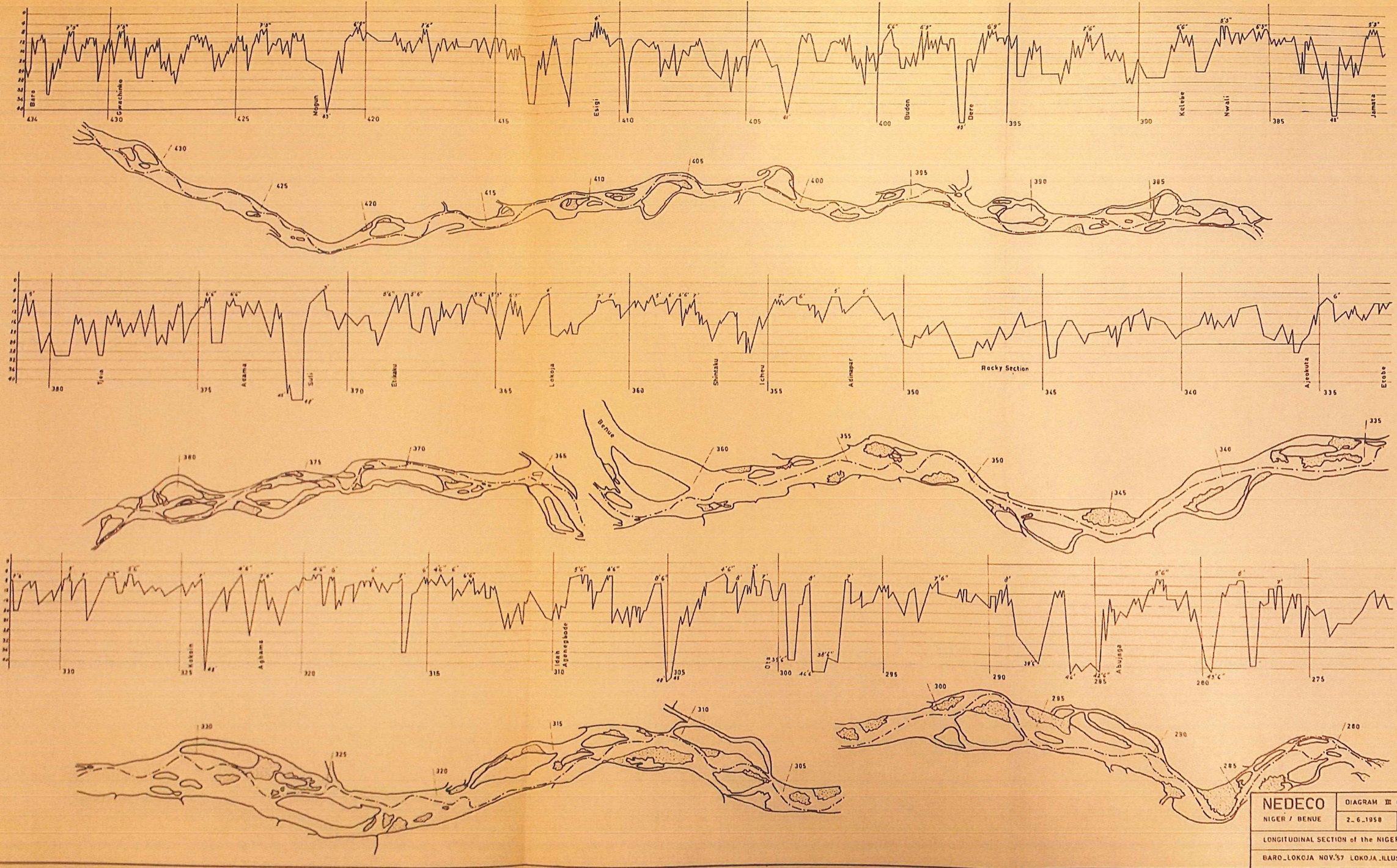
2.5.1. The waterway characteristics

The *slope* (i) and *water velocities* (v) are related according to the formula of DE CHEZY

$$v = C\sqrt{Ri}$$

where C is the coefficient of de Chezy, and

R is the hydraulic radius, practically equal to the depth a.


Baro
Gwachinko
Mogun
Esigi
Buden
Dere
Kelebe
Nwali
Jamata
Tjela
Akama
Suli
Etikaku
Lokoja
Shintaku
Ichru
Akimapar
Rocky Section
Ajaokuta
Etobe
Benue
Kakasin
Aphama
Idah
Agenegbode
Otu
Abuluga
NEDECO
NIGER / BENUE
DIAGRAM III 6.4.1 - 1
2-6-1958
N
LONGITUDINAL SECTION of the NIGER
BARO-LOKOJA NOV.'57 LOKOJA-ILLUSHI JULY '57

I, 2.4.5 - 1

The average slope over longer river-stretches will not show much variation as it is dependent on the valley slope, whilst water velocities can increase considerably with rising water as the depth increases.

On the Niger, during low water, the average slope of the water surface is between 6 and 8×10^{-5} in the lower reaches, increasing to $11—13 \times 10^{-5}$ in the Baro—Lokoja stretch. During high water the slope may increase by $2—5 \times 10^{-5}$. On the Benue, during the navigation season, slopes vary between $10—13 \times 10^{-5}$ in the lower sections to $20—25 \times 10^{-5}$ in the upper reaches. Above the Faro Confluence, in the Garua Creek, the gradient is between 5 and 7×10^{-5} (Diagram 2.3.2-1).

As a result of the slope a ship has to overcome a difference in height when sailing upstream. However, the engine power required for this is negligible compared with the power required to eliminate the water velocity in the river.

Water velocities have been computed from comparison of upward and downward sailing. The averages come down tot 2—3 m.p.h. on the Niger during low water, whilst during high water they are between 3 and 4 m.p.h. on both the Niger and Benue. Diagram 2.5.1-1 (i.e., IV, 3.1.1-2) gives the relation between the increase in water velocities and the water-stages as well as the maximum velocities (between the piers of the Makurdi Bridge and in a narrow cross-section near Numan).

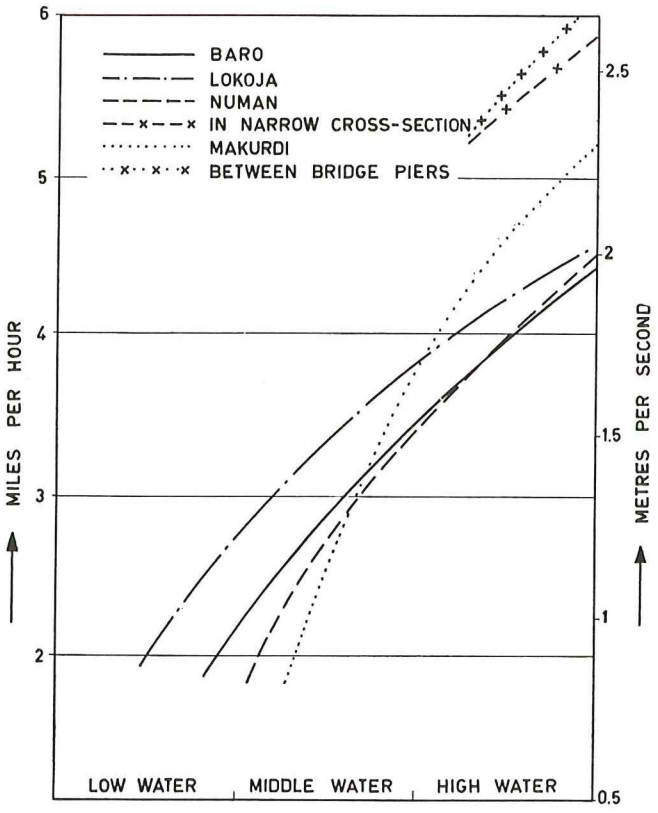


DIAGRAM 2.5.1 - 1

Water velocities on Niger and Benue

In general, the *width* of the navigable stretches does not restrict shipping, as normally the navigation channels measure well over 500 feet; but under exceptional conditions the width of the navigation channel (depending on the draught) can be locally restricted to 150 feet. This will not happen during high water, but occurs only when shipping reaches its limitations by middle-water stages (on the Benue) and low-water stages (on the Niger). From the viewpoint of resistance to ships, however, the rivers (including the Benue tributaries) can be assumed to have a channel of infinite width.

The *depth* of the navigable stretches will be separately discussed in the following paragraph.

The *curvature of the talweg* is such that ships with 5—7 feet draught and up to 700 feet in length can navigate the Niger up to Jebba and the Benue as far as Gamadio during high-water stages. Reduction of this length over the Gamadio and Wuro Boki Flats and in the Garua Creek can be necessary to prevent unjustified risks. During low water, when navigation on the Niger with 4—5 feet is still possible, the channel width is normally at least 300 feet while the radius of curvature is well over 1,500 feet. This applies also for the Benue when this river is navigable with 4 to 5 feet draught, with a possible exception for the above-mentioned flats.

A few bends in the Delta, notably those near Gbekebo (Mile 60) and Siama (Mile 89), are only safe for a tow length of 400 feet. These bends have a radius of only 800 feet and a channel width of 250 feet, with hazardous cross-currents. In the Garua Creek near Kinada (Mile 930) a bend exists with a radius of only 1,000 feet and a width of 200—300 feet, while near Mile 962 a bend occurs with only 700 feet radius and a channel width of 200 feet.

2.5.2. Depths related to stages and discharges

The lowest talweg depth sounded in a given river-stretch is called the least available depth (L.A.D.). For the navigation this L.A.D. is of high importance. As the L.A.D. cannot be directly observed, it is useful to relate it to gauge-readings in each river-stretch. However, it has appeared that gauge-readings and the accessory river-stages do not always have a fixed relation to the L.A.D. in a river-stretch. Differences may occur:
(i) when the bed-formation near the gauge changes; and
(ii) as a result of shoaling and scouring which cause different L.A.D.'s during rising and falling water at the same gauge-reading.

The former difference can be nearly completely eliminated when not the river-stage but the discharge is related to the L.A.D. However, the difference in L.A.D. for a certain discharge before high water and after high water will remain, as there is a time-lag between the adaptation of the river-bed to a certain discharge and the occurrence of that discharge. This phenomenon has been called retarded scour and shoaling.

The L.A.D.'s in the different river-stretches related to discharges are very important with respect to discharge regulation by means of a reservoir. The size of a reservoir can only be determined from the requirements in L.A.D. (and thus in discharge) or, in the reverse, from the most economic reservoir-size the duration of discharges (and thus of L.A.D.) can be determined. It is then necessary to know the minimum required discharge to maintain a certain L.A.D., and this is called the "limit discharge" (for that L.A.D.), which can differ for each river-section and is different before and after high water. These limit discharges have been determined by

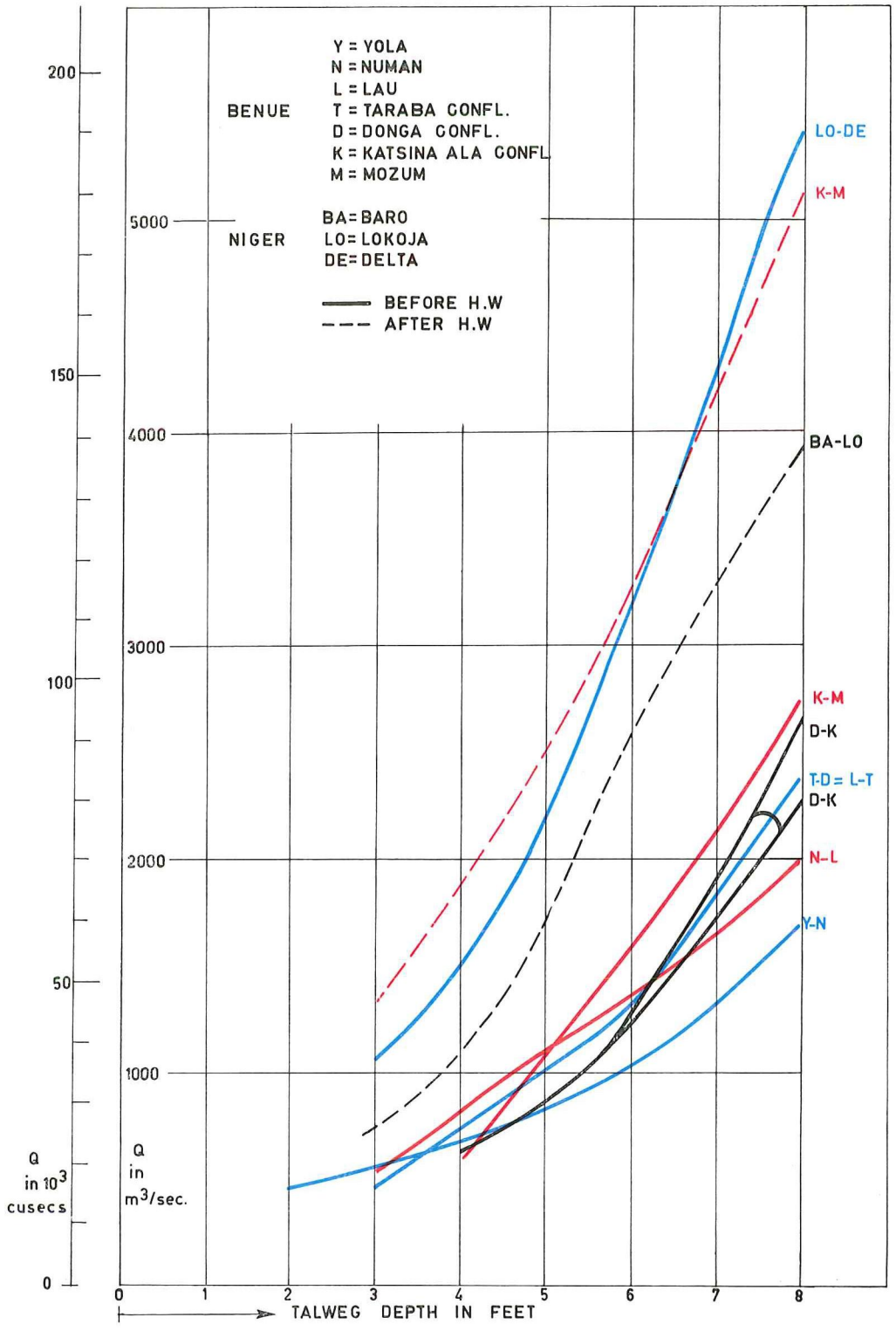


DIAGRAM 2.5.2-1

Limit discharges

measurements, based upon the present discharge hydrographs (see 2.5.2-1, i.e., Diagram VI, 8.5.3-2), thus taking into account the retarded scour and shoaling. When the actual regulation is carried out, the differences between the "limit discharge" during rising and falling water-levels will become smaller, as the discharge will be kept as constant as possible throughout the year.

At present, the L.A.D. during high-water stages varies between 15′ and 20′ near Baro and 25′ and 35′ near Onitsha on the Niger and between 6′ and 9′ on the Gamadio and Wuro Boki Flats and 20′ and 30′ on the Lower Benue. During high water it is possible for coasters with 12′—14′ draught to navigate as far as Makurdi and Baro without taking undue risks. During middle-water stages shipping on the Niger and Lower Benue is quite possible with 8′—10′ draught, but on the flats near Gamadio and Wuro Boki navigation is then restricted to 3′6″—5′. During low-water stages this picture changes considerably. The Benue is not navigable with more than 1′—2½′ draught after November and before June, whilst the Niger remains to a certain extent navigable during the dry season as a result of the Black Flood; 4—5 feet can be expected to be the L.A.D. until the Black Flood recedes and then no more than 2—3 feet will be available above Onitsha during two to three months. Diagram 2.5.3-1 (i.e., IV, 3.2.2-1) gives the graphical précis of the navigation restrictions for different river-sections.

Too much emphasis is in general laid on the shallowness of the Niger and Benue Rivers. This may be correct insofar as it is a restriction of the draughts and a warning against possible groundings, but it is incorrect with regard to the drag encountered from the bottom by a ship. It has been calculated that the present ships encounter a drag from the bottom — when they sail throughout the navigable period — which is comparable with the drag encountered by the same ships in a canal with a depth of 3—4 times the draught of the ship and infinite width. From this viewpoint, the Niger and Benue are deep rivers (See also Diagram 2.4.5-1).

2.5.3. Average navigable periods

With the relation between least available depth and the discharge, the theoretical navigable periods have been calculated from the 50 % frequencies of discharges (Diagram 2.5.3-1, i.e., IV, 3.2.2-1). This is the most reliable average which can be obtained.

The diagram has been divided into two parts: the upper half represents the available depth in each river-section over the year, while the lower half compiles these data so that it indicates the theoretical periods in which river ports along the Niger and Benue can be reached from Delta ports. The scour during low water has been taken into account in calculating the available depth during rising water. The average navigable period for different draughts can be read on the horizontal axis of this graph.

2.5.4. Groundings and delays

The main causes of groundings can be classified as:

(i) lack of acquaintance with the situation;
(ii) insufficient available depth;
(iii) lack of manoeuvrability; and
(iv) inattentiveness of bridge personnel.

(i) Unacquaintancy with the situation is the result of the frequent and fast shifting of the talweg, especially of the channels over the crossings during high water. Then, depths in the Niger are large and groundings are rare, but especially on the flats in the upper reaches of the

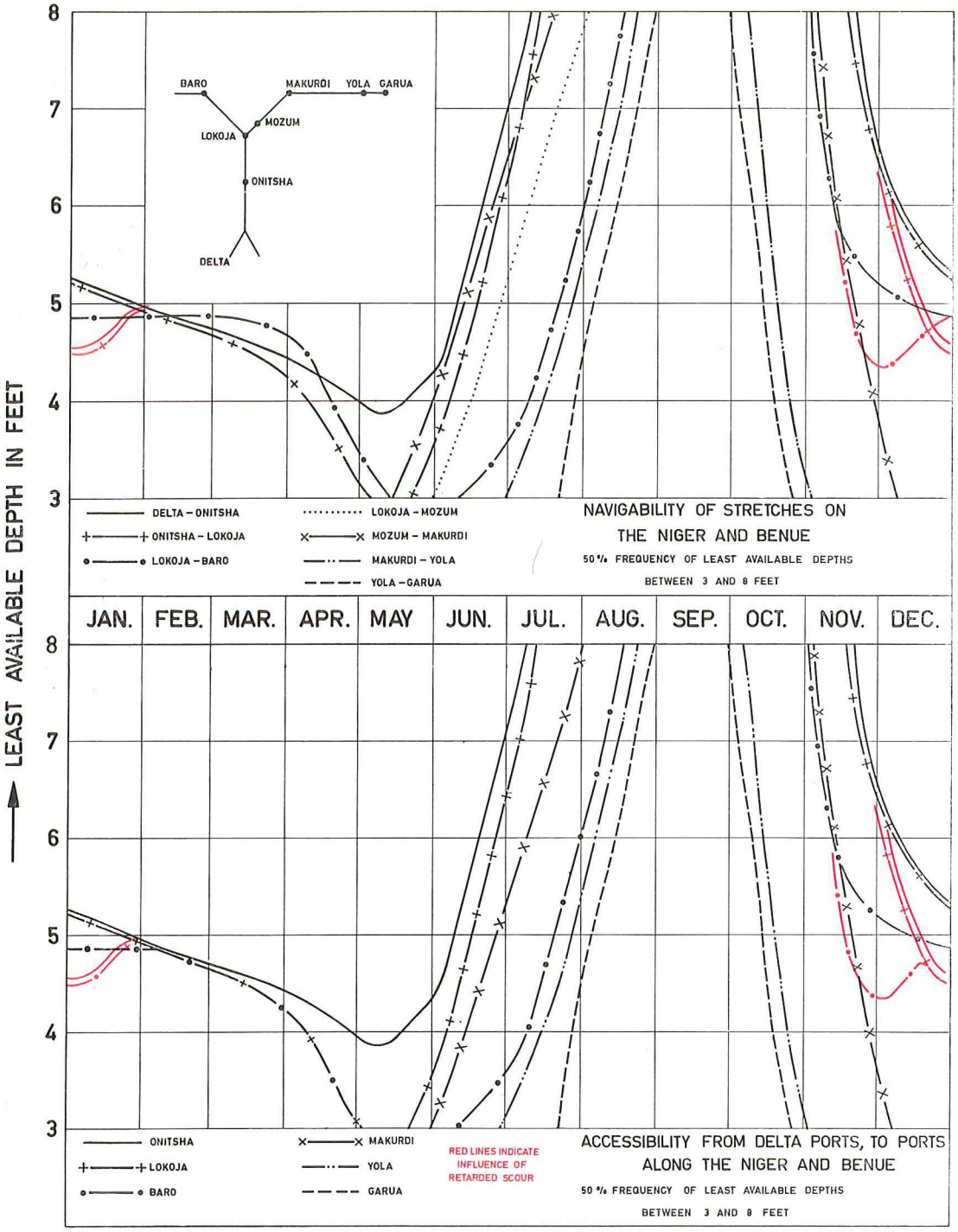


DIAGRAM 2.5.3-1

Navigability of Niger and Benue

Benue, depths remain restricted and groundings may occur. To anticipate this, river pilots make an orientation trip on the Benue by canoe during low water. Benue pilots board the river tows in Lokoja during the Benue Season and at particularly bad stretches local pilots guide navigation. During low water, when ships ply on Baro, it frequently happens that a channel shifts and a grounding may result. A system of channel demarcation will be of great help in guiding the navigation.

(ii) Insufficient available depth is a cause of groundings. River operators have to take the risk at the beginning and end of the Benue season and during the Baro season of loading their ships to a draught which is practically equal to the available depth. A small drop in water-level may then result in a grounding or in delay of their ships. If river operators did not take these risks to a certain extent, they would not be able to utilise the already restricted possibilities of the navigation seasons. Experience has taught them that when the Baro gauge drops below 8—9 feet the end of the Black Flood has come and ships must remain below Onitsha. The same practice of using the water-level as a guide for the moment of evacuation of ships from the upper stretches of the Benue is normal, although greater precautions are taken as a result of the rapid drop in water-levels occurring on the Benue and the danger of having a tow caught for a long period. A system of water-level prediction can greatly reduce these risks and help to utilise the navigation seasons to their full extent.

(iii) and (iv). Lack of manoeuvrability and inattentiveness of bridge personnel speak for themselves. The former can be improved by greater engine power and an improved rudder arrangement, while the whole design of the ship should aim at the highest degree of manoeuvrability. The latter, a human factor, can only be reduced by increasing responsibility among the crew members and rewarding good performances, while the training and working conditions of pilots and captains could also be improved.

Delays are inherent in groundings. Together with prevented groundings, i.e., waiting due to river conditions, they produce a loss of about 5—7 % of the navigable periods. A sharp drop in this percentage to 1 or 2 % can be reached with channel demarcation and water-level predictions, as has already been proved by these services to navigation initiated by NEDECO during the Investigation.

Further delays occur mainly in river ports. Congestions in ports are rare, but they do occur, however, in Garua where shipments have to take place in a period of only 6—8 weeks, and in the base-ports Burutu and Warri where all river traffic concentrates. The turn-round in ports is being improved by port management.

Finally, the period April-May-June often shows non-activity of a large part of the commercial river-fleets. This is not actually a delay, but finds its cause in insufficient discharges and consequently deficient available depth. A part of this period is being utilised for the necessary overhaul of vessels.

2.6. NAVIGATION

2.6.1. River fleets

a. *Commercial fleets*

Two main shipping companies ply on the Niger and Benue with a fleet of ships. They are (i) Niger River Transport (N.R.T.) with 27 power units and 92 barges and a total carrying capacity of 22,000 tons;

(ii) Holt's Transport (H.T.) with 13 power units and 51 barges and a total carrying capacity of 5,500 tons.

Some other companies have one or a few vessels in operation, among which are the Compagnie de Transport et Commerce (C.T.C.) with a semi-integrated tow and the Socony Vacuum Oil Company (S.V.O.C.) with a semi-integrated tanker which together with two self-propelled vessels chartered from the Monrovian Navigation Company regularly carry petroleum products upriver. Further, the Compagnie Française de l'Afrique Occidentale (C.F.A.O.) operates locally with a small tonnage. Also, African shipowners are using the river as a transport route not only with canoes but also with barges of small size and ferries which are nearly all built in Nigeria and mostly in the boatyards at Makurdi, Opobo and Epe.

The barge capacity ranges from very small to 700 tons. The N.R.T. has two semi-integrated river tows capable of carrying approximately 3,600 tons each, while a number of medium-sized tows carry 1,000—1,200 tons pushed by tugs of some 400 h.p. In general, the tow-size of H.T. is smaller, a unit of one tug and 3 barges lifting between 350 and 500 tons being standard.

In the past few years important improvements have been made to the fleets, including new rudder arrangements which increased manoeuvrability, conversion of coal-burning into oil-burning or diesel engines, and introduction of radio-telephone equipment facilitating a more flexible operation of the fleet. Also very modern push-tows have appeared on the river, one of which is 630 feet long.

b. *Governmental fleet*

From the beginning of the twentieth century a Governmental fleet has existed which has always served all departments. An old map (Diagram IV, 4.2.1-1) has revealed some data about the fleet in 1907: it then consisted of 14 self-propelled vessels, 15 poling house-boats, 4 lighters and 2 pontoons.

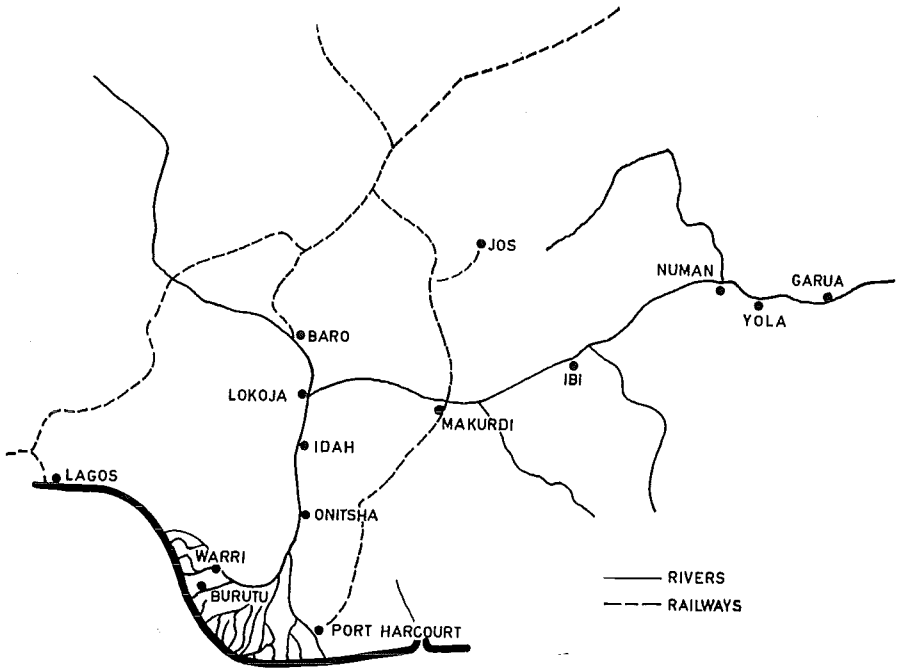
At present the Navigation Branch of the Inland Waterways Department has 179 units of various craft in operation, which participate in a wide range of Governmental activities from services to the Administrative and Medical Departments, operating ferries and creek services to assisting navigation in the widest sense (channel demarcation, river patrol and surveys).

2.6.2. Ports and transport

A description of the main *river ports* along the Niger and Benue must necessarily remain rough and incomplete in this Report. In Diagram 2.6.2-1 (i.e., IV, 2.1.1-1) a summary is given of some of the aspects of the principal river ports along these two rivers. A great number of imperfections which delay a quick turn-round of ships in ports is linked with the small tonnage handled in these ports. All provisions already made in the river ports are the result of private enterprise. Mention should be made of the building of sheds, quays and berths, the installation of a radio-telephone communication system, and the improved organisation of the ports management. The ports of Warri, Burutu and Onitsha have been improved considerably in the past decade and plans are in hand for the building of quays and berths at Baro. In the French Cameroons, the Government has strongly stimulated the extension and improvement of the port of Garua.

Ports are well-sited along high banks and are sufficiently accessible from the river and the hinterland, and the conclusion is that — although much remains to be done to river ports — their condition does not at present affect river transport adversely.

The ports are junctions in the feeder and distribution routes to and from the production and consumption areas, and their function is the transshipment of goods. In all river ports this



	approx. annual tonnage handled	covered storage near waterside	facilities	remarks
Warri	100,000	12,000	Q B L M	Q = quay
Burutu	350,000	40,000	Q T M	B = berth
Onitsha (1	80,000	25,000	Q T L M	T = tanks for petroleum products
Idah (2	20,000	6,000	L	L = man-handling
Lokoja	10,000	8,000	T L	M = mechanised handling
Baro	75,000	10,000	L R	R = railway connection
Makurdi	12,000	10,000	L R	(1 including Asaba opposite Onitsha
Ibi	3,000	4,000	L	(2 including Agenebode opposite Idah
Numan	7,000	8,000	L	(3 including Dalmare opposite Yola
Yola (3	8,000	9,000	L	(4 large covered storage away from waterside
Garua	35,000	17,000 (4	Q T L	

DIAGRAM 2.6.2 - 1

Principal ports along the Niger and Benue

is road transshipment, except in Baro where practically exclusively rail transshipment exists, and in the Delta Ports where most of the loads are exchanged between river-tows and sea-going vessels. Man-handling is still the normal practice in the ports, although mechanised handling exists in the Delta Ports and partly at Onitsha and Garua. The handling costs, the quality of handling, the capacity wanted and the labour available are the main factors in the choice between man and mechanised handling. A daily handling of 800—1,000 tons seems at present about the minimum to warrant mechanisation of port handling in Nigeria. It is important that mechanised handling makes port operations much clearer, as the human occupation of decks, quays and sheds is greatly reduced.

River transport takes merely a small part of the total transport services in Nigeria. Regarding the importance of the major transport means — road, rail and river — only a bare indication can be given, as the origin and destination of the river transport as far as the main shipping companies are concerned are solely in the external trade. A total of approximately 275,000 tons and 130 million ton-miles is now carried by them annually and Diagram 2.6.2-2 (i.e., IV, 5.1.5-2) shows the distribution over the river system in the middle 1950's. The proportion 10:8:1 for rail, road and river transport may be estimated to give an idea of the present situation.

In the past decades this proportion had been more in favour of river transport. But the rapid development of motor transport and the very large investments in rail and road development have caused river transport to lose its fair share in the transport services of the country. The result has been that the ratio of cost per ton-mile between rail and river transport is approximately 1, whereas this ratio in most developed countries varies between 2 and 4. River transport should be the cheapest means of transport and this ratio can certainly be improved. With the present quantity of river transport, the future prospects and the practically unlimited capacity of the Niger-Benue system, capital investment certainly seems justified (see 4.6).

2.6.3. Navigation on the Niger and Benue

The tonnages and ton-mileage of river transport as mentioned in the preceding paragraph is carried in two distinct seasons called the Baro and Benue seasons, when navigation concentrates on the Niger and on the Benue respectively. It is a structure of transport which is determined by the river conditions throughout the year.

In Nigeria, with its predominant agricultural production, by far the largest quantities of produce are offered for shipment from mid-November to February or March. As the Benue is not navigable before June, the fleets serve the Niger ports and in particular Baro from the end of the Benue season onwards, i.e., from November until the end of the Black Flood period in April. During a part of April, May and a part of June only the river-stretch between the Delta and Onitsha is navigable with restricted draughts (see Diagram 2.5.3-1), so only a part of the fleet is in operation and the period is used for the annual overhaul of the vessels. At the onset of the new rains in June, the Benue starts to rise and is normally navigable some time before the Niger above Lokoja is navigable, as the drainage basin of the Benue lies more south, where the rains start earlier and are more intense. As the produce of the latest crop has already been stored in ports along the Benue for some months, and only relatively small quantities of palm products become available in the Niger ports during this period, practically the whole fleet then concentrates on serving the Benue ports, in particular the ports of Garua, Yola and Numan, where the largest quantities are available and the navigable period is shortest. The Benue season ends in October or November and the whole cycle is repeated.

The river conditions on the Benue above Lau are hazardous, as an unpredictable drop in water-levels often occurs in the first half of the Benue season (the so-called August-fall) and the season ends with a fast and sudden drop. The available depth is by some crossings restricted to 5—8 feet, and it is not often that ships sail with more than 6'6" draught on the Benue. During the first trip of the season, when ships are normally loaded between 4'6" and 5'0", time is often lost at crossings when water-levels have not risen sufficiently. On the Niger, conditions are more predictable since the Black Flood has a more or less steady flow. NEDECO has proved that the height and the duration of this flow can be predicted some months beforehand with the aid of gauge readings from Mopti and Diré in the upper reaches of the Niger. However, shipping during the Baro season makes use of middle-water stages, and the available depth is again restricted to 6—4 feet until the Black Flood ends and navigation remains restricted to the

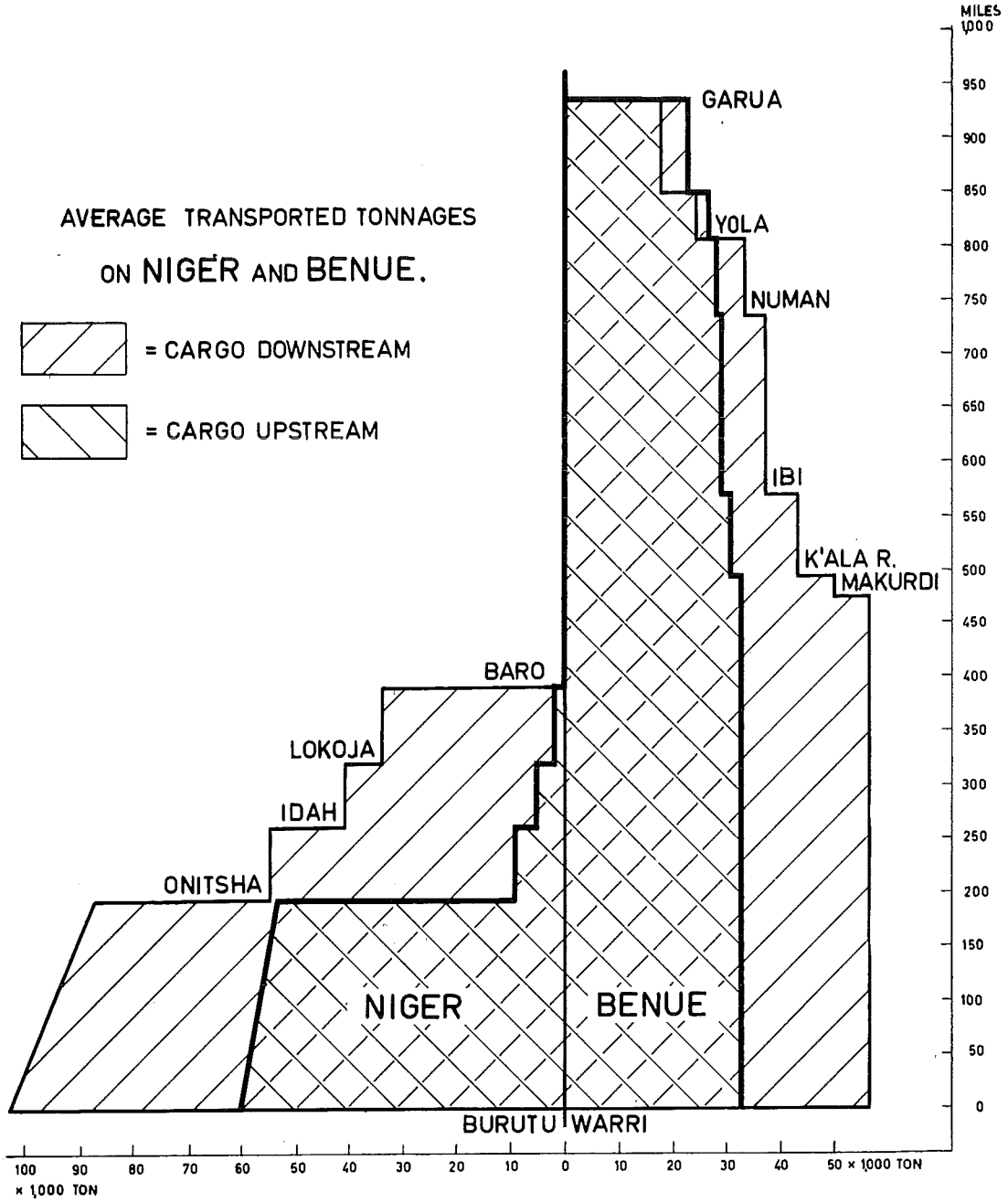


DIAGRAM 2.6.2 - 2

Average annual transported tonnages; upstream and downstream

river-stretch below Onitsha during low water. Further more, shifting and crooked channels hamper navigation.

Under these difficult and risky circumstances, whereby the utilisation of a maximum draught always meets with the risks of a grounding, navigation is most efficient when the draught of the power unit is 4—5 feet and the maximum draught of barges 5—7 feet. The speed of the tows should be at least 6—7 knots in still water as water velocities of 5 knots can be encountered. Propellors in tunnels are the most modern solution for shallow-draught tow-boats and push-towing is the obvious method of propulsion, while manoeuvrability should be as good as possible. Further, special shipping systems can be used to increase the efficiency of the total fleet. Apart from direct shipment between two ports, there are several systems, each of which has advantages in special circumstances. They are described in Chapter VI, 2 as false shuttling, true shuttling and shipment with additional barges.

The river-operators, however, are fully aware not only of the limitations but also of the possibilities of navigation on the Niger and Benue, as they have shown in the recent additions to and the modernisation of their fleets, as well as in the application of a system of shuttling.

CHAPTER 3

RESULTS

3.1. ORIGIN OF DEFECTIVE NAVIGABILITY

3.1.1. The discharges (see V, 1)

The Niger discharge hydrograph (see Diagram 3.1.1-1, i.e., V, 1.2.1-1) can be divided into three distinct parts, viz., high water, middle water and low water.

High-water discharges (August-November) are plentiful and ships drawing some ten feet can then navigate the river.

Middle-water discharges of the Black Flood (November to March or April) are generally just sufficient to enable navigation with draughts of 4—5 feet. But the fall from high water to the sustained middle water is rapid, and many shoals formed by the flood need some time to be adjusted by scour to the middle water. Therefore navigation experiences difficulties between Baro and Lokoja early in the Black Flood period, and similar phenomena of retarded scour occur in the section below Lokoja a few months later, i.e., in January and February after the Benue discharge has fallen to an almost negligible quantity.

Moreover, there is a wide variation in the duration of the Black Flood period. Previously, it was not possible to predict the length of the shipping season any appreciable time in advance. But as the Black Flood season has an economic importance in view of the evacuation of the groundnut and cotton crops then becoming available for transport, this inter-annual irregularity presented many difficulties to a regular and efficient river transport.

The low-water discharges of the Niger (April-June) are too low for navigation with any appreciable and economic draughts. Only canoes and small-powered vessels can then use the Niger channels; but below Onitsha some larger vessels are still able to navigate the Niger at low water.

Hydrological studies have shown that the French irrigation project near Sansanding on the Niger has not affected the discharges or the navigability of the Niger within Nigeria. If in the distant future the project should be in full operation, its influence on the available depths during the Black Flood could be several inches (see IV, 3.3.2).

The Benue discharge hydrograph (Diagram 3.1.1-1) can be divided into two parts: high and low water. Large-scale navigation is only possible during the high-water period (July to October or November) and the duration of the high water determines the length of the navigation season. The pronounced inter-annual irregularity presents its difficulties to the operation of regular shipping services on the Benue. In the upper reaches of the river, i.e., above Lau, the length of the shipping season is very short owing to the deficiency of the discharges during the greater part of the year.

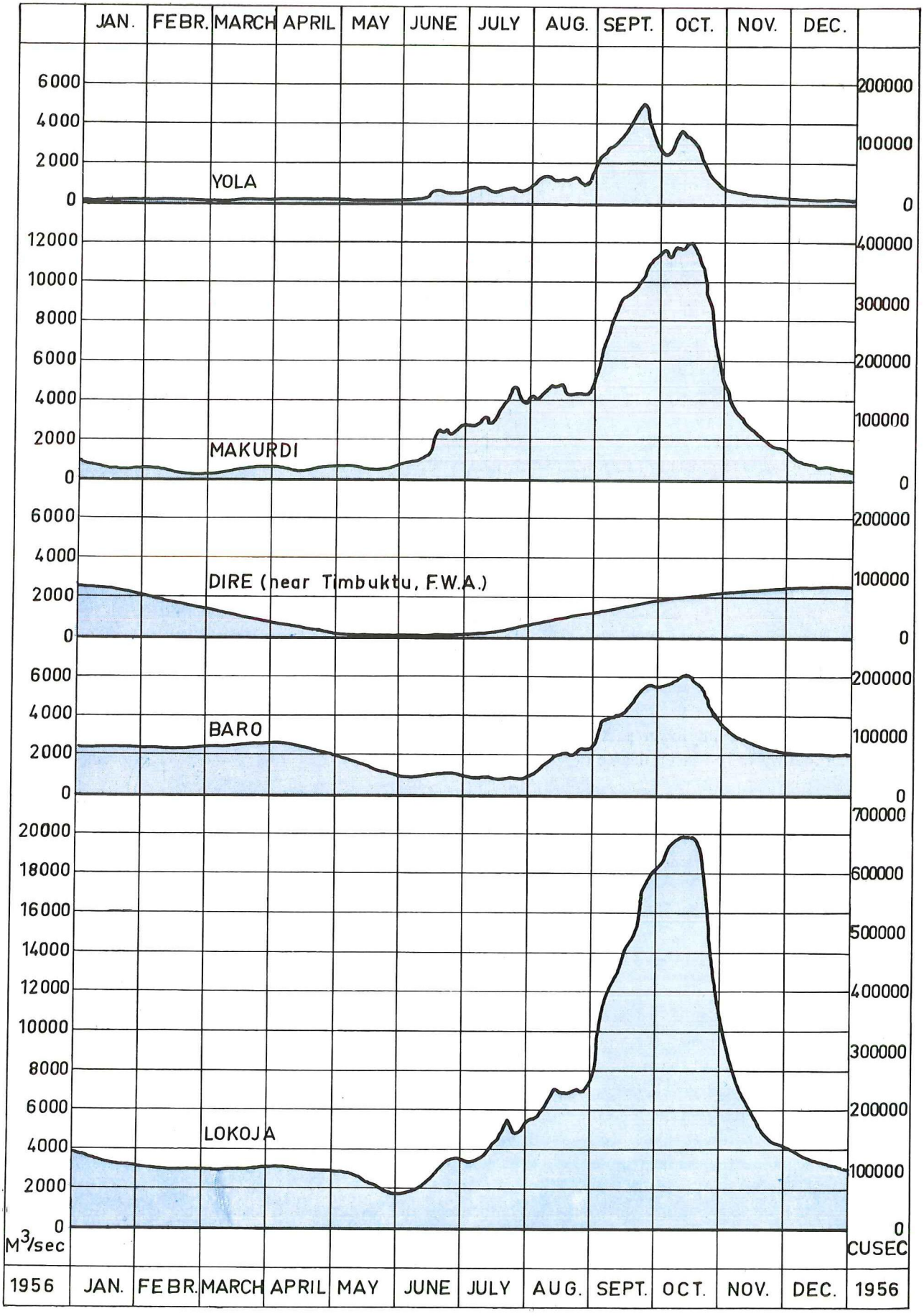


DIAGRAM 3.1.1-1

1956 Discharges of Niger and Benue

After the shipping season has commenced, there is often a marked drop in discharges, with a consequent reduction in available depths. Ships are frequently delayed by this so-called August fall.

Another problem is offered by the steep fall of the Benue in October. Ships must have cleared the river by that time, but it is very difficult to predict the exact time of this fall. As a result, most of the ships leave the Benue well before the beginning of the sudden drop in water-level, thus shortening the navigable season considerably. Occasionally, ships do not manage to leave in time, or have to leave barges behind, which then become locked up until next year's flood.

The range of the discharges is excessively great on the Benue, a phenomenon — common for tropical rivers — which has its adverse influences on the channels.

3.1.2. The river-bed (see V, 2)

Morphological studies have explained the fact that the natural cross-sections of the Niger and Benue are most unfavourable: the width is often five hundred times the maximum depth of the channel. Therefore, even at discharges of a reasonable size there is only little depth available.

This is mainly caused by the erodibility of the river-banks. The general pattern of the Niger and Benue shows fairly straight high-water banks with a channel meandering between sandy shoals. Every two or three miles the channel crosses from one bank to the other, and these crossings are the shallowest spots in the navigation channel.

Moreover, they are subject to seasonal changes, such as sedimentation during floods and a general downward propagation. These shifting channels offer a problem, as they are difficult to locate when the rivers are in spate.

During middle and low water, these winding channels often present sharp bends that are difficult to navigate.

In the extreme lower part of the Niger, in the Delta area, the channels are tortuous. The middle-water bed has a degree of sinuosity different from that of the high-water bed, and where these two do not conform, a shallow crossing results.

The natural unfavourable profile of the Niger and the Benue beds is accentuated by the many islands, with parallel channels that are even less efficient than a single undivided river. Many shoals occur in such split channels, or just upstream or downstream from the islands.

Some places are exceptionally difficult for special reasons, such as the notorious Wuro Boki and Gamadio Flats, where frequent shifting of channels takes place.

3.1.3. The tributaries (see V, 3)

Tributaries cause two problems to navigation on the main rivers.

In the first place, the water-level downstream of the confluence is a function of the total discharges of both the tributary and the main river, but for some distance upstream of the confluence the water-level on each river undergoes an influence from the other (backstage). Not only the water-level but also the river-bed is affected by a prolonged draw-down or raise of the river, which causes erosion or deposition of sand. This is especially so when the hydrographs of the main river and the tributary show marked differences in shape, such as a non-synchronisation of the floods.

A notorious example of backwater influence is the existence of a shallow bar in the North Entrance of the Benue near Lokoja.

The second effect of tributaries on the navigability of the main river is their pulsatory supply

of sand during a local flood period. The sand-transporting capacity of the main river cannot normally cope with this excessive supply, and so deposition just below the confluence is the result, although in course of time, the sustained discharge of the upper main river will scour this buffer stock of sand.

The Lokoja Flats, below the confluence of the Benue and the Niger, are an example of this second defect caused by a tributary.

3.2. FEASIBLE IMPROVEMENTS (see VI, 1)

3.2.1. Ships and shipping

In a balanced development, the type of ships and the system of shipping will more or less be adapted to the obtaining conditions of transport and navigability. No major improvement in river navigation may then be expected from modification of the type.

But an improvement of the navigability itself will in its turn invite a response by the shipping companies, as, for example, greater depths and longer navigation periods may ask for different sizes and types of ships.

Moreover, advances in the system of inland water transport are evident from developments on rivers both inside and outside Nigeria.

The following characteristics of ships and shipping may be adapted to the obtaining conditions: size, draught, speed, manoeuvrability, and type. Further, the number of ships may be increased and the system of transport may be adapted by applying various kinds of shuttling to ensure the most efficient use of the towboats and barges.

These possibilities of adaptation will be dealt with in detail in Chapter VI, 2. No recommendations will be made, however, as it is considered that these measures should be the natural response by shipowners to a development of the river trade and to improvements of the navigability.

3.2.2. Guiding the navigation

Although river vessels, as all ships, may be independent of man-made navigational aids, such assistance will be a great contribution toward a more efficient and less hazardous navigation, especially on untrained rivers as the Niger and Benue.

Such means of improving the navigability without affecting the regime (channels, water-levels, discharges, etc.) may originate from the shipping companies as well as from the authority in charge of the river management, and it is evident that any improvement of the aids to navigation will greatly assist shipping and will result in a more efficient use of the available natural channel-depth.

The following measures for an improved guidance of the navigation may be mentioned:

a. *maps* as a general reference, indicating the channels, sand-banks, landmarks, towns and villages;

b. *buoys and beacons* to be used for marking the channel. The advantage of these navigational aids is evident when there are fixed obstructions in the channel such as rocks or wrecks. When the position has to be marked of a channel liable to frequent shifting, care should be taken that the buoys and beacons are re-positioned as required, which means that they should be of a type that can easily be handled;

c. *lights or luminous buoys* will make it possible to navigate at night, which naturally will extend the period of navigation and thus increase the efficiency and capacity of the river fleet;

d. *channel patrols* are essential for maintaining and re-positioning the channel markers. In addition, these patrols will provide valuable information on the depths and conditions of the channels, may remove snags where necessary and give assistance to ships whenever required;
e. *pilots* may collaborate with the channel patrol officers and eventually be trained and/or licensed by the river authorities;
f. *stage and discharge measurements* yield data on the navigability of the rivers, whilst a prediction of the water-levels will also become possible — provided that a fair number of gauges, at regular intervals along the rivers, are read frequently; and
g. *communications* are of great importance, both to the operators of the river fleets and to the river authorities. Ship-to-shore and ship-to-ship radio telephone systems may be used to pass on information about available depths, expected rise and fall of the river, and the positions of channels, buoys and snags. The positions of the various ships are of interest to the shipowners and to those responsible for the operation of ports as well as to the channel patrol officers.

In Chapter 3 of Part VI these measures will be further explained and recommendations be made where necessary. Several items have already been introduced during the past few years, some by the shipowners and others in the course of the NEDECO Investigation. In the latter case, a beginning was made on an experimental basis and the responsibility was subsequently taken over by the Inland Waterways Department.

3.2.3 Improving the bed

The navigability of rivers flowing in easily-erodible alluvial sediments such as the Niger and Benue can generally be ameliorated by deepening the channel in a direct or indirect way, without improving the natural stages and discharges of the rivers. The following range of solutions may be considered:

(i) recurrent dredging;
(ii) other temporary improvements;
(iii) channel regulation; and
(iv) channel normalisation.

Ref. (i). *Local dredging* at reputedly bad places or crossings will usually be a recurrent operation, with the amount of maintenance dredging dependent on the extent of possible regulation-works. The main object would be to clear the Niger crossings after the rapid fall of the river and thus assist the natural scouring process (see Chapter VI, 4, where recommendations will be made).

Ref. (ii). The dominating bottle-necks for navigation may also be eliminated by *provisional river-works*, effecting greater depths during one low-water season only and with the influence disappearing again during the high-water period. These light works may consist of timber screens (bandalling), or floating or submerged guide-vanes (see VI, 5).

Ref. (iii). *Channel regulation* aims at a permanent elimination of these dominating bottle-necks by giving the river a more regular course, and a discussion of these methods is given in VI, 6, where some recommendations are made. It involves normally a fixation of the bed by means of bank protection, guiding walls or groynes, the closing of minor branches, the stabilisation of concave bends, etc. By guiding the river in this way, the crossings will be made more gradual and no high sills need be formed. In other words, the river is given over great parts the appearance and characteristics of its most favourable natural sections. This system is recommended as a long-term improvement of the Niger.

Ref. (iv). *Normalisation* involves an artificial narrowing of the bed along the entire stretch

that has to be ameliorated. The narrowing is accomplished by means of groynes or training-walls that confine the discharges to a narrower channel, thus provoking greater depths. Normalisation of rivers is usually preceded by a channel regulation, and no recommendations have therefore been made, although the system is discussed in VI, 6.

3.2.4. Improving the water-levels

A weir across the river will raise the water-level on the upstream side, thus giving a greater depth of water even when discharges are low. The amount of raising is at a maximum just above the weir and decreases gradually upstream (the backwater curve).

The logical continuation of this principle is a complete canalisation. This comprises a chain of weirs built all along the river in such a way that another weir is placed upstream at the place where the raise of water-level by the downstream weir has a too small effect.

The minimum discharge to make a canalised river navigable would be very low indeed, as water has only to be supplied to balance leakage and evaporation losses. For evacuating a far greater flood discharge of the river, the weirs may have to be made movable. Locks will have to be provided at each weir to enable ships to pass.

This means of improvement is discussed in Chapter 7 of Part VI, but no recommendations are made because of its unsuitability for the Niger and Benue.

3.2.5. Improving the discharges

When a river shows a deficient discharge in a certain season and discharges an excessive quantity of water during another season, then a regulation of the discharges may be considered as a means of improving the navigability. Reservoirs for storing the water may effect such a drainage regulation by distributing the available annual volume of water more regularly. Such reservoirs are usually constructed in the upper reaches of the main river or of the affluents, where gorges and sparsely-populated areas offer opportunities for building large dams with more or less extensive reservoir areas.

When a dam with a reservoir can be constructed in the navigable reach of the river, then the advantage of raising the water-level on the upstream side goes with the advantage of a regulated discharge below the dam.

It has appeared that the construction of reservoir-dams is desirable and possible both on the Niger (above Jebba) and on the Benue (above Yola). In the first case, the advantages of an improved navigability would go with the generation of great quantities of hydro-electric energy and with the possibility of irrigating a considerable area of fertile land.

Discharge regulation is discussed in Chapter 8 of Part VI, where the appropriate recommendations are made.

CHAPTER 4

RECOMMENDATIONS

4.1. RIVER MANAGEMENT

4.1.1. Organisation (see VI, 3.8)

River management, with a view to improving the navigability of the Niger and Benue, should deal with the following subjects:

a. Studies and observations on hydrology (stages, discharges, rainfall, evaporation) and morphology (sediment, channel depths and behaviour);
b. gauges, archives and publications;
c. hydrographic surveys;
d. mapping and drawing;
e. channel demarcation (buoys, beacons, mile-boards, patrols, contact pilots, buoy-cleaning);
f. dredging;
g. communications, such as radio and bulletins;
h. traffic statistics, research and development; and
i. hydraulic engineering, i.e., the design, execution and maintenance of temporary and permanent training-works, groyning, bank stabilisation, and eventually the operation and maintenance of dams, reservoirs and locks.

Each of these items, having a direct bearing on the navigability, should be a responsibility of the Inland Waterways Department, as follows from paragraphs (ii), (iv) and (v) of the summary of duties in the Statement of Policy for the Establishment of an Inland Waterways Department (Sessional Paper No. 7, 1956).

Its organisation should at all times be adequate to meet the requirements imposed by the recommendations of the present Chapter. A functional and geographical sub-division will be necessary for this.

As to the functional tasks, the following main subjects will be evident:

Hydrology	(a) observations, studies and research;
	(b) archives and publications;
Hydrography	(c) surveys and mapping;
Channel demarcation	(d) channel demarcation;
	(e) communications;
Hydraulic engineering	(f) dredging;
	(g) training-works, dams, locks, etc.;
Statistics	(h) traffic statistics, and related economic research.

These five principal subjects connected with river management and improvement of the rivers may develop into separate sections.

The geographical sub-division implies a decentralisation along the rivers of a part of the above activities. It is recommended to establish separate divisions and districts, the boundaries of which should coincide with the watersheds of rivers. But close contact and good coordination between the various districts and Headquarters will always be essential.

Inter-departmental consultations should take place to coordinate the observations and investigations regarding the use and utilisation of the water of the rivers.

International consultations with the other countries bordering the Niger and Benue Rivers should be initiated by the Government whenever measures affecting the regime or navigability of these rivers would be contemplated.

4.1.2. Channel information (see VI, 3)

Navigation maps on a scale of 1 : 50,000 (as appended to this Report) should be revised every two years, which implies that new Niger and Benue maps should be issued alternately every year, preferably in June. Single-strip aerial photography averaging 500 miles of river-length per year is required for this, as well as a suitably-equipped drawing office.

Survey charts of those sections of the Niger below Baro not yet covered by NEDECO sounding charts should be prepared within the next few years. Special survey charts should be made when necessary for the construction of river training-works, for buoying purposes and eventually for dredging operations.

Flood-plain maps of the area between Yola and Ibi should be prepared within five years, unless other priorities for such mapping exist. In due course these maps should be prepared of the entire flood-plain of the Niger and Benue Rivers.

A *Contact Pilot* should be appointed as a liaison between commercial shipping and the channel demarcation service.

A *Channel Patrol Service* of the Inland Waterways Department should be established. Apart from its task in the marking and patrolling of the navigable channels of the Niger and Benue Rivers, it should supply information regarding the buoyage of, and the least available depths in, these channels.

Communications should be further improved by allocating a second wave-length (radio-frequency) for the use of river information, and by close cooperation between shipping companies and the Inland Waterways Department. All survey and patrol launches should be equipped with a radio-telephone transmitter/receiver. Navigation bulletins should be issued containing the following information:

(i) gauge-readings, and predictions of stages;
(ii) available depths of river-sections between two ports;
(iii) buoyed crossings, least available depths thereof, and numbers of buoys; and
(iv) any other information regarding the river which will be of interest to navigators or shipowners.

Predictions of stages and if possible of depths should be prepared where feasible. Efforts should be made to supplement the present system of daily predictions of the Upper Benue stages by the French Cameroun authorities and the long-term predictions of the Upper Niger stages during the Black Flood (November to April) by predictions for other sections of the rivers. Special studies must be made for this purpose.

4.1.3. Studies (see III, 7.2)

River-gauges should be erected in greater numbers; their maintenance and the organisation of the readings deserve special attention. Water-levels of the main gauges should be daily transmitted by radio; a synopsis should be published annually.

Hydrological and morphological studies should be continued for the benefit of navigation and of river improvements. A further study of the hydrological cycle, in particular of rainfall, run-off and evaporation, is recommended, whilst an intensified study of these characteristics in a pilot-basin should be made. The variation of the slopes of the water surface, the sediment sizes, the channel roughness and the behaviour of crossings are all subjects for a continuous study in view of their complicated nature.

Observation of the least available depths for all sections of the Niger and Benue that are or will be suitable for navigation is required not only for guidance of the present shipping but also for determination of the actual navigability as a statistic phenomenon. In general, it is highly advisable to follow closely the actual behaviour of the river-bed, its formation and deformation, and to analyse the causes and consequences.

4.2. CHANNEL DEMARCATION

4.2.1. Organisation (see VI, 3.4)

A Channel Patrol Service should be established within the Hydrography and Channel Maintenance section of the Inland Waterways Department. It should be in charge of the marking and patrolling of the navigable channels. The Service should consist at first of three separate units, which will be sufficient for a day-time buoyage of the Niger below Baro, and of the Benue. For a complete night-signalisation, which should be effected as soon as the day-time buoyage is operating satisfactorily, one or preferably two additional units will be necessary.

It is considered in view of the operation requirements for a small manoeuvrable vessel that the optimum crew will be in the order of a Patrol Officer, Quartermaster, Driver and two shifts of four Able Seamen. One or two cleaning vessels should be detailed to each unit for clearing the buoys of floating debris. Adequate housing facilities on a floating or permanent shore base should be made available in the various districts. The training of Nigerian Patrol Officers should commence at an early date.

A Senior Patrol Officer, in charge of the operations, should have the disposal of a fast and specially-equipped launch for supervising the work of the several Patrol Districts.

The cleaning procedure of the buoys may develop into a cantoning of the rivers. River Cantonments, covering sections of 20—50 miles of river-length, may have personnel consisting of a headman and a number of labourers who have available a small self-propelled cleaning vessel and a number of canoes.

4.2.2. Patrol vessels (see VI, 3.4.2)

Three special patrol/buoyage vessels will be required for a day-time buoyage on the Niger below Baro and on the Benue within Nigeria. For maintaining a continuous night buoyage, at least one additional vessel is required, but a fifth vessel will lessen the strain on the service and may, on the other hand, be seen as a reserve. These special vessels should meet the requirements regarding velocity, manoeuvrability, accommodation and equipment which have been set out in VI, 3.4.2.

4.2.3. Channel markers (see VI, 3.3)

Day-time buoyage of the difficult sections of the entire Niger below Baro (November to June) and of the Benue within Nigeria (June to October) should be carried out in the lateral

system by using painted 45-gallon drums for buoys anchored to concrete sinkers by means of galvanised iron wire.

Mile-boards should normally be placed every five miles along the river, commencing along difficult sections of the rivers where the distances between them should be one mile. They should show the distance to the zero of mileage (Escravos Lighthouse) in accordance with the Book of River Charts annexed to this Report. The figures and boards should be fairly large and fitted with reflecting patches.

For night-signalisation of the entire Niger below Baro (year-round) and the entire Benue within Nigeria (June to November), more buoys have to be positioned, supplemented by shore-marks, at distances of not more than 1 or 2 miles between two marks or buoys, and with the buoys provided with reflecting red or white patches.

Where stable channels run along the shore-line, beacons may be useful for night navigation as channel markers in addition to buoys at crossings and mile-boards at regular intervals. It is recommended to adopt in this case the beacons as suggested for the Benue by the French Cameroun investigators.

4.3. DREDGING

4.3.1. Organisation

Dredging offers a direct way to improve the river-bed by removing soil from it, whilst the mobility of dredging equipment ensures the elastic nature of this method of improvement. This is an obvious advantage for rivers which show yearly differences in the places where difficulties occur. Dredging proper, however, does not cure the causes of undesirable qualities of the river, as the improvements realised in this way are only of a temporary nature.

The best results of dredging will probably be obtained when the dredged channel follows the flow direction which prevails during the low-water season. Cross-currents loaded with sediment will then not be given the chance of evening out the channel. Under such circumstances the dredging plant will also be most easily handled and ships can best navigate the channel. A channel width of 150 feet seems at present the minimum for safe navigation, whilst the length of the channel to be dredged is determined by the situation. The dredged-cut need not be very deep (3—5 feet) but should be as even as possible to prevent dredging too large quantities.

Dredging on the Niger River system meets with the following uncertainties by which the organisation of dredging is largely determined:

(i) the tenability of the dredged channel is unknown;

(ii) the exact location where dredging is most effective cannot be indicated long beforehand;

(iii) the quantities to be dredged depend on the discharges which are not predictable;

(iv) the output of the dredging equipment depends to a certain extent on the qualities of the river-bed materials; and

(v) the depth and width of the cut after dredging has been completed are not reliable measures for the dredged quantities.

In relation to these five points, the best method of administrative organisation seems to be to draw up an agreement with a contractor to put the necessary staff and equipment at the disposal of Government on a cost-plus basis, but with the works being carried out by Government.

Two other ways of administrative organisation are:

(a) A contractor carries out the works according to Government specifications and under supervision after a tender has been submitted and accepted; and

(b) Government carries out the works with its own staff, equipment and materials.

Each of these, however, will meet with grave difficulties, as in case (a) it is not possible to draw up sharply-outlined specifications and in case (b) experience is lacking. Nevertheless (b) seems applicable when channel dredging has outgrown its experimental stage and when the possibilities of the most suitable apparatus and the behaviour of the dredged channels are better known.

It is recommended that during the experimental stage of dredging operations cooperation with an experienced contractor should be sought, which may result in sufficient experience being gained by Nigerian Government staff and an adequate insight into the possibilities and methods to enable Government to decide:

(i) whether the resulting assistance to navigation justifies further development of the dredging operations; and

(ii) whether Government should build up its own dredging organisation or utilise the apparatus of a contractor.

4.3.2. Type of Dredger

From the great variety of dredgers available a choice should be made as to which best suits the conditions encountered on the Niger River system. The dredger should be able:

(i) to dredge in rather coarse and cohesive soils in the river and to dredge in harbours during high water as well as to dredge short-cuts in various soils, etc.;

(ii) to dredge an even and shallow cut of at least 150 feet wide; and

(iii) to dispose of the soil as a water-soil mix through a floating pipe-line, which is the cheapest method.

The type of dredger which best satisfies these requirements is the cutter-head suction dredger, preferably equipped with a floating pipe-line which requires no anchoring. Such a pipe-line, which has the discharge terminal kept in position outside the dredged channel by force of the discharge jet on a kind of rudder, requires very little time for positioning and preparations for sailing, both of which are frequently necessary when moving from crossing to crossing. Further, a spud-carriage system, special anchor-derricks and self-propulsion are recommended for such a dredger. All these specifications should be met to obtain the maximum effect of the dredging plant.

The capacity of the dredgers should be large for the following reasons:

(i) cost of dredging will to a certain extent decrease with increasing capacities;

(ii) sudden appearance of "bottle-necks" can be cleared quickly;

(iii) less supervision and crew is required;

(iv) large units can be more self-supporting and have their own workshop; and

(v) fewer dredgers are fewer obstacles for shipping and need less organisation.

A limit to capacity is set by the productive days of a dredger. An extremely large output will cause an inefficient ratio between productive dredging days and transport from site to site, positioning and preparing for shipping.

A cutter-head suction dredger with an output of between 700 and 1,300 cuyards/hour is recommended in view of all these points.

4.3.3. Dredging programme

When the transported tonnages on the river system have increased to twice or three times the present volume, dredging the Niger and the Benue Bar will warrant its expenditure. It is likely that river management including night-navigation will produce this increased transport

in a few years, and therefore it is recommended to commence test-dredging by a contractor as soon as possible. This test-dredging should be executed by a cutter-head suction dredger of about 500 cuyards/hour capacity, in order to discover the uncertainties of dredging here, to gain experience and to be able to develop a dredging programme for the execution of a large-scale dredging programme of the River Niger and of the Benue Bar.

On the Benue, improvements by dredging of one or two feet cannot be obtained before a discharge regulation is carried out.

From the frequency curves of available depths and from observations during the NEDECO investigation, it has been calculated how large the dredged quantities will be to maintain a certain depth in an average year. From these it seems that 5'0", 5'3" and 5'6" can be maintained on the Niger upto the beginning of April when the quantities are in the order of 700,000, 1,000,000 and 1,500,000 cuyards respectively. This includes maintenance dredging. Normally it will be necessary to start dredging in November and December on the Baro—Lokoja river-stretch, supplemented by dredging the Niger below Lokoja from December to March, while maintenance dredging should be continued until the end of March. In April (in an average year), the water-levels fall so rapidly that continued dredging over the entire river below Baro does not seem practicable.

It is estimated that a 30 % increase of the present fleet's capacity in the Baro season will result when a 5'6" programme is executed.

Further, it will be possible to dredge the Benue Bar in May with the dredging equipment available. On an average the Benue can then be entered 10—14 days earlier, which may result in a 5 % increase of the fleet's capacity in the Benue season.

In the near future, after test-dredging has been carried out for one or two years, a dredging programme of approximately 1,500,000 cuyards is foreseen in an average year to maintain a 5'6" navigable channel from the Delta to Baro during the months of December to April and to open the Benue 10—14 days earlier than ships can at present enter the Benue. A 2,000—2,500 cuyards/hour capacity of the dredger fleet will be sufficient to reach these targets, and it is not recommended to try and gain a larger improvement than 2 feet during the entire Baro season as this would be better obtained and at less cost by other river-works.

From calculations it appeared that three dredgers with a total capacity of about 2,000 cuyards/hour can execute the same programme as 2 dredgers of about 2,500 cuyards/hour, owing to the fact that the ratio of productive days against the total length in days of the dredging programme in a year for the former is higher than for the latter. However, the annual cost of the execution of the dredging programme will be approximately the same in each case.

4.4. BED-REGULATION

4.4.1. Temporary training-works (see VI, 5)

Ships are frequently prevented from entering the Benue River at Lokoja early in the navigable season by the presence of a bar in that river just above its confluence with the Niger. Although recurrent dredging will probably provide a solution to this problem, a cheaper improvement may result from the use of fascine bottom-flow vanes as described by POTAPOV. These screens would have to be positioned during the low-water season of each year, as they will be destroyed by the flood discharges and, moreover, the channel topography will still be subject to annual changes.

It is recommended that, after the results of current experiments regarding the Soudanese

Niger have become fully available, tests be carried out to deepen the Benue Bar in this way. After these tests on the Benue Confluence have led to a satisfactory result, it may be considered to make this improvement a permanent feature by providing new screens on the Bar each year. It will then be advisable to make further tests on the upper reaches of the Benue with the object of securing more depth over the Gamadio and Wuro Boki Flats early in the navigation season.

4.4.2. Bed-regulation

One way to improve a river for navigation purposes is to regulate its low-water bed. For the Benue this type of improvement is not recommended as this river does not offer favourable conditions for such a system. The Lower and Upper Niger offer better conditions to improve the river by regulation-works in the low-water bed. As it is a special advantage of this system that the river can be improved step by step in accordance with the demands of navigation, it will be possible to improve the Niger in the first stage to a depth of about eight feet at Low River Level (L.R.L.), in a second stage ten feet may be set as a target, while the final stage will probably give more than 12 feet available depth at L.R.L.

Apart from this, it must be kept in mind that a regulation scheme never can be 100 % safe and that therefore it will always be necessary to have one or two dredgers on hand to remove unexpected shoals.

The improvements brought about by regulating a river are to be considered as independent from and complementary to buoyage and discharge regulation schemes. Channel demarcation will remain essential, although in case of a channel contraction the course of the navigation channel will become more discernible. The efficiency of a discharge regulation which aims at the prolonged maintenance of certain water-levels by spreading out the available discharges over a longer period will be increased by the regulation scheme of the river-bed, as this bed-regulation will increase the available depths for shipping purposes, corresponding to the sustained discharges by the discharge regulation.

Apart from the improved navigability, there are other advantages that result from a bed-regulation. The river valley will benefit from a regulation and fixation of the rivers because the banks of the river will become better accessible and the danger of shifting channels will have disappeared. At present many villages along the Niger have to be moved occasionally because of serious bank-erosion. This can no longer happen with a regulated river. Also the river ports will be accessible every year, without the risk of an odd sand-bank moving in front of the sheds and other shore-facilities, whilst the threat of erosion to the installations on the banks will disappear after the execution of regulation-works.

Riparian economy such as irrigation, industrialisation and urbanisation will to some extent depend on the fixation of the rivers, and, in fact, no full development of the river valley can be visualised without regulation of the river running through it.

4.4.3. Rock clearing

It is recommended to improve the channels of the Niger just downstream from Lokoja by clearing the rocks from the Sacrifice Channel running along the western bank of the Niger (Miles 358—361), to eliminate a part of the Lokoja Flats. The rocks in the South Channel of the Benue at its confluence with the Niger should also be cleared in order to have, subject to the general channel topography, a better alternative to the North Channel. This work should be done within the next five years.

4.5. DISCHARGE REGULATION

4.5.1. Jebba Dam (see VI, 8.3)

Some general remarks on this project can be made here when bearing in mind that the figures and ideas are still subject to further studies. More detailed information is given in the special Report on the Feasibility of a Jebba Scheme.

To meet the navigational demands, a large reservoir is necessary. If a useful capacity of between 10 and 15 milliard cubic metres (8 and 12 million acre-feet), which is still only 15 to 20 % of the average annual run-off, would be used solely for navigational purposes, then an increase of over a foot draught during the Black Flood period (December to March/April) and also an extension of the navigable season into the present low-water period would be possible.

The benefits of such an exclusive navigation project, however, would never meet the cost, owing among other things to the shape of the present discharge hydrograph. But a multi-purpose scheme is very attractive, although no recommendations on such a Jebba Scheme will be made in this Report, as other interests (notably the generation of water-power) prevail over the resulting river improvements.

The following improvements to shipping conditions will presumably result from a multi-purpose scheme:

(i) in many years the draughts of vessels sailing on the Niger below Jebba can be increased by half a foot during the Black Flood;

(ii) the low-water stages (April-June) will be heightened, an effect which is of importance to all-the-year-round navigation on the Niger, if only with a restricted draught in two or three months;

(iii) a Yola discharge-regulation scheme will be greatly assisted by these increased low-water stages of the Niger;

(iv) a flood control would reduce the peak discharges on the Niger and thus ameliorate the channels by reducing the deposition of sand on the sills at the crossings during high water; this effect may lead to another half a foot increase of depths on the Niger upstream from Lokoja; and

(v) the Niger upstream from Jebba would be opened and during nine months per year become navigable into the Sokoto Province and the French Niger Territory as far as Niamey and Tillabery.

4.5.2. Lagdo Dam (see VI, 8.4)

About 40 miles above Garua, in the Cameroun, the Benue flows through a narrow gap (180 m or 600 feet) of which the boundary consists of sound rock. The level country upstream offers ample room for a reservoir of reasonable capacity, estimated at more than 6 milliard cubic metres (5 million acre-feet). The cost of the project has been estimated at £6 million.

The following improvements to shipping conditions will result from a Lagdo Scheme:

(i) for a draught of 5 feet the average shipping season of the port of Garua would be extended to 3 months, which is 1 to 1½ months more than at present;

(ii) in dry years, the season would still be 2 to 2½ months; and

(iii) the unpredictable August fall in the water-levels, which renders navigability uncertain during the present shipping season, would be overcome.

The Lagdo Scheme is therefore of interest to the Upper Benue ports of Numan and Yola, whilst Garua-bound traffic in particular would benefit from it. But the Lagdo Scheme might be influenced unfavourably by the Faro River, and perhaps lead to a deterioration of the channel downstream from the Faro/Benue Confluence, unless this area is drowned by a Yola reservoir.

It is recommended that a Lagdo Scheme should precede a further regulation of the Benue discharges by a Yola Scheme.

4.5.3. Yola Dam (see VI, 8.5)

Although a dam at Lagdo is considered the first step towards discharge regulation on the Benue, such a scheme on its own does not appear quite satisfactory for the following reasons:
(i) Faro River, the main cause of trouble, has been left out of the scheme, which means that the effects of the intended regulation on Wuro Boki Flats may not be fully adequate; and
(ii) the intended regulation would have a limited effect; it was calculated that instead of 6 milliard cubic metres (5 million acre-feet) more than twice that amount would be required to satisfy the shipping demands also on the middle part of the Benue.

Therefore, whilst fully recognising the merits of a Lagdo Scheme, it must be appreciated that it would yield full value only when supplemented by a reservoir constructed below the confluence of the Faro and the Benue.

Fifteen miles above Jimeta (the port of Yola), in the valley-narrowing near Dasin Hausa, a reasonably good dam-site exists (Mile 904). The feasibility investigations included a geological survey regarding the site of the dam, the permeability of the reservoir walls and the availability of building materials for the construction of the dam; reconnaissance drilling proved the existence of a buried valley necessitating the construction of a cut-off (1 and drainage system underneath the dam. Contoured maps have been made from aerial photographs, using limited ground control.

The construction of two heights of dams and consequently two sizes of reservoirs may be envisaged:
(i) a reservoir of some 6 milliard cubic metres (5 million acre-feet) useful capacity, the normal highest retention level being around 182 m (597 feet) above Mean Sea Level; in discussions with the French Cameroun Consultants this has been termed the Yolette Scheme; and
(ii) a reservoir of some 12 milliard cubic metres (10 million acre-feet) useful capacity, of which the normal highest retention level would be around + 187 m (613 feet); this is known as the larger Yola Scheme.

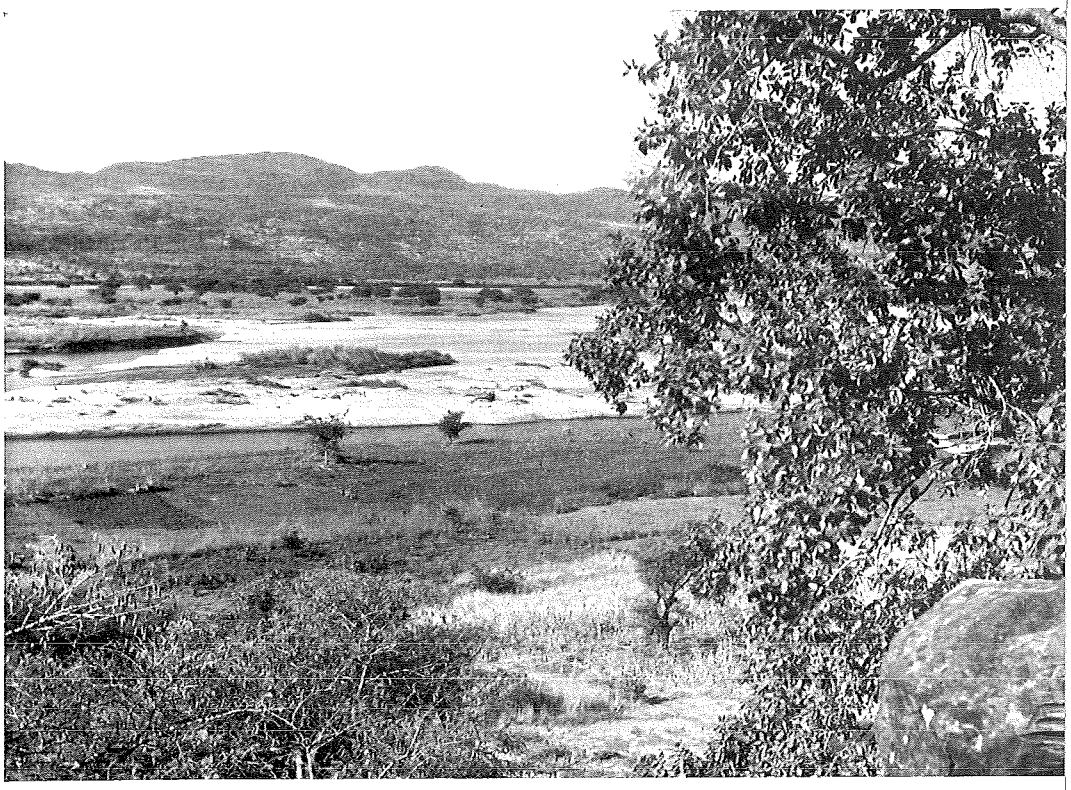
The Yolette Dam is estimated to cost about £10 million; it should work in conjunction with a Lagdo Reservoir. The larger Yola Dam would entail the flooding of fertile and extensive plains upstream from Garua, whilst flood-protection measures would have to be taken at the port of Garua where the edge of the native settlement would have to be removed to higher levels. The cost of a larger Yola Dam is estimated at £14 million.

A Yola Dam, or a combined Lagdo and Yolette Scheme with a reservoir capacity of 12 milliard m^3 or 10 million acre-feet, will double the length of the present shipping season of Yola and Numan, and even quadruple that of Garua, whilst the Yola (Dasin) to Garua stretch will be navigable throughout the year. In addition, there will be an improvement in depths, resulting from reduced peak discharges downstream of the dam.

Apart from the extension of the season, another navigational improvement is the prediction of the opening and closing dates of the Upper Benue season. This guaranteed season gives advantages for the operation of ports, of shipping, feeder and distribution lines and for ocean traffic in the Delta Ports.

The generation of electricity throughout the year will not be possible in the above scheme. Agriculture and fisheries will benefit, but flood-plains in the reservoir area will be lost for agricultural use. Measures would also have to be taken to prevent an increase of insect life (malaria) in the reservoir area.

(1 a vertical screen preventing seepage of water through the underlying sand layers.



PHOTOGRAPH 4.5.3 - 1

Dam-site
Dasin Hausa

4.6. SUMMARY: THE PROGRAMME

4.6.1. Sequence

a. *General*

Before a short explanation can be given of some of the economic aspects of each of the above described improvements, a summary of the present situation in river transport, as well as an indication of the future trends, is essential.

(i) The accessibility of ports is given in Diagram IV, 3.2.2-1. The river fleets are alternatively used on the Niger and Benue, respectively during low and high water.

(ii) From the total time available in one year about 50 % is not used, as neither night navigation nor night shifts ashore are common practice at present. An analysis of the available day-hours for navigation shows the following division:

Steaming	35—40 %
In ports loading and discharging	20 %
Lost due to non-availability of cargo	15 %
Lost due to unnavigable river during April and May	15 %
Grounded or waiting due to river conditions	5—7½ %
Repairs	5—7½ %

(iii) In the middle 1950's river transport on the Niger and Benue reached a volume of 250,000 tons producing 115 million ton-miles. At present (1958) 125—130 million ton-miles are transported along the Niger and Benue system, while the yearly increase over the last decade has been 6—7 %. A faster development of river transport is for a large part dependent on the interest taken in this transport route, i.e., in the employment of capital to improve the transport route.

(iv) The average freight rate of river transport (2.5d per ton-mile) is very little below the average freight rate of the railways (2.9d per ton-mile).

On Diagram 4.6.1-1, i.e., VI, 9.1.1-1, the areas of economic influence have been drawn. On the boundaries the average costs of transport by rail and by water are equal. For the calculation of these lines, the following rough assumptions have been made:

(i) Road transport to and from railway stations and river ports is roughly estimated to cost 5.8d per ton-mile (twice the railway freight).

(ii) For each transshipment an extra cost of £-/5/- per ton has been included.

(iii) On the Benue above Makurdi additional expenses for river transport at an average of £ 3 per ton have been taken into account, due to cost of storage and loss of interest.

(iv) It has further been assumed that after the improvement of the Escravos Entrance — an essential condition for the development of river transport — the ports of Lagos, Burutu and Port Harcourt will have equal tariffs for calling ships.

(v) Calculations have been based on average freight rates although they do not exist. In so far the influence areas are theoretical.

When under these circumstances river and rail transport tariffs have a ratio of 1 to 1, 1 to 2 or 1 to 3 (in some countries with a well-developed transport system it may even reach 1 to 4), different areas of economic influence appear (Diagram 4.6.1-1).

To and from light shaded areas traffic can be by river under special circumstances, such as lack of proper road connections. At present, for instance, between Calabar and an area south of the Benue above Makurdi no direct roads exist and transport from the latter area is partly attracted by the river. From the North of Nigeria a limited amount of cargo is railed to Baro and shipped via the river. This is often a matter of policy. Also between Lokoja and Makurdi the river does attract some traffic.

The ratio 1 to 1 (Diagram 4.6.1-1A) reflects the present situation very well as follows from Diagrams IV, 1.1.3-2 to 4.

When river transport becomes cheaper it will happen that to and from Jebba and Markudi rail and river transport is approximately equal in price. Large areas in the North may then be indirectly affected by the possible water-route (light shaded in Diagram 4.6.1-1B).

In Diagram 4.6.1-1C is assumed that the ratio of river to rail transport cost has changed into 1 to 3, which is only possible after large improvements have been executed. Navigation throughout the year as far as Niamey on the Niger and during 6—8 months on the Benue should then be possible. The Niger and Benue will then become the master transport route of West Africa.

If, in this way, the areas of economic influence of the Niger and Benue would increase, the transport quantities drawn to the river would increase. It is clear from Diagram 4.6.1-1 that only a slight reduction in transport cost will draw a large part of the goods conveyed by the railways north of Minna into the influence area of the River Niger. The whole north of Nigeria, with its important groundnut and cotton crops will then have the benefits of a cheap waterway for a part of the evacuation route. This cheap transport will gain even more importance when the Escravos Bar is improved, so that sea-going vessels can reach the Delta ports as easily as Lagos and Port Harcourt. At the same time, it will relieve these two latter harbours, where from time to time congestions occur due to the rapidly increasing transport. The benefits of an improvement are not only dependent on the freight reduction but also on the quantity of goods conveyed along the river. Cheaper transport will result in a sharp increase of transport and consequently show a sharp increase in the benefits.

The cost of improvements can often best be expressed in annual costs. The annual cost of permanent river-works consists for the greater part of interest on invested capital. The annual cost of the temporary improvements must mainly be evaluated from the direct cost to be made to attain the improvement.

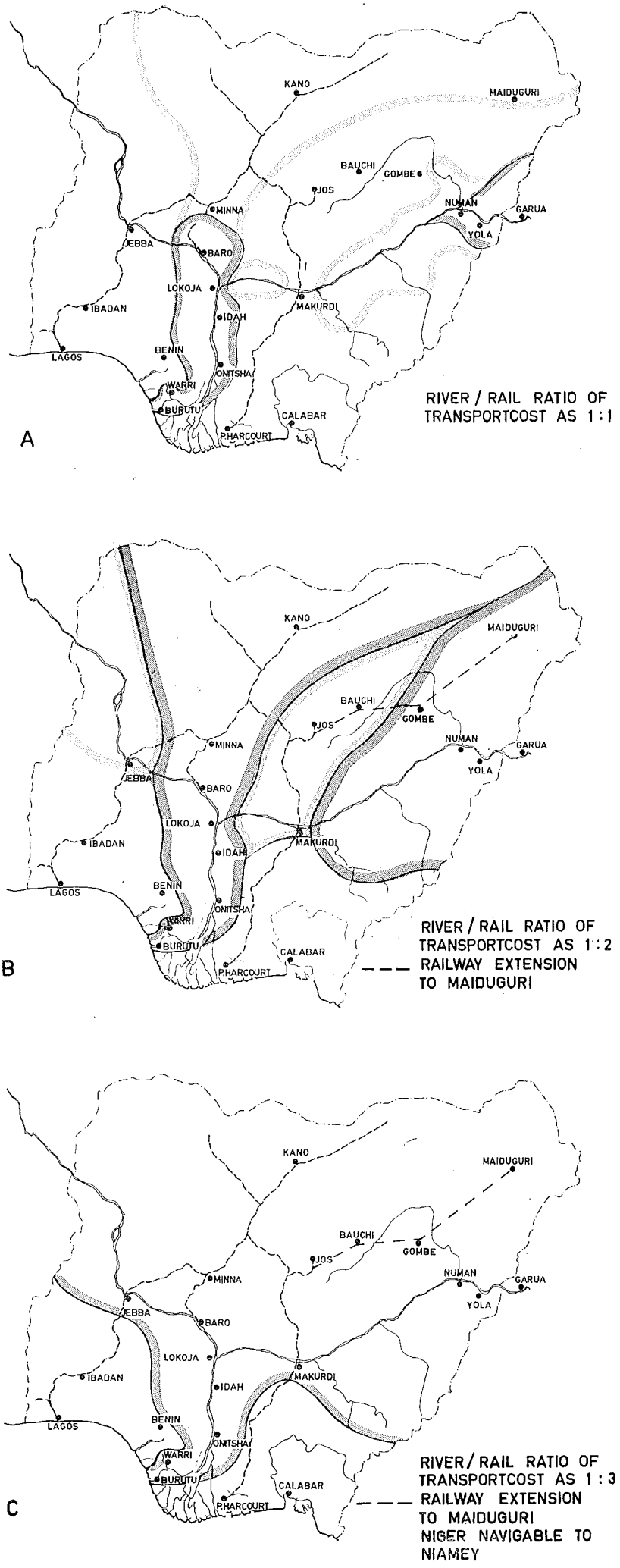


DIAGRAM 4.6.1 - 1

Regions of Economic Influence of Niger and Benue for Transport to and from Delta Ports

The benefits of a certain river improvement should be expressed in social benefits to the country, but the evaluation of these benefits meets with some particular difficulties some of which are:

(i) the decrease in transport cost as a result of the improvements;
(ii) the total transport volumes for which this decrease applies in a succession of years;
(iii) the increase of production as a direct result of the improved transport facilities; and
(iv) the number of years which is a fair base for rentability calculations.

As this would be beyond the Terms of Reference, the present Report does not deal with an economic study of the improvements which are of such wide importance to the whole country. However, the advantages of some of the improvements are so clear that a rough calculation of costs and benefits can give an indication of the sequence of the necessary improvements, now and for some time in the future.

b. *The required improvements*

First and foremost is the improvement of the Escravos Bar necessary. The execution of this work, to be taken in hand in 1959, will open the Niger hinterland and tremendously stimulate river traffic. The second step will be to make river traffic less hazardous, more regular and suitable for larger units, all with the aim of decreasing transport cost and extending the use of the cheapest mode of transport.

To decrease the risks in navigation and to increase the optimum use of the available natural depths, leading to greater permissible barge draughts on the Niger and Benue, guiding is necessary. This can be given by maps, pilots, channel markers and patrols, communications, stage information and predictions, as well as by all research directly or indirectly connected with river management.

A more regular river traffic, by which the river fleets can be used to the full extent, will be reached when:

(i) night navigation is introduced, depending on a proper night signalisation and buoyage;
(ii) the river fleets can navigate throughout the present navigable seasons without delays, with barge draughts close to their maximum, which should be taken as 6 feet and which can be effected in a practical way on the Niger by dredging, local river training-works and a reservoir dam or a combination of this and on the Benue by a reservoir upstream of Yola.

For the future is required a depth of some 8 or 9 feet to continue the decrease in transport costs and to maintain the position of cheapest mode of transport of river traffic among the other competing means of traffic, for the benefit of the country. For the Niger a dam and reservoir as well as river training-works along a large part of the river would then be required, while for the Benue a dam in the upper reaches near Yola and a dam near Makurdi are required to attain this target.

A modernisation and enlargement of the commercial fleets is considered a logical response by the shipping companies to improved river conditions. In this way the river operators will obtain the maximum effect of improvement. Already river operators have recently made a beginning with modernising their fleets. Modern tows have appeared on the Niger and Benue, and old tugs have been converted from coal-burning to oil-burning, which proved a considerable amelioration.

A more efficient operation of the feeder lines, especially of the Minna—Baro railway, in order to avoid losses of time is one of the requirements of an improved transport, but above all it is required that the riverfleets obtain more upward cargo.

c. *Comparative merits*

(i) *River management* consisting of all measures to guide navigation, leads directly to a decrease in transport costs.

Many items of river management are imponderable. Studies and research, for instance, must always precede all improvements. How much such research will save is not calculable, but such an approach to problems is generally felt essential. The formation of a Hydrological Branch of the Inland Waterways Department, as was decided upon in 1957, is in this spirit.

However, the direct effects of channel demarcation and channel patrols, combined with stage information and water-level prediction, can be roughly calculated.

In paragraph VI, 9.1.3 has been explained that such a calculation leads to an expected decrease by $12\frac{1}{2}$ % of cost per ton-mile river transport.

At the present volume of traffic (130 million ton-miles) and the present freight rate (averaging £ 1/-/- per 100 ton-miles excluding loading and discharging), the annual potential savings will be $0.125 \times$ £ 1,300,000 or £ 160,000, while the annual cost of these services will almost certainly be less than this amount. The net benefit will increase with the increasing volume of transport, as the cost will not increase. The adaptation of the fleet to the new circumstances will probably lead to an even higher efficiency than has been calculated above.

(ii) *Night navigation* can be made possible by a good system of night buoyage and night signalisation. The number of sailing hours for a certain fleet can then be increased by at least 60 % over the present number of sailing hours (see VI, 9.1.1). Buoyage and signalisation for night navigation will follow day demarcation and the rough calculation in Paragraph VI, 9.1.3 shows that in addition to the decrease of $12\frac{1}{2}$ % due to day-services, an extra decrease of $22\frac{1}{2}$ in cost per ton-mile river transport can be expected as a result of night signalisation.

The annual potential savings reach, with the present volume of traffic, $22\frac{1}{2}$ % of £ 1,300,000 or £ 290,000 which is certainly much more than the cost of night buoyage, while the net benefits will increase rapidly with the growth of traffic.

(iii) *Dredging* operations on the Niger with annual quantities of over 1.5 million cuyards (see VI, 4) do not seem very effective at present, as the quantities to be dredged rise sharply against equal additional improvements. Dredging operations for 1.5 million cuyards are estimated to cost in the region of £ 200,000 in an average year, although this amount may decrease by 25 % if sufficient other objects with the dredger can be carried out during high water.

In VI, 4.2.2 it has been explained that dredging 1.5 million cuyards will result in an increase of 30 % in efficient fleet capacity during the Baro season from November 15 to April 15. On the same basis, calculated as in Paragraph VI, 9.1.3, this could lead to a reduction in transport cost of 14 % during this period. The total ton-mileage on the Niger ports during that period can be taken as 40 million, with a transport cost of £ 400,000. So the annual potential savings from the dredging operations are thus in the order of £ 56,000.

Apart from dredging the Niger, the Benue Bar could also be dredged at the beginning of the Benue season. From this improvement a 5 % increase of the capacity on the Benue for the river fleets is estimated and the freight reduction would then be 3 %. On the Benue 90 million ton-miles are transported, and the annual potential savings from dredging the Lokoja Bar will then be $0.03 \times$ £ 900,000 or £ 27,000.

The total annual potential savings of some £ 80,000 from dredging do not warrant the execution of such a dredging programme as an economic enterprise until the volume of traffic increases.

However, it seems at present that the combination of channel demarcation, channel patrol, stage information, prediction, night navigation and dredging operations will reduce the cost

per ton-mile of river transport on the port of Baro to 60 or 65 % of the present cost. No doubt this will be even more when upward transport of merchandise to the port of Baro increases. Increase of up-river traffic to the port of Baro is thus very likely and from a viewpoint of efficient operation of railway and river-fleets this is very necessary.

The conclusion that during the months of December to April a considerable part of the produced crop will be conveyed via Baro along the river to the Delta ports when the above-described improvements are carried out and when the Escravos Bar is no longer a restriction for ships calling at the Delta ports. Under such circumstances 300,000 tons downward shipped from Baro, being about 50 % of the total groundnut crop, and 100,000 tons upward shipped to Baro is a fair estimate, and then also would dredging be a paying proposition. It is understood, however, that the present capacity of the Baro—Minna Line is 120,000 tons in each direction, so that capital investment is necessary to increase the capacity of this railway-line accordingly.

(iv) *Discharge regulation* asks for very large investments, and the benefits of such schemes must be calculated over a large number of years. Two such schemes should be considered:
1. One or two dams and reservoirs upstream of Jebba where good sites exist. The reservoir size could be 12—15 milliard cubic metres, or 10—12 million acre-feet, according to rough estimates; and
2. a dam or two smaller dams with reservoirs in the upper reaches of the Benue, where good sites exist upstream of Yola and near Lagdo. The most suitable reservoir size is 10—12 milliard cubic metres, or 8—10 million acre-feet, according to preliminary calculations.

The present volume of river transport does not warrant these dams as long as they are not a part of a multi-purpose plan, but certainly future transport will to a considerable extent contribute to a sound economic base of these multi-purpose plans (see also Paragraph VI, 9.1.3).

When comparing a Jebba and Yola scheme, the conclusion is that the benefits will be approximately equal from a viewpoint of navigation. However, a Jebba scheme has four important advantages above a Yola dam. They are:
1. The better situation (from the viewpoint of consumption) to generate and distribute large quantities of electricity as a part in a multi-purpose scheme;
2. the opening of the River Niger above Jebba as far as Niamey, which will render accessible a complete new hinterland of the Niger and eventually be of great importance;
3. the effect of a Yola dam depends on the improved navigability of the Niger below Lokoja in April-June, which can best be improved by construction of a Jebba reservoir first; and
4. a dam and reservoir near Yola is not suitable for the generation of electricity as it cannot supply power troughout the year. Apart from navigation, only flood control and subsequently irrigation would benefit from such a dam, whilst a Jebba project will produce all these beneficial effects.

(v) *River training-works* will be only applicable on the Niger as has been outlined in Paragraph VI, 6.4.3. These works aim at navigation depths of 8 or 9 feet. The large cost will be off-set by the considerably more efficient fleet exploitation than the use of a 5—6 feet draught fleet. A condition is again a large volume of transport on the river, but there is little doubt that traffic will have increased sufficiently in the 30—50 year period required to carry out the complete regulation of the Niger from the Delta as far as Lokoja or Baro. It must be realised, however, that it will be difficult to exploit effectively a river-fleet in a combined operation on the Niger with 8 or 9 feet available depth and on the Benue with 5 to 6 feet available depth. A further improvement of the Benue with a second dam near Makurdi would be indicated to follow such river training-works on the Niger when in this 30—50 year period transport on the Niger remains largely dependent on agricultural crops. The agricultural crops cause a peak in transport over a comparatively short period. If industrialisation has developed sufficiently for a river-fleet

solely for the Niger to be efficiently exploited during the whole year, it will prove even easier to decide on river-training works for the Niger.

d. *The sequence of improvements*

From all the considerations as described in this Report the following sequence of improvements has been outlined in Paragraph VI, 9.1.3.

(i) River management, including research, channel demarcation, channel patrols, prediction and stage information combined with communications. This has already proved to give a net benefit, and the organisation already existing should be extended so that full profits of these relatively cheap measures are obtained.

(ii) Night navigation should be introduced as soon as the necessary buoys, beacons, etc. can be installed, as this improvement also will pay for itself as soon as it has reached full effect.

(iii) Dredging dominating sills in the Niger River as well as the Benue Bar should be the third step of improvements, as it will be economically justified in combination with (i) and (ii) as soon as the decreasing transport cost attracts sufficient additional water-borne traffic, which may be in a few years' time. Meanwhile, test-dredging should be carried out as described in VI, 4. Further, tests should be carried out with floating training works and bandalling.

(iv) A dam and reservoir upstream of Jebba, which as a multi-purpose project may soon prove economic and then precede:

(v) A dam and reservoir upstream of Yola to supplement a dam near Jebba. Through a combination of the water release of these two dams, the most effective navigation channels can be created. Extension of the navigation season and increase of available depth can from year to year be combined to serve the river-fleets with the best transport route, depending on the distribution of the freight market over Niger and Benue in each year.

(vi) River training-works on the Niger should be completed within 30—50 years, which will ask for the first steps to be taken in the near future.

(vii) A dam near Makurdi will eventually bring about the further improvement of the Benue to a river navigable below Makurdi troughout the year with an available depth of 8 or 9 feet, and further extension of the navigable season between Makurdi and Garua to 8 or 9 months with 4 feet draught, or 5—6 months with 6 feet draught, or 3—4 months with 8—9 feet draught will then be the least result.

In conclusion it may be stated that the improvements (i) and (ii) should be carried out without delay, as they are already economic propositions. At the same time, test-dredging should be started to establish whether the results of dredging will be in accordance with the assumptions in VI, 4. If this proves to be so, dredging proper should follow the improvements (i) and (ii) directly.

The other improvements can be carried out when the volume of traffic has increased. In the long run, all the above suggested improvements will prove remunerative. This may in the first years appear to be partly at the expense of other means of traffic (railway- and road-transport) but the overall traffic will develop so quickly, partly as a result of the river improvements, that eventually also the other means of transport will benefit. The impressive revival of the Mississippi navigation of the past decades had no unfavourable effects at all on the railways running parallel to that river. The Rhine and other European rivers are frequently flanked by railways; together with road transport, these transport systems are complementary to each other, and the only effect of a normal and free competition should be that the most efficient means of transport is provided for any type of goods.

4.6.2. Capital and recurrent expenditure

River observations and studies will ask for annual increases in the present recurrent expenditure over a period of at least ten years.

An amount of £ 75,000 will cover for the coming 3—5 years the expense of mapping and charting the rivers.

Day-time buoyage on the Niger and Benue requires a capital expenditure of some £ 150,000; the recurrent cost will be about £ 70,000.

Night-signalisation on the Niger and Benue requires over and above the cost of a day-time buoyage a capital expenditure of £ 100,000; the additional recurrent cost will be about £ 45,000.

Test-dredging will require a sum of between £ 40,000 and £ 50,000 per season, during two years.

A dredger-fleet, when Government-owned, would require a capital investment of between £ 800,000 and £ 900,000. The annual recurrent expenditure for river improvement by dredging would be between £ 150,000 and £ 200,000, depending on the use and ownership of the dredger-fleet.

For experiments with light provisional training-works a total sum of £ 500 should be allocated. If successful, the expenditure should be gradually increased to £ 10,000 or £ 15,000 per annum, for improving the Benue Bar and the Wuro Boki and Gamadio Flats.

A summary regulation of the difficult crossings of the Niger to L.R.L.—8 feet between the Rocky Section and Idah will require a capital investment of about £ 4.5 million, to be spread out over 15 or 20 years. The recurrent cost, composed of maintenance, interest and amortisation, is estimated at about 5 % of the cost of the completed works, rising to £ 200,000 or £ 250,000 after all crossings in this section have been regulated.

A further regulation of the difficult stretches of the Niger in the section between Lokoja and Samabri would require additional capital investment of £ 5.5 million spread out over perhaps 10 or 20 years, with annual cost of maintenance etc. rising to some £ 250,000 or £ 300,000.

A complete regulation of the Niger between Lokoja and Samabri to attain depths of 10 feet below L.R.L. as a sequence to the elimination, mentioned above, of difficult stretches, would require another £ 10 million investment, whilst the additional recurrent cost would be £ 500,000.

A regulation of this section, with contracted crossings to reach depths of 12 feet below L.R.L. would ask for an additional £ 20 million investment and £ 1 million recurrent cost.

A summary regulation of the Baro — Lokoja stretch to 8 feet below L.R.L. would ask for an investment of £ 2 million; a complete regulation to L.R.L. — 10 feet would cost £ 3 million more and a regulation with contracted crossings to L.R.L. — 12 feet would cost an additional £ 5 million. Recurrent cost may again be estimated at about 5 %.

The cost of a discharge regulation through a Jebba scheme will not be given here, being a part of a multiple-purpose scheme.

The cost of a Lagdo dam, for a regulation of the discharges of the Benue and effective between Garua and Ibi, has been estimated by the Cameroun investigators at £ 6 million.

The cost of a Yola dam will be between £ 10 and £ 14 million, depending on its size. The annual recurrent cost, composed of maintenance, operation and amortisation, is estimated at about £ 1 million.

4.6.3. Resulting benefits

a. *Improved navigability*

The improvements described each lead to an improved navigability, which may be shortly summarised thus:

(i) *River management* can be properly organised in 1961 or 1962, effecting a half foot gain

in utilisable navigable depth throughout the present shipping seasons. Not only will the number of groundings be greatly reduced, but the prediction of water-levels and available depths will enable the maximum use of these available depths until the end of the Baro and Benue seasons. The estimated lengthening of the serviceable season is from 10 to 15 %.

(ii) *Night buoyage and signalisation*, as a part of river management, will increase the capacity of a fleet by some 60 % compared with the present situation.

(iii) *Dredging* by a dredger fleet of some 2,500 cuyards/hour capacity will increase the available depths by one foot in the Baro season, i.e., from December to April and entering the Benue will be possible 10 to 14 days earlier in an average year. Dredging the Benue would mean excessively large expenditure and is not recommended as long as the Benue season is not extended and the water-levels be kept partially in hand by discharge regulation. Test-dredging during a couple of years should precede the building of a special dredger-fleet, but navigation can in the meantime benefit to a small extent from such dredging. This experimental dredging could start immediately, if it is to be carried out by a contractor.

(iv) *Temporary training-works* will probably not give any real improvement, although trials should give a definite conclusion on this subject. Locally, it can in some places achieve the same effect as dredging and reduce the dredging programme, thus in combination with dredging attain the same improvements in navigability as dredging only. On the Wuro Boki and Gamadio Flats it could lead to channels through these flats which would permit passing of ships perhaps a fortnight earlier than at present. This would lead to an improvement of the accessibility of the ports Yola and Garua by half a month, which would be a far from negligible lengthening of the navigable season for these ports.

(v) *Bed-regulation* is only feasible on the Niger, and the execution of a complete regulation of this river between Baro and the Delta will probably enable navigation with 8 or 9 feet throughout the present season, i.e., excluding April, May and June, when draughts would be limited to 5 or 6 feet. These works will take from 30 to 50 years, and it is very likely that a dam and reservoir upstream of Jebba will have been built before this time has elapsed. If that is so, 8 or 9 feet navigation throughout the year will then be possible, an improvement of 4 feet and an extension of the Baro season by two to three months as compared with the present situation.

(vi) *Discharge regulation* on the Niger by means of dams and reservoirs of up to about 12 milliard cubic metres (10 million acre-feet) upstream of Jebba will be used in the first place for power requirements. Nevertheless, an extension in navigability to year-round navigation in an average year can be expected and the Black Flood can be heightened some inches. Moreover, the crossings and the channels will no longer be exposed to the deteriorating effect of the flood-peaks and consequently the total increase of available depth during the Black Flood period will rise to $\frac{1}{2}$ or 1 foot. Further improvement of the available depth can be obtained when the storage volume is raised by some 7 milliard cubic metres to almost 20 milliard cubic metres (16 million acre-feet), the cost of which is estimated at only £ 2,500,000. But owing to the fact that this extra volume cannot be filled in drier years, the full benefits will only be reached $1\frac{1}{2}$ to 2 out of every 3 years on an average. Lastly, navigation upstream of the rapids between Jebba and Yelwa will get an outlet to the sea, as the dams will eventually drown all rapids.

A Yola dam or a combined Lagdo and Yola (Yolette) Scheme with a reservoir capacity of between 8 and 10 million acre-feet will lengthen the navigable period at ports in the upper reaches of the Benue. The season at Yola will be doubled, whilst the Garua season will be extended to roughly four times its present length (see Table VI, 8.5.6-1). The Yola (Dasin) — Garua stretch will be navigable throughout the year. On an average, navigation will gain from this improvement a 100 % increase of cargo shipped to and from the Benue without enlarging the present fleet capacity. When the fleet is adapted to the new possible draughts, a much more favourable ex-

ploitation of the fleet will result. An eventual dam in Makurdi may provide for a year-round 8—9 feet navigation channel downstream from the dam, and conditions on the Niger below Lokoja would also greatly benefit from this regulation. But between Yola and Ibi the navigation channel cannot be more than 8—9 feet during 3 to 4 months, or 6 feet during 5 to 6 months or 4 feet during 8 months, according to conservative assumptions for the discharge hydrographs and to the present limiting discharges. However, a Yola dam will precede a dam near Makurdi by many years, and there are good grounds to expect considerable changes in the morphology in the Yola—Ibi stretch as a result of a discharge regulation (see VI, 8.5.5). The river-bed may narrow and the limiting discharges may considerably decrease, so that it may very well be possible that large depths over longer periods will be available on this stretch.

b. *Increased and improved transport*

All the measures taken to improve the navigability of the Rivers Niger and Benue aim at a cheaper exploitation of the river fleets by minimising the time of idleness of invested capital in ships and by increasing the available depths, which reduces the invested capital and, to a smaller extent, the recurrent expenditure per ton-mile of carried transport. It is beyond the scope of this Report to investigate further the reduction in transport costs per ton-mile, but there is no doubt that the improvements described in this Report will bring water transport cost per ton-mile in the same position as in more developed countries, i.e., in the order of 1 to 2 or 1 to 3 compared with rail transport cost per ton-mile.

The results of these reduced exploitation costs can be partially understood from Diagram 4.6.1-1, i.e., VI, 9.1.1-1. The influence area of the railways north of Minna will be drawn into the Niger River influence area via the railway-line Minna—Baro. Furthermore, the direct influence areas of the rivers will considerably increase. New developments of the railway and road transport routes cannot, however, be overlooked, so that the influence on river transport routes is very difficult to estimate. However, if the river transport will remain cheaper, bulk transport will mainly follow the water route provided port facilities in the Delta are equivalent to those in Lagos and Port Harcourt.

Rough estimates made of the increased tonnages moved by the cheaper river transport following the improvements are:

(i) Resulting from river management, night navigation, dredging and the expected response from shipping and port agencies:

1. an extra increase of transport from Baro of 250,000 tons/year and up-river to Baro of 100,000 tons;
2. an extra increase of 20 to 40 % of the present transported tonnages from the increasing Niger influence area; and
3. an extra increase of 60 % of the tonnage handled during the Benue season.

(ii) Resulting from a Jebba dam subsequent to (i), and from a further increase of the Niger influence area:

an extra increase of 10 % over the increased transport mentioned under (i) 1, and 2.

(iii) Resulting from a dam near Yola following (i) and (ii):

a doubling of the Benue transport as has been mentioned under (i) 3.

A further normal annual increase of 5—7 % can be expected over all the above tonnages.

A necessarily inaccurate extrapolation of the transport into the future has lead to the estimate of a 10 to 15-fold increase of the present transport within 40 years, i.e., between 1,300 and 2,000 million ton-miles transported per year between the Delta ports and the ports along the Niger

and Benue. This is excluding local traffic between ports along the Niger and Benue, which may also become very important, as can be realised from the fact that the ratio of exported to total volume of agricultural produce is at present about 1 to 15 and that Nigeria has a considerable industrial potential.

In the decreased cost of transport due to improvements will also be found expressed the more reliable, shorter and year-round transport which will be possible. All transport from and to places within the present area of influence of the river will benefit to the full extent by the improvements. Places within the enlargements of the influence area will benefit only partly and at places situated at the new periphery of the influence area nothing will be gained until further improvements are made. From Diagram 4.6.1-1 it can be seen that approximately 65 % of the country will profit from the improved transport facilities and from the reduced transport cost when the ratio of water and rail transport cost has become as 1 to 2.

The recommended programme of improvements will bring about many additional advantages not directly connected with improved navigation. The most important of these are:
(i) the stimulation of production in cultivated and not yet cultivated areas above the present increase in production, as a result of the improved and cheaper transport facilities;
(ii) the generation of power, which will be the main interest of a dam and reservoir near Jebba, as well as the flood-control made possible by dams including the irrigation prospects;
(iii) the agricultural and industrial development of the river valleys which will become increasingly attractive as the rivers are being brought under control;
(iv) the opening of a water-route along the Niger as far as Niamey;
(v) the creation of employment by the execution of the river-works for a group of the population in skilled labour of different levels; and
(vi) the imponderable advantages of hydrological research beyond the direct results for navigation.

All these extra advantages should be added to the calculation when seeking to find an economic basis for the improvements. This is not necessary when the benefit for navigation only already surpasses the expenditure as in the case of river management and night navigation, but it certainly is necessary for those large-scale projects as dams and reservoirs or river training-works for which the economic justification must be sought in all their aspects and over a large number of years.

PART II

THE INVESTIGATION

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CHAPTER 1

PLANNING

1.1. PROGRAMME OF THE INVESTIGATION

1.1.1. Required studies

The comprehensive investigation, as summed up in the Terms of Reference, includes three main fields of activities, viz., observation, interpretation of natural phenomena and application of the knowledge gained.

Where the target is to determine how shipping conditions on little-studied rivers can be improved, the Investigation can be sub-divided into four characteristic parts:

(i) what the present natural condition and development of the rivers is;
(ii) how this development is being accomplished;
(iii) why the condition and development are in the described way; and
(iv) what will be the future development with and without human interference.

The studies required for each of these parts will be briefly described in the following paragraphs.

1.1.2. Present condition and development of the rivers

For this, a study of the past conditions is required as well as a study of the present. Facts dating back some centuries are equally useful as, and sometimes of more importance than, present-day information, which may only give seasonal influence, for instance.

Unfortunately, very little historical information is available about the Niger and Benue Rivers. Their lower course was unknown until the first half of the 19th century, when a series of courageous explorations established the fact that the great and well-known river of the Sudan takes ultimately a southerly course and debouches into the Atlantic Ocean through the numerous deltaic estuaries of the Oil Coast. But the lower valleys of the Niger and Benue remained for a very long time particularly insalubrious and the early expeditions on these rivers suffered many hardships.

In 1841 and 1854 surveys, including mapping and soundings, were made of the navigable parts of the Niger and Benue; but since that time very little survey work has been done on the rivers. River-gauges were established early in this century at several stations along the main rivers and daily or weekly readings of these gauges are available.

In the course of the present investigation the number of river-gauges had to be greatly increased. Previously there were six gauges positioned over a river length of roughly 1,000 miles, and at present seventeen primary and twenty secondary gauges are in operation, supplying valuable information on the river-stages.

A comprehensive mapping programme had also to be undertaken: from aerial photographs

specially taken for this purpose by the Federal Survey Department of Nigeria, detailed river-maps were prepared in Holland. On a scale of 1 : 20,000 these maps show banks, islands, sand-plates, roads and tracks, villages, minor water-courses and some altitudes of the riverain areas relative to the water-level.

An accurate levelling of the primary gauges, in order to obtain the gradient of the river, was carried out by the Federal Survey Department, whilst secondary levellings have been done in the course of the investigation by NEDECO.

Further important and new information on the rivers was obtained by measuring discharges of water, silt and sand at various stages and at many stations on the main rivers and the tributaries. Samples of the river-bed material were collected for determining the grain-sizes of the sand. Present-day development has also had to be studied by means of frequent soundings to detect seasonal changes in bed-level and to study the available depths and the shifting of sand-banks.

All the above-described data together have established what is known as the regime of the rivers. In addition, the present condition of navigation needed studying to obtain an understanding and also a location and classification of the problems encountered. It could also follow from this study of shipping that the navigability could be improved without affecting the regime of the rivers, for example, by predicting the water-levels and channel-depths, or by marking the deepest channel at shallow places by means of buoys and beacons.

1.1.3. Mechanics of the rivers

The above investigations led to the second question, namely, how the recorded changes are being effected and what are the governing forces of the system. For this, the field of observations had to be widened to include studies of rainfall, erosion and sedimentation. Calculations of waterflow and sediment transport assist in obtaining an understanding of the behaviour of the river.

The application of theories of hydrology and morphology may provide an answer to the above question. But it should be kept in mind that the problems of natural water-courses are so complex that theory can be applied in a limited number of cases only.

1.1.4. Explanation of the development

Next to determining what is happening and how this occurs, the question arises as to why the situation is developing or has developed in this way. For this a study of the boundary conditions was required, including studies of the upper reaches of the rivers outside the areas where navigability has to be improved.

In this particular case, for instance, the propagation of the flood waters of the Upper Niger in the swamps near Timbuctu in French West Africa appears to have a special bearing on the conditions on the Lower Niger. Also, ancient changes in the river pattern and the drainage system south-east of Lake Chad, in the Upper Benue, Mayo Kebi and Logone areas may still have their influence on the gradient and profile of the Benue River.

In explaining the state and the development of the rivers, the geological history and the geological conditions could not be neglected; so a study of the geology of the river valleys has been included in the investigation.

1.1.5. Future developments

From the information gained on the three preceding problems, it may be possible to determine what the natural development of the river characteristics will be, although more important still

is the question as to what artificial developments will be required to effect desirable changes, such as deepening of the rivers and also what the after-effects may be of a direct solution to the problems.

This involves a study of the possibilities of improving the navigability as well as the application of the knowledge from the regime observations and the boundary conditions.

A comparison with other rivers the navigability of which has been improved has yielded valuable information. In particular the Rhine and Mississippi Rivers, both being major waterways carrying a transport of many tens of millions of tons a year after far-reaching improvements to their channels had been carried out, have been used for comparing the possibilities, effects and after-effects of improving the shipping conditions.

1.2. TIME SCHEDULE

A period of three years was considered necessary for the complete investigation. It is doubtful whether a shorter period, even if it had been possible to concentrate the measurements at the cost of more personnel and facilities, would have been sufficient to acquire a thorough understanding of the characteristic qualities of the river system and of their variations.

The first year was intended for general measurements, which would be supplemented in the second year on the strength of the indications they had given. This would then leave opportunity in the third year for more detailed studies on specific objects, such as verification of tentative conceptions and closer investigation on behalf of outlined projects.

The measuring campaigns for the different districts did not coincide in point of time. For the Upper and Lower Benue measurements on the river could only be carried out from July through to October (on the lower river somewhat longer), with the dry season periods being utilised for surveying and levelling activities. For the Niger districts the main interest has been directed to the low-water season from September to May, supplemented by a limited number of measurements during high-water stages.

To ensure obtaining the full benefit of the 1955 measuring campaigns, a representative of NEDECO went to Nigeria during the course of 1954 for preparatory work. The senior NEDECO staff arrived in Nigeria during the first months on 1955. This was preceded by a certain amount of preparation in Holland (construction of launches, etc., acquisition of instruments, study of aerial photographs, instruction of fresh staff members, etc.).

The completion of the investigation was anticipated at the end of the measuring season 1957—1958.

It has been possible to maintain this schedule.

1.3. TERRITORIAL SUB-DIVISION

1.3.1. Headquarters

It was considered essential that the entire study should be treated throughout as one comprehensive undertaking. A division into separate districts was unavoidable for the organisation of the measurements, but as regards the compilation, classification and analysis of the data and the gradual building up of a complete picture of the nature and behaviour of the river system, the closest possible continuous contact between the leader of the team and its various members had to be ensured.

This was possible only when the staffwork was concentrated in one central headquarters. Such a plan was also economical because of the centralisation of the administration, drawing office, and facilities at laboratory, installations for photographic work, sample analysing, etc.

After due consideration, Lokoja was chosen for the location of headquarters. Though from the viewpoints of position relative to the entire area, of communications and general facilities both Onitsha and Makurdi were equally or perhaps slightly more eligible, the existence of a Marine depot at Lokoja, providing a slipway and repair shop, was decisive in fixing the choice.

1.3.2. Districts

Considering the nature and the topographical extension of the area concerned, a sub-division into different sections was indicated. This would have to take into account the length of the rivers, the accessibility of the locations and the nature and extent of the work.

The following sub-division, subject to later modifications which were imposed by the development of the study, was planned:

a. General Management, dealing with general affairs, coordination of activities, administration of buildings, craft, cars and instruments, official representation, outside contacts, etc.
b. District Upper Benue, dealing with the Benue River from the limits of the French activities down to the Donga, with the Rivers Gongola, Taraba and possibly Faro.
c. District Lower Benue, dealing with the Benue River from the Donga down to the outfall in the Niger, with the Rivers Donga and Katsina Ala.
d. District Upper Niger, dealing with the River Niger down to Idah, with the River Kaduna.
e. District Lower Niger, dealing with the River Niger below Idah down to the junction with the Delta Investigation.

1.4. FUNCTIONAL SUB-DIVISION

1.4.1. Introduction

As the investigation progressed, it became desirable to make a functional sub-division to ensure a good coordination of the various subjects previously dealt with by the District Staff. This was also necessary in view of the preparation of the Final Report.

Notwithstanding this concentration of studies, the observations that were still necessary were taken by the District Staff.

1.4.2. Subjects

The following studies were centralised in 1957:

(i) hydrology, i.e., the knowledge, interpretation and explanation of the characteristics of the water-flow, including precipitation, river-stages, discharges, evaporation and the inter-relations;
(ii) morphology, including the knowledge, interpretation, and explanation of the channel-formation and the sediment transportation;
(iii) geology, i.e., the knowledge of the crust of the earth and its (tectonic) movements;
(iv) navigation, including the characteristics of, and difficulties encountered by, Niger and Benue shipping, as well as the possibilities of guiding these ships;
(v) transport, i.e., an overall impression of the nature of transport in Nigeria, of the tonnages available for transport and the expected development and of alternative transport routes; and
(vi) constructions, such as groynes, screens and dams, including the local materials that would be available.

CHAPTER 2

STAFF AND EQUIPMENT

2.1. EUROPEAN STAFF

2.1.1. Establishment

According to the Agreement between the Government of Nigeria and NEDECO (I, 1.1.3), the senior staff of the Niger and Benue Investigation would consist of:

one chief engineer, directing and coordinating all activities and representing NEDECO;
one second chief engineer, assisting the chief engineer and acting as his deputy;
eight civil engineers; for each of the four districts one senior engineer responsible for all activities in his district, and one assistant;
one secretarial officer; and
one assistant secretary.

The following expatriate staff of NEDECO has worked in Nigeria on this investigation:

H. C. Frijlink,	Chief Engineer, March 1955—March 1958;
D. J. Blom,	Second Chief Engineer, Jan. 1955—Nov. 1955;
W. L. Kwint,	Second Chief Engineer, July 1955—May 1958;
A. C. de Gaaij,	Senior Engineer, later Assistant Chief Engineer, March 1955—Feb. 1958;
J. G. Jongenelen,	Senior Engineer, Feb. 1955—Dec. 1955;
H. A. Berdenis van Berlekom,	Senior Engineer, March 1955—March 1958;
J. Zeper,	Senior Engineer, Feb. 1955—Feb. 1958;
J. van den Berg,	Engineer, later Senior Engineer, Feb. 1955—Feb. 1958;
G. Dekker,	Engineer, later Senior Engineer, Jan. 1955—April 1958;
J. J. van Dijk,	Engineer, Feb. 1955—Feb. 1958;
J. Volbeda,	Engineer, March 1956—Feb. 1958;
J. C. Vogel,	Engineer, June 1956—May 1958;
A. Prins,	Engineer, Feb. 1955—Nov. 1957;
W. Adriaans,	Engineer, May 1956—March 1958;
B. P. Zwarenstein,	Secretarial Officer, July 1954—July 1958; and
A. Lubbers,	Assistant Secretary, Oct. 1955—June 1958.

In the course of the investigation it appeared useful to establish the additional post of Assistant Chief Engineer, so that the Chief Engineer could spend some time on matters only partly related to this investigation, whilst also a ninth civil engineer has been employed. It was then possible for NEDECO-Lokoja to be concerned with studies such as those concerning the practi-

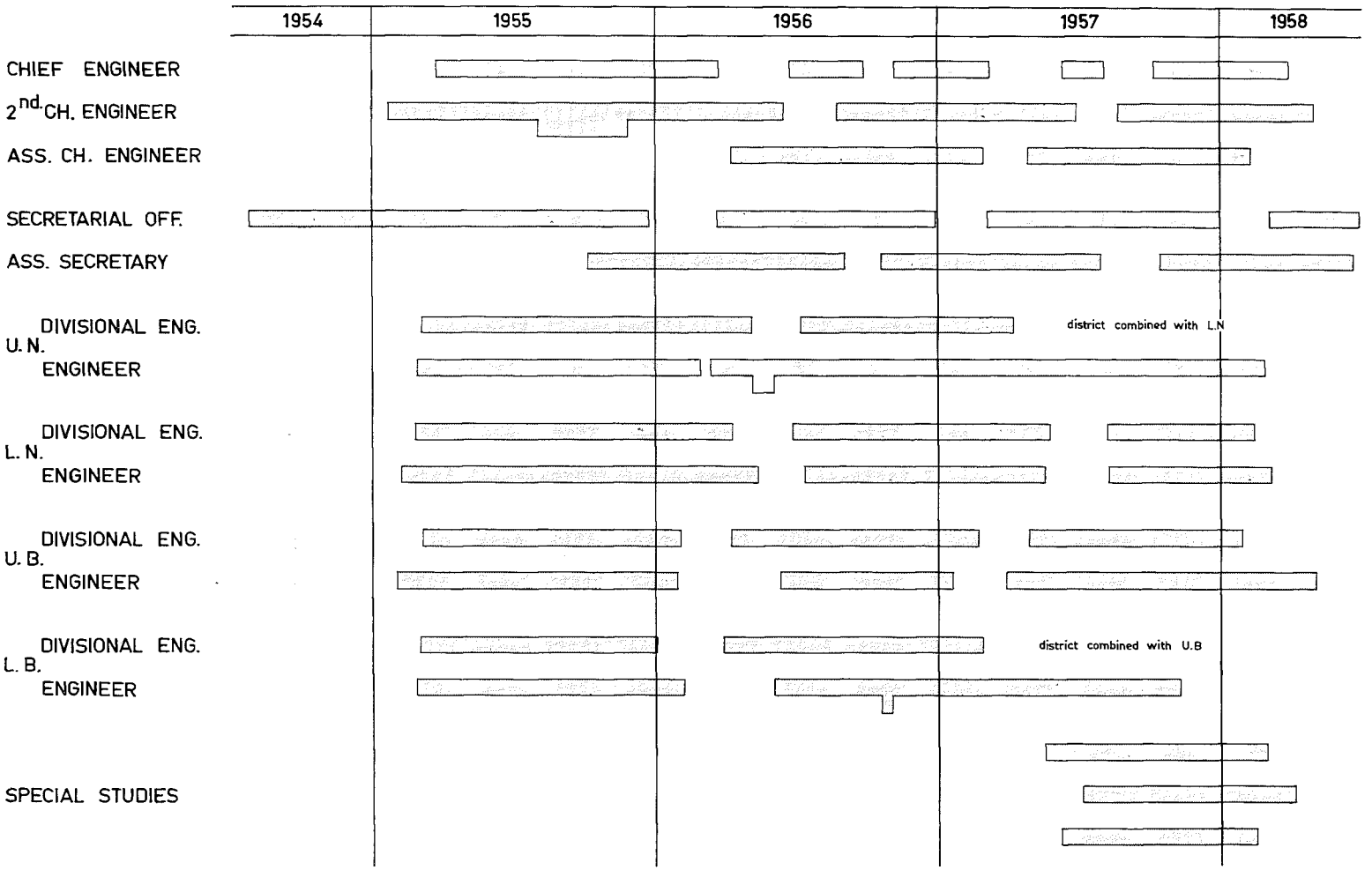


DIAGRAM 2.1.2-1

Time schedule of senior staff members

cability of a Niger Bridge at Onitsha, a preliminary reconnaissance of the upper reaches of the Niger between the French border and Baro, and severe erosion of the river-bank near Idah; while advice could also be given on some local problems concerning, for instance, gully erosion, establishment of ferries, water consumption of industries, and the construction of quays.

As from the beginning of 1957, the division into four districts was partly changed after it had been decided that the programme of taking observations on the rivers was in an advanced stage. As far as the Divisional Engineers were concerned, both Niger districts were combined, as were the two Benue districts. Special studies on hydrology, morphology and navigation could then be undertaken.

2.1.2. Schedule

A total of 500 man-months has been spent in Nigeria (leave periods included) on the Niger and Benue Investigation by the above staff. The requirements of Clause 1 (b) of the Agreement have thus been amply fulfilled, as the agreed staff of twelve expatriate officers would have spent in three years only 432 man-months in Nigeria (also including leave periods).

Diagram 2.1.2-1 gives a detailed picture of the periods in which the various members of the NEDECO team have been actually working in Nigeria, excluding their periods of absence by leave, illness or other reasons.

2.1.3. Inspections

The Niger and Benue Investigation has been supervised by a panel of specialists, consisting of

Professor J. Th. Thijsse,	Professor of Hydraulics, Delft Technological University; Director, Hydraulics Laboratory;
Professor P. Ph. Jansen,	Directing Senior Engineer in charge of the Service of the Delta Works, Rijkswaterstaat, The Hague; Professor of Hydraulic Engineering, Delft Technological University;
J. B. Schijf,	Chief Engineer, Central Research Division, Rijkswaterstaat, The Hague; and
Professor L. van Bendegom,	Professor of Hydraulic Engineering, Delft Technological University.

Apart from regular supervision from Holland, the Niger and Benue Mission in Nigeria has been inspected several times on behalf of NEDECO by its Managing Director, Mr. E. W. H. Clason, by Chief Engineer Mr. H. K. van Zijll de Jong, and by members from the above panel, according to the following schedule:

Mr. Clason,	August 4—13, 1955
	Dec. 24, 1956—Jan. 11, 1957
	March 17—27, 1958
Mr. van Zijll de Jong,	February 15—19, 1956
Professor Jansen,	Dec. 24, 1956—Jan. 11, 1957
Mr. Schijf,	July 11—Aug. 7, 1955
Professor van Bendegom,	Sept. 22—Oct. 21, 1955
	Dec. 24, 1956—Jan. 11, 1957
	Dec. 16, 1957—Jan. 2, 1958.

2.1.4. Special staff

Short visits for special investigations were made by experts from Holland.

Mr. C. Voûte, Geologist, made a study and reconnaissance of the Niger/Benue Basin in October and November 1956, and was accompanied by Mr. A. Driessen, Geographer. Mr. B. Steenstra, also a professional geologist, supervised the Yola dam-site exploration in February and March 1957.

Mr. G. W. Koopman, Chief Engineer of the Netherlands Rijkswaterstaat, was in Nigeria in September and October 1957 for an investigation into the most suitable type of channel patrol vessel.

Mr. J. Wardenier, surveyor, carried out a small-scale levelling programme in order to measure the slopes of the river at various locations. He stayed in Nigeria in April and May 1957.

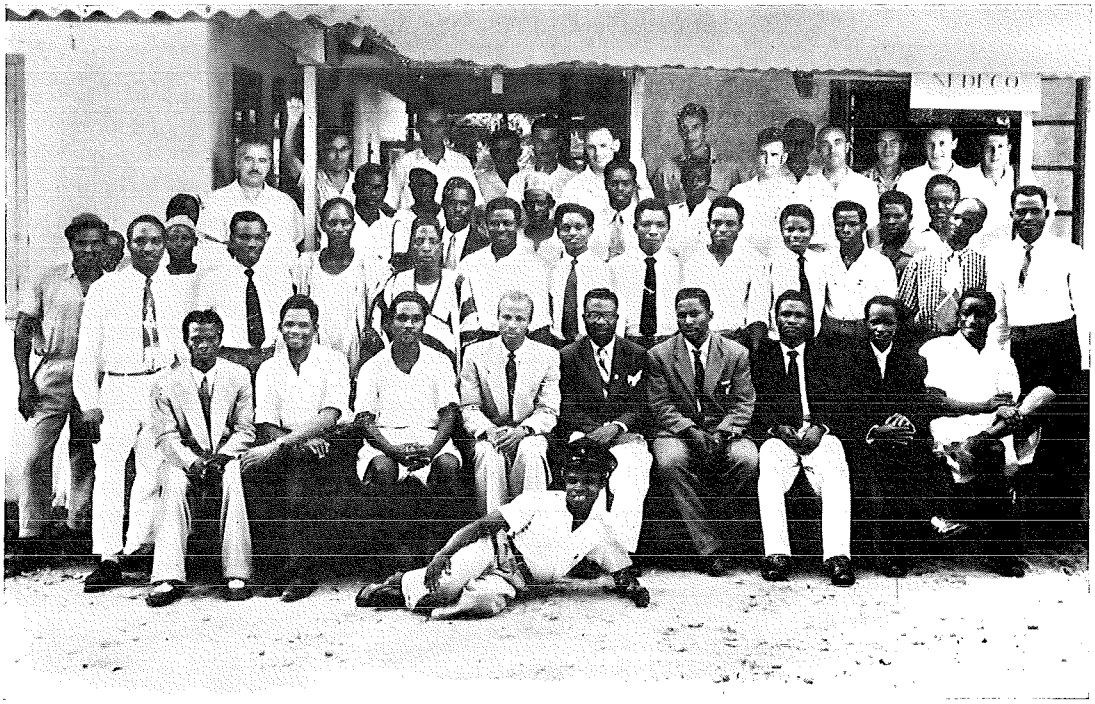
2.2. NIGERIAN STAFF

2.2.1. Establishment

The total number of Junior Staff employed on the investigation was subject to minor changes, but averaged some 30 Nigerians under contract to NEDECO. In addition, five labourers and a night-watchman were employed as daily-paid staff. The general composition of the Junior Staff was as follows:

3 Engineering Assistants (in 1957/1958 only)
11 technical clerks
3 draughtsmen
1 laboratory assistent
1 chief clerk (adm.)
1 typist
2 wireless operators
2 generator drivers
4 car-drivers and
1 messenger.

A large part of this Junior Staff was taken over from the Western Niger Delta Investigation carried out by NEDECO in 1953/1954. During this Delta Investigation, the various members could already be partly trained in their jobs, which was especially important for the technical clerks. Although hydrological work was hitherto completely unfamiliar to them, while a combination of office work (calculating and computing, drawing and plotting) and field work (handling of instruments, erecting benchmarks and beacons along the river-banks, but also surveying) appeared rather exceptional in Nigeria, it was essential that the technical assistants were able and willing to do both. The training of such all-round technicians progressed satisfactorily, and in the second half of the investigation it was possible to send Nigerian Engineering Assistants or even Recorders A out on tour with a rather complicated measuring programme without the direct supervision of an engineer. Also the elaboration of the observations in the office was carried out by Junior Staff. As a result the Senior Staff was relieved of a considerable amount of routine work, while it was possible at the end of the NEDECO Investigation to transfer to the Inland Waterways Department a number of well-trained Nigerian employees capable of continuing the regular hydrological work on the rivers.



PHOTOGRAPH 2.2.1-1
Nedeco staff, October 1957

2.2.2. Qualifications

The technical clerks were established in various grades, each of which was connected with a certain ability to execute hydrological and survey work, while a minimum education was required as a basis for further training. These requirements were:

Grade	*Minimum education*	*Desired ability*
Engineering Assistant	Cambridge Certificate	Replace the engineer Carry out and elaborate all measurements entirely independently Supervise other staff
Recorder "A"	Middle IV	Carry out and elaborate measurements on discharges of water and sand, including positioning of the ship in the cross-section with range-finder and sextant, and sounding of the cross-section with echo-sounding and lead or pole Execute levelling Supervise other staff
Recorder "B"	Middle III	Carry out measurements on discharges of water and sand, including positioning of the ship in the cross-section Elaborate measurements on water discharge Manipulate slide-rule

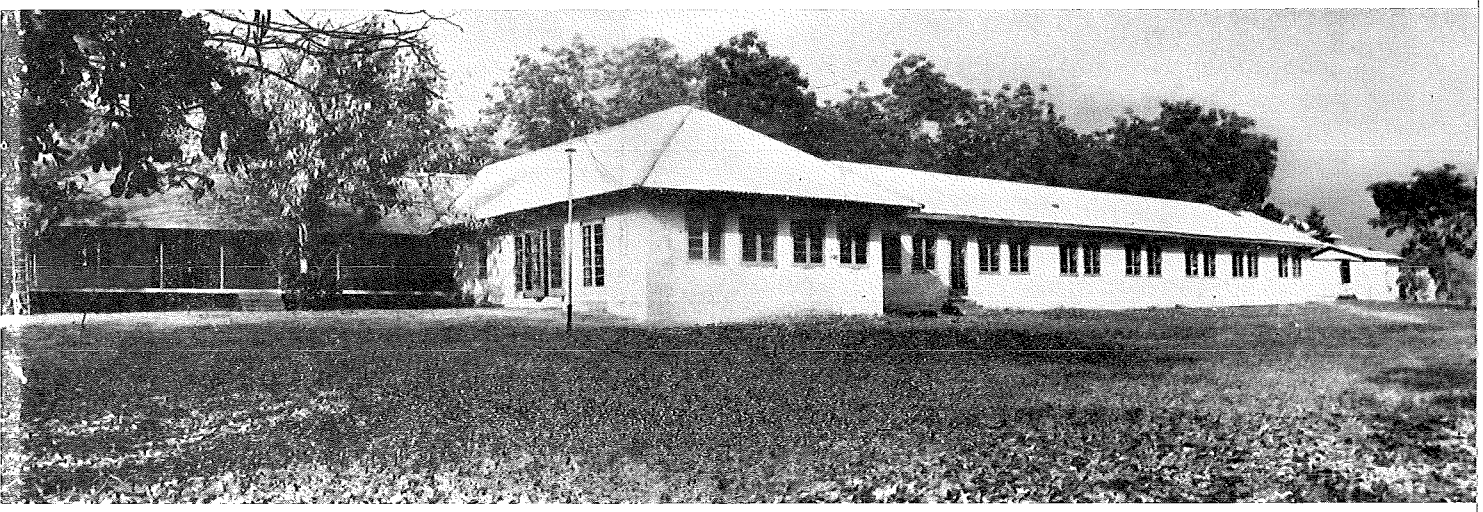
Grade	*Minimum education*	*Desired ability*
Recorder "C"	Standard 6 = Middle II	Carry out measurements on discharges of water and sand, excluding positioning of the ship Elaborate measurements on water discharge Read and prepare graphs Master the decimal system
Recorder "D"	Standard 6 = Middle II	Be acquainted with arithmetic
Assistant Recorder	Standard 6 = Middle II	

An "Assistant Recorder" can be seen as an apprentice for the status of Recorder, while a Recorder "D" had a task of general assistance.

2.3. HEADQUARTERS

2.3.1. Office

On a one-mile long ridge a few miles south of Lokoja Township, old hospital buildings had become vacant by the completion of a new hospital. Two of those existing buildings were converted and connected by a new wing to serve as an office. The main part of this work was completed in March 1955 (see Photograph 2.3.1-1).



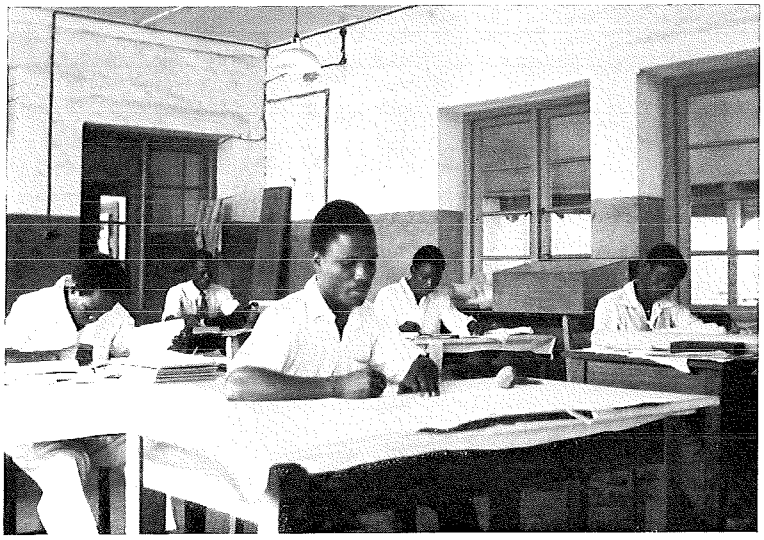
PHOTOGRAPH 2.3.1-1
Nedeco headquarters, Lokoja

The office building was very satisfactory and provided ample space for the various staff members and their activities. It included 7 offices for expatriate staff, a spacious office for technical clerks (Photograph 2.3.1-2), offices for the chief clerk and typist, a drawing office, a conference room with library, a dark room and a laboratory.

The latter housed precision instruments for sieving and weighing sand samples (see 3.5.2), a duplicator machine and a white-print machine. In the course of the investigation nearly 3,000 sand samples have been sieved, 6,500 stencilled copies have been made and some 5,400 drawings have been printed.

Three small separate buildings in the vicinity served as instrument store, wireless room and power-house.

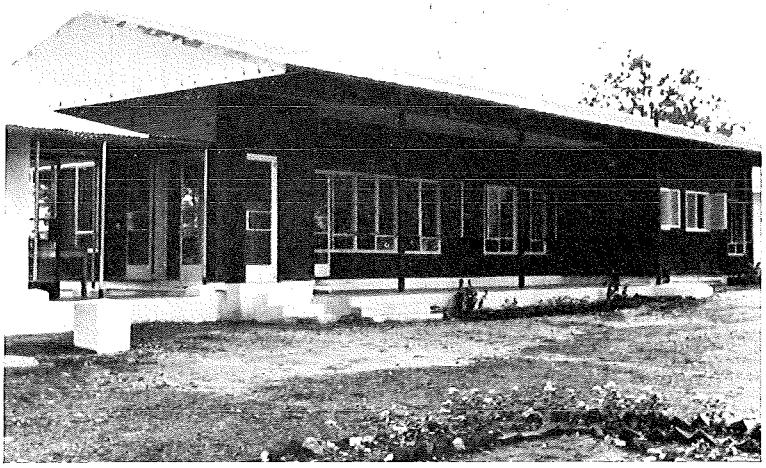
Routes leading from the main road to "Nedeco Ridge" have been improved.



PHOTOGRAPH 2.3.1-2
Recorders' office

2.3.2. Staff quarters

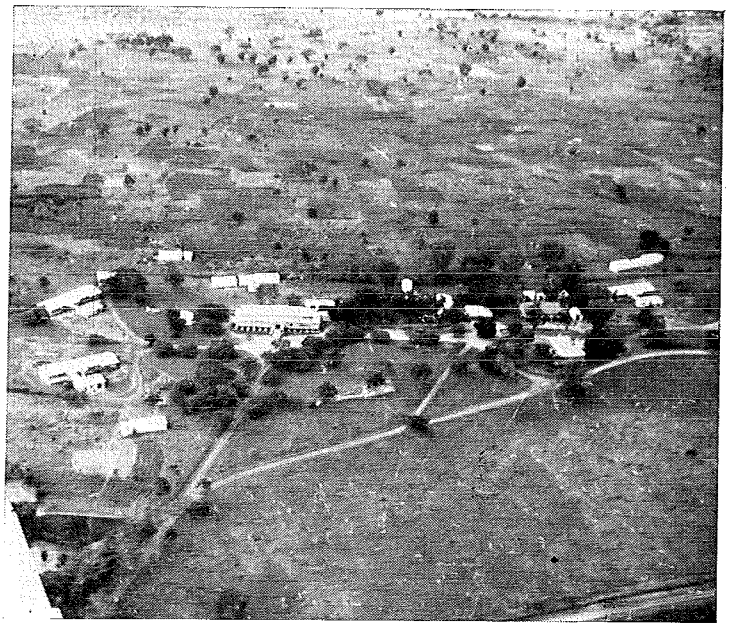
Seven pre-fabricated houses have been constructed to serve as married quarters for the senior staff (Photograph 2.3.2-1). The first of these was completed by the end of May, and the last in August 1955. Two existing fifty-years old "Lugard Houses" were repaired and redecorated to



PHOTOGRAPH 2.3.2-1
Pre-fabricated quarters for senior staff

serve as married quarters, being completed in December 1955 and April 1956 respectively. An old hospital building was converted into bachelors' quarters, suitable for five to six single expatriates, but later, in the course of the investigation, a part of this was re-converted into married quarters. A pre-fabricated guest-house for visitors has been erected.

All these buildings have been erected or converted by or on behalf of the Federal Government and they are all situated on the "Nedeco Ridge" (Photograph 2.3.2-2).



PHOTOGRAPH 2.3.2-2
Nedeco ridge

For the Junior Staff and their families, quarters have been constructed on a site in Lokoja Township (Photographs 2.3.2-3 and -4).

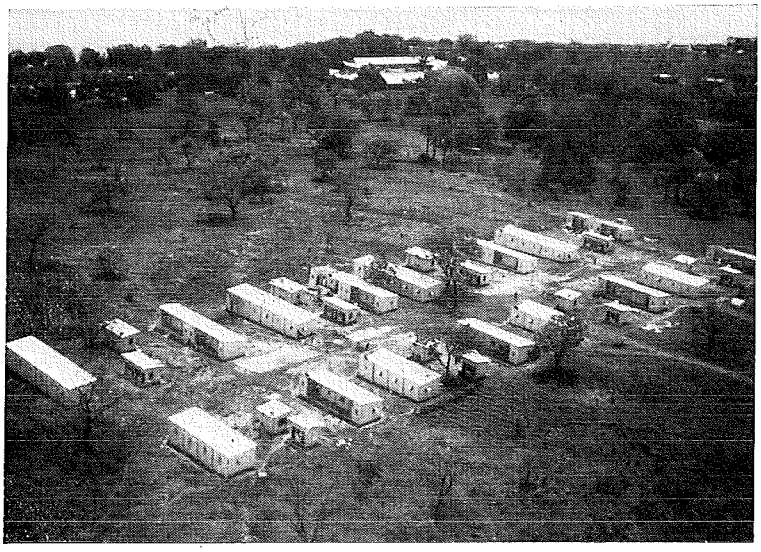
2.3.3. Electricity supply

A power-plant has been installed by NEDECO to provide electricity for the office and laboratory, for the wireless and for domestic purposes of the Senior Staff. It consisted of a 15-KVA generator for use in the evening and a 8-KVA generator for use during the day-time and was housed in the mortuary of the old hospital in close vicinity of the office building. It was in full operation from 0700 hours to 2400 hours daily.

Two drivers ran and maintained the plant, while regular supervision was carried out by an engineer from the I.W.D. Dockyard, Lokoja.

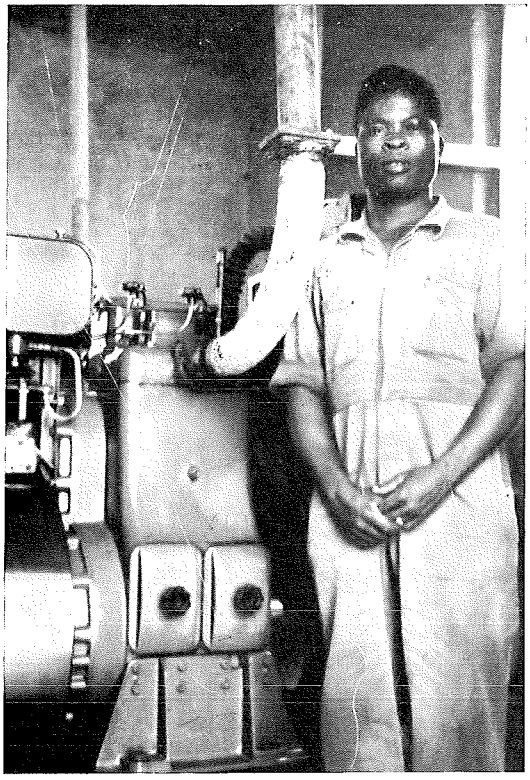
2.3.4. Water supply

In the first instance "Nedeco Ridge" was connected to the water-supply system of Mount Patti, serving the whole of Lokoja Township. However, the quantity of water available was very unsatisfactory and a special supply-system, pumping and purifying Niger water, had to be constructed. It was manned and maintained by the Public Works Department, Lokoja.



PHOTOGRAPH 2.3.2-3
Junior staff quarters

PHOTOGRAPH 2.3.2-4
Junior staff quarters



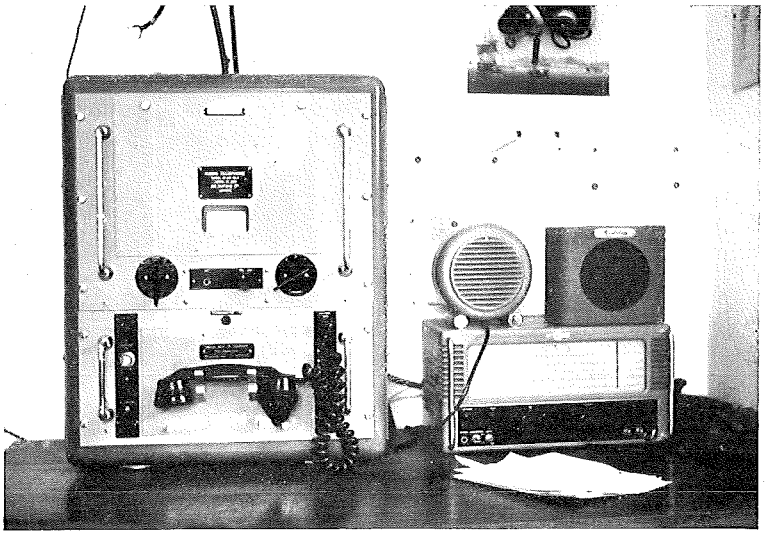
PHOTOGRAPH 2.3.3-1
Generation of electricity

2.3.5. Radio equipment

Wireless has played an increasingly important role in the investigation. This was partly in direct connection with the programme of observations: by the installation of a 50-watt output transmitter/receiver in Lokoja, regular contact was maintained between NEDECO headquarters and the field parties. Most of these field parties were equipped with receivers only, so that twice a day at fixed hours they could receive messages and general information from Lokoja, while answering was possible through the normal telegraph system of P. & T. The house-boat, however, serving as temporary field headquarters to the Upper Benue District, and later also the survey launch "Woodlark", were provided with transmitter/receivers, enabling a two-way conversation with Lokoja Headquarters and with each other.

A very useful contact was maintained twice weekly with the headquarters of the French Benue Investigation team at Garua, during which water-levels and other regime data were exchanged.

As the V.H.F. telephone-network between Lokoja and Lagos was not yet in operation, it has been most welcome that through the kind cooperation of Post & Telegraph Headquarters at Lagos, radio communication with Lagos could be established whenever required. This greatly facilitated contacts with Government officers and with NEDECO engineers passing Lagos.



PHOTOGRAPH 2.3.5-1

Radio station "Nedeco Lokoja"

One of the river navigation companies, the Niger River Transport (N.R.T.) at Burutu, established in the course of the investigation a number of shore radio-stations, and in addition ten river towboats were equipped with transmitter/receiver sets. All these N.R.T. transmitters were operating on the same frequency as NEDECO (7663 kc/s). A time-schedule had been agreed upon, leaving certain hours to NEDECO and other periods of the day to N.R.T.

Mutual contact between N.R.T. and NEDECO took place frequently. Reports on the movements of N.R.T. river-vessels were received by Lokoja and recorded for study purposes. Touring NEDECO engineers were kindly allowed to use N.R.T. transmitters for urgent discussions with Lokoja, while reversely the NEDECO transmitter was open for urgent N.R.T. messages to and from U.A.C.—Lokoja regarding river transportation.

In the course of the investigation, the wireless at Lokoja was used with increasing frequency to receive records of water-levels from various stations along the river, ranging from Garua on the Benue and Jebba on the Niger to Aboh in the Delta. Several authorities, including the Railway Corporation with its radio transmitter at Jebba, have given full cooperation. As a result, it was possible to establish a service to river navigation by a daily broadcast from Lokoja about water-levels, condition of the rivers, least available depths, predictions, etc. This broadcast was given in English and in Hausa, in the first instance in 1956 on a small scale, but later extended and finally taken over by the Inland Waterways Department in 1958.

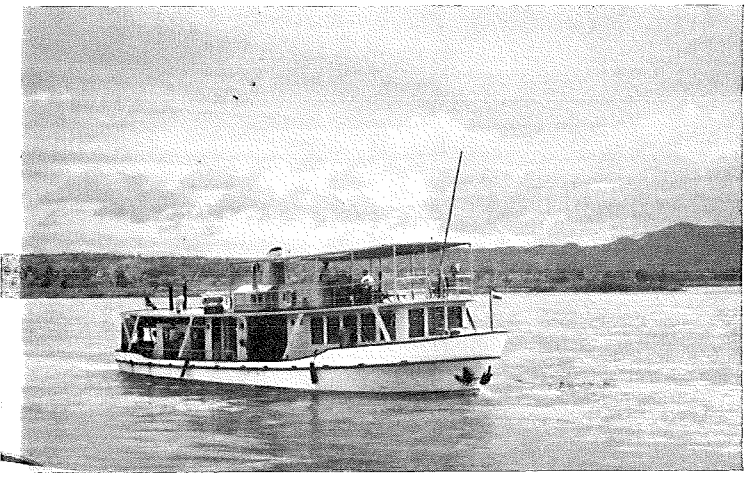
2.4. SURVEY VESSELS AND MOTOR-CARS

2.4.1. Vessels

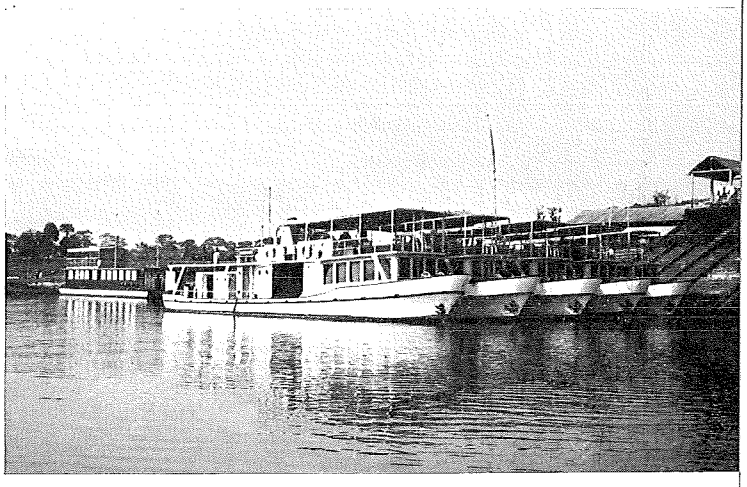
The fleet of vessels used in the Niger and Benue investigation was the property of the Federal Government of Nigeria, while crew and maintenance was supplied by the Nigerian Ports Authority. After the establishment of the Inland Waterways Department in 1956, both the ownership and the responsibility for crew and maintenance were transferred to this department. Maintenance was carried out in the Lokoja Dockyard. With the exception of the steel canoes mentioned below, the vessels were specially designed for the survey work in the Nigerian rivers, and were built in Holland under the supervision of NEDECO.

The fleet consisted of the following vessels:

a. Five *survey/accommodation launches* ("Woodlark", "Woodpecker", "Woodchat", "Woodspite" and "Woodowl") with accommodation for two senior officers, a crew of seven, two technical clerks and two servants (Photographs 2.4.1-1 and -2). Their overall length is 78 feet, and the draught varies between $2\frac{1}{2}$ and $3\frac{1}{2}$ feet, depending on the supplies of oil and water. They have a speed of 7—8 knots. A special survey deck over the full width of the ship facilitates the handling of instruments, while a hold below this survey deck serves as store. Three davits provide means of lowering an instrument into the water, while a clockwork device indicates its depth.



PHOTOGRAPH 2.4.1-1

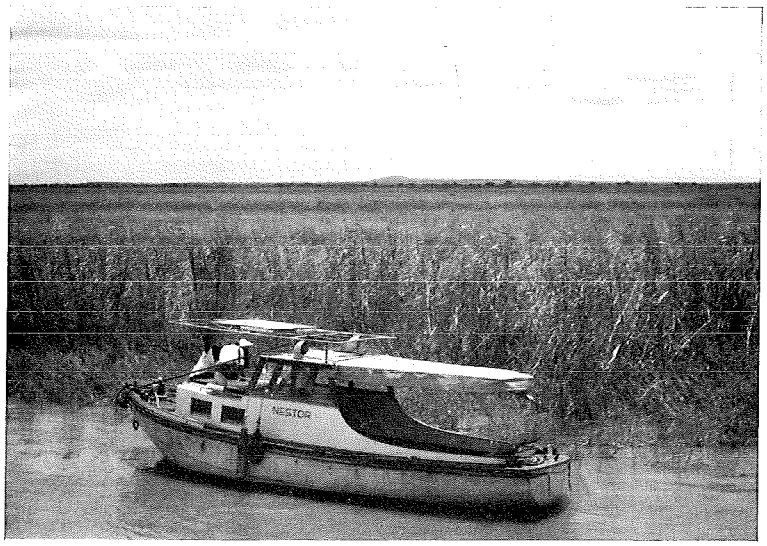


PHOTOGRAPH 2.4.1-2

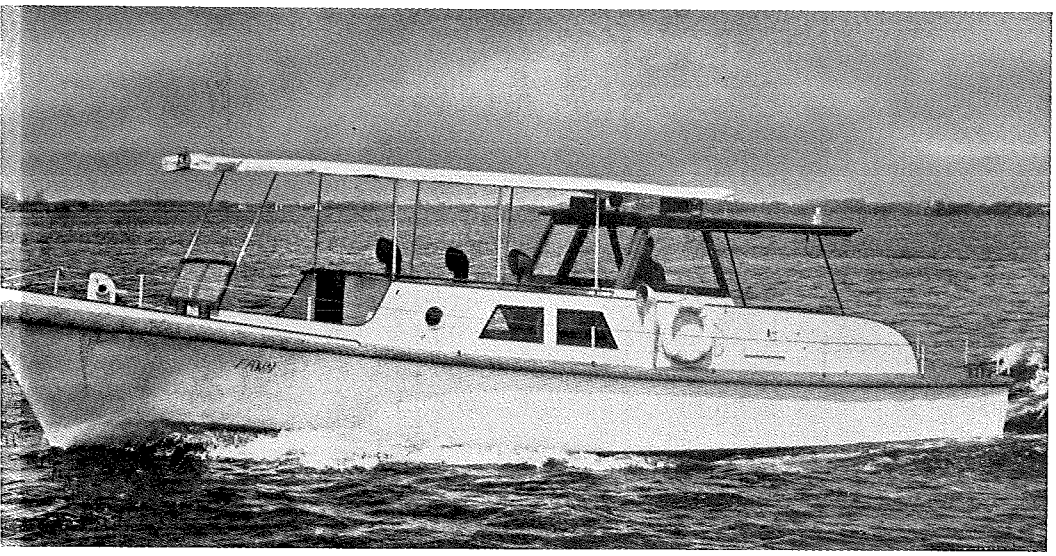
Survey launches ("Wood-class")

The launches are provided with two sets of batteries giving electric power of 110 Volts. A generator can maintain the stored capacity by a regular loading period of four to six hours daily.

b. Four *motor dinghies* ("Norah", "Nuphar", "Naiad" and "Nestor") with accommodation for two members of the crew (Photograph 2.4.1-3). The length of these vessels is 28 feet, the draught 2½ feet and the average speed 6—7 knots. They are highly manoeuvrable and can be operated by a crew of two. All dinghies are equipped with echo-sounding gear running on two



PHOTOGRAPH 2.4.1-3
"Nestor" on survey



PHOTOGRAPH 2.4.1-4
Communication launch "Fawn"

24-volt sets of batteries alternatively used for sounding while the other one was loaded by a dynamo. The dinghies have been used very frequently for sounding purposes and for velocity observations.

PHOTOGRAPH 2.4.1-5
Nedeco houseboat "Nixnut"

c. One *communication launch* ("Fawn") with a speed of 9 knots and limited accommodation for two officers (Photograph 2.4.1-4). During the second half of the investigation the launch was provided with echo-sounding gear and was used satisfactorily for sounding and current-measuring purposes. The Fawn was very suitable for quick inspection tours in the vicinity of her base.

PHOTOGRAPH 2.4.1-6
Glass-fibre dinghy

d. One large *houseboat* ("Nixnut") serving as office and providing accommodation for a married couple and a single officer when operating on the more distant reaches of the rivers (Photograph 2.4.1-5). The houseboat was equipped with a wireless transmitter/receiver on 7663 kc/s for regular contact with NEDECO headquarters at Lokoja. A 24-volt battery set provided sufficient power for radio and domestic consumption. A large storage capacity for drinking water and fuel enabled a full party of houseboat and survey launches to operate on its own for periods of four to five months.

e. Two *steel canoes*, serving as accommodation for Junior Staff accompanying the houseboat party.

f. Two *glass-fibre runabouts* with 10-h.p. outboard engines, capable of carrying one or two officers at a speed of 15—20 knots. They could be transported on the roof of a motor-car (Photograph 2.4.1-6) and were efficiently used for quick reconnaissance trips and for small measuring tours, particularly on the Benue during the dry season, since their draught was practically zero.

2.4.2. Motor-cars

NEDECO operated for the purpose of the investigation a fleet of three kitcars (Photograph 2.4.2-1), two stationwagons and one saloon car. In addition, six saloon cars, privately owned by senior members of the staff, were used for overland touring by their owners.

Maintenance has partly been carried out by the P.W.D. workshop at Lokoja.

During the three years' investigation, a total of 185,000 miles has been driven by the NEDECO cars and 127,000 miles by the privately-owned cars, often on very rough roads and under difficult circumstances (Photograph 2.4.2-2), in order to take observations or make explorations.

PHOTOGRAPH 2.4.2-1

PHOTOGRAPH 2.4.2-2

Nedeco kitcars

CHAPTER 3

MEASUREMENTS

3.1. RAINFALL

3.1.1. Instruments

Rainfall observations within Nigeria are mainly made with 5-inch rain gauges the rim of which is 18 inches above the ground.

The number of autographic rain gauges installed in Nigeria so far is relatively small, but efforts are being made to increase the total.

3.1.2. Procedure

The British West African Meteorological Services have built up the organisation necessary to record daily rainfall at many stations.

Readings are made daily at 1000 hours and records are sent monthly to the Headquarters of the Meteorological Services at Lagos.

Records of the 5-days rainfall figures from all existing rainfall measuring stations are published monthly.

3.2. EVAPORATION

3.2.1. Piche evaporimeter

This instrument is usually exposed in meteorological screens. It consists of a vertical glass tube closed at the top, whilst the bottom end is closed by a piece of blotting paper which is pushed against the rim of the tube by a spring.

The tube is filled with water which evaporates through the blotting paper. The graduation on the tube enables the observer to read the level of the water inside the tube and thus find the daily evaporation.

The Piche evaporimeter will not, however, give a magnitude of evaporation which equals that from an open water surface. The result of the evaporation as determined from this instrument is almost solely dependent on the relative humidity and the temperature of the air.

Piche evaporimeter observations are made throughout Nigeria by the British West African Meteorological Services.

3.2.2. Tank evaporimeter

The tank evaporimeter used in Nigeria is a steel tank mounted on wooden bearers lying on the ground. The tank is rectangular, measuring $4'2\frac{1}{4}'' \times 3'$ and $1'5''$ deep. The bottom of

the tank is 2″ above the surface of the ground. It is painted black inside and cream outside.

The tank evaporimeter is filled with water up to 3″ below the rim, a level at which the point of a hook gauge is mounted in the tank.

Daily at 1000 hours the amount of water needed to fill the tank upto the point of the hook gauge is measured. This enables the observer to compute how much has evaporated from the tank during the preceding 24 hours.

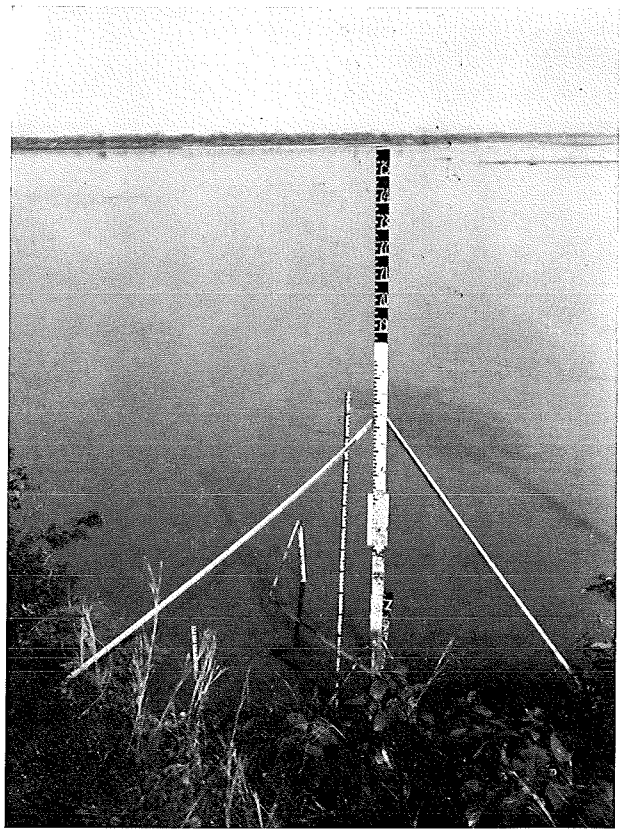
When appreciable rainfall has occurred, however, splashing and blowing of the water surface makes any measurement valueless; therefore, only observations over days without rain are used to compute the monthly tank evaporation.

A tank evaporimeter of this type has been installed at Yola by the British West African Meteorological Services during July 1957, and since then, others have been installed in the Niger-Benue Basin within Nigeria.

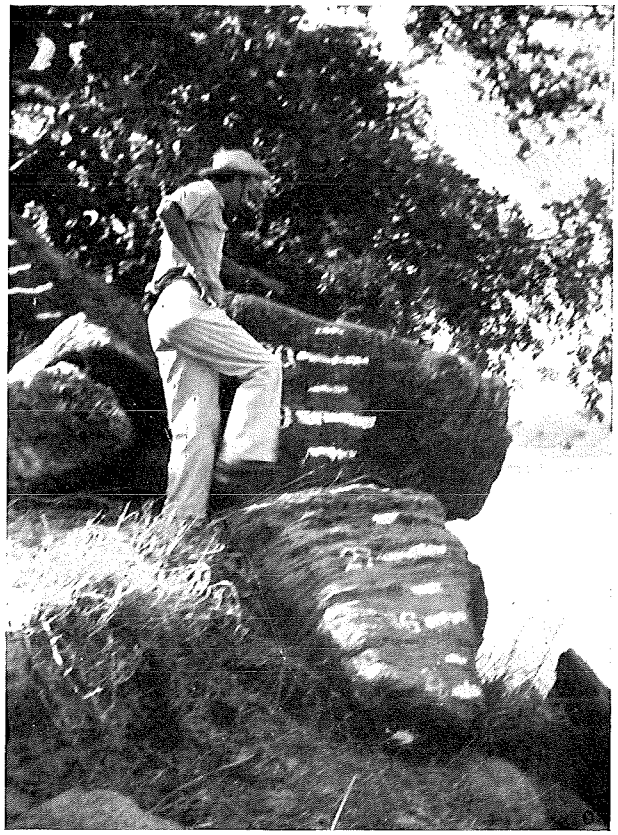
3.3. WATER-LEVELS

3.3.1. Staff gauges

The most simple system of recording river-stages is to erect a pole in the water with a division at some linear scale painted on its side and to read at regular intervals the position of the water-



PHOTOGRAPH 3.3.1-1
Baro gauge



PHOTOGRAPH 3.3.1-2
Gauge at kombo

level relative to that division. This system of staff gauges has been used throughout this investigation. In most cases, the "pole" was a 20-feet steel angle-bar, supported by other angle-bars onto the bank (Photograph 3.3.1-1), although wooden poles or iron tubes have also occasionally been used.

Normally, the division was painted in feet and inches, although in some cases tenths of feet were used. In a part of the Upper Benue District a division was established by the Cameroun investigators in metres with its decimal system.

A concrete benchmark erected on the bank served as a basis for regular check on possible vertical changes in the position of the gauge, while for the primary gauges along the rivers these benchmarks have been connected to the system of the geodetic levelling (see 4.5).

Mostly it was necessary to place in a single site a series of various gauges at different heights, to meet the full range of water-levels from lowest to highest record.

Several gauges were read by employees of the Railway Corporation, the Irrigation Department, the United Africa Company, or John Holt & Co. The majority, however, was read by local schoolmasters or other intelligent inhabitants of the villages, who were paid by NEDECO for this purpose. Their reports were usually submitted to NEDECO by mail, telephone or radio, or were collected by inspecting NEDECO staff.

Readings were taken daily, as a rule every morning at sunrise, but in some cases an additional reading in the evening was necessary where irregular fall or rise of the river prevented correct conclusions.

Most gauges required regular maintenance as they were liable to be washed away by bank erosion, or damaged by ships or canoes. The investigation, however, did not usually suffer from this, as the local supervisors soon replaced the gauge and readings were continued. NEDECO engineers during their inspections then levelled the gauge in its new position toward the old benchmark. Only in a few cases has a break appeared in the readings.

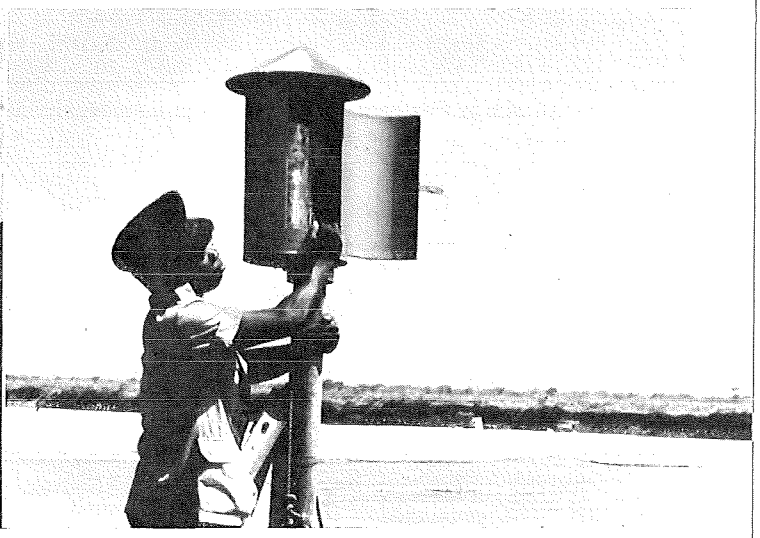
Special circumstances at certain stations allowed the painting of the division on a structure already existing, thus avoiding the expensive erection of a delicate construction. In Lokoja, for instance, the old Marine gauge was established by means of figures fixed onto the side of the stairways leading to the pier. In Makurdi a gauge is fixed against a pier of the bridge. In Kombo, the division is directly painted on a rock (Photograph 3.3.1-2). Such gauges, however, have relatively less accuracy since the water-level is locally disturbed. Therefore, in some of those cases where accuracy of reading appeared to be very important, NEDECO engineers erected and maintained an additional gauge in the vicinity.

Finally, readings at Jebba were taken by means of a steel tape lowered from the bridge, measuring the vertical distance between a certain spot on the bridge and the water-level. This distance amounted at low water to some 60 feet, and it is clear that the result lacks accuracy. Comparison of these readings with records on a newly-erected gauge some hundred feet upstream from the bridge resulted in the discovery of errors of upto 6 inches.

3.3.2. Light automatic gauges

At those places along the rivers where no local people for a daily reading were available or where a recording of twice daily was not sufficient for the required purpose, an automatic gauge had to be used. The type used by NEDECO was the "Fuess" gauge, a small portable instrument which was also very useful for temporary observations during a short period. Erecting a gauge of this type takes about three-quarters of an hour.

The apparatus is fixed on top of a steel tube placed vertically in the river (Photograph 3.3.2-1). The water-level in this tube will rise and fall coincident with the water-level of the river as holes in the tube allow the water to flow in and out. In the tube a float is connected by a thin cable which is kept taut by means of a counterweight. When the stage rises, the float is raised and the counterweight lowered, which in its turn moves a pen upward over a certain height proportional to the actual rise of stage, for instance, on a scale of 1 : 20.



PHOTOGRAPH 3.3.2-1 PHOTOGRAPH 3.3.2-2

"Fuess" Automatic gauge

A cylinder placed in the top of the apparatus (Photograph 3.3.2-2) is rotated by clockwork, and the pen then marks an ink-line on the paper that is wrapped around the cylinder, thus producing a continuous recording of the stages as they occur. The instrument can work 8 days without inspection.

3.4. DISCHARGES

3.4.1. Instruments

The quantity of water discharged by the river per unit of time (for instance, in m^3/sec or in cubic feet/sec) can be measured by taking observation of the water velocity at various points of the cross-section. For this purpose, the *Pendulum Current Meter* "Planeta" has been used. This instrument, which has been developed by the Hydraulic Laboratory at Delft, Holland, is based upon the following principle.

An angle-shaped body (wing) is hung in the stream by means of a steel wire. Under influence of the pressure exerted by the current, the wing is pushed away, causing the steel wire to make an angle φ with the vertical (see Diagram 3.4.1-1) and which is measured on the instrument above the water surface by means of a universally suspended spherical dial consisting of radials and concentric circles containing a frame (also hung universally) through which runs the wire leading to the wing. At the end of this frame a pointer moves along the dial.

The deviation of the steel wire from its vertical position is a measure of the velocity of the current, and the latter can be calculated after the relation between φ and the velocity v has been established.

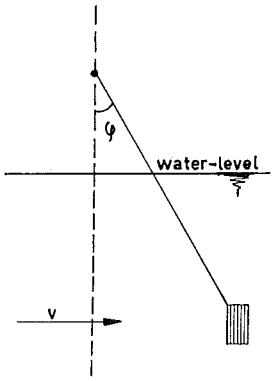


DIAGRAM 3.4.1-1

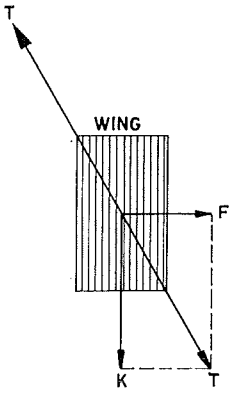


DIAGRAM 3.4.1-2

Principle of Planeta

The pressure of the water-flow on the wing can be expressed by the formula

$$F = \frac{CA\ \rho\ v^2}{2} \qquad \ldots\ldots\ldots \quad (1)$$

where C = coefficient of flow-resistance, dependent on the shape of the wing
A = exposed surface of the wing
ρ = density of the water
v = velocity of the water

Let K be the weight of the wing under water and T the tension of the steel wire; it then follows from Diagram 3.4.1-2

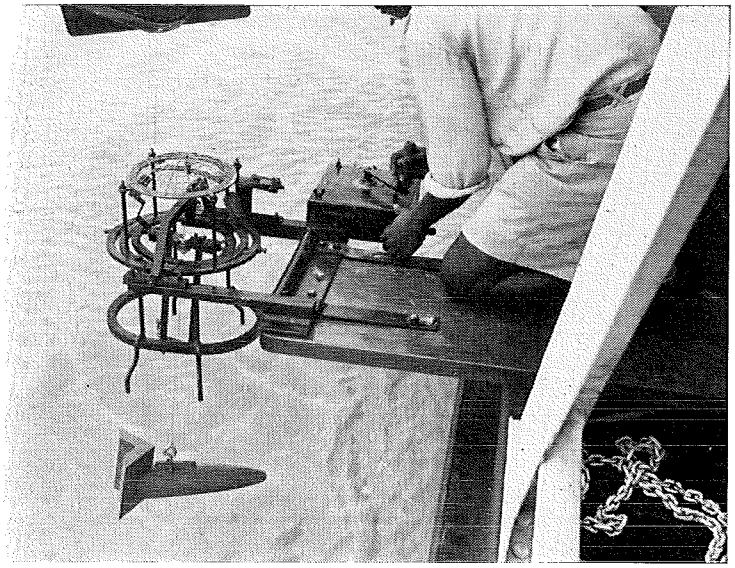
$$\tan \varphi = F/K$$

or, in combination with formula (1),

$$v^2 = \frac{2\,K}{CA\rho} \tan \varphi \qquad \ldots\ldots\ldots \quad (2)$$

A series of wings, ranging from one of small weight K and a large exposed surface A (giving a very sensitive measurement with large values of φ under small velocities) to one with a heavy weight and small exposed surface (enabling the measurement of great velocities), is used for the various circumstances. For each type of wing the appropriate relation between v and φ has been determined according to the above formula. Deviations from this simple relationship, caused by the influence of the flowing water on the steel wire itself, are taken into account by correcting the observed angle on the instrument into the angle that is computed to occur near the wing.

A series of observations is taken with the wing lowered to various depths in one vertical (Photograph 3.4.1-3). Collection of the results in a diagram gives a clear picture of the existing distribution of velocity in the vertical.



PHOTOGRAPH 3.4.1-3
Pendulum current meter "Planeta"

Another means for determining the velocity of the river is a *float*, thrown into the river from aboard ship or from a bridge. The time it takes to drift from one previously fixed transversal sight line to another (the mutual distance between which must be known) is a measure of the velocity. It is essential that both sight lines run parallel, preferably perpendicular to the direction of velocity.

The float should consist of a stick so weighted at its lower end that it floats vertically and emerges above water over only a small part of its length. Its full length should be as great as possible, but never should the end touch the bottom. The more the length approaches the depth, the better does it indicate the average velocity, but an insight into the velocity distribution is not obtained.

Although curvature of flow-lines, wind and waves affect the accuracy, the method can be used efficiently in small streams which are not accessible to other ships than canoes. Dry season observations in the Upper Benue and in some tributaries have been taken in this way.

The *screw-type* of velocity meter has not been used by NEDECO, as it was considered to be too vulnerable an instrument under these rough conditions.

3.4.2. Procedure of discharge measurements

A great number of discharge measurements have been taken in various stations along the rivers. For that purpose the velocity is measured in several verticals in a cross-section, the normal distance between them being some 40 to 80 m (130—260 feet). By plotting for each vertical the average velocity and the sounded depth (Diagram 3.4.2-1), a clear picture results of the distribution of the velocity over the width. By multiplication of the velocity by the depth the local discharge q is obtained which must be integrated over the full width of the cross-section in order to arrive at the total discharge Q.

This general principle can be applied in several ways. Firstly, it is possible to combine the measured velocity with the depth as measured at the same point of observation. This method is particularly easy when the velocity measurement has been taken with the Planeta. The local

discharge q is then simply the area of the velocity-depth graph as follows directly from the observations. However, if the point of observation is not situated in the exact location of the cross-section — which is very well possible on wide rivers like the Niger and Benue — then the depth at this point of observation differs from the actual depth in the cross-section. Based on the assumption of transversal exchange of water at such a rate that the average velocity does not change abruptly due to local variation of depth, the conclusion is drawn that a better result can be obtained by computing the average velocity at the point of observation, and combining it with the depth from a sounding of the exact cross-section. This so-called v.a-method has been frequently used in this investigation (Diagram 3.4.2-1).

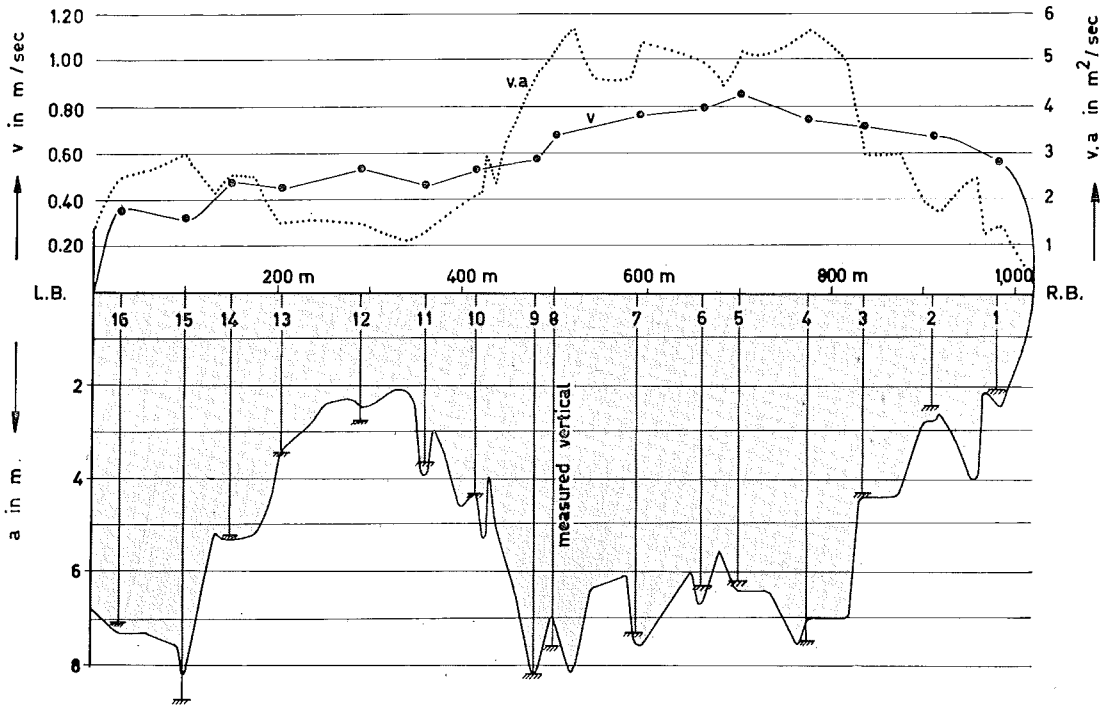


DIAGRAM 3.4.2-1
Computation of discharge

Under certain circumstances, however, this method would give a false result: for instance, when a huge bed-ripple exists over the full width of the river and perpendicular to the river axis. In that case an acceleration and deceleration of flow would indeed occur. It is, therefore, essential that the computation of the discharge from a number of Planeta observations and a sounding in a cross-section is handled with great care and understanding and is adapted to all conditions met on the river.

3.5. SEDIMENT

3.5.1. Samples of sediment

The collection of samples of sediment in the river is most important for obtaining an insight into the characteristic magnitudes determining the behaviour of the river.

Bottom samples have been taken by a so-called grab, which is kept open by a small iron bar when lowered into the water. As soon as it touches the bottom, it closes and catches a quantity of bottom sand down to a depth of 4 inches. When lifted, the grab remains closed and the sample can be hauled on deck. Before the instrument is opened, it is necessary to wait until all the water has gently drained away: it is then possible to collect the whole of the sample, including even the fraction with the finest grains.

Samples of the silt (wash-load) carried by the stream have been taken by ordinary bottles with a stone tied underneath. After the bottle is lowered to the desired depth, the cork is pulled out and a sample of water with sediment can be hauled up. After settling and drying, the silt remains. This simple method was found to be preferable to those using specially-constructed samplers.

Samples of sediment transported by the water-flow as bed-load, as saltation-load or as suspended load have been collected from the yield of sand-transport instruments, described in Paragraph 3.5.3.

3.5.2. Elaboration of samples

The above-mentioned samples were transferred to the headquarters in Lokoja, and elaborated in the laboratory (Photograph 3.5.2-1).

The *sand samples* (bottom, bed-load, saltation-load and suspended load), after having been dried in an electric oven, were sieved to prepare a sieve-curve (see III, 5.1.2). Sieving took place with a set of sieves with openings of 11.2, 5.6, 2.8, 1.4, 0.6, 0.3, 0.15, 0.09, 0.075 and 0.06 mm respectively. After the sieves were placed on top of each other, the dried sample was put in the

PHOTOGRAPH 3.5.2-1
Laboratory

top one, and the whole set was shaken during five minutes in an electric sieving machine. The quantity of sand ultimately remaining on each separate sieve was weighed on a precision scale (upto an accuracy of 0.1 gramme) and a sieve-curve could then be drawn.

A limited number of samples were sent to the Delft University Mining Laboratory for determination of the mineral composition.

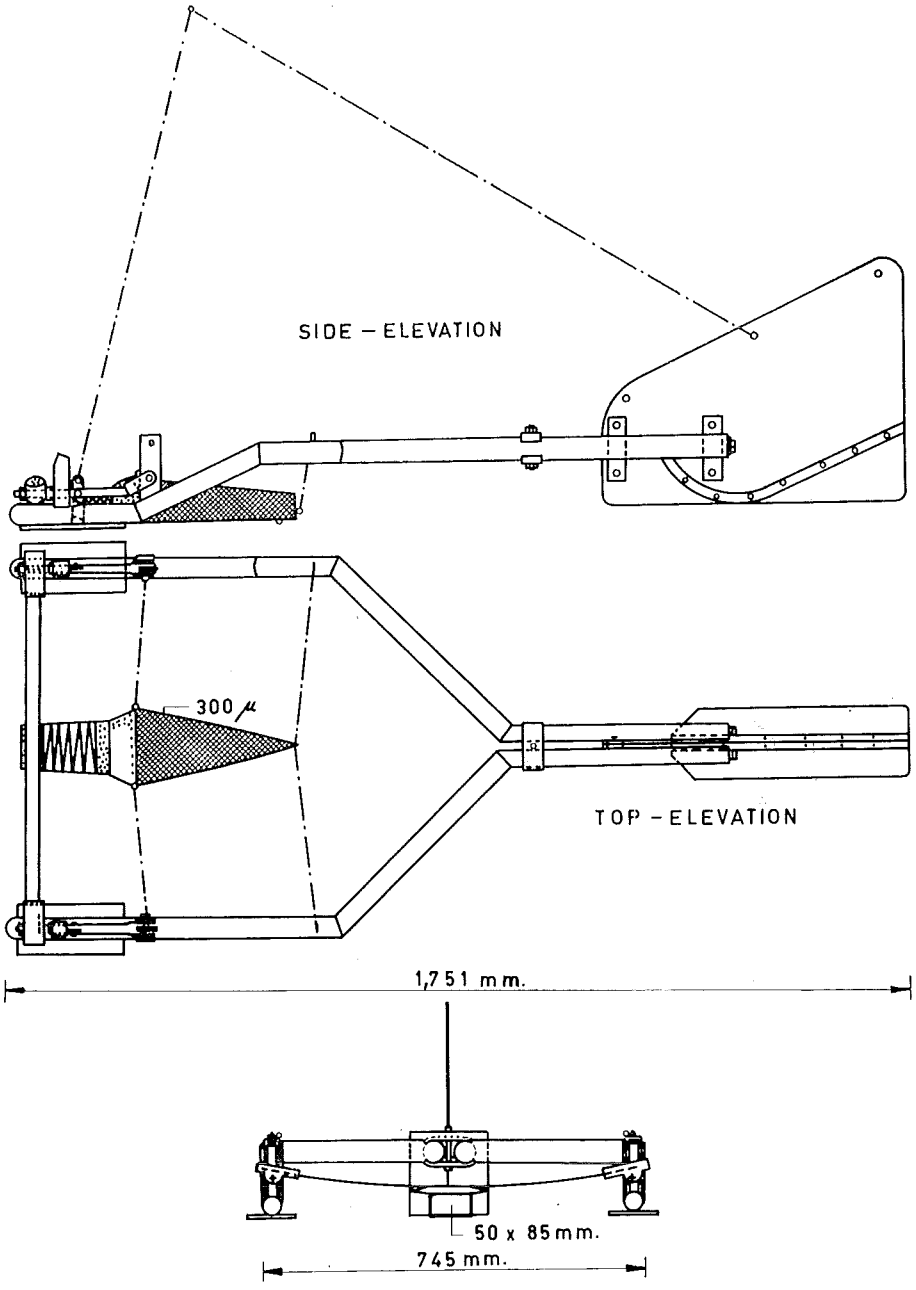


DIAGRAM 3.5.3-1

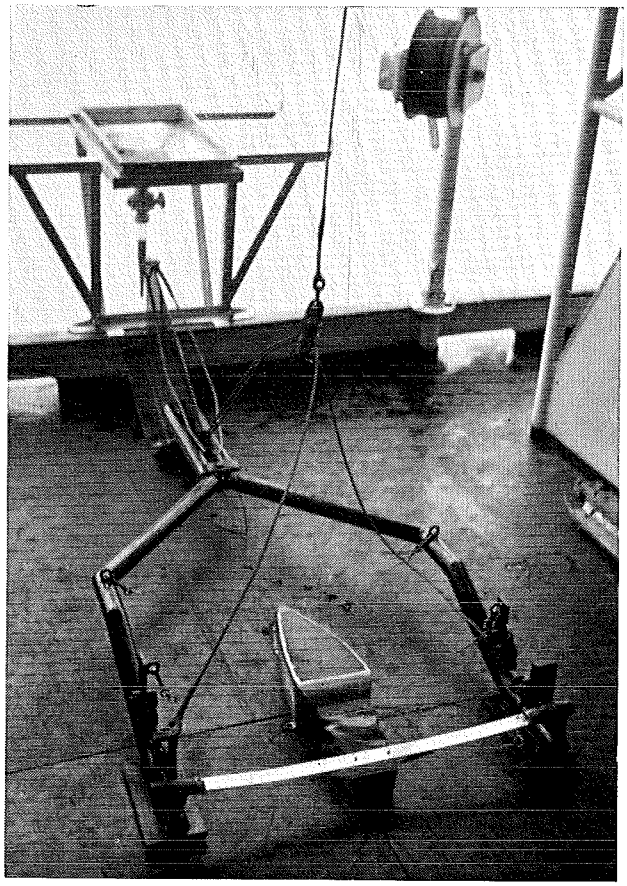
Bed-load transport meter "Arnhem"

The *silt samples* were brought together in large containers and were left standing quietly for about ten days until the silt had settled sufficiently to pour off the bulk of the water. The remaining highly-concentrated silt-water mixture was dried in the electric oven, ultimately resulting in a dry powder. As one single sample contained only a very small amount of silt, many samples were needed to yield a reasonable quantity. Such mixtures have been collected for seven separate river-sections, and have been further analysed by the Laboratory for Soil Mechanics at Delft, Holland.

3.5.3. Instruments on sand-transport

The quantity of transported sediment has been measured at various stations along the river, a special instrument having been designed for each separate type of transport.
a. *Bed-load* is measured with the Bed-load Transport Meter "Arnhem" (B.T.M.A.), designed and developed by the Netherlands Rijkswaterstaat (Diagram 3.5.3-1).

PHOTOGRAPH 3.5.3-2



PHOTOGRAPH 3.5.3-3

B.T.M.A. in operation

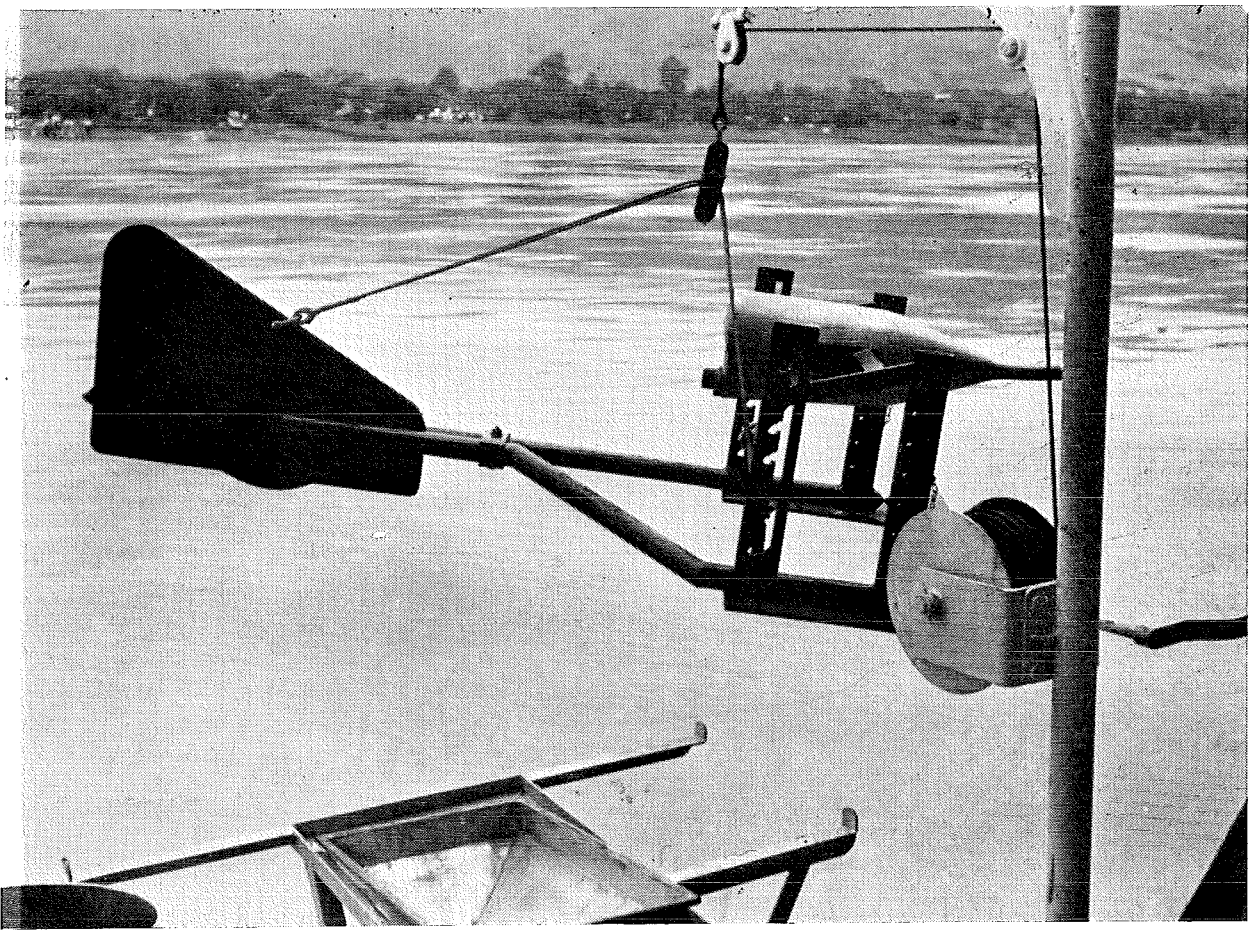
The instrument consists of a frame with a steering fin which keeps the apparatus in the right direction relative to the current. In that frame a catch-basket is fixed, with an entrance opening

of $3\frac{1}{2} \times 2$ inches and a content of about half a gallon, the basket being made of wire mesh through which water can flow easily but by which the sand is caught inside.

The B.T.M.A. is lowered onto the river-bottom (Photograph 3.5.3-2) and remains there some time (mostly 2 minutes), the amount of sand caught being measured by emptying the basket via a basin into a measuring glass (Photograph 3.5.3-3). This procedure is repeated several times (usually ten) in order to arrive at a correct average figure for the quantity of bed-load.

The amount of sand entering the basket is relatively smaller when the basket is filled at a great rate. This has been taken into account when, by extensive laboratory tests, a relation table has been established between the quantity of sand caught in a period of two minutes and the actual magnitude of bed-load per metre width. This entails that the period during which the instrument is placed on the bottom should invariably be two minutes. Only when the sand-transport is very large and the rate of filling would be greater than has been gauged by the laboratory tests, may the period be reduced to, for instance, one minute. But in that case the obtained figure of sand-transport per unit width should be multiplied by 2 and certainly not the captured volume.

b. *Saltation-load* is dealt with by the so-called "Delft Bottle on sleigh" (DF_2), designed and developed by the Hydraulic Laboratory at Delft, Holland (Photograph 3.5.3-4). This bottle-shaped instrument has a nozzle with an opening of 0.9 inch diameter. The apparatus is placed on the river-bottom with its nozzle pointing right into the current at heights ranging from 6 to



PHOTOGRAPH 3.5.3-4

Delft bottle on sleigh, DF_2

16 inches from the bottom, and remains there some 10 to 20 minutes. The water containing a certain amount of sand enters through the nozzle, the sand settles in the interior, and the water leaves the bottle at the rear. The slope of the apparatus is designed in such a way that the exterior figuration of the flow pattern around the nozzle is least disturbed. The quantity of sand caught is again measured in a measuring glass.

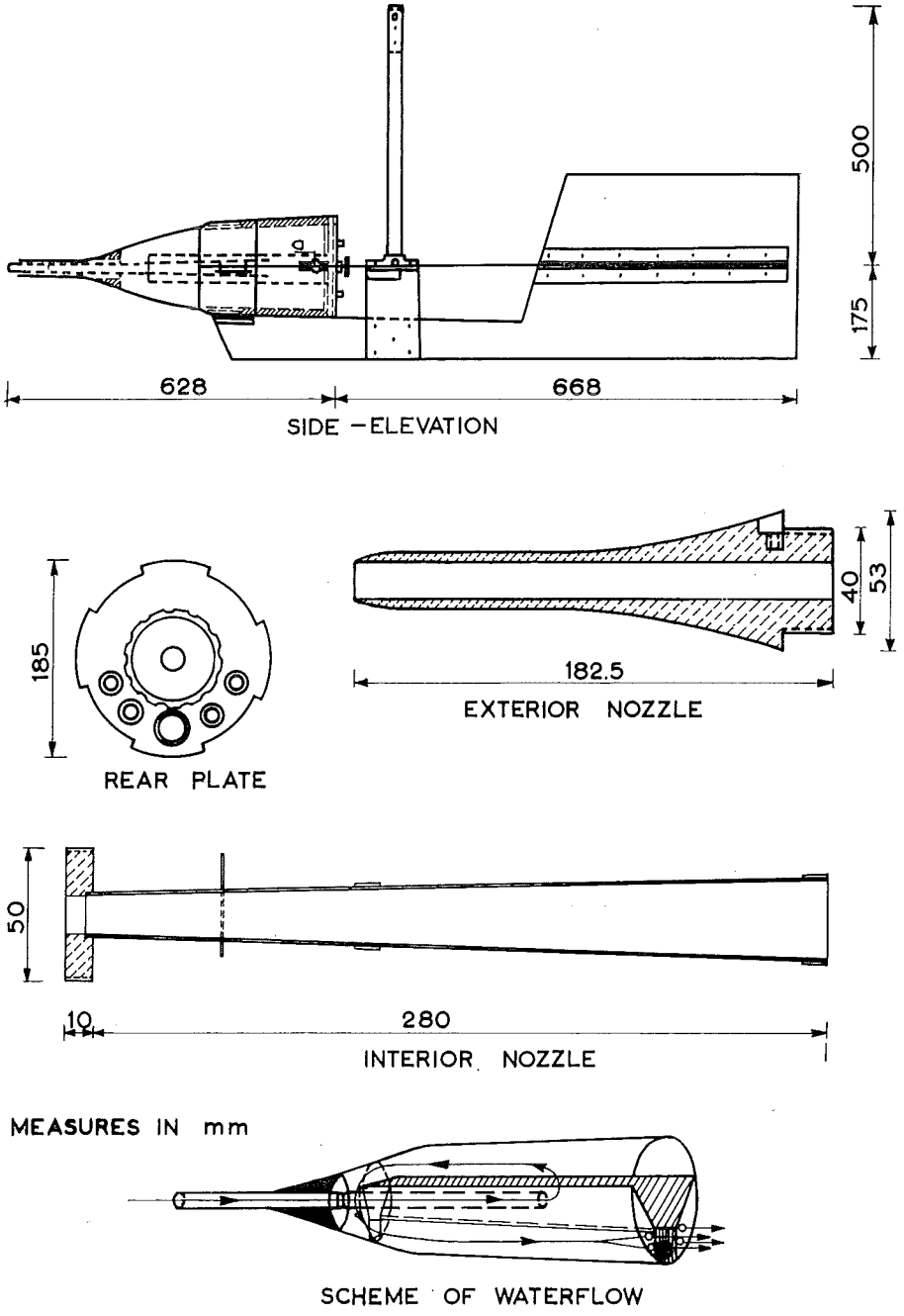


Diagram 3.5.3-5
Delft Bottle on wire, DF_1

c. *Suspended load* is measured by a similar instrument, the "Delft Bottle on wire", DF_1 (Diagram 3.5.3-5). Here the bottle without sleigh is hung at various depths, ranging from 16 inches from the bottom to the surface.

d. *Wash-load* is measured in an indirect way, compared with the above-mentioned types of sediment transport which are all observed directly as the quantity of sand passing per unit of time. This is not possible with regard to wash-load, as this very fine material does not settle quickly but remains in suspension. A sample of the water-silt mixture was taken with an ordinary bottle (see previous Paragraph) ([1] and further elaborated in the laboratory at Lokoja. Here, the mixture was poured into a special container and placed in a "turbidimeter". This instrument is based on the absorption of light by the silt particles in the water. Two rays from one single source of light are led through the instrument, one via the container with the mixture and the other via an adjustable diaphragm. By an ocular both rays can be compared and adjustment of the diaphragm should give them equal intensity. The position of the diaphragm is then a measure of the concentration of the silt in the water, after a calibration has been done.

By assuming that the silt particles travel at exactly the same speed as the water particles, the total transport of wash-load can then be computed.

3.5.4. Procedure of sand measurements

With the exception of wash-load, all types of sand-transport have been repeatedly measured in various cross-sections along the rivers by the following method. Each cross-section is first sounded, on the basis of which several positions are chosen for the sand measurements. The survey launch is then anchored with its survey deck as close as possible to the desired position, and the observations with B.T.M.A., DF_2 and DF_1 are commenced, one instrument being attached to each of the three davits.

PHOTOGRAPH 3.5.4-2

Measuring the captured volume of sand

Ten bed-load observations are taken, each time lowering the B.T.M.A. onto the river-bottom and leaving it there for two minutes. The amount of sand caught at every measurement is written on the appropriate place in the observation form (Diagram 3.5.4-1), and each such figure is

([1] The amount of suspended sand in a wash-load sample is negligible.

NEDECO NIGER and BENUE SURVEY — TRANSPORT OF SEDIMENTS — page 13 total 17 p.

Survey vessel WOODSPITE
Observer WA. OT/IK
Date 10.12.57
River NIGER
Gauge — fall / rise "

Crossection KECERE
Location L1-L3 36'00" L3-L5 67'14" L5-L7 12'05
L5. PORT 10'0"
S.B. 9'0"

DF Suspension & DF Saltation

Initial Time	Height above bottom	Depth below waterlevel	Period in min	Captured volume in cm³
1530		040	8	
		120	8	
		200	8	
		280	8	
		360	8	1.2
1609	34		10	0.6
1552	24		10	0.9
1535	14		10	1.4

REMARKS

TRANSPORT m³/m'/24 hrs per cm height	× D (cm)	TRANSPORT m³/m'/24 hrs per instrument
0.0011	Suspended load →	0.45
0.0023	saltation load →	0.023
0.0034		0.034
0.0053		0.053
	bed load →	2.67

× ϕ/t × 0,00063

VERTICAL: II

a b c d e f — D (cm) 400 — Suspended load
40 34 24 14 10 5 — D = 10 cm — Saltation load — bed load

TOTAL DEPTH: 440 cm

SAND-SAMPLES

	d10	d50	d90
DF1			
DF2			
BTMA			

Worked out:

rec.	OT	10.12.57
mir.	W.A	10.12.57
dir.	T.Z.	18.12.57

BTMA

No.	Period in min	Captured vol. in cm³	Captured vol. per 2 min	TRANSPORT m³/m'/24 hrs	REMARKS
1	2		195	1.95	
2	2		105	0.90	
3	2		15	0.13	
4	2		170	1.60	
5	2		185	1.80	
6	2		20	0.17	
7	2		25	0.21	
8	2		40	0.34	
9	2		495	7.40	
10	2		510	7.75	
11					
12					+ 15%
AVERAGE				2.325 + 0.348	

3.23 = TRANSPORT m³/m'/24 hrs in total vertical

DIAGRAM 3.5.4-1

Form for sand measurements

translated into an actually transported amount of sand by means of the table giving this relation (see 3.5.3.). The mean of these ten numbers is taken as the average quantity of sand-transport per unit width over a height of 2 inches from the bottom. An addition of 15 % to this amount is assumed to be the transported quantity over the height from 2 to 4 inches, which still belongs to the bed-load but which is not directly measured by the B.T.M.A.

The DF_2 is placed on the river-bottom three times, each for a period of 10—20 minutes and each at a different height, viz., at 6, 10 and 14 inches from the bottom respectively (Photograph 3.5.3-4). The transport per cm height can be determined by multiplying the amount of sand caught by $\frac{60}{t} \times 0.00063$, where t is the period in minutes during which the instrument remained on the bottom (see Diagram 3.5.4-1). As each observation concerns a height of 10 cm, the total transport is found by multiplication by 10.

The DF_1 is hung at various depths more or less evenly distributed over the vertical. The instrument is not hauled up between these observations, but only the total quantity of sand caught is measured and further elaborated, as shown in Diagram 3.5.4-1.

The entire measurements of all three types of transport in one vertical can be carried out in $\frac{3}{4}$ to $1\frac{1}{2}$ hours, depending on the depth, water velocity and possible difficulties encountered from various causes, such as floating debris, a strong wind that swings the survey launch over large distances in transversal direction, etc.

In this way, several verticals in the cross-section were measured, while a linear interpolation between these verticals was applied to arrive at a total figure for sand-transport over the full width.

With regard to wash-load, the procedure followed will be described under III, 5.3.2.

3.6. SOUNDINGS

3.6.1. Lead and pole

The most simple devices to determine the water depth in a point are the lead-line and the pole, the former having the advantage over the latter in that it can be used in great water depths if necessary. It consists of a line and a piece of lead, which helps to sink the line quickly and allows the observer to tauten the line when this is in a vertical position without lifting the lead from the bottom. The line is divided into length units, such as feet or fathoms, which are indicated by knots, coloured material or leather strips from which the observer reads the water depth.

The lead can be thrown over a limited distance in front of the sailing ship, and must be allowed to sink to the bottom, the time depending on the water-depth. Maximum time can be gained by throwing the lead as far as possible forward, by walking back along the deck of the ship, and by reducing the ship's speed. At sea, where sometimes very large depths must be measured, special precautions must be taken to be sure of a vertical line, and the ship may even have to stop for measurements to be made.

On the Niger and Benue, the lead-line is normally used in the ordinary navigation, and needs not be much longer than 15 to 20 feet. The lead is approximately 8 inches long and 2 inches square. The general practice is to start the zero of the line at the top of the lead, which means that the actual water depth may be 8 inches more than the readings and this is then taken as an allowance for the ship's clearance. A small hole is often made in the bottom of the lead so that an indication of the soil composition can be gained from the bed material that is, or is not, caught up.

For survey purposes the lead-line is often not accurate enough. In the absence of an echo-sounder, or when such an apparatus fails, the use of a lead-line has the following imperfections:

(i) the vertical positions of the line in running water and on a moving vessel is sometimes difficult to guess;

(ii) the observer is not always certain of the position of the oblong lead, horizontal or vertical, and should know the zero mark of the lead-line at the top or the bottom of the lead, whilst the extent of penetration in the bottom is also uncertain; and

(iii) the rope which is used is inclined to shrink or stretch, dependent on its wetness, so it is normal practice to use survey lead-lines with a flexible steel core and to wet them before use, although even then a regular check of the lengths is necessary.

Particularly in shallow waters the accumulation of the possible errors may lead to unacceptable inaccuracy in proportion to the measured depth. Experience has shown that even when taking all possible precautions, the readings in water depths of 4 to 8 feet may still be accurate only to within 3—6 inches, while at greater depth errors of 1 to 2 feet must be accepted.

In shallow water, therefore, the use of a pole has advantages. There is no shrinking or stretching, the pole itself is straight, and the penetration of the bottom can be largely prevented by a flat plate at the end of the pole. The accuracy of the readings is between 1 and 3 inches.

Lead-line and pole soundings both have the disadvantage that they show discontinuous depths along the sailing route, so that a minimum or maximum in the depth may easily be missed in the successive point-measurements. Further, survey-measurements require at least one man more than when use is made of an echo-sounder (see next paragraph), which records automatically and continuously. However, water-depth of less than 4 feet can practically only be measured by pole or lead-line, as a motor dinghy has too much draught. In such circumstances a canoe or rowing-dinghy can be used.

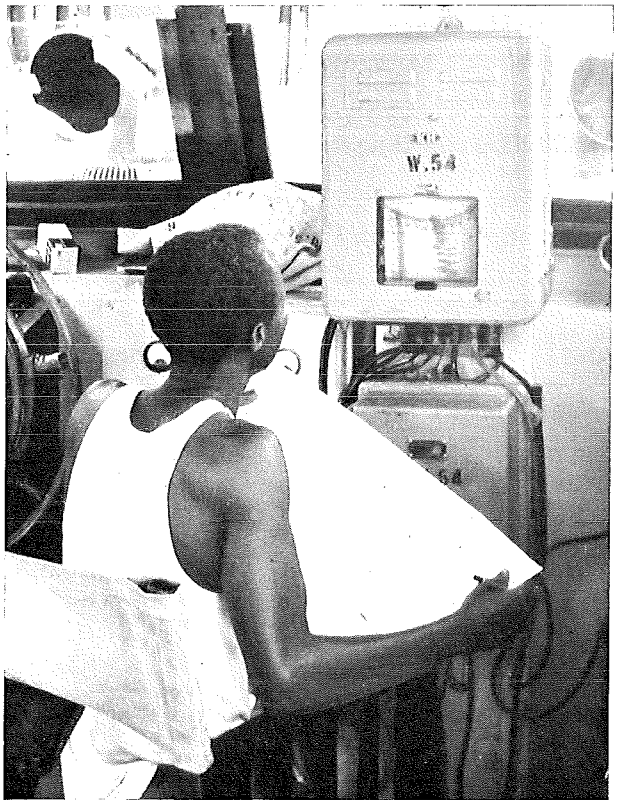
3.6.2. Echo-sounding apparatus

The principle of an echo-sounder makes use of the propagation speed of sound in water. At very short time intervals sound-impulses are transmitted from a ship which are reflected from the bottom and received back on the ship as an echo. The time interval between transmission and reception of an impulse is the measure of the depth. Each sound-impulse is recorded as a depth, so that an almost continuous bottom profile can be sounded (the echo-sounders in use during the Investigation transmitted 500 sound-impulses per minute).

There are various types of echo-sounders and the technical details, which are for the greater part of a mechanical and electronic nature, can be obtained from the makers' handbooks. Even small repairs need a thorough knowledge of the instrument, which is a disadvantage. During the investigation a version of Kelvin and Hughes type MS 26 was used. This instrument records the depth along a circle segment (see Photograph 3.6.2-1). By making a short-cut in the electric system, it is possible to record black lines (plots) on the recording paper. In this way the records can later be related to the position of the vessel.

As accuracy of depth is most important for the surveyor, several factors are essential. The instrument must be regularly set and checked properly; the actual depth below the water surface of built-in oscillators should be known (which can be easily measured when an outboard shoe for the oscillators is used); and a constant voltage is necessary to prevent a decline in speed and recording of the instrument. The propagation speed of a sound-wave in water is dependent on the water temperature and although the divergences per degree of change are only very small, the total error can become important when sounding in deep water. The propagation speed of sound in water is also proportionally related to the density of the water, but the instrument can be regulated to the circumstance of temperature and density.

When measuring shallow water it is important to note that the horizontal distance between the receiving and transmitting oscillator can then play a not negligible role in the depth-recording. Where outboard oscillators are used, this distance is only small, but in the N-class survey launches as in use by I.W.D. this distance is approximately 2 feet. At a water depth of 4 to 5 feet, with the oscillators 1'6" below the water surface, the error is 2".



PHOTOGRAPH 3.6.2-1
Echo-sounder

The penetration of the sound-wave into the moving upper layers of the bottom is not exactly known, but it is believed, however, that the error is negligible as it will probably not reach more than a quarter of an inch. Cavitation in the oscillators, experienced more with built-in than with outboard oscillators, will prevent a depth-recording, as some of the sound-waves go directly from the transmitter oscillator into the receiving oscillator without reaching the bottom.

Finally it may be remarked that the position of the oscillator in relation to the water surface when the survey vessel is in motion is not exactly known. Squatting of the vessel in shallow water can be a few inches.

When great care is taken, the echo-sounder for survey purposes will give recordings with an accuracy of 6 inches in shallow water and up to 1 foot in deep water, i.e., it is more accurate than a lead-line and less accurate than a pole in shallow water.

3.6.3. The procedure

There are several methods of recording the soundings on charts, all based upon positioning with the aid of fixed points. Preferably two or more points should be permanently recognisable, so that successive charts of the same area can be related in the field. In Nigeria along the rivers

this is not always possible without erecting permanent beacons, but the slowly-eroding bank lines can for many years serve as a guide.

The difficulties in river mapping encountered under the circumstances in Nigeria can be briefly summarised thus:

(i) the mutual visibility and the visibility of beacons from the river were difficult as a result of the high overgrowth on the banks and the great distances, and called for the local removal of overgrowth and large beacons; and

(ii) readings of the beacons with the rangefinder and the sextant became inaccurate and difficult at distances of over half a mile and two miles respectively.

While preparing soundings these special difficulties had to be taken into account and in principle two systems have been used, the choice at any one time depending on the results which could be obtained with the least efforts.

The first method uses the *rangefinder* for the positioning on the river in a system of straight lines, which must first be set out and mapped. The density of the network of straight lines can be chosen according to the circumstances; in general, a mutual distance between sounding-lines of 250 to 500 feet was considered sufficient for the Niger and Benue maps, which had to be drawn on relatively small scales. There are many methods of mapping the network, but most of them need much time. A speedy, simple and still sufficiently accurate method proved to be the setting out of a base-line of beacons along the one bank (beacons A in Diagram 3.6.3-1) of which the mutual position was measured by rangefinder and compass. The line which crossed

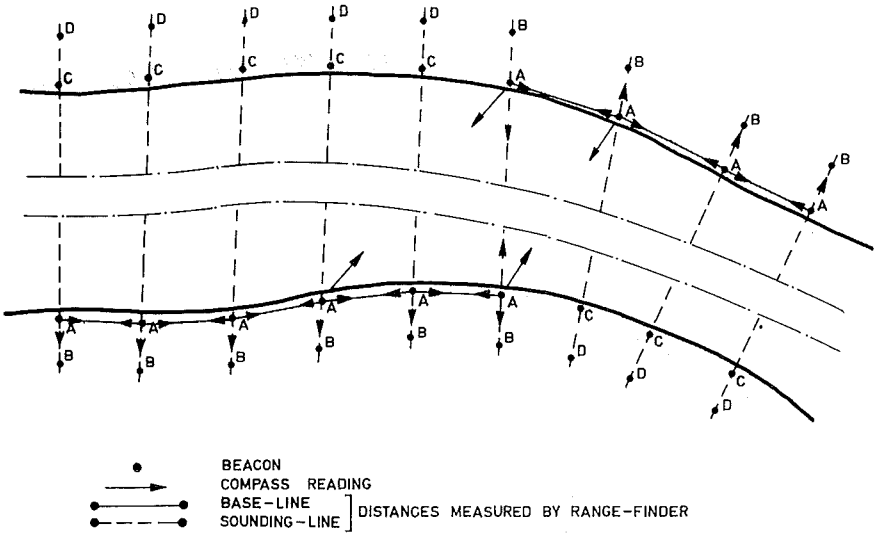


DIAGRAM 3.6.3-1

Sounding with the system of straight lines

the river practically at right angles could then be determined by compass and set out (points B in the Diagram) and the network of lines then be directly drawn. This system has the advantage that the group responsible for setting out the network can remain on one side of the river and need only to switch to the other bank when the conditions for setting out the base-line (mainly dependent on the extent of overgrowth and mutual visibilities of successive beacons) are more favourable there. When the river-width is over half a mile or when visibility is poor (harmattan), another beacon C can be erected in line with A and B by use of binoculars. To simplify the

sailing of the run along the straight line the erection of beacons D may help the helmsman, although an experienced quartermaster will be able to do without this beacon D and to fix by eye a point in the field which he uses as a guide.

When a compass cannot be used because of magnetic influences (such as in the neighbourhood of Lokoja where iron ore is present) a sextant or other survey instrument can be used to determine the mutual angles between the beacons. However, in such circumstances the speedy setting out of the network can be considerably slowed down.

The second method of positioning on the river is based on the method of *backward incision* (the Snellius method). Two angles taken in a point X suffice to fix the position of that point in a system of base-points (angles α and β and basepoints A, B and C in Diagram 3.6.3-2), for instance, by means of a station pointer. This instrument consists of three rulers radiating from one centre into variable directions. After setting the appropriate angles enclosed in between the rulers, the instrument can be shifted over the chart till all three base-points coincide with the three rulers, and the position X is then marked in the centre.

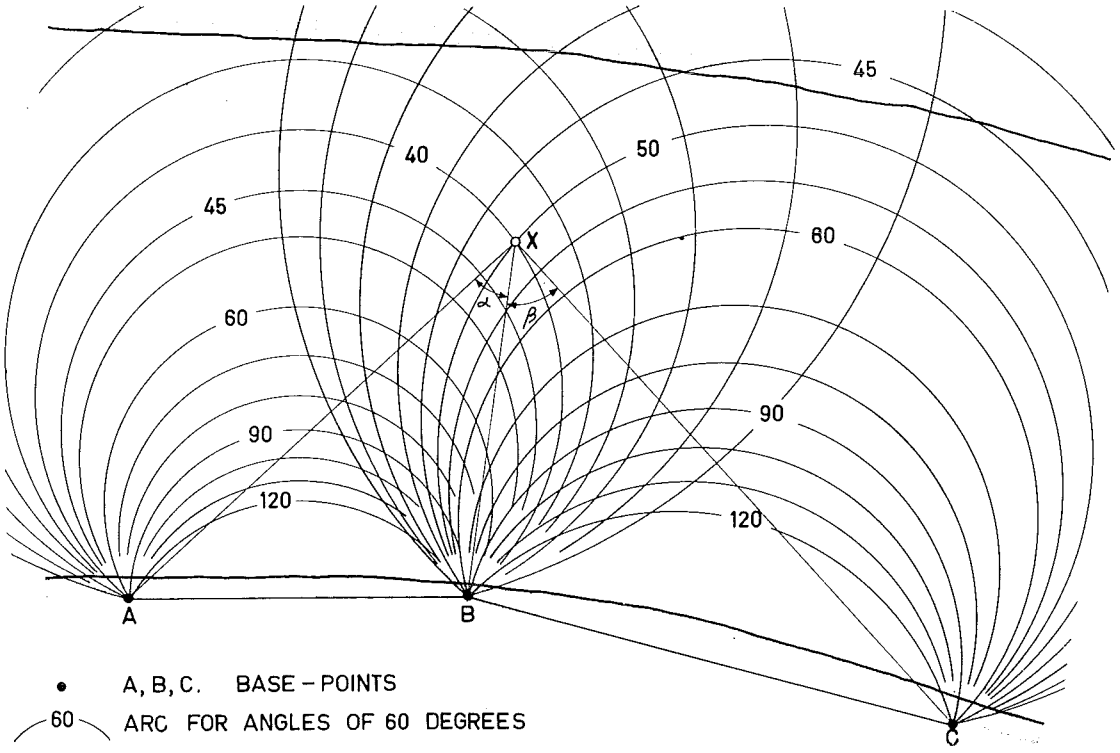


DIAGRAM II, 3.6.3-2

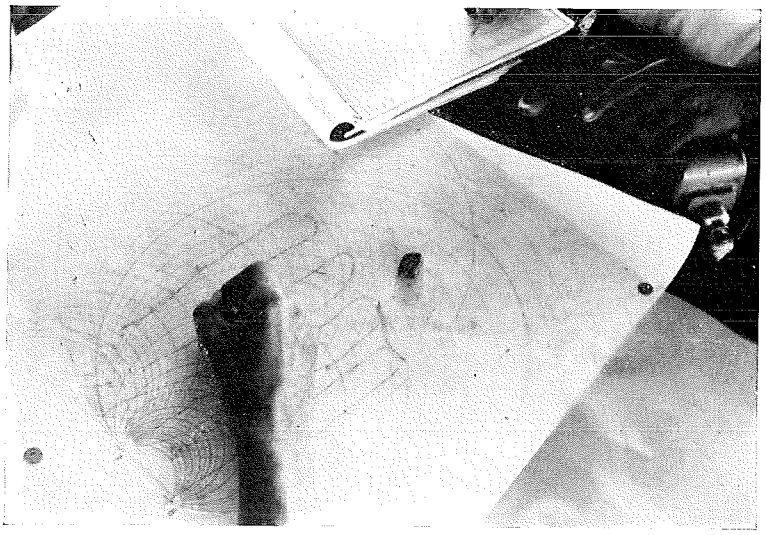
Circle chart on three base-points

The base-points must be mapped, for which a terrestrial survey is necessary. When the distance between two base-points is measured, the whole system of base-points can be mapped when sufficient angles are taken in triangles formed by the base-points. Taking angles in a point is normally much easier than taking distances between two base-points and gives a greater accuracy. It is often easiest to measure the one distance necessary to obtain a scale for the map on a sand-bank between two auxiliary points.

To simplify the plotting of many points during or after the observation, a circle chart is constructed, each circle representing the geometric system of points which form the same angle with two base-points (points A and B; B and C in Diagram 3.6.3-2). A circle chart is much easier than a station-pointer when a great number of points must be plotted, as handling of a station-pointer takes much time. In this way, too, plotting can even be carried out during the sounding, which would be impossible with a station-pointer. On the survey vessels angles are taken at regular intervals and plotted with the aid of the circle chart. As an example, the position X with angles of 40 and 50 degrees is indicated in the Diagram.

To keep the maps as accurate as possible, plots of positions with two circles intersecting each other at too small angles (20 degrees or lower) should be avoided.

In general, several sets of circle charts are necessary, as the intersection of the circles in the charts is normally only favourable over 1—1½ times the average distance between the base-points and the half of the river which lies opposite the bank where the base-points are situated. It is, therefore, necessary to construct for each half of the river a set of circle charts overlapping each other sufficiently to permit a continuous measurement.



PHOTOGRAPH 3.6.3-3
Plotting the course of vessel

The advantages and disadvantages of the two systems are:

(i) The beacon system allows the drawing of clear maps in which the depths are recorded along straight lines. However, it asks for more skill of the quartermaster to steer straight lines than when sounding by the second method.

(ii) With the aid of circle charts for positioning, the number of base-points used for circle charts is smaller and can be more freely chosen in the field than the beacons for a network of straight lines. The base-points can therefore be marked points in the field which need not necessarily lie on the bank and the visibility of which can be improved if necessary (such as by paint or flags). In sounding, the runs of the vessel are not bound to a strict pattern and a less experienced quartermaster can handle the survey-vessel.

The beacons for a network of straight lines must all be positioned and therefore be light and stand as much in the foreground as possible to make them visible on the river and to reduce the cutting of overgrowth.

(iii) The first method asks for more field work but allows quick and clear mapping. The beacons were often stolen or eroded, however, and a more permanent life of such beacons could not in the circumstances of the investigation be made efficient. When this changes and a network of straight lines can be used several times, this method will in many instances have preference. However, when using marked points in the field as base-points (in most instances trees), these points can normally be used several times, a circumstance which made it efficient to construct the circle charts. Of great importance is that circle charts allow the plotting of the course of the survey-vessel at the moment of sounding (see Photograph 3.6.3-3), so that maps of the surveyed area can be ready, if necessary, shortly after the sounding has been taken. This would be also possible with a network of straight lines when the beacons for such a network could be used several times.

3.7. SUB-SOIL INVESTIGATION ([1]

3.7.1. General

Sub-soil investigation is an essential part of the preparation of civil-engineering constructions. The object is to assess the lay-out and suitability of the sites for adequate and economical foundations of the proposed engineering works insofar as they are connected with the sub-soil conditions. Knowledge of the sub-soil conditions may also help the investigator in a better understanding of the natural characteristics he observes and to forecast further development.

To obtain samples below ground-surface, borings are necessary. The boring equipment used during the Investigation is described below.

Boreholes are sunk into the ground and samples taken at intervals of depth, and on which laboratory tests are carried out to obtain the wanted data. In some circumstances it is not possible to obtain undisturbed samples and in such cases the judgment of the soils is often restricted to in-situ field-test from what is brought up from the boreholes. Marine site investigations present special problems because of the need to conduct the investigation over water. If the boreholes are required only to determine dredging conditions, they need only be sunk a little deeper than the final dredging level and laboratory tests may not be necessary.

The kind of boring tool used depends on the data wanted, the depths from which the samples are required, and the expected soil conditions. When the soils are cohesive or in rock, no casings are required, but in most instances when boreholes have to be deeper than just a thin upper layer, the variety of soils through which it passes is great. If in such circumstances no casings were used, great chances would exist that the sides of the holes would collapse and that the boring tools could not be driven deeper or would even jam. Moreover, there is no guarantee that the samples would be representative for the depths. NEDECO experienced such difficulties in its investigation of the Dasin Hausa dam-site, even though great care was taken.

3.7.2. The boring equipment

a. *Hand-auger*

This type of instrument with the boring tool at the end of a rod is manually rotated and raised and lowered continuously. For sand and gravel the boring tool is a heavy metal cylinder

([1] Some aspects of borings discussed here have been derived from "Dock and Harbour Authority", Sept. 1958.

with cutting edge and flap valve. In clays a double spoon-shaped tool is used. By means of extension rods a depth of 10—15 feet can be reached, dependent on soil conditions. This soft ground boring equipment is used in soil exploration on the surface and normally only bag samples are taken. No casings are used.

b. *Water-jet*

The water-jet has been used to find the depth of rock below the river-bed near Lokoja (see III, 6.5.8). For dredging schemes in the rocky areas of the river jetted probings are also very useful. A great advantage of the use of a water-jet is that hard stratum can be rapidly indicated over large areas.

Jetted probings are made by applying a high pressure water-jet through a 2-inch diameter pipe and washing away the soil beneath and around the lower end of the pipe. As the soil is washed away the pipe is allowed to follow and penetration continues until the hard stratum is reached.

No samples are taken, but during penetration an experienced operator can tell the difference in the consistency of the soil being penetrated by the "feel" of the pipe when it is worked up and down. It is sometimes necessary to increase the water pressure and this can also be a measure of the consistency of the soil.

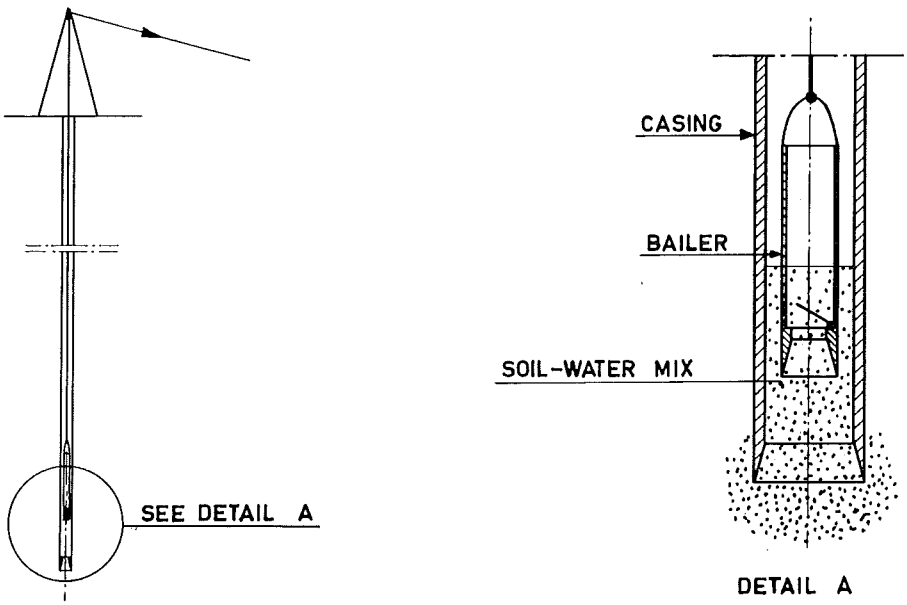


DIAGRAM 3.7.2-1

Principle of bailer borehole

c. *Banka boring equipment*

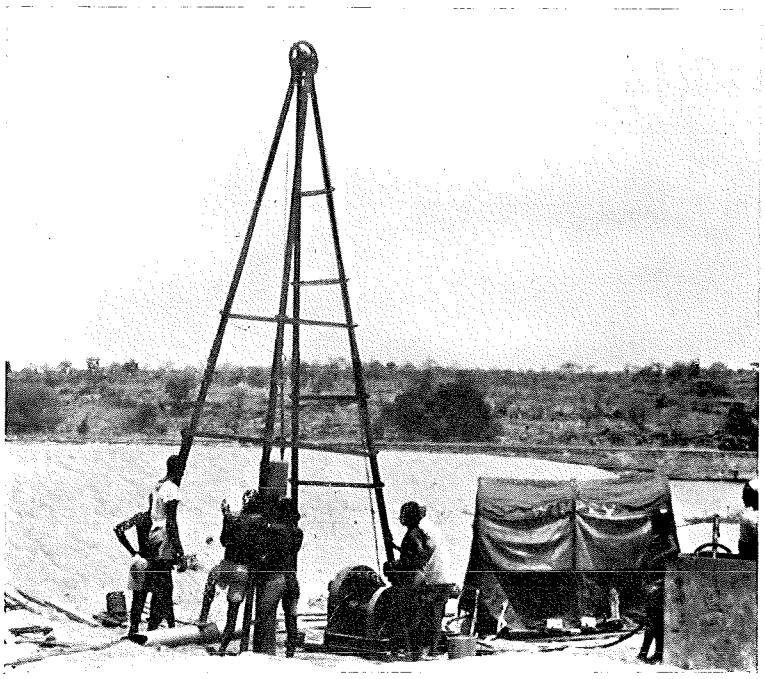
The Banka boring equipment in use during the Investigation is a type of bailer. This soft ground boring equipment can only be used in sand and sandy clays with only little cohesion. A casing is necessary to prevent the collapse of the sides in the boreholes. A bailer is continuously moved up and down into the bottom of the hole, where it fills with a soil-water mix (see Diagram 3.7.2-1). The presence of water is essential. Normally this will be ground-water which will press up in the borehole and cause a negative water-pressure which decreases the cohesion

of the soil. A valve in the bailer prevents the soil-water mix running out of it when it is heaved. The casing follows the borehole which normally happens without much efforts. When the borehole has proceeded to a depth where a sample should be taken, the bailer is removed and a sampler is put into the hole after it has been cleaned out. With the Banka boring equipment manually or mechanically-driven holes upto 100—300 feet can be made.

The sampler is a thin-walled tube which is carried on a rod into the borehole and is continuously and rapidly inserted into the sampled soil. A valve (or a rubber ball) closes the space above the sample when it is drawn and the under-pressure prevents the sample from falling out of the thin-walled tube.

d. *Rock core drill*

A core drill is a hard formation boring equipment. Special coring bits containing industrial diamonds are rotated into the rock, and some types used give a very quick advance in making the bore. Outlets on the bits permit water to be pumped to the bottom of the hole to wash the churned material to the surface. If necessary casings are brought in when the drill penetrates soft or crumbling layers. The equipment is mechanised (Photograph 3.7.2-2) and with the heavier ones depths of over 10,000 feet can be reached.



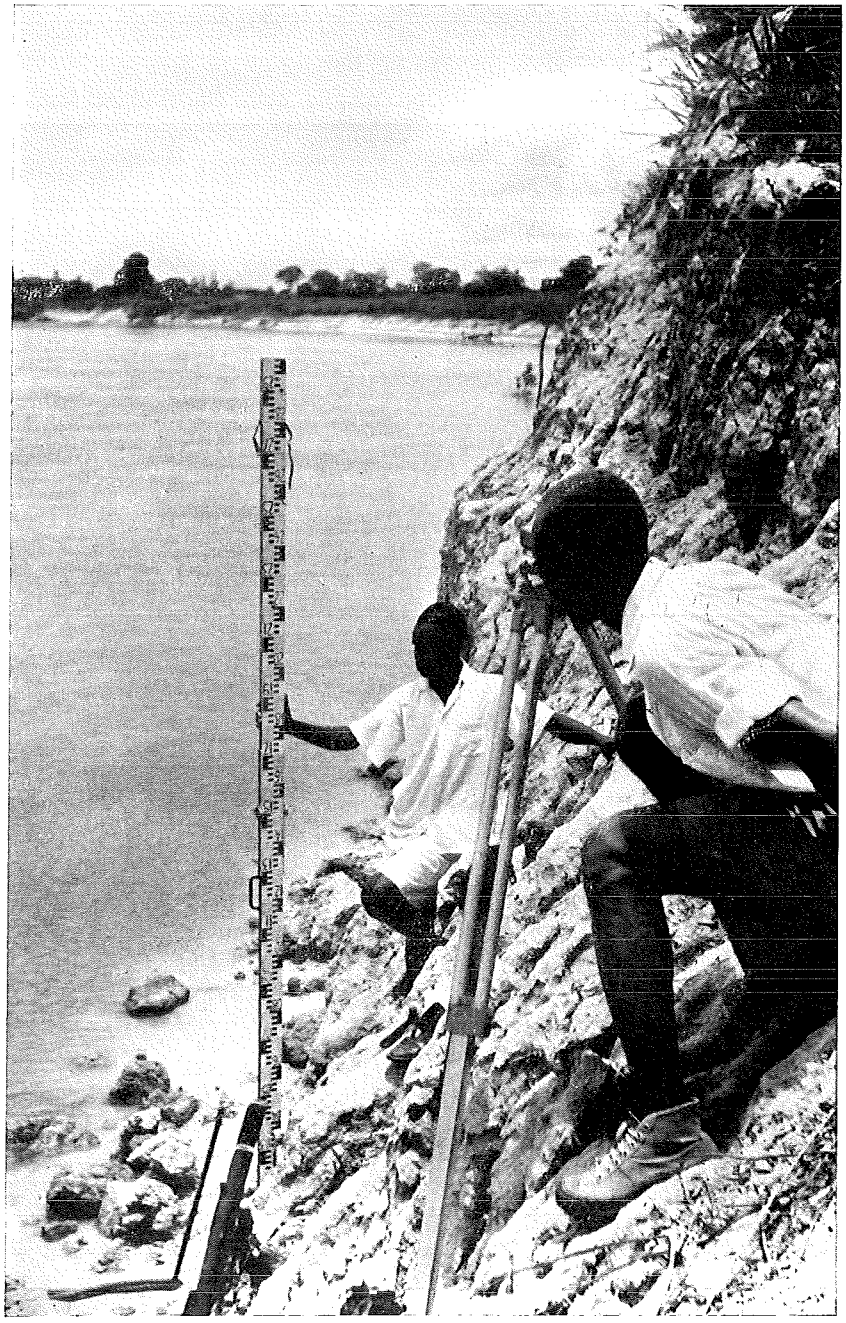
PHOTOGRAPH 3.7.2-2
Core drill at work near Dasin Hausa

When a core must be drawn, a special bit is used which chips outside as well as inside. The cylindrical sample thus formed is held by the core catchers and finally the sample is sheared off at the bottom by turning it. From the recovery, i.e., the percentage to which the sampler is filled from the total penetration, some information about the soil can at once be gained, whilst the core samples can also be tested further at the laboratory.

3.8. TERRESTRIAL SURVEY

3.8.1. Levelling instruments

Levelling instruments are mainly used for the determination of heights (Photograph 3.8.1-1), but when they are fitted with a horizontal scale angles can also be measured. For the determination of heights it is necessary to know the direction of the vertical in each point. When a restricted accuracy suffices a plummet can be used, but more accuracy is obtained with a liquid surface. Both are combined in a level, which is a glass tube cut cylindrically and filled with fluid except for a small vapour bubble. The tangent in the highest point of this bubble is always



PHOTOGRAPH 3.8.1-1
Levelling of a gauge

horizontal, and the instrument is so constructed that the line of sight can always be brought parallel to this horizontal tangent. In this way it is possible to level the height difference between two points with the aid of a staff. Diagram 3.8.1-2 shows schematically how the height difference H between points A and B is measured. The readings on the staff, x and y, allow directly the relation: $H = x - y$.

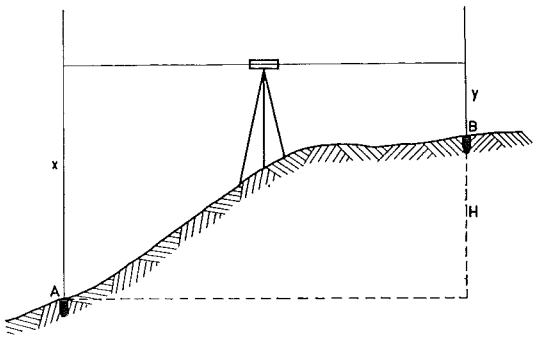


DIAGRAM 3.8.1-2
Principle of leveling

Various types of levelling instruments have been used during the Investigation, the differences between them mainly lying in the accuracy which can be reached. Very precise instruments were used for the levelling of benchmarks along the rivers in relation to Mean Sea Level, which was carried out by the Federal Survey Department. Such precision instruments also had to be used when measuring the slope of the water surface in the river, as only small differences in height over large distances had to be recorded. Very often the relation between the zero mark of the gauges had to be checked on the benchmarks, but for this a less accurate instrument could be used as normally large differences in height over short distances had to be measured.

For the technical details of the various instruments reference should be made to the respective manuals.

3.8.2. The rangefinder

The rangefinder used during the Investigation was of the coincidence type (Photograph 3.8.2-1). These instruments have a base-length in the position of the observer and no extra man is necessary at the point to which the distance will be determined.

In Diagram 3.8.2-2 *b* is the base-length and D the distance to be measured. The ray of light through the left end of the base *b* to the point P is always at right angles to the base, while the angle δ is measured with the aid of optic instruments on the right side. S_1 and S_2 are mirrors or prisms through which the light rays are brought together. The object-glasses O_1 and O_2 form an image in plane *p*. When all the mirrors have an angle of 45° to the base-line, the views of P through the left and right rays of light will be shifted in the plane, and this shifting of the two images is a measure of the distance. With the aid of a double prism the shifted images can be made to coincide and the rate of distortion of the double prisms to reach this is made directly readable on a distance scale.

The accuracy of the instrument depends on the base-length *b*, and for the instruments used this amounted to 80 cm (2 feet $7\frac{1}{2}$ in), which resulted in an accuracy that was sufficient for the purpose. At a distance of 500 feet the error is less than 1 %, but for distances of over half a mile it should not be used for accurate mapping.

PHOTOGRAPH 3.8.2-1
Rangefinder in operation

3.8.3. The sextant

The sextant (see Photograph 3.8.3-1) is a special kind of angle mirror of which one mirror is movable. As the angle between the two mirrors can be changed and can be read from a scale, this instrument is suitable for angle measurements. The coincidence of a direct view of one point

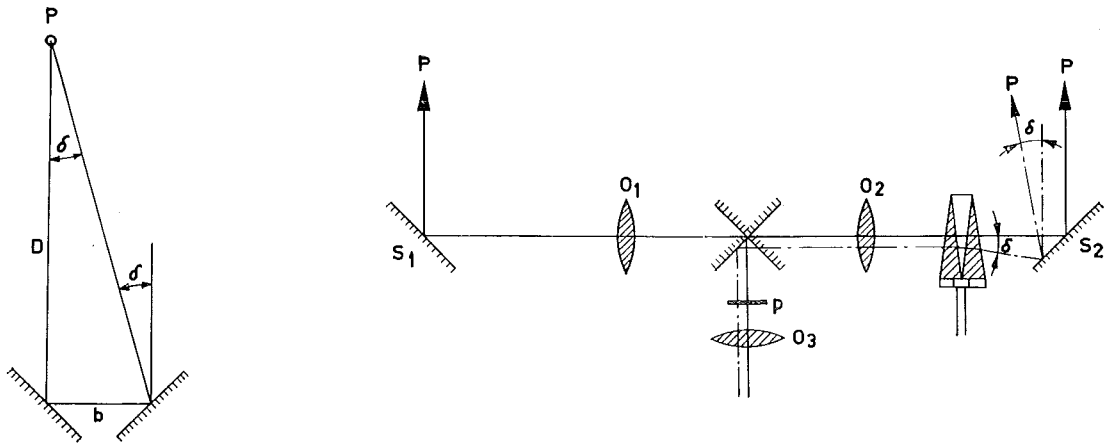
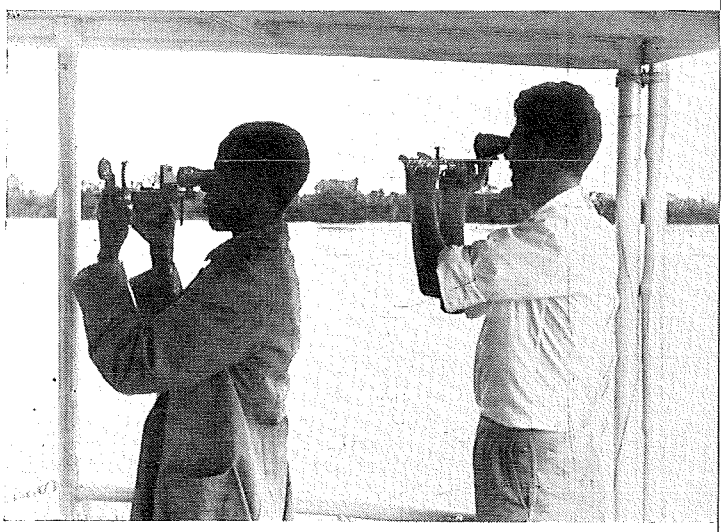


DIAGRAM 3.8.2-2
Principle of the rangefinder



PHOTOGRAPH 3.8.3-1
Shooting angles with sextants

and a twice-reflected view of another point must be obtained. Diagram 3.8.3-2 graphically explains how the angle φ is measured. The circular scale is connected with the centre of the circle. A small mirror K is fixed and a larger mirror G revolves round a vertical axis through the centre of the circle. The telescope only serves to enlarge and clarify the view. The centre line of the telescope intersects the upper rim of the small mirror, so that in the upper half of the telescope the direct view of point L is obtained, while in the lower half the twice reflected view of R can be seen. When these views coincide, the angle φ can be read on the scale upto half a minute accuracy with the aid of a vernier.

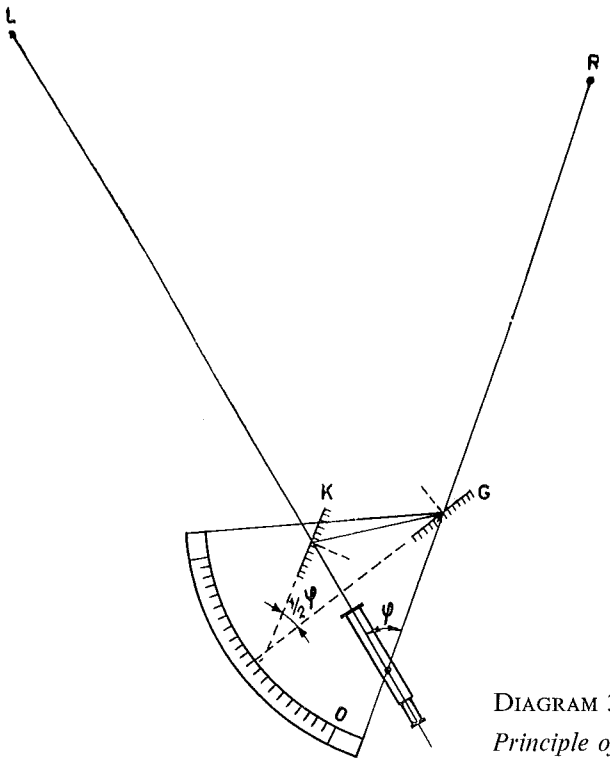
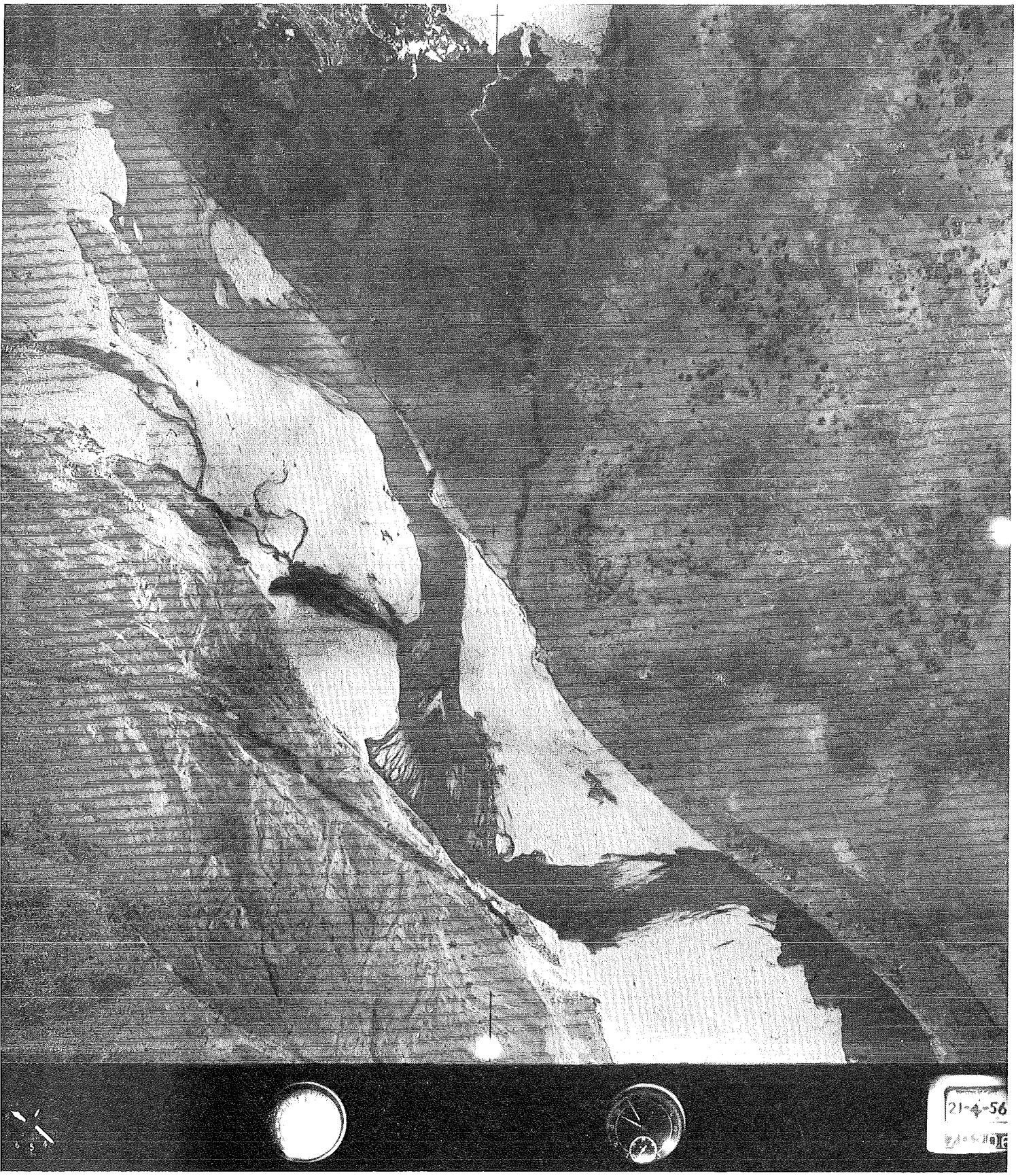


DIAGRAM 3.8.3-2
Principle of a sextant



PHOTOGRAPHS 3.9.1-2
Aerial photograph of the Benue near Ribadu, Mile 907

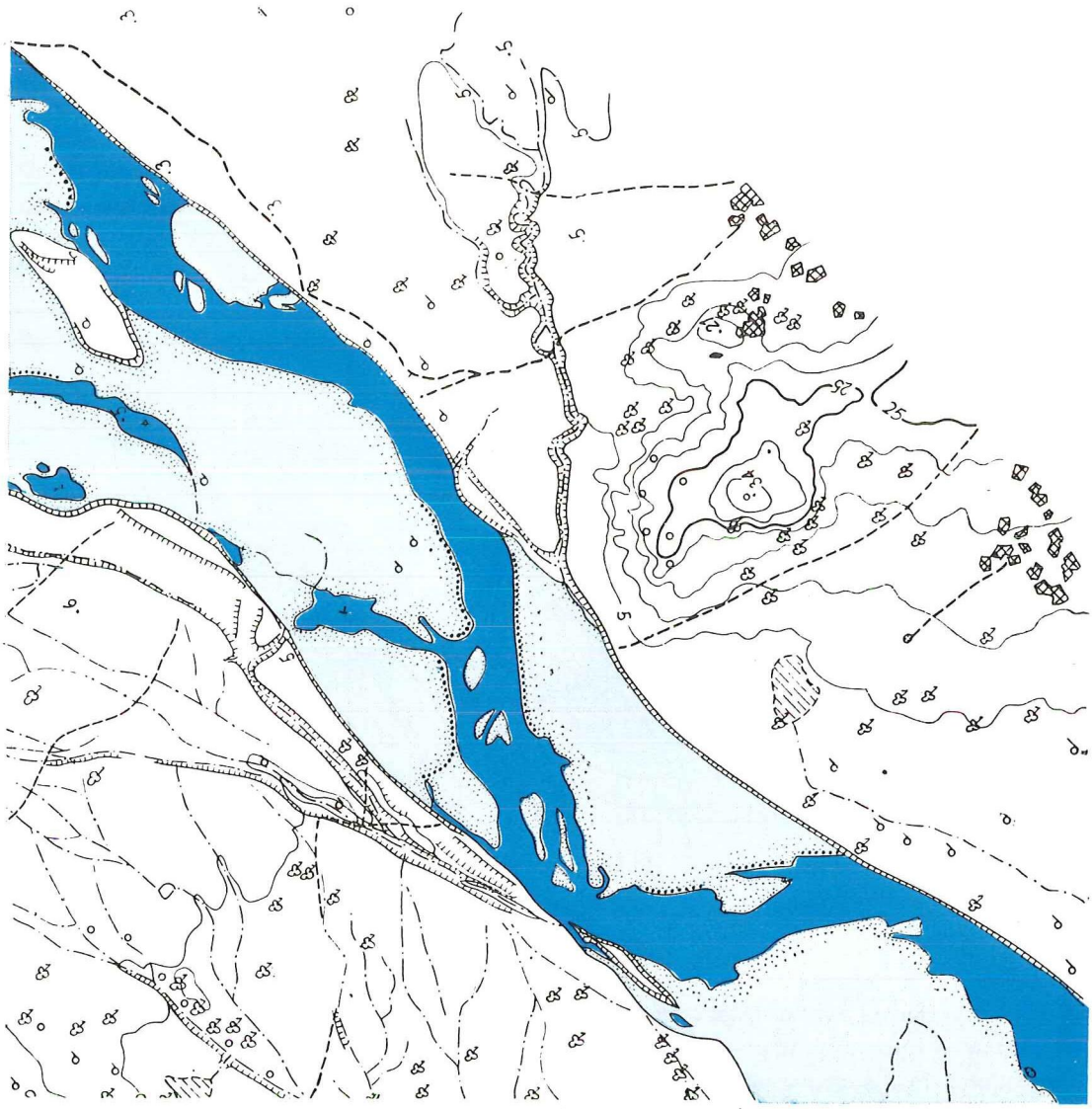


DIAGRAM 3.9.1-3

Map constructed from air photograph

3.9. MAPPING

3.9.1. Aerial photography and plotting

Aerial photography has a wide range of applications.

In the first place it should be mentioned that photographs can be the basis for topographical maps with or without contour-lines. Especially in unexplored areas does the use of photographs and maps therefrom facilitate the preparation of all kinds of engineering and land-development works. A second application is the study of the geological structure of such areas.

The aerial photography of the Rivers Niger and Benue and the adjacent areas has, therefore, also been of great importance for NEDECO in its investigation of these rivers. It is, in fact, not wrong to say that such an investigation would have been hardly possible without the help of aerial photography.

Without going into details, the main principle of aerial photography may be discussed. From a plane photographs are taken over the area in such a way that two consecutive photographs overlap one another by 60 to 70% (see Diagram 3.9.1-1). In the time interval between two shots

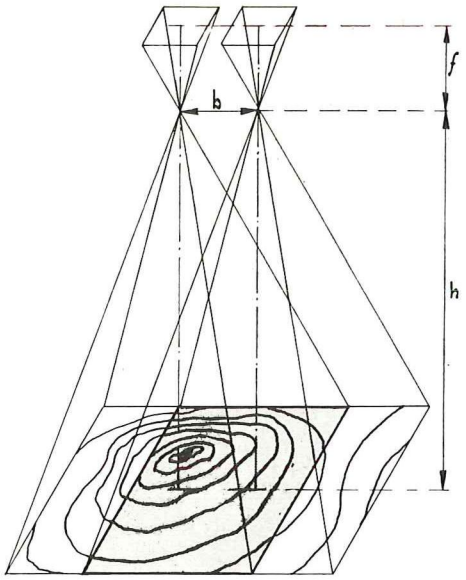


DIAGRAM 3.9.1-1

Scheme of approximately vertical photograph readings

the plane has moved over a distance *b* and the overlapping areas are thus photographed from two angles. In this way a three-dimensional view can be obtained when the course of the rays is reproduced in a stereoscopic mapping instrument or autograph. It is then possible to scan this spatial view with a measuring mark optically brought in the view and mechanically connected with a pencil on the drawing-board, where an orthogonal projection of the spatial view is then obtained. Photograph 3.9.1-2 gives an example of an aerial photograph and Diagram 3.9.1-3 shows the result of mapping.

It is normal practice in aerial photography to keep the optical axis of the camera as vertical as possible. In that way photographs have the same scale over the whole area and even without plotting already resemble a map. Moreover, the plotting, if necessary, is much simpler when the optical axis is practically vertical. The scale of the photographs is approximately equal to the flight height *h* divided by the focal distance *f* (see Diagram 3.9.1-1). Slight variations in height of the plane and of the vertical position of the camera axis can be relatively easily eliminated in the mapping instrument.

For accurate mapping a terrestrial survey is also necessary. By means of ground control terrain heights and positions of marked points are obtained and related with the corresponding points in the photographs. In this way scale differences and changes in scale over one photograph as a result of flight height difference and non-vertical axis can be completely eliminated.

Aerial photography of the Niger and Benue was carried out in 1954, and river maps were constructed in a scale of 1 in 20,000. This process was done without the aid of ground control, as the object was primarily to acquire reliable topographical maps that showed the relative positions of channels and creeks, sand-banks, islands, roads and villages (see Diagram 3.9.1-3). Still, it proved possible to indicate the heights of the banks and islands in relation to the low water-level at the time of photography. These heights were shown either as spot-levels or were applicable as contour-lines at 5-metre intervals.

During the further observations of NEDECO it was discovered that the existing maps of the Rivers Niger and Benue showed considerable variations in scale. These maps were made directly from the photographs flown in 1954 and the scale was obtained by the ratio of flight height and focal distance. Ground control was not considered essential and would have been costly. Probably as a result of varying atmospherical conditions from place to place during the photo flights, and also as a result of great variations from the vertical position of the camera axis due to the winding course which had to be flown to follow the Niger and Benue, these photographs and maps of 1954 did not by themselves prove reliable as regards to scale ([1]. This resulted in a marked difference between the river-lengths stated by NEDECO and those by the United Africa Company (U.A.C.) and also locally in differences between distances as measured on maps and as observed during soundings. To obviate this, NEDECO carried out a provisional ground control before a new series of aerial photographs was taken in December 1956. The data of this ground control have been used in the working-out of new maps and at present the river-lengths according to the new maps correspond much better with the river-lengths as stated by U.A.C.

([1] Differences of up to 10% have been found.

CHAPTER 4

DATA FROM GOVERNMENT AGENCIES

4.1. MAPS

4.1.1. Geographical and hydrological maps

The catalogue of maps ([1] published by the Director of Federal Surveys mentions the geographical maps which are obtainable from the Survey Department Offices at Lagos, Kaduna, Jos, Enugu and Ibadan and from various Agencies in Nigeria and in London. There are index maps on scales 1 to 2, 3, 5 and 12 million showing available sheets on scales varying from 1 : 62,500 to 1 : 500,000.

The production of topographical maps of the required accuracy for different, mostly technical, purposes has made tremendous progress since World War II, due to an extended air photography by the Royal Air Force as is shown on an Air Coverage diagram. The maps produced in Nigeria from aerial photography do not, however, show contour-lines or other heights, as no ground-control has been provided. Striking relief features are indicated by form-lines. Maps of the Niger Delta area have been produced from special aerial photography carried out on behalf of the Shell-B.P. Petroleum Development Company of Nigeria.

From the extensive exploration work in the period from 1854 to 1914 (See III, 1.1.2), some hydrographical maps exist, namely the Admiralty Charts, most of them showing the coastal and lagoon areas. Those regarding the Rivers Niger and Benue will be described in the next paragraph.

The only hydrological map of the River Niger was published by Dr. K. NIEHOFF ([2] in 1917. This map is considered to be of historic value and is therefore reproduced in Diagram 4.1.1-1.

4.1.2. River Charts

As will be described in III, 1.1.2, the River Niger and later the River Benue have played the principal parts in the discovery and exploration of Nigeria. That is why the oldest charts of the Nigerian country are river-charts of which the following are worth recording here:

In the "Geographical Illustrations" published as an appendix to Mungo Park's "Journal" the geographer Major J. Rennel produced in 1799 a map of a part of the Niger near Segou, which is, in fact, the first map of the river based on reconnaissance by Mungo Park.

In 1854 Daniel John May, R.N., the hydrographical assistant of Dr. Baikie, produced river maps of the Niger and the Benue Rivers. These maps still serve as a basis for the Admiralty Charts of those rivers.

([1] FEDERAL SURVEY, 1957. GEN. 11
([2] NIEHOFF, 1917. GEO. 32

The map, "The Rivers Niger and Benue showing the territories of the Royal Niger Company" of 1889, shows only very simply the course of the rivers.

The map of the Marine Department in 1907 shows, in addition to the position of the canteens and fuel stations, only the distances in miles.

The first maps with more hydrographical details such as soundings are based on a sketch survey by Lt. Coulton Elliot, R.N.R., assisted by Lt. A. E. Cripps of the Northern Nigerian Marine, produced during 1910—1912. The so-called Rocky Section of the Lower Niger from Maconochie Island to Lokoja was surveyed in 1933 by A. L. E. Dennis, F.R.G.S., a Master Mariner of the Nigerian Marine, and his sketch maps show the position of the rocks and soundings taken at that time.

4.2. GEOLOGY

4.2.1. Reports

For geological references much use has been made of various publications of the Geological Survey Department of Nigeria. The authors and titles are to be found in the List of References, Geological Section.

There, also a great number of other reports and books are mentioned. No attempt will be made to select the most distinguished authors or the most important publications, but one exception must be made for J. D. FALCONER whose "Geology and Geography of Northern Nigeria", written in 1911, still stands as a standard work.

4.2.2. Geological maps

General data have been obtained from the 1 : 3,000,000 Geological Map printed by the Federal Survey Department. For more detailed information the 1 : 100,000 sheets prepared by the Geological Survey Department have been used; these sheets chiefly refer to the Jos Plateau and the Lower Gongola area, parts of which were selected as a start for the geological mapping of the whole of Nigeria.

Additional information has been drawn from the Geological Series of 1 : 250,000 maps compiled by the Shell-BP Petroleum Development Co. of Nigeria Ltd. for the geological survey of Nigeria.

In special cases, more details could be obtained from the special maps and drawings included in the publications consulted. In this respect the maps of Joyce's "Geological Report on the area situated immediately upstream of Jebba railway bridges" should be mentioned.

For the upper reaches of the Benue the "Carte Géologique du Cameroun" and its "Notice explicative" of 1956 have been consulted.

4.3. METEOROLOGY

4.3.1. Climate

The British West African Meteorological Services in Nigeria is the agency collecting climatic data of the country from about 20 observation stations (Photograph 4.3.1-1). The length of the period of record, however, is not the same for all stations, as records of some stations started more than 50 years ago whilst others started rather recently.

Some of the climatic data available will be found in III, 1.3.

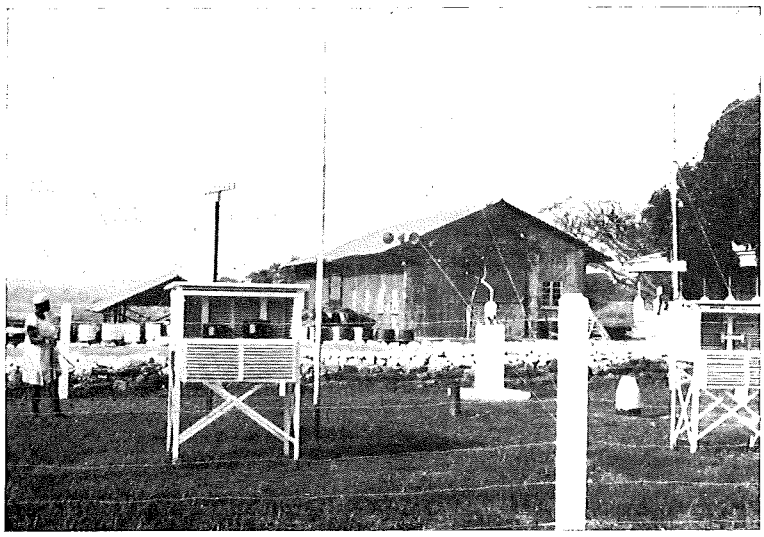
4.3.2. Rainfall data

Rainfall data collected by the Meteorological Services consist mainly of 24 hours rainfall measurements, generally made by people on a voluntary basis, which makes it understandable that the accuracy of all records cannot be guaranteed.

The periods of the records of the various rainfall stations differ greatly. Some of them are rather long; for Lagos, for example, records of daily rainfall are available from the year 1897 onwards. But most of the measuring stations have been installed only recently.

Table III, 4.1.2-3 gives the number of rainfall stations in the Niger and Benue Basin within Nigeria. Efforts are being made by the Meteorological Services to increase both the number of the stations and the reliability of the records.

Autographic records over some years are only available for Lagos (Apapa), Ikeja and Kano, but more recording rain gauges are being installed.



PHOTOGRAPH 4.3.1-1
Met. station, Lokoja

4.3.3. Evaporation data

During 1957 a tank evaporimeter was installed by the Meteorological Services at Yola. In the Niger-Benue Valley only data from this tank are available, but some more gauges have been installed since (see Section III, 4.4).

The Ibadan University is doing experimental work on potential evapotranspiration.

4.4. GAUGE READINGS

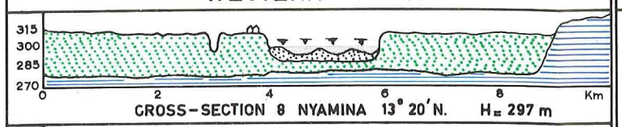
4.4.1. Periods available and sources

In Table 4.4.1-1 an outline is given of the major gauges along the Niger and Benue and their tributaries within Nigeria, together with the periods over which records were available in 1955. The agencies responsible for the reading of the gauge are also listed.

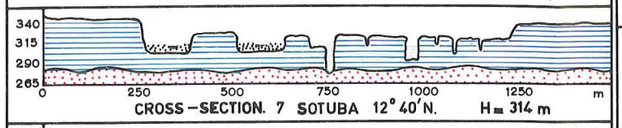
NEDECO	DIAGRAM
NIGER/BENUE	II,4.1.1-1

PROFILES OF THE NIGER
BY DR. KURT NIEHOFF

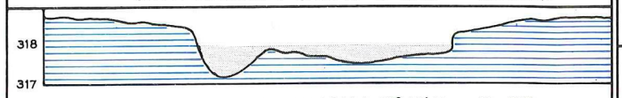
WESTERN NIGER



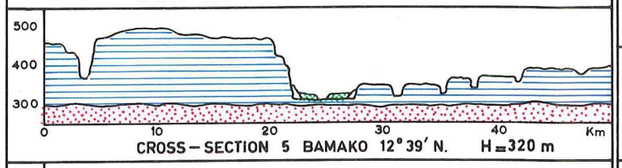
CROSS-SECTION 8 NYAMINA 13° 20' N. H = 297 m



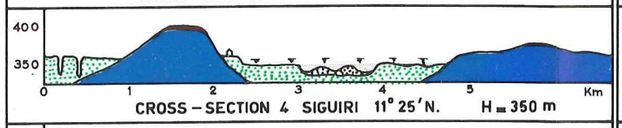
CROSS-SECTION. 7 SOTUBA 12° 40' N. H = 314 m



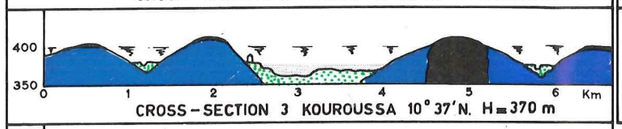
CROSS-SECTION 6 MASSALA 12° 40' N. H = 318 m



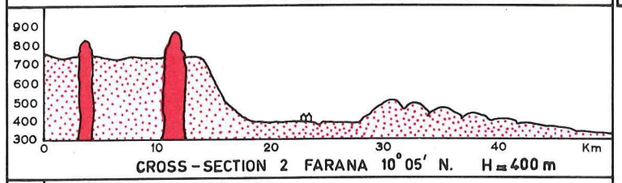
CROSS-SECTION 5 BAMAKO 12° 39' N. H = 320 m



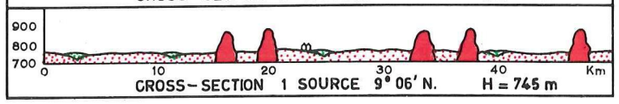
CROSS-SECTION 4 SIGUIRI 11° 25' N. H = 350 m



CROSS-SECTION 3 KOUROUSSA 10° 37' N. H = 370 m

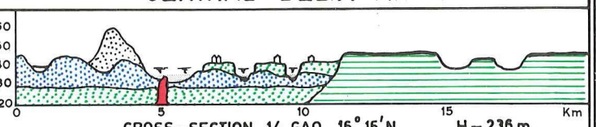


CROSS-SECTION 2 FARANA 10° 05' N. H = 400 m

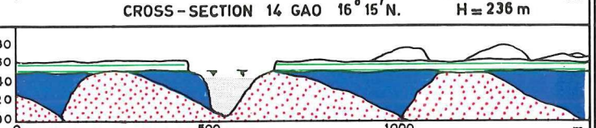


CROSS-SECTION 1 SOURCE 9° 06' N. H = 745 m

CENTRAL DELTA AREA

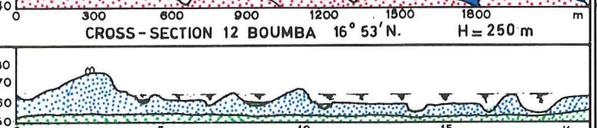


CROSS-SECTION 14 GAO 16° 15' N. H = 236 m

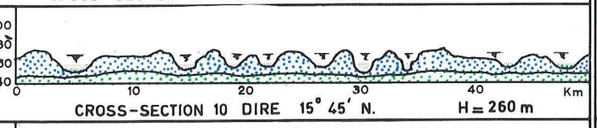


CROSS-SECTION 13 TOSAY 16° 56' N. H = 245 m

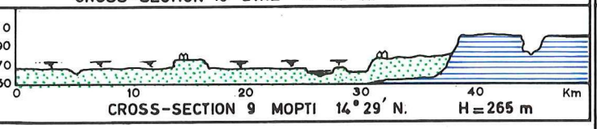
CROSS-SECTION 12 BOUMBA 16° 53' N. H = 250 m



CROSS-SECTION 11 TIMBUCTU-KABARA 16° 40' N. H = 257 m



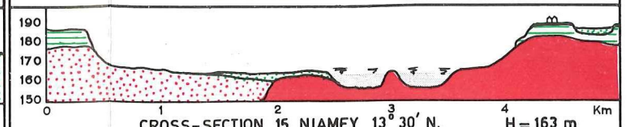
CROSS-SECTION 10 DIRE 15° 45' N. H = 260 m



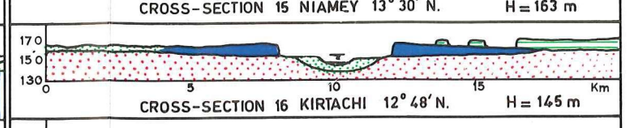
CROSS-SECTION 9 MOPTI 14° 29' N. H = 265 m

H.W.-LEVEL
L.W.-LEVEL
WANDERING DUNES
FOSSILISED DUNES
ALLUVIUM
TERTIARY SANDS
SANDSTONES OF THE CRETACEOUS AND EOCENE
SANDSTONES OF DEVONIAN OR CARBONIFEROUS AGE
SILURIAN ROCKS
GREISSES AND SCHISTS
POST-SILURIAN VOLCANIC ROCKS
PRE-SILURIAN VOLCANIC ROCKS
LATERITE CRUSTS
FAULTS

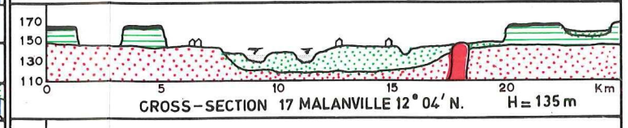
EASTERN NIGER



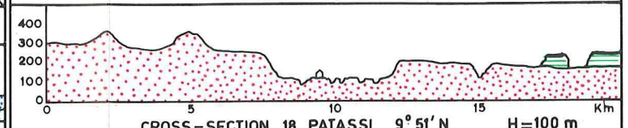
CROSS-SECTION 15 NIAMEY 13° 30' N. H = 163 m



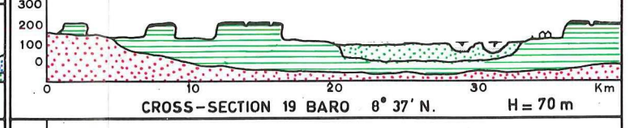
CROSS-SECTION 16 KIRTACHI 12° 48' N. H = 145 m



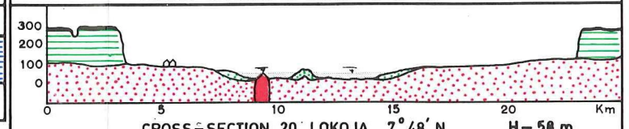
CROSS-SECTION 17 MALANVILLE 12° 04' N. H = 135 m



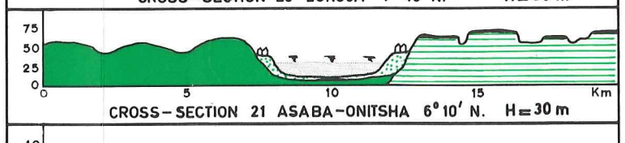
CROSS-SECTION 18 PATASSI 9° 51' N. H = 100 m



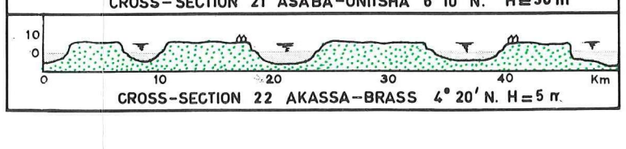
CROSS-SECTION 19 BARO 8° 37' N. H = 70 m



CROSS-SECTION 20 LOKOJA 7° 48' N. H = 50 m



CROSS-SECTION 21 ASABA-ONITSHA 6° 10' N. H = 30 m



CROSS-SECTION 22 AKASSA-BRASS 4° 20' N. H = 5 m.

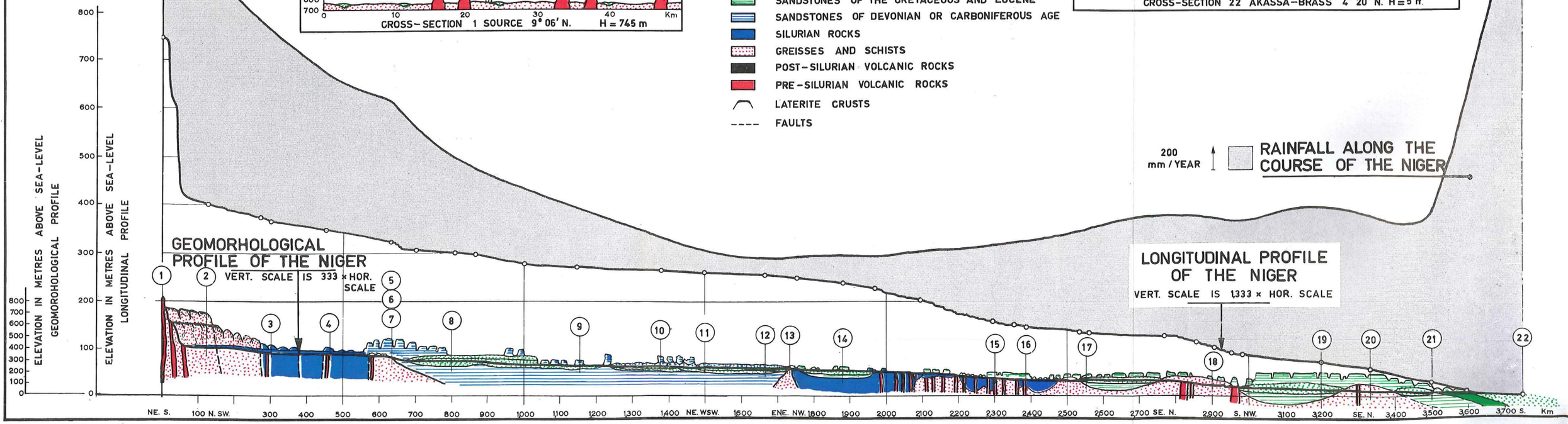
200 mm / YEAR — RAINFALL ALONG THE COURSE OF THE NIGER

ELEVATION IN METRES ABOVE SEA-LEVEL
GEOMORHOLOGICAL PROFILE

ELEVATION IN METRES ABOVE SEA-LEVEL
LONGITUDINAL PROFILE

GEOMORHOLOGICAL PROFILE OF THE NIGER
VERT. SCALE IS 333 × HOR. SCALE

LONGITUDINAL PROFILE OF THE NIGER
VERT. SCALE IS 1,333 × HOR. SCALE



Of the 30 primary gauges now in operation within Nigeria (see Tables III, 4.2.1-2 and III, 4.2.1-3) only 12 (as marked with a cross in Table 4.4.1-1) were in existence in 1955 at the beginning of the investigation, the others having been erected as and when required.

TABLE 4.4.1—1

GAUGES WITHIN NIGERIA OF WHICH DATA WERE ALREADY AVAILABLE

RIVER	STATION	MILE)[1]	Gauge installed in	AGENCY	PERIODS OF RECORDS	PRESENT IN 1955
Niger	Jebba	556	1908	Nigerian Railways	1915—1925 1948—1955	+
Niger	Baradogi	480	1951	Irrigation Department	1951—1955 Northern Region (Kaduna)	+
Kaduna R.	Wushishi	570	1954	P.W.D. Northern Region (Kaduna)	1954—1955	+
Kaduna R.	Wuya	about 505	—	Irrigation Department Northern Region (Kaduna)	1948—1955	+
Niger	Baro	434	1914	Nigeria Marine Department	1914—1955	+
Niger	Lokoja	361.2	1914	Nigeria Marine Department	1914—1955	+
Niger	Idah	310	1914	Nigeria Marine Department	1914—1923	
Niger	Onitsha	232.3	1914	Nigeria Marine Department	1914—1955	+
Benue	Wuro Boki	916	1953	P. & V.N.)[2]	1953—1955	+
Benue	Yola	888	1934 1954	U.A.C. P. & V.N.	1934—1955 1954—1955	+ +
Gongola	Dadin Kowa	about 935	1951	U.A.C.	1951—1955	+
Gongola	Bare	855	1953	O.R.S.T.O.M.)[3]	1953—1955	+
Benue	Numan	846	1933	U.A.C.	1933—1935	
Benue	Lau	777.5	1948	U.A.C.	1948 1950—1953	
Benue	Ibi	614	1914	Nigeria Marine Department	1914—1938	
Benue	Makurdi	511.6	1914	Nigeria Marine Department	1914—1916	
			1931	Nigerian Railways	1932—1955	+

)[1] Miles from Escravos Lighthouse, measured along the river-axis
)[2] P. & V.N. "Ports et Voies Navigables" Douala
)[3] O.R.S.T.O.M.: "Office de la Recherche Scientifique et Technique Outre-Mer, Paris.

Along the French part of the Niger many gauges exist in addition to those mentioned above. The central agency supervising all present gauges along the Niger is the "Service Hydraulique" at Bamako in French Soudan. Similarly along the Benue and the Faro River in the French Cameroun the gauges are supervised by the "Service des Ports et Voies Navigables" at Douala.

4.4.2. Correlation and corrections

When a study has to be made of the frequency of water-levels, the gauges with a long period of record are of great interest, although caution is also needed, as gauges with a long history might have shown some changes in position, in an absolute sense as well as relative to the situation of the river-bed.

The following gauges are to be considered as those with a history:

Niger:	Kouroussa	Mile	2,307
	Koulikoro	„	2,041
	Mopti	„	1,765
	Diré	„	1,574
	Niamey	„	995
	Jebba	„	556
	Baro	„	434
	Lokoja	„	361
	Idah	„	310
	Onitsha	„	232
Benue:	Garua	„	972
	Yola	„	888
	Ibi	„	614
	Makurdi	„	511

The possible changes and the correlation between two or more gauges in one station have to be carefully studied.

The French have checked the accuracy and calculated the necessary corrections of the gauges at Kouroussa, Koulikoro, Mopti and Diré.

As to the new gauge at Niamey which was erected in 1952, some differences were found during the calculation by NEDECO of the behaviour of the Black Flood as described in III, 4.5.4, and Diagram III, 4.5.4-4 shows the correlation between the old gauge of the "Office du Niger" and the present one.

At Jebba the records over the period 1915—1925 have to be linked with the present readings by means of a hydraulic computation, as the datum of the old gauge is lost. Fortunately the Black Flood gives a possibility to correlate the water-levels of Jebba during the Black Flood period with those from the French Niger as well as with the readings at Baro.

The correlation between the water-levels at Mopti and Diré respectively with the water-stages of the Black Flood at Baro are discussed in detail in III, 4.5.4, and with the use of the (partly corrected) discharges of this Black Flood at Baro, the correction of Jebba gauge can be calculated.

During its survey NEDECO has found that the discharge of the Niger during the Black Flood period at Jebba is about 50 m^3/sec (1,750 cusecs) larger than that at Baro. In Table 4.4.2-1 the Black Flood discharges at Jebba are obtained by augmenting those of Baro by 50 m^3/sec (1,750 cusecs). With the use of the discharge-rating curve as established by NEDECO, the corresponding water-levels at Jebba have been derived. A comparison with the actual readings gives the possible correction of the zero of the old gauge.

The difference between the correction of 47'3" over 1915—1917 and of 43'10" over 1918—1924 can possibly be explained by a sudden rise of the river from August 9 onto August 10, 1917, of 3'6". This is not shown by Baro gauge, and may therefore be explained by a change of the

position of the gauge. In 1925 the gauge had probably a slanting position before it disappeared, resulting in a higher reading and thus in a smaller correction.

The tape readings from the railway-bridge down to the water-level over the period 1948—1953 are not very reliable. Inspections have shown that the last 2 feet of the tape were missing, which is a possible explanation of the difference found in the correction over 1948—49 and 1954—57.

TABLE 4.4.2—1

CORRECTION OF JEBBA GAUGE

Year	Black Flood discharge at Baro m^3/sec	Q Jebba col (2) + 50 m^3/sec m^3/sec	h Jebba from col (3) with discharge-rating curve	h Jebba observed	col (4) minus col (5)	Correction
1915	1,360	1,410	55′ 1 ″	7′ 8 ″	47′ 5 ″	+ 47′ 3″
1916	1,600	1,650	55′ 9 ″	8′ 8 ″	47′ 1 ″	
1917	—	—	—	9′ 3 ″	—	
1918	1,620	1,670	55′10 ″	12′ 1 ″	43′ 9 ″	
1919	1,710	1,760	56′ 1 ″	12′ 3 ″	43′10 ″	
1920	1,560	1,610	55′ 8 ″	11′ 8 ″	44′ 0 ″	
1921	1,510	1,560	55′ 7 ″	11′ 9 ″	43′10 ″	+ 43′10″
1922	1,530	1,580	55′ 7 ″	11′ 8 ″	43′11 ″	
1923	1,700	1,750	56′ 1 ″	12′ 3 ″	43′10 ″	
1924	1,640	1,690	55′11 ″	12′ 1 ″	43′10 ″	
1925	1,930	1,980	56′ 8 ″	13′ 7 ″	43′ 1½″	gauge slants
1948	1,600	1,650	55′ 9 ″	— 47′ 0 ″	102′ 9 ″	+ 102′ 7″
1949	1,650	1,700	55′11 ″	— 46′ 6 ″	102′ 5 ″	
1950	1,650	1,700	55′11 ″	—	—	
1951	—	—	—	—	—	
1952	2,050	2,100	57′ 0 ″	— 44′ 0 ″	101′ 0 ″	
1953	2,050	2,100	57′ 0 ″	— 43′10 ″	100′10 ″	
1954	2,080	2,130	57′ 1 ″	— 43′ 6 ″	100′ 7 ″	
1955	2,105	2,155	57′ 1½″	— 43′ 4 ″	100′ 5½″	+ 100′ 6″
1956	2,225	2,275	57′ 5 ″	— 42′11 ″	100′ 4 ″	
1957	1,830	1,880	56′ 5 ″	— 44′ 2½″	100′ 7½″	
1958	2,050	2,100	57′ 0 ″	— 42′ 4 ″	99′ 4 ″	

The tape readings since 1954 are fairly good and over 1956 the summation of the tape reading and the reading of the NEDECO gauge showed 100′6″ throughout the year with only a few minor differences. Since 1958 another and more exactly defined mark has been used as zero point of the tape reading, resulting in a different correction.

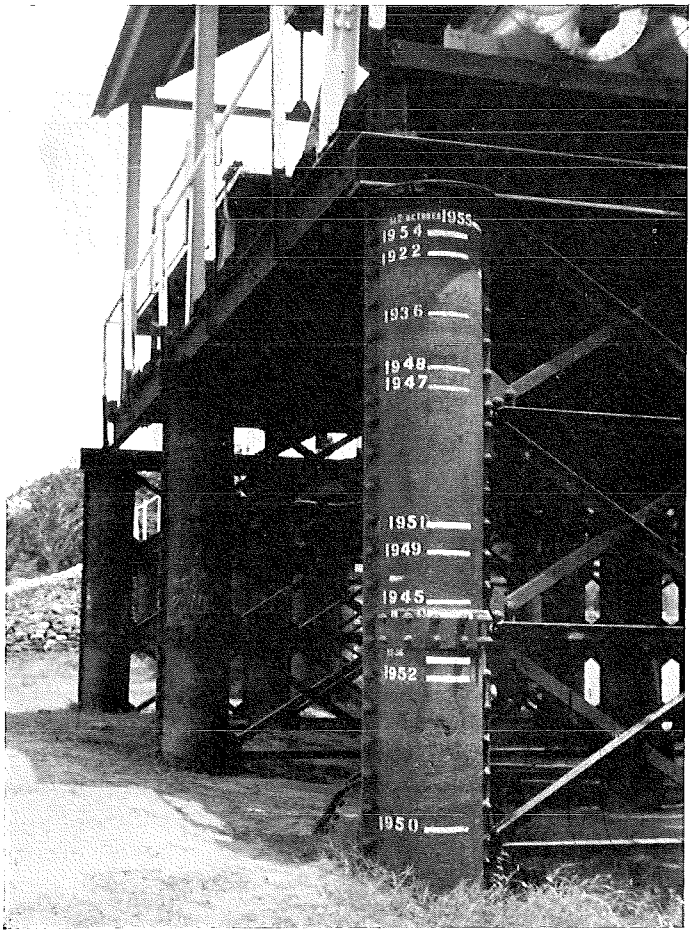
At Baro the readings of the gauge have been correlated with those of some gauges in French Soudan while studying the Black Flood phenomenon in III, 4.5.4. In the course of this study it became apparent that some corrections to the Baro readings had to be made, as is described in detail in the just-mentioned paragraph.

The gauge at Lokoja shows no changes in its correlations with other gauges. The only period when the readings are suspect is during 1933—1934, when a discussion was going on about the correct zero of the gauge. Fortunately this only concerned the interpretation of the readings and the gauge itself was not disturbed. Annual maximum levels were marked on a tree near the Lokoja Dockyard, and these levels were later transferred to the pillar of the Dockyard jetty (see Photograph 4.4.2-2).

At Idah the datum of the readings over 1914—1923 has been lost, and correlations between Lokoja — Idah and Idah — Onitsha respectively show too great a divergence to decide on a

practical correction. As this gauge is situated between two gauges with a rather good period of records, the importance of this lost period is not very large.

At the point where the discharge of the Niger River system finds its maximum stands the gauge of Onitsha which is therefore of great interest. This gauge was erected in 1916 and up to 1925 the readings show some irregularities, as given in Diagram 4.4.2-4, where the relation between the water-levels at Lokoja and Onitsha are drawn for the years 1914, 1924, 1929, 1939 and 1955 respectively. From these graphs it can be seen that 1916 and 1924 each show rather great differences from 1929 and 1939 which almost coincide; 1955 runs almost parallel to 1939. The neatness of the gauge book at Onitsha shows that someone became more interested in the water-level information in about 1925, so possibly after that time the work was done with more precision.



PHOTOGRAPH 4.4.2-2
High-water records at Lokoja

The differences between 1929 and 1939 mainly lie in the low-water levels and may have been influenced by small changes in the situation of the river-bed.

The line of 1955 runs, as has been said, parallel to the line of 1939. This could be the result of a moving of the zero of one of the gauges concerned, or even both. As the history of the Lokoja gauge is fairly well-known, it would seem that the error must be looked for in the Onitsha

gauge. If the readings of the latter are reduced by about 2 feet, the line of 1955 almost coincides with that of 1939. But if an attempt is made to alter the 1955 line by increasing the Lokoja readings by a constant figure, a less acceptable coverage is obtained of the two lines: an indication that the first suggestion is the more likely.

As another check, the maximum H.W.-levels of Lokoja and Onitsha have been plotted in Diagram 4.4.2-3. Here again it can be seen that some of the earlier years, such as 1916, 1919 and 1922, do not follow the general trend, while during the period 1930—1933 again some divergence is found. It appears from old files on the Lokoja gauge that in 1933 there were complaints that the gauge there was in really bad condition. An improvement was made, but in 1934

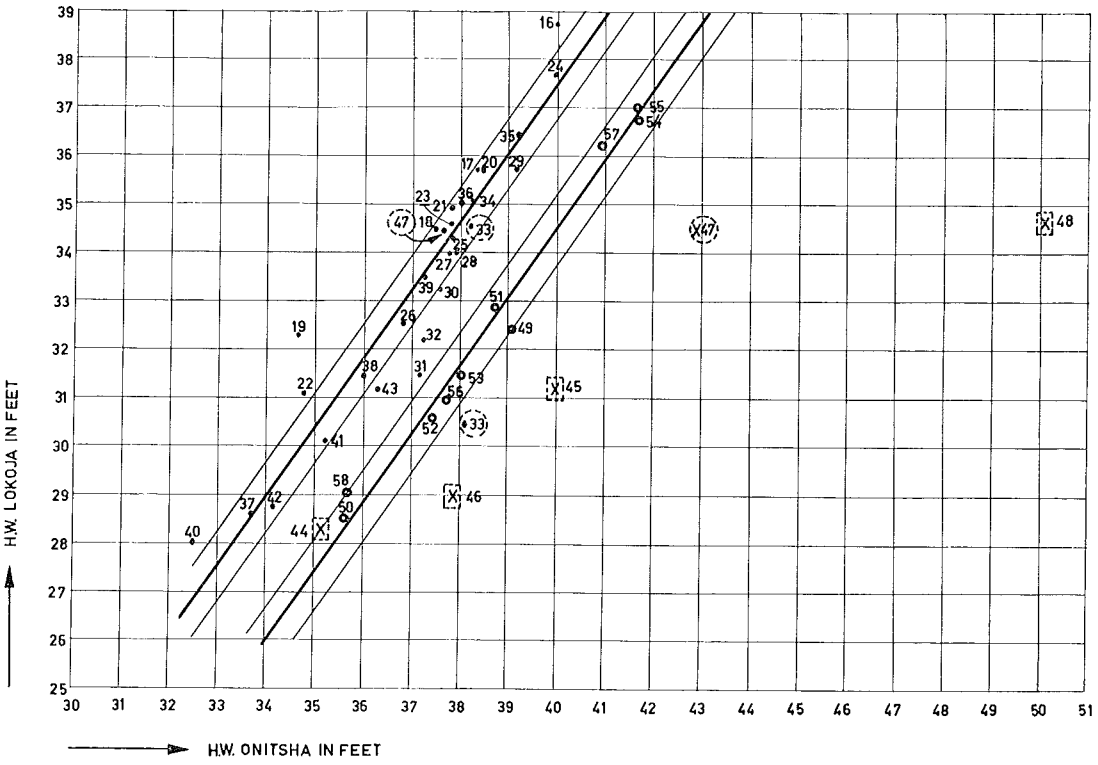


DIAGRAM 4.4.2-3

Relation of H.W.-level at Lokoja and Onitsha

it was found that a mistake of 4 feet had been made. This correction applied to 1933 gives that year a good position in the graph, and the divergence of 1930, 1931 and 1932 must be found in small inaccuracies of the Lokoja gauge.

Around 1940 the plots scatter again, culminating between 1944 and 1948 into something that is obviously incorrect. Old files about the Onitsha gauge refer to painting and repainting during the second World War, and finally a new gauge was erected in March 1949 which came into use on May 1949. "The zero of this gauge appears to be *about* the same or perhaps *exactly* the same as that of the pre-1947 gauges" (from a letter from the Nigerian Ports Authority to NEDECO of Jan. 4, 1956).

From Diagrams 4.4.2-3 and -4, however, it can be seen that the gauge at Onitsha, in use since 1949, is situated about 2 feet lower than the pre-1947 gauge (although it would be better to say from before 1944, as can be seen from Diagram 4.4.2-3).

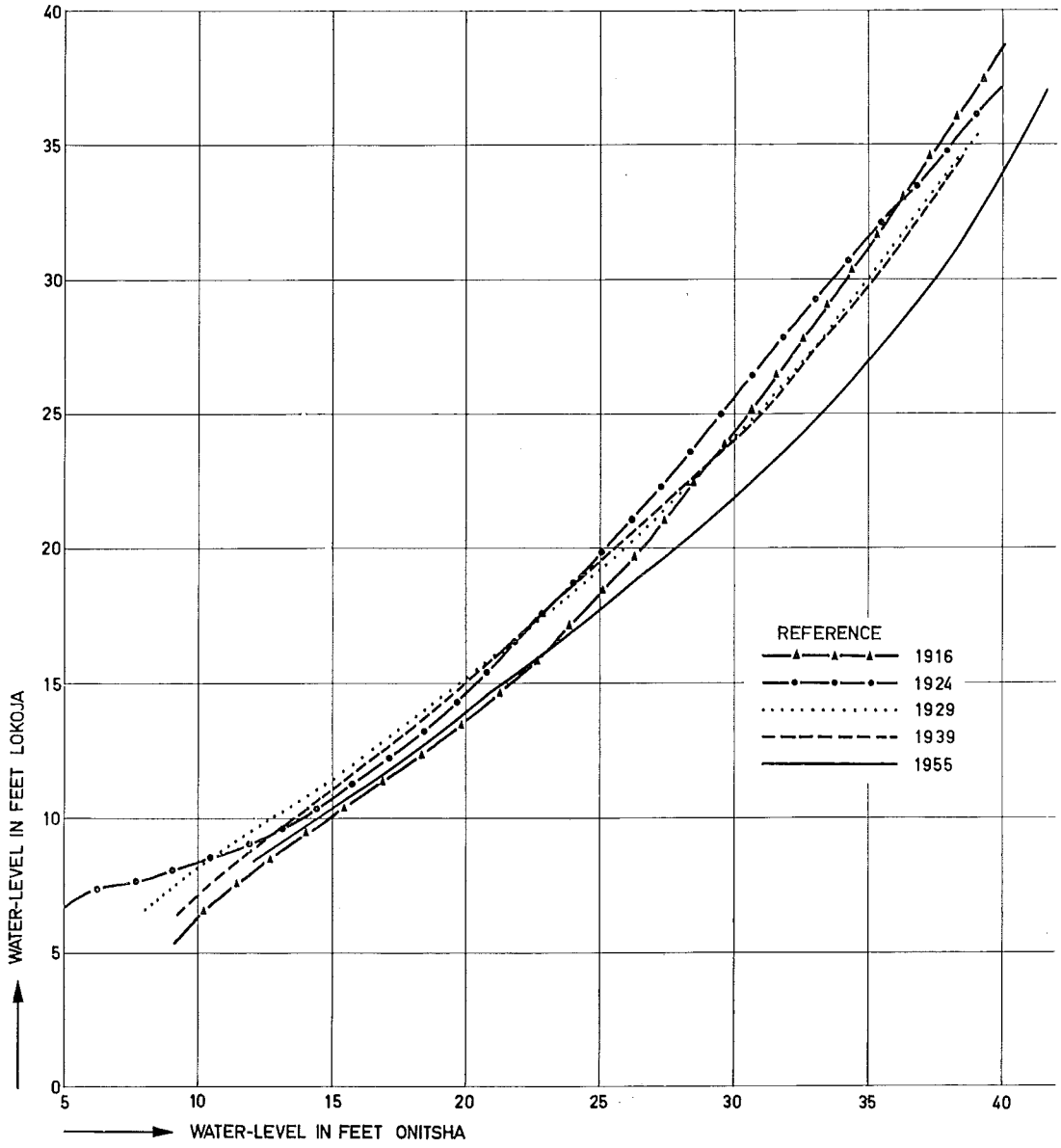


DIAGRAM 4.4.2-4

Relation curves of water-levels at Lokoja and Onitsha

Concluding, it can be said that the readings of Onitsha gauge before 1925 are not fully reliable. The period 1925 upto 1944 looks rather good, while the 1944—1949 period has to be left out as unreliable. Since 1949 a difference of two feet with the old gauge occurs. For simplicity the old readings have been corrected by adding 2 feet, thus making them comparable with the present readings on the Onitsha gauge.

On the Benue, matters are less complicated. In Garua and Yola no deviations have been found, and no datum has been lost. Only at Ibi very unfortunately the datum of the readings of the period 1914—1938 was lost. A comparison of the recession curves of the floods during 1914—1938 and of the present period might give a way to find the correction, but to arrive at an accurate

result more observations on the present gauge are needed in order to even out the annual irregularities of the recession curves.

Finally, at Makurdi only the period 1914—1916 cannot be linked up with the present railway gauge, of which continuous readings since 1932 are available. These, however, are not so very accurate because of the 3-inches division of the gauge, the turbulent current near the bridge pillars, and the great distance from which the gauge has to be read.

As a result of the above considerations it can be said that the stations along the Niger and Benue with a usable period of records for frequency calculations are Koulikoro, Diré, Baro, Lokoja and Onitsha on the Niger and Garua, Yola and Makurdi on the Benue. The results of these frequency calculations can be found in III, 4.2.3.

4.5. LEVELLING

A geodetic levelling along the rivers has been undertaken by the Federal Survey Department with the object of determining the datums of the primary river-gauges. The results became available in the course of 1957, and are collected in Tables III, 4.2.1-2 and -3.

The levelling programme could be based upon the Nigeria Datum at Lagos, established at a Primary Levelling, which was carried out between 1928 and 1935, and which provided heights

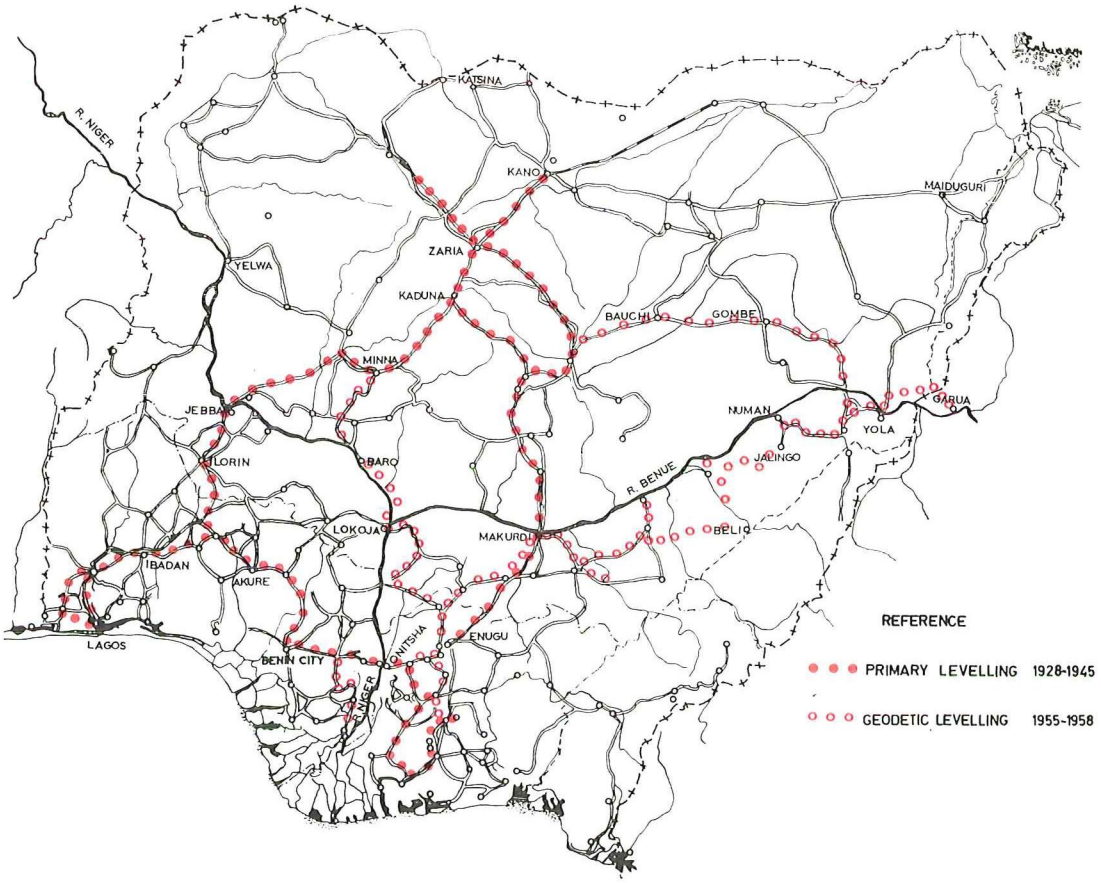


DIAGRAM 4.5.1-1

Routes of precision levelling in Nigeria

of benchmarks as far east as Makurdi (Diagram 4.5.1-1). The Nigeria Datum is Mean Sea Level, as determined from an automatic tide-gauge on the inner side of the East Mole of Lagos Harbour.

Observations of the geodetic levelling were taken with precision levels equipped with parallel-plate micrometers and with "Nilex" staves. They can be read to three decimals of a foot, the fourth decimal being estimated.

The primary levelling formed one very large circuit and three small circuits. The misclosure of each of the three small circuits was of the order of 0.10 foot, while that of the very large circuit was about 19.0 feet. In 1948 an attempt was made to locate this large misclosure in the line between Makurdi and Enugu and a difference of about 17 feet was found in one section. However, the geodetic levelling has replaced the primary levelling between Makurdi and Awka and the misclosure is now found to be 3.75 feet.

Nevertheless, the difference between the British and the French levelling concerning the height of the benchmark at Pitoa (near Garua), amounts to only –0.21 foot. Under the provisional assumption that the location of the misclosure in the large circuit will effect Makurdi to a rate of not more than two feet, the discordance between the British and French values at Pitoa would be 1.79 feet at maximum: this is a rather good result when bearing in mind that the values are derived from over 1,200 miles of double-levelling in Nigeria and from not less than 700 miles in the French Cameroons, all over rough country.

The results on heights of benchmarks and gauges along the rivers are, therefore, provisionally based upon the Pitoa datum.

PART III

THE RIVERS

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CHAPTER 1

GENERAL DESCRIPTION

1.1. INTRODUCTION

1.1.1. Comparison of Niger and Benue with other rivers

The River Niger is the largest river in West Africa. In former days it was one of the main highways from the Coast to the Interior and it is fairly well possible to make it the master transport route in future. Nigeria, which of course takes its name from the river although only less than one-third of its length is actually situated in Nigerian Territory, is very fortunate in being traversed by this major waterway.

The total drainage area of the Niger and Benue Rivers within the territory of Nigeria is 222,000 sq.miles and covers 60% of the country's total area.

Nigeria's inland waterways system is extensive, with about 4,000 miles being regularly used by navigation, of which the Niger and its main tributary the Benue River provide 1,350 miles. It is not surprising therefore that Nigeria has planned progressive activities for the future development of these two rivers as they form the main artery of the country.

A comparison of the Rivers Niger and Benue with a number of large rivers of the world has been compiled in Table 1.1.1-1, showing rivers with a total length of more than 1,200 miles (2,000 km). The River Rhine is added to complete the picture as it will be mentioned several times in other chapters of this Report. These data are derived from various sources and their relative accuracy cannot be guaranteed.

With its total length of 2,550 miles from the source to the sea, the Niger is one of the eleven longest rivers of the world. The others are, according to Diagram 1.1.1-2: the Amazon, Nile, Yangtze Kiang, Ob, Congo, Missouri/Mississippi, Lena, Hwang Ho, Amur and Mekong Rivers. It should be added that the Missouri, although a tributary of the Mississippi, is actually longer than the Upper Mississippi above its confluence with the Missouri. Thus, the distance from the source of the Missouri to the mouth of the Mississippi in the Gulf of Mexico is 6,750 km (4,194 miles) which surpasses that of the Amazon River.

The total drainage area of 730,000 sq.miles gives the Niger River the seventh place in the world after the Amazon, Mississippi/Missouri, Congo, Nile, Parana and Ganges/Brahmaputra (Diagram 1.1.1-3). With regard to the respective maximum discharges, the Niger River, with more than 1,000,000 cusecs, also is one of the largest rivers of the world.

In Diagram 1.1.1-4 the Niger and Benue Rivers are projected on Europe on the same scale, which is yet another demonstration of its size.

TABLE 1.1.1-1

COMPARATIVE BASIC DATA OF RIVERS

river	total drainage area		total length miles	annual water discharge		annual sediment discharge 10^6 ton	max. water discharge		min. water discharge		remarks
	sq. km	sq. miles		10^9 m³	10^6 acre feet		m³/sec.	cuft/sec.	m³/sec.	cuft/sec.	
Amazon	7,050,000	2,722,000	4,160	3,000	2,430	900	203,000	7,160,000	—	—	
Nile	2,862,000	1,105,000	3,800	85	60	60	—	—	—	—	
Yangtze K.	1,830,000	707,000	3,470	700	570	970	80,000	2,830,000	5,270	182,000	
Congo	3,700,000	1.430,000	2,920	1,400	1,130	70	65,000	2,300,000	27,000	953,000	
Missouri	1,370,000	529,000	2,900	—	—	—	25,500	900,000	—	—	
Hwang Ho	771,600	298,000	2,880	200	160	1,890	25,000	880,000	245	8,700	
Mekong	795,000	307,000	2,610	400	320	80	60,000	2,120,000	1,700	60,000	
Niger	1,112,000	430,000 (*	2,550	180	200	40	30,000	1,060,000	1,200	42,500	(* + 300,000 sq. miles desert without "run-off"
Mississippi	3,222,000	1,244,000	2,470	600	490	600	76,500	2,700,000	3,500	100,000	
Wolga	1,500,000	580,000	2,420	250	200	25	—	—	—	—	
St. Laurens	—	—	2,360	300	240	3	—	—	—	—	
Parana (*	3,000,000	1,161,000	2,360	600	490	90	—	—	—	—	(* Rio de la Plata
Indus	452,000	175,000	2,050	200	160	400	26,000	920,000	490	17,300	
Brahmaputra	938,000	361,200	1,800	380	310	—	—	—	425	15,000	
Danube	1,165,000	450,000	1,800	200	160	80	10,000	350,000	—	—	
Zambesi	1,300,000	502,000	1,680	500	400	100	—	—	—	—	
Ganges	905,000	349,000	1,600	—	—	—	60,000	2,130,000	1,740	61,500	
Dnjepr	—	—	1,410	50	40	50	—	—	—	—	
Irrawaddy	415,000	160.000	1,240	520	420	290	64,000	2,260,000	1,306	46,100	
Rhine	362,000	140,000	820	80	60	3	12,000	425,000	500	17,700	
Benue	337,200	130,000	810	100	80	25	15,000	531,000	200	7,100	

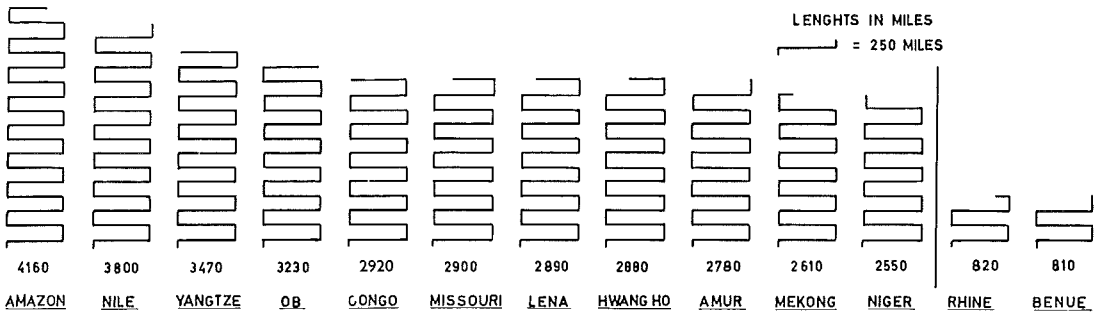


DIAGRAM 1.1.1-2

Comparison of lengths

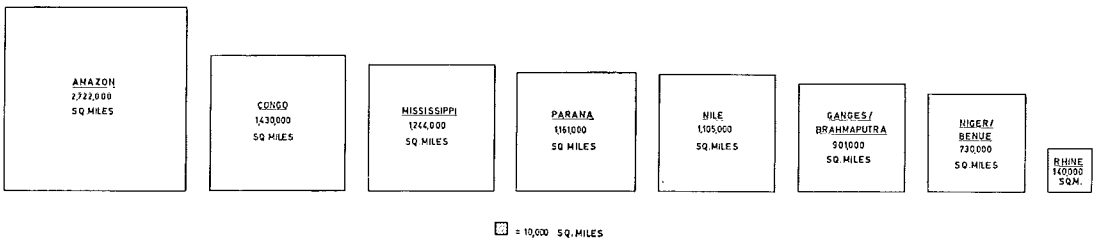


DIAGRAM 1.1.1-3

Comparison of drainage areas

1.1.2. History (discovery, old charts, and settlements)

Few areas of the world have been enveloped with more mystery and adventure than that which forms the subject of this investigation, especially as it is only within the past century or so that man's knowledge about the Rivers Niger and Benue, and the area served by them, has really started to expand.

In general it may be said that the history of the discovery of the Continents and the development of the knowledge about them by means of exploration can perhaps best be seen in the successive maps of the cartographers of the 16th to the 19th centuries. This is certainly true of Nigeria, even as it also shows how difficult the territory was to delineate and how divergent were the opinions of the various geographers and explorers. With regard especially to the interior of West Africa, there is considerable literature available ([1 and from these works, as well as from the old maps, its exploration and discovery is here chronologically summarised.

Rumours about a great river in this area were current for centuries before any real exploration was carried out, and even the people of ancient times seemed to have heard vaguely about the Niger. There was, for example, the old story of HERODOTUS (424—429 B.C.) about the Nasamonian youths of a semi-desert tribe who walked for months from Egypt in a westerly direction across the desert and found a large river flowing eastwards: "as large a river as the Danube running from west to east which could probably be a distant tributary of the Egyptian Nile" ([2, although some writers have tried to identify that river with the Niger.

Then there was PLINY (A.D. 23—79) who talked about the Nile running from the west, al-

([1 a.o.: CRONE, 1952. GEN. 9; FAGE, 1956. GEN. 12; BATTEN, 1955. GEN. 2 and QUINN-YOUNG & HERDMAN, 1951. 31
([2 NIVEN, 1955. GEN. 24

though he suggested that it was a separate river. Three-quarters of a century later the maps of CLAUDIUS PTOLEMY (A.D. 150) also showed this river running from west to east and stretching over one-half the width of Africa.

DIAGRAM 1.1.1-4

Niger/Benue projected on Europe on the same scale

Coming to more recent times, perhaps one of the first maps to notice is that of SEBASTIAN MUNSTER, from his "Cosmographica", published in Basel in 1540 (Diagram 1.1.2-1). This map is an extension of Ptolemy's limitations by Portuguese discoveries. And it is particularly interesting to note that despite all the argument that was registered during those centuries, our present-day knowledge (gained only in the past 150 years) shows that the west-east direction of the current of the Upper Niger, as given by those early writers, was correct.

Among those who thought otherwise — and wrongly — Arabian traveller EL EDRISI (A.D. 1153) stated that the direction of the then-called "Nile" or "Neel of the Negroes" (Neel meaning large river) was from the east to the west, thus copying what DIONYSY had said about 1,200 years earlier. Even ABUFEDA (1274—1331) made the same error, reporting that the Niger, then called "the Nile of Gana", flowed westwards ([1.

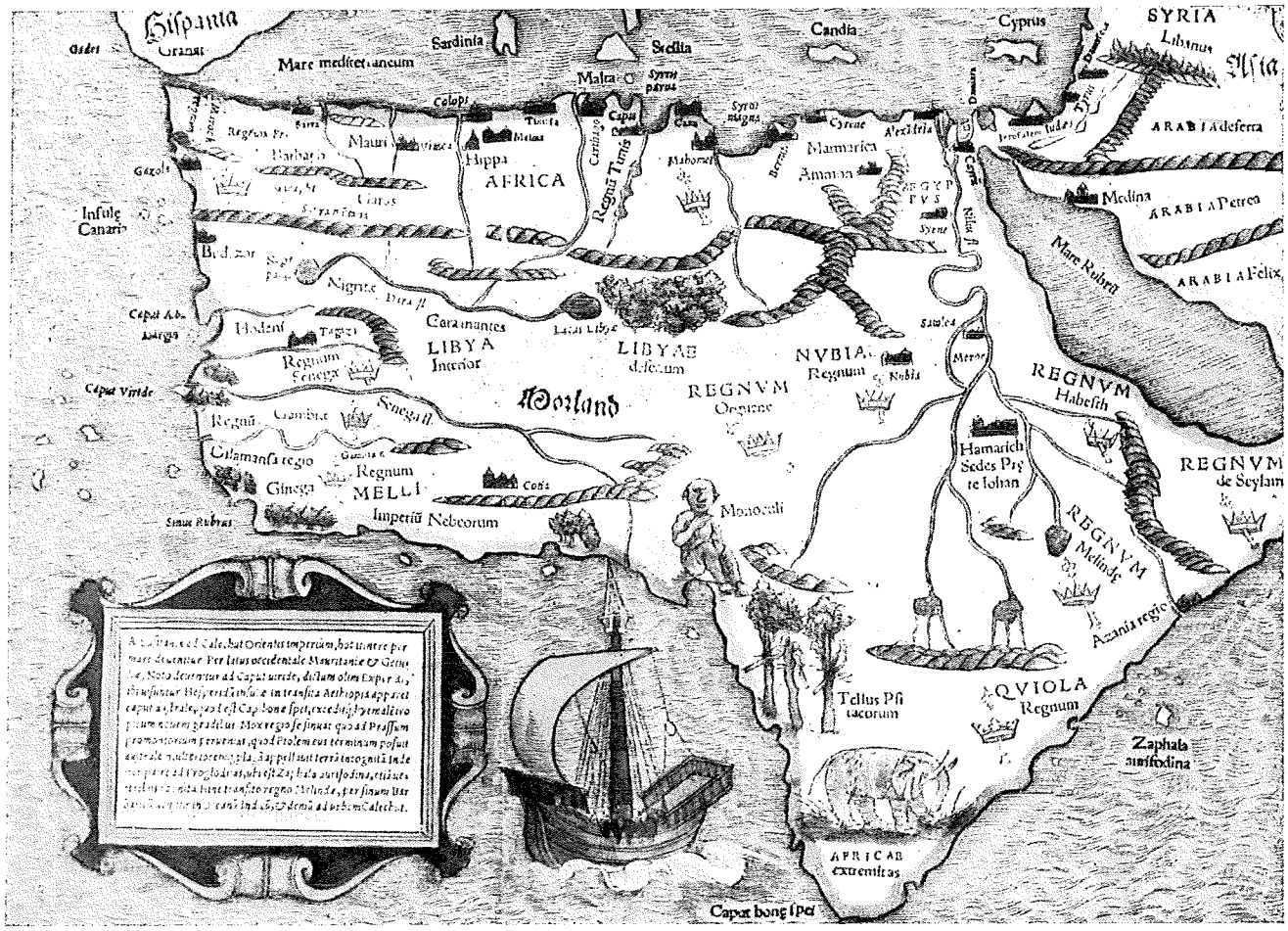


DIAGRAM 1.1.2-1

Sebastian Munster — "Cosmographica" — 1540

In the course of the centuries other travellers said they had seen the river and published vague descriptions of it, but the majority declared it flowed towards the east. IBN BATUTA, for instance, who travelled all over the then known world and who finally crossed the desert to the Niger in about 1350, said quite clearly that the Niger went eastwards. But another great traveller, LEO AFRICANUS, who visited Timbuctu and the Niger Valley in 1513, reported that the river flowed to the west. There is no special explanation of how he made such a mistake, but so great was his reputation that, after his book was published, the map-makers were thrown into great confusion.

([1 BURNS, 1951. GEN. 4

However, as a result of the journeys of these explorers, the world realised that there was an enormous area drained by a great river called the Niger, but they did not know where it debouched into the sea. In the 15th century the Portuguese even thought that the Senegal River was the Niger, whilst in 1588 SAMUTO suggested that the Rio Grande was one tributary of the Niger and the Senegal was the other.

Maps of Dutch cartographers of that century repeated the error, as seen in PETER PLANCIUS' "Map of North-West Africa and Brazil" made in 1592 (Diagram 1.1.2-2) and JODOCUS HONDIUS' "New Description of Guinea", 1606 (Diagram 1.1.2-3). Decades later, the maps in the Atlas of JOHANNES JANSSONIUS HEIRS, 1664 (Diagram 1.1.2-5), still showed the Niger Fluvius in connection with the Senegal, the Bambia and the Rio Grande Rivers.

Even in the 18th century, when with the French cartographer GUILLAUME DE LISLE (about 1703) the more modern method of map-making without elaborate decorations started, the reproductions of the interior of Nigeria still depend on the old sources (Diagram 1.1.2-6). Here the Niger River is still shown as flowing to the west, although De Lisle published a map in 1714

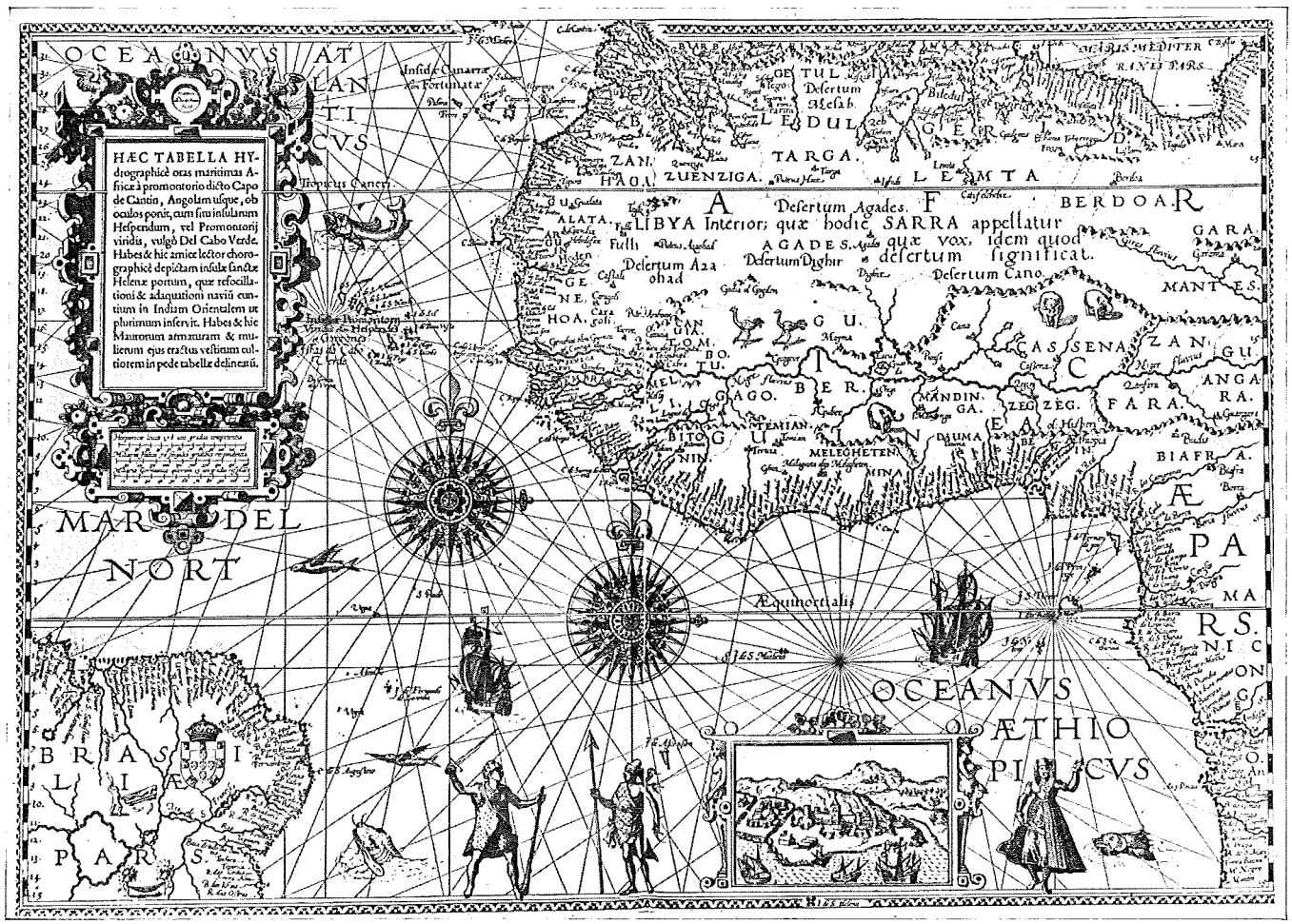


DIAGRAM 1.1.2-2

Peter Plancius — map of North-West Africa and Brazil — 1592

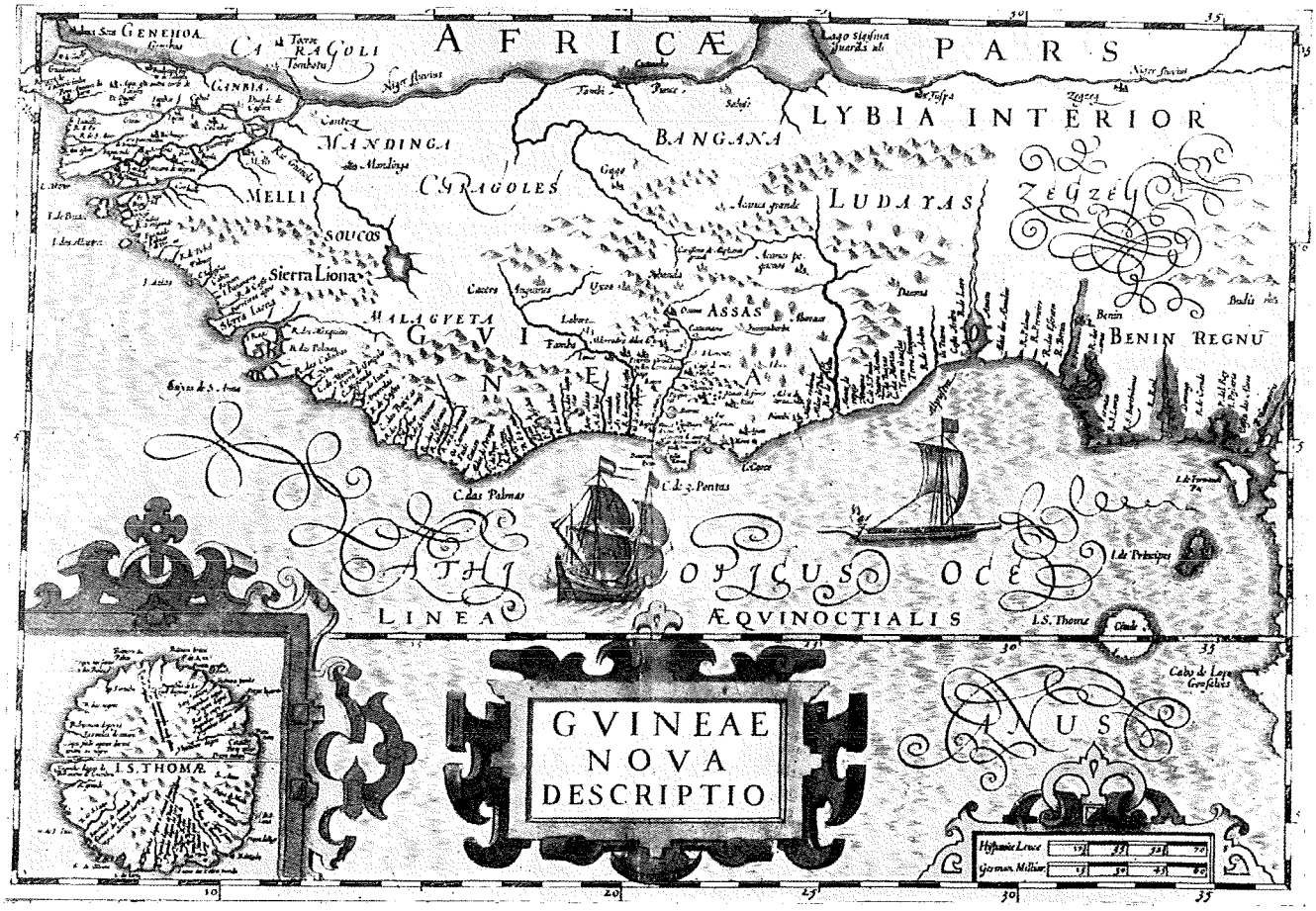


DIAGRAM 1.1.2-3

Jodocus Hondius — "New Description of Guinea" — 1606

giving the true direction of the river and treating the Senegal as a separate river. Meanwhile, certain geographers thought that the mysterious Niger might drain into some internal basins which had no outlets, an idea they supported by pointing to the definite existence of Lake Chad.

D'ANVILLE, who published a map in 1749, gave the Niger an easterly course and made it meet another river flowing westwards at the place he called Wangara. Yet others were of the opinion that the Congo River was probably the mouth of the Niger. It was not until 1796, however, that the direction of the Niger River was finally settled beyond doubt. July 20 of that year proved, indeed, a great day in the history of West African exploration. For it was on that day that MUNGO PARK (1 reached the bank of a great river at Ségou and saw "the long-sought for majestic Niger or Joliba River flowing slowly to the east".

Later, after an imposing expedition authorised by the English Government had suffered the loss of almost the whole of its members, Mungo Park returned overland to the Niger in this area and travelled from Sansanding downward in two canoes converted into a schooner. All who remained of his original party seem to have reached Bussa, about 1,300 miles down the Niger, but perished when their ship struck a rock in one of the rapids upstream from Jebba in 1805.

(1 MUNGO PARK, 1799. GEN. 28

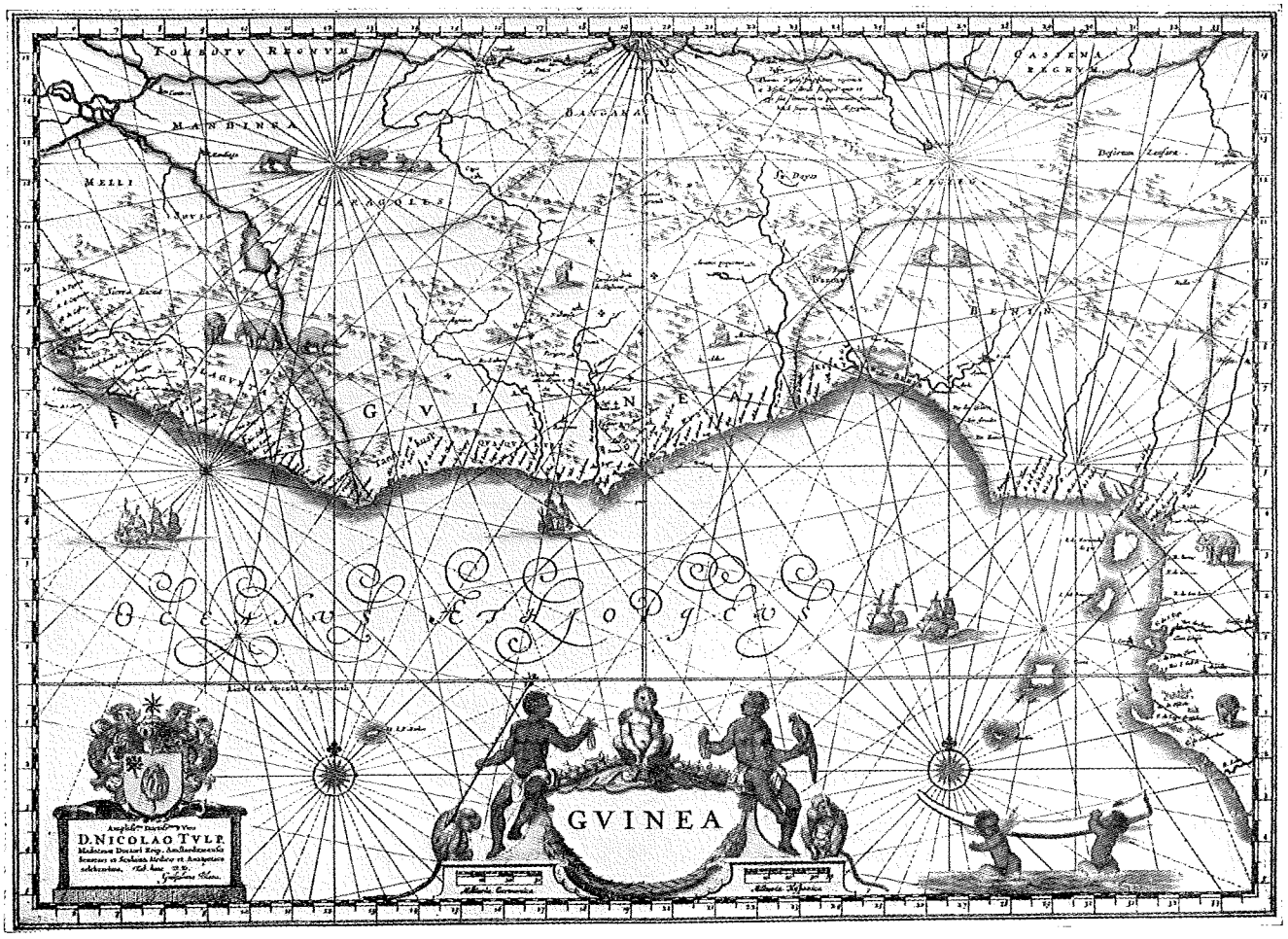


DIAGRAM 1.1.2-4

The Atlas of William Blaeu — 1635—1670

Knowledge about the river increased from then onwards, as one explorer after another unveiled Nigeria's secrets. Yet even then, with HORNEMANN travelling (1 along the old caravan route which had existed since the days of Herodotus, the reports said that the Niger in Bornu flowed more southwards and had a confluence with the Nile south of Darfour. But in the "Geographical Illustrations" published as an appendix to Mungo Park's "Journal", the geographer MAJOR J. RENNELL sought to prove the impossibility of a confluence of the Niger and the Nile by two hydrological facts, namely, by the great difference in levels of the two rivers if the Niger flowed as far as Abyssinia (2,300 miles in a straight direction), while Mr BRUCE's barometer gave an altitude of over 2 miles above sea-level for the source of the Nile; and by the rainfall, because the rise of the Niger River and that of the River Nile did not coincide, even taking into account a possible time-lag. His conclusion was that after 22 centuries the facts were still the same, the only knowledge being of a River Niger flowing eastwards. He concluded further that the Niger ended in a lake called Wargana, basing such a conclusion on reports by BEN ALI to the explorer BEAUFOY.

(1 ERWIN MAY, 1953. GEN. 20

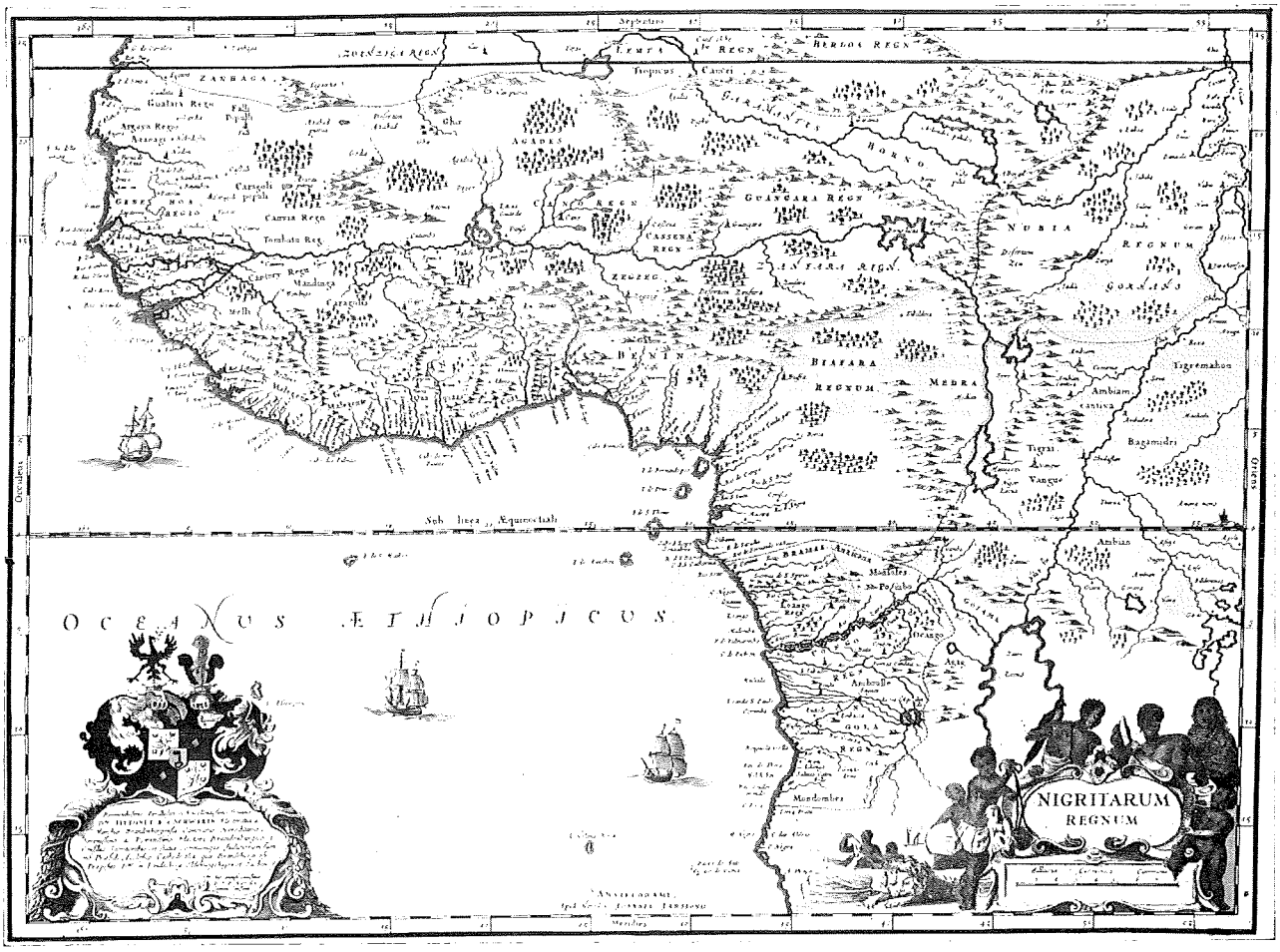


DIAGRAM 1.1.2-5

The Atlas of Johannes Janssonius Heirs — 1664

Later, VON ZACH assumed that the Niger did not drain into any lake, even though such lakes contained fresh water, but that, running more to the south, the river joined another and ran down to the sea. This belief, coupled with the theories of REICHARDS and MCQUEEN which supposed that one of the estuaries was located somewhere in what is now known as the Niger Delta, was correct, although it received at that time little attention.

Nevertheless, in 1816 MAJOR PEDDIE planned to enter West Africa from Sierra Leone with CAPTAIN TUCKEY at the same time going up the Congo; they hoped to meet each other at the end of their trip. Unfortunately, both expeditions ended in disaster.

Then in 1821 CLAPPERTON's first expedition started from Tripoli, by which he reached Mursuk in 1822 and Lake Chad in 1823. Travelling from Kano to Sokoto he received information that the Niger reached the sea near Fundah. The second expedition of CLAPPERTON and LANDER in 1825 failed to find very much new, for after Clapperton's death in 1827 Lander was compelled to turn back along the route they had followed.

By this time, however, it was becoming more or less generally accepted that the theories of Reichard and McQueen on the termination of the Niger were correct, which makes it seem

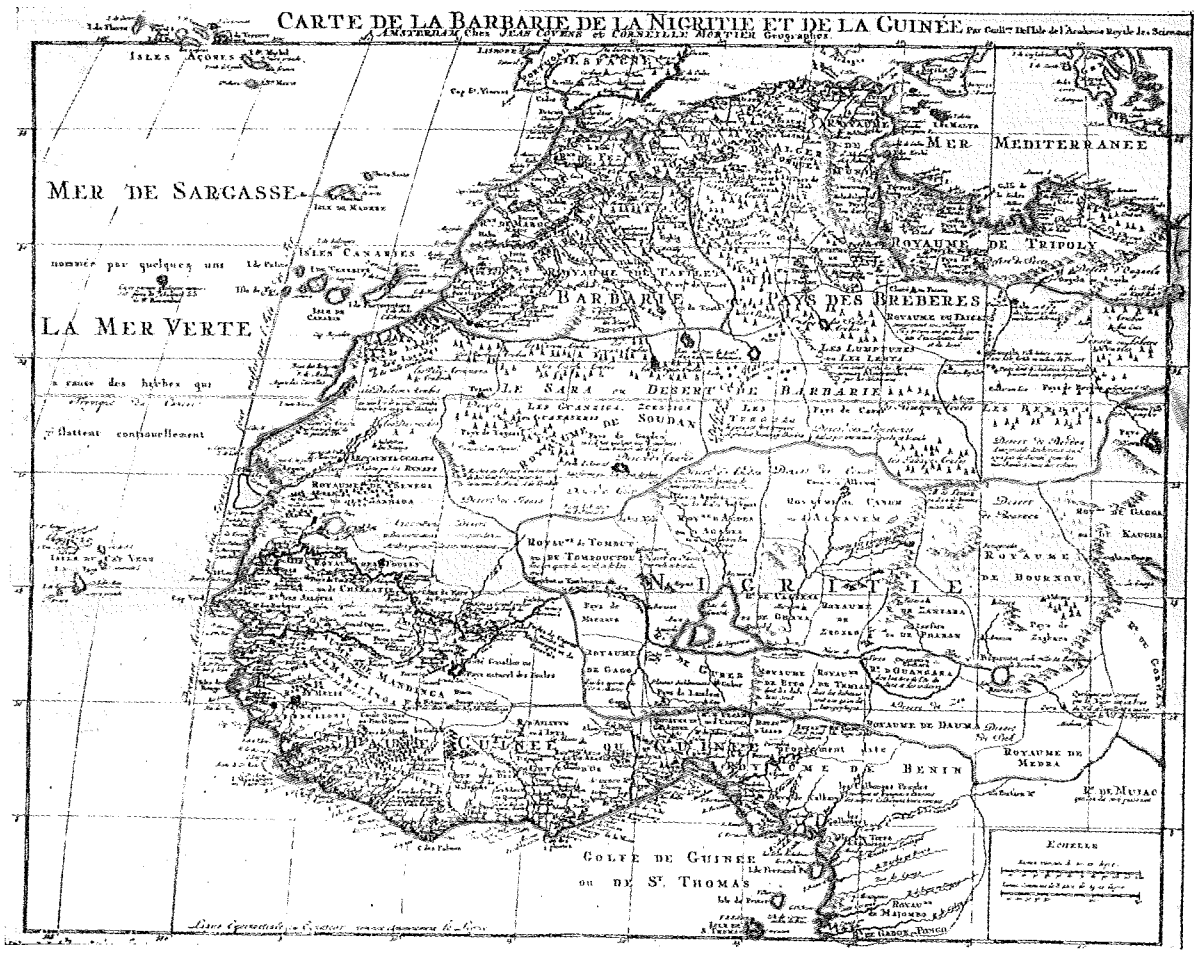


DIAGRAM 1.1.2-6

Guillaume de Lisle — 1703

strange that no attempt was made to ascend the supposed outlets from the sea. Yet even then there were still fanciful theories about the course of the Niger, and GENERAL DONKIN actually tried to prove that the river flowed north across (and under) the sands of the Sahara Desert to the Mediterranean.

It should be realised, however, that two formidable obstacles postponed for a long time any thorough exploration of the middle and lower courses of the Niger and Benue. Penetration inland from the estuaries in the south was halted by the prevalence of malaria and other diseases which took a heavy toll of the lives of non-indigenous peoples, whilst penetration from the north, that is, from Sokoto or Bornu, was rendered very difficult by the tsetse fly which killed off so many horses. Only when adequate precautions were taken against malaria mosquitoes, or when the travellers used other transport methods than horseback, could the true courses of the Niger and Benue be reconnoitred.

But those 19th century explorers were both intrepid and determined, despite the obstacles. In September, 1830, RICHARD and JOHN LANDER left in two canoes for a trip down the Niger ([1

([1 LANDER, 1832. GEN. 19

(also then known as the Joliba, Kworra, Quorra, Kowara, or Fari'n Rua). They passed the Benue Confluence on October 25, but were taken prisoner at Asaba on November 5. After many difficulties they managed to escape in the Brig "Thomas" and were landed at Fernando Po, thus definitely clearing up the mystery that had been puzzling the world for centuries.

The first attempt to put the discovery of the Landers to practical use was made by MACGREGOR LAIRD, who arranged for two small steamers, the "Quorra" and the „Alburkah", to enter the Delta in 1832. After making a rough survey of that region they steamed into the main river, which they ascended to just above Lokoja. This, however, was only a small start, although the disaster that overtook a naval expedition of four vessels in 1841 caused a temporary halt to the early attempts to open up the Niger.

In 1854 DR. BAIKIE ([1] ascended the Niger and the Benue (the latter also being known as the Chadda, Tschadda, Shari or Baki'n Rua) in the "Pleiad", sent out by Laird with the aid of a Government subsidy. This vessel made careful surveys for four months (Diagram 1.1.2-7), and

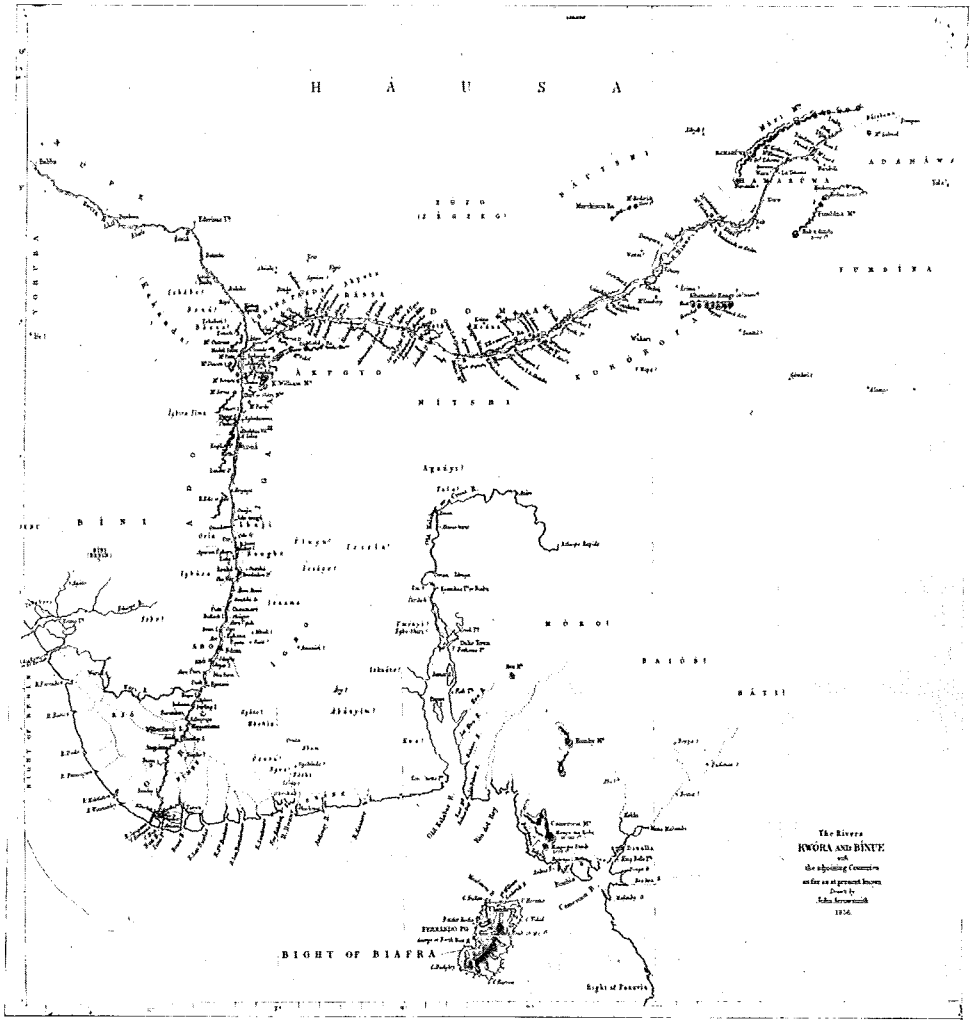


DIAGRAM 1.1.2-7

Map of Dr. Baikie's report — 1854

([1] BAIKIE, 1855. GEN. 1

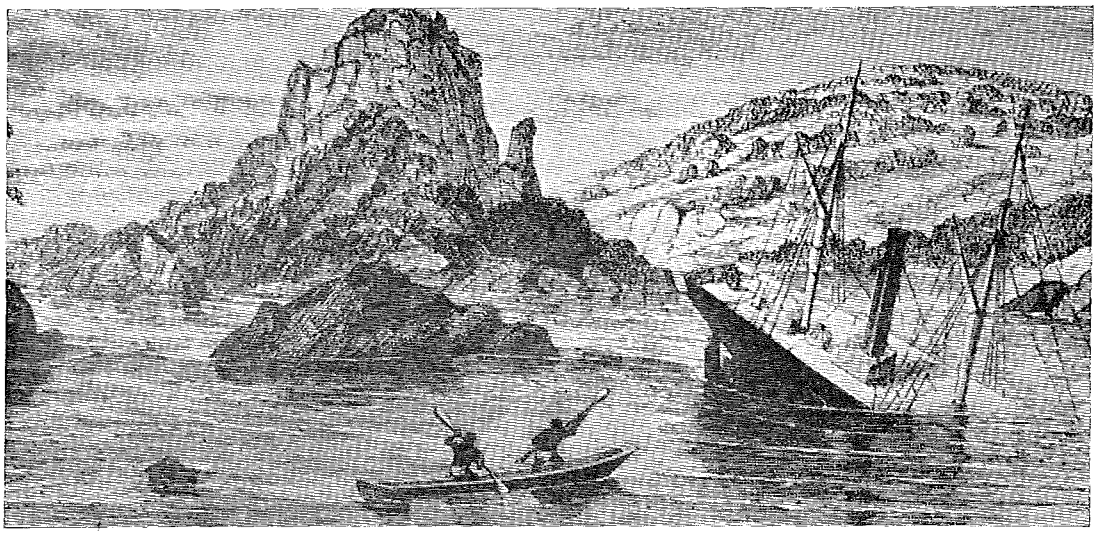


DIAGRAM 1.1.2-8

"Dayspring", wrecked on the Juju-rock near Jebba — 1857

carried out successful trading for the first time. The trip was the first exploration without casualties, owing to the prophylactic use of quinine against malaria.

In 1857 Baikie, in command of the "Dayspring", sailed up the Niger as far as Jebba, only to be wrecked there on the Juju Rock (Diagram 1.1.2-8). However, LIEUT. J. H. GLOVER explored the river as far as Bussa, and trading stations were established at Abo, Onitsha and Gbebe just below Lokoja. The party was rescued in 1858 by another of Laird's vessels, the "Sunbeam".

By 1865 a good deal of irregular trading by individual firms and persons had sprung up on the Niger and many ships were sent inland with cargoes for disposal. These were the real start of the opening up of the river which from then onwards steadily increased. In 1878 striking progress had been achieved. Four British Companies were then operating in the Niger Valley: the West African Company (Manchester), Messrs. Alexander Miller Brothers & Co. (Glasgow), the Central African Trading Company (London), and James Pinnock & Co. (Liverpool); whilst in addition several small firms and individual merchants pushed their way up the Delta rivers to a point 600 miles inland. These Companies used 14 steamers in the Niger trade, all of them maintaining river stations at Akasa, Aboh, Ndoni, Abragada, Odogiri, Utchi, Osamari, Akuso, Lower Oko, Onitsha, Gbokem, Lokoja, Yamaha, Egga, and many other smaller places along the Niger and Benue. The approximate quantity of produce shipped from the Niger Valley in 1878 was:

5,000 tons of palm oil	at £	39 per ton	= £	195,000
65 tons of ivory	at £	800 per ton	= £	52,000
1,500 tons of shea butter	at £	39 per ton	= £	58,500
150 tons of benniseed	at £	24 per ton	= £	3,600
50 tons of groundnut	at £	12 per ton	= £	600

giving a total of £ 309,700 for that year.

The time came, however, when the natives would trade only for spirits and firearms for their local wars, so that there was the great danger of demoralisation of the Lower Niger area

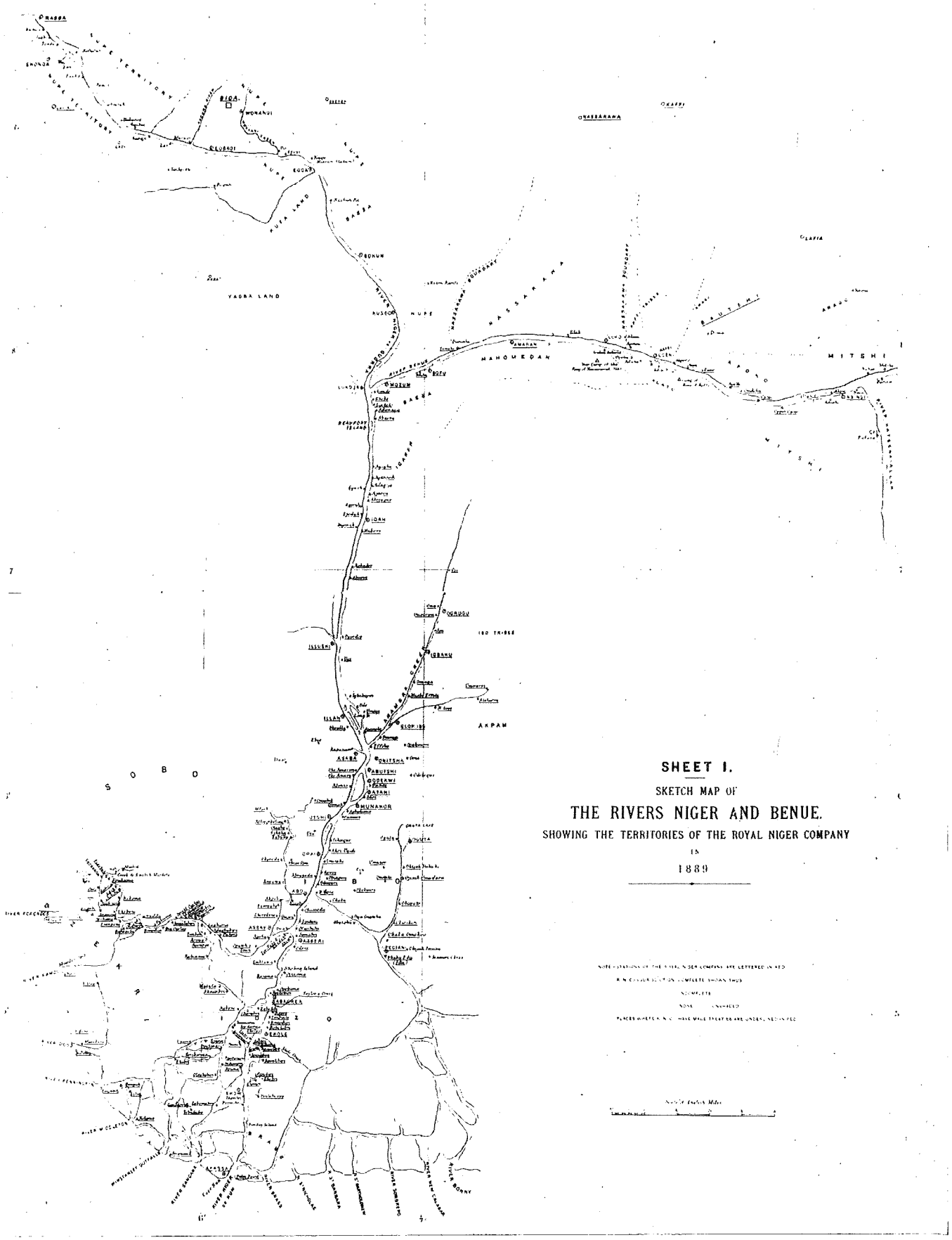


DIAGRAM 1.1.2-9

Map of Royal Niger Company

as complete as it has already become in the Delta. Finally it was decided in 1879 to form one Company, with GOLDIE TAUBMAN behind the plan, and the United African Company (later the National African Company) was established. In 1888 this Company received a "Charter" from the British Government, and again changed its name, this time to the Royal Niger Company.

In those days its headquarters was located at Akassa on the Nun River, a few miles from the sea, from which it controlled its extensive territories (Diagram 1.1.2-9). But when towards the end of the century the Nun became shallower, the Company looked for another location, and finally selected Burutu, a small island 12 miles from the coast.

In 1900 the British Government, by arrangement with the Royal Niger Company, revoked the Charter and assumed full and direct control of the Company's territories.

In this century, many more scientific and commercial expeditions have explored the Niger and Benue Rivers. Special reference should be made to the exhaustive description of the rivers and watersheds, including the rainfall and run-off, which has been given by Dr. KURT NIEHOFF (1. His work was based on thorough studies made during the years preceding the First World War. Being the only comprehensive description available, it has served as a welcome basis for the present NEDECO investigation (see Diagram II, 4.1.1-1).

1.1.3. International status and national laws of the Niger and its tributaries

Internationally free navigation of the Niger and its affluents was first established by the *General Act of Berlin* (2, which was signed on February 26, 1885 by Great Britain, Germany, Austria, Belgium, Denmark, Spain, France, Italy, Holland, Portugal, Russia, Norway, Sweden and the United States of America. It was ratified by all save the last. No time limit was set to its operation. The treaty was concerned with far wider issues than the prevention of preferential tariffs (3. It dealt with important issues of equality, without respect of nation, in the exploitation of African resources, both in matters of industrial development and of individual settlement. It included declarations relating to the abolition of the slave trade, and the neutrality of these African territories in the event of war. It provided for the free navigation, also on the Congo River.

These wider issues must be remembered in any discussions on the abrogation of the Treaty, for in many respects it has been of immense benefit to both the development of Africa and to the position of investors in African territories. The original treaty provided for completely free trade within the area to which it applied. This was considerably wider than the Congo Basin proper.

The original Act of Berlin was modified by various subsequent treaties, and in particular by the *Treaty of Brussels*, signed in 1890, which authorized the powers which had signed or acceded to the Act of Berlin to impose duties for revenue purposes, not to exceed 10 per cent ad valorum and without differential treatment or transit duties.

In the British areas unaffected by the Congo Basin Treaties, preference to British goods is sometimes prevented by treaties of more local application. In Nigeria any exclusively imperial preferential duties have been prohibited by the *Anglo-French Convention* (2 of June 14, 1898. The relevant Article of the Convention was, however, renounced by France with effect from October 1936, and the tariff regime to be adopted was further considered.

The 1914—1918 war put an end to all treaties as between opposing belligerents, but left unaffected treaties between allied belligerents, or between belligerents and neutrals. A conference

(1 NIEHOFF, 1917. GEO. 32

(2 HAILY, 1938, PP. 1341—1343. GEN. 13

(3 This subject was dealt with exclusively by the group of treaties conmonly known as the Congo Basin Treaties

was therefore called at *St. Germain-en-Laye* in 1919 for the purpose of revising the Acts of Berlin and Brussels. The Treaty was signed on September 10, 1919. The resulting Convention, which now governs the trade of the Congo Basin convential zone, was ratified by Great Britain, Belgium, France, Japan, Portugal, and the United States of America. It provides that the signatory Powers shall maintain between their respective nationals and those of State members of the League of Nations which may adhere to the Convention a complete commercial equality in the area defined in the Act of Berlin.

Since, except in regard to the Schedule of areas, the Convention abrogates the Treaties of Berlin and of Brussels, the limitation of customs duties to 10% no longer applies, and the sole requirement is equality of treatment to nationals of all States.

CONVENTION OF SAINT GERMAIN-EN-LAYE, 1919

ARTICLE 5

Subject to the provisions of the present Chapter, the navigation of the Niger, of its branches and outlets, and of all the rivers, and of their branches and outlets, within the territories specified in Article 1, as well as of the lakes situated within those territories, shall be entirely free for merchant vessels and for the transport of goods and passengers.

Craft of every kind belonging to the nationals of the Signatory Powers and of States, Members of the League of Nations, which may adhere to the present Convention, shall be treated in all respects on a footing of perfect equality.

ARTICLE 6

The navigation shall not be subject to any restriction or dues based on the mere fact of navigation.

It shall not be exposed to any obligation in regard to landing, station, or depot, or for breaking bulk or for compulsory entry into port.

No maritime or river toll, based on the mere fact of navigation, shall be levied on vessels, nor shall any transit duty be levied on goods on board. Only such taxes or duties shall be collected as may be an equivalent for services rendered to navigation itself. The tariff of these taxes or duties shall not admit of any differential treatment.

ARTICLE 7

The affluents of the rivers and lakes specified in Article 5 shall in all respects be subject to the same rules as the rivers or lakes of which they are tributaries.

The roads, railways or lateral canals which may be constructed with the special object of obviating the innavigability or correcting the imperfections of the water-route on certain sections of the rivers and lakes specified in Article 5, their affluents, branches and outlets, shall be considered, in their quality of means of communication, as dependencies of these rivers and lakes, and shall be equally open to the traffic of the nationals of the Signatory Powers and of the States, Members of the League of Nations, which may adhere to the present Convention.

On these roads, railways and canals only such tolls shall be collected as are calculated on the cost of construction, maintenance and management, and on the profits reasonably accruing to the undertaking. As regards the tariff of these tolls, the nationals of the Signatory Powers and of States, Members of the League of Nations, which may adhere to the present Convention, shall be treated on a footing of perfect equality.

ARTICLE 8

Each of the Signatory Powers shall remain free to establish the rules which it may consider expedient for the purpose of ensuring the safety and control of navigation, on the understanding that these rules shall facilitate, as far as possible, the circulation of merchant vessels.

ARTICLE 9

In such sections of the rivers and of their affluents, as well as on such lakes, as are not necessarily utilised by more than one riverain State, the Government exercising authority shall remain free to establish such systems as may be required for the maintenance of public safety and order, and for other necessities of the work of civilisation and colonisation; but the regulations shall not admit of any differential treatment between vessels or between nationals of the Signatory Powers and of States, Members of the League of Nations, which may adhere to the present Convention.

In addition to the Convention of St. Germain, various Conventions on the Freedom of Transit, the Regime of Navigable Waterways of International Concern, and the International Regime of Maritime Ports were entered into in *Barcelona* in 1921 and in *Geneva* in 1923.

In 1950 the *International Conference on Transport* in Central Africa South of the Sahara recommended joint consideration by the French and British of the problem of the Benue route and the Port of Burutu.

Although Burutu is a private port, it is open to all ships desiring to use it. All traffic is subject to the same customs regulations as in other Nigerian ports ([1.

In 1956 a "*Statement of Policy* by the Government of the Federation for Navigation in the Ports of the Western Delta and on the Niger and Benue Rivers" concerns the following matters that have been the subject of study by the Federal Government:

1. The future relationship of the Nigerian Port Authority to the Delta Ports where the shore-based installations are privately owned (at Burutu, Warri and Sapele). From this Statement of Policy the following may be quoted:

> The Federal Government has decided that the Ports Authority shall not take over the privately-owned shore installations at Burutu, Warri and Sapele for a period of at least twenty-five years from the 1st of January, 1957. The Authority will continue to be the port authority as at present. This undertaking will be subject to two conditions:
> (a) Sea-going ships calling at these ports must be treated on the principle of first come, first served — irrespective of nationality and ownership. This is merely a reaffirmation of current practice at these ports and conforms with the international Conventions governing the regime of maritime ports to which the Federal Government is a party.
> (b) The maximum charges to be levied for the services of these privately-owned facilities will be subject to the approval of the Federal Minister of Transport, the companies being, however, free to vary their charges within the approved upper limits to suit their commercial operations. These charges will apply without discrimination equally to all ships and cargoes at the three ports, irrespective of nationality and ownership. In fixing these maximum charges the Minister will have regard to the companies' operating costs and also to the interest and amortization payments on capital investment.

2. Government's obligations under International Law for navigation on the Niger and Benue Rivers, where traffic is likely to increase with the increase of trade at the Delta Ports.

There is considerable *legislation concerning the inland waterways* distributed over a number of enactments. One of these laws is the Minerals Ordinance, 1945, which deals with "ownership" and "rights" of water and waterways of Nigeria ([2.

This law, with minor amendments by the Minerals (Amendment) Ordinance No. 8 of 1948, repeals and re-enacts the Minerals Ordinance of 1916 and all subsequent amending Ordinances and came into operation on February 22, 1946. Its relevant provisions are:

S.3 (1) The entire property in and control of all minerals and mineral oils in, under or upon any lands in Nigeria, and of all rivers, streams and water-courses throughout Nigeria, is and shall be vested in the Crown, save insofar as such rights may in any case have been limited by any express grant made before the commencement of this Ordinance.

S.3 (2) Except as in this Ordinance provided no person shall prospect or mine on any lands in Nigeria, divert or impound water for the purpose of mining operations.

Crown "ownership" concerns: Minerals and mineral oils; foreshores and beaches; inland water and right of fishing, etc. therein; unoccupied lands; swamps and grasslands; unsettled districts; and forest reserves.

Another form of these laws is the "Legislative List" of the Nigeria (Constitution) Order in Council, 1954. The Constitutional Order in Council places within the exclusive jurisdiction of the Federal Government "shipping and navigation on the River Niger and its affluents and on such other Inland Waterways as the Governor-General may by Order declare to be an international waterway or an inter-regional waterway" and "water from sources declared by the Governor-General by Order to be sources affecting more than one Region or a Region and the Southern Camerouns" (Item 22 (b) and 39 of the First Schedule). On the other hand, "water power" appears on the concurrent Legislative List (Item 31). The Federal Inland Waterways Department is, therefore, concerned with waterways declared to be international or inter-regional

([1 UAC: Stat. and Ec. Review 1948, No. 2. p. 46. GEN. 36
([2 OLAWALE ELIAS, 1953. GEN. 25

under the terms of the Constitutional Order in Council. Legal Notice No. 59 of 1955 defines such waterways and, in effect, defines the scope of the Inland Waterways Department.

It will be noted that the Niger Transit Ordinance (Cap 150) defines the River Niger as including "all its affluents, branches and outlets within Nigeria".

The *International Law Association* discussed (1 at its meeting in New York in September, 1958, the subject of the use of international rivers and adopted the principle that "except as otherwise provided by treaty or other instruments or customs binding upon the parties, each co-riparian State is entitled to a reasonable and equitable share in the beneficial uses of the water of the drainage basin".

At its meeting in London, early November 1958, the Association approved this principle and other fundamental general principles governing the use of international waters.

Important amongst others is that the discussions within the Association have resulted in unanimous rejection of the thesis, advanced at one time or another in the past by some Governments, that so long as changes in a river regime were made wholly within the territory of one State, that State need not, as a matter of law, concern itself with possible adverse effects outside its boundaries, and therefore with objections of others as to alleged infringements of their legal rights.

Regarding "water rights" there have been different developments in *the other countries of Africa* which for a long time have been administered by Great Britain. At present the general policy is to enact or to revise existing legislation with regard to water rights and water economy. In South Africa, however, the tradition of unlimited rights on property is still unbroken and it will take a long time and expensive procedure to change it, while in Kenya the water rights have been legislated for by a far-seeing policy of water economy (2 (3.

The *Public Lands Acquisition Ordinance* No. 9 of 1917 empowers the Governor to acquire lands when required for public purposes.

It seems important to ensure that Government explorers have adequate powers for acquisition of land for such purposes as the erection of beacons, leading-lights and mile-posts and the construction of river works, etc.

1.2. GEOGRAPHICAL OUTLINE (4

1.2.1. Population

The Niger drainage area, which covers half of West Africa south of the Sahara, supports a population of over 20 million people. The largest part of this population lies in Nigeria, although the drainage area in Nigeria is not more than one-third of the total. Nigeria, with a population of over 31 million according to the 1952/1953 census and at present with an estimated population of 34 million, is by far the most densely-populated country of West Africa.

Some figures of 1955 are given below in Table 1.2.1-1 for comparison. Although the population of Nigeria is over one-half of the population of West Africa and at present may reach 92 per square mile, it is sparsely populated when compared with all European countries and many countries in Asia.

(1 "The Times", London, November 21, 1958
(2 The Kenya Water Ordinance No. 56, 1951
(3 The Water Rules, 1953
(4 see Maps A and B inside back cover.

Large differences in concentration of the population exist. These differences are related with rainfall, the accessibility of ground-water, infestment by tsetse fly, the nature of the soil, natural vegetation and historical factors. These relations have been described by several authors ([1].

TABLE 1.2.1-1

POPULATION OF VARIOUS COUNTRIES

	Area in 1,000 sq.miles	Population in millions	Population density per sq.mile
Nigeria	375	32	86
British West Africa	425	36	84
French West Africa	1,810	16	9
Africa	11,600	224	19
Asia	17,300	1,470	85
Europe	3,900	610	155
USSR	8,700	200	23
India	1,280	380	300
China	3,800	585	155
France	215	43	200
United Kingdom	95	51	535
The Netherlands	13	11	850

Diagram 1.2.1-2 to 5 inclusive indicate these differences roughly for West Africa and in more detail for Nigeria, according to the latest available statistics ([2]. Important are the three thickly-populated areas around Kano, Owerri and Ibadan. The coincidence with three export areas of groundnuts, palm-oil and cocoa respectively is marked. In between these areas just below the

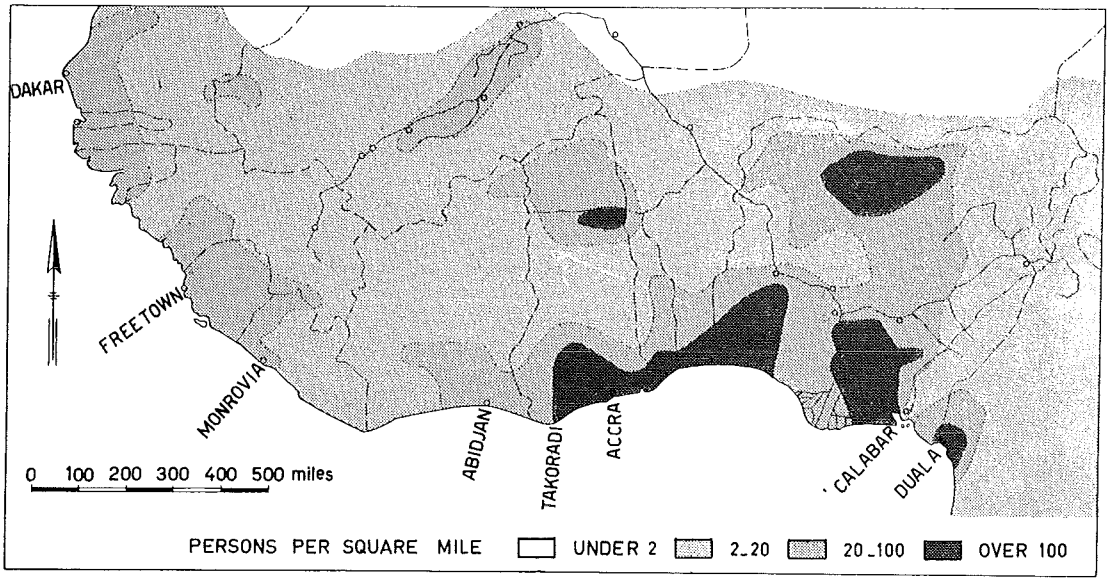


DIAGRAM 1.2.1-2

Rough Indication of population density over West-Africa

according to Pedler

([1] PEDLER, 1955. GEN. 29 and BUCHANAN and PUGH, 1955. GEN. 3

([2] FEDERAL STATISTICS, 1958. TRP. 3

latitude of 10°N (i.e., in the Niger and Benue Valleys) sparsely-populated areas are found, where the sleeping-sickness caused by the tsetse fly has resulted in the population being small and scattered.

The average annual increase of the population is between 1.2 and 1.5 per cent. This is a high rate which means a doubled population in approximately 60 years.

Urbanisation has not progressed far in West Africa, as its economy is almost entirely based on agriculture. In Nigeria, the largest and most numerous concentrations are found in the Western Region, the capital of which is Ibadan, the largest town in West Africa, with a population of 500,000. In the Northern Region the urbanisation is smallest, and many of the Fulani tribe lead a nomadic life as herdsmen. Kano is the largest town with a population of 130,000. The Eastern Region has a population density of approximately 265, which is higher than that of the Western Region with 150 and the Northern Region with 65, as the towns in this Region are more numerous and closer together than in the other Regions. Onitsha is the largest town in the Eastern Region with a population of 80,000. Lagos, the Federal Capital and principal port of Nigeria, is thickly populated, and has about 325,000 inhabitants (1957).

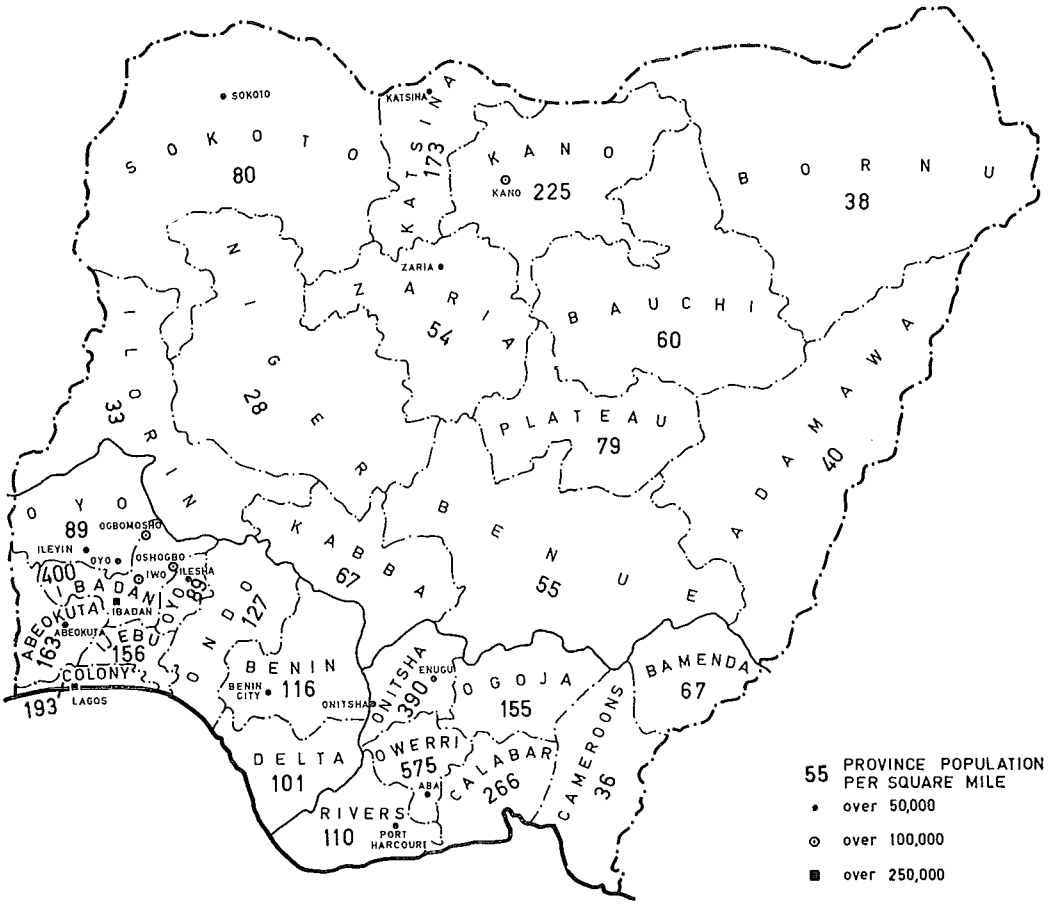


DIAGRAM 1.2.1-3

Province population and urbanisation in Nigeria
derived from Digest of Statistics 1958

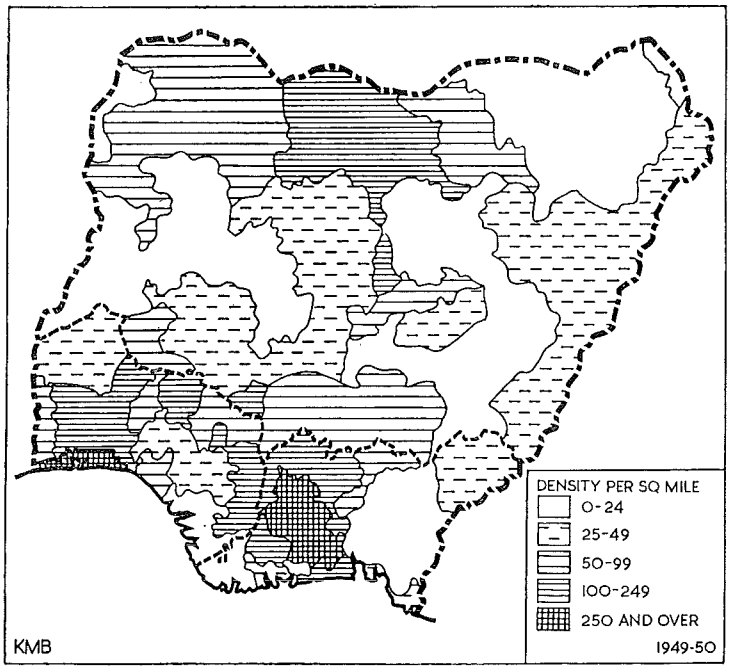


DIAGRAM 1.2.1-4

Population density of Nigeria in 1949—1950

according to Buchanan and Pugh

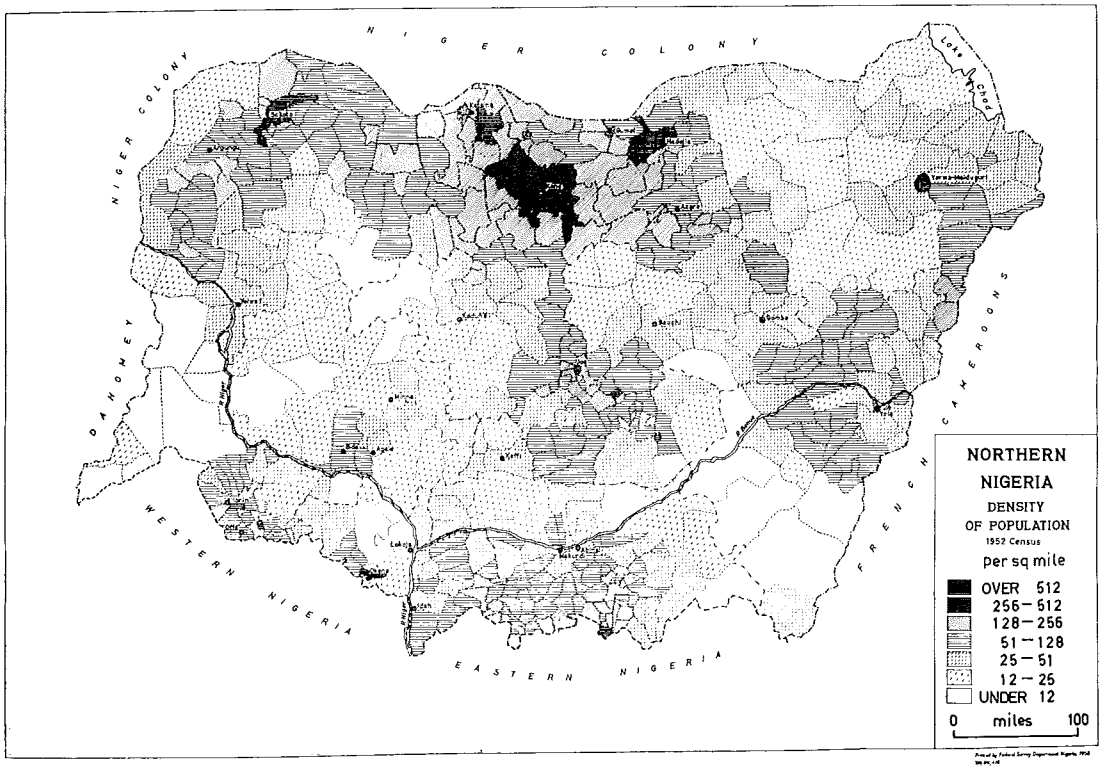


DIAGRAM 1.2.1-5

Detailled density of population in Northern Nigeria

according to Federal Survey Department Nigeria (1958)

PHOTOGRAPH 1.2.1-6

Small communities are the normal pattern

Table 1.2.1-7 lists towns with over 50,000 population according to the 1952/1953 census:

TABLE 1.2.1-7

LARGE TOWNS IN NIGERIA

Town	Population	Town	Population
Western Region		*Northern Region*	
Abeokuta	85,000	Katsina	55,000
Benin City	55,000	Kano	130,000
Ibadan	500,000	Sokoto	50,000
Ilesha	75,000	Yerwa	55,000
Iseyin	50,000	Zaria	55,000
Iwo	100,000	*Eastern Region*	
Ogbomosho	140,000	Aba	60,000
Oshogbo	125,000	Enugu	65,000
Oyo	75,000	Onitsha	80,000
Lagos Township (1957)	325,000	Port Harcourt	75,000

Along the Niger and the Benue a certain amount of urbanisation has taken place in centres of administration, agriculture, trade and in traffic junctions. A summary of the most important places along these two rivers follows (see Map A inside back cover):

NIGER	Mile	
Kouroussa	2,307	At the upstream end of the navigable stretch Bamako—Kouroussa with a rail-link to the harbour Konakri in Guinea. A railway bridge over the Niger.
Bamako	2,081	At the downstream end of the navigable stretch Kouroussa—Bamako with a railway link to Dakar. Administration centre of French Soudan. A ferry at high water and a road at low water over the Niger.
Koulikoro	2,041	The rail-head of the railway-line to Dakar. Upstream end of the navigable stretch Gao—Koulikoro. Base of river fleet.
Segou	1,940	A dam and a bridge over the Niger (Sansanding) with centre of the large irrigation scheme of the Office du Niger.
Mopti	1,765	Concentrations in the relatively thickly-populated Central Delta. The former at the Confluence of the Niger and Bani Rivers, Timbuctu at the junction of several caravan routes and the latter with a ferry over the Niger.
Timbuctu	1,528	
Gao	1,270	
Niamey	995	Administration centre of the Niger Territory in French West Africa. Routes to: Chad area and Gao, Timbuctu in the Central Delta, and Ouagadougou, centrally situated in the densely-populated area south of the Central Delta. Ferry over the Niger.
Malanville	811	A bridge over the Niger on the southward route to the railhead at Parakou and the harbour Cotonou.

Jebba	556	A bridge and a railway-line over the Niger, linking the groundnut and cotton areas in the triangle Sokoto—Zaria—Kano with the harbour Lagos.
Pateggi	486	On the Confluence of the Niger and Kaduna Rivers, centre of a potential irrigation area.
Baro	434	Terminus of railway-line linking the Northern producing areas with a river route to the seaports Warri and Burutu.
Lokoja	362	On the Confluence of the Niger and the Benue, with ferries over the Niger. Headquarters of Inland Waterways Department. Cotton ginnery.
Idah	310	Important port for palmoil transhipment via the Niger from the southern provinces of Northern Nigeria. Ferry over the Niger.
Onitsha	232	Largest town along Niger and Benue with very important market, the largest in West Africa. Ferry over the Niger.

PHOTOGRAPH 1.2.1-8

Jebba Bridge

BENUE	Mile	
Garua	972	Well-equipped harbour in the French Camerouns. For commercial ships highest up-river harbour on the Benue. Ferry (in dry season, road) over the Benue.
Yola	888	Ferry over Benue.
Numan	846	Ferry over Benue.
Makurdi	510	A bridge and a railway-line over the Benue, connecting the Northern producing provinces with the harbour Port Harcourt.

PHOTOGRAPH 1.2.1-9

Ferry at Yola

1.2.2. Railways and roads, bridges and ferries in the river valleys

There are not many main roads or railways parallel and near to the river ([1]. An exception is the road Timbuctu—Gao—Niamey. Roads and railways concentrate on those points where crossing of the Niger and Benue is possible and they connect normally the densely-populated and cultivated areas with ports on the coast.

Routes (rail as well as road) have developed surprisingly quickly and it is amazing that one can reach, with relative ease, areas which 50 years ago were completely unexplored and 20 years ago were only attainable after trying journeys on horse-back (see also Section IV, 1.3).

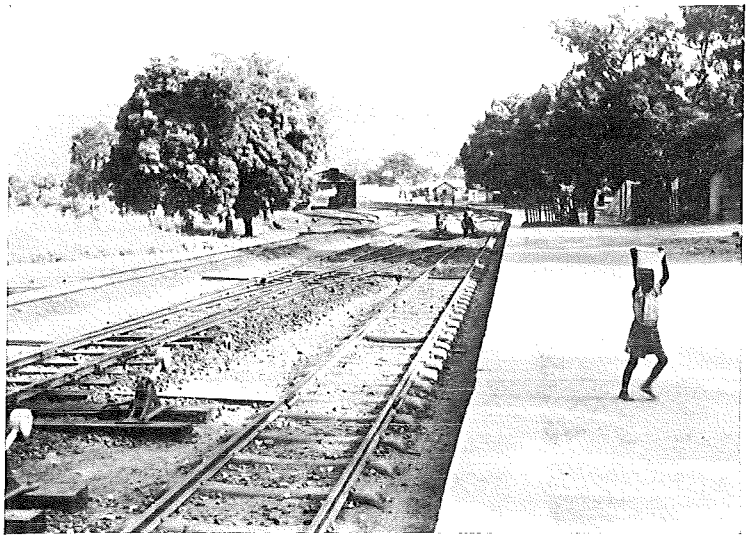
The first railway-line in West Africa was started from Dakar in 1885, and by 1923 about 800 miles of line to Koulikoro on the Niger were completed. From Konakri, Abidjan, Lagos and Port Harcourt — all harbours on the West Coast — railway-lines penetrate deep into the drainage area of the Niger. From Lome and Cotonou, the railway goes north to Atakpame and Parakou, from where road connections reach the Niger Basin.

In Nigeria, the Lagos—Jebba line, built between 1898 and 1909, was in 1912 connected at Minna to the Kano—Baro line, which itself was completed in 1911. The Port Harcourt—Enugu line, serving the coal-mines at Enugu, opened in 1916. Soon after the First World War this line was extended over the Benue near Makurdi to Kafanchan where it forks to Jos and Kaduna on the Kano line. Kaura Namoda and Nguru eventually became the railheads of the Nigerian railway system which at present comprises 1,770 miles. An extension of this system to Maiduguri has been approved and work commenced in August, 1958.

The development of roads in the Niger drainage area started under very difficult circumstances. The small population and the quantities for transport did not really justify the development of roads, whilst as the existing railway-lines already ran at a loss the competition of motor transport would not improve the position. Laws were therefore made to stop this competition and road-

([1] see Map A inside back cover.

building was restricted to extensions of railways from the existing railheads. Under such circumstances it was too costly to build roads of high standards, and so many thousands of miles of roads consist only of laterite without a stone foundation.



PHOTOGRAPH 1.2.2-1

Baro station

The French roads form a system. Two main roads travel eastward from Dakar and Konakri with many interlacing connections in the area between Ségou, Bobo Dioulasso, Ouagadougou and Timbuctu, and they join at Niamey, from where a road leads east to Fort Lamy. This system is linked to the south coast of West Africa by roads to the ports of Abidjan, Accra, Lome, Cotonou, Lagos and Port Harcourt.

In Nigeria, the roads from Lagos and Port Harcourt, which join in Kano, cannot be con-

PHOTOGRAPH 1.2.2-2

One of the south-north roads

PHOTOGRAPH 1.2.2-3

Ferry at Lokoja

sidered efficient main roads over large distances of their tracks. Also the connection between Kano and the French road system leaves much to be desired. In fact, each territory maintains a separate network, and the French preferred tracks leading to the coast over their own territory to keep traffic and transport in their own hands. Good coordination between the different territories could lead to a better system of main roads in West Africa with economic advantages for all concerned.

The roads from Lagos and Port Harcourt to Kano and the not yet completed Bamenda—Yola road are three south-north arteries (Photograph 1.2.2-2), which together with four east-west arteries form a framework linking the major towns in Nigeria. This framework crosses the Niger and Benue Rivers at several places.

The number of bridges is very small, mainly because the rivers are so wide (a stream channel of $\frac{1}{2}$—1 mile with extensive flood-plains of mostly several miles) that bridging has remained an uneconomic proposition. Not long ago a bridge over the Niger near Onitsha was studied, and it might be stated here that to bridge the Niger at this point seems at present the most balanced plan — geographically as well as economically — for such a bridge would connect the densely-

populated parts of the Western and Eastern Regions of Nigeria. The Government of the Federation of Nigeria has consequently decided to build this bridge.

Bridges are found near Kouroussa, Sansanding, Malanville, Jebba and Makurdi, and ferries for motor traffic are near Bamako, Gao, Niamey, Lokoja, Idah, Onitsha, Garua, Yola and Numan.

1.2.3. Ports

The main ports along the Niger and Benue are Koulikoro (Mile 2,041), Ségou (Mile 1,940), Onitsha (Mile 232), Baro (Mile 434) and Garua (Mile 972). Each of these harbours is situated at the end of a navigable stretch or at a railway-head, except Onitsha and Ségou, the latter being situated just above the dam at Sansanding. Apart from Baro, all these ports have certain facilities as quays, cranes, motorized quay transport and goods sheds. At Baro, a rock embankment provides ample space for the railway sidings; by man-handling the cargo along improvised flights of steps, daily totals of loaded produce of 1,000 tons can still be reached.

PHOTOGRAPH 1.2.3-1

Handling at Baro

To indicate the importance of the main ports, a list of tonnage handled in the middle 1950's is here given:

Koulikoro (estimated)	60,000 tons
Ségou (estimated)	20,000 tons
Baro	36,500 tons

Lokoja	9,500 tons
Idah/Agenebode	19,000 tons
Onitsha/Asaba	76,000 tons
Garua	40,000 tons
Yola/Dalmara	13,000 tons
Lau/G'Usumanu	5,500 tons
Ibi	6,500 tons
Katsina Ala (K'Ala River)	8,000 tons
Makurdi	9,500 tons

In recent years Baro has participated to a greater extent in the evacuation of the cash crops from the North of Nigeria to the seaports: in the season 1957—1958 over 70,000 tons of groundnuts were handled at Baro. Needless to say, this route by water eventually is the most economic route for bulk products. Above all, the improvement of Escravos Bar projected for 1960 is of essential importance for Baro and all other river ports.

The port of Makurdi is of more importance than would follow from the above list. Temporary storage there makes it possible during the short navigable season of the upper reaches of the Benue to use the fleet tonnage more effectively through a shuttle system on Makurdi.

Burutu and Warri are ports at the mouth of the Niger.

Ocean-going ships can only cross the bar in the entrance (Escravos) if their draughts are 12—14 feet during H.W. This severely restricts trade via the Western Delta up and down the Niger-Benue river system. Main-line ships sailing on the West African Coast can only be part-loaded (1,200—1,400 tons) and have to wait for high-water before crossing the bar. This means that the shipping companies have been obliged to introduce coasters and creek services to supplement their main-line ships in clearing the ports. Cargoes are transhipped from the Delta ports to and from ocean-going vessels at Lagos, and the cost of these operations is met by a surcharge of 15/- a ton on all cargo shipped from the Western Delta ports. However, a projected deepening of the Escravos Bar to 20 feet is due to commence in 1959 ([1. This will strongly stimulate trade through the Western Niger Delta and open up many of the possibilities of the Niger-Benue system as a major transport route.

During the 1955—1956 shipping season in Warri 17,500 tons were sent up and 44,000 tons were received from the Niger and Benue. For Burutu these figures were 63,000 tons and 115,000 tons respectively. Their importance in relation to the other seaports follows from Table 1.2.3-2:

TABLE 1.2.3-2

CARGO 1955/1956

tousands of tons

	Loaded		Unloaded	
	Foreign trade	Coastwise trade	Foreign trade	Coastwise trade
Lagos	950	120	1,450	225
Burutu	60	65	60	25
Warri	40	35	55	10
Sapele	270	35	70	20
Port Harcourt	435	150	410	20
Calabar	115	—	50	15
Degema	85	—	5	—
Victoria & Tiko	85	—	35	10
Total	2,040	206	2,135	325

([1 NEDECO, 1954. GEN. 23

The coastwise traffic from the Delta ports of Burutu, Warri and Sapele is explained above. The large tonnage shipped coastwise between Port Harcourt and Lagos consists of coal from the Enugu coalfields.

1.2.4. Use of the Rivers

a. *Navigation*

Of its total length of 2,550 miles, about 75% or 1,950 miles of the Niger are useful for commercial shipping, divided over four navigable stretches:

(i) Kouroussa—Bamako 200 miles
(ii) Koulikoro—Ansongo 800 miles
(iii) Labbenzenga—Yelwa 400 miles
(iv) Jebba—Ocean 550 miles

The last-mentioned stretch has an important side-branch: the Benue, which is navigable up to Garua, 600 miles from the Confluence with the Niger at Lokoja.

Over the interjacent parts navigation is obstructed by rapids. A few canoes manage to pass the rapids during the H.W.-period, but no barge with a reasonable tonnage can pass without taking unjustifiable risks.

Although the Niger is navigable over rather long stretches, commercial navigation on the river is relatively small compared with the possibilities which are offered by the river. The question whether this originates from a lack of cargo to be carried or as the result of the difficult position of the shipping companies to compete with other kinds of transport is dealt with in IV, 1.3. In Diagram 1.2.4-1 a sketch is given of the navigable stretches, together with the period during which commercial shipping is possible in an average year. A similar sketch for the navigable periods on the Benue is given in Diagram 1.2.4-2.

Ref. (i). There is hardly any shipping between Kouroussa and Bamako. This is probably due to the fact that there are railway stations at each end of this river stretch, which makes the maximum haul by river only 100 miles. Over such a short distance the transport by lorry seems to be more economical.

Ref. (ii). The shipping on the next stretch, Koulikoro—Ansongo, is of more importance, because this part of the river can be considered as the extension of the railway-line Dakar—Bamako—Koulikoro.

Yet the river transport is not as important as it could be as a part of this transport route to Dakar. Another railway-line, which runs parallel to the Niger at a distance of about 200 miles, namely, the line from Ouagadougou via Bobo Dioulasso to Abidjan on the Ivory Coast, makes it cheaper to bring the goods from the area south of the Niger by lorry to this railway-line and rail them to Abidjan than to bring them to the Niger, ship them to Koulikoro and then finally rail them to Dakar. For goods which originate from north of the Niger or from towns along the Niger, the cheapest method of transport is via the river to Koulikoro and then by rail to Dakar. But as the rainfall north of the Niger is relatively low, the amount of produce to be transported from this northern area is not very important.

It is mostly due to the agricultural products and the requirements of the steadily-expanding area of the cultivated land of the irrigation scheme near Sansanding (as discussed later in this paragraph) that the average transport by river between Koulikoro and Ségou-Sansanding amounts to 25,000 tons a year in each direction, giving a total of 50,000 tons a year. This tonnage is likely to grow, following the further cultivation of this area (at the moment only 6% of the

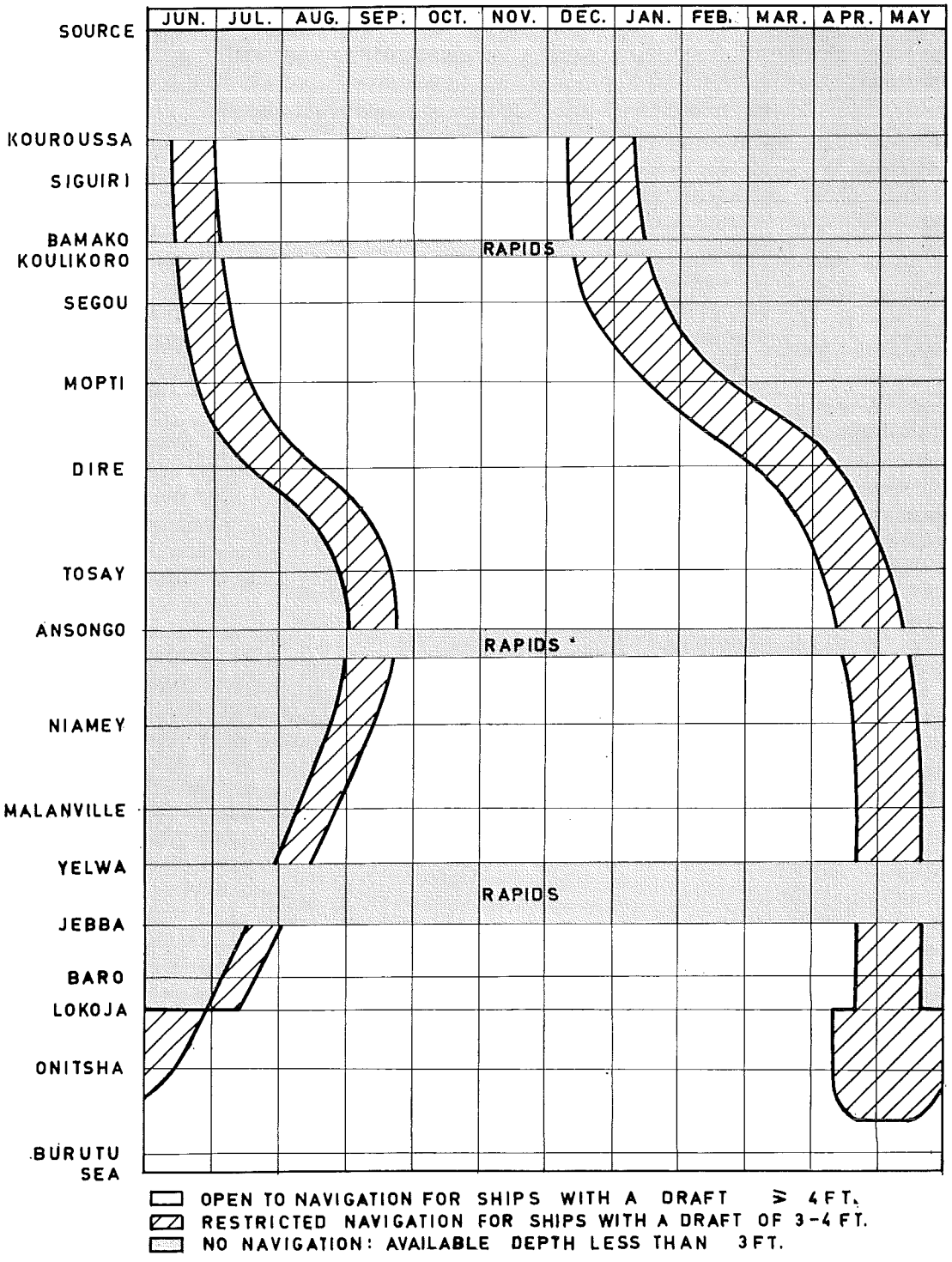


DIAGRAM 1.2.4-1

Navigability of the Niger

total area of the scheme has been brought into use), although the crop becomes available for transport at the moment when the river is low, and navigation is difficult.

Downstream from Sansanding the transport of goods is comparatively small, and only the bulk transport of fuel is worth mentioning. During the navigable period, there is a fortnightly passenger service between Koulikoro and Gao, which also carries a little cargo.

Ref. (iii). Between Labbenzenga and Yelwa the possibilities for navigation are rather good. The main flow of export crops, however, crosses the Niger at right angles, as the transport along the Niger has hardly any chance when the rapids below Yelwa cannot be passed. As a result, the last commercial ship, the stern-wheeler "Van Vollenhoven", has been in 1957 removed from this stretch when it sailed down the Yelwa/Jebba rapids and finally reached Lagos via Burutu and the creeks. The building of a rather low-lying bridge, which will cross the Niger at Malanville, emphazises the superiority of road transport over river transport in this area.

Ref. (iv). The commercial shipping on the Niger downstream of Jebba, from where the ships can reach the ports on the Gulf of Guinea, has more perspectives, also because of the relatively long period during which the Niger is navigable, i.e., nearly nine out of the twelve months. The river transport between Baro and the Delta ports serves as the extension of the railway-line from Kano to Baro, and in addition to this through transport, much cargo is carried between the coast and the major towns along its course, i.e., Lokoja, Idah and Onitsha.

Apart from this river transport, a reasonable amount of cargo is carried during the wet season via the Benue from the French territory around Lake Chad and also from the major towns along this river, i.e., Yola, Numan, Lau and Makurdi, using the Niger below Lokoja.

A more detailed view on the Niger and Benue as a shipping route in Nigeria is given in

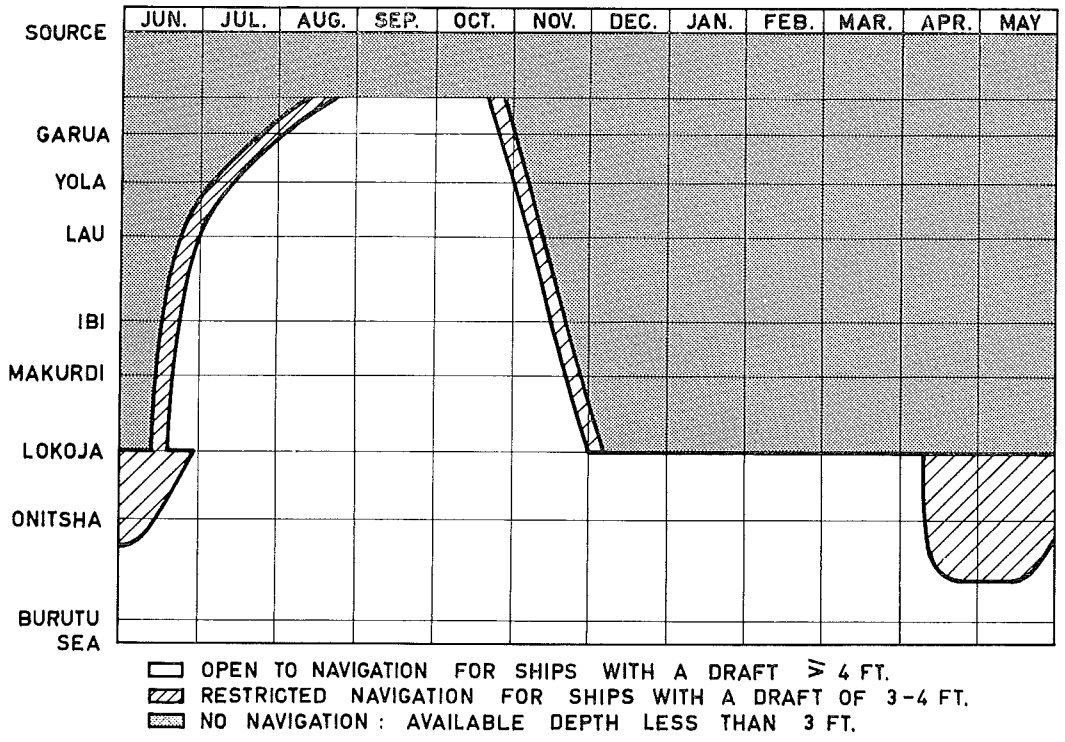


DIAGRAM 1.2.4-2

Navigability of the Benue

Chapters 3, 4 and 5 of Part IV. In total 120 million ton-miles per year are carried on these stretches of the Niger and the Benue. This is more than ten times the average annual transport on the river-stretch between Koulikoro and Ansongo.

Some projects which could improve the possibilities of the navigation on the Niger are:

(i) To make shipping possible over the 40-mile stretch between Bamako and Koulikoro to connect the upper two navigable parts of the Niger. The fall between Bamako and Koulikoro is concentrated in two rapids, namely, those of Sotuba and Kenié. The solution sought for is found in the construction of small dams and lateral canals and locks. But as the amount of river transport does not yet justify the necessary expenditure, this project will be considered in a later stage of the development of the river.

(ii) To improve the possibilities of the navigation over the stretch between Koulikoro and Ségou. Studies have been made, and are still in progress, to determine the best solution of the problems of this particular stretch. The difficulties for shipping originate in the lack of a sufficient discharge during 5—6 months of the year. It is found that about 650 m^3/sec (23,000 cusecs) are required to obtain a least available depth of 4 feet in the navigable channel.

Two plans of improvement are under consideration. The first involves the improvement of the channel over the stretches where the crossings limit the draught of the ships. The second provides for a dam in one of the tributaries of the Niger with which the discharge during the dry season can be raised to the required minimum of 650 m^3/sec, in order to effect a depht of 4 feet; or (if sufficient storage cannot be obtained) to 350 m^3/sec (12,500 cusecs), which would enable at least light shipping with a draught of about 2′6″.

Both plans are being examined on their merits, and it will depend on the total costs and the attendant advantages which one will be ultimately executed. In the meantime an extensive sounding of the river has been made on which a buoyage scheme is planned to mark the deepest channel.

(iii) If the development of a hydro-electric scheme near Jebba is found feasible (see under c of this Paragraph), the drowning of the rapids between Yelwa and Jebba might be an additional advantage, as this would connect the navigable stretch between Labbenzenga and Yelwa with the Atlantic Ocean. In that case Niamey would have a navigable waterway about 1,000 miles long, down to the Delta Coast of the Niger, which could be used during about 8 months out of the year. This would put Niamey in a much better situation than Garua on the Benue, which is situated at a similar distance from the Delta Coast but can only be reached 1 or 2 months per year.

(iv) Although the shipping conditions on the Niger below Jebba are rather good when compared with those on the upper reaches of the Niger, especially as to the period of navigability of the river, the navigation is hampered by numerous crossings during about six months of the year, and in an average year the shipping conditions on the Niger below Jebba are bad during three months. The amount of cargo carried by the Niger makes it worthwhile to study the matter of improving the possibilities of navigation over this most downstream stretch of the river; and this, indeed, has resulted in the present NEDECO investigation.

b. *Irrigation* (1

In general there has been no urgent need for irrigation along the Niger and its tributaries, mostly because the rainy season has provided ample possibilities of growing sufficient food crops for the local population. But in the areas with an average annual rainfall of less than 20″, the farmers were compelled to use irrigation water to obtain an adequate crop for their daily needs. Roughly speaking, such a shortage of rainfall within the catchment area of the Niger

(1 The information contained in this review was partly collected during a reconnaissance of the Niger in French West Africa in 1957.

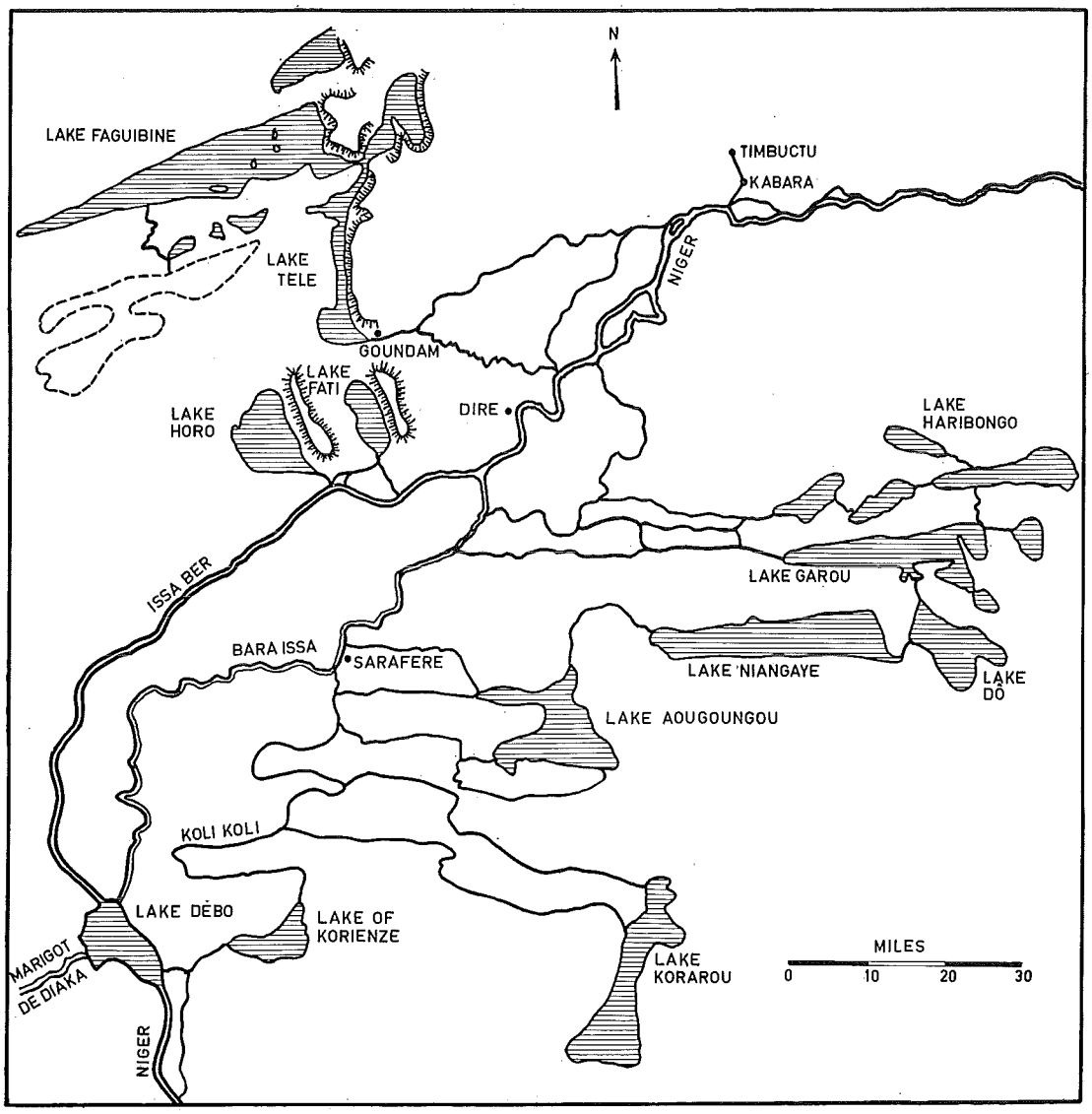


DIAGRAM 1.2.4-3

Central Delta Area

occurs only north of the 15th parallel, thus including a part of the Central Delta and the land around Gao and Ansongo (see Diagram 1.3.3-1).

In the Central Delta (see Diagram 1.2.4-3) the presence of large areas with lakes and swamps facilitates the use of a traditional irrigation for farming purposes. In the remaining part of the catchment area of the Niger, north of the 15th parallel, no irrigation is practicable and this area has only a population of less than 3 inhabitants per sq.mile.

The uncertainty whether the river will flood the so-called naturally irrigated areas, and to what extent and for what period, makes cultivation rather hazardous and sometimes results in the complete failure of the crop. To overcome these difficulties the French authorities are carrying out a survey in the Central Delta to investigate the possibilities of regulating the traditional methods of irrigation in this area.

For example, along the lakes Telé and Faguibine, the population can only use a narrow strip of land between 1 meter (3 feet) above the highest and 35 cm (15″) above the lowest water-level of the lake, i.e., just where the ground-water level is sufficiently high for successful farming. As a result of the evaporation and the infiltration, the water-level of these lakes drops every year about 1.60 m (5′3″) and rises about the same amount during the flood of the Niger. As the water-level of this chain of lakes is always below that of the Niger, the flow of water is always in one direction, i.e., from the Niger into the lakes. This inflow starts as soon as the water-level at Diré rises above 4.50 m (14′9″) on the gauge. As the minimum and maximum high water-levels at Diré are respectively 5.30 m (17′4″) and 6.10 m (20′), the amount of water which flows into the lakes is closely linked with the height and the duration of the flood of the Niger at Diré. This inflow varies between 3,500 × 10^6 m^3 and 150 × 10^6 m^3 (120 × 10^9 cuft and 5 × 10^9 cuft) during a high and a low flood respectively.

A series of wet years results in a rise from year to year of the water-level of the lakes, and a sequence of low floods on the Niger gives a gradual drop of the water-level (Diagram 1.2.4-4). This means a constant shifting of the farms along the banks of these lakes, as the total recorded variation of the water-level of Lake Faguibine is over 10 metres (30 feet).

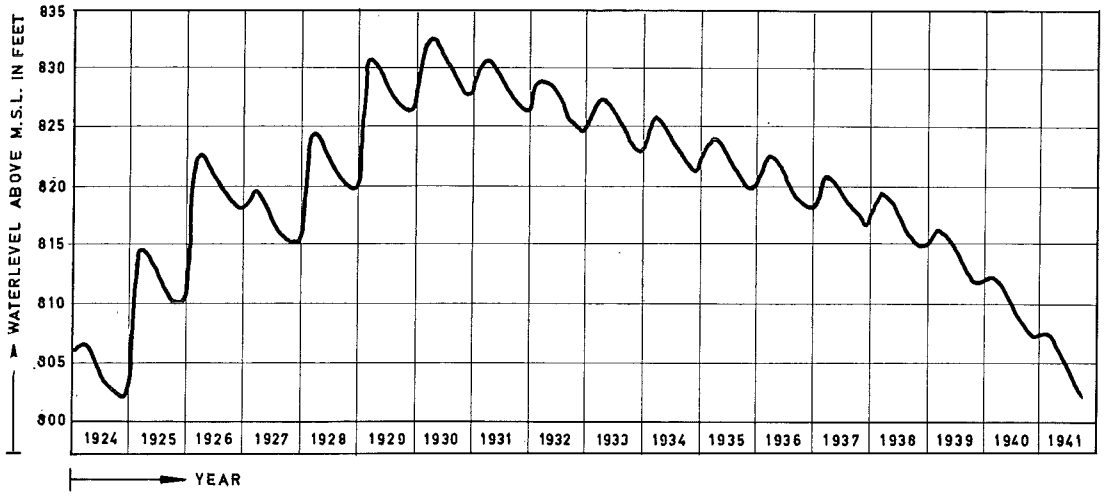


DIAGRAM 1.2.4-4

Variation of the water-level of Lake Faguibine

By means of a small dam and a sluice in the feeder creeks of this system of lakes, the projected scheme provides for a constant inflow during each flood of 650 × 10^6 m^3 (23 × 10^9 cuft), which equals the yearly evaporation and infiltration of the lakes in question. The ultimate aim is to keep the water-level of the lakes between two fixid levels in such a manner that a maximum of cultivable land becomes available for farming purposes, with a suitable kind of soil. It has been calculated that the Faguibine-Telé scheme can provide 37,000 ha (92,800 acres) of cultivable land and would have given in the year 1956 a possible increase in value of the harvest from £ 100,000 to £ 600,000, an increase about equal to the *total* estimated cost of this scheme.

A similar scheme has been executed on Lake Horo and is planned for Lake Fati. Originally the water-level of these lakes rose and fell with the Niger, thus giving the farmers the opportunity to grow their crops with the fall of the water-level, and, depending on the height and duration of the flood, to have just sufficient water (or not) to overcome the dry period between

the fall of the river and the beginning of the next rainy season. By damming the creeks between the Niger and the Lakes Horo and Fati, the water-level can be regulated to suit the needs of the farmers around the lakes, thus giving them a better and safer chance to obtain a good crop.

The same problems also arise around the lakes south of the Niger. Here about 10 lakes, covering an area of 1,000 km^2 (400 sq.miles) are filled and emptied through numerous winding creeks with a flow capacity inadequate to ensure a regular level of the water in the lakes. For years these lakes are nearly dry and then suddenly with a sequence of high floods they become full to the brim. The best exploitation of this region could be reached if the Lakes Dô, Niangaye and Aougougou were regulated in the same way as the Lakes Horo and Fati, with the remaining lakes kept as full as possible in order to raise the ground-water level of the adjacent pastures.

Apart from the areas where irrigation is absolutely needed as described above, there are situations where Nature provides the farmers with seasonally flooded riverine or fadama. These seasonal swamps are found all along the Niger and its tributaries, and mostly allow all-the-year-round cultivation with sometimes even two crops a year.

The success of this method of farming depends largely on the height of the flood-level of the river, as, for example, an exceptionally high flood will damage the crop on the fadama. But altogether the fadama is a very rich source for the agriculture and allows the growing of rice, cotton and sugar-cane in an area where the annual rainfall alone is not sufficient to grow such crops. It is interesting to note that mechanised cultivation of the fadama, of which the soil can be very heavy to handle, has proved successful in Sokoto Province (Sokoto Rice Scheme) and also, although on a smaller scale, at Shemankar in Plateau Province.

Special mention must be made of the fadama along the Niger between Jebba and the Kaduna River, which lies about level with the so-called Black Flood (see 4.5.4). This fadama is inundated by the flood, caused by the local rains, but from December until March/April the water-level remains nearly constant with an annual variation of about two feet. This phenomenon has two apparent advantages: first of all, the variation in water-level is rather small and the crop will not be drowned by this flood, and secondly, the time between the moment when the Black Flood recedes and that of the beginning of the rain is only 1 to 2 months.

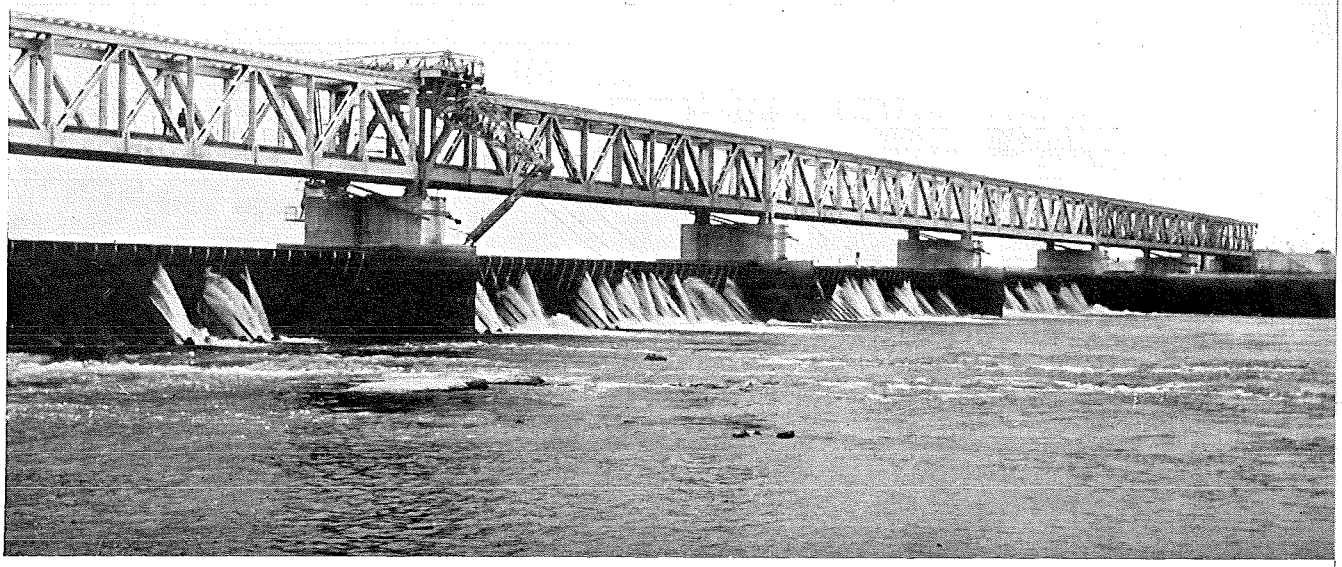
Finally, there is the artificial, man-controlled irrigation which would make possible a considerable expansion in the production of specialised crops, such as rice, sugar-cane and vegetables and would possibly help to even out the highly seasonal pattern of farming in the savana region.

In Nigeria promising small-scale irrigation schemes have been undertaken in Niger Province along the Kaduna River (Wuya—Edozhigi scheme) and along the Gbako River above Badeggi. Small irrigation works have also been built to prolong the natural flood irrigation of the fadama along the Niger between Jebba and Pategi, by means of damming up some of the streams which run down from the adjacent hills on the right bank of the river.

If in the future a dam in the Niger near Jebba will be built, the possibilities of an artificial irrigation of the fadama downstream of the dam will cover an estimated area of at least 50,000 ha (125,000 acres), and as this region belongs to the so-called "pioneer fringes", where the man/land ratio is far below the optimum, the development of such an irrigation scheme would change the whole pattern of life.

A fine example of such a change is the irrigation scheme between Ségou and Mopti in the French Niger.

In 1922 the French started an experimental scheme on the right bank of the Niger near



PHOTOGRAPH 1.2.4-5

The weir of Sansanding

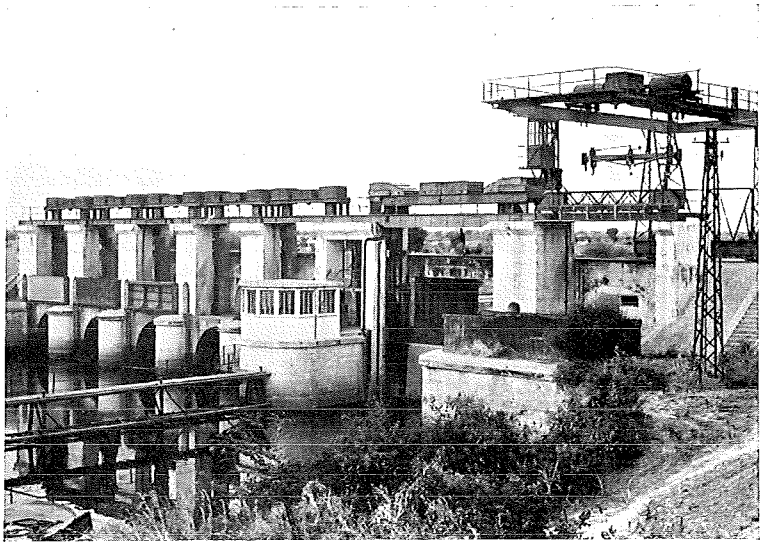
Niénebalé (between Bamako and Koulikoro) of about 1,500 ha (3,750 acres), which was followed seven years later by a larger scheme with a small dam in the Niger near Sotuba (1 mile below Bamako) and a canal 22 km (14 miles) long, to irrigate 7,500 ha (18,750 acres) of land. The results of these experiments were rather hopeful and in 1932 the "Office du Niger" was founded "to study, to arrange and to exploit the valley of the Niger", and plans were made to irrigate large parts of the Central Delta Area.

At Sansanding, near the apex of the old Interior Delta, the construction of a movable weir with 14 openings each about 50 meters (165 feet) wide, started in 1934 (Photograph 1.2.4-5). In 1948 this weir — more than 800 meters (2,650 feet) in length, together with an earthen dam of 1,800 meters (5,900 feet) — closed the river-bed of the Niger. This made it possible to raise the river about 5 m (16′6″) above L.W.-level, and as a result a part of the discharge of the river was forced to flow through two branches of the old interior delta, i.e., the "Canal du Sahel" and the "Canal du Macina", which are used as main irrigation canals, each with a capacity of 350 m^3/sec or 1,250 cusecs (Photograph 1.2.4-6). Roughly 500,000 ha (1,250,000 acres) of land can be irrigated through this system, but in 1957 only 6% of this vast area was under cultivation of rice and cotton. Seen agriculturally, there are possibilities of irrigating upto a million ha (2,500,000 acres) (see Diagram 1.2.4-7).

The reason for the rather small percentage of land yet under cultivation lies in the nature of the difficulties with which the "Office du Niger" has to deal with. This method of irrigation is completely new for the population of this area, and their re-training takes much time. Moreover, it is difficult to attract sufficient labour, so that the clearing of the land goes rather slowly and after ten years only about 30,000 ha (75,000 acres) have been brought into cultivation, although this area is now increasing by about 4,000 ha (10,000 acres) annually. This is why a reduced scheme of 300,000 ha (750,000 acres) is kept in mind.

Even for an economical use of the cleared area of a reduced scheme of 300,000 ha (750,000 acres), the low-water discharge of the Niger is not large enough. A minimum discharge of about

400 m³/sec (14,000 cusecs) is needed during February, March and May to obtain two rice crops a year, to grow Egyptian cotton which has to be irrigated longer than American cotton, and to apply crop rotation.



PHOTOGRAPH 1.2.4-6

Main Distributor in the Canal du Macina

For this purpose the building of a reservoir in the upper reaches of the Niger or in one of its tributaries is the indicated solution. These plans for damming the tributaries coincide more or less with those for the improvement of the navigation between Koulikoro and Ségou (as already mentioned).

Some figures about the irrigation scheme at Sansanding follow here:

The amount of water needed for the irrigation of cotton is 1,000 m³/ha (14,000 cuft/acre) every 12 days, which means an average of about 1 liter/sec for every ha (0.09 gallon/sec for every acre) planted with cotton. To compensate for losses in the minor distribution canals, this figure must be augmented by 30%, thus giving a total of 1.3 liter/sec to the ha (0.115 gallon/sec to the acre).

For rice the figures are 3 liter/sec to the ha (0.27 gallon/sec to the acre) during the first month and 2 liter/sec to the ha (0.18 gallon/sec to the acre) during the next months, in which 1 liter/sec to the ha (0.09 gallon/sec to the acre) is incorporated as losses due to evaporation and infiltration.

The losses of infiltration in the main distributor canals are, according to measurements in the field, 0.12 m³/sec for every kilometer length of the canal (6.75 cusecs/mile). The total length of these main canals being 400 km (250 miles), the total losses are 50 m³/sec (1,750 cusecs).

In the secondary distributor canals, of which 4 metre length is needed for every ha irrigated land (5 feet for every acre), the losses calculated according to INGRAM are 0.08 liter/sec/kilometer (4.5 cusecs/mile).

When the total area of 300,000 ha (750,000 acres) has been irrigated, 96 m³/sec (3,400 cusecs) will be needed to counter-balance the losses in the secondary distributing system, bringing the total of the losses to 146 m³/sec (5,150 cusecs).

The present system of cultivation aims at

(i) 230,000 ha (575,000 acres) cotton, of which 2/5 of the area is planted with cotton, 2/5 of the area lies fallow, and 1/5 of the area is planted with rice.

(ii) 70,000 ha (175,000 acres) rice.

The cotton is sown on June 15 and irrigated between September 15 and January 15. In the intermediate period the rainfall is sufficient for the crop. The rice is also sown in June and continuously irrigated until October 15.

A second irrigation plan provides for the cultivation of Egyption cotton on 160,000 ha (400,000 acres) and American cotton on 70,000 ha (175,000 acres) with the same sub-division in the areas planted with cotton, lying fallow and planted with rice as in the present system. The Egyptian cotton needs the same irrigation but only one month longer, i.e., until March 15. The rice is planted earlier, from May 15 onwards, in order to have the labourers available for the sowing of the cotton in June.

In a third irrigation plan the complete crop rotation between rice and cotton is applied, each on half of the area, while the division between American cotton and Egyptian cotton is the same as in the second plan.

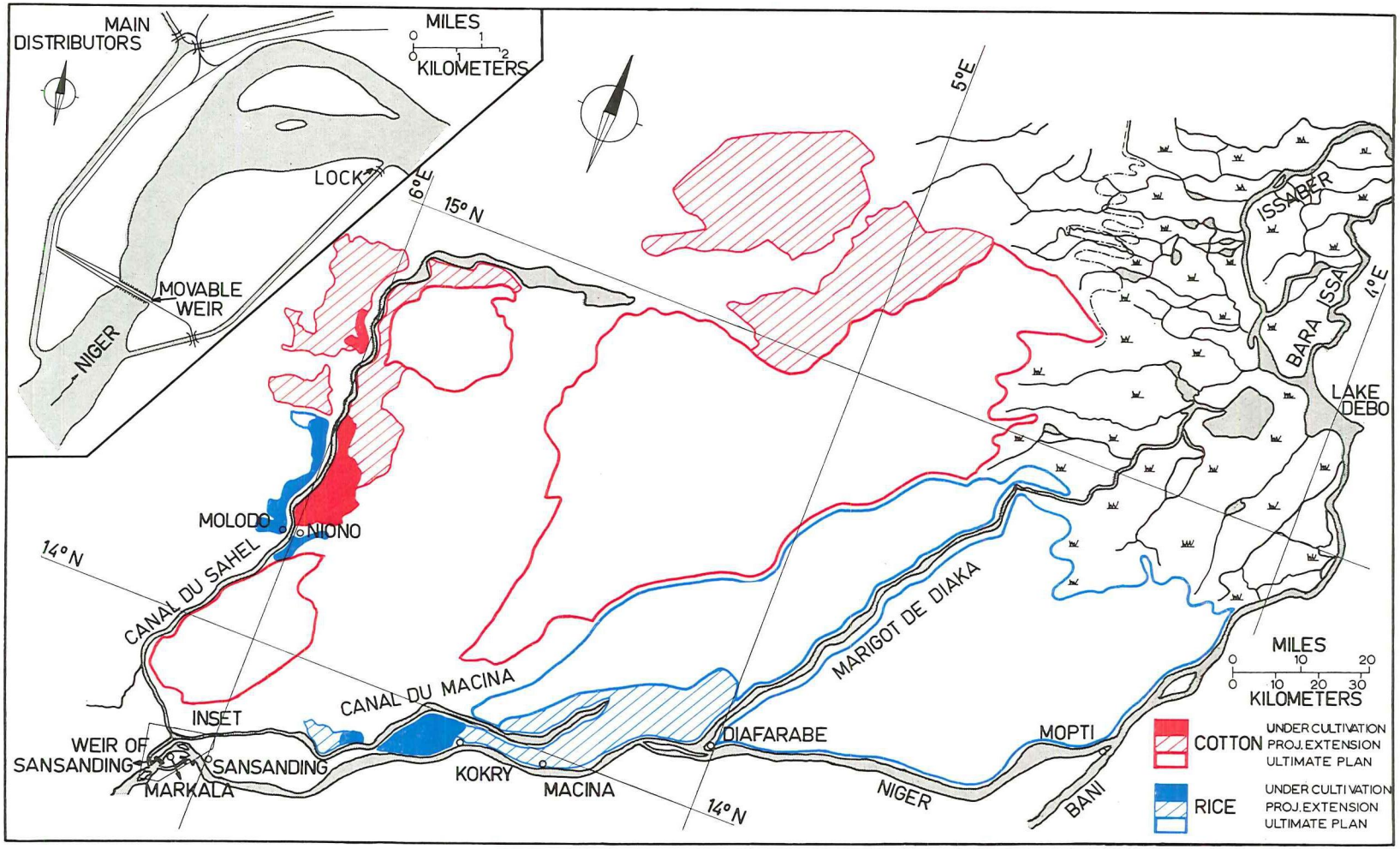


DIAGRAM 1.2.4-7

Irrigation projects in Central Delta

The last and most extensive plan provides for 2 crops of rice in one year on the 70,000 ha, which are kept apart for the culture of rice only: a first culture from June 1 until October 15 and second from December 1 until April 1.

It will be clear that the amount of irrigation water needed for these plans increases from the first to the last plan. In fact, they involve resp. 6.6×10^9; 8.7×10^9; 11.4×10^9 and 13.4×10^9 m³ annually (230, 305, 400 and 470 $\times 10^9$ cuft) compared with the average annual discharge at Koulikoro of 48×10^9 m³ ($1{,}700 \times 10^9$ cuft). The second, third and fourth irrigation plans can only be executed when the discharges of the Niger during the dry season are artifically increased by means of a reservoir in the Niandan.

c. *Hydro-electric energy*

Apart from a small hydro-electric plant installed at Sotuba in the rapids of the Niger between Bamako and Koulikoro, the water-power of the Niger and its tributaries has not yet been harnessed. This is mostly due to the fact that the technical development of the adjacent country has only recently started, and the first demand for electric power could be met by thermal power-stations. But because of the rapid expansion of the development and the rising standard of living of the population in the Niger Basin, the demand for power is growing rapidly and it is likely that in a short time the use of hydro-electric power will greatly increase.

Several sources of water-power are already under examination, such as:

(i) A hydro-electric power station in the "W" between Niamey and Malanville (Diagram 2.3.1-14). The preliminary plans ([1 provide for a dam 13—14 feet high and a reservoir of about 100×10^6 m³ (3.5×10^9 cuft). This is not meant as an accumulation basin, and the dam only serves to cause a fall (run-of-river station). The maximum output through the turbines will amount to 1,000 m³/sec (35,000 cusecs), although even at a discharge of 650 m³/sec (23,000 cusecs) the efficiency of the plant will still be satisfactory. The maximum output of the power-station will be 40 megawatt and as the discharge of the Niger is rather evenly distributed throughout the year, the so-called "hydraulic effect" of this scheme is said to be 80%. This means that over a year the average flow through the turbines equals 80% of the maximum capacity of the turbines.

(ii) A hydro-electric project on the Kaduna River at Shiroro Gorge. Preliminary calculations ([2 indicate that a sufficient output could be generated to satisfy the needs of the towns of Kaduna and Zaria and also future industrial development in the North. It is estimated that the large dam and power-station could produce in the first stage some 400 million Kwh in a year of average rainfall with an installed capacity of about 35 megawatt at 55% load factor. To generate this amount of power it would be necessary to build a dam of 200 feet height.

(iii) A multi-purpose project on the Niger near Jebba. Investigations into the feasibility of constructing a dam are well in hand ([3 and if the scheme is found to be feasible, it is estimated that about 1,500 m³/sec (50,000 cusecs) will be available throughout the year to generate hydro-electric power with a probable maximum output in the region of 1,200 megawatt.

Of course, many other possible dam-sites can be found where the circumstances would probably allow the generation of hydro-electric power. In Section VI, 8.2 a description of such sites on the Niger/Benue system within Nigeria is given.

1.3. CLIMATE

1.3.1. Wind systems and air properties

The climate in Nigeria is dominated by its situation in the world air currents. Diagram 1.3.1-1 gives the pressure distribution and prevailing winds over the Continent of Africa and

([1 From verbal information collected during a reconnaissance of the Niger in French West Africa in 1957

([2 by SIR ALEXANDER GIBB & PARTNERS, Consulting Engineers

([3 jointly by BALFOUR, BEATTY & CO. and NEDECO

its surroundings for January and July, the months in which the pressure distribution becomes extreme.

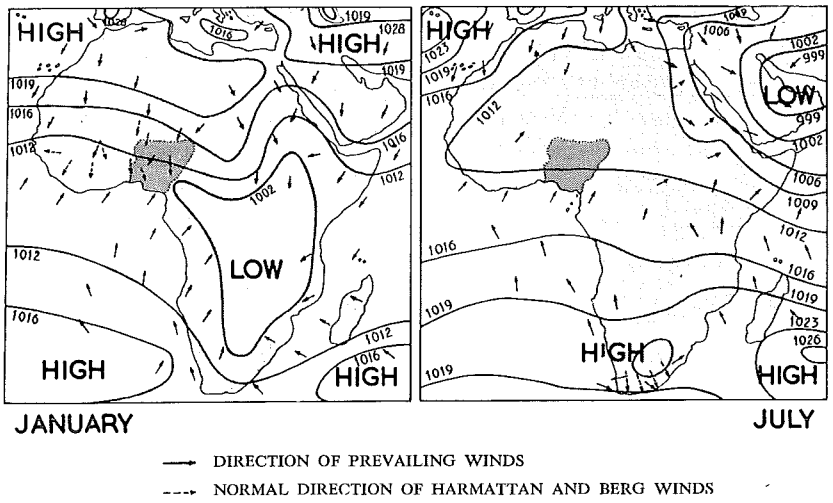


DIAGRAM 1.3.1-1

Pressure distribution and prevailing winds over Africa

In January there is a low over the southern part of Africa and an anticyclone over North Africa and Eurasia. Another anticyclone is over the South Atlantic. North of the equator this wind becomes south-west before entering into Nigeria and is then known as "monsoon". It contains a great deal of moisture and is the main source of rain in Nigeria. Its northern limit

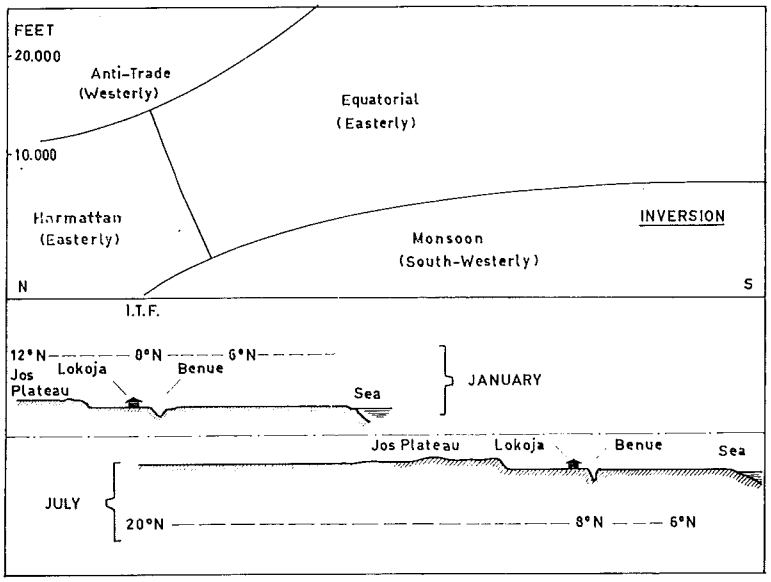


DIAGRAM 1.3.1-2

North-south cross-section of the atmosphere over Nigeria

is know as the *intertropical front*, although the term "front" must not be understood in the meaning it has in the higher latitudes. The intertropical front is sometimes described as a quasi-stationary front dividing the two air currents blowing north and south of it. Surface wind over the Sahara and south of it is east-north-east and is very dry. This wind is known as the Harmattan.

In July the pressure is high over the Azores and over South Africa, and low over South-West Asia. The monsoon enters far into West Africa.

Diagram 1.3.1-2 (1 shows a north-south cross-section of the atmosphere above Nigeria. It is seen that in January the intertropical front is situated approximately along latitude 8° N and in July approximately along 20° N. However, it must be borne in mind that the intertropical front is subject to short-period fluctuations with considerable amplitude.

1.3.2. Temperatures (2

In Nigeria the principle of the stabilising effect of the ocean on the temperatures over land is well illustrated. The annual mean of daily maximum temperatures is about 87° F on the coast rising to about 94° F in the north. The annual mean of daily miniumum temperatures is about 72° F over Southern Nigeria, but falls to 66° F in the north. Hence the mean range on the coast is 15° F and in the north 28° F.

In the south, maximum temperatures are highest from February to April, in the north from March to June. They are lowest in July and August over most of the country.

Minimum temperatures in the south are highest in February, March and April, and lowest either in January or in August, but the variation throughout the year is small. In the north the seasonal variation is considerable. Minimum temperatures are highest in April, May and June, lowest in December, January and February.

Table 1.3.2-1 shows some monthly means of daily maximum and minimum temperatures, which will give an indication of the difference in seasonal variation between the coast and the north.

TABLE 1.3.2-1

MONTHLY MEANS OF DAILY MAXIMUM TEMPERATURES OVER 1943—1947

	Latitude	Longitude	Altitude	Jan.	Febr.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Ikeja	06°35'N	03°20'E	132 ft	90.5	91.0	91.5	90.2	87.9	84.2	82.2	81.7	83.9	85.7	89.3	89.3	87.3
Warri	05°31'N	05°44'E	20 ft	88.4	90.8	91.1	90.8	88.6	86.1	82.6	83.1	83.9	86.0	88.8	88.6	87.4
Lokoja	07°48'N	06°44'E	130 ft	91.3	94.5	96.5	96.5	91.6	87.7	86.0	84.8	85.3	87.2	91.2	90.7	90.3
Kano	12°02'N	08°32'E	1,500 ft	85.6	89.9	95.7	100.8	99.3	94.5	87.2	85.1	88.0	93.5	92.5	87.1	91.6

MONTHLY MEANS OF DAILY MINIMUM TEMPERATURES OVER 1943—1947

	Latitude	Longitude	Altitude	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Ikeja	06°35'N	03°20'E	132 ft	69.8	72.6	73.1	71.7	72.1	71.2	70.0	69.7	70.3	71.0	71.7	70.9	71.2
Warri	05°31'N	05°44'E	20 ft	71.4	72.1	73.7	73.9	73.1	72.4	72.0	73.2	71.9	71.9	72.4	72.0	72.4
Lokoja	07°48'N	06°44'E	130 ft	69.1	73.3	76.7	77.5	75.5	73.5	72.8	71.8	72.3	72.5	71.1	68.3	72.9
Kano	12°02'N	08°32'E	1,500 ft	56.1	59.5	65.9	72.4	74.6	73.9	71.1	69.6	69.4	68.1	61.6	56.9	66.6

(1 After HAMILTON AND ARCHBOLD, 1945. HYD. 3

(2 Data from British West African Meteorological Services.

1.3.3. Rainfall, humidity and evaporation

The *rainfall* distribution on the Niger Basin is determined by:

(i) the movement of the intertropical front, the situation of which determines which part of the continent lies under the influence of the rain-bearing western and south-western winds; and (ii) the orographic pattern, as on the windward side of the mountains precipitation will generally increase compared with the rainfall over the adjacent plain.

The effect of the orographic pattern is shown by the relatively high rainfall on the Jos Plateau (more than 60″ per annum) and by the belt of high rainfall over the Cameroun Mountains.

The seasonal variation of rainfall in Nigeria can best be explained by using Diagram 1.3.1-2. The Harmattan is an easterly, hot and dry wind. The Monsoon carries very much moisture, and the land over which the wind blows will receive rain. However, rain is generally absent just south of the intertropical front where the south-westerly wind does not blow above the level of 3,000 feet. But more south is a zone of intense rainfall, mainly caused by storms which, while travelling westward, may cover great areas ([1]. South of this zone there is an inversion, or sometimes only an isothermal layer at a height of about 6,000 to 7,000 feet. Owing to the stable condition of the air big storms do not occur and rains are rather light.

When in the spring the intertropical front (I.T.F.) is moving north, a zone at a certain latitude over which during the winter the Harmattan has been prevailing will become subject to the south-westerly winds. Cloudiness will occur, but at first only storms without precipitation pass. When the I.T.F. moves farther north, big storms will pass from east to west. However, by still further moving north of the I.T.F. the latitude will be covered by the inversion and conditions are no longer favourable for storms. Hence the rainfall will decrease.

When, after having reached its most northern position, the I.T.F. is moving south again during the second half of September, October and November, the zone which is considered here will again become subject to the Disturbance Lines, and rainfall will increase again. But at the approach of the I.T.F. rainfall will soon cease.

This explains the occurrence in the south of two rainy seasons per year. Stations situated sufficiently north are subject to only one rainy season, because they are not reached by the inversion which brings stable conditions.

It will be understood from the above that the length of the rainy season will decrease from south to north. Further, that the Monsoon will lose moisture on its way inland because of precipitation. These two factors cause the yearly rainfall to decrease from the coast to more inland.

The fact that rainfall on the Niger Delta and the eastern part of the Nigerian coast is higher than at Lagos can perhaps be explained by the difference in angle between the direction of the prevailing rain-bearing wind and the direction of the coastline. The same effect takes place in the south-western part of West Africa, where the wind blowing inland more or less at right angles to the coast also causes higher precipitation than in the north and the east where winds are more parallel to the coast line. Along the coast to the north the effect of the trade wind, which becomes the prevailing wind throughout the whole year, is noticeable.

Isohyets giving the average yearly rainfall over West Africa are drawn on Diagram 1.3.3-1. but the seasonal variation is not expressed on this diagram. Generally there is in the south-west of Nigeria a principal rainy season in May, June and the first half of July with a second rainy season occurring in the latter half of September and October. More to the east and the north there is a single rainy season from July to September. In the most south-westerly part of the Niger

([1] Locally these storms are known as "tornadoes", a word which is not suited for the phenomenon; it is better to speak of line squalls. A group of line squalls is called a Disturbance Line.

headwater area (French Guinea) the rainy season has two noticeable maxima, but immediately south of Bamako only one maximum occurs.

Seasonal variation will be considered in more detail in Paragraph 4.1.3.

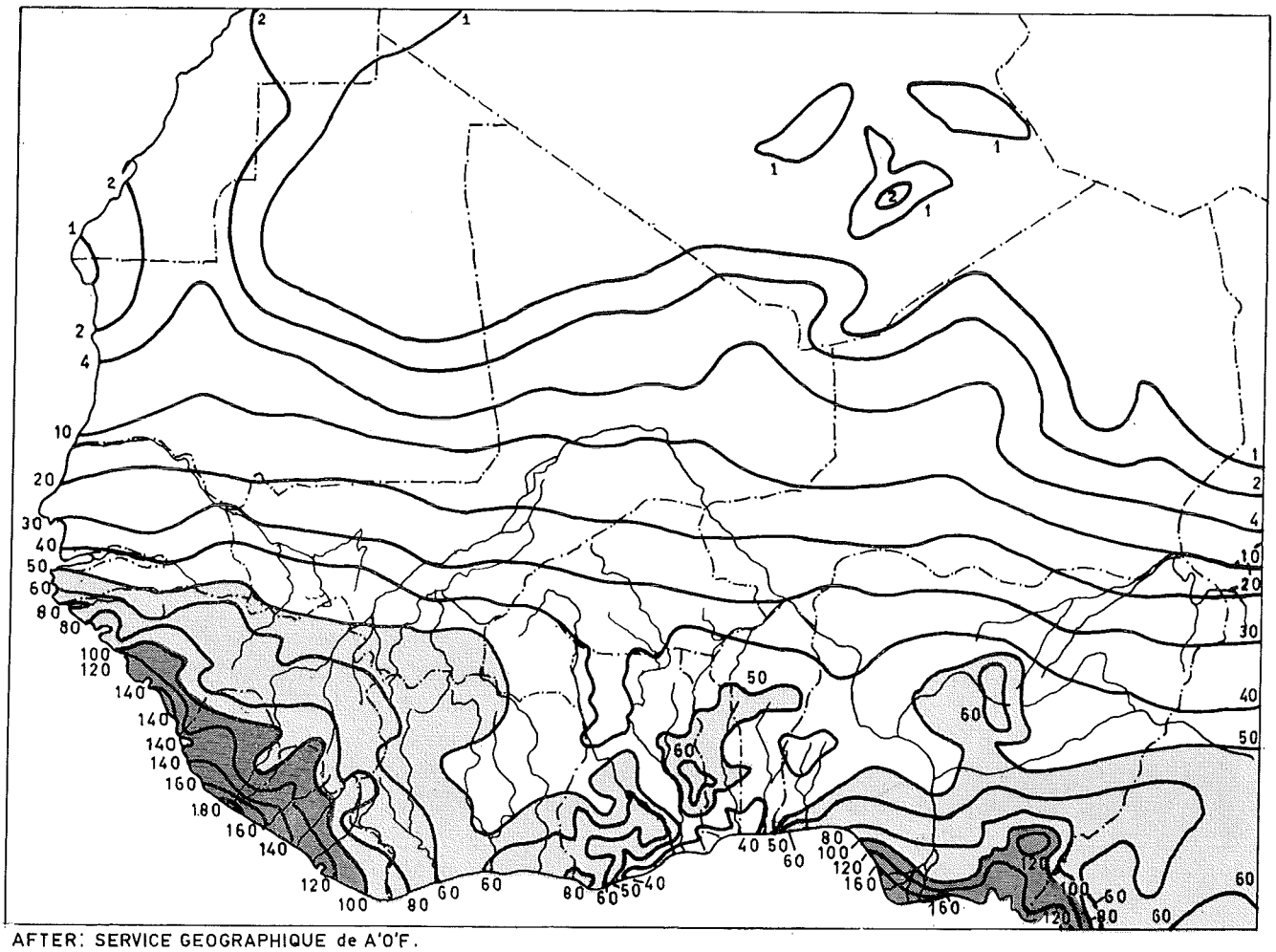


DIAGRAM 1.3.3-1

Average yearly isohyets of West Africa

(in inches)

As the wind blowing inland loses moisture it will be clear that the *humidity* ([1] will decrease. With the increase of altitude, humidity will also generally decrease.

Near the coast, relative humidity at dawn — usually the time of minimum temperature — is generally very high, between 95 and 100%. It decreases to 70—80% in the early afternoon when normally maximum temperatures occur. The seasonal variation is slight, but periods of a few days of very low humidity may occur in January and February when the Harmattan reaches the coast.

More inland, the relative humidity decreases steadily (Diagram 1.3.3-2). This humidity shows seasonal variations depending on whether the locality is under the influence of the moist south-

([1] Data from British West African Meteorological Services.

westerly or the very dry easterly current. This is illustrated for Makurdi (lat. 07° 41′ N, long. 08° 37′ E, alt. 400 feet) and Kano (lat. 12° 02′ N, long. 08° 32′ E, alt. 1,600 feet) in Diagram 1.3.3-3, where the effect of the dry easterly wind blowing longer at Kano than at Makurdi is apparent.

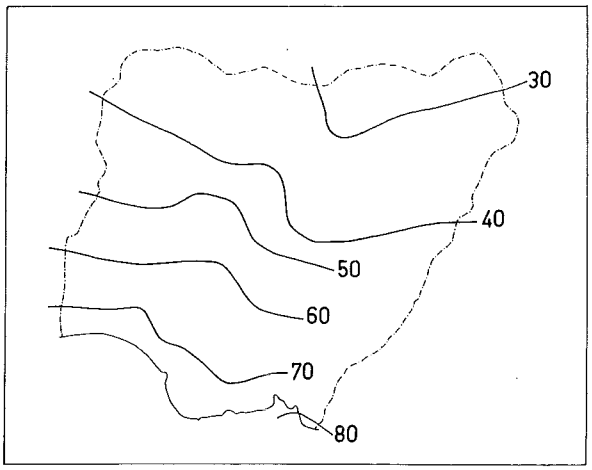


DIAGRAM 1.3.3-2

Mean annual relative humidity (%) at 1200 hrs. G.M.T.

Mean monthly values of relative humidity at 0600 hrs. and 1200 hrs. G.M.T. are given for a few other stations in Table 1.3.3-4. No figures are given for the drainage basin of the Niger outside Nigeria, but in accordance with altitude and distance from the coast relative humidity will show a similar picture as in Nigeria.

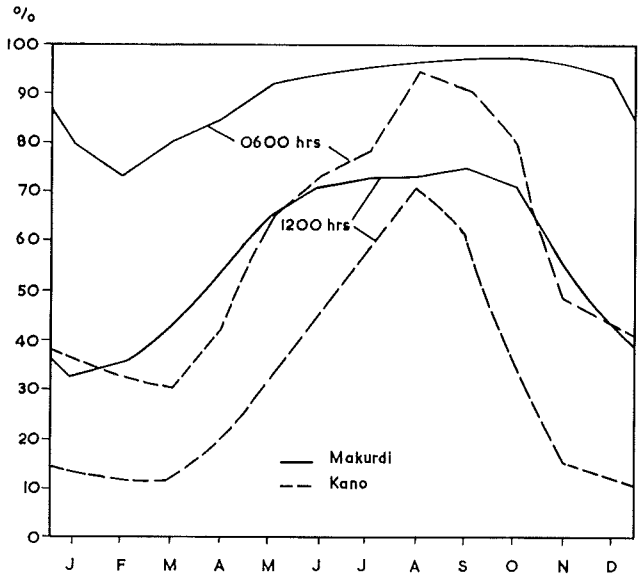


DIAGRAM 1.3.3-3

Seasonal variation of relative humidity in Makurdi and Kano

TABLE 1.3.3-4

MEAN RELATIVE HUMIDITY AT 0600 G.M.T. OVER THE YEARS 1943—1947

	Latitude	Longitude	Altitude	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec	Year
Warri	05°31′N	05°44′E	20 ft	99	98	98	98	95	98	98	99	99	99	98	98	98
Ilorin	08°26′N	04°30′E	1,200 ft	79	77	81	86	86	86	90	89	91	91	89	83	86
Yola	09°10′N	12°29′E	600 ft	35	33	34	55	76	87	90	92	93	91	71	47	67
Sokoto	13°01′N	05°16′E	1,130 ft	28	31	23	33	56	71	81	90	90	82	47	38	36

MEAN RELATIVE HUMIDITY AT 1200 G.M.T. OVER THE YEARS 1943—1947

	Latitude	Longitude	Altitude	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Warri	05°31′N	05°44′E	20 ft	70	65	68	70	73	78	82	79	81	78	71	71	74
Ilorin	08°26′N	04°30′E	1,200 ft	39	39	39	47	57	65	69	72	68	66	50	43	55
Yola	09°10′N	12°29′E	600 ft	16	15	17	26	39	61	66	68	69	60	29	19	40
Sokoto	13°01′N	05°16′E	1,130 ft	12	16	10	17	29	41	55	68	63	41	16	17	32

As the relative humidity more inland is lower than at the coast and temperatures remain as high or become higher, it can be expected that *evaporation* from open-water surfaces will increase. A greater potential evaporation from the leaves of the vegetation (transpiration) can be expected as well. In general, however, the amount of rainfall further inland is relatively

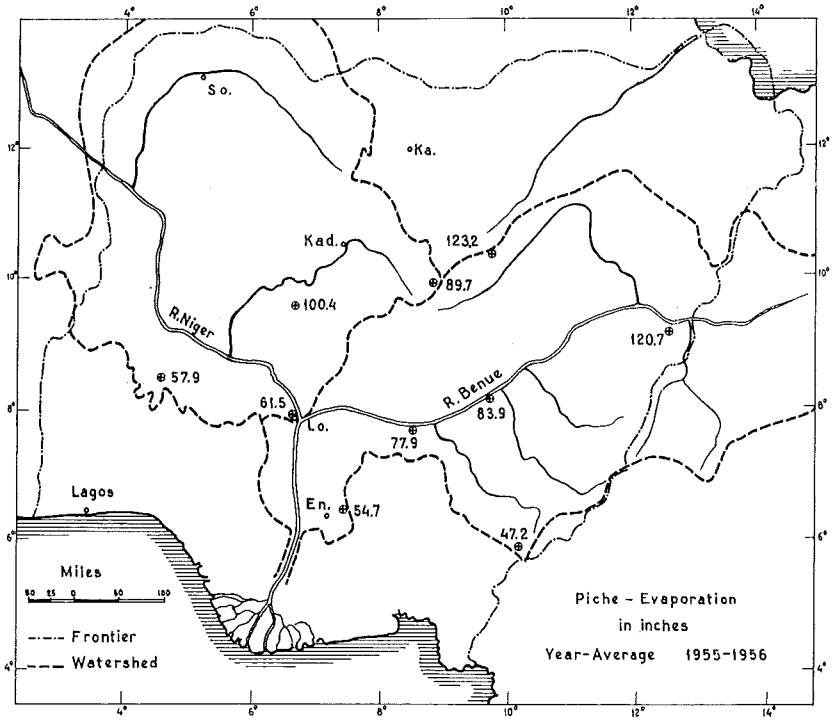


DIAGRAM 1.3.3-5

Piche evaporation in inches

Year-average 1955—1956

small, which is the cause of the scarcity of the vegetation and water-surfaces and which in turn causes a relatively small actual evaporation when considered as a mean over the whole drainage area. If there is no water available, no evaporation can occur. In cases, however, where the relief causes a great area of holes and lakes as in the old interior delta of the Niger in the neighbourhood of Timbuctu, evaporation is great.

Diagram 1.3.3-5 gives some values of the evaporation as measured by the Piche evaporimeter. The figures must not be considered separately, but a comparison between them will give an indication of the trend of the potential evapotranspiration over the country.

1.4. VEGETATION

1.4.1. Natural vegetation

The natural vegetation is the result of the simultaneous action of a number of conditions obtaining in a region: the physical environment, which comprises the distribution of mineral and water resources, and the topographical and climatological conditions. Though the pattern may vary considerably from place to place, a number of common features can be found ([1 resulting in the following outline (Diagram 1.4.1-1):

a. *Swamp forest*, composed of 11,000 square miles of brackish-water mangrove forest and, more inland, 7,000 square miles of fresh-water swamp forest. In fact, most of the Niger Delta is covered with swamp forest.

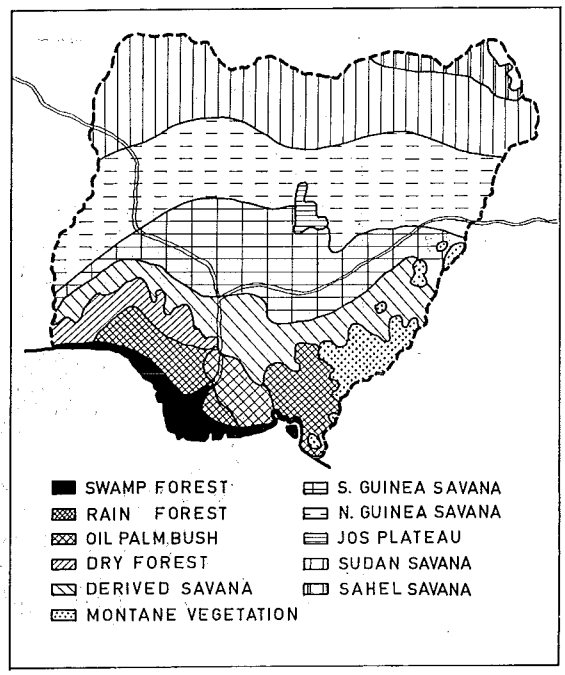


DIAGRAM 1.4.1-1

Vegetation zones ([2

Note the recession of high forest suggested by the broad belt of Derived Savana and the replacement of rain forest by oilpalm bush over much of Iboland.

([1 KEAY, 1949. GEN. 18

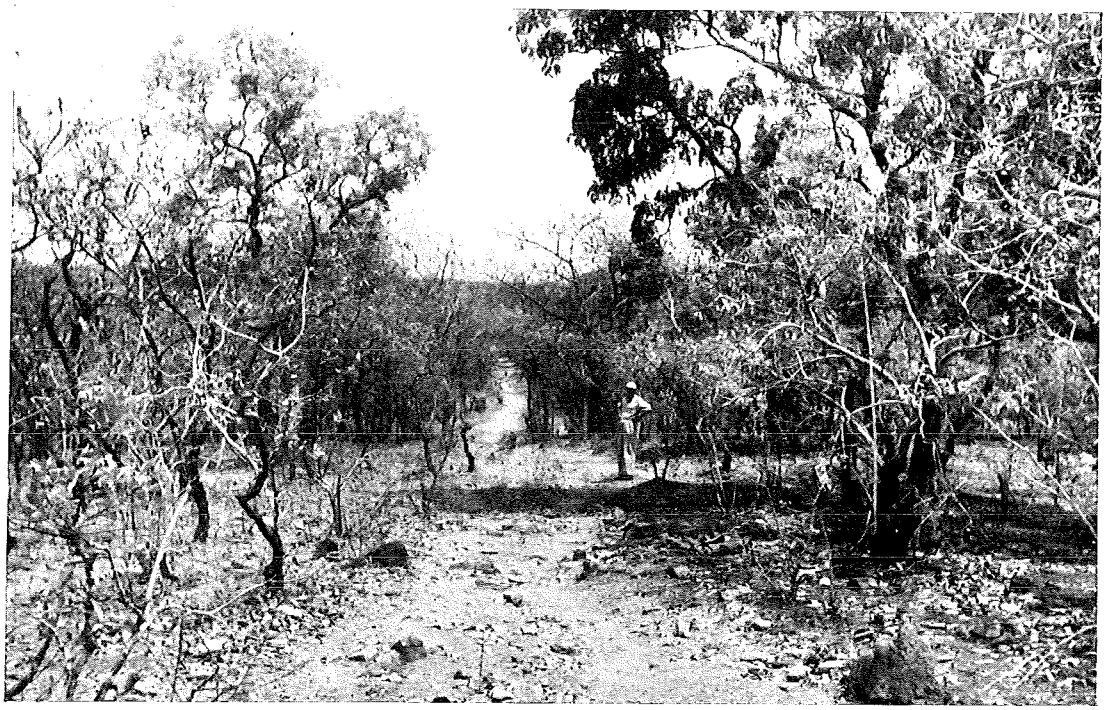
([2 After BUCHANAN & PUGH, 1955. GEN. 3

The mangrove forest consists for 99% of red mangroves (rhizophora racemosa). These trees play an active role in the formation of the tidal basin: their protruding roots in search of nourishing water provoke the accretion of the banks, especially in the inner bends of the tidal creeks, whilst at the same time, by the scour of flowing water, the outer banks are forced to recede. The action of vegetation, here, assists in causing creeks with peculiar hydraulic aspects in that they are comparatively narrow and deep. Because of this, the young trees along the accruing banks are flourishing, but as the action continues, and at the same time the soil is silting up, the affluence of nourishing water decreases and the trees fall into decay. The bottom of the swamp which is left is full of roots and has the appearance of a thick felt carpet; it may bear a "second crop" of no more than scanty shrubs ([1.

The fresh-water forest consists of stilt-rooted trees, shrubs, lianes, raphia and such, and has a more dense and flourishing appearance than the mangrove areas. It is, in fact, a gradual transition to the "rain forest".

b. *High rain forest*, which really occupies an area of about 42,000 sq.miles of which 9,000 sq.miles is forest reserve. Variations in the high forest coincide very roughly with the annual rainfall. Dry soil north of the swamps bears the "humid forest", and its modification oilpalm bush up to the rainfall limit of 64″ per annum (according to KEAY); then follows the "dry forest" which changes into "derived savana" as far north as the 45″ rain limit. Only in the western part and in Dahomey does the savana, by human interference, reach down south to the sea.

The high forest zone is characterised by the presence of fire-tender trees, amongst which the oilpalm tree is easily recognizable.



PHOTOGRAPH 1.4.1-2

Savana shrub north of Jebba

([1 ROSEVEAR, 1947. GEN. 28

Practically nowhere can virgin forest be found. For cultivation purposes the population traditionally clear most of the forest vegetation of relatively small plots. After a period of cultivation these plots are left alone in order to restore their fertility (bush fallowing system) and then become overgrown with a dense vegetation in succeeding grades tending towards the original cover. How much of the original forest will redevelop depends on the duration and frequency of the cultivation and on the quality of soil and climate.

Generally speaking, the quality of the soil is rather poor, and as more fields are continuously required the fallow periods tend to be shortened and the soil to be exhausted. This tendency is most apparent towards the north where former high forest has been turned into derived savana. In that region it will be hardly possible to restore the original type of forest. There are, however, no clear indications that the forest zone in the past extended far north of the Derived Savana area.

c. *Savana*, which comprises nearly the whole area north of the forest zone. This type of vegetation is characterised by grasses and fire-tolerant trees or shrubs. Bush fires are dominantly typical of this area, one of the reasons for burning the plains probably being to destroy disease-bearing insects.

The scanty population does not require excessive areas for cultivation, but fallowing is the general practice. Only around the towns are there closely farmed areas, where fertility is maintained by the application of manure provided by the cattle, rather common in this area. In Nigeria, the greater part of the Niger flows across lands covered with a savana-type of vegetation (see Photograph 1.4.1-2).

d. *Montane vegatation.* Chiefly in the Cameroun Mountains various types of "Montane vegetation" are encountered. Between 3,500′ and 6,000′ altitude "mist forest" is predominant, changing into grasslands in the higher regions. These grasslands offer grazing grounds for nomadic Fulani cattle.

The Jos Plateau is mainly covered by grassland.

1.4.2. Agricultural vegetation

Agriculture in Nigeria is predominantly based upon peasant production. Since industrial development is only incipient and internal exchange economy still limited, production is directed in the first place to the local market.

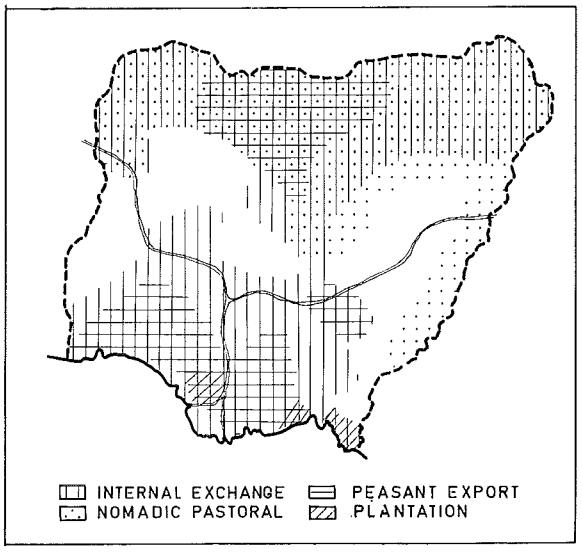


DIAGRAM 1.4.2-1

Dominant types of agricultural economy

After Buchanan & Pugh, 1955. Gen. 3

BUCHANAN distinguishes four elements in the agricultural economy (Diagram 1.4.2-1):
(i) basic subsistence economy — present everywhere, though of varying relative importance;
(ii) internal exchange economy — increasingly important in the developing country, but dependent on transport facilities; commodities are: basic foodstuffs including guinea corn and cattle in the north, yams in the Middle Belt and palm-oil in the south, and more specialised crops, such as rice, fruit, sugar or kola nuts;
(iii) peasant export-production economy — existing in certain areas, but extension possible to other areas if communications develop; export crops are: cotton and groundnuts from the north, benniseed and soya beans from Benue Province, and cocoa, palm produce and rubber from the south; and
(iv) plantation economy — not at present playing a significant part in the Nigerian economy except in the Southern Camerouns.

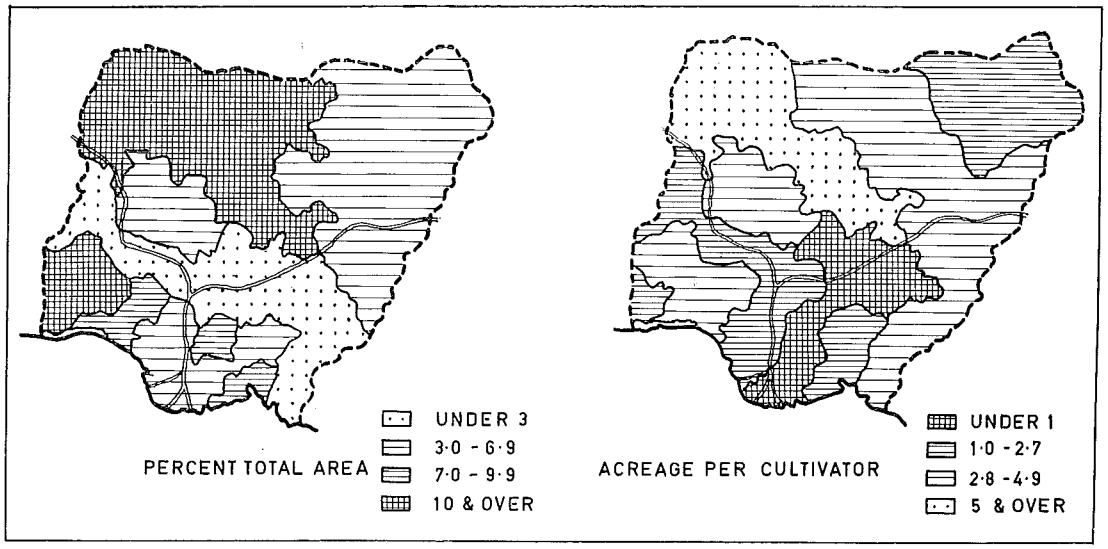


DIAGRAM 1.4.2-2

Cultivated areas (1

Data from 1931

Both the extent and intensity of agriculture vary considerably throughout the country (Diagram 1.4.2-2). Buchanan discusses at considerable length the various aspects of agriculture in Nigeria, and many figures and diagrams are given to illustrate the conditions of various crops in the producing areas. In Chapter IV, 1 of this Report some details are given about the present scope of agricultural production and future developments, data which are related to the matter of communications in general and river transport in particular.

There are, however, other aspects of changes in vegetation and those which affect the hydrological pattern are discussed in the following paragraph.

(1 after BUCHANAN & PUGH, 1955. GEN. 3

1.4.3. Reciprocal influences of hydrology and vegetation

Both the growing population and the increasing export figures of the country are necessitating a greater output of the national agricultural production. Improved production methods and transport facilities will, of course, be essential, but in addition an extension of the farmed area, however dangerous in some cases from a pedological point of view, will be unavoidable.

The hydrological consequences of present and future rural production will now be briefly summarised according to the zonal sequence of Paragraph 1.4.1. For an inventarisation of the potential suitability of the Benue Valley for agriculture, reference is made to the reports by GROVE (1 and PITTS (2.

a. *Swamp forest*

Interest in the use of the brackish soil in the tidal areas is not very likely to influence the regime of the estuaries and creeks in the relevant area.

But in the fresh-water swamps, and in those parts of the brackish-water swamp which can be irrigated with fresh water from adjoining areas, possibilities for agricultural activities might be attractive. In that case, the water in these cultivated areas should be kept at a certain level, and parts of the tidal basin must be kept free from flooding. This entails, on the one hand, that the capacity of the basin, and more particularly of the access creeks, will decrease; and on the other hand, if the excluded areas originally formed part of a discharge system, that the alternative discharge channels will tend to increase their capacity.

In major projects, these tendencies and their consequences, for better or worse, must not be overlooked. Rice-schemes already in production or under consideration may prove to be of increasing interest in this zone.

b. *High rain forest*

This zone between the coastal swamps and the savana owes its agricultural significance very often to a thin fertile top-soil which may be rapidly exhausted and not be able to bear a dense vegetation afterwards. Both the water-retaining capacity of the soil and the evapotranspiration may then decrease, causing an intensified run-off of rain water. Leaving aside the dangers of erosion by surface run-off, an accelerated drainage of denudated areas will cause less regular discharges in these rivers. Short high peaks instead of prolonged floods are detrimental for rivers and riverain areas and any sound river management will seek to prevent these torrent floods as a primary means of improving the serviceability of the river.

In the present case, the Niger and Benue are hardly affected by conditions in the zone of the rain forest. But most rivers in the Western and Eastern Regions are liable to suffer.

c. *Savana*

In the northern part of the country, where the rainfall is less and restoration of the vegetation slow, and where bushfires frequently destroy any useful fallowing, the consequences of denudation and exhaustion are similar to those set out for the rain forest area. They would have been far more serious but for the fact that the major part of the country is already rather barren. The rivers usually are capricious in their discharge and irregular in the shape of their beds.

Nevertheless conditions can become worse in cases where virgin savana comes under cultivation. When grasses and shrubs are cleared and furrows made, wide valley areas after heavy storms drain themselves in a short time, eroding gullies and choking the rivers with sand. The

(1 GROVE, 1957. GEN. 14
(2 PITTS, 1956, GEN. 30

sudden peaks then scour the banks and widen the bed, thus spoiling the possibilities for irrigation and navigation. It appears that these things have already occurred in a number of cases. For example, in the areas of the Rivers Gongola, Kilunga and Taraba, which are stated to have had shipping at the beginning of this century, the present chances of navigation are negligible.

A contrary influence is produced by irrigation schemes. Their purpose is to retain a certain amount of water, sometimes by damming up river water in reservoirs and sometimes by simply retarding the run-off. In either case, the effect is beneficial to the rivers and their use. In this respect, the expansion of the culture of rice and sugar may be welcomed. Rice is grown in swampy areas along the Niger, Kaduna and Gbako, and further schemes are under consideration. Sugarcane is grown in many river valleys throughout the north, but especially in Zaria, Kano, Sokoto and Bida. Here also a further development is envisaged both in acreage and in technique.

d. *Montane vegetation*

Here, in the mountains, the same problems are arising as in the lowlands, though perhaps only incipient and on a smaller scale. Denudation and exhaustion of soils by grazing, farming and burning tend to promote accelerated run-off and increased erosion, causing reduced fertility and humidity of the soil. These consequences are similarly detrimental to the potential development of rural and pastoral economies and to the justifiable use of water resources.

From the foregoing it will be clear that the interests of management of land and water resources run largely parallel to each other. Improvement of one will beneficially affect the other. On the whole, the tendency is to put preservation of the soil in the first place, being a prior phase in the circular course of water.

However, mutual interests also exist in the next phase, where the water is assembled in rivulets and rivers. Regulation of flow by means of retaining dams will favour navigation and generation of electricity, but at the same time may open fresh possibilities for the use of land by means of irrigation. These possibilities can be summarised in the following three groups:

(i) availability of water at regular level in the retention area, the regularity depending on the regime of the headwaters, the programme of reservoir operation and the shape and dimensions of the reservoir;

(ii) availability of water at regular level in the downstream area, the regularity depending on the programme of reservoir operation. It is to be noted that by the action of the dam top floods will be restricted in a measure that will probably result in the creation of flood-free, habitable and arable lands; and

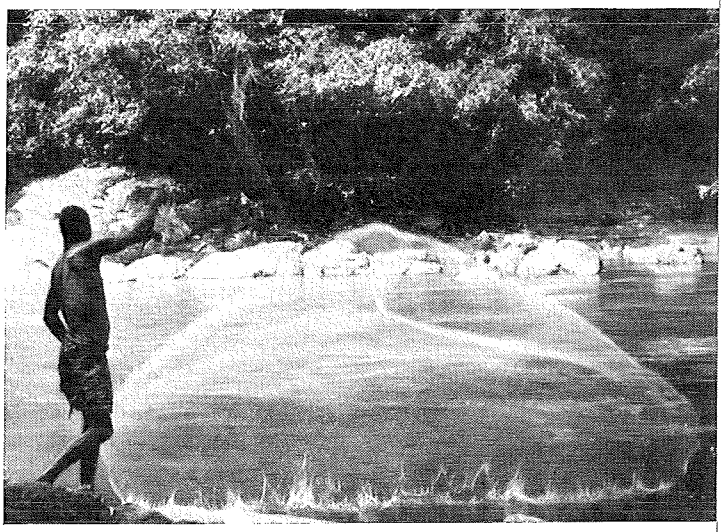
(iii) availability of water at reservoir level in the downstream area. This water becomes available for gravity irrigation of higher soils in the downstream area.

The potentialities pointed out here in a general way may, however, very well represent interests of such importance that, in particular cases, they will come to outweigh the hydrological advantages. The areas involved may amount to hundreds or thousands of square miles for the largest cases, but the economic interest, in the first instance, may be considerably restricted by the human factors. Most of the potential areas will be found in the "Middle Belt", which is sparsely populated, not only for reasons of hitherto poor hydrological conditions but also because they are disease-ridden.

Extensive studies will therefore be required to evaluate the problems created by the realisation of such projects, not only in the field of agriculture and health, but also in connection with the sociological aspects.

More detailed reference to opportunities and potentialities of this kind, together with some of their consequences, will be made at relevant places later in this Report.

PHOTOGRAPH 1.5.1-1



PHOTOGRAPH 1.5.1-2

Net fishing

1.5. ANIMAL LIFE

1.5.1. Fish and Fisheries

These subjects play an important role in the economics of the Niger and Benue Rivers, and also of certain improvement schemes, namely, those involving the creation of reservoir-pools. It was, therefore, felt that the subject of fish and fisheries should be treated in the present Report. But as none of the engineering experts of NEDECO who were in Nigeria could claim to be a specialist in the field of fisheries, a compilation has been made of the relevant literature.

An important part of the local inhabitants near the river are often amphibious people who spend a large part of their lives in or upon the water, with fishing as one of their main activities. Their methods of fishing vary according to the seasons ([1.

1. Net fishing from small dug-out canoes. The net is circular and is weighted with bits of lead. After being spread very artfully it sinks down in the water until the leads meet together, enveloping some fish within (Photographs 1.5.1-1 and 2).

2. Fishing by hooks positioned from canoes. The hooks are attached to lines about a foot or so in length, and tied at intervals along one by-rope. Broken bricks or small stones are attached to the rope at greater intervals, causing the baited hook lines to sink, while floating calabashes indicate the position.

3. When the water is low one of the fishing tactics called "Omuna Akisi" is employed, but it is one that demands labour and patience. A shady spot is made near the bank with small branches and leaves, which in time attracts and harbours some fish; after about eight or ten days the fish inside are shut up in a kind of enclosure made with long sticks fastened together.

4. Another form of net fishing is the "Ikpu Attala". Attala is a fishing material prepared from the split bark of a kind of rattan palm from which a screen is formed, with the four edges kept in position by a framework of "Ofolo" or bamboo stick. It is operated either from a small dug-out canoe or from the bank in another shape (Photograph 1.5.1-3).

5. Other main methods of fishing are by use of small nets, baskets, spears, rods, hurricane-lamps, and also by the use of poison, although there are many other fishing tactics among the riverine people too numerous to mention.

([1 UNIGWE, 1939. GEN. 37

PHOTOGRAPH 1.5.1-3

Ikpu Attala

The main food species are the catfish *(A. occidentalis, B. docmac, C. Cazera and H. longifiles)* preferred by the natives above all others, the *Tilapia*, and then the big fish *G. Niloticus. H. Niloticus* and *L. Niloticus* (the Niger Perch) ([1.

Fish have traditionally been important in the Nigerian diet as a source of animal protein, but in view of the rapid growth of population and the protein deficiency in the diet, the production and consumption of fish needs to be substantially increased ([2. Animal protein, and especially fish protein, are important for the well-being of everyone, and experiments in the Belgium Congo have shown that not only the worker's daily output but also his intelligence rises when fish is a main dietetic constituent ([3. Animal protein, with its consequent benefits of mental and physical energy, is either expensive or not available because of the comparatively few pounds of meat which can be produced per acre of grazing land from normal food animals.

In general, man has endeavoured to increase the area of land available for agriculture and to reserve and canalise water for the special purpose of agriculture: where land has been found to be too wet, man has endeavoured to remove the excess of water by draining and has despatched the water again on its course to the sea. But there has been insufficient recognition of the fact that the bodies of water in the rural regions are as important to the total economy of the rural complex, and just as productive, as the areas of land ([4. With only a few exceptions almost

([1 HOLDEN, 1958. GEN. 17
([2 WORLD BANK, 1954, page 281. GEN. 41
([3 ZWILLING, 1954. GEN. 42
([4 UNITED NATIONS, 1954. GEN. 39

every body of water is potentially a producer of foodstuffs; in each there is a process of organic productions corresponding to the best growths of plants on dry land. And if this process is properly directed through appropriate links in a food chain, such water masses may produce more protein per unit acre than the adjacent stretches of dry land.

In Nigeria the latest cropping of the pilot pond in the Panyam Scheme, Jos Plateau, which was originally understocked with Tilapia, showed a yield of 1,250 lbs of fish per acre without any addition to the food which grows naturally in the water ([1.

In Indonesia the interior fisheries occupy a definite place in the agrarian system, which in its turn is a link in the entire economy, so that this source of food production can only be viewed from all its correlating angles ([2.

A study of the hydrographical economy of the Lower Congo has shown that the fish culture will play, in the absence of good agricultural land, an important role ([3.

The Revised Ten years Plan of Development and Welfare for 1951—1956 includes a scheme for fisheries development, which is designed to produce increased supplies of fish for consumption in Nigeria and thereby to improve the protein content of local diet. This is to be achieved by fish farming, the introduction of village fish ponds, and by improved methods of deep sea fishing from powered vessels and inshore fishing from canoes ([4.

Open water systems, such as rivers, streams, irrigation canals and large reservoirs, may not be exploited as restricted bodies of water, at least without modification of the practices, because of the size of such systems and the inability to control certain factors ([5. However, specially selected species may be planted in the waters, and work be done on water "improvement", such as by control of pollution, eradication of weeds, reduction of predators, protection of spawning, and the placing of valuable fish.

It will be obvious, nevertheless, that the measure of control which can be exercised over the fish stocks in open systems and over their environment is very much less than that which can be exercised in restricted bodies of water. The work is at once less direct and more difficult. It requires a substantial integrated programme of research whose main elements must be:

a. fauna survey to analyse the composition of the stocks of fish and other animals in the waters;
b. flora surveys;
c. bionomic study of important species of fish and other animals;
d. comprehensive ecological investigation of the water, including planktonology, hydrology and so forth; and
e. population studies of the economically-important species.

For streams the detailed modifications of physical conditions necessary are:

(i) building of barrier dams and deflectors;
(ii) cover plantings on the embankments;
(iii) removal of debris and obstructions; and
(iv) control of erosion.

With regard to the recent investigation of the feasibility of a hydro-electric system at Jebba, the dam placed across the natural water course introduces a number of major changes in the natural situation. Firstly, the flow of water is interrupted, so that the normal movement of the fish across the point where the dam stands is prevented. Secondly, the depth of water behind

([1 ZWILLING, 1954. GEN. 42
([2 HOFSTEDE, 1949, GEN. 16
([3 DECEUNINCK, 1952. GEN. 10
([4 THE NIGERIA HANDBOOK, 1954, page 136. GEN. 21
([5 UNITED NATIONS, 1954. GEN. 39

the wall is greatly increased, the area of water is extended, and new types of bottoms are brought below the water surface. Thirdly, below the dam the normal regime of the flow of water becomes substantially changed.

Thus the construction of a dam creates two problems:

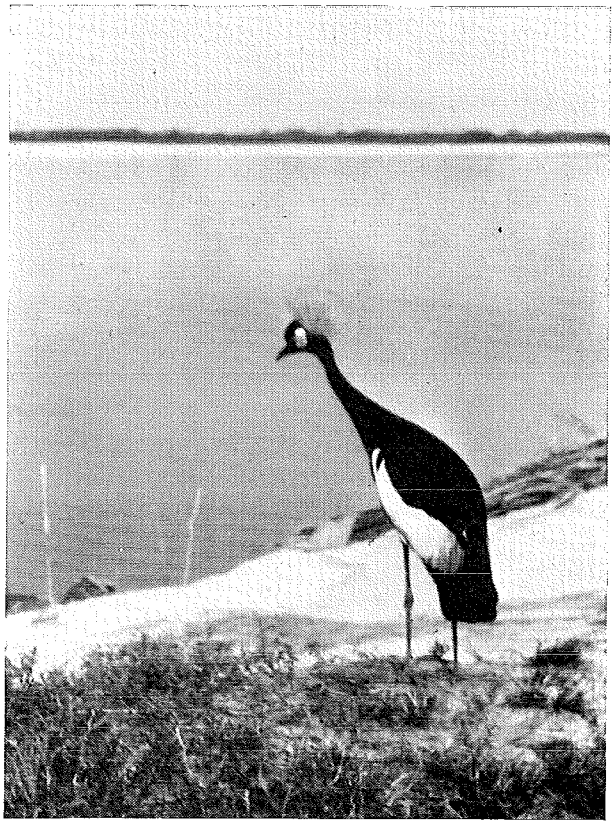
1. The effect on the movement of fish and perhaps the need to construct fish-ladders or fish-passes; and
2. the questions whether the indigenous species can populate effectively and use fully the new body of water, or whether new species must be introduced.

In any case, it is obvious that the increased volume of water constitutes a greatly increased natural habitat, which can carry a greatly increased stock of fish.

The 207 km² (80 sq.miles) reservoir created by the building of one of the hydro-electric dams of the Katanga (Belgium Congo) gives the following figures of the increased stock of fish (1. Before the dam was built in 1951 the river produced $6\frac{1}{4}$ tons of fish. In 1954 400 tons of fish had already been caught, whilst in 1955 a total of 1,500 tons.

1.5.2. Other Wild Life near or in the rivers

Nigeria is not a country for big game hunting, but some animals living adjacent to the rivers may be mentioned.



PHOTOGRAPH 1.5.2-1

Crown-Bird

The hippopotamus is found in the Niger, the Benue and the Cross River as well as in Lake Chad, but is local in these and nowhere plentiful (2.

(1 RENSON, 1956. GEN. 32

(2 THE NIGERIA HANDBOOK, 1954, page 206. GEN. 21

There are three different types of crocodiles. The largest and most common is the much-feared Nile Crocodile, which is to be found in all large rivers and lakes. The next largest is the Long-nosed Crocodile, which is the fish-eater, and the third kind is the little Stumpy Crocodile, which is found in the smaller streams and on their banks. The crocodiles can be found mainly on banks with overgrowing vegetation, and during the middle and low stages of the rivers on exposed sand-banks.

Amongst the lizards the largest are the Monitors. The Nile Monitors are widely distributed throughout the country wherever there is thick cover adjacent to water.

The avifauna of Nigeria is abounding. Amongst the water birds there is a large selection of ducks to be seen, mostly in the Northern Region, though many migrate to rivers and pools of water in the south during severe harmattan weather. Geese are also to be seen on the lakes, all the year round in the north and in the south during the dry season. There is a very large variety of river and lake-haunting birds, amongst them many Herons, Egrets and Storks ([1. The striking and beautiful Crowned Crane, or Crown-Bird, is a very common sight wherever there is open ground in the Sudan zone (Photograph 1.5.2-1). Pelicans and the Greater and Lesser Flamingos are known in the Upper Benue Area, the latter sometimes in large flocks. Of the smaller water-loving species the Sand Pipers, Greenshank, Redshank, Curlew, Crocodile Bird and the White-headed Plover are worth mentioning.

The plentitude of insect life in the tropics is a byword. Nigeria is no exception. Not only are there untold millions of individual creeping, crawling and flying insects but there are many thousands of different kinds. Of the huge family of two-winged flies only the mosquitoes and the sand-flies will be mentioned here. As the transmitting agents of malaria, filariasis, yellow fever, dengue and encephalitis, mosquitoes are amongst man's worst enemies. Since water may be the breeding-place or habitat of disease-transmitting organisms, the practice of fish culture should be integrated with measures to control whatever harmful creatures may be able to breed or live in the waters concerned.

([1 CANSDALE, 1953. GEN. 5

CHAPTER 2

PHYSIOGRAPHY

2.1. RELIEF

2.1.1. Mountains and valleys, hills and plains

The greater part of West Africa is a vast plain with an elevation between 600 and 1,200 feet above the sea (Diagram 2.1.1-1). This plain is surrounded by old mountain ranges which generally rise to between 1,500 and 3,000 feet (see Map B inside back cover). In the south-west there are the Futa Jalon mountain range and the Liberian Hills. The inland base of these mountains is at an elevation of 1,200 to 1,600 feet above the Mean Sea-Level but parts rise higher than 2,500

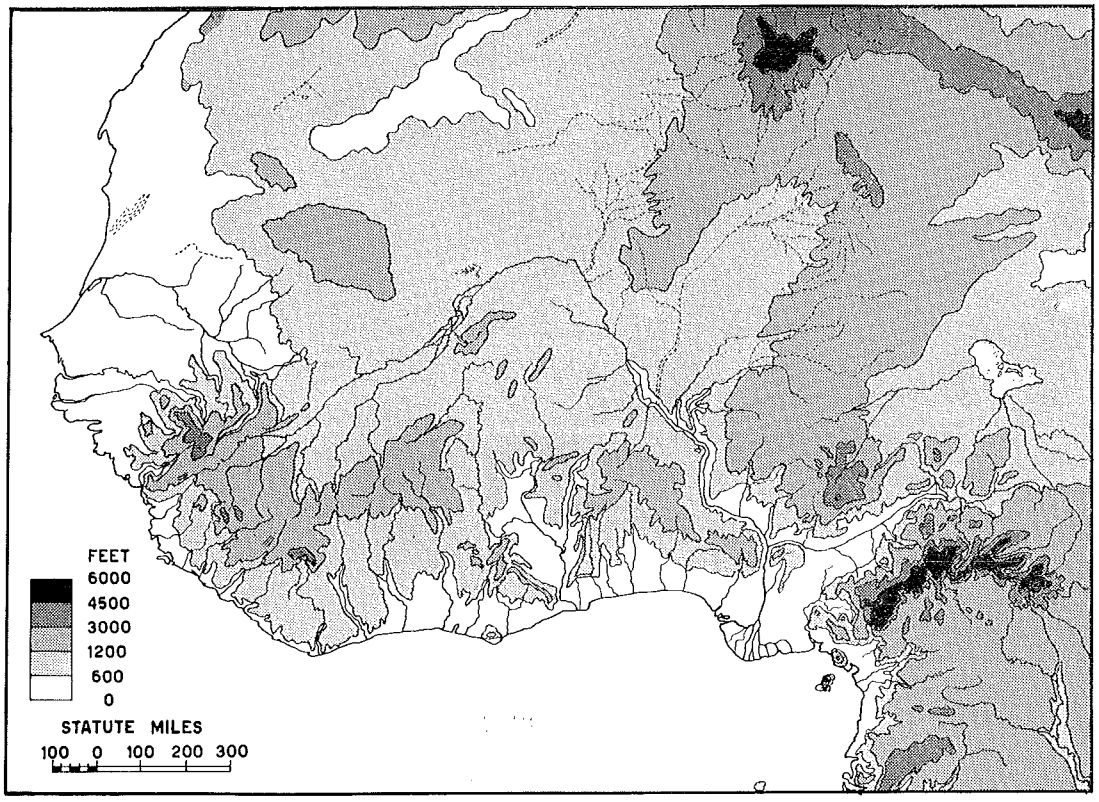


DIAGRAM 2.1.1-1

Relief features of the Niger Basin

feet. The Futa Jalon reaches even over 3,000 feet. To the north and the north-east are situated the Iforas Adrar, the Aïr and the Ahaggar Mountains, and the Jos Plateau. The Ahaggar rises above 4,500 feet. The greater part of the Jos Plateau has an altitude of 4,000 feet, but some hills rise over 5,800 feet. To the south the plain is separated from the sea by the higher land of the Ivory Coast and the hilly range which runs from Dahomey into Nigeria where it crosses the Niger between Baro and Idah. In the south-east the Adamawa Mountains rise higher than 6,000 feet.

The area bordered by the above-mentioned mountains is drained by the Niger and its tributaries. The headwater area of the Niger is in the south-west from which the Niger flows to the centre of the plain, where it passes through a lake area which is the remnant of a former interior delta. This lake area is situated at an altitude of 800—850 feet. After having passed the ridge of Tossay the Niger turns to the south-east. At some distance west of the Nigerian frontier the Niger passes the 600-feet contour and at the confluence with the Benue the altitude of the valley is less than 200 feet above sea-level.

The valley of the Benue, the main tributary of the Niger within Nigeria, is bordered to the north by the Mandara Hills and the Jos Plateau. The Mandara Hills rise to 4,000—5,000 feet. To the south the valley is bordered by the Adamawa Mountains. At the headwater area to the north-east (Mayo Kebbi) the basin of the Benue does not show much relief. The altitude varies from 1,000 to 2,000 feet above the sea. The Benue passes the 600 feet contour near the frontier between the French Camerouns and Nigeria.

Where the Niger reaches the Gulf of Guinea a vast delta has been formed.

2.1.2. Area-elevation curves

Diagram 2.1.2-1 gives area-elevation curves for the Benue Basin at the confluence with the Niger, for the Niger Basin between Jebba and Lokoja, and for the Niger Basin at Koulikoro which is situated at the apex of the old interior Niger delta. The diagram shows that at the higher altitudes there is relatively more variation in elevation in the upper parts of the Niger Basin than in the region between Jebba and Lokoja and in the Benue Basin above Lokoja. The reverse is true for the lower altitudes. This can be explained by the peculiar geological history of the Niger (see 3.1.2).

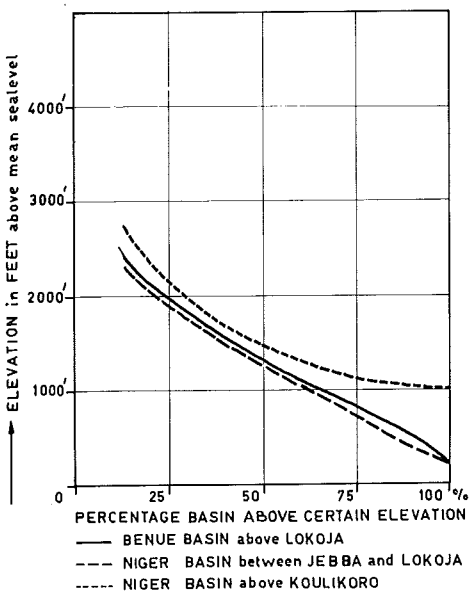
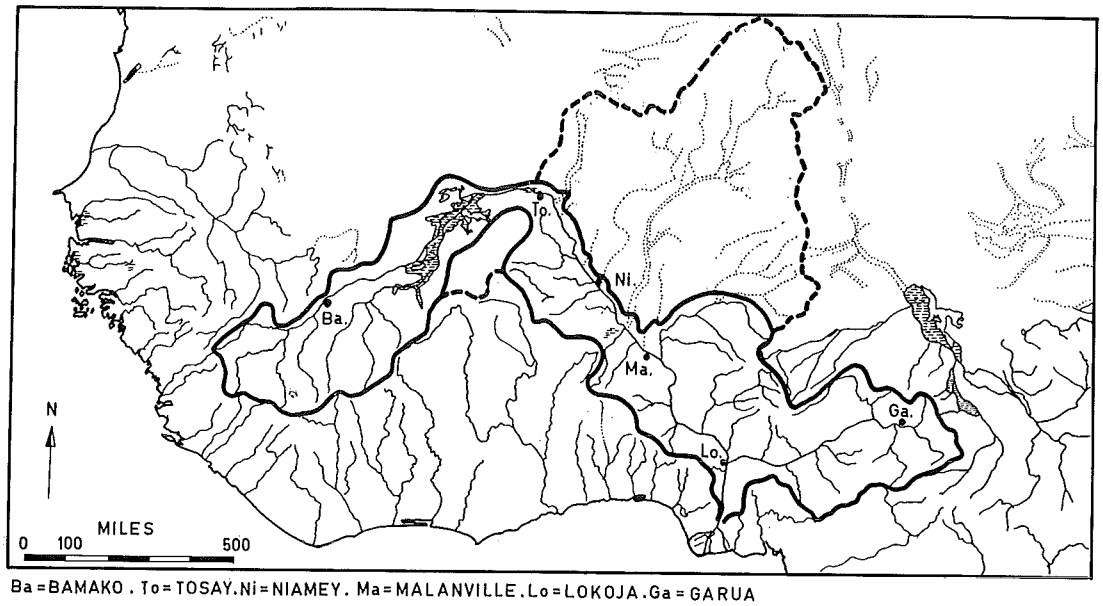


DIAGRAM 2.1.2-1

Area-elevation curves Niger Basin



Ba = BAMAKO . To = TOSAY. Ni = NIAMEY. Ma = MALANVILLE. Lo = LOKOJA. Ga = GARUA

DIAGRAM 2.2.1-1

Watersheds and drainage basin of the Niger River system

2.2. DRAINAGE PATTERN

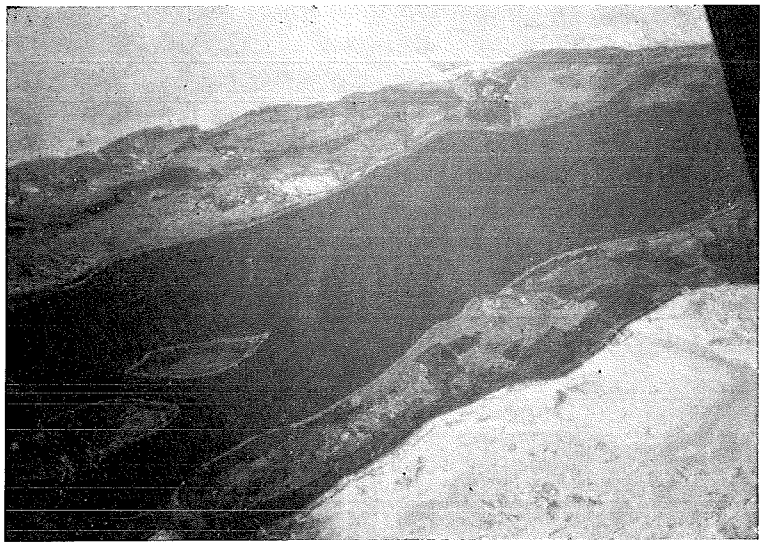
2.2.1. Watersheds

A watershed divides two drainage basins and generally corresponds with a line along the highest points of the topography. As in the Niger Basin the magnitude of the sub-surface flow is still practically unknown, this flow will not be taken into consideration. Moreover, it is expected that such a sub-surface flow would bring only minor local changes into the pattern put forward here. The outer thick line on Diagram 2.2.1-1, either full or dotted, runs along the highest points of the topography and connects the bordering mountains mentioned in 2.1.1.

Along *the Niger* in the mountainous area in the south-west, this line virtually separates the land draining to the south from that draining to the Niger. But it is rather difficult to estimate which part of the country adjacent to the lake area of the former interior delta belongs to the drainage area of the Niger. Since there is hardly any relief in the land on both sides of the river, it is nearly impossible to find the correct position of the natural watershed. This is, for instance, the case south of Tosay.

As the rainfall is rather low (Timbuctu has only 250 mm or 10″ per year) there will be nearly no contribution from the semi-desert areas where the scarce rainfall evaporates almost as soon as it comes into touch with the hot sandy surface. Hence the limit of the flooded area during high-water stage is considered here as the boundary of the catchment area (see Photograph 2.2.1-2).

North and east of Tosay, the dotted line on Diagram 2.2.1-1 runs along the highest point of the topography. The rainfall in this area, however, is less than 10″ annually. Due to the large penetration and evaporation the amount of water which reaches the Niger must be ignored. Only from a small strip of about 10 miles along the river may run-off reach the Niger, and this small part has therefore been included in the actual drainage area. The dotted line has accordingly been replaced by the full line.



PHOTOGRAPH 2.2.1-2

Niger drainage area near Timbuctu

South and west of Malanville the watershed is formed by the granite and gneiss mountains in the north of Ghana and of Dahomey. This mountain range continues towards the east past Ilorin and crosses the Niger in the neighbourhood of Lokoja, where the granite is locally covered by sedimentary rocks. Erosion has formed table-mountains between which the Benue and Niger join.

A striking feature of the northern watershed of the Niger Basin is the Jos Plateau, from where rivers drain in all directions; except those which run into Lake Chad in North-east Nigeria, all these rivers join the Niger either directly or indirectly.

In the middle course of *the Benue*, the northern watershed runs from the Jos Plateau along a line north of the Gongola to the Mandara Hills. In the east (French Camerouns), the watershed between the north-west part of the drainage basin of the Mayo Kebbi (the main tributary of the Benue above Garua) and the basin of the Logone (which runs towards Lake Chad) consists of a swampy area. During high floods on the Logone a small part of the discharge flows across this area into the Mayo Kebbi. The watershed is thus not well defined, but is considered to be situated across this swampy area.

Between the Jos Plateau and the Mandara Hills the position of the watershed between the Gongola and the Chad Basin is difficult to determine because of the little relief.

To the south-east the watershed of the Benue Basin is partly formed by the Adamawa mountain range. These mountains run to the sea in the neighbourhood of Calabar. But the area between the southern part of these mountains and Lokoja is partly drained by the Cross River. The watershed between the Benue and the Cross River is not well defined.

At Onitsha the eastern and the western watersheds of the Niger approach the river very closely. Below this point the Niger divides itself into many branches which form the delta.

When the watershed, as illustrated in Diagram 2.2.2-1 and described in this paragraph, is compared with the relief features (Diagram 2.1.1-1), it is remarkable that the inland part is

lower than the southern part. This is caused by the peculiar geological history (see Section 3.1).

The southern watershed of the Niger Basin has an elevation of 1,200—3,000 feet above the sea, except in the east where the Adamawa Mountains rise over 6,000 feet. The watershed between these mountains and Lokoja is situated at an altitude between 400 and 1,200 feet. On the other hand, the northern watershed does not rise above the elevation of 1,200 feet except at the Jos Plateau and the Mandara Hills.

2.2.2. River basins

Having left the headwater area in Guinea, the Niger at Koulikoro has a drainage area of 47,000 sq.miles. On entering the interior delta the river is joined by the Bani, the last main tributary before entering Nigeria.

From the position of the watershed, as outlined in the previous paragraph, there is an area of 117,700 sq.miles of the drainage basin above Diré, and of 119,400 at Tosay.

Considering the highest points of the topography as being the watershed (the dotted line on Diagram 2.2.1-1), the drainage basin between Tosay and the Nigerian frontier would cover an area of 3000,000 sq.miles of semi-desert. But the effective drainage area between Tosay and the Nigerian border, when considered with the description of Paragraph 2.2.1, will amount to about 45,000 sq.miles, bringing the total drainage area above Malanville at the Nigerian frontier to 170,000 sq.miles.

Above Malanville, two old river systems are still recognisable which long ago contributed largely to the discharge of the Niger (see 3.1.2). These are:

a. The valley of the Tilemsi in the north which joins the Niger above Ansongo, and
b. The valley of the Azouak which includes many old tributaries, the sources of some of which lie more than 1,000 miles away from the Niger. In the effective drainage area is included the lower 30 miles of the Azouak Valley, the so-called Dallol Bosso.

The position of major and minor watersheds within the Niger Basin in Nigeria have been drawn on Diagram 2.2.2-1. The areas of the various drainage basins within these watersheds are given in square miles.

In Nigeria the first great tributary is the Sokoto River. Its drainage area is not well defined either, but probably covers about 34,000 sq.miles (Table 2.2.2-2), mostly consisting of sedimentary soils.

Between Awuru and Jebba some rather steep hills reach the river. The Jebba Valley narrowing with the Juju Rock is well known. The total drainage area above this place is 244,000 sq.miles.

Downstream from Jebba the first important affluent is the Kaduna River, which drains an area of 25,600 sq.miles. The headwater area of this river is on the Jos Plateau. A great part of the basin consists of Basement rocks.

Because at Jebba, as at Baro, gauges have been installed for a long time, it is of interest to determine the drainage area of the Niger between these two stations. This area is 38,000 sq.miles.

Above the confluence with the Benue, the Niger drains 290,000 sq.miles.

The Benue, the main tributary of the Niger in Nigeria, drains an area of 130,000 sq.miles, of which 90,000 are within Nigeria (Table 2.2.2-3).

The drainage area above the Nigerian frontier can be divided into that of the Mayo Kebbi (at Famou: 11,600 sq.miles), that of the Benue (at Riao: 12,000 sq.miles), and that of the Faro (at the confluence with the Benue: 11,300 sq.miles). Although the Faro Basin is not larger than the other basins, it proves to be the most important when considering the contribution of dis-

TABLE 2.2.2-2

AREA DRAINAGE BASINS OF THE NIGER AND ITS TRIBUTARIES

MAIN TRIBUTARIES			MINOR TRIB.	NIGER	
River	Station	area drainage basin (sq. miles)	area drainage basin (sq. miles)	Station	area drainage basin (sq. miles)
				Kouroussa	7,000
Niandan	Confl.	4,870			
Milo	Confl.	3,830			
Tinkisso	Confl.	7,740			
Sankarani	Confl.	12,780			
			10,780		
				Koulikoro	47,000
Bani	Douna	39,650			
	Confl.	53,000			
			8,500		
				Mopti	108,500
			9,200		
				Diré	117,700
			1,700		
				Tosay	119,400
Gorouol	Confl.	5,500			
Sirba	Confl.	8,900			
			9,200		
				Niamey	143,000
Gourobi	Confl.	4,640			
Mekrou	Confl.	5,030			
Alibory	Confl.	6,040			
Sota	Confl.	4,750			
			6,540		
				Malanville	170,000
Sokoto	Confl.	34,000			
			40,000		
				Jebba	244,000
Kaduna	Wuya	25,300			
	Confl.	25,600			
			4,900		
				Pategi	274,500
Gbako	Badeggi	2,320			
Kampe	Eggan	3,120			
			1,000		
				Baro	282,000
Gurara	Confl.	5,700			
			2,300		
				Lokoja	290,000
Benue	Lokoja	130,000			
			2,320		
				Idah	423,000
Anambra	Onitsha	5,150			
			2,320		
				Onitsha	430,000

charge from this basin to the total discharge below the confluence of the Faro and the Benue (see Paragraph 4.3.6).

At Wuro Boki, just within the Nigerian frontier, the area drained by the Benue is 40,500 sq.miles. At Yola, a point along the river where the hills from both sides come near to each other, the drainage area covers 41,400 sq.miles.

At Numan the Benue is joined by the Gongola. Although the northern watershed of this river is not very well defined, an area of 21,500 sq.miles of sedimentary rock can be taken as a fair estimate for its drainage basin. Because of the relatively small amount of rain falling on the greater part of the Gongola Basin, the run-off from this river is not very important.

At Angwan Taru, above the first more important tributary from the south (the Taraba), the drainage area of the Benue is 79,500 sq.miles. The Taraba, which rises in the Adamawa Mountains, drains 8,240 sq.miles; the basin consists of volcanic and granite rocks, partly covered with only thin layers of sediment.

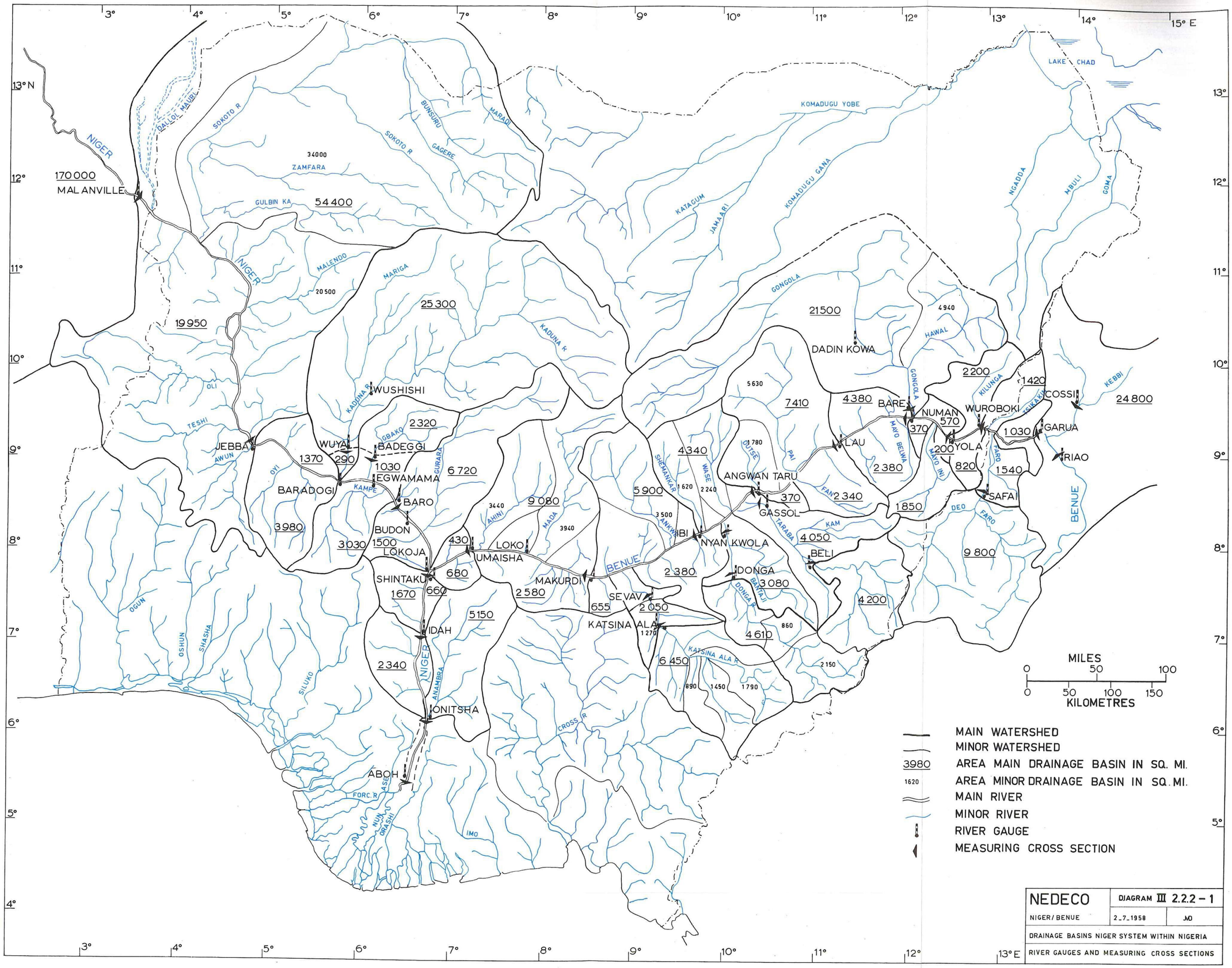
Some miles above Ibi the Benue is joined by the Donga, which also arrives from the Adamawa Mountains and drains 7,650 sq.miles. The nature of the basin is comparable to that of the Taraba. At Ibi the area drained by the Benue has become 99,500 sq.miles.

The last main tributary of the Benue is the Katsina Ala, which runs more or less parallel to the Donga and joins the Benue just above Makurdi. Between Angwan Taru and the Makurdi Defile, the area drained by the Benue increases from 79,500 to 117,500 sq.miles, an increase of about 50 %. On the other hand, the yearly run-off at Makurdi is more than twice that at Angwan Taru, which illustrates the importance of the basin between these two stations.

TABLE 2.2.2-3

AREA DRAINAGE BASINS OF THE BENUE RIVER AND ITS TRIBUTARIES

MAIN TRIBUTARIES			MINOR TRIB.	BENUE	
River	Station	area drainage basin (sq. miles)	area drainage basin (sq. miles)	Station	area drainage basin (sq. miles)
				Riao	12,000
Mayo Kebbi	Famou	11,600			
			1,200		
				Garua	24,800
Faro	Safaie	9,800			
	Confl.	11,300			
Kilunga	Confl.	1,390			
			3,110		
				Wuro Boki	40,500
				Yola	41,400
Mayo Ini	Confl.	1,850			
Gongola	Confl.	21,500			
			1,250		
				Numan	66,000
Mayo Belwa	Confl.	1,120			
			2,480		
				Lau	69,600
Fan	Confl.	1,470			
Pai	Confl.	5,650			
Dutse	Confl.	1,780			
			1,000		
				Angwan Taru	79,500
Taraba	Beli	4,200			
	Gassol	8,240			
Wase	Confl.	2,240			
Donga	Donga Town	4,600			
	Confl.	7,650			
Shemankar	Confl.	1,620			
			250		
				Ibi	99,500
Ankwe	Confl.	3,520			
Katsina Ala	K'Ala Town	6,450			
	Sevav	8,500			
			5,980		
				Makurdi	117,500
Mada	Confl.	3,940			
Ahini	Confl.	3,440			
			4,000		
				Umaisha	128,860
			1,140		
				Niger Confl.	130,000



MILES
0 50 100
0 50 100 150
KILOMETRES

- MAIN WATERSHED
- MINOR WATERSHED
- 3980 AREA MAIN DRAINAGE BASIN IN SQ. MI.
- 1620 AREA MINOR DRAINAGE BASIN IN SQ. MI.
- MAIN RIVER
- MINOR RIVER
- RIVER GAUGE
- MEASURING CROSS SECTION

NEDECO	DIAGRAM III 2.2.2 – 1	
NIGER/BENUE	2-7-1958	JVO
DRAINAGE BASINS NIGER SYSTEM WITHIN NIGERIA		
RIVER GAUGES AND MEASURING CROSS SECTIONS		

At Makurdi, rocks form the river banks. To the north and to the south, a watershed is clearly defined, running more or less at right angles to the river. Along this watershed the railway connection between Port Harcourt and Jos had been constructed.

Where the Benue joins the Niger its total drainage area has become 130,000 sq.miles. Although the drainage area of the Niger above the confluence is more than twice as great (290,000 sq.miles), the average run-offs of both rivers are about equal (about 100,000 cusecs).

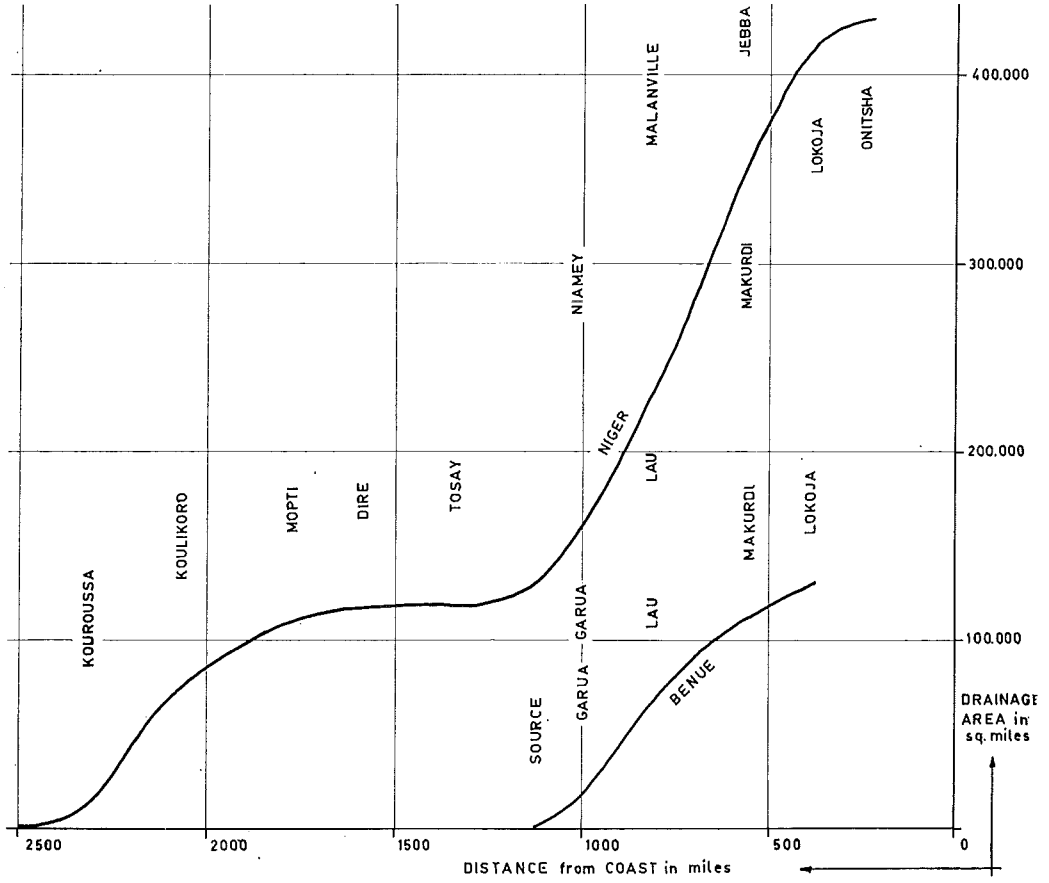


DIAGRAM 2.2.2-4

Drainage area of Niger and Benue as a function of the distance from the river-mouth

Below the confluence with the Benue, the increase of the Niger drainage area is relatively small (10,000 sq.miles between Lokoja and Onitsha). At Onitsha, situated near the apex of the Niger Delta, the total drainage area of the Niger is 430,000 sq.miles, of which 222,000 lie within Nigeria. As the Nigerian territory covers an area of 372,700 sq.miles, the Niger-Benue system therefore drains 60 % of that area.

The relation between the drainage area above a certain station and its distance from the Niger mouth is shown on Diagram 2.2.2-4. To establish this curve, the areas of the basins above stations along the Niger and its tributaries, which all have the same distance to the ocean as measured along the river, have been determined and added together. For the Benue stations

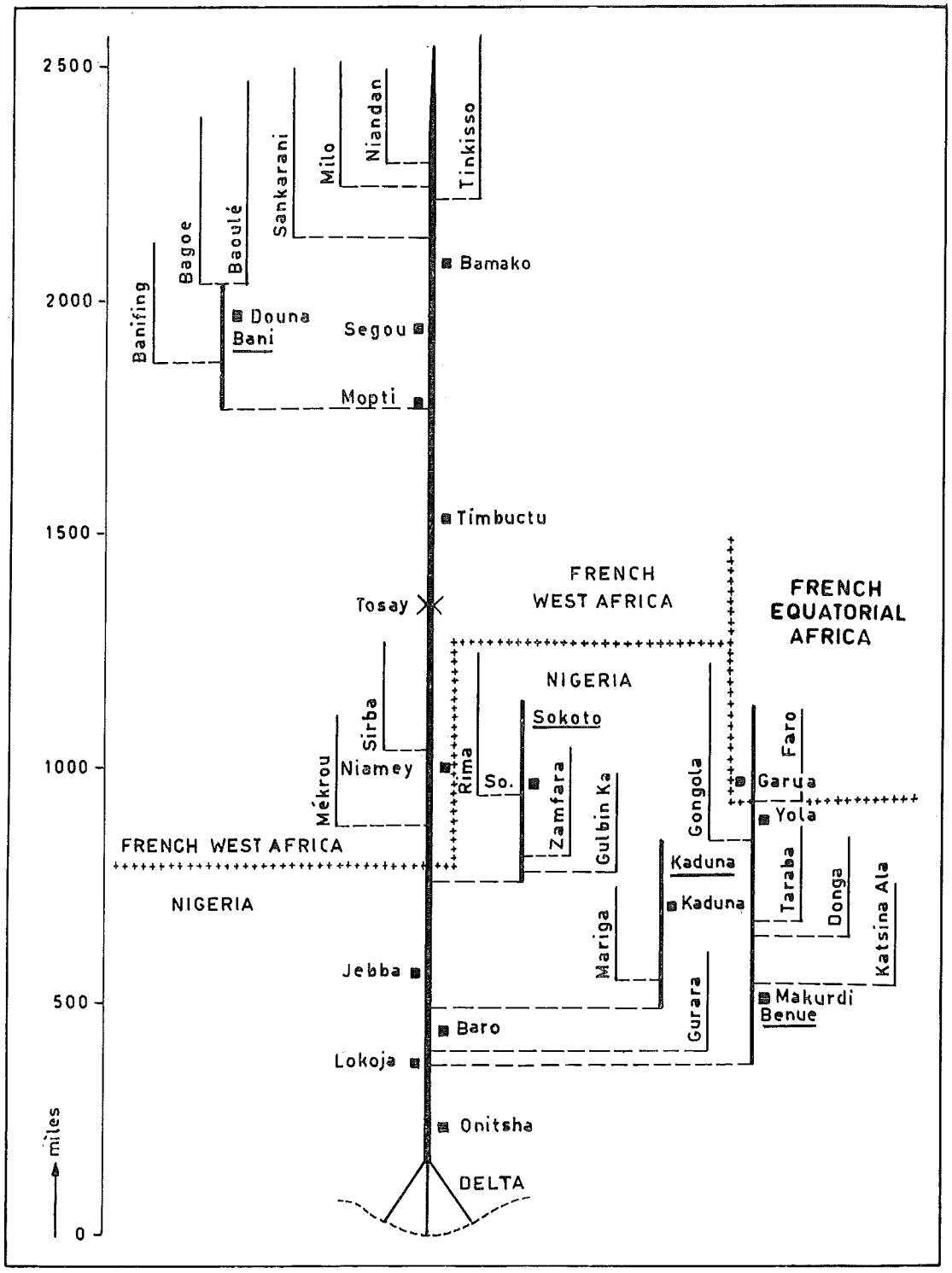


DIAGRAM 2.3.1-1

The Niger and its main tributaries

a similar process has been followed. The small increase of drainage area along the river stretch between Koulikoro and Tosay is well illustrated.

2.3. DESCRIPTION OF THE MAIN RIVERS

2.3.1. The Niger from French Soudan to the Delta

The Niger rises in the mountains of Sierra Leone (see Map A inside back cover), on the Futa Jalon Highlands, only 150 miles from the Atlantic Ocean, but as its source is on the landward side of this mountainous ridge, the river runs off in a north-easterly direction towards the centre of the Western Soudan depression.

After the river has passed the swamp-area around Timbuctu, which is the remainder of an old interior delta (probably during the Kanjerian Period) it breaks through a rocky ridge near Tosay and flows in a south-easterly direction through a semi-desert area with hardly any rainfall. Near the Nigerian border the rainfall increases again and the river takes a more southerly course and reaches the ocean about 2,550 miles from its source through many branches of its vast delta.

The drainage area of the Niger (amounting to 430,000 sq.miles according to the assumptions of the preceding Section) is drained by many affluents, and in Diagram 2.3.1-1 and Table 2.3.1-2 an outline is given of the most important tributaries of the Niger, in which the rivers with a total length of less than 200 miles have been omitted. Table 2.3.1-3 shows the mileage (counted from the navigation outlet of the Niger into the Gulf of Guinea) of various major towns on the banks of the Niger system, while the stations of the main gauges have also been indicated.

TABLE 2.3.1-2

THE NIGER AND ITS MAIN TRIBUTARIES (longer than 200 miles)

Niger	2,550 miles				
Niandan	200 miles				
Milo	270 miles				
Tinkisso	355 miles				
Sankarani	360 miles				
Bani	700 miles	—	Bagoe	430 miles	
			Baoulé	360 miles	
			Banifing	260 miles	
Sirba	235 miles				
Mékrou	235 miles				
Sokoto	390 miles	—	Rima	300 miles	
			Zamfara	235 miles	
			Gulbin Ka	205 miles	
Kaduna	360 miles	—	Mariga	205 miles	
Gurara	210 miles				
Benue	810 miles	—	Faro	235 miles	
			Gongola	380 miles	
			Taraba	200 miles	
			Donga	210 miles	
			Katsina Ala	215 miles	

The Futa Jalon Highlands and the Liberian Slaty Mountains, — on which the Niger and its upper tributaries the Tinkisso, the Niandan, the Milo and the Sankarani find their respective sources — have an average elevation of about 2,350 feet above Mean Sea-Level, with only a few peaks of over 3,000 feet.

The Niger itself is said to have its source at about 2,500 feet above M.S.L. During the first part of its source it flows over the impermeable plateau of Crystalline Rocks of the Futa Jalon, which is covered by extensive swampy areas. From this plateau the Niger drops over more than 1,000 feet into a valley which finds its origin in tectonic subsidence of this mountainous area. Over the first 100 miles the river flows due north and then takes a NE course. Up to Kouroussa (2,307 miles from the outlet into the Atlantic Ocean) the river is obstructed by many small rapids and the average slope amounts to about 20×10^{-5}.

TABLE 2.3.1-3

MILEAGE OF VARIOUS TOWNS ALONG THE NIGER AND ITS MAIN TRIBUTARIES

NIGER	2,550 miles
Escravos	0
Burutu	40
Warri	44
Siama	88
Patani	130
Aboh	177
Onitsha	232
Illushi	272
Idah	310
Itobe	332
Lokoja	362
Budon	399
Baro	434
Jebba	556
Bussa	642
Yelwa	688
Frontier	790
Malanville	811
Say	955
Niamey	995
Tillabery	1,068
Labbenzenga	1,149
Ansongo	1,211
Gao	1,270
Tosay	1,341
Timbuctu	1,528
Diré	1,574
Mopti	1,765
Sansanding	1,918
Ségou	1,940
Koulikoro	2,041
Bamako	2,081
Siguiri	2,209
Kouroussa	2,307
Source	2,550

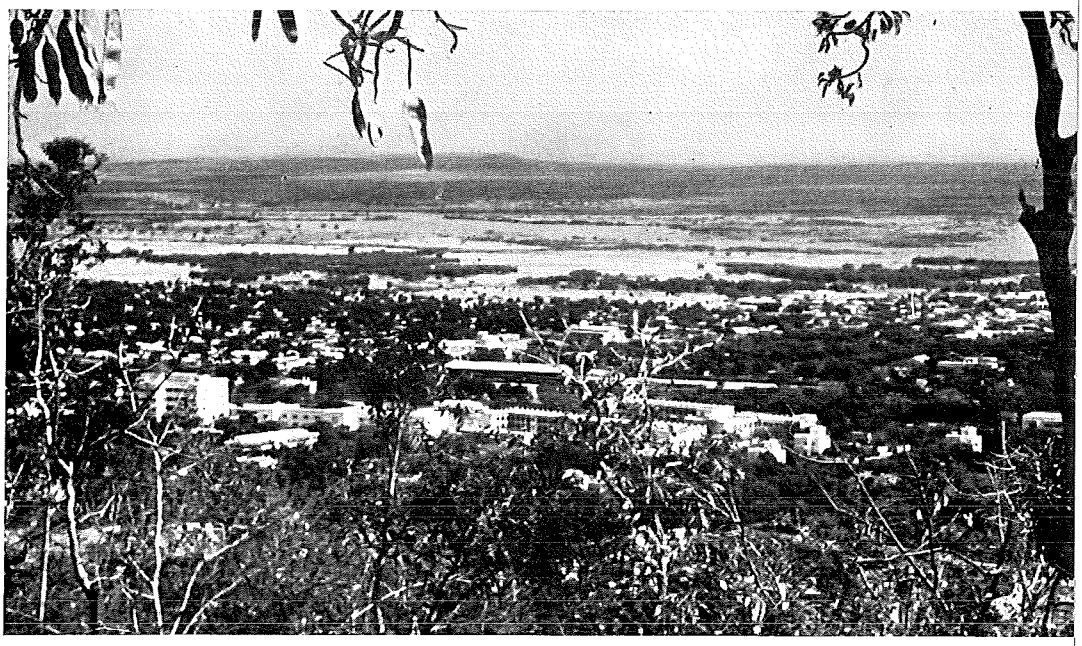
BANI	700 miles
Mopti	1,765
Douna	1,963
Source	2,465
SOKOTO	**390 miles**
Confluence	753
Birnin Kebbi	860
Sokoto	884
Source	1,143
KADUNA	**360 miles**
Confluence	485
Zunguru	565
Kaduna	705
Source	845
BENUE	**810 miles**
Lokoja	362
Umaisha	401
Bagana	434
Loko	454
Makurdi	510
Abinsi	528
Ibi	614
Kwatta Nanido	712
Lau	778
Gamadio	815
Numan	846
Yola	888
Wuro Boki	916
Frontier	926
Garua	972
Riao	1,008
Lagdo	1,011
Source	1,172

FARO	235 miles
Confluence	926
Beka	950
Safai	983
Source	1,160
GONGOLA	**380 miles**
Confluence	846
Bare	855
Shellem	877
Dadinkowa	935
Nafada	1,001
Source	1,226
TARABA	**200 miles**
Confluence	672
Gassol	691
Beli	753
Source	872
DONGA	**210 miles**
Confluence	636
Nyankwala	649
Donga	686
Source	846
KATSINA ALA	**215 miles**
Confluence	536
Sevav	570
Katsina Ala	610
Source	751

At Kouroussa (left bank) the railway line from Konakry to Kankan crosses the Niger and from this point downward the river becomes navigable for small craft. Between Kouroussa (left bank, Mile 2,307) and a point some 50 miles upstream from Bamako, the four upper tributaries as already mentioned join the Niger, resulting in the annual discharge increasing to about 1700×10^9 cuft, being five times the annual discharge at Kouroussa. The average peak discharge reaches 200,000 cusecs, which mostly occurs in the month of September.

From Siguiri (l.b., Mile 2,209) downward, the river-bed becomes sandy and has an alluvial flood-plain about one mile wide, and the slope of the river decreases to about 10×10^{-5}.

The adjacent country of the upper course of the Niger (or Djoliba, as the native name goes) and its tributaries, consisting mainly of impermeable granites and gneisses, is for the major



PHOTOGRAPH 2.3.1-4

Bamako

part covered with wooded savana. The annual rainfall in this area averages 60 inches, of which about one-third contributes to the discharge of the rivers.

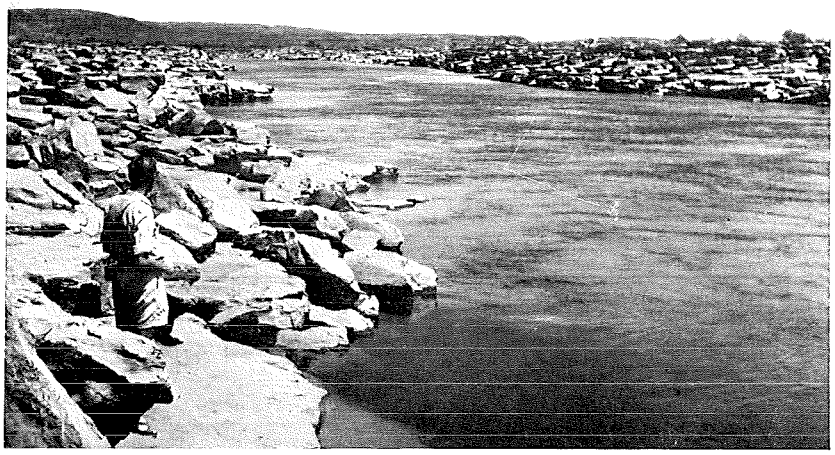
Near Bamako (l.b., Mile 2,081), the capital of the Territory of French Soudan and the second largest town on the entire Niger, the Crystalline Rocks are covered by a sandstone plateau generally reaching to about 300 feet above river-level, with the exception of the Mandigo Mountains on the left bank of the Niger reaching to 600 feet above river-level. Direct downstream from Bamako the Niger cuts through this sandstone plateau and also partly into the underlying Crystalline Rocks, which results in a section of 40 miles with two major rapids, those of Sotuba and those of Kenié, having a total fall of about 100 feet.

At Koulikoro (l.b., Mile 2,041), the head of the railway-line from Dakar, the river again becomes navigable and can be used for shipping over a distance of more than 800 miles. Going downstream from Koulikoro some rocks are found in the sandy river-bed over the first 20 miles, but gradually the sandstone hills become lower and recede from the river, the river-bed widens and, together with the adjacent flood-plain, occupies a width of about 2 miles. The characteristics of the river and its floodlands are similar to those obtaining on the Niger and Benue within Nigeria.

Some 60 miles downstream from Koulikoro the Niger flows in its own alluvium, which lies about 30 feet above the present H.W.-level, except for a NNE running depression on the north bank, between the villages of Niamina (l.b.) and Tamini (r.b.) with a minimum height of only 3—7 feet above H.W. river-level. The general direction of the Niger, which was NE, gradually changes to ENE from the point where the river is no longer bordered by rocks.

Opposite Ségou (r.b., Mile 1,940), which is a rather large town and headquarters of the "Office du Niger", another depression is found, running NNW and having a connection with the above-mentioned one. They are probably the remainders of old courses of the Niger during the time this river flowed more northward into the Sahel area.

Near the village of Sansanding, some 20 miles downstream from Ségou, a 2,650 feet movable weir and an earthen dam 5,900 feet in length close the river-bed of the Niger for irrigation purposes. The ships pass through a 5-mile canal, with a shipping lock, on the right bank of the river.

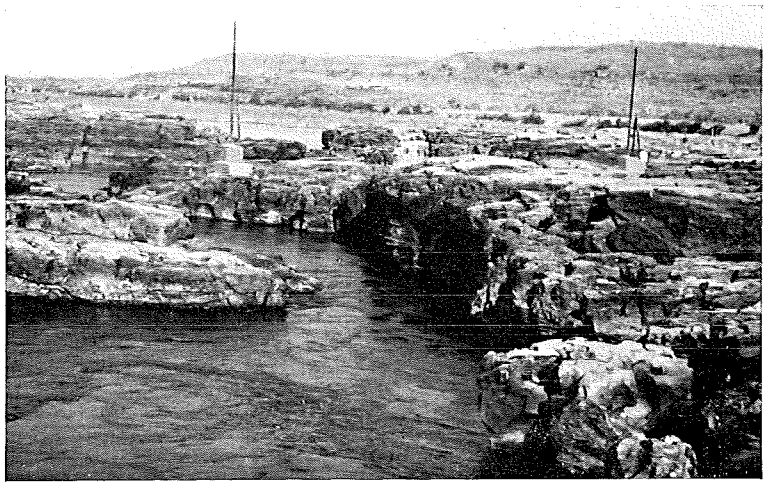


PHOTOGRAPH 2.3.1-5

The Niger between Bamako and Koulikoro during low water

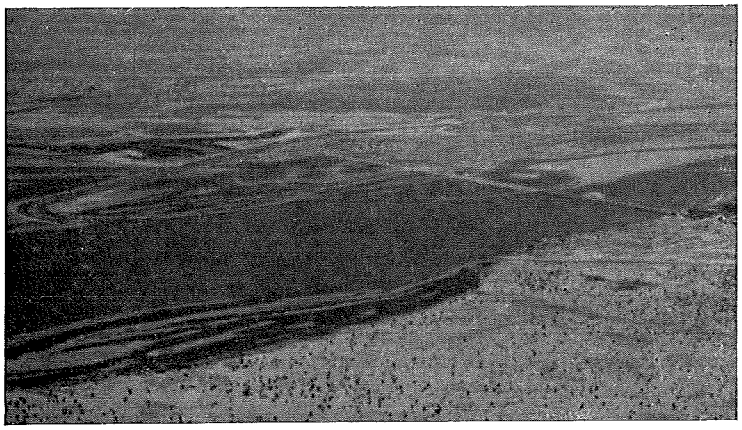
Over this weir one of the few bridges crossing the Niger has been built, which will perhaps in the future carry the Trans-Saharian Railway.

The irrigation water is led through two old branches of the Niger: the "Canal du Sahel", leading north, and the "Canal du Macina" into the "Marigot de Boki-Were", running NNE.



PHOTOGRAPH 2.3.1-6

A part of the rapids of Sotuba during low water

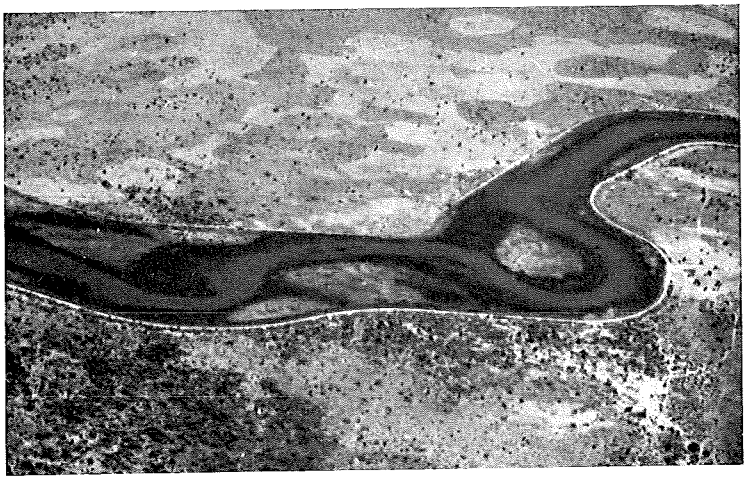


PHOTOGRAPH 2.3.1-7

An aerial view of the dam at Sansanding, looking north

For a more detailed description of the irrigation scheme of Sansanding see Paragraph 1.2.4.

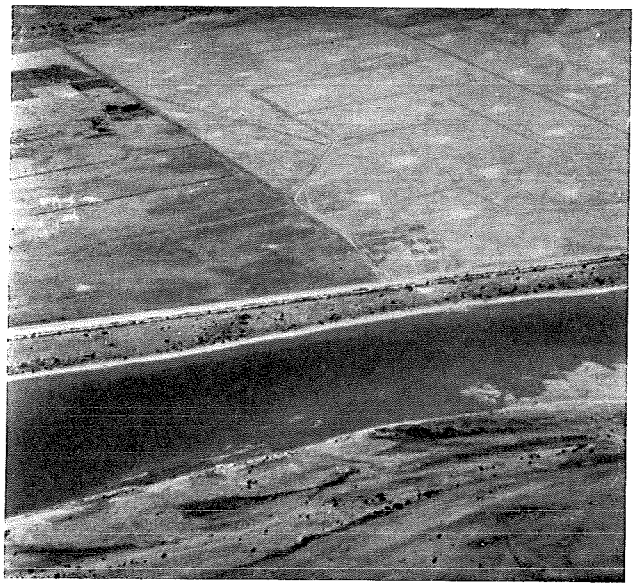
Downstream from Sansanding the northern bank of the Niger is artificially closed over the first 50 miles upto about Ké-Macina (l.b.) by the dike along the Marigot de Boki-Were and the adjacent irrigated areas. The height of the south bank becomes gradually lower and opposite Ké-Macina the flood-plain widens to about 10 miles.



PHOTOGRAPH 2.3.1-8

The "Marigot de Boki-Were", now used as irrigation canal

The Niger now enters its Interior Delta Area and during the H.W.-period large areas on both sides of the river are flooded. Near Diafarabe (l.b.) some 60 miles upstream from Mopti the "Marigot de Diaka" branches northward and joins the Niger again some 70 miles further downstream. This branch takes about 25 % of the annual discharge of the Niger, while it is estimated that 40 % of the peak flow runs off via the bank of the river upstream from Mopti. The slope of the water-level decreases to 5×10^{-5} over this stretch of the Niger.



PHOTOGRAPH 2.3.1-9

The dike along the north bank of the Niger and the irrigated area behind it

The Bani, which joins the Niger at Mopti (r.b., Mile 1,765) and is its largest tributary on the right bank, increases the annual discharge of the Niger by nearly 50 %. During the high-water period the waters of the Bani and the Niger intermingle in the extensive flood-plain between both rivers. In this a slight flow is observed from the Niger to the Bani, as the water-level of the latter is a little lower than that of the Niger, because of a smaller slope (3×10^{-5}).

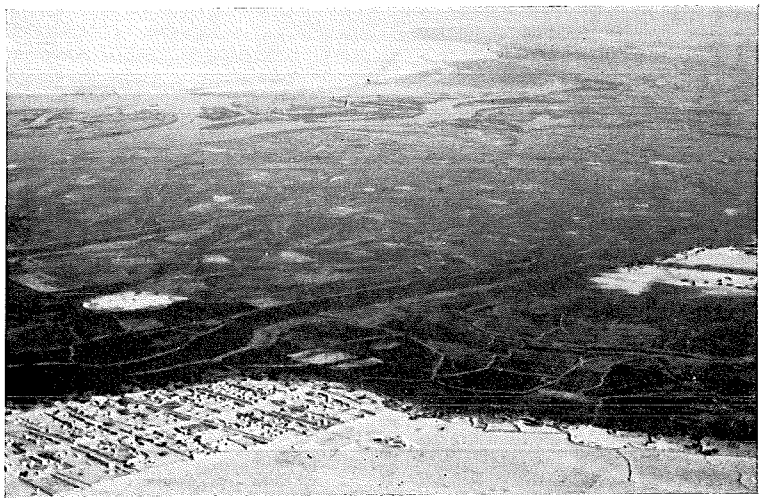
Downstream from Mopti the slope of the water-level decreases still more (to about 1×10^{-5}). The river bifurcates again and again, the major branches being the Issa-Ber, the Bara Issa and the Koli-Koli (Diagram 1.2.4-3). During the H.W.-period the many lakes and pools on both sides of the river are filled with water, a part of which flows back into the main river during the fall, although from those lakes which are situated below low-water level, no return flow is possible. As the rainfall in the Interior Delta is rather small (10 to 20 inches per year) and the annual potential evaporation is estimated at 5 to 7 feet, much water is lost over this stretch

PHOTOGRAPH 2.3.1-10

Dunes in the interior delta

PHOTOGRAPH 2.3.1-11

The Niger at Gao



of the Niger (see 4.4.3) and at Diré, situated below the Interior Delta (l.b., Mile 1,574), only 35 % of the annual discharge of the Niger and its tributaries remains.

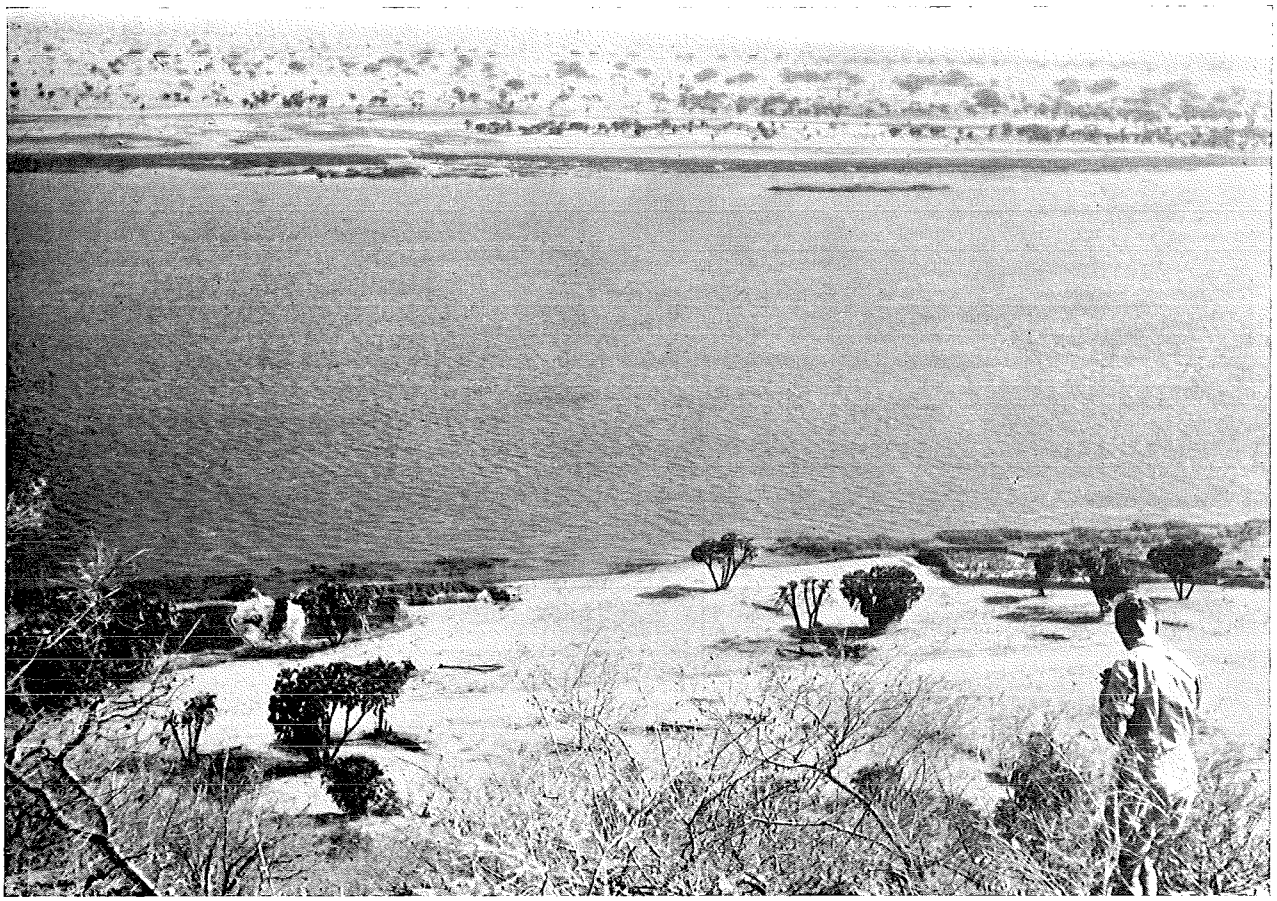
A striking feature in this area are the WSW-ENE ridges through which the branches of the Niger between Mopti and Diré try to find their way in a NNE direction. These ridges originate from a period when the climate in this area was much drier and the desert wind formed sandy dunes situated at right angles to its prevailing direction, being NNW.

Between Diré and Timbuctu (r.b., Mile 1,528) the width of the swamp area decreases to roughly 10 miles. Timbuctu, situated 5 miles north of the river, is connected with the Niger by a small canal at the end of which Karaba acts as the port of this well-known junction of caravan routes.

From Timbuctu downward over about 120 miles the river roughly follows the WSW-ENE trend of the sandy ridges, mentioned before, and flows with a sandy meandering course through

PHOTOGRAPH 2.3.1-12

The Niger between Gao and Ansongo



PHOTOGRAPH 2.3.1-13

The Niger near Niamey

a rather straight valley from 2 to 5 miles wide, until the Niger reaches its most northern point at the latitude of 17° 5′ N. The river then flows over about 60 miles slightly SE within a valley from 1 to 2 miles wide, mostly in one river-bed and with a slight increase of the slope presumed (3×10^{-5}).

Then suddenly in this area of sandy ridges and swamps, a rocky ridge obstructs the Niger's course near Tosay (Mile 1,341). This ridge of Cambrian rock was probably overflowed during the Gamblian Pluvial (Paragraph 3.1.2), since when the connection between the Soudanese Niger and the "Lower Niger" has existed. The defile of Tosay is more than one mile long, has an average width of about 800 feet and a depth at some places of over 100 feet. Downstream from this narrowing the river widens considerably and flows down to Gao in a SEE direction, through a flood-plain 3 to 6 miles wide. At Gao (l.b., Mile 1,270) the old bed of the Tilemsi River (3.1.2) joins the Niger.

After the Niger has passed through the gap at Tosay, the slope of the water-level again gradually increases, but as no accurate levels along this part of the Niger have been established the figure of 7×10^{-5} is only an indication of its magnitude.

Over the stretch Gao—Ansongo (l.b., Mile 1,211) the river flows SE and its flood-plain gradually narrows to about 1 to 3 miles in width. The whole reach between Tosay and Ansongo is marked by the presence of innumerable small and large islands, most of which are situated just below H.W.-level. When seen from the air during the H.W.-season this part of the Niger looks like a blue and green strip finding its way through a brown-yellowish and dry landscape of sandy ridges and laterite-crusted table-mountains.

Ten miles downstream from Ansongo the river passes through the first narrowing of a series of defiles and rapids, some of which are very difficult for ships to pass. Especially over the stretch between Labbenzenga and Tillabery (Miles 1,149 and 1,068 respectively) navigation is hardly possible. The average slope over this part of the river is about 17×10^{-5}, a rather steep slope which continues over the next stretch down to Niamey (l.b., Mile 955), the capital of the Territory of NIGER.

Downstream from Niamey the slope of the water-level decreases again to about 7×10^{-5} and the river shows about the same picture as between Tosay and Ansongo, with many islands and a H.W.-bed 1 to 2 miles wide, bordered by table-mountains which lie about 200 feet above river-level. Just below Niamey the valley of the old desert river Zigarat forms a depression on the left bank.

As the H.W.-bed of the Niger passes west of Say (r.b., Mile 955), this town is situated on an island during the H.W.-period. Near Kirtachi, some 25 miles below Say, the scenery changes as the soft sandstone peneplain makes place for the quartzite layers of a SW-NE spur of the Atakora Mountains. In these rather regularly deposited layers, which are folded with a maximum dip of 15° to 20°, local phenomena such as crossing layers and layers with symmetric ripple marks on its surface are to be seen.

Especially between the confluence with the Tapoa (r.b.) and the village of Bossia (l.b.) over a distance of 30 miles, the course of the Niger is disturbed by this rocky interference, and the river flows zig-zag with a few minor rapids through the well-known "Double V" (Diagram 2.3.1-14). South of this defile, which is bordered by steep cliffs on each side, the "National Park of the W", covering an area of 4,000 sq.miles, constitutes a vast refuge for the Soudanese fauna.

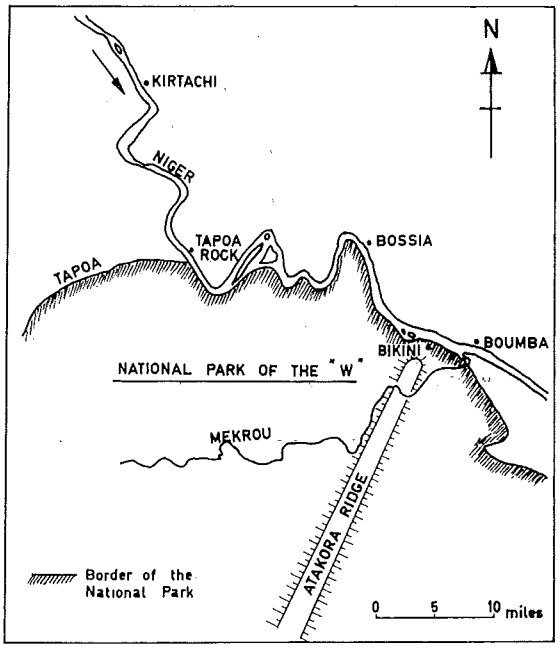


DIAGRAM 2.3.1-14

"W" between Niamey and Malanville

Ten miles down from the "W" the river breaks through the major ridge of the Atakora Mountains, known as the rocky sill of Bikini, and the familiar scenery of flat-topped hills once again borders the Niger. Soon the Mékrou joins the Niger on the r.b., after it has cut its ways twice (first in a NW-ly direction and then SE-ward) through the Atakora ridge. On the left bank,

a large depression indicates where the old river-bed of the Azouak joins the Niger. This river, which was over 1,000 miles long, formed the headwaters of the Niger before the area between the Adrar, Ahaggar and Aïr Mountains dried up, and the importance of this ancient river is still reflected in its 7-mile wide valley, known under the name of Dallol Bosso. Nowadays only the lower part of this river contributes a little water to the Niger after periods of heavy rainfall.

Down to Malanville (r.b., Mile 811) which, like Say, lies on an island during the H.W.-period, the scenery changes little: still flat-topped mountains but less numerous than in the vicinity of Niamey, and a gradually widening flood-plain in between them. Between Malanville and Gaya on the left bank the first bridge since the one over the weir at Sansanding will cross the Niger, serving the road transport from the French territories north of Nigeria, to the coastal harbours of Dahomey.

At Mile 790, as the Niger enters Nigeria, the H.W. river-bed is 5 miles wide and is joined on the left bank by the swampy lower course of the Dallol Foga. The vegetation in the Dallols and swamps mainly consists of Borassus palm trees. In the south the gently undulating plain

PHOTOGRAPH 2.3.1-15

Borassus Palm trees in the Dallol Foga

is only broken by some scattered groups of flat-topped hills, while the northern bank remains flat and swampy. When the Niger is some 50 miles within Nigeria the Sokoto River debouches from the north into this swampy flood-plain. This tributary carries more water than the previously mentioned Dallols, as some of its affluents have their respective sources on the well-watered northern slopes of the Jos Plateau, whereas the Dallols run off from the now arid desert areas.

These broad flat-bottomed trench-like valleys of the Dallols and of the Sokoto River, which are bordered by two steep escarpments leading to the plateaux on either side, form a sharp contrast to the narrow canyon valleys of the Kaduna and Gurara Rivers.

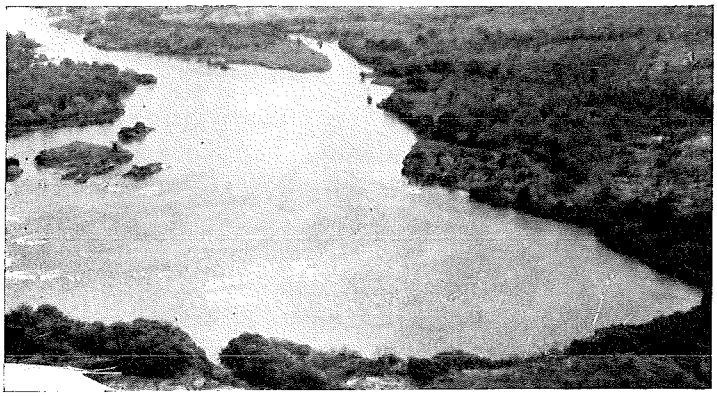
An explanation for this phenomenon can probably be found in the occurrence of hard Crystalline Rocks between Yelwa and Jebba through which the Niger has cut its way in a southerly direction, resulting in many rapids and falls, the average slope over this stretch being about 30×10^{-5}.

Geologically speaking this cutting backward and downward of the Niger into the Crystalline Rocks has just begun and the level of the first set of hard rocks just upstream from Yelwa (near Sakachi) can be considered as an erosion-base of the Niger from the rapid section Labbenzenga-Tillabery downward. Hence the rather gentle slope of this section of the river, being 7×10^{-5}.

This erosion-base is also felt by the tributaries of the Niger, and as the lateral erosion continues and the sediment-transporting capacity of the main rivers is limited by the small slope available, flat-bottomed and swampy river-valleys will result.

The aspect of the Niger changes as soon as the hills begin to close in, and between Yelwa (l.b., Mile 688) and Agwarra some 20 miles farther downstream the river is bounded by low rounded hills and innumerable islands rise from the river-bed, while several lesser rapids obstruct the channel.

At Agwarra the Niger is formed of two branches: the more westerly is rather calm while the easterly one is obstructed by some rocks and rapids. Between both branches the Foge Island forms a part of an extensive flood-plain, which exists on both sides of the calm flowing part of the river. Near Bussa (r.b., Mile 642), the scene of the explorer Mungo Park's murder in 1805, both channels join again and the river is much obstructed by projecting rocks and islands, whilst the small cascades render navigation rather difficult if not impossible.

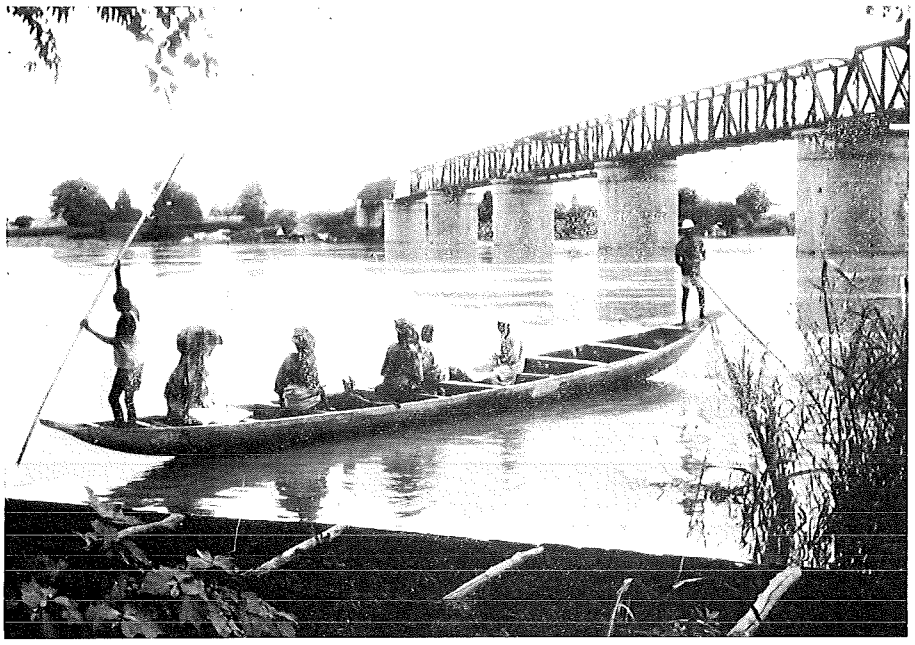


PHOTOGRAPH 2.3.1-16

The rapid of Buburu

In the rocky valley of the Niger between Bussa and Jebba (r.b., Mile 556), bordered by two belts of broken hilly ground leading up to the plains of Kontagora and Bornu, three important sets of cascades occur. First are the rapids of Garafini, whose falls and whirlpools occupy a stretch of about three miles between Buburu (Photograph 2.3.1-16) and Garafini. Then twenty miles farther on is the rapid of Patassi, which is separated by a 2—3 mile long reach of comparatively smooth water from the Great Rapid of Awuru, where the Niger roars down around a rocky island over a length of about $^3/_4$ of a mile.

The river then follows a remarkably straight rocky gorge over a distance of 10 miles and after passing a number of small rapids and whirlpools becomes navigable again downward from



PHOTOGRAPH 2.3.1-17

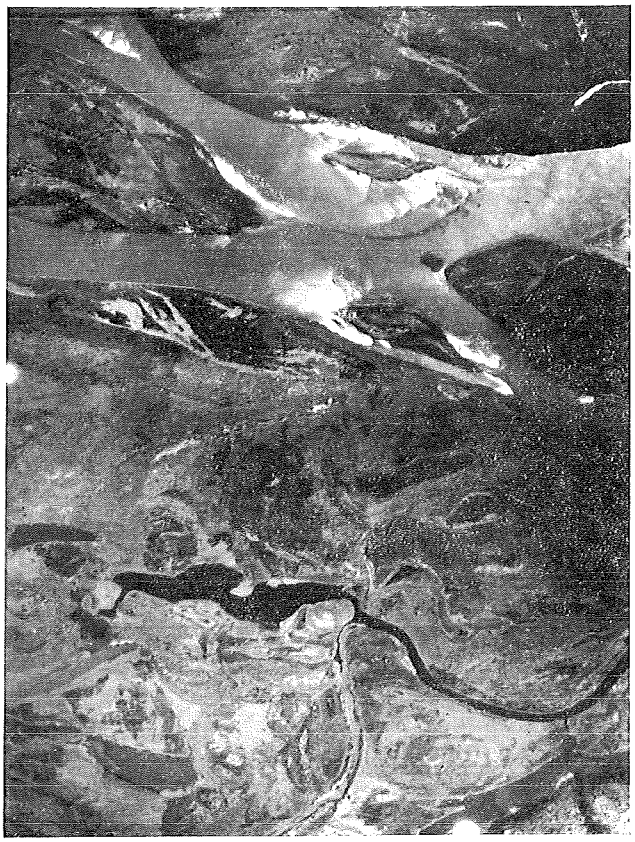
The railway bridge over the south channel of the Niger near Jebba

Bajibo some 20 miles from Jebba, although great caution is needed in this stretch. Near Jebba the gorge is narrow and bounded by vertical walls of quartzite, and the Juju Rock and other islands rise steeply from the river. Here the railway bridge of the line from Lagos to Kano, constructed in 1916, crosses the Niger in two sections of 522 feet and 1,526 feet over the north and south channels respectively (Photograph 2.3.1-17).

Downstream from Jebba ([1] the river flows ESE through a broad and shallow valley 5 to 10 miles wide with extensive fertile swampy plains on either side and many islands within the river. Only at Rabba on the left and at Shonga on the right bank does the rising ground approach the river, which elsewhere bounds the valley at a distance. These low-lying grounds, known as fadama land, are very suitable for irrigation purposes (Paragraph 1.2.4). The Kaduna River, which joins the Niger 80 miles below Jebba, is the first major tributary within Nigerian territory and contributes about 25 % to the annual discharge of the river below the confluence. The regime of the Niger gradually changes as the influence of the local rainfall increases in relation to the discharge originating from the Soudanese catchment area (Black Flood, see Paragraph 4.5.4). The transport of sediment increases considerably and the low swampy plain upstream from the confluence with the Kaduna River gives place to regular sandy flood-plains just a few feet below the H.W.-level, intersected by many old courses, loops and oxbow-lakes.

Before Baro is reached the river turns SSE and on the left bank a few flat-topped hills are to be seen. Baro (l.b., Mile 434) is the railhead of the line from Kano and plays an important rôle in the evacuation of the groundnut crop from the Northern Region. In fact, it is one of the most important ports on the Niger.

([1] Reference is made, for the mileage and description of the Niger below Jebba, to the Book of River Charts accompanying this Report.



PHOTOGRAPH 2.3.1-18

The Niger between Jebba and Pategi

PHOTOGRAPH 2.3.1-19

The port of Baro (Mile 434)

Some miles downstream from Baro the table-mountains also appear on the right bank and at places the flat-topped hills still rise up over considerable distances in all their ancient grandeur, with precipitous slopes on each side. More frequently, however, the escarpments are rounded off and much eroded by lateral valleys, while at times they recede to a distance and leave between themselves and the river a more or less extensive plain with here and there a flat-topped remnant of the once continuous plateau. For more than 20 miles the Niger flows between the broken walls of what once was a magnificent river gorge two miles wide in the ancient peneplain.

Near Koton Karifi the hills on the left bank disappear and only the right bank is flanked by the worn escarpment of the plateau, of which Mount Patti near Lokoja forms the southernmost extremity. The huge plateau of Patti is at a level of about 1,000 feet above the river-level.

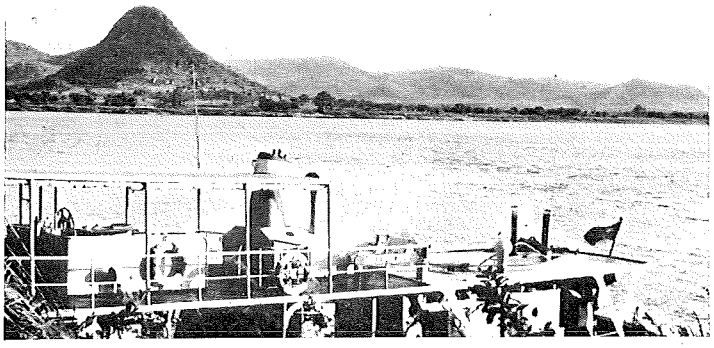
PHOTOGRAPH 2.3.1-20

Mount Patti and the native town of Lokoja (Mile 362)

At Lokoja (r.b., Mile 362) the Niger is joined from the east by its largest tributary, the Benue (2.3.2), which about doubles the annual discharge of the river. Downstream from Lokoja the hills close in rapidly and the channel becomes narrow and rocky. Lofty granite domes and rounded hills separated by wooded valleys rise up on each bank, and this part of the Niger, from Igbo to Itobe, is considered the most picturesque section of its lower course. The few rocks which protrude into the shipping channel are marked by buoys, and as the combined eroding forces of the Niger and Benue have been strong enough to cut a deep channel into the rocks of the Basement Complex, the currents are only a little swifter than in the other parts of the river, so that navigation through the so-called Rocky Section of the Niger is comparatively easy.

Beyond Itobe (l.b., Mile 332) the river broadens and long islands frequently divide the river into two or sometimes even more parallel branches. A broken plain stretches inland below Itobe to distant groups of low hills. A little farther on the hills close in again and at Mile 324 on the right bank the river flows for the last time along some hills of the Basement Complex, while on the left bank also a group of hills runs up to the riverside.

After a short stretch where the river flows through its own alluvium, the Niger narrows



PHOTOGRAPH 2.3.1-21

The rocky section of the Niger (Mile 350)

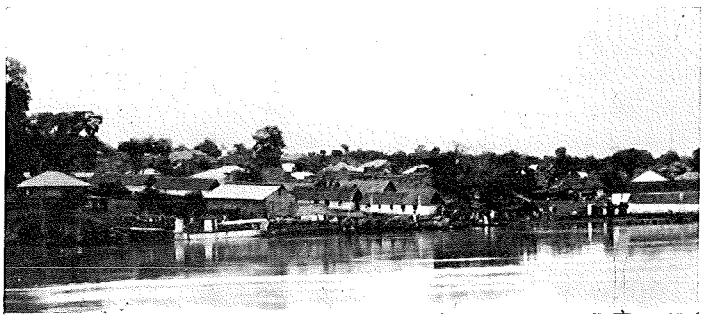
again at Idah (l.b., Mile 310) and flows between cliffs of false-bedded sandstones, which pass into stretches of wooded rising ground.

The Niger below Idah is bordered on the right bank at a distance by gently-sloped low hills of Tertiary sandstones of the Imo Shale Group and the Bendi Ameki Group. On the left bank a 20-mile wide plain of alluvium, tapering towards the valley-narrowing near Onitsha, stretches as far as the course of the Anambra River. Since the Niger left the Rocky Section, the river banks are for the greater part sandy and covered with rather dense vegetation. Many villages and small towns are found along this part of the river, which flows with a rather uniform slope of 8.5×10^{-5} through a one-mile wide river-bed. The numerous sand-banks emerging from the river as soon as the water-level falls some 5 to 10 feet below its H.W.-stage tower above the river during the low-water season, when shipping, although with some restriction, is still possible due to the Black Flood phenomenon (Paragraph 4.5.4).

At Onitsha (l.b., Mile 232), which is the largest town along the Niger with a very important and large market, the river valley narrows for the last time and the Niger finds its way through a probable fault of the sandstones of the Bendi-Ameki Group.

After passing this last rocky obstruction and still heading due south, the Niger flows in its own alluvial deposits, which are now bordered on both sides by the Coastal Plains Sands of the Pleistocene-Oligocene Period, until the river bifurcates in many branches and reaches the ocean, into which it has built out a vast delta (Section 2.4).

The annual discharge of the Niger reaches its maximum at Onitsha, averaging $7{,}000 \times 10^9$ cuft with a distinct peak discharge in October of about 800,000 cusecs. Below Onitsha the river-



PHOTOGRAPH 2.3.1-22

The port of Idah during high water

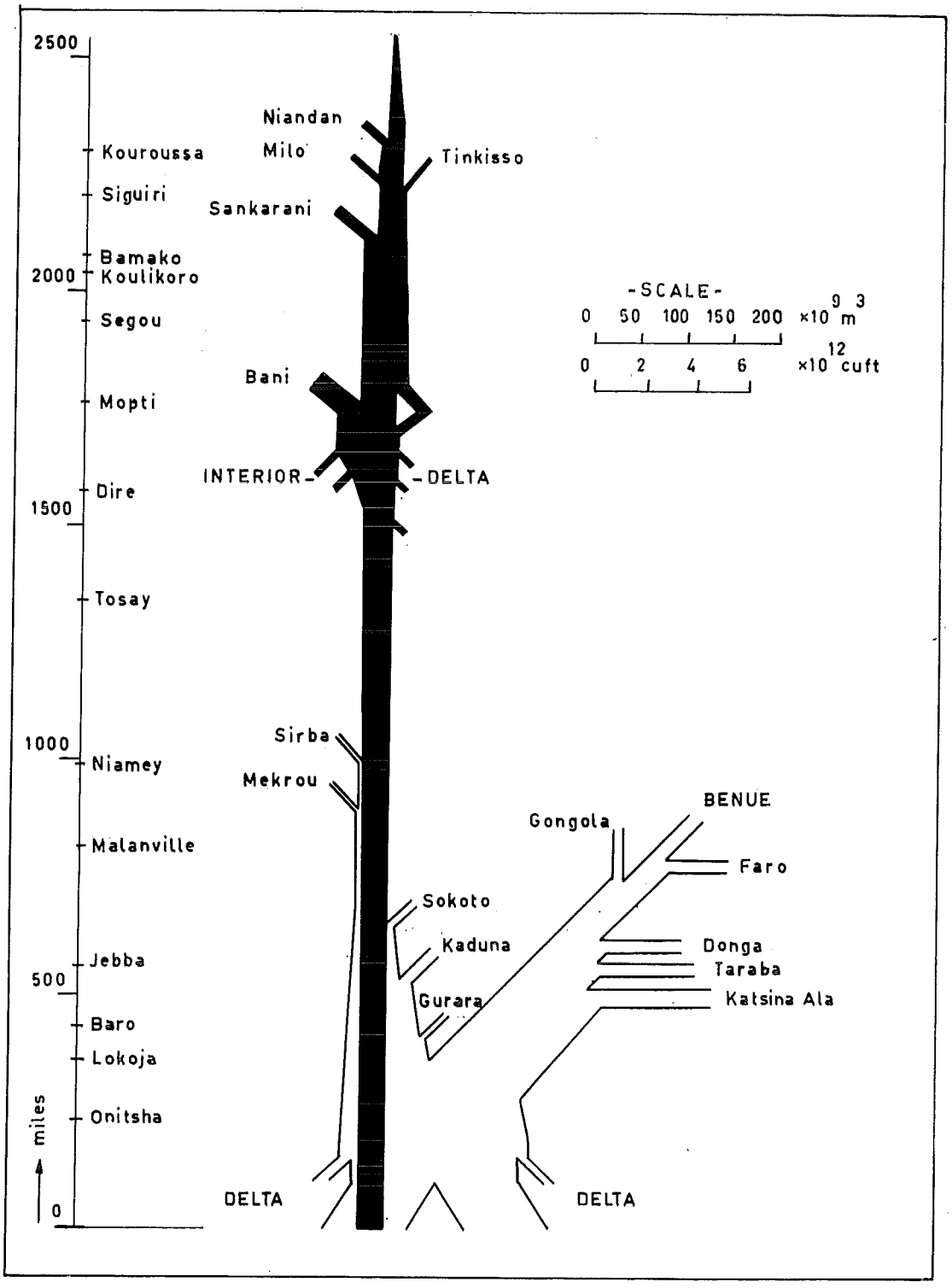


DIAGRAM 2.3.1-23

Schematic representation of the annual discharges of the Niger system

banks gradually become lower and during the H.W.-period much water flows over the adjacent flood-plain into the Orashi River on the left and the Asé River on the right. This results at Aboh (r.b., Mile 177), which is considered to be the apex of the Delta, in a decrease of the annual discharge to about 65 %, when compared with Onitsha. Diagram 2.3.1-23 gives a schematic representation of the annual discharges of the Niger system.

2.3.2. The Benue from French Camerouns to Lokoja

The Benue, by far the largest tributary of the Niger, rises in the French Camerouns on the Adamawa Plateau at about 4,400 feet above sea-level. In its drainage area the average annual rainfall varies from 120″ in the upper reaches of the Katsina Ala River to 35″ in the middle course of the Gongola River.

Over the first 20 miles the river falls 2,500 feet and over the next 90 miles another 1,200 feet, leaving for the remaining 700 miles to the Niger Confluence a fall of only 570 feet.

Between Wuro Boki (Mile 915) and Yola (Mile 888) and at Makurdi (Mile 510) the river flows through sandstone rocks, but even at those places the bottom of the former rock valley is buried under many feet of sand deposits.

For 80 % of its length the Benue is a typical alluvial river, the greater part of which is of a somewhat braided type, with broad and fertile flood-plains on each side. During the wet season, when miles of adjacent land are flooded, the Benue discharges 10,000—14,000 m^3/sec (350,000—500,000 cusecs) into the Niger, whereas in the dry season only an insignificant stream of some 100 m^3/sec (3,500 cusecs) remains.

If a distinction in sections had to be made, then the first 110 miles, from the source to a few miles above the Mayo Rei Confluence, could be regarded as the upper reaches. Downstream of this confluence, rapids are absent and the river has moderate slopes (25×10^{-5} to 15×10^{-5}). In this middle course, from Mile 1,050 to Mile 536 (Katsina Ala Confluence), the Benue grows to its fullest extent, whilst from the Katsina Ala downwards, the Benue in its lower course undergoes no important changes.

However, other classifications than these can be proposed. For instance, a division into two parts: the upper reaches from the source to Lau or thereabout and the lower reaches from Amar to Lokoja. The first part (Mile 1,172 to Mile 777) is characterised by sudden peaks and falls in water-level and discharges, and the latter part (Mile 682 to Mile 362) is much less subject to these abrupt changes (see Diagram 4.2.2-1).

At the junction with the Niger, the yearly run-off of the Benue has become of the same order as that of the Niger above Lokoja.

The Benue, after its first precipitation from the Adamawa Plateau at about 4,400 feet above sea-level through gneiss chasms into the valley 2,500 feet lower, takes a NNE-ly course for about a hundred miles, during which the bed material changes from pebbles to gravel and from gravel to sand. After that the river turns NW and runs with a slope of 25×10^{-5} through a valley which may possibly constitute the reservoir of Lagdo.

At 1,010 miles from Escravos Lighthouse the river cuts through the granite rocks of the valley narrowing of Lagdo. Downstream of this defile the Benue enters large alluvial plains, bordered by sandstones (see Map Yola Reservoir, Diagram VI, 8.5.1-1).

The Tinguelin Mountains force the river into a westerly direction. The plateau on top of these table-mountains belongs to an old peneplain, remnants of which appear in various places in Nigeria. The plateau of the table-mountains at Lokoja have also formed part of that peneplain. These plateaux, remarkably flat, are of stronger consistence than the underlying sandstone rocks,

with the result that erosion mainly takes place on the mountain slopes. In the valley at the foot of the Tinguelin Mountains, at Mile 985, the Mayo Kebbi, second largest tributary in the French Camerouns, joins the Benue. Vast flood-plains extend for miles on each side.

At Mile 972 ([1] high land takes the place of the flood-plains. Here the North-South road crosses the river, whilst on the embankment of Garua river tows evacuate produce of the French Camerouns.

Downstream from Garua the slope of the Benue decreases to 13×10^{-5} at high water. The river, here often called the Garua Creek, meanders through a flood-plain and forms a fairly good shipping route. The river-bed and the banks consist of sand and clayish material, but rock outcrops are locally visible. The flood-plain, about 2 miles wide between Mile 972 and Mile 942, widens to 6 miles at the Faro Confluence (Mile 926). This area is, contrary to the flood-plain above Garua, only sparsely cultivated, but there is an abundance of game. The lakes on each side of the river are well-known homes of hippos.

The large quantities of sand brought down into the Benue by the Faro River are the reason for the completely different aspect downstream of the confluence (Photograph 2.3.2-1). As the slope of the river below the confluence (25×10^{-5} at high water) is not sufficient to transport all the sand from the Faro and the Garua Creek, the result is that through sand-deposits the valley-floor downstream from the Faro Confluence is slowly being raised (see 5.4.5). The heightening of the confluence is the cause of the gentle slope of the Garua Creek.

The steeper slope and the wider bed lessen the range between high and low water-levels. This range, 22′ at Garua (Mile 972), decreases downstream from the Faro Confluence (Mile 926) to about 17′, remains at 17—18′ until Numan (Mile 846) and increases at Lau to 21′. The range than stays at about 21′ throughout the rest of the Benue, except at Makurdi (Mile 511) where it is 2′ more.

The Benue at the Faro Confluence itself is not shallow, because even at high-water stages of the Faro, when the sand-banks move close to the northern bank of the Benue, a reasonably deep and for navigational purposes wide enough channel still exists along the northern bank (see V, 3.2.2).

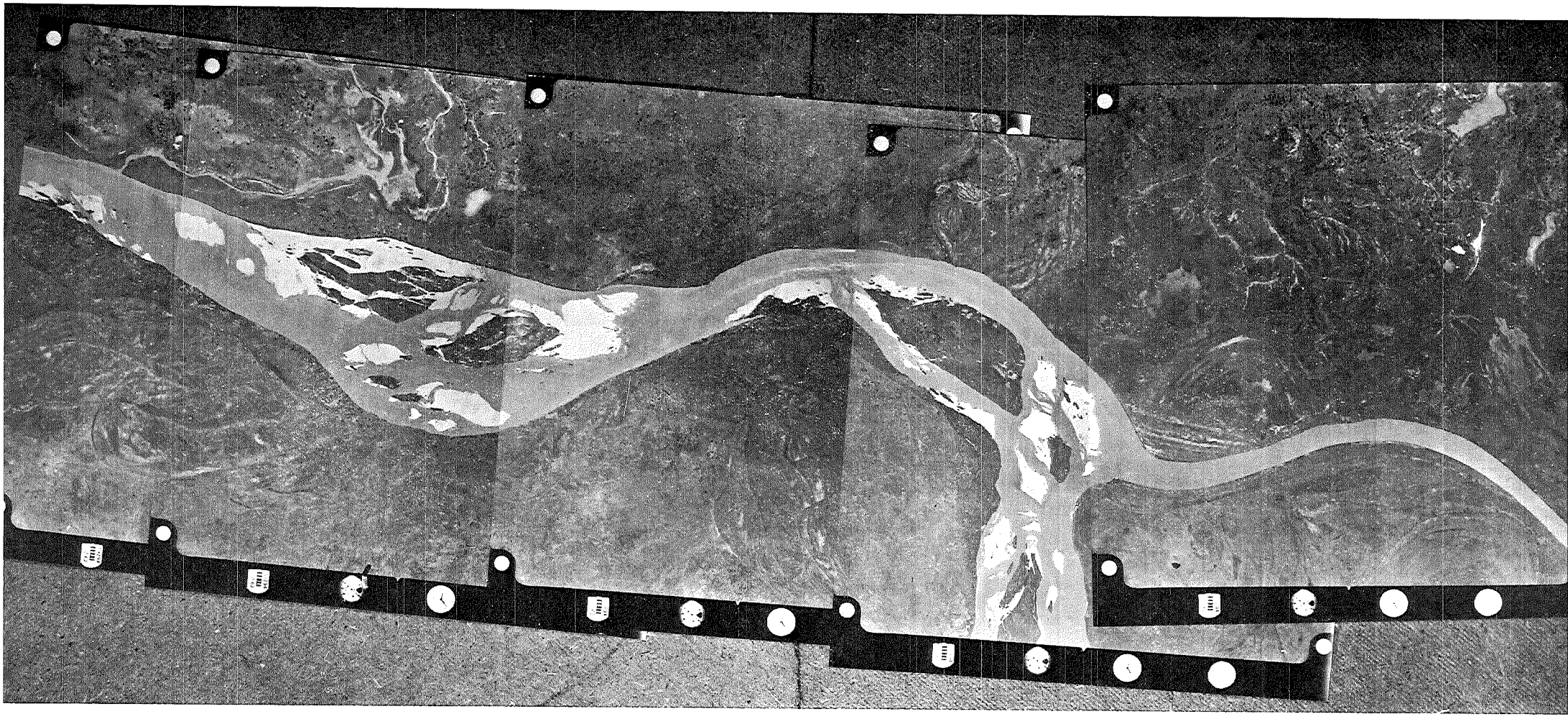
After the confluence with the Faro the river flows NW for 10 miles, changing to WSW at Wuro Boki village, five miles inside the Nigerian frontier, at the Kilunga Confluence. At the Wuro Boki Flats, and especially at Mile 922, the channel bifurcates into shallow crossings. Even when the absolute depth in the channel would have been enough, ships often run aground on the edges of the tortuous channel. Buoyage is an improvement of these rapidly-changing areas with braided channels, but the river will still remain wide and shallow. The flood-plain, in parts 6—7 miles wide, decreases towards Dasin Hausa (Mile 904) where the total high-water bed has a width of only 4,000 feet.

At Dasin Hausa, sandstone rocks on the south side of the river approach the Bagele Hills (north of the Benue) close enough to form the defile which is considered a dam-site of a possible Yola reservoir (see Diagram VI, 8.5.1-1). From Mile 904 to Mile 897 the Bagele Hills and the hills of Dasin Hausa, Dasin Pagan and Njobolyo border the river. The Bagele Hills are wooded, in contrast to the more cultivated country south of the Benue, where only scattered trees and brushwood survive.

Between Njobolyo (l.b., Mile 897) and Dalmare (r.b., Mile 885) the Benue flows for the greater part along sandstone hills, with small flood-plains in between, changing its course towards NW.

Yola, or rather Jimeta which is the name of the town at the river-side (Mile 888), is after

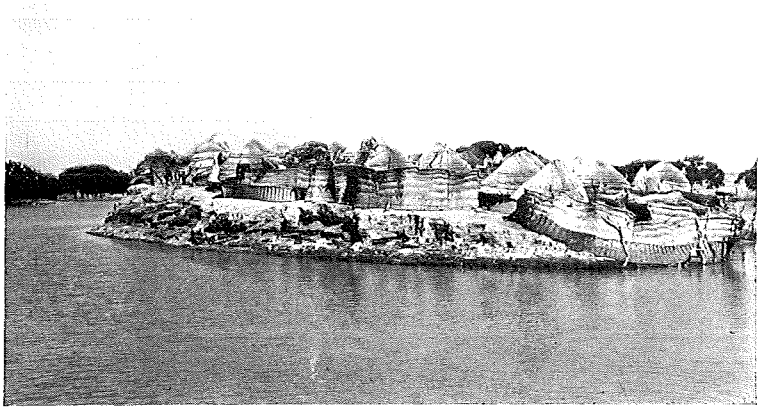
([1] Reference is made, for the mileage and descriptions, to the Book of River Charts accompanying this Report.



PHOTOGRAPH 2.3.2-1

Confluence of Benue and Faro (Mile 919—929)

Benue flows from the right

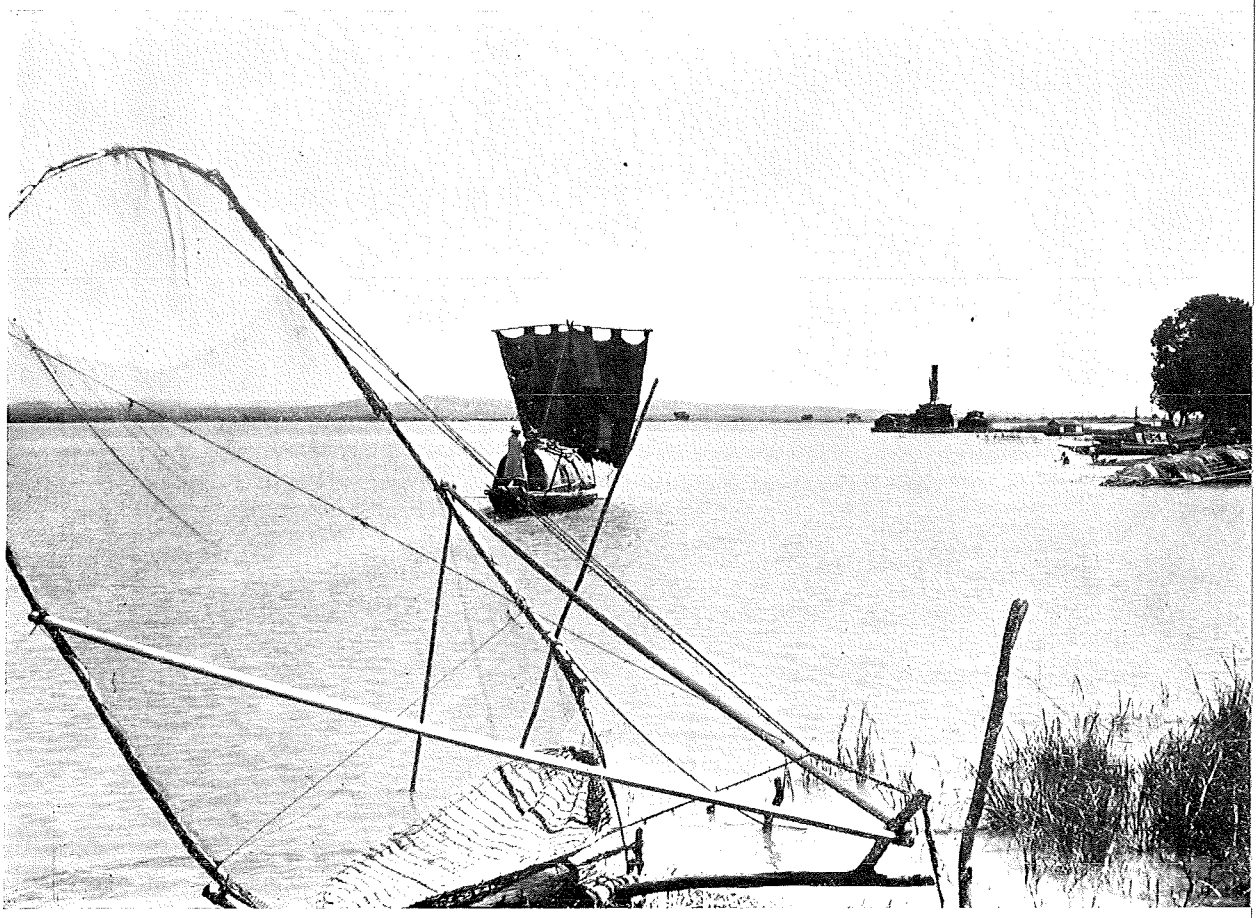


PHOTOGRAPH 2.3.2-2

One of the Ndom villages (Mile 850)

PHOTOGRAPH 2.3.2-3

Numan, looking north-east across the Benue (Mile 845)



Makurdi the most important Nigerian port on the Benue. The rocky shore at Jimeta (left bank) and also at Dalmare (right bank) prevent erosion of the embankment.

The river between Yola and Numan (Miles 888—846) shows its general aspect: sand-banks, fairly straight high-water shores and one or two meandering channels mostly with islands in between and flood-plains covered with grass, brushwood and scattered trees. Villages perched on ridges slightly higher than the adjacent land, inhabited for the greater part by the Batshema fishermen, are found all along the river. Those ridges, common in virgin rivers flowing through flood-plains, can be explained by the seasonal variations in water-level. Every high water the river rises above its banks and pours silt-laden water over its sides into the flood-plains. The velocity of the water over these flooded areas is much less than in the river itself, with the result that silt settles down as soon as it enters the flooded area. Therefore the origin of ridges in the flood-plains can often be described as the result of old courses of the river.

In some instances the villagers themselves build highwater-free places. Example are the villages of Ndom, Mile 850, where the native huts, consisting of clay from ponds nearby, collapse after some years. On the remnants of the old one a new hut is then built with fresh material. During this investigation potsherds were found at Ndom many yards below the present ground-level.

Some 25 miles upstream from Numan, the Mayo Ini joins the Benue, draining almost 2,000 square miles of country between Yola, Numan and the Vere Hills which can be seen south from the Benue.

Opposite Numan the Gongola flows into the Benue. This is Benue's main tributary from the north and is described later in this Paragraph along with the other tributaries of importance. Numan lies on the left bank on high ground and its river-side just after the rock outcrop at Mile 846 would be excellent for port installations. The rocks divert the current, thereby protecting the embankment downstream against erosion. Moreover, the geographical situation makes it unlikely that sand-banks would obstruct the place in the near future.

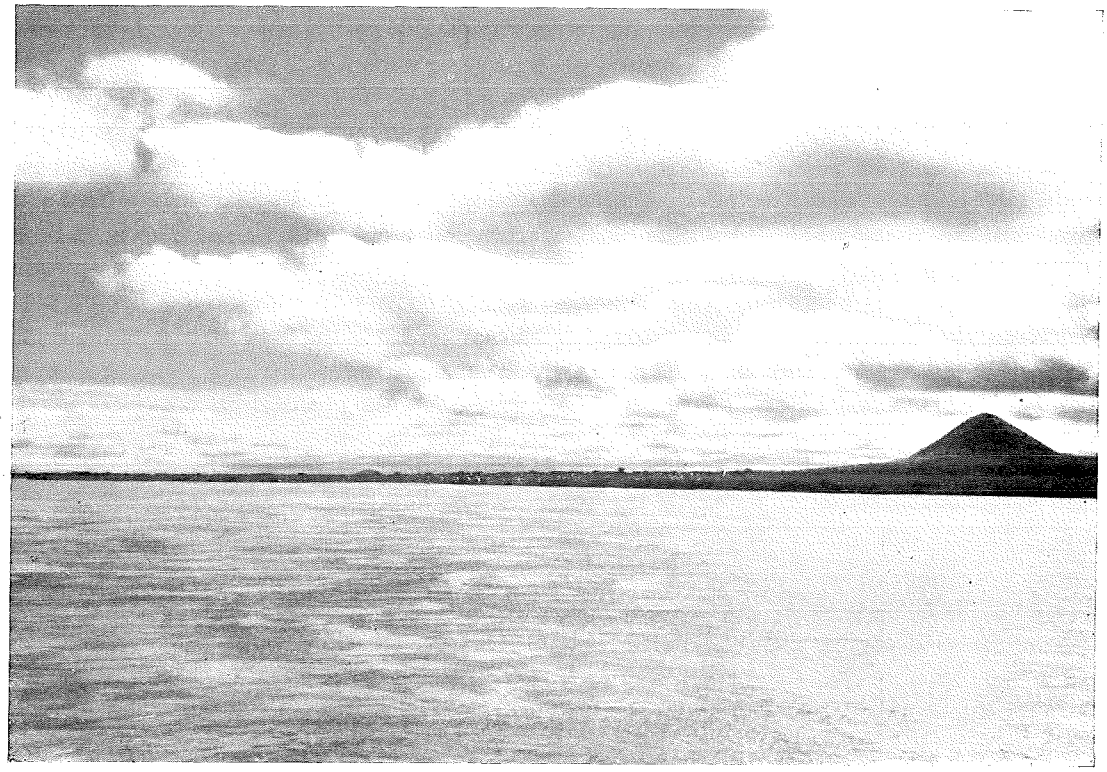
Downstream from Numan, at Mile 836, a small affluent, the Mayo Belwa, enters the Benue. Immediately beyond this point the river bifurcates into two channels, separated by a six-miles long island. These winding and shallow channels are known as the Kabawa Flats. These Flats and in fact the whole river-stretch from Numan to Lau are difficult to navigate. Rapidly-changing shoals often delay ships that either run aground or have to wait for a rise. The Gamadio Flats (around Mile 818) are, together with the Wuro Boki Flats (Mile 922), the most notorious places on the Benue. The Gamadio Flats are described in detail in 6.5.3.

The north bank of the Benue is fairly straight from Numan to Lau, with the exception of the ten-mile stretch between Gamadio and Tungaladan. The shore is made up of fairly consistent material; a footpath running parallel and close to the Benue on this natural levee links the many villages along the river, such as Yumburu, Zeken, Kabawa, Gidan Muba and Jen. North of this levee, wide areas are frequently flooded and many lakes survive the dry season.

The foothills of the rugged Lamurde and Kwoni Hills, clearly visible from the Benue, border the flood-plains on the northern side. These mountains are also referred to as the Muri Hills. South of the river, at Mile 882, a small volcano, 600 feet high, leaps to the eye. On the south side the valley slowly rises to higher land, and in the distance the Lankoviri Hills (Fumbina Mountains) are visible.

The Benue, flowing west from Boron (r.b., Mile 860) to Gamadio (l.b., Mile 818), bends in a south-westerly direction at Gamadio, and, apart from local deviations, maintains flow directions between WSW and SW until Abinsi (Mile 528).

The villages along the river are often of a semi-permanent character because of the instability of the river channel. Shifting of the channel may put a fishermen's village a mile from the river,



PHOTOGRAPH 2.3.2-4

Mount Gabriel or Jeme Hill (Mile 882)

and erosion of the banks sometimes destroys a whole settlement. Yet a number of names mentioned already in 1854 by BAIKIE ([1] still exist. Jen, (r.b., Mile 799), which at Baikie's time was some distance from the river, is still at about the same spot, although the river has since shifted northward over more than its width. Lau (l.b., Mile 777), situated only slightly higher than flood-level, still lies on the river-bank. Downstream from Lau the left bank is very straight and at Mile 774 suddenly rises above flood-level. The clayish spot is only some twenty yards wide, but it already existed in 1854: "Below Lau we examined on the south bank what had seemed to us, during our ascent, a rocky cliff; but we now found it to consist of a bank of red clay some fifteen feet high (the river was in spate) with a layer of vegetable mould on top", wrote Baikie.

Although in a less spectacular way than at the Faro Confluence, the river changes considerably at Lau, or rather between Lau and Amar (Miles 777—682). The slope, 25×10^{-5} at Wuro Boki and still 20×10^{-5} between Numan and Lau, decreases to an average of 15×10^{-5} between Lau and Amar. The channel improves, that is to say, the least available depth is greater than above Lau for the same discharges. Secondly, the vast flood-plains are causing a marked difference in the discharges between Lau and Amar. The abrupt rises and falls, common in the upper reaches and still discernible at Lau, have faded out at Amar (see Diagram 4.2.2-1). Further, the banks, on which grass, brushwood and a few trees are growing above Lau, become wooded near Amar, thus forming a green screen between the river and the flood-plains. Also on the flood-plains themselves more trees in groups appear and many Borassus palms can be seen

([1] BAIKIE, 1855. GEN. 1

PHOTOGRAPH 2.3.2-5

Lau, Mile 778

Benue main branch behind island; notice enormous sand-banks exposed in dry season

from the river. And finally the population decreases towards the tsetse-infested areas of the Taraba and the Donga tributaries.

Between Numan and Amar no important affluents enter the Benue, although the sum of the discharges of the smaller rivers is quite noticeable. They are the Mayo Belwa, Kunini, Lamurde and Mayo Fan from the south and the Pai and Duchi from the north.

The high-water channel, fairly straight in most places, forms a great loop near Kambari (r.b., Mile 696). At high-water levels much water enters the southern flood-plain via the outer bend. Trees falling into the water from the eroded outer bend have to be cleared occasionally. The development of the loop will be described in Paragraph 6.5.4.

The channel downstream from Kambari is over 6 miles remarkably straight and narrow. Here, at Amar (Mile 682) and at the Taraba Confluence (Mile 672), rocks are visible in the north bank. A buoyage of the dangerous spots is being maintained since a long time. South of the river a vast flood-plain extends, in which water of the Benue mingles with that of the Taraba and Donga.

The tributaries of the Benue, even the larger ones such as the Katsina Ala, Donga and Taraba, enter the Benue unobtrusively. To the uninformed observer, sailing without maps, they look like branches of the Benue, flowing round large islands and joining the main river somewhere ahead. When W. B. Baikie went up river with the "Pleiad" in 1854, he and his skilful assistant

PHOTOGRAPH 2.3.2-6

Vast flood-plains intersected by narrow creeks between Lau and Amar

PHOTOGRAPH 2.3.2-7

Benue, Mile 673

Notice ripples on sand-bank

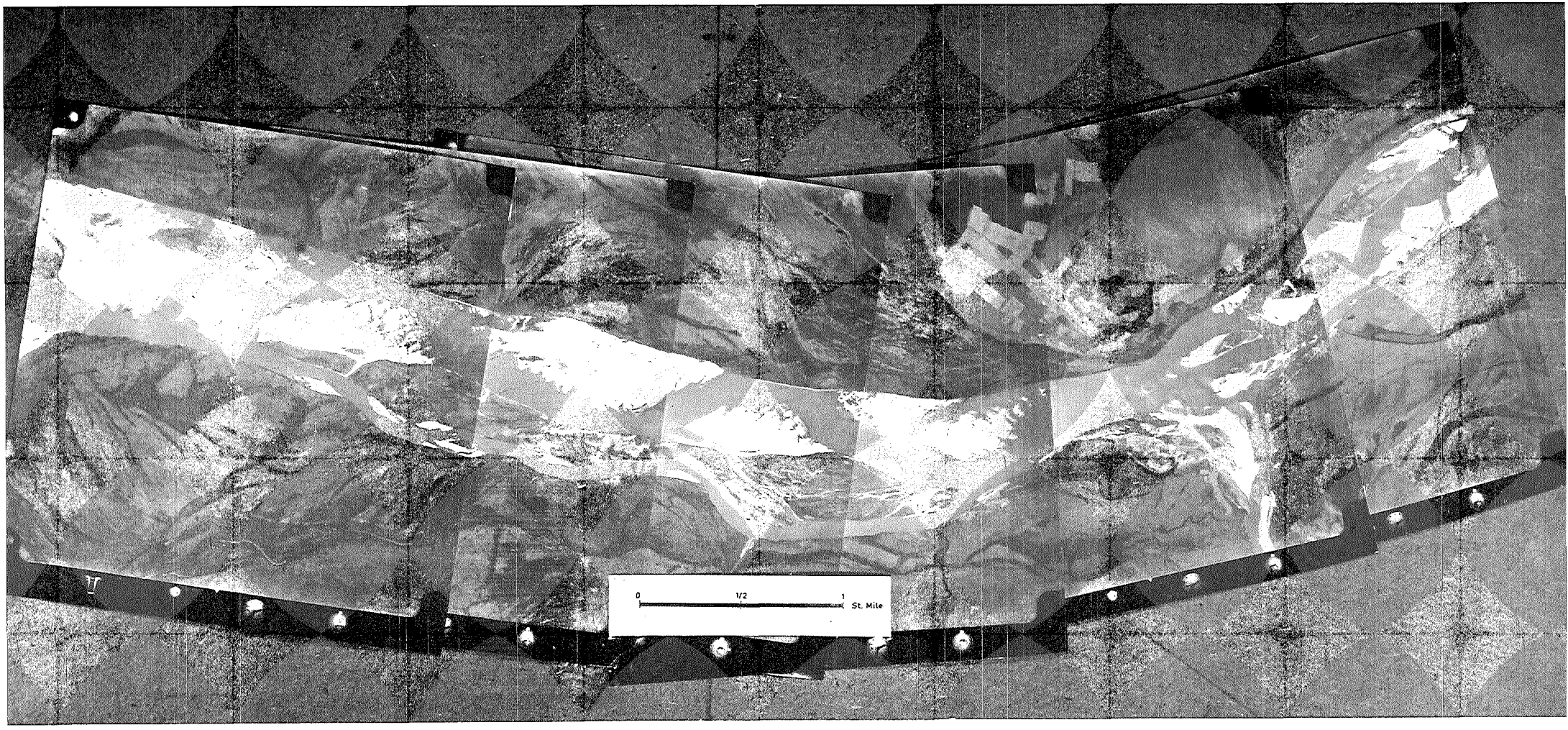
Daniel John May also had difficulties in distinguishing affluents from branches. There is no mention of the Katsina Ala and Donga in their account or on their map, whilst also the situation at the Taraba Confluence does not appear to have been clear to them, although they mention that tributary.

The Taraba forms a fluviatile delta where it enters the Benue. The main channel flows into the Benue at Mile 672 (Photograph 2.3.2-8) and secondary branches debouche at Miles 670 and 643. Older courses had their junction at Miles 685 and 652.

One or two miles below the Taraba Confluence flats occur; these would have been a hindrance to navigation if the narrow deep creek along the left bank had not been there. Not only here, but on many other places on the Benue and Niger these secondary channels are preferable to the main channel. This creek, from Mile 671 to Mile 667, is often called the Taraba Creek. It is a branch of the Benue, but it carries almost exclusively water from the tributary. There is a sharp distinction between Benue water and Taraba water, the latter being much clearer and darker, containing less silt. Not until many miles downstream from the confluence is the water of the two rivers completely mixed, a phenomenon also found at other confluences and in the sea, where fresh water can be found many miles off the mouth of a large river.

The high-water channel follows a winding course from the Taraba to the Donga Confluence. At Dampar (r.b., Miles 651—655) the river takes a sharp S-bend in which shallow crossings often occur. Five miles above Dampar many snags form a danger to ships. The trees originate from a forest on the left bank, at Mile 662, where the bank is severely eroded, due to a sharp bend in the high-water channel.

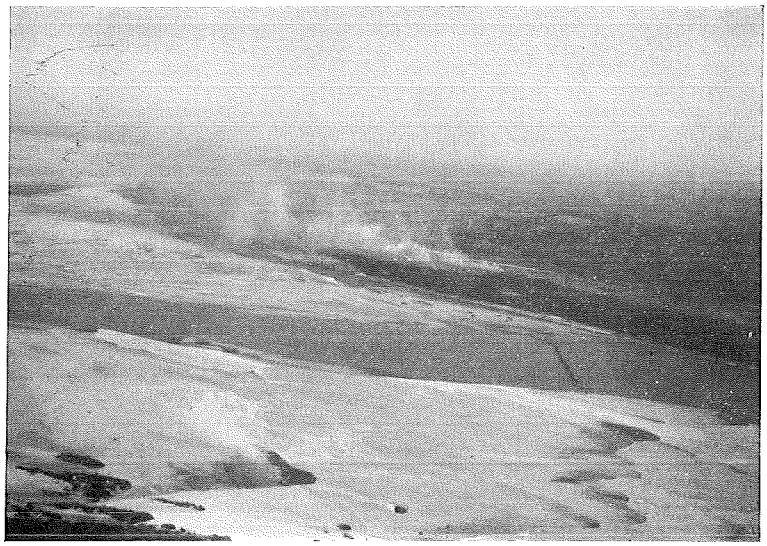
The Benue below the Donga Confluence is 50 % wider than above the Taraba Confluence, whereas its depth is roughly the same. The average slope decreases from 15×10^{-5} to 13×10^{-5}, which is maintained until Lokoja, although locally this slope varies considerably between high water and low water. On deep and narrow stretches it varies from 40×10^{-5} (or more) at H.W.



PHOTOGRAPH 2.3.2-8

Confluence of Benue and Taraba (Miles 665—675)

Benue flows from right to left



PHOTOGRAPH 2.3.2-9

Benue (Mile 658)

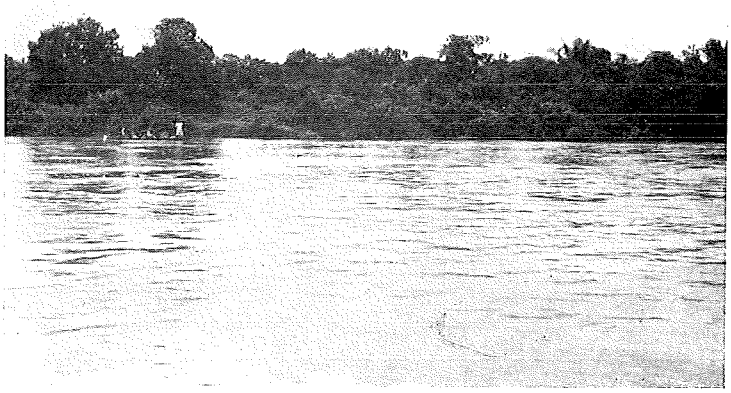
Small bushfire on right bank
Fishermans' fence across channel

to 5×10^{-5} (or less) at L.W. On the wide and shallow river stretches the variation is roughly vice-versa, although at high water the slope is generally not less than about 10×10^{-5}.

Ibi (l.b., Mile 614), important in the history of Northern Nigeria, lies on high ground. When the river is in spate, the town is almost situated on an island. On the river-side an enormous tree is visible miles ahead. Sandstone rocks, perceivable at low water, act as groynes and keep the embankment intact. The high-water channel remains fairly straight until the Katsina Ala Confluence, here and there bordered by volcanic outcrops on each side.

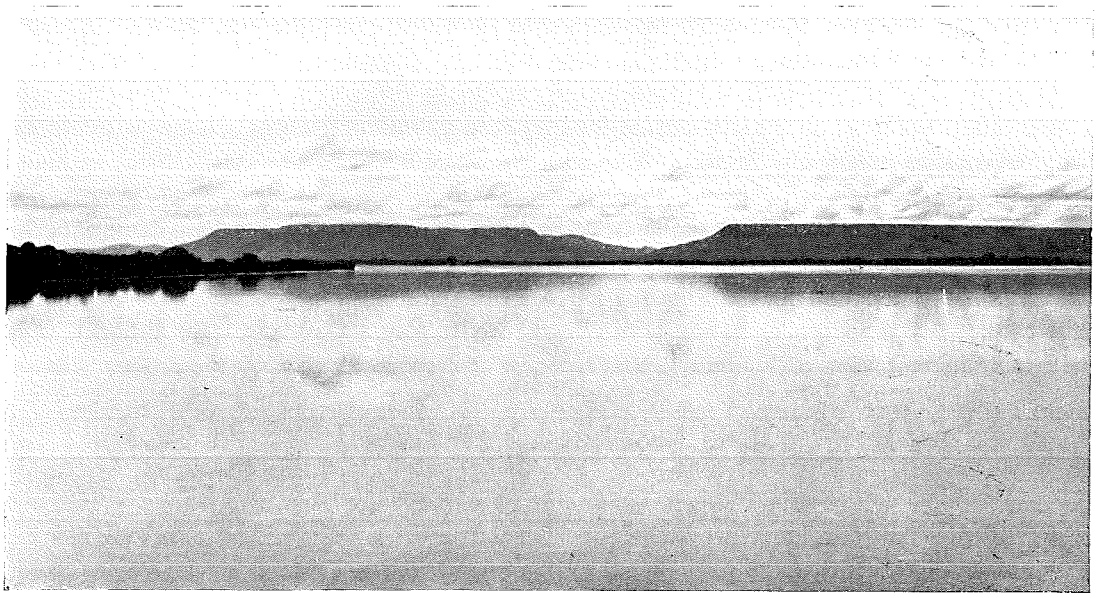
The Katsina Ala is the last large tributary of the Benue. From here until the confluence with the Niger, the Benue undergoes no major changes in slope, discharge, sand or vegetation. Upto a few miles beyond Abinsi (l.b., Mile 528) the river winds round large islands, yet the least available depth is about the same as downstream of Makurdi.

At Makurdi sandstone hills force the river into a 2,200-feet wide bed, where the only bridge across the Benue has been built. The river-side at Makurdi south bank is over a distance of more than a mile suitable for the loading and unloading of barges.



PHOTOGRAPH 2.3.2-10

In the lower reaches green walls of trees and undergrowth hide the floodplains from the eye



PHOTOGRAPH 2.3.2-11

View from the Benue on Mount Patty

Downstream from Makurdi, the Akpanaja Flats (Miles 502—506) have been regarded as troublesome to navigation, but, although they indeed belong to the shallowest parts of the river between Lokoja and Makurdi, the Benue Bar at the Niger-Benue Confluence in its present natural state determines the opening of the season in most years. The river flows along a chain of islands, thus forming two or three channels most of the way. The straightness of the high-water channel is remarkable. There are places where, looking down the river at H.W., an uninterrupted water surface exists as far as the eye can see. Green walls of trees and undergrowth hide the flood-plains from the eye. Loko, Bagana, Umaisha and some minor villages are built on rock outcrops, but in between the river runs along easily erodible banks.

Passing Umaisha towards Mozum (l.b., Mile 400) the table-mountains, a common feature of the Niger Valley, become visible. And 810 miles from its source, in annual run-off comparable with the Niger above Lokoja, the Benue debouches in the Niger (Photograph 2.3.2-11).

The larger *tributaries of the Benue* rise to the south of the river with the exception of the Gongola which has its headwaters in the Jos Plateau. They are shallow rivers, often with two or more channels around islands or through sandbanks. The abrupt rises and falls and the rapidly-changing shoals make them unattractive for navigation.

There now follow short descriptions of the affluents Faro (235 miles), Gongola (380 miles), Taraba (200 miles), Donga (210 miles) and Katsina Ala (215 miles).

a. *Faro*

The Faro rises on the Adamawa Plateau (Mile 1,160) but, contrary to the Benue which leaves the plateau just after its source, the Faro has extended headwaters and remains on the plateau over 100 miles. The river then descends as a torrent into the valley, and, unlike the Benue, maintains a steep slope after that.

At about Mile 994 the Faro is entered by the Deo, which receives its water for the greater

part from the Alantika Mountains, the watershed of which constitutes the frontier between Nigeria and the Camerouns.

Over the last 70 miles to its confluence with the Benue (Mile 926), the river flows through a wide valley, bordered on the east side by the Poli Plateau and on the west side by the Alantika Mountains. It is a typically braided river, with slopes of 150×10^{-5} to 50×10^{-5}. At high-water peaks shallow draught launches can sail the river some miles, but for commercial purposes the river is useless. From the viewpoint of the river engineer, however, the Faro is important, because it doubles the discharges of the Benue and because it is responsible for huge quantities of sand thrown into the Benue and for the nature of the river-bed which it forces on the Benue. Indeed, the Faro is so similar in appearance to the Benue inside Nigeria, and so different from the Benue above the Faro Confluence, that it might be considered as being the original Benue, and the Garua Creek its tributary.

b. *Gongola*

The Gongola is a peculiar affluent. It flows for the first 200 miles parallel to the Benue, but in an opposite direction, and then suddenly changes course to due south, towards the Benue. The reason for this is that the Gongola may have belonged to the river system of Lake Chad, but has since been captured by a tributary of the Benue (see Paragraph 3.1.2). The watershed north-east of the point of capture is still indistinct and probably the groundwater there still flows towards the Chad Basin. The headwaters of the Gongola, on the Jos Plateau, are 50 miles farther from the sea than the source of the Benue itself.

For the first 225 miles, to Nafada, the river flows in a generally north-easterly direction. Then it takes a 90° turn and flows due south for about 60 miles, after which it runs through the SW-NE range near Dadin Kowa (Mile 935). Forty miles later the river cuts through a low but very pronounced ridge at Kombo (Mile 897). At Mile 886, the Hawal joins the Gongola 40 miles above the confluence with the Benue.

At this confluence with the Benue the Gongola water is easily distinguished from Benue water by its brownish colour. Generally speaking, the tributaries north of the Benue have a higher silt concentration than the Benue itself, whereas the tributatries south of the Benue, flowing from the Cameroun Mountains, have a lower silt concentration than the main river.

The Gongola is navigable for a good distance, but unexpected falls and shifting channels make navigation a tricky business. In the old days stern-wheelers plied the river as far as Nafada, but roads and railways have since taken over almost all traffic.

c. *Taraba*

The Taraba rises in the Cameroun Mountains. In its headwaters, on the Mbambila Plateau, the tsetse-fly-free meadows are appreciated by the Fulani herdsmen.

A hundred miles from its source the river leaves the mountains. Here, at Beli (Mile 753), a bridge has recently been laid across the river, an engineering achievement not to be underestimated in these far-off places. The river-bed, consisting of sand and some gravel, is of a braided type downstream from Beli. At Mile 725 the Kam and Wurkam enter the Taraba. There are a few villages, but the presence of tsetse flies discourages expansion of the population.

Twenty miles above Gassol, near Dalli, a possible dam-site has been envisaged between two hills on each side of the river. The distance to be spanned by a dam, however, is more than a mile.

Gassol (Mile 691) is a produce evacuation centre. Small stern-wheelers sailed the river from July till September, but recently the activity has been shifted to Kwata Nanido on the Benue.

Below Gassol the river enters the fluviatile delta, where the Taraba diverts into three meandering branches, the principal channel flowing north and two secondary channels flowing west.

d. *Donga*

The Donga, flowing between the Katsina Ala and the Taraba, rises in the Alantika Mountains, some 6,000 feet above sea-level. In its upper course the river runs through tropical rain forest. The silt concentration is low, expressed by the local people when they say "the river has black (i.e., clear) water". After Abong (Mile 766) the silt concentration increases, exceeding that of the Katsina Ala, but remaining smaller than the silt concentration of the Benue. At Mile 704 the Zambana River (i.e., rock river) enters the Donga, after which the absence of rapids permits navigation in flood periods.

Donga (Mile 686) is the only town of some importance on the river. On the riverain fadamas tobacco and benniseed are grown. Small stern-wheelers and other small craft call at Donga in the rainy season.

The river above Donga winds around rock outcrops. Downstream from Donga Town it meanders through an alluvial plain, with a slope of about 30×10^{-5}. Population is sparse, as along the Taraba, due to the tsetse fly. A dominating hill west of the river is visible almost until the confluence with the Benue. Below the confluence with the Suntai (Mile 658), the country flattens, changing into the large flood-plains of the Benue and into the fluviatile delta of the Taraba and Donga Rivers.

e. *Katsina Ala*

The Katsina Ala is the most important tributary of the Benue. Its discharge exceeds that of all other affluents; it forms a route to Katsina Ala Town and Sevav where stern-wheelers evacuate the produce of riverain areas; and its total length is only exceeded by the Faro and the Gongola.

The headwaters of the Katsina Ala are situated in an area of 120″ annual rainfall. The rains in this part of the Camerouns usually start earlier than in the north-eastern parts. Therefore the Katsina Ala, more than any other tributary, is responsible for the first rise on the lower reaches of the Benue. In addition to the early start, the wet season also has a later ending, resulting in a much later fall at Makurdi than at, say, Yola. The phenomenon is effected by the movement of the Intertropical Front (see 1.3).

The Katsina Ala descends 5,000 feet in its upper reaches from the source (Mile 750) to the defile at Munka (Mile 668). Between Munka and Kasimbilia (Mile 647) the Imba and Tunga Rivers double the discharge, but after the junction with the Gamana River (Mile 632) the Katsina Ala receives only minor tributaries.

Fifteen miles above Katsina Ala Town the last rapids mark the upstream limit of navigability. The river gets a moderate slope, averaging 30×10^{-5} from Katsina Ala Town to Sevav. Sand takes the place of gravel in the river-bed.

Katsina Ala, situated on sandstone rocks, is clearly visible from the river, particularly the white buildings of the Provincial Secondary School. Here the river flows along and over sandstone shoals. On the fertile fadamas in the flood-plains opposite Katsina Ala Town the Agricultural Department is promoting (mechanised) rice cultivation.

From Katsina Ala Town (Mile 610) to Sevav (Mile 570) the river winds its way through gently rolling country. Downstream from Sevav the hills recede and the river gets a more braided character, the high-water bed widens to about 2,000 feet, and islands are more frequent. The banks are mostly of erodible material, but there are still a few rock outcrops.

Opposite Bajimbo, a village picturesquely situated on a hill, the Katsina Ala debouches into the Benue.

2.4. THE NIGER DELTA

2.4.1. General description

The main characteristic of a classical delta is, as the Greek name illustrates, a triangle formed by the distributaries and ramifications of the original river when it approaches the sea. Along the river, as a rule, the range between the L.W.-levels and the average H.W.-levels increases when going downstream to a point which is called the apex of the delta, where the range starts to decrease until it reaches the tidal range of the sea into which the river debouches. According to this definition, the apex of the Niger Delta is situated near the village of Aboh (r.b., Mile 177) as can be seen on Diagram 2.4.1-1.

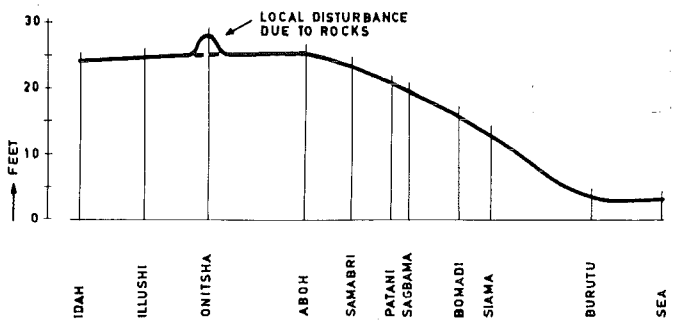


DIAGRAM 2.4.1-1

Variation of the range between H.W.- and L.W.-levels along the lower course of the Niger

Below Aboh the aspect of the Niger changes: the bifurcations, ramifications and meanders begin, and about 150 miles downstream from Aboh the Niger reaches the ocean through many outlets. Diagram 2.4.1-2 shows the present distribution of the annual discharge of the Niger over the various outlets ([1].

A part of the sediment which is transported by the river is deposited on the low-lying banks of the rivers and creeks of the Delta, but the major part of the sediment is discharged through the outlets, and is used to build out the delta into the sea.

The Delta area can for its upper layers be divided into three parts (Diagram 2.4.1-3):

(i) a sandy area, seldom flooded, along the branches of the Niger;

(ii) a mangrove swamp area, largely tidal; and

(iii) a series of sandy beaches and ridges along the coast.

Ref. (i). The sandy area, extending some 75 miles downstream from the apex of the Delta, is a prolongation of the flood-plain as found along the Niger since it left the Rocky Section, the only difference being a gradual increase of the silt and clay content, resulting in a more erosion-resistant bank material. This is probably a reason, together with a decrease of the slope of the water-level to about 5 to 7 $\times$ 10^{-5} (and other factors perhaps), which contributes to the remarkable change in appearance of the Niger as soon as it passes into the Delta Area. The somewhat braided river-bed changes downstream from Aboh into an undivided channel with

([1] NEDECO, 1954. GEN. 23

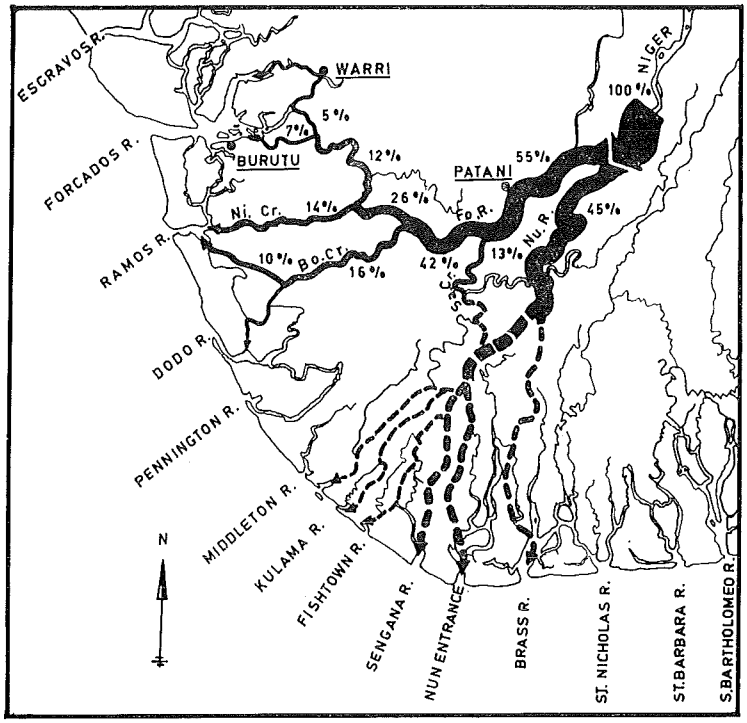


DIAGRAM 2.4.1-2

Distribution of the annual discharge of the Niger over the various outlets into the ocean

a strongly meandering course, until a few miles below Samabri (l.b., Mile 156) the Niger forks into the Nun and Forcados Rivers, which each in turn bifurcate again and again into meandering river branches and at last enter the tidal swamp area.

Ref. (ii). The mangrove swamp area covers about 4,000 sq.miles along 250 miles of the coastline, thus averaging 15 miles in width. The semi-diurnal tide, with an average range of 3 feet in the western part and increasing to 7 feet in the eastern part of the Delta, enters the swamp area through about 20 entrances and it is estimated that about 150×10^9 cuft of water flow in and out during every cycle of the tide. The creeks which intersect this mangrove-covered muddy and hardly inhabited area have an average depth of 30 feet, and the discharge seems only to affect their respective widths. On the whole the creeks are reasonably navigable, except for some sharp bends and some shallowings in the regions where the tides meet.

Ref. (iii). The strip of sandy ridges — which separates the mangrove area from the sea — varies in width from less than 100 feet upto 10 miles. These ridges are slightly eroded from the landward-side by the creeks of the swamp area, but their size and shape is mainly controlled by the eroding and accreding forces of the littoral drift, as will be discussed in the following Paragraph 2.4.2.

With the exception of the mangrove swamps, in which trees grow only along the borders of the creeks, the whole area of the Delta is covered with a dense vegetation (1.4.1). The annual rainfall increases from 120 to 200 inches when going from the apex to the coast of the Delta.

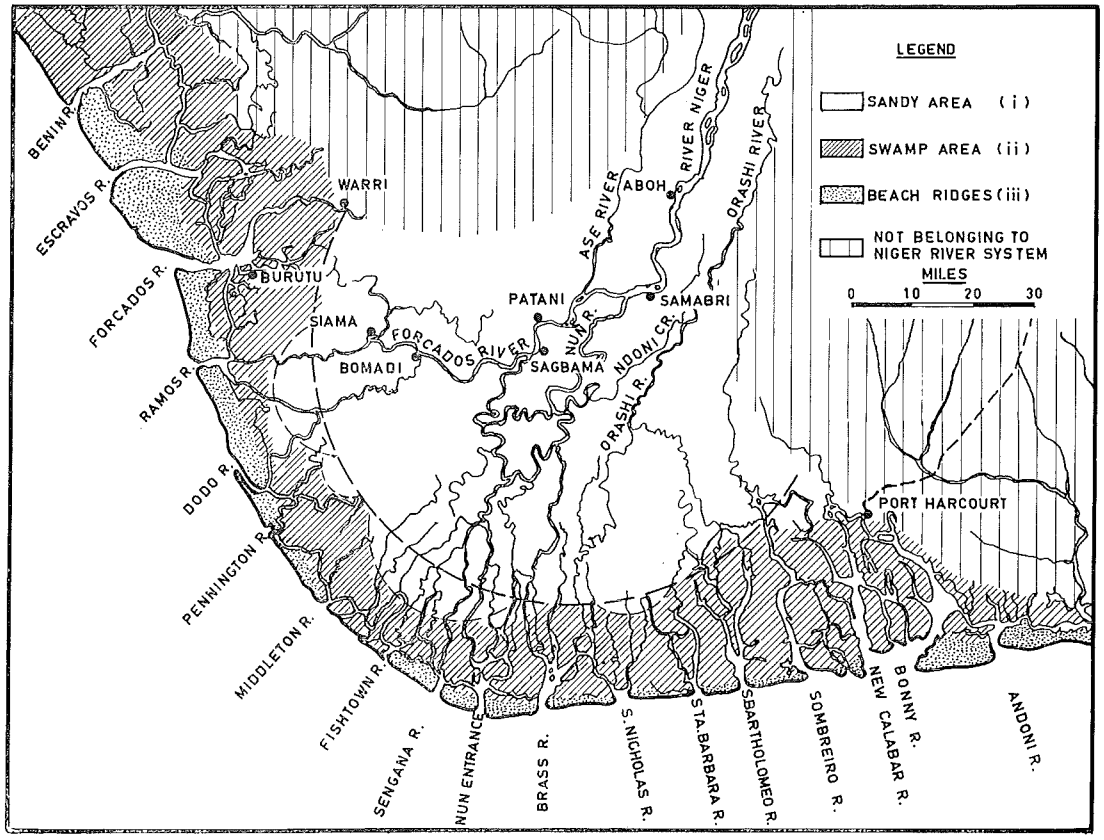


DIAGRAM 2.4.1-3

The Niger delta

2.4.2. Theoretical build-up of the Delta Area

To find a possible explanation of the present building up of the Niger Delta, it seems worthwhile to consider its geological development during the past 75,000 years, and special attention will be given to the influences of a fluctuating sea-level on the build-up of a delta.

When a river with a certain discharge and a certain sediment load debouches into the sea, there are three possibilities relating to the sea-level:

(i) the sea-level is constant,
(ii) the sea-level falls,
(iii) the sea-level rises,

all three, of course, considered over a long period.

Ref. (i). When the level of the sea remains constant, the river will build a delta into the sea and at the same time raise the bed of its lower course, thus about maintaining the same longitudinal profile in order to be able to carry the given sediment load with the given discharge of water.

Ref. (ii). When the level of the sea falls, the river will erode its lowest part and this erosion will gradually cut backward. In the meantime the remainder of the lower course will still raise its bed, as nothing has changed. The sediment load of the river which reaches the sea, together with the eroded material from the lowest part of the river, will yield an increased rate of growth of the delta into the sea.

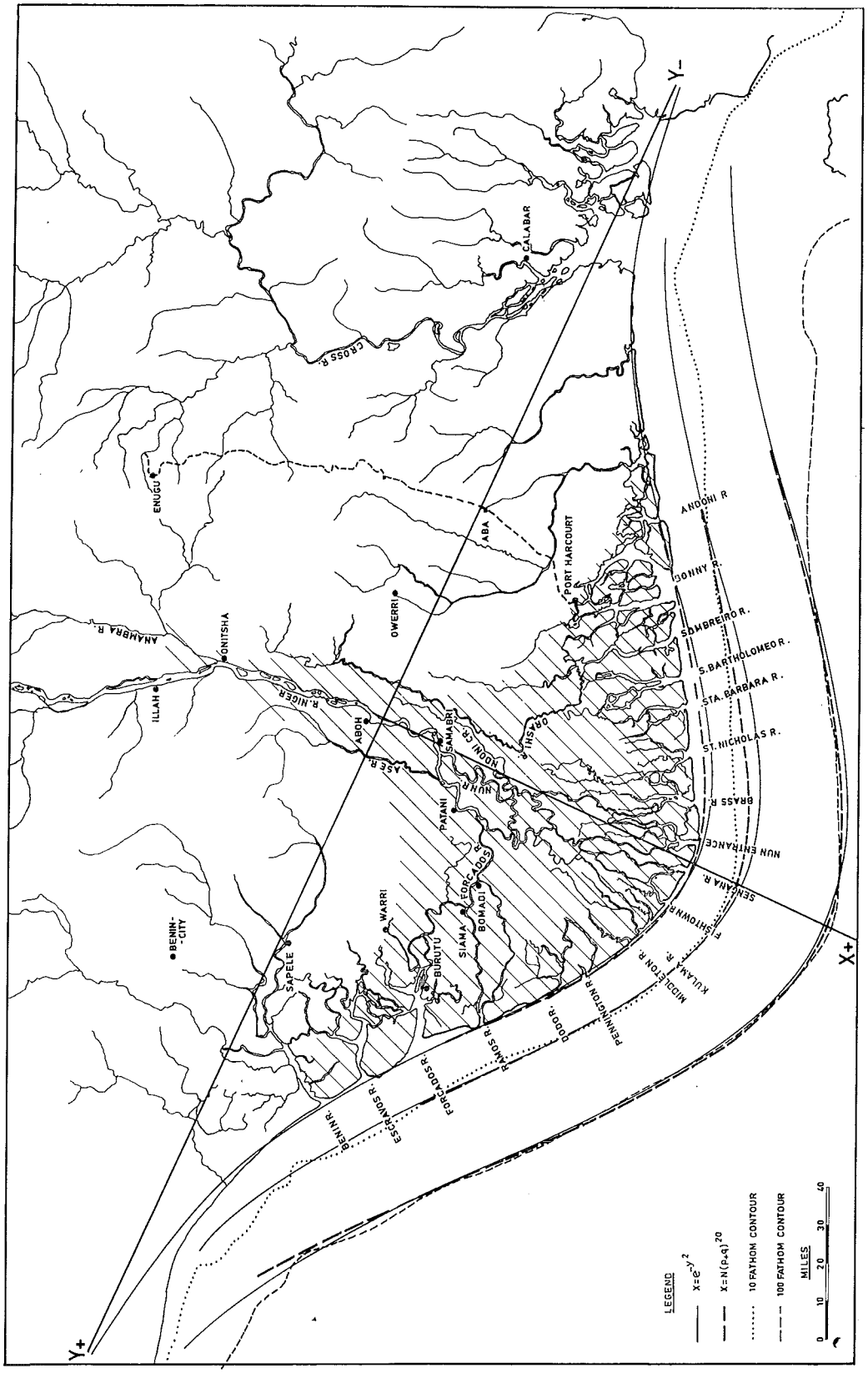


DIAGRAM 2.4.2-1

Mathematical description of the Niger delta

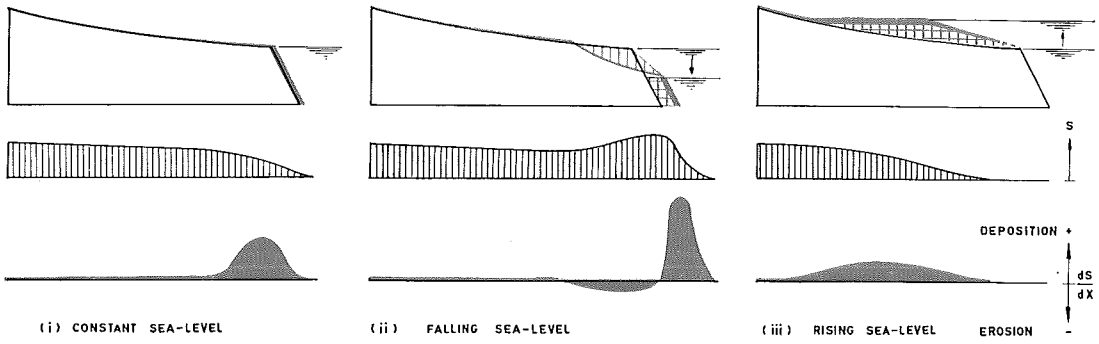


DIAGRAM 2.4.2-2

Theoretical influence of a changing sea-level on the build-up of a delta

Ref. (iii). When the sea-level rises, the lower course of the river will be raised, thus using much of the sediment load of the river. It will depend on the ratio of the rise of the sea-level and the sediment load still available to raise the delta area, whether the delta will grow seaward, or the sea will move landward.

In Diagram 2.4.2-2 sketches are given of the three above-mentioned situations.

According to the tentative geological table (3.1.2-1) these three conditions did occur alternately, as can be seen in Table 2.4.2-3 below.

For the rough calculations in this paragraph, the following assumptions have been made:
(i). The sediment load at Onitsha throughout the past 75,000 years consisted, as at present (see Table 5.3.3-1), of:
3 parts of sand transported along the river-bed,
5 parts of sand in suspension, and
48 parts of silt.

At present one part stands for approximately 330,000 m^3/year (12×10^6 cuft/year) but as the present period is, geologically speaking, a dry one, and the catchment area of the Niger

TABLE 2.4.2-3

PROBABLE CHANGES OF THE SEA-LEVEL OVER THE PAST 75,000 YEARS

Period		approx. years B.C.	sea-level		
			movement	relative elevation	
				m	feet
WURM I (Gamblian)	a	75,000	constant	− 90	− 300
	b	60,000	rising		
WURM I/II	c	45,000	constant	+ 5	+ 16
	d	25,000	falling		
WURM II (Makalian)	e	10,000	constant	− 25	− 80
	f	7,000	rising		
Flandrian	g	5,000	constant	+ 4	+ 13
Nakuran wet phase	h	3,000	falling		
	i	present		0	0

during wet periods has been larger (see Diagram 3.1.1-2), it is assumed that the maximum sediment load has been about three times as large as the present one. In Table 2.4.2-4 a tentative list is given of the sediment loads during the various periods as mentioned in Table 2.4.2-3.
(ii). At the beginning of the Würm I (Gamblian) period, the shaded area as shown on Diagram 2.4.2-1, belonging to the Niger River system, was eroded with the -90 m (-300 feet) sea-level as an erosion-base.
(iii). During this period, the coastline of the Delta coincided roughly speaking with the present 50-fathom contour.

When the whole period of the past 75,000 years is considered, the total volume of the Delta Area between Onitsha and the present 50-fathom contour, above the erosion-base of 90 m (300 feet) below the present sea-level, must have been built up by the sediment of the Niger. This volume roughly amounts to 25,000 km^2 (10,000 sq.miles) (shaded area of Diagram 2.4.2-1) $\times$ 95 m (310 feet) (rise of sea-level) + 400 km (250 miles) (length of the coastline) $\times$ 2 $\times$ 10^6 m^2 (21 $\times$ 10^6 sq.feet) (cross-section of the underwater delta between the 0- and 50-fathom contours) = approx. 3 $\times$ 10^{12} m^3 (100 $\times$ 10^{12} cuft), a figure which is in accordance with the total sediment load as mentioned in Table 2.4.2-4.

TABLE 2.4.2-4

PROBABLE SEDIMENT LOAD OF THE NIGER OVER THE PAST 75,000 YEARS

period	approx. years B.C.	relative sediment load	total sediment load over period
b	75,000 — 55,000	3 $\times$ present load	1.2 $\times$ 10^{12} m^3
c	55,000 — 30,000	2 $\times$ present load	1.0 $\times$ 10^{12} m^3
d	30,000 — 15,000	1 $\times$ present load	0.3 $\times$ 10^{12} m^3
e	15,000 — 10,000	2 $\times$ present load	0.2 $\times$ 10^{12} m^3
f/g	10,000 — 5,000	2 $\times$ present load	0.2 $\times$ 10^{12} m^3
h	5,000 — present	1 $\times$ present load	0.1 $\times$ 10^{12} m^3
			3 $\times$ 10^{12} m^3

$$\text{Average load} = \frac{3 \times 10^{12} \text{ m}^3}{75{,}000 \text{ yrs}} = 40 \times 10^6 \text{ m}^3/\text{years} = 2 \times \text{present load}$$

In Diagram 2.4.2-5 tentative sketches are given of the sequence of the development of the Delta during the past 75,000 years, with the figures of the sediment load of Table 2.4.2-4 in mind. From these sketches it can be seen that as a result of the 95 m (310 feet) rise of the sea-level after the Würm I (Gamblian) Period, the coastline receded to about between Samabri and Aboh, and that the major part of the present delta was deposited during the Würm I/II interval. During the fall of the sea-level in the beginning of the Würm II (Makalian). Period, the river cut backward to about Onitsha, which erosion was filled up again during the next rise of the sea-level. Finally, over the past 7,000 years, the river again cut backward and at present this erosion appears to have reached a point a little upstream of Siama.

In the foregoing, only the distribution of the sediments in the x- and z-direction (i.e., along the river axis and in a vertical direction) has been considered as a function of time. By this the regular shape of the present Delta has been taken for granted, but this needs further explanation.

If no currents or waves are available for further transport of the sediment, the river mouths may be built out individually and birds-foot deltas will be the result. If, however, the delta coast is subject to wave action or littoral currents, the river sediments may be transported along the coast to places well away from the river outlets, and between the area where the sediment is

supplied by the rivers and the area of final deposition, a littoral drift, generated by the waves, would occur. The coarser river sediments will settle along the coast in rather shallow water, while the finer sediments, after reaching the sea, may remain in suspension for some time, and will ultimately be deposited outside the area where excessive turbulence created by waves in shallow water prevents their settling.

The prevailing direction of wind and swell in the Gulf of Guinea is SSW to SW, and it hits the coast at right angles near the Nun and Sengana Entrances. At each side of this point, the angle between the wave crests and the coastline will cause a littoral drift of sediment, the magnitude of which varying with the angle between the wave crests off-shore and the coastline.

Several formulae exist for the relation between littoral drift and angle of approach ϑ of the waves. Mostly the littoral drift is found to be a function of sinus ($n\vartheta$), n being a whole number, and with the given shape of the Delta the transportation of sediment is increasing on each side of the nodal point near Nun River, reaching its maximum at the inflexion points of the delta shape near Bonny River in the east and Ramos River in the west, and decreasing further east and west.

As for a state of equilibrium an increase in littoral drift means supply of sediment by some source and decrease means deposition of sediment, it appears that for maintaining the coastline it is necessary for sediment to be supplied by the river between the inflexion points, a supply which should be greatest near the Nun and Sengana Rivers. In other words, the supply (or erosion) and the deposition of sediment along the Delta Coast is a function of the differential curve of sinus ($n\vartheta$), and when considered over a long period the sediment load of the Niger will have been distributed accordingly. As an approximation of the present shape of the Delta, it seems that the coastline and the deeper contours can all be described by the probability function of Gauss $x = e^{-y^2}$, but when considered in more detail the probability distribution is found to be slightly askew and the contours can better be approximated by a binomial distribution $N(p + q)^{20}$ for values of p and q of 0.4 and 0.6 respectively, twenty being roughly the number of outlets of the Niger Delta (Diagram 2.4.2-1). The reason for this skewness of the distribution may be a geological one (a continued rise of the volcanic axis of the Cameroun Mountains and Fernando Po) or it may be the result of the acceleration of Coriolis (see 6.1.4).

The origin of the coordinates on which the distributions are based is located near the village of Aboh on the undivided Niger, which was found to be the apex of the Delta (Paragraph 2.4.1), and the direction of the axis of the distribution (roughly coinciding with the undivided Niger) is S 27° W, which happens to correspond with the aforementioned direction of wind and swell in the Gulf of Guinea.

Slight deviations from the theoretical shape of the Delta may be the result of a preference given by the Niger to certain outlets over geologically short periods. At present preference is being given to the outlets west of the Nun River (Diagram 2.4.1-2) and this may explain the planed-off stretch of the coastline and the 10-fathom contour, east of Nun River, where the actual coast lies well inland of the ideal shape (Diagram 2.4.2-1).

As for the distribution of sand and silt over the Delta Area, it can be said that for the movement of sand a certain minimum slope of the river is needed, and in case of a constant or a rising sea-level the slope of the river near the coast of the Delta will be rather small and no or little transport of sand will take place. Only when the sea-level is falling can a reasonable movement of sand in the coastal area be visualised.

At present the sandy area, which is seldom flooded, is concentrated roughly within a semi-circle with a radius of 75 km (47 miles) (Diagram 2.4.1-3), of which the centre is situated near the village of Patani. At two places sand is found outside this circle, viz., near the Ramos River and the Middleton River—Nun River stretch and on the beach-ridges. A possible explanation

for this phenomenon is the above-mentioned tendency for sand to be deposited as far as the point where the energy-slope of the river becomes too small to move the sand, with the exception of the rivers through which the Niger at present discharges into the sea and where, due to the falling sea-level, there is ample slope to move the sand farther downstream. The river-bottom will remain sandy some 25 km (15 miles) downstream from the edge of the sandy area as described above and, as can be seen from Diagram 2.4.1-3, the sand-load will reach the Ramos, Middleton, Fishtown, Sengana and Nun Entrances. The littoral drift will distribute this sand-load along the coast, thus forming the sandy beaches and ridges, having a width of anything up to 10 miles. Here again a preference for the western half of the Delta is shown (as already mentioned when discussing the skewness of the distribution of the Delta).

Based on the above-mentioned assumptions, the sandy parts have been tentatively drawn in the sketch of the geological build-up of the Delta. From this the conclusion could be drawn that only in recent times, and during the beginning of the Würm II (Makalian) Period 25,000 years ago, has the Delta been bordered by sandy beaches.

2.5. LONGITUDINAL PROFILE OF THE VALLEYS

2.5.1. Introduction

Almost all rivers in the world follow the same trend of longitudinal profile with their slopes decreasing gradually from source to mouth, a general accordance which has led to efforts by many scientists to analyse the profile mathematically. A formula would, indeed, be very useful, because it would allow

(i) comparison of different rivers or different sections of one river;
(ii) determination of local behaviour of the river with respect to its deviation from the mathematical form;
(iii) extrapolation to those river sections, where no data are available; and
(iv) insight into the present dynamic trend of the river and possibly in future circumstances.

Literature on this subject is abundant and various formulae exist, each of which is based upon certain assumptions which in most cases are merely empirical or have an empirical basis.

The greatest difficulty in the analysis of such a longitudinal profile is the fact that lateral inflow of water and sand disturbs any simplification of boundary conditions. When a river has constant discharges of water and sand per unit width throughout its course, a theoretical derivation of the equilibrium of the longitudinal profile can be made under certain approximations and assumptions. This has been done by STERNBERG ([1], putting as conditions for the status of equilibrium that the river neither erodes nor accretes. He concludes that this is only possible when the mean velocity in any cross-section equals the so-called "pick-up velocity", v_{cr}. Based upon this assumption, together with some experimental and observational results (among which was a gradual and continuous decrease of grain-size in downstream direction), he determined the profile as an exponential function

$$z = A\,(e^{\vartheta x} - 1)$$

where z = the vertical height of the river-bed above a datum,
x = the horizontal distance in upstream direction from a zero upon this datum,
A and ϑ are constants.

The function has been drawn in Diagram 2.5.1-1. The asymptote of the curve is, according

([1] STERNBERG, 1875. MOR. 28

to many authors, the erosion-base. This is either the sea or, in case of a non-alluvial disturbance in the valley, the fixed point, mostly being a rocky bed with resistance against erosion.

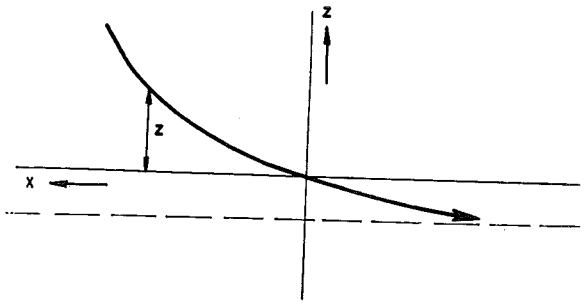


DIAGRAM 2.5.1-1

Sternberg's function of a longitudinal profile

Although Sternberg's assumptions, especially the one concerning v_{cr}, do not correspond with the natural circumstances of the river, it is striking to find a rather good concordance between this formula and the actual profile of many alluvial rivers. Nevertheless, this formula does not satisfy. It is static, while a river with sediment transport is very dynamic. PUTZINGER ([1] therefore states that the river is continuously changing its profile, with moreover each profile being a balanced status of continuity of water and sand. By bringing sand into the sea, a delta is being built up, thus taking the mouth outward and lengthening the river. On the other hand, the mountains are lowered by erosion, and a tilting of the profile is the result, as shown in Diagram 2.5.1-2.

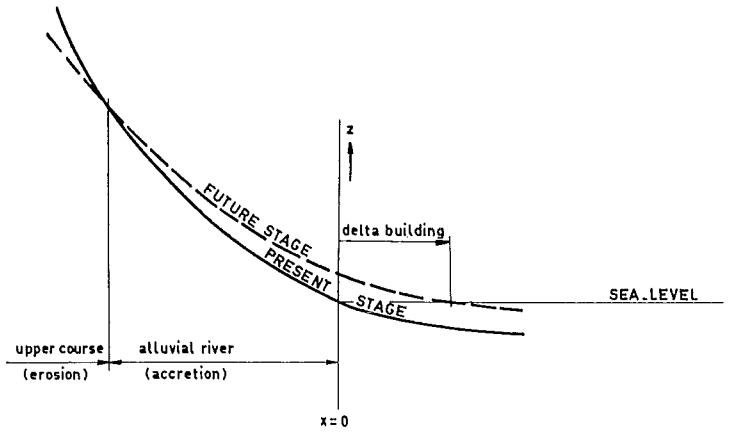
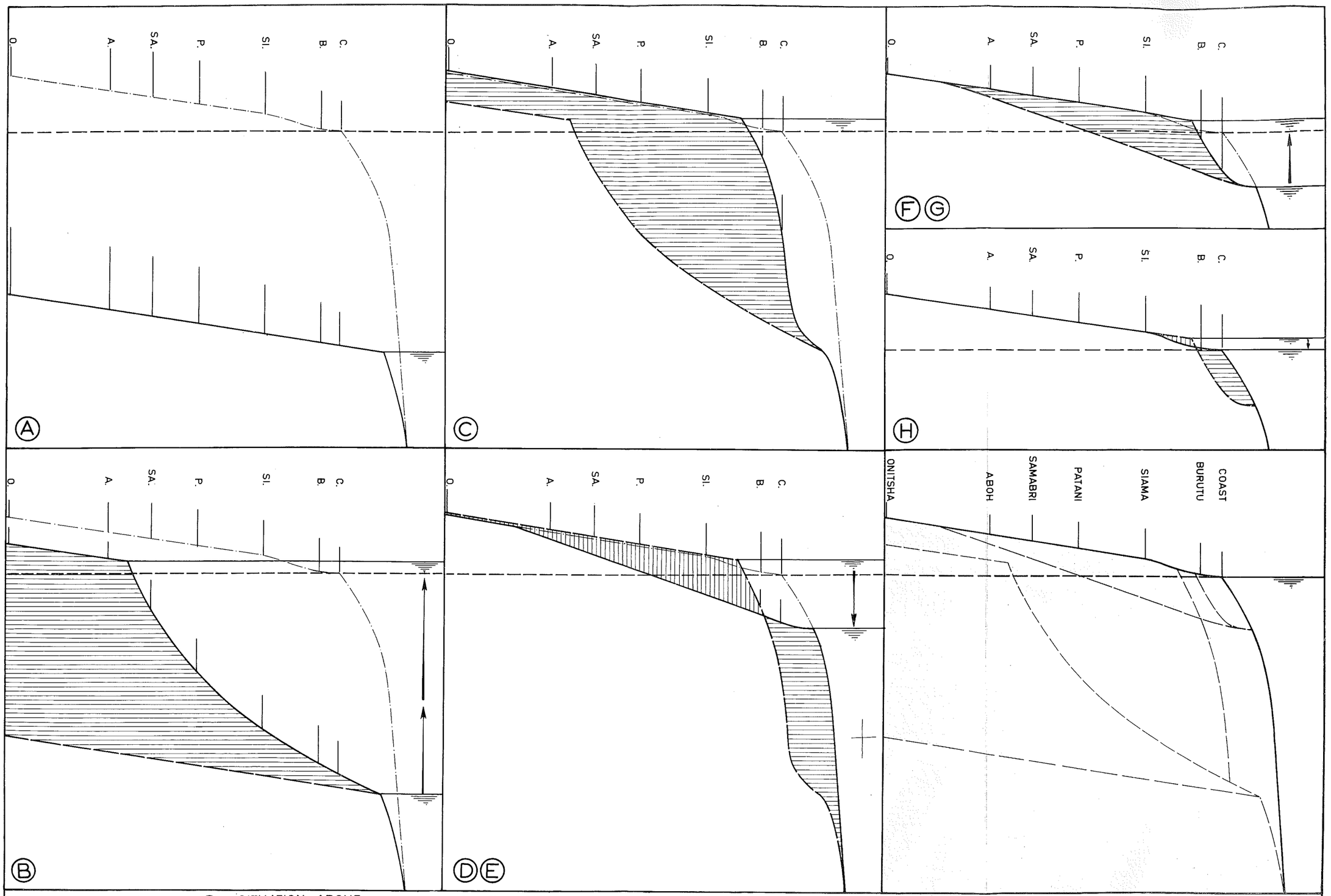


DIAGRAM 2.5.1-2

Tilting of the profile by delta building and mountain erosion

Thus, according to Putzinger, the profile is really a series of profiles, each of which is in equilibrium by itself, but not static. The ultimate shape of the river valley, where the movements at last come to an end, will be reached when the mountains have been so eroded that the rains

([1] PUTZINGER, 1954. MOR. 26



NEDECO NIGER/BENUE | DIAGRAM III 2.4.2_5

TENTATIVE SKETCHES OF THE VERTICAL BUILD_UP OF THE DELTA

cannot wash away more material, and the sand transport in the river must stop. In such a case, the formula of Sternberg might be valid. But even then, his theory has been based mainly on the decrease in size of sand particles of the river bottom in downstream direction, which is not accepted as a general rule. On the Upper Niger, for instance, as well as on the Benue, no such tendency of decrease has been observed (5.1.2). In that case, according to the theories, the profile would take the form of a straight line and the river would have a constant slope throughout its course.

Such a straight line would occur also when sand transport along the river is not zero but is in complete equilibrium without accretion or erosion anywhere. In that case, the slope of the river would be greater than the one with $v = v_{cr}$.

However, the circumstances of a non-transporting river do not come into consideration. The river still transports sediment, and the tilting process is at work, which means the raising of the bed in the lower and middle courses and deposition of sand. This could mathematically be expressed by a sharper curvature of the profile than would occur from Sternberg's formula. Further, sand must be transported as far as the sea, where the delta is being built up. Sand transport, however, is only possible where the slope is not zero. It is concluded that even at the mouth of the river, the slope cannot decrease to zero, and the asymptote of the profile is situated *below the sea*, and not at sea-level.

Both effects, the possibility of a straight line as the final equilibrium and a curvature because of the tilting phenomenon, might lead to the conception that the mathematical equation of the profile of a sand-transporting river is composed of a straight line, superimposed by a logarithmic function. This would explain the seeming accordance of the observations on many rivers with Sternberg's formula, although the theoretical derivation of the latter is doubtful. The equation is then:

$$z = A\,x + B\,(e^{\vartheta x} - 1)$$

where z and x are height and distance respectively as defined above, and A, B and ϑ are constants. The function has been drawn in Diagram 2.5.1-3. Such a solution of approach involves that the asymptote of the profile is not a horizontal line (and certainly not the sea), but a slanting one.

However, the function in this form is still static and does not take into account changes in time, caused by

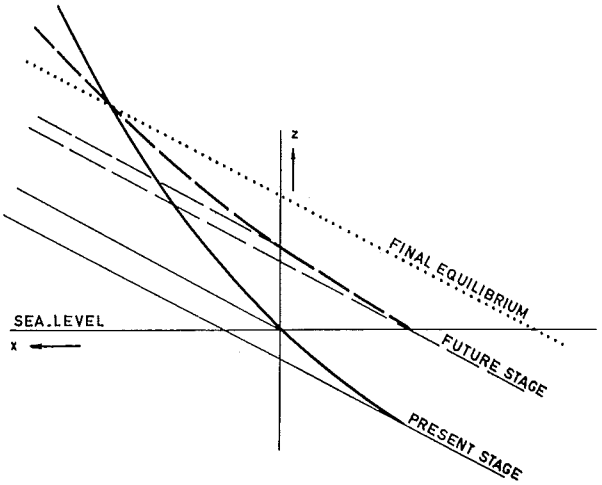


DIAGRAM 2.5.1-3

Various stages of the gradual changing equilibrium profile

(i) tilting effect;
(ii) raise of the bed in the lower course; and
(iii) variation in sea-level.

Ref. (i). Because of the tilting effect of the profile, the curvature of the logarithmic function must decrease with the time, which may be effected by a decrease of the constant ϑ. Since variations in time are very slow, ϑ is deemed to be constant during, humanly speaking, even a long period (see Diagram 2.5.1-3).

Ref. (ii). At a certain place $x = x_1$, in the lower course of the river, tilting of the profile involves a raise of the bed. This can be expressed by a term

$$+ C (1 - e^{-\lambda t}).$$

The ultimate and final equilibrium, as follows from this term, is approached by means of a logarithmic function with the time. At the actual condition, as the profile is observed now, in the present system of co-ordinates, time $t = 0$, from which it follows that the term $C (1 - e^{-\lambda t}) = 0$.

Ref. (iii). Variation of sea-level will influence the entire upper river only after a very long time. The adaptation of the profile to the new level starts from the mouth and gradually propagates upward. In a case where the sea-level, to which the whole river is adjusted, differs from the present sea-level, a correction-term D must be added, which can include the transformation term due to a horizontal movement of the very river mouth ($x = 0$) when sea-level varies.

As a result, the equation for the longitudinal profile of the river could be

$$z = A x + B (e^{\vartheta x} - 1) + C (1 - e^{-\lambda t}) + D$$

When the profile is considered on its appertaining system of coordinates with the river-mouth $x = 0$ correctly located at the occurring place, then time $t = 0$ and $C (1 - e^{-\lambda t}) = 0$, and

$$z = A x + B (e^{\vartheta x} - 1) + D$$

Taking the natural logarithm, it appears that

$$\ln (z - A x + B - D) = \ln B + \vartheta x$$

or when

$$Z = (z - A x + B - D):$$
$$\ln Z = \ln B + \vartheta x$$

which shows a straight line when Z is plotted on a logarithmic scale against x on a linear scale.

In this equation, A, B, ϑ and D are unknown for a given river, but by trial and error it appears possible to solve the problem graphically by taking into account all stations along the river of which the height is known by levelling.

Concerning the origin of the coordinates the following can be said. Sand grains will not reach the outer boundary of the delta where only silt is found. Mostly, the tidal effect has made a tidal basin composed of mud and very fine sand (silt and the finest fraction of suspended load; see chapter 5). The sand grains from the bed-load are deposited on top of this mud-composition, while the river extends its mouth into this tidal basin gradually outward. This place can be considered as the mouth of the river.

2.5.2. The Niger and Benue

The longitudinal profile of the whole Niger does not comply with the afore-mentioned formula, as the river does not flow over its entire length in its own alluvium. At several places the

profile is influenced by rocky sills, and geological changes have also disturbed the course of the river (Diagram 2.5.2-1).

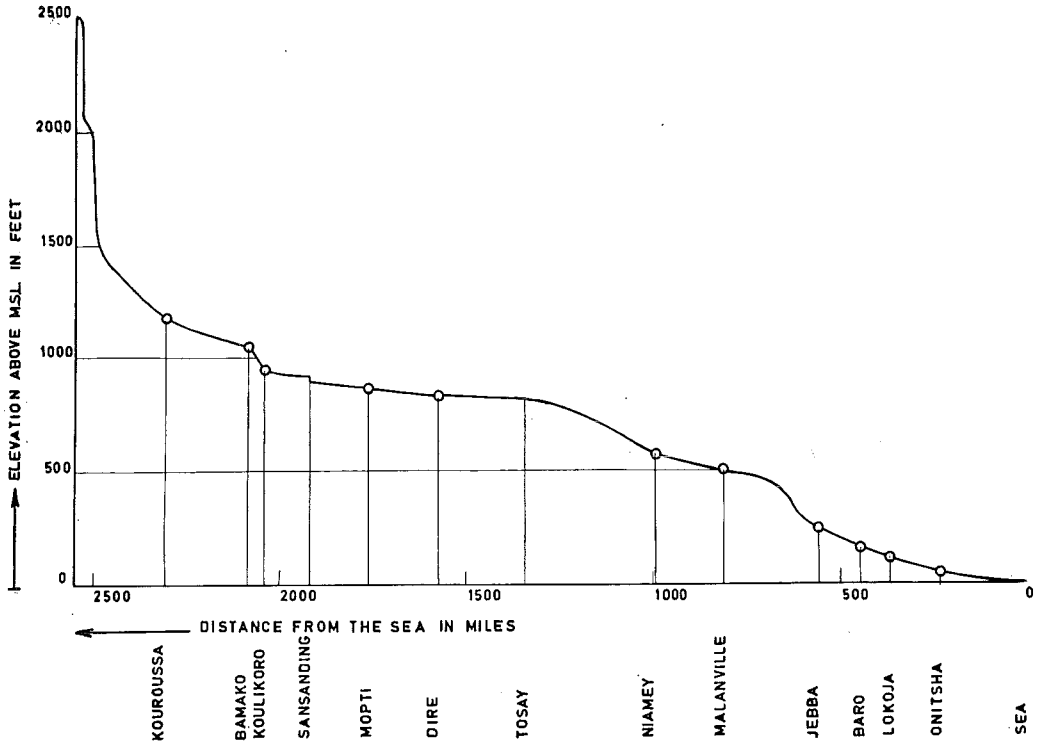


DIAGRAM 2.5.2-1

Longitudinal profile of the Niger

The source of the Niger is situated some 2,500 feet above M.S.L., but over the first miles of its course about one-half of this height is lost and the average slope of the river over the remaining 2,500 miles is about 11×10^{-5} or 7 inches per mile. Upstream from Bamako the slope gradually decreases from 20×10^{-5} to 10×10^{-5}, and apparently the rocky section between Bamako and Koulikoro acts as an erosion-base for this stretch of the river.

After passing through this rocky section with an average slope of about 50×10^{-5}, the slope decreases again from 7×10^{-5} to only 1×10^{-5} within the Interior Delta Area at the downstream end of which the Defilé of Tosay forms a second erosion-base of the Niger.

The slope of the Niger downstream from Tosay steepens again and with some fluctuations due to local rapids averages 14×10^{-5}, until it gradually decreases downstream from Niamey to about 7×10^{-5} as the river approaches its third erosion-base, viz., the rocky section above Jebba, through which the Niger flows with an average slope of 30×10^{-5}.

Downstream from Jebba the river flows in its own alluvium and its slope gradually decreases from 13×10^{-5} to about 5×10^{-5} in the Delta Area, where it reaches its final erosion-base: the sea. For more detailed information about slopes on the Niger and Benue, see 4.2.5.

The longitudinal profile of the Benue (Diagram 2.5.2-2) is less complicated, as only over the first 20 miles, similar to the Niger, the river falls some 2,500 feet. From a point some hundred miles from the source the Benue flows in its own alluvium, joins the Niger at Lokoja and can be considered to form one river system with the Niger below Jebba.

For a mathematical analysis of the slopes of this Niger-Benue system, the alluvial valleys may, in the absence of a detailed flood-plain levelling, be considered to have about the same longitudinal slopes as the respective water-levels at a medium H.W.-stage, such as occurred on September 25, 1956. On this date, the Benue at the Lokoja Confluence appeared to be raised by the Niger only six inches (0.15 m), which is negligible. The mouth of the system is considered to be situated in the tidal Forcados Lake near Burutu, at Mile 40.

When the constant A (see 2.5.1) is assumed to be 5×10^{-5}, with the longitudinal coordinate x

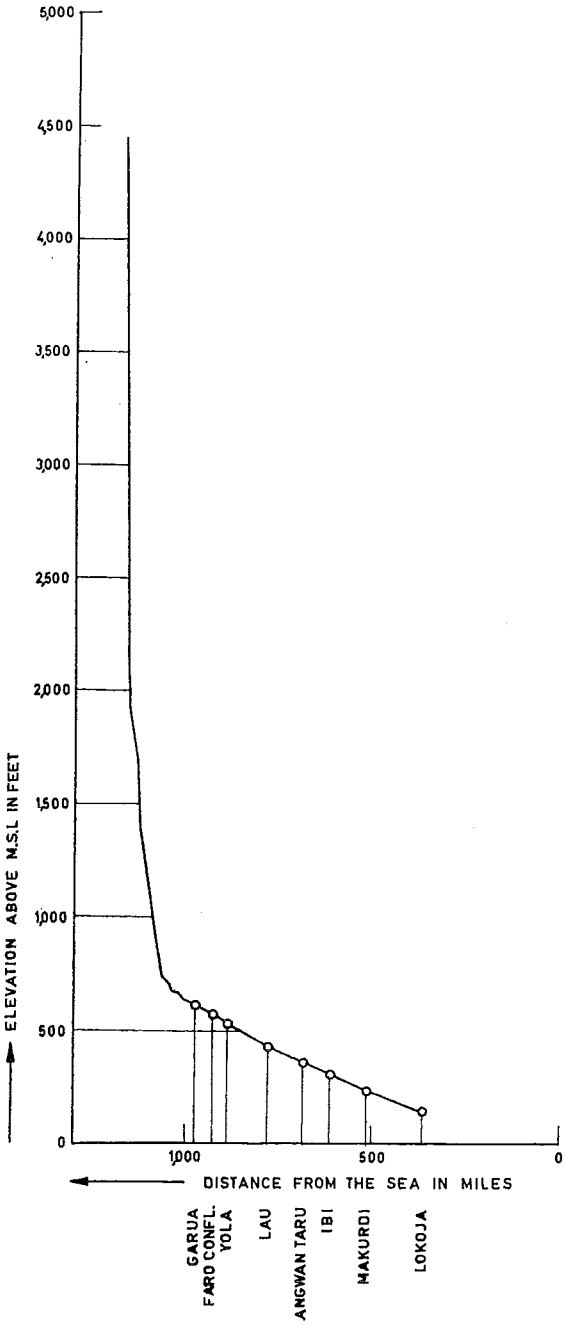


DIAGRAM 2.5.2-2

Longitudinal profile of the Benue

expressed in metres from Burutu upward, and the altitude z in metres above M.S.L., the function ln Z against x appears to be a straight line with

$$B = 34.7 \text{ m};$$
$$\vartheta = 0.97466 \times 10^{-6}; \text{ and}$$
$$D = -7.3 \text{ m}.$$

The straight line, as drawn on Diagram 2.5.2-3, extends as far as Garua on the Benue and nearly all levelled stations are remarkably well covered by the line.

Jebba and Baro have also been shown in the graph. However, as the Niger is raised by the Benue at the Lokoja Confluence to more than 5′ (1.50 m), the water-level at Baro must be assumed to be 5′ higher, in order to attain equilibrium on the Niger, corresponding with an increase in

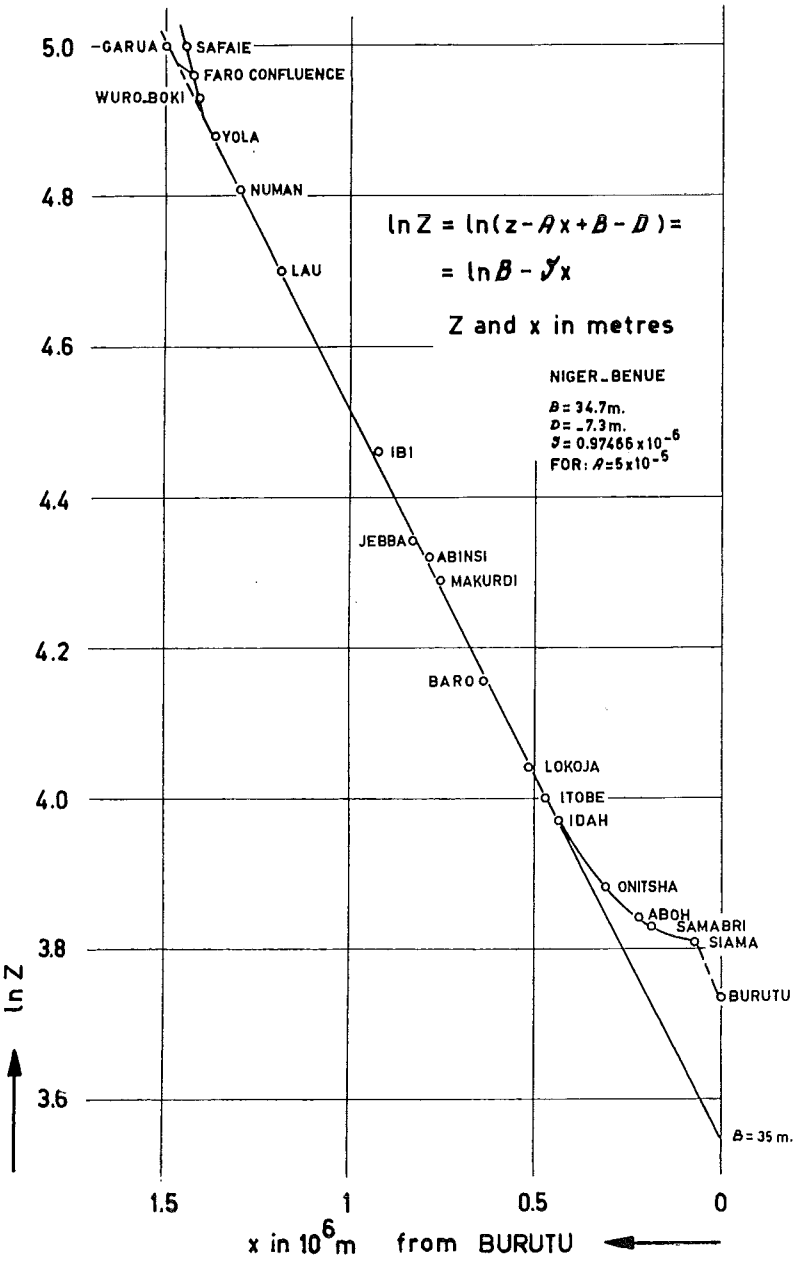


DIAGRAM 2.5.2-3

Mathematical analysis of the elevations of stations along the Niger-Benue system

discharge of 3,850 m^3/sec. Consequently, also the stage at Jebba must be higher. When it is assumed that half of the extra discharge would originate from the Kaduna River and other smaller tributaries between Jebba and Baro, it follows that the water-level at Jebba must be 4'6" higher than the one actually occurring on September 25, 1956. These water-levels of Jebba and Baro have been plotted on Diagram 2.5.2-2. The points appear to coincide with the straight line.

The magnitude of D being $-$ 7.3 m would indicate that the river is adapted to a sea-level lower than the present one. Since a lower sea-level possibly involves a river-mouth farther outward, the value for D does not necessarily mean that the sea-level was exactly 7.3 m below the actual stage. It could be more.

A transfer of the river-mouth, outward or inward, effects a transformation of the values for B, D and Ax.

Geologists frequently speak of a former sea-level which has been about 25 m below the present stage. With this figure taken as a basis instead of the above-mentioned 7.3 m, it has been computed that the river-mouth would have been located some 100 miles outside Forcados out into the sea. It is clear, however, that such a circumstance would not have been possible.

Firstly, those 25 m are doubtful; and secondly, the question is raised whether the river is actually adapted to a specific stage of sea-level. It is generally assumed that since the glacial period of Würm I the sea-level has several times been rising and falling (see 2.4.2). If this movement of the sea-level prevails over its steady stages, it would be possible that the river could not keep up with these changes over its entire length. Every variation of the sea-level affects the longitudinal profile, an effect which propagates very slowly upward, but is flattened out gradually.

In this respect, it would perhaps be best to speak of a so-called dominant sea-level to which the entire river has adapted its profile, while superimposed upon the lower part of this profile are the latest effects due to the most recent deviations of the sea-level from that dominant stage. The height of the dominant sea-level would be something like the mathematical average of all sea-levels, their respective frequency taken into account.

With this conception, a level of adaptation of 7 m below the present stage has no special physical meaning, firstly, because the exact location of the river-mouth with respect to the present coast-line is not known, and secondly, because the dominant stage of sea-level does not necessarily correspond with a certain stage actually having occurred at a more or less recent period.

From Diagram 2.5.2-3 it would follow that a more recent raise of level has effected adaptation of the system from the mouth upward. This adjustment has a slow propagation, and at present has not reached further than Idah. This influence involves a great deposition of sediment below Idah at a much higher scale than would effect a mere tilting. This is in good accordance with the results of sediment transport measurements and computations (see 5.2.3).

This lower part of the river, from Itobe to Burutu, could be analysed separately with the same equation but with different values for the constants. It appears that here, with A still assumed to be 5×10^{-5},

$$B = 3 \text{ m};$$
$$\vartheta = 3.36 \times 10^{-6};$$
$$D = 2 \text{ m}.$$

It is concluded that the sea-level to which this section of the profile is adapted is situated 2 m above the actual one; or probably a little more than 2 m, taking the possibility of variation in the location of the mouth into account.

Geologists speak of a sea-level some 5,000 years ago which was 2 to 4 m above the present stage. When these 4 m are assumed to be correct, the river-mouth would have to be transferred inward over a distance of 36 km (22 miles), which is quite possible.

Finally, the most recent lowering of the sea-level to its present stage has effected another superposition, extending as far as Siama. The latter phenomenon has been described in the Section 2.4 of this Chapter.

It has been stated that the value for ϑ decreases with the time, when the degree of curvature diminishes. It is striking that indeed ϑ, as it has been calculated for the upper river, is only 0.97×10^{-6}, while for the stretch Idah—Siama it is 3.36×10^{-6}. This would indicate that the latter profile is of a more recent origin.

Another deviation from the straight line is seen in the Upper Benue. While Garua is still on the line, Wuro Boki and the Faro Confluence deviate from it. It seems that this deviation originates from the Faro River, because the points for Safaie, the Confluence, and Wuro Boki are situated on another straight line with a greater value for ϑ. From this theory, therefore, the cause of the deviation would be found in a recent change of the Faro regime, involving steepening of the slope of the Faro River as well as gradual adaptation of the main river below the Faro Confluence, as will be described under 5.4.5 and under V, 3.2. The Benue above the Confluence is gradually raising its bed, but this raising effect has not yet reached Garua.

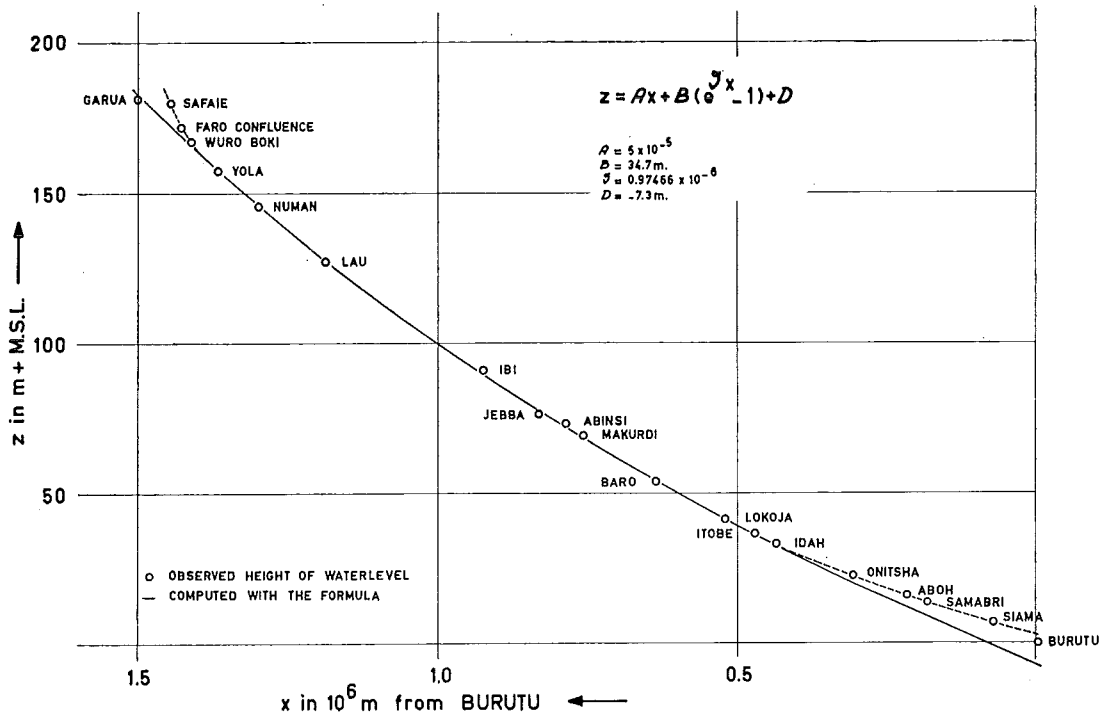


DIAGRAM 2.5.2-4

Linear comparison of the observations with the mathematical analysis

It must be stated that the assumption of $A = 5 \times 10^{-5}$ is not founded on certain arguments, but merely on an estimation. Different assumptions, however, lead to results which do not illustrate this conception distinctly.

Although the conception of the shape of the longitudinal profile is not proved, it is striking to find the results in good accordance with the known facts. Regularities as well as irregularities in the Niger and Benue Valley slopes are clearly pictured in this way.

The theoretical idealised valley elevations, together with the actual levels, are shown on linear coordinates in Diagram 2.5.2-4.

CHAPTER 3

GEOLOGY

3.1. THE GEOLOGY AND GEOMORPHOLOGY OF THE NIGER-BENUE SYSTEM

3.1.1. A geological outline

The landscape of Northern Nigeria is relatively level. A few ridges, plateaux, scattered volcanoes and "inselbergs" (monadnocks) produce most of the relief.

On closer scrutiny the rather monotonous-looking country, with its seemingly uncomplicated history of consecutive periods of peneplanisation alternating with phases of epeirogenetical upheavals, reflects in its manifold and complicated modifications the interplay of very different landscape-building processes and agents. The plateaux, hills, plains and valleys often have a very senile appearance to the casual observer. A rejuvenation has been brought about, however, in various periods by epeirogenetical movements, tectonic processes, eustatic sea-level variations, volcanic activity, climatic variations and modifications in the drainage pattern as a result of erosion and sedimentation. Many of these modifications have occurred in geologically recent times. Knowledge of them is still very incomplete and in drawing an overall picture it is necessary to depend on the very scant information at hand, correlation of which proves to be difficult in many cases.

The main watershed between the principal rivers does not consist of a mountain area, but is formed by an undulating marshy plain with low hilly ridges and small granite domes. The hydrographical centre of this entire area is formed by the Jos Plateau, from which flow the Delimi, Sungo, Gongola, Kaduna and other rivers. All rivers flowing from the North Nigerian upland plain are drained by two major hydrologic systems, the Niger-Benue River System and the Chad Basin.

In Western Nigeria much of the country is characterised by low hills and hummocks of granite and other rocks of the Basement Complex, bordered to the east and to the south by sedimentary deposits dissected into plateaux and ridges. The sedimentary formations have been the subject of several studies, but much less is known about the morphological history of the areas underlain by basement rocks.

In Eastern Nigeria the landscape is more varied. In the area situated between the Benue and the Lower Niger plateaux, ridges and scarps have been formed from the sedimentary deposits which occur with a considerable development. Farther to the east, Basement Rocks outcrop, capped by extensive peneplains with scattered monadnocks, followed in the Camerouns by high mountains which also consist partly of Basement Rocks, but partly, however, of volcanic deposits much more recent in age. Nigerian geologists have concentrated their attention mainly on the sedimentary deposits, for instance in the Enugu area, because of the occurrence of economically-exploitable coal and lignite beds. A few papers have also been published on the volcanoes of the Camerouns.

One of the conspicuous geomorphological features of the region is the Enugu-Afikpo Escarpment, which takes the shape of an open V, suggestive of an underlying broad anticline

TABLE 3.1.1—1

GEOLOGICAL TIMETABLE

International Chronology (Europe and Mediterranean)	African Chronology	Absolute Chronology in years B.C.	Climate	Sea-level	Tectonic Activity	Volcanic Activity	Soudanese Niger (Urvoy)	Northern Nigeria	Tchad Basin
Modern period			dry	0			Soudanese Niger flows into Nigerian Niger through the eroded Tosay Gap. The Aklé and Arouane lakes have dried up by lack of supply from the Soudanese Niger	Nigerian Niger and Lower Benue filled their former deep valleys with alluvial sediments. The Saharian affluents of the Nigerian Niger have become fossilised	Logone discharges into Tchad Basin; floods of the Logone occasionally flow into Mayo Kebi which filled its former deep valley with alluvial deposits
	Nakuran		wet phase						
Flandrian	Makalian	5,000	dry	+ 6′ to + 13′ transgression		continued volcanic activity of Mt. Cameroon			
Würm II (Mankabo glaciation Australia)		9,000 (Australia) 12,000 (Mediterranean) 30,000	wet phase	— 80′ to — 160′ (Australia) regression (Mediterranean)					
Würm I/II (Monastirian II or Tyrrhenian III)		55,000		+ 16′			The Soudanese Niger fills the lakes of Timbuctu, Aklé and Araouane; and finally flows through the Tosay Gap into the Nigerian Niger	Saharian affluents like the Azouak River system discharge considerable quantities into the Nigerian Niger; Niger and Lower Benue erode deep and partly canyon-like valleys (near Makurdi) more than 70′ below present-day-sea level)	Logone discharges into Tchad Basin; Lower Mayo Kebi and Upper Benue erode very deep valleys (Lagdo and Cossi sites)
Würm I maximum (Versilian regression)	Gamblian	75,000	Pluvial IV (H3 of Urvoy?)	— 300′ regression					
Riss/Würm interglacial (Tyrrhenian II or Monastirian I) (Ouljian)		103,000	Interpluvial (S2 of Urvoy)	+ 16′ to 50′ transgression	latest tectonic movements east of Yola; upheaval of catchment area of Mayo Kebi. Faulting in Kenya	latest volcanic activity east of Yola	Soudanese Niger flows into Lake Araouane, a basin of internal drainage	250′ to 300′ terraces formed in Niger Valley between Jebba and Awuru; 60′ to 75′ terraces in Lower Niger Valley near Onitsha; ancient Faro-Benue Valley between Jobolio and Beka. At the end of the period this valley becomes obstructed by a tectonic upwarping. Low-lying terraces in Benue area	Logone and Mayo Kebi become disconnected; Logone discharges into Tchad Basin
Riss/Grimaldian regression	Kanjerian	125,000	Pluvial III (H2 of Urvoy)	regression	second phase of upheaval in Northern Nigeria along two sets of axes	volcanic activity (Upper Black volcanic series of Gèze)	Soudanese Niger flows into Lake Araouane, a basin of internal drainage. Tilemsi Basin divided into two separate basins, the Northern branches draining off towards the Tanezrouft the Southern branches towards the Niger	Saharian River systems (Azaouak, Tilemsi and others) discharge into the Nigerian Niger, through the Badjibo Gap; 310′ to 350′ terraces formed in Niger between Jebba and Awuru; 100′, 150′ and 300′ terraces in Lower Niger Valley near Onitsha; 600′ to 750′ terraces on both sides of the Benue between Abinsi and Ibi; 730′ to 840′ erosion surface in Benue Valley east of Yola. During Kanjerian-pluvial laterisation of terraces	Logone captured by Mayo Kebi and flowing towards the Benue. Formation of Tchad deposits
Mindel/Riss interglacial (Tyrrhenian I)		175,000	Interpluvial	+ 65′ to + 115′ transgression					
Mindel (Roman Regression)	Kamasian	200,000	Pluvial II (H1 of Urvoy)?	— 650′ (Egypt) regression	faulting in Kenya during interpluvial between Kamasian and Kagerian.		Accumulation of drift: Soudanese Niger flows into Gulf of Senegal; lacustrine deposits formed in Araouane Basin	Maximum subsidence east of Zinder-Yola watershed	Middle and Upper Benue and Faro and Upper Gongola drain towards Chad area. Formation of Tchad deposits
Günz/Mindel interglacial (Milazzian)			Interpluvial	+ 180′ to + 200′ transgression					
Günz	Kagaran		Pluvial I	regression					
Sicilian (Villafranchien)		600,000		+ 230′ to + 310′ marine maximum	second phase of subsidence				
Calabrian (top of Pliocene) Pliocene	African peneplain (End tertiary peneplain)		Humid climate and formation of laterites	+ 420′ to + 650′	first phase of upheaval		Laterite and ironstone (Mt. Patti etc.)	1500′ to 1000′ plateau above Niger and Benue level; 1500′ level north of Cameroun Mts and south of Central Plateau area. Watershed Zinder-Yola formed, erosion of central Plateau Area	Lake Tchad drains towards Congo basin
					first phase of subsidence				
Pliocene	Gondwana land surface (Miocene peneplain).				continued upheaval	Volcanic activity (White volcanic series of Gèze)		Formation of drift cover: Central Plateau area show the maximum elevation; erosion on much of the area	
Terminal Eocene									
Eocene	Eocene				subsidence			Two sedimentary basins are formed in the Sokoto region and in the Upper Gongola region, divided by a ridge extending from Zinder southward	Connection interrupted between Logone drainage area and Benue drainage area
Terminal Cretaceous					upheaval folding and faulting	Volcanic activity (Lower Black volcanic series of Gèze)		Upheaval folding and faulting accompanied by volcanic activity	Connection between Logone drainage area and Benue drainage area
Cretaceous	Cretaceous				Gondwana continent divided; Africa and South America drifting apart; origin of rift valleys and downwarped basins		Marine transgressions in basins which extend far into the African Continent in rift-valleys and in downwarped basins, marine and lagoonal sediments (sandstones and shales, some limestone beds)		
Early Cretaceous and pre-Cretaceous	Karroo and continental Intercalaire				upheaval		Erosion and peneplanisation		

pitching to the south-west. The sedimentary deposits which occupy the central part of Nigeria extend southward into the delta area of the Niger, where sedimentation has been accompanied by subsidence, as a result of which sediments of great thickness accumulated. These are of considerable interest to the Nigerian economy as they appear to contain oil and gas accumulations in commercially-exploitable quantities. The recent deltaic deposits grade downwards more or less continuously into the various Tertiary and Cretaceous formations.

The underground of a large part of Northern Nigeria consists of metamorphic and crystalline rocks belonging to the Pre-Cambrian Basement Complex. They are diverse in origin as well as in age, and some of them contain valuable ores. But it is not possible to enter here into more details about these formations with their long and complicated history (vide the Geological Time-table 3.1.1-1). They have been subjected to long periods of erosion and peneplanisation during the entire Paleozoic and most of the Mesozoic. According to PUGH and KING ([1, remnants of some of these older surfaces have been preserved in the Jos area, the Cameroun Mountains and in other places. In Nigeria during the last period of the Mesozoic (Cretaceous period) only sedimentary deposits were formed.

Marine transgressions during the Cretaceous inundated part of the African continent, connecting the Mediterranean with the Gulf of Guinea. At the end of the Cretaceous Period upheaval of the continent took place, accompanied by folding and faulting of large areas, and some volcanic activity (Lower Black Volcanic series as mentioned by GÈZE ([2. The main volcanic activity took place in the Camerouns.

The Cretaceous sedimentary sequence consists not only of arkosic sandstones and similar clastic deposits, but also of clay shales with thin beds of limestones. The occurrence of clay shales, and especially of limestones, could be an indication that these sediments have been deposited in the open sea. However, adherents of the theory that Africa once formed part of the Gondwana Continent, broken op during the early Cretaceous period, are of the opinion that the shales and limestone beds have been deposited in narrow basins, bordered by faults or warped zones, instead of in an open sea environment. The narrow basins would have originated as a result of "rift-valley" formation at the time the Gondwana Continent broke up and South America drifted away from Africa. The fine-grained sediments (such as the shales) would have been washed away from the peneplanised Gondwana land surface.

The deposits formed during the Cretaceous Period are different in various parts of Nigeria. The Lower Cretaceous (Albian-Cenomanian), as far as present, occurs in the north-west of the country and in the Benue Basin in an arkosic non-marine facies. In the south of Nigeria, east of Enugu for instance, fossiliferous marine sediments of the same age are found, including limestones. The Upper Cretaceous (Turonian-Maestrichtian) is arkosic in most of the country, with varying intercalations of lignite and coal, indicating its lagoonal or continental origin. But even far upstream in the Benue Basin thin marine intercalations occur, characterised by the presence of limestones with Turonian ammonites.

Subsidence during the Eocene Period resulted in the deposition of marine sediments in the north-west, in the area around Sokoto (calcareous group and clay shale group) and in other parts of Northern Nigeria (Kerri-Kerri sandstones of Bauchi and Bornu). During this period probably two basins existed, divided by a ridge extending from Zinder southward, of which the present Murchison Range possibly formed part. The fact that the Eocene sandstones west of the River Gongola are gradually thinning out is an indication of this ridge having existed. In the western basin marine limestones occur, and there is no doubt that this basin was in open connection with the ocean.

([1 PUGH and KING, 1952. GEO. 36
([2 GÈZE, 1943. GEO. 20

In Southern Nigeria subsidence and sedimentation continued until late in the Tertiary Period, alternating with temporary and often localised interruptions. In the extreme south (the delta area of the Lower Niger) these processes went on even during the Quaternary Period. They resulted not only in a differentiation of the facies of the sediments, lagoonal or continental in Central Nigeria, more often marine in the underground of the Delta areas, but also in a much greater thickness of the sediments in the extreme south. The Coastal Plain sand group (Oligocene and more recent), for instance, is represented in the Onitsha area by a thickness of a few tens of metres of sandy brackish water sediments with some lignite and some gravel, while in the delta area marine sand and clay deposits occur with a thickness of more than 2,000 metres (6,500 feet).

Towards the end of the Eocene Period the sedimentary basins in Northern Nigeria ceased to exist. Upheaval of the entire region took place and continued until the beginning of the Pliocene Period. Products of erosion were carried away to the south and deposited in the area of modern Southern Nigeria. The highest elevation was probably in the Jos Plateau. In the Cameroun Zone and in other places volcanic activity continued (white volcanic series as mentioned by Gèze). Thus the northern part of Nigeria is in strong contrast to the south where sedimentation continued during most of the Tertiary Period.

In describing the crustal movements and ensuing erosion or sedimentation in Northern Nigeria, it should first be pointed out that the slow but seemingly regular movements of upheaval in the north were interrupted at the beginning of the Pliocene Period when crustal warping and a first phase of subsidence took place in part of the area. The elevated parts of the crystalline rocks were still subjected to erosion, but the debris was no longer carried away to the coast. The land surface of the lower lying areas was covered with a blanket of "drift" — fine-grained clastic sediments resulting from the erosion and disaggragation of the crystalline rocks and transported by wind and small rivers.

The movements of subsidence alternated with movements of upheaval. The first phase of subsidence was followed by a first phase of upheaval, during which erosion took place on the Central Plateau area (Hausaland, Nassarawa, Muri and Jos Plateau). A watershed was formed extending from Zinder to Yola and from there to the Cameroun Mountains (see Diagram 3.1.1-2). The Lower Benue and Niger Rivers drained the area situated to the west of the watershed. East of the watershed the rivers flowed towards the Congo Basin via Lake Chad and the Shari Valley. No important sedimentation took place in the area concerned ([1.

The already-existing and newly-formed peneplains became covered with a very thick mantle of lateritic soil, formed probably under a uniform hot and humid climate. The ironstone intercalations and capping hardpan are supposed to have developed from the lateritic soil subsequently at the end of the Pliocene Period or in a very early stage of the Quaternary Period during a climate characterised by prolonged periods of heat and drought. For a discussion of the origin of various types of laterites see, for instance, DU PREEZ ([2. Several authors assume the climate of the Pliocene to have been evenly warm and moist during a very considerable span of time, in contrast to the climatic variations which form such a striking feature of the Quaternary Period (KUBIENA ([3 and BUEDEL ([4 in explanation of the fossil red soils of the Hoggar Massif in the Central Sahara; BRUECKNER ([5 in a description of the mantle rock of Ghana). The hard lateritic caprock, which under very favourable conditions is found nowadays as an iron ore of

([1 MORTELMANS, 1957. GEO. 31
([2 DU PREEZ, 1949. GEO. 34
([3 KUBIENA, 1955. GEO. 25
([4 BUEDEL, 1955. GEO. 5
([5 BRUECKNER, 1955. GEO. 4

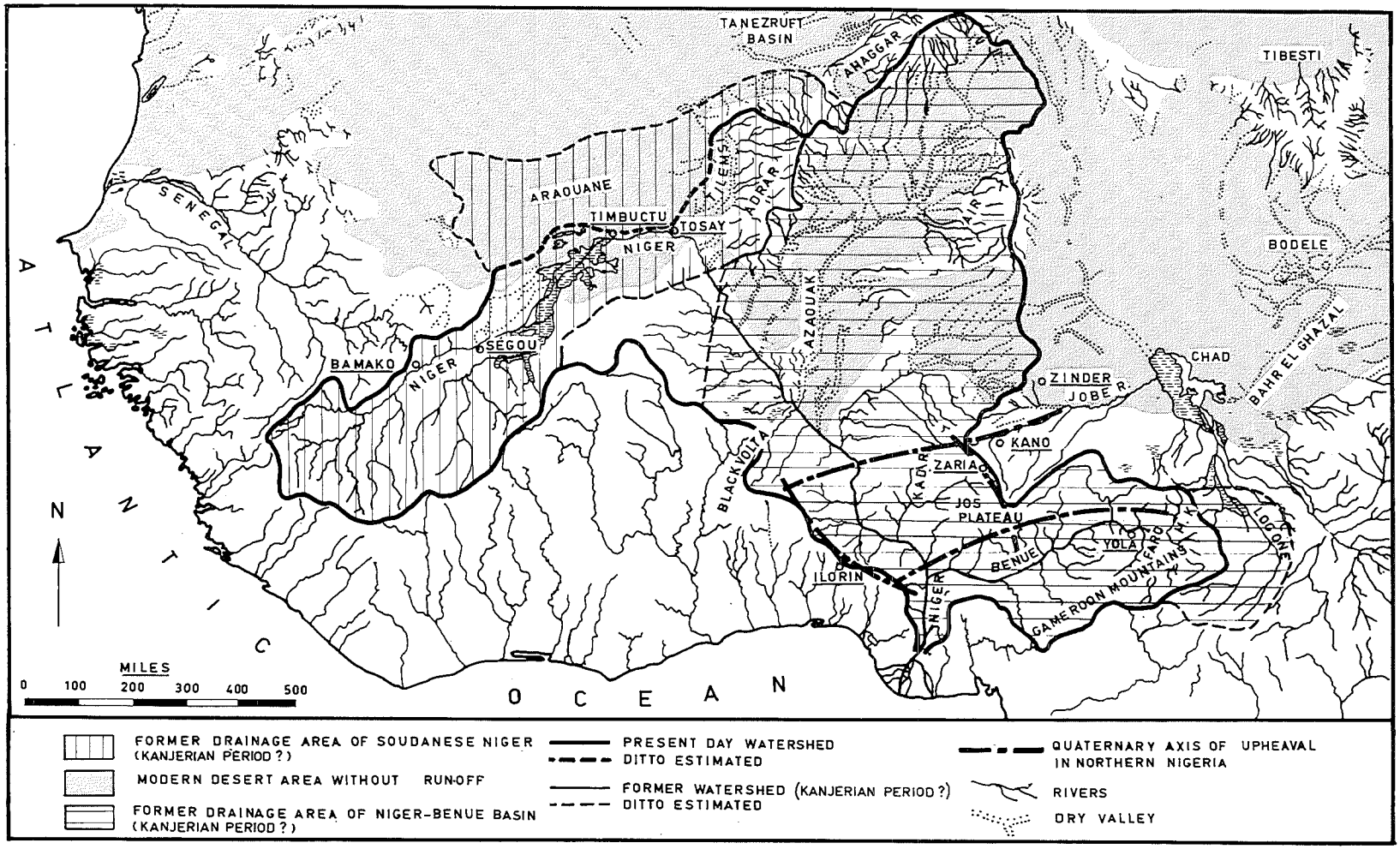


DIAGRAM 3.1.1-2

Evolution of the Niger drainage basin

economic interest, fossilised and preserved the ancient surfaces on which it had been formed. Thus the Pliocene and Pre-Pliocene surfaces, described under various names in many parts of Africa ("Gondwanaland surface" formed during the Miocene and the "African surface" formed at the end of the Tertiary, for instance), dissected by subsequent erosional phases, still are very apparent in the landscape where they form striking table mountains. Examples can be seen between Baro and Lokoja (Mount Patti), along the rocky section of the Lower Niger downstream of its confluence with the Benue River, and in many other parts of Nigeria, although it will often be very difficult to prove to which stage of the Pliocene the surface observed belongs. Remnants of ancient surfaces now lie between 150 and 300 m (500 and 1,000 feet) above the present level of the River Niger on Nigerian territory.

Likewise the Benue Valley shows features of a more ancient landscape, the transition of which to the more recent landscape lies at an altitude of approximately 500 m (1,500 feet) ([1. The surface, rising from the 500 m (1,500 feet) contour-line towards the Cameroun Mountains to the south and towards the Jos Plateau to the north possibly once pertained to the Chad Basin drainage system during the early Pliocene Period. Other surfaces lying at altitudes between 450 and 900 m (1,500 and 3,000 feet) have been mentioned by GROVE ([1, GÈZE ([2 and other authors.

According to Gèze, part of the African continent, including the Camerouns, Nigeria, Dahomey, etc. rose about 200 m (600 feet) in relatively recent geological times. This relative rise is to be attributed rather to eustatic sea-level variations than to epeirogenetical movements. In many regions, first recorded, however, from the Mediterranean area, a high sea-level has been observed varying between 130 m and 200 m (420 and 650 feet) above present-day sea-level. These sea-levels occurred at the end of the Pliocene Period (the so-called Calabrian sea-level). On the accompanying tentative Chronological Table 3.1.1-1 there is indicated the recorded former sea-levels as well as other data which serve to establish the chronology of the Quaternary Period and to correlate its sub-divisions in many parts of the world.

During a second phase of subsidence, drift was again deposited. Subsidence was at its maximum east of the watershed Zinder-Yola, but the watershed itself also underwent subsidence and the valleys in Bauchi and Bornu became filled with 120—150 m (400—500 feet) of drift. In the eastern parts of Bornu and the Chad and in the area of the Logone River a lacustrine environment predominated (Chad series). To the south of Zaria and to the west of Bauchi another area of subsidence probably existed. Even today remnants of the cover of drift are still found on the plateau, where they form flat-topped hills 60—90 m (200—300 feet) high. At the beginning of this second phase of subsidence the rivers flowed towards the area of maximum subsidence, e.g., the Middle and Upper Benue, and Upper Gongola towards the Chad Basin. But at the end of this period the drainage pattern may have been altered as a result of the considerable accumulation of sediments. There are no indications that the basins formed during this phase were related to basins of earlier periods.

In Bornu the deposits of the Chad Series lie on top of the laterite cover of the older peneplains. The "Sables de Kélo" which occur in the Logone Basin to the north-east of Garua, and which in all probability represent a lateral facies of the Chad deposits, include a laterite level, while another laterite level caps them, attesting to at least two pluvial periods ([3. These arguments lead to the assumption that the Chad Series originated in the early Pleistocene age, which is in accordance with the finding of fossilised fragments of Hippopotamus Imaguncula Hopwood (Lower Pleistocene) in these deposits ([4.

([1 GROVE, 1956. GEN. 14
([2 GÈZE, 1943. GEO. 20
([3 ROCH, 1953. GEO. 37
([4 TATTAM, 1943. GEO. 41

A second phase of upheaval took place during the Pleistocene period, leading to a gradual change of the drainage pattern (see Map 3.1.1-2). Upheaval took place along two NNW-SSE directed axes and along two WSW-ENE directed axes. The first set consists of an eastern axis extending from Zaria to the Jos Plateau and a western axis near Ilorin. The second set consists of a northern axis of upheaval, extending from Bornu through the upland plains of Kontagora, Sokoto and Katsina to Zinder and one from Ilorin to the Jos Plateau and the Biu Plateau. As a result of this process gently updomed ridges and shallow troughs were formed. The northern ridge forms the watershed between the River Sokoto to the north and the Kaduna and Yo Rivers to the south. The Benue flows through the trough between the southern ridge and the Cameroon Mountains. The eastern ridge forms the watershed between the River Yo and the River Kaduna. The western ridge lies to the west of the Niger.

The two NNW-SSE directed axes seem to continue beyond the Nigerian boundaries well into the French Niger and Soudan territories. The northernmost of these axes lies in line with a presumed axis of upheaval mentioned by KARPOFF ([1], which can be followed to the north of the Niger and at a distance of about 350—400 km (200—250 miles) from this river across the drainage areas of the Azouak, the Tilemsi and other valleys, which all show conspicuous bends at its crossing. The ancient drainage area of the Tilemsi, according to this author, has been divided into two separate parts as a result of the tectonic movements, the northern part (with the Wadis Tamanrasset and In Ouzzal) draining nowadays towards the Tanezrouft Basin and only the southern part still draining southward towards the Niger.

The course of the rivers and the main trends of the topography have been influenced by the direction of each separate axis of elevation as well as by the interference of the axes in these areas where they cross each other approximately at right angles.

The movements of subsidence and of upheaval which occurred during the Pleistocene Period were again accompanied by volcanic activity producing mostly basalts, but also some rhyolithic rocks (Upper Black Volcanic Series of Gèze). Although the volcanic activity in many areas seems to have been restricted to the early phases of the Pleistocene, in other regions the volcanoes were active up to very recent times, while in the Camerouns some volcanoes are still active now. For the time being, however, there is no certainty about the chronological position of the fluvio-volcanic series of the Jos Plateau.

3.1.2. Morphological evolution of the Niger and Benue Valleys

In the previous paragraph a general picture has been drawn of the geological history of Nigeria, based on a great many facts recorded by various writers, as well as some personal observations. This evidence enables the evolutionary stages of the Niger and Benue Valleys to be traced. As no written record has been found of terrace deposits in Nigeria with prehistoric implements in situ or other data normally used for determing the chronological sequence of the events described, the given synthesis regarding the synchronism of several areas of the main rivers and their affluents is highly hypothetical. Nevertheless the synthesis, however imperfect and liable to future modifications and corrections, provides a better understanding of the evolutionary history of one of the major river systems of the African Continent.

a. Drainage systems

During the very first stages of the second phase of upheaval the drainage pattern of Nigeria in its main lines probably resembled already the modern river system. Possibly the 220—250 m

([1] KARPOFF, 1953. GEO. 24

(730 to 840 feet) erosion surface observed on the Dasin-Gurin ridge to the south of the Benue, east of Yola and on the northern foot-plain of the Vere Hills (see Paragraph 3.4.7 describing the morphology and geology of the Yola area), the 180—225 m (600—750 feet) surfaces north and south of the Benue between Abinsi and Ibi and the terraces lying at about 30, 45 and 90 m (100, 150 and 300 feet) above the presant river-level in the Niger Valley near Onitsha and at about 95—105 m (310—350 feet) above mean sea-level in the Niger Valley between Jebba and Awuru, represent erosional stages of the ancient Benue and the ancient Niger at this time.

Several of the terraces and erosional surfaces of the Benue Valley mentioned by GROVE (1 may also belong to this river system. The tectonic movements must have occurred very gradually, for the Niger has been able to cut its valley into the hard rocks of the Basement Complex in the areas where it crossed axes of upheaval, e.g., between Jebba and Yelwa and between Idah and Lokoja (see Diagram 3.1.1-2). The Lower Gongola also is seen to cross an axis of upheaval at about right angles. Other rivers, however, such as the Sokoto, Kaduna and Gurara, show considerable changes in direction, possibly under the influence of the tectonic movements.

The various upland plains, table-lands and plateaux are not lying at the same altitude, which shows that the rate of upheaval has not been the same along the various axes of elevation. The plains of Nassarawa, Muri and Northern Bauchi have remained behind when compared with the Plateau of Jos and the Nassarawa Table-land. Faulting, or more probably a rejuvenation of already-existing fault zones, occurred at the same time. The tectonic movements were accompanied by volcanic activity, for instance, in the Central Plateau area.

The ancient Faro-Benue Valley found between Jobolio and Beka to the east of Yola and the terraces at 18—22 m (60—75) feet above dry season water-level (corresponding to 95—105 m or 310—350 feet above Mean Sea Level) in the Niger Valley between Jebba and Awuru are supposed to be erosional stages of the Benue and the Niger Rivers dating from after the end of the second phase of upheaval. The morphological history of the Yola region shows that tectonic movements, causing the formation of local watershed and some very late volcanic activity (the watershed across the ancient Benue-Faro Valley near Padaro and volcanoes near Ribadu), continued until very late in geological history. Several of the lower-lying terraces and erosionaal surfaces in the Benue area as described by Grove also seem to enter into this category.

The River Gongola shows several anomalies in its development. At first it takes its course in a north-easterly direction, but near Nafada bends to the south. During the first phase of upheaval of the Pliocene, valleys were eroded south of Kerri-Kerri, which were filled with drift during the second phase of subsidence. Probably the Gongola, which first flowed into the Chad Basin, then altered its course and made use of one of these ancient valleys after the second phase of upheaval, flowing through the already-existing Gap of Kombo and joining the Benue. Outflows of basalt during the Tertiary Period on the plateaux and in the plains north of Numan have also altered the drainage system. Longitudinal consequent rivers became obstructed and a radial drainage pattern was formed (Biu Plateau). The rivers eroded their valleys through the basalts into the underlying sedimentary series, over which they now flow to the largest of all consequent rivers, the Benue, cutting across folded structures. To the west (Biliri Hills and Kaltungo area), where no basalt cover exists, beheading of rivers by others has taken place. The most recent tectonic movements, during the last phase of upheaval, were accompanied by numerous volcanic outbursts, each of them on a very small scale, for instance, in the area around Kiri-Bobore.

Boreholes in the valleys of the Benue and the Lower Niger have demonstrated the existence of buried ancient valleys lying deep below the present river-bed. Near Onitsha the bottom of

(1 GROVE, 1956. GEN. 14

the ancient valley lies at least 45 metres (150 feet) below the present river, as boreholes made for a bridge did not reach the bottom of the ancient valley at that level. Near Makurdi boreholes going down 90 m (300 feet) proved the existence of a very deep canyon-like buried valley, the bottom of which lies at least at that depth below the present river-level. In the Benue Valley near Dasin Hausa the depth of the ancient valley exceeds 33 m (100 feet) and near Lagdo 40 m (130 feet) below the present river-level. Important rivers in other parts of Africa and on other continents show identical features. For this reason the downcutting of the river valleys to a considerably lower level (near Makurdi about 20 m or 70 feet below present sea-level, near Onitsha even lower) and the filling up of the deeply-incised valleys during a more recent period, may be attributed to so-called "eustatic" (world-wide) variations in sea-level which can be correlated with the ice ages in Northern America and Eurasia.

b. *Variations in climate and sea-level*

Although in some cases buried valleys occurring above present-day sea-level can be explained by climatic variations leading to variations in run-off and in flow of the rivers, the levels of the buried valleys of the Niger and Benue Rivers definitely indicate sea-level variations. Climatic variations however, also occurred, as exemplified by the huge, now fossilised, river system which debouches into the Niger Valley near Boumba (downstream of the "Double V"). This river system, originating under the name of Tin Tarabin on the southern slopes, of the Ahaggar in the Sahara, known under the name of Azouak in its main course and attaining the Niger on the left through the Dallol Bossi, has a length of about 1,600 km (1,000 miles). Occasional floods occur nowadays flowing over a distance of less than 270 km (160 miles) before disappearing into the sands. The fossilised drainage system can only have originated during a period of a considerably higher rainfall. It formed the first headwaters of the Lower Niger, prior to the capture of the Soudanese Niger near Tosay.

BUTZER ([1] like may other authors, gives arguments for the synchronism which existed between pluvial periods and glaciations. He also draws attention to the contemporaneous occurrence of pluvial periods and regressions (lowerings of the sea-level), the latest of which took place during the Würm glaciation (late Paleolithic Period).

On the tentative Chronological Time-table (Table 3.1.1-1) there are indicated the various sea-levels and climates which occurred during the Quarternary Period, and which by their world-wide occurrence enable the establishment of chronological subdivisions of this period and the correlation of events which took place in distant areas and continents. The latest figures regarding the absolute age in years of the subdivisions of the Quaternary, are also added, together with the stratigraphical nomenclature adopted for the Quaternary in Europe and the Mediterranean area as well as on the African Continent. Use has been made of the works of several authors ([2–6]. There is, however, not yet unanimous agreement on the Quaternary time-table and its chronological correlations, some authors advocating a synchronism of climatic variations and others basing their work on prehistoric finds or on paleontological or geological evidence. COOKE ([7] shows the difficulties which still exist in establishing the Quaternary Glacio-Pluvial correlation in East and Southern Africa.

Emphasis is again put on the hypothetical character of the chronology and the correlations

([1] BUTZER, 1957. GEO. 6
([2] CASTANY, 1956. GEO. 9
([3] CHOUBERT, 1956. GEO. 11
([4] EMILIANI, 1955. GEO. 16
([5] PFANNENSTIEL, 1956. GEO. 33
([6] ZEUNER, 1956. GEO. 52
([7] COOKE, 1957. GEO. 12

of Table 3.1.1-1, which should be regarded as illustrative of the general trend of the morphological evolution of Nigeria and not as being firmly established.

For this chronology of the evolution of the Niger Basin use was made of the following arguments:

Firstly, the eustatic sea-level variations recorded in many regions were taken into account, a very typical lowering of the sea-level having occurred during the Würm glaciation. During this Würm regression the sea-level lay approximately 90 m (300 feet) below the present level, which would explain the existence of a buried valley of about that depth below the modern Niger and Benue Rivers. The — 90 m (— 300 feet) sea-level has been recorded in several parts of the African coastal area: for instance, in the Nile Valley ([1, in British Somaliland ([2, on the West Coast of South Africa (Oliphants River ([3 of which is not stated, however, the exact sea-level during the regression), and Ghana (Volta, Den and Ankobra Rivers ([4 of which is stated that a Pleistocene sea-level occurred at least 18 m (60 feet) below its present sea-level). Levels higher than the present one, resulting in raised beaches and terraces, are at least equally widespread, and even more often cited than the low sea-levels, as the raised beaches and terraces are easier to observe without the need of making boreholes.

In the second place, attention has been paid to the possible geological influence of climatic variations. There is, however, no need to cite here the numerous publications, of unequal value for the present purpose, in which facts are mentioned concerning inferred climatic variations in African territories with a discussion of their chronological correlation. The literature on the subject concerning Europe, the Mediterranean area, and North America is also very abundant. The existence of four major pluvial periods has been agreed upon, which are more or less synchronous with major periods of glaciation in Northern Europe and North America, as well as with regressions of the sea, alternating with dry periods (interpluvials) or in the northern parts of Europe and Canada and the northern part of U.S.A. with warm periods (interglacials), synchronous with transgressions of the seas.

Nigeria stretches from the tropical forest belt in the south to the Savana belt in the north, where semi-arid and arid conditions prevail. Each of these climatic belts is characterised by special kinds of sediments (in the arid belt, for instance windblown sand deposits) and by various weathering and soil-forming processes (such as laterite soils in the tropics). It may be concluded therefore that climatic variations, leading to a shifting of climatic belts, have taken place in those areas where characteristic sediments or soil types are found which could not have been formed under present-day weather conditions.

This is true in particular for Northern Nigeria and the adjacent regions in the French Camerouns and for the French Soudan and Niger territories, composing the border area between the tropics and the arid Sahara region and providing almost ideal conditions to record such climatic variations in its superficial deposits. Fossil dunes, testifiying to a former dry climate, have been observed in areas now covered by vegetation. Elsewhere red soils, indicating a humid climate, are found in areas which are arid today.

On the other hand, several authors, among whom is URVOY ([5, advocate climatic variation as an explanation for the formation of lateritic soils and ironstone deposits, the laterite clays having been formed under moist conditions, and the hardpans under more arid conditions. From the fact that laterites are found on ancient terraces (e.g., the 220—250 m or 740—840

([1 PFANNENSTIEL, 1956. GEO. 33
([2 MISS CATON-THOMPSON, 1957. GEO. 10
([3 MABBUTT, 1957. GEO. 27
([4 DIXEY AND WILLBOURN, 1951. GEO. 14
([5 URVOY, 1942. GEO. 47

feet erosion surface in the Benue Valley to the east of Yola) and that they do not occur on the latest fluviatile deposits, it may be concluded that the ancient terraces were formed in a humid period prior to the Würm pluvial period (Gamblian pluvial in Africa) and the Würm low sea-level, during which the deeply entrenched buried valleys of the Benue and the Niger, below the level of the laterised surface, originated. The formation of the above erosion surface in the Benue Valley east of Yola and the almost contemporaneous second phase of upheaval would coincide, according to these views, with the second humid period mentioned by Urvoy for the Soudanese Niger area, probably the Riss period or Kanjerian pluvial of the African nomenclature.

The laterites and ironstones which cap the Pliocene land surface seem to have originated, at least in part, during moist periods in the Pliocene which are not related to glaciations or sea-level variations. However, they are helpful in marking the limit between the Pliocene (and Pre-Pliocene) features and the Pleistocene events.

The drift which was deposited in Bornu during the last of the described phases of subsidence has not the same composition as that which was deposited in Hausa Land. The latter area was not included in the movements of subsidence when terrestrial and subaerial deposits were accumulated in this area. In Bornu, however, marshy and lacustrine environments predominated. The Chad area remained a depression even during the last phase of upheaval. Its water was drained southward. After the formation of a watershed north of the Congo Basin, the water from Lake Chad was diverted into the Bodele depression through the Bahr el Ghazal River. This change caused erosion of the drift and lake deposits in Bornu. Climatic variations also played a role. The composition of the drift accumulated in Bornu Province shows that this area has long formed a border area between the desert and the Savana. During arid periods windblown sand was deposited. During an arid period also the supply of rain-water and river-water diminished and Lake Chad, cut off from the Bodele depression, was reduced to its present extent.

During the Pleistocene and Recent periods the Niger built out its large delta. The boundary of the various Tertiary rocks in the south with the delta deposits of the Niger and other rivers is very indented and not known in detail. Seawards the delta deposits increase considerably in thickness, as they have been deposited in a subsiding area. Towards the apex of the delta the deposits grade into the alluvial fill of the Niger Valley, still having a thickness of at least 90 m (300 feet). During the river survey a ferruginous sandstone was discovered in the river near Aboh, which might belong to a hard horizon of the Coastal Plains Sand Group. This might indicate that the present river-bed of the Niger, as a result of sideward shifting, does not coincide everywhere with the axis of the older deeper lying valley, but locally might lie possibly to the side of the ancient valley.

c. *The Upper Benue and the Logone*

Apart from the buried valley of the Benue, lying more than 40 m (130 feet) below present river-level near Lagdo and Garua, and which forms the upstream continuation of the buried valleys of the Niger and the Lower Benue, mention must be made of the relation between the Benue and Logone Rivers. The available published data — most of the information concerned has been taken from ROCH ([1 and from the French reports on the Benue River and on the Lower Logone River ([2 — do not give a detailed chronology of the events which influence the relation between these two rivers. The correlations put forward hereafter and in the Chronological Table are based on the same assumptions as used for establishing the chronology of the evolution of the major valleys in Nigeria and are therefore entirely tentative.

([1 ROCH, 1953. GEO. 37
([2 ORSTOM, HYD. 7 and HYD. 8

The region situated between the Benue and the Logone forms the catchment area of the Mayo Kebi. It originates on a plateau with several lakes. The first section of the river is known under the name Djermé River. Further downstream, but still upstream from the Lake Fianga, its name is changed into River Kabia. The present watershed between the Kabia and the Logone Rivers is formed by an area covered with marshes. At periods of very high water in the Logone River, water from this river inundates part of the marshes and flows towards the River Kabia. These two drainage areas were already in close connection towards the end of the Cretaceous when the thick lagoonal and fluviatile continental sandstones of Garua were accumulated. At the beginning of the Tertiary Period the connection between the Logone and the Kabia no longer existed. During the early Pleistocene Period, however, when the Chad deposits accumulated in a large basin, the Middle and Upper Benue, Faro and Upper Gongola Rivers are believed to have drained towards this basin. Afterwards, when the present patterns of the Benue and of the Nigerian Niger became established, the River Logone still was supplied with water from the Kabia River by way of Lake Fianga. These rivers deposited the Kelo Sand formation which in this area forms the top of a lateral facies of the Chad Formation. The Kelo Sands contain at least one laterite intercalation and they are capped by a laterite dissected by later erosional phases, thus attesting to at least two pluvial phases during this period.

In some period after the Kelo Sands were capped by a laterite and again dissected, the Mayo Kebi captured the Logone River which from then on belonged to the Benue drainage system. Gravel from the Logone River system washed into the Kebi Valley, filling its upper reaches as far downstream as Lake Tréné. The upper part of the gravel is cemented by a lateritic iron crust. Because of these lateritic crusts a correlation is put forward here of the laterised gravel deposits with the second humid period as mentioned by URVOY ([1] from the Soudanese Niger area and with the laterised 220—250 m (730—840 feet) erosion surface in the Benue Valley east of Yola. The laterite capping the Kelo Sand Formation could perhaps be correlated with the first humid period by Urvoy. The connection of the Logone with the Mayo Kebi, and thus with the Benue, would coincide according to these views with the first stages of the second phase of upheaval and the 45 and 90 m (150 and 300 feet) terraces of the Niger Valley near Onitsha and the 95 to 105 m (310 to 350 feet) terraces of the Niger Valley between Jebba and Awuru, to be placed chronologically either in the Kamasian/Kanjerian interpluvial or the Kanjerian pluvial.

Later on during the Quaternary Period upheaval took place in the catchment area of the Mayo Kebi, probably accompanied by some subsidence in the Chad area. The tectonic movements, contemporaneous possibly with the last tectonic movements registered in the Benue Valley near Yola, disconnected the Logone and the Benue drainage systems, and the Logone from then on once again formed part of the catchment area of Lake Chad. Most probably also faults and flexures in the Mayo Loué and Mayo Kebi area and south-east of Garua, as well as the Gauthiot Falls in the River Kebi, date from this period. Their origin may be attributed to the same tectonic movements.

Subsequent to the tectonic movements which caused the River Logone to drain again towards the Chad Basin, the Niger and Benue and the Lower Mayo Kebi eroded their river-beds to a level well below that of the modern rivers, as has been mentioned earlier in this paragraph. Also in the Lower Mayo Kebi near Cossi a valley-fill of more than 40 m or 130 feet has been found underneath the present river-bed. During this period, chronologically dated here as belonging to the Gamblian on account of the synchronous low sea-level (90 or 300 feet below the modern sea-level), the higher rainfall must have caused regular and extensive inundations in the Logone drainage area. It seems justified, therefore, to attribute the deposition of at least part of the "Berbéré-clays" with their limy nodules, found to cover large areas in the Logone

([1] URVOY, 1942. GEO. 47

Basin and Upper Mayo Kebi Basin around Toubouri Lake and near Tikem ([1], to this period. Should this be correct, it has to be assumed that from the Gamblian pluvial onwards the River Logone, although belonging to the Chad catchment area, during high floods already tended to inundate the watershed dividing it from the River Kabia drainage area. The French studies of the Logone Basin have indicated, however, the improbability of the Logone becoming captured again by the Mayo Kebi.

d. *The Upper Niger in the French Soudan*

The following consists mainly of a summary of the monograph on the Soudanese Niger Basin, written by URVOY ([2], completed by a few data from other sources.

At the end of the Tertiary Period, as a result of the tilting of large areas, subsidence of some and upheaval of other regions (for instance, upheaval along an axis directed from the Aïr Massif to Kano, more or less in continuation of the Zinder Yola axis), the Upper Soudanese Niger (including the Bamako area and the Ségou Basin) drained towards the Gulf of Sénégal by way of the Sénégal River (see Diagram 3.1.1-2). During the same period lacustrine deposits were formed in the Araouane Basin, which is an internal drainage area like the Chad Basin, to which it may be compared, also regarding the period of formation. The ancient Tilemsi River, to which at that time the Wadis Tamanrasset and In Ouzzal ([3] still belonged, was probably part of the drainage area of this basin. During the second phase of upheaval, which made itself felt in Northern Nigeria possibly during the Kamasian/Kanjerian interpluvial (S 1 phase of Urvoy) the drainage pattern underwent considerable modifications also in the Soudan region. Either because of the forming of a barrier by sand dunes (the Erg du Ouagadou) or as the result of some slight crustal warping of the Ségou Basin area, the connection between the Upper Niger and the Senegal was severed, the Upper Niger becoming part of the Araouane Basin. Similar movements might also be the explanation of the capture of the Upper Black Volta near Dedougou, which appears to have flown formerly through the Gondo Plain towards the paleo Niger drainage area (nowadays Nigeria), but which now suddenly turns southward to join the modern Volta River system. There possibly exists a relation between these movements and the western axis of upheaval near Ilorin, mentioned in Paragraph 3.1.1. Movements along another NNW-SSE directed axis divided the drainage area of the Tilemsi into two separate parts, as has already been mentioned, its northern part draining from then on towards the Tanezrouft Basin and its southern part towards the Niger. It is of much more direct interest for this study, however, that the Lower (or Nigerian) Niger River system became definitely established at this time. Its Saharian affluents like the Azaouak River System and the Lower Tilemsi join the main river which has cut a valley through the Bajibo gap. It is suggested that the volcanism of the Aïr and the extensive basalt flows of the Hoggar ([4] took place in this period, thus belonging to the Upper Black Volcanic series of GÈZE.

The period S 2 of Urvoy (the Kanjerian/Gamblian interpluvial) saw a partial drying out of Lake Araouane and a considerable extension of the ergs (sand dune deserts) lying to the north of the Ségou Basin. A partial degradation of the drainage system occurred in the Soudan.

During a humid recurrence (H 3 period of Urvoy, most probably the Gamblian Pluvial) the drainage pattern again underwent a considerable modification. The Soudanese Upper Niger filled the Ségou Lakes and the Timbuctu Lakes, as well as the Lakes Aklé and Araouane. Finally

([1] BETREMIEUX, 1949. GEO. 3
([2] URVOY, 1942. GEO. 47
([3] KARPOFF, 1953. GEO. 24
([4] BUEDEL, 1955. GEO. 5

it overflowed the threshold of Tosay, eroding a gap into the underlying Cambrian rocks. Timbuctu Lake emptied through this gap into the Nigerian Niger. From this time on only the Soudanese Niger formed the headwaters of the Nigerian Niger. Lake Araouane and Lake Aklé having lost their supply gradually dried out, but in the Timbuctu area near Goundam extensive marshes and temporary lakes are still found up to this very day.

In the modern, relatively dry period partial degradation of the Soudanese drainage system and an entire degradation of the Saharian drainage pattern are again observed.

e. *The Lower Niger and Benue*

The Niger and Benue Valleys show marked differences within the Nigerian territory. The Niger flows alternatively through wide valleys with extensive flood-plains, bordered by scarps and sedimentary plateaux capped with laterite, and through narrow rocky sections eroded in the Basement Complex, with numerous rapids upstream of Jebba. In contrast to this, the Benue Valley is generally extremely wide, with large flood-plains and marshlands, and is bordered on both sides by escarpments. The Benue River has no rapids or falls, owing to the fact that it flows for the greater part on top of sedimentary deposits. Moreover, borings have proved a valley-fill exceeding 40 m or 130 feet in thickness below the recent river-bed. In this respect it is comparable to the Lower Niger downstream of the Benue Confluence, where also a considerable valley-fill has been proved.

It has already been explained how a deeply entrenched valley was eroded by the Benue and by the Lower Niger during the Gamblian Pluvial in response to a lowering sea-level. The entrenched valley cuts through sedimentary deposits as well as Basement Rocks and across axes of elevation of the subsoil. This does not seem to have occurred to the same extent in the Niger Valley upstream of Jebba. Between Jebba and Yelwa this valley shows a considerable steepening, with many rapids, for instance near Awuru. Possibly the eroding power of this part of the Niger with its irregular supply from the Saharian Valleys was less and not sufficient to cut a similar entrenched valley in that area.

When at the end of the Gamblian Pluvial the sea-level rose again, eventually attaining a level of 2 to 4 m (6 to 13 feet) above the modern sea-level, the Lower Niger and the Benue in response filled their valleys in upstream sense in order to attain a new equilibrium of their gradients. An analysis of the longitudinal sections of the Lower Niger and of the Benue Rivers shows that Jebba actually lies lower than might be expected from the theories on the longitudinal section of the main river (see 2.5). It seems as though the filling up of the valleys in response to the rising sea-level in the Lower Niger and Benue Valleys occurred rapidly while it was retarded in the Niger Valley upstream of Lokoja. This feature may have found its origin, then, in the fact that the sediment supply by the Saharian valleys was completely stopped during the period of an arid climate, while the other affluents like the River Sokoto and the River Kaduna provided a diminished supply only. Should this be the case, it may be assumed that if ever rapids were formed in the Rocky Section downstream of Lokoja, a supply of (Benue?) sediments sufficient to bury them under a thick cover of sand was provided after the rising of the sea to its actual level, whereas the rapids in the river-section between Jebba and Yelwa still subsist to our days.

f. *Conclusions*

It appears from the geological and morphological history of Nigeria, as described in the aforegoing pages, that although it is part of the African Shield, the area from the Cretaceous Period onward has shown less stability than might be expected from a continental shield area. A mountain building comparable to the Alps, for instance, did not take place, although nevertheless vertical tectonic movements of at least 600 m or 2,000 feet must have taken place in order

to elevate the Jos Plateau to an altitude of 1,200 m or 4,000 feet. The tectonic movements consisted of faulting, the formation of horsts and grabens, combined with updoming and downwarping and some occasional folding. They were accompanied by volcanic outbursts. The movements which started at the end of the Eocene Period, and which continued with a few interruptions until the Pleistocene Period, have been of the utmost importance for the modern morphology of Nigeria. Apart from these tectonic movements, Northern Nigeria, lying in the periphery of a desert, has been subjected to climatic variations, and furthermore the base-level of its rivers has been modified several times as a result of the eustatic variations of the sea-level and of epeirogenetical movements of large parts of the African Continent. These are important factors governing the course of the rivers, the evolutionary stage of their valleys with alternating periods of erosion and filling up, the enlargement or reduction of their catchment areas, and so on.

In the preceding pages and in the tentative Chronological Table it has been shown that the Benue and the Nigerian Niger upstream as far as Bajibo belong to a single drainage system from the early Pleistocene onward. The Upper or Soudanese Niger, upstream from the Interior Delta, has had an entirely different evolution. It was captured by the Lower Niger at Tosay only during the late Pleistocene. The area elevation curves of the Niger Basin, as shown on Diagram 2.1.2-2, are in good accordance with these conclusions. This diagram has been prepared for the Benue Basin as far as the confluence of the Niger and Benue, for a part of the Niger between Jebba and Lokoja, and for the Niger Basin from the source to Koulikoro, which is situated at the apex of the old Interior Delta (of the Upper or Soudanese Niger). The difference between the Benue and the Lower Niger on the one side and the Upper Niger or Soudanese Niger on the other is very apparent, and may readily be explained by the fact that in reality the Lower Niger and the Benue belong to one single drainage system, with the ocean as a base-level, while the Soudanese Niger originally formed a separate unit, graded to a high-lying base-level, formed by an endoreic basin (a basin of internal drainage). The connection between the two Niger river systems, which only came into being in geologically very recent times, is more or less of an incidental nature, and not genetically related to the origin of either of the two river systems.

Within the drainage system of the Nigerian Niger and the Benue differences also occur between the two branches, as has already been stated. The explanation can be found in the geological history, which shows different trends in the separate areas, the Benue flowing through a major graben area where sedimentation started in the Cretaceous, while the Niger crosses sedimentary basins as well as structures formed by rocks of the Basement Complex. Moreover, the evolutionary history of the Niger Valley and of the Benue Valley did not undergo the same influence of climatic variations which occurred during the Quaternary Period. The geographical position of the Niger drainage area makes it more sensitive to climatic fluctuations than the Benue drainage area. In the past the flow of the Benue most certainly must have varied, not only because the Logone belonged temporarily to its drainage area, but also during more humid periods rainfall in its catchment area was more abundant. As for the Niger, a very large part of its northern drainage area belongs not only to the Savana, but even to the desert proper. The Saharian part of the drainage area, bordered by the Adrar des Ifoghas, the Ahaggar and the Aïr, nowadays contributes at the best an insignificant quantity of groundwater to the Niger. No surface run-off is possible under the present arid conditions. During humid or even pluvial periods in the past, however, the rainfall in its desert catchment area exceeding a certain limit caused a surface run-off to become possible. At that time floods swept more or less frequently through the now dry valleys and they supplied the River Niger with water and sediments. During relatively dry periods, such as the one now being lived in, the desert valleys degraded and conse-

quently the sediment supply to the main river diminished considerably. These factors may have contributed to the present condition of the rivers.

g. *Application on hydrology*

The purpose of this study being a practical one pertaining to the shipping possibilities, and not necessarily a scientific one, it would be useful if conclusions on the present and future behaviour of the rivers could be drawn from the geological and morphological features described and the evolution of the drainage area as reconstructed here. Most important would be to determine whether the rivers are in equilibrium, or whether they are in certain sections either in an erosional or in an aggradational stage. In view of the very marked seasonal variations of the rivers and of the complicated and only partly-clarified history of the main drainage systems, it is difficult to indicate whether erosion or sedimentation is taking place in the river-beds; but for the foreseeable future it may be assumed that the morphological type of the main rivers will not naturally be changed.

The longitudinal profiles of the rivers (see Section 2,5) have been analysed and compared with the outcome of the geological history of the area. The average slopes and gradients of the Benue and of the Lower Niger show several irregularities, and a clear picture of the origin and influence of these irregularities on the future development of the river-beds has not yet been obtained. For instance, it is not yet certain if and to what extent the gradients of the river have been influenced by the crossing of the ancient axes of upheaval of the subsoil (in the Abinsi-Makurdi area and in the Rocky Section downstream of Lokoja).

The influence of relatively small-scale sea-level variations, of a few metres only, on coastal areas where active sedimentation and erosion processes are going on, such as in deltaic regions, and their effect on the equilibrium profiles of rivers, is still subject to discussion. This is the case, for instance, with the sea-level of 2 to 4 m (6 to 13 feet) above datum-level which appears to have occurred about 5,000 years ago (as discussed by LEBLANC and BERNARD (1). A tentative explanation of the influences of sea-level variations on the Niger Delta has been given in 2.4.2.

Calculations about conditions during the past and for the future based on present sediment transport have to be used carefully. The analysis of data of the River Mississippi which has been studied for many years and in much detail (thousands of borings being available) shows that sedimentation on its delta proceeded at an average rate of about 0.8 milliard cubic metres (0.19 cubic mile) per year during the early phase of a rising sea-level after the deeply-entrenched valley had been formed. It decreased to an average of 0.32 milliard cubic metres (0.07 cubic mile) per year about 10,000 years ago; and the rate of sedimentation in the present-day birdfoot delta is but 0.28 milliard cubic metres (0.068 cubic mile) per year (FISK and MCFARLAN (2). The same authors are of the opinion that the Mississippi River did not suffer major variations in discharges.

It is probable, however, that in the case of the Niger and Benue Rivers not only the slopes of the rivers, but also their discharge, underwent considerable modifications in response to sea-level variations and alternations of humid and dry climatic phases, which will not have been without influence on the sediment transport. In Paragraph 2.4.2, a tentative calculation has been given applied on the Niger Delta morphology and based upon approximated values. However, the equilibrium conditions might have altered somewhat during historical times because of a large-scale deforestation and soil degradation, leading to a less regular run-off and an accelerated erosion of the drainage areas, and therefore an irregular flow of the rivers combined

(1 LEBLANG & BERNARD, 1954. GEO. 26
(2 FISK & MCFARLAN, 1955. GEO. 18

with a large transport of sediments. At present the amount of sediments carried down by the Lower Niger is in the order of 0.02 milliard cubic metres (0.005 cubic mile) per year.

3.2. ROCK AND SOIL TYPES

3.2.1. Rocks and soils in Nigeria

A simplified geological map of Nigeria has been prepared in Diagram 3.2.1-1 showing the sites where various rocks and minerals have been found, and indicating the areas where Basement Rocks outcrop and where sedimentary formations occur. In most areas along the Niger and Benue sedimentary formations are found, mainly sandstones with shales and clay beds. They contain a few beds of limestone, as well as in some regions layers of coal or lignite. In the actual river valleys alluvial sand and clay deposits occur.

Between Yelwa and Jebba the River Niger has cut its bed through the sedimentary beds into the underlying rocks of the Basement Complex, consisting of granites, gneisses, schists and quartzites. Other Basement Rocks occur to the south-west of the Niger Valley, to the north of the Niger and Benue Rivers, as well as to the south of the Benue Valley in the area of the Cameroon Mountains. Moreover, in the Central Plateau area in Northern Nigeria the so-called "Younger-Granites" are found, which are of a considerable economic interest because of their mineralisation.

In several areas of the Benue Basin, for instance in the Lower Gongola area, there are volcanic rocks, varying in age from the Cretaceous Period to the Recent Period. They consist of plateau basalts, of small volcanoes formed of basalts and sometimes also of rhyolites.

In the southern part of Nigeria and on the more ancient surfaces in Northern Nigeria a red lateritic soil has been formed, often with ferruginous crusts and ironstones. The crusts and ironstones form the cap of many of the sedimentary plateaux which border the valleys of the Niger and Benue Rivers. Characteristic examples are found near Baro, Lokoja, Idah and Onitsha along the Niger and between Abinsi and Ibi along the Benue.

The distribution of the main types of rocks as sketched above is of great importance, especially for the provision of natural building materials and for the occurrence of mineral deposits. The sedimentary formations do not normally contain suitable rock for building purposes, with the exception of some limestone bands and of the lateritic ironstones, the latter being a building material of rather poor quality, although it is extensively applied for road-making. On the other hand, many of the volcanic rocks and the Basement Rocks form building stones of good to excellent quality.

The most important deposits within the sedimentary formations consist of coal, lignite and oil. Limestones, although scarce, are of importance for the manufacture of cement. Mention should also be made of the phosphates found to the north of Lagos and of the deposits of diatomaceous earth occurring in Bornu. Ore deposits are of less importance, and consist mainly of lateritic iron ores. Bauxite, although found in considerable quantities in other parts of Africa, does not occur in Nigeria as far as is known. Mention should also be made of alluvial deposits rich in tinstone, columbite, gold and monazite, although it would be better to classify them with the primary ores of the Basement Rocks from which they have been derived. The lead-zinc ores found by substitution in limestone beds are only of little importance.

The Basement Complex also contains several important mineral components, the Younger Granites particularly being outstanding in this respect. Among others the following minerals have been found: cassiterite, columbite-tantalite, thorite, monazite, xenotime, allanite, fluorite, zircon, ilmenite, topaz, beryl, wolfram, pyrochlore, cryolite, thomsenolite and fergusonite. Not

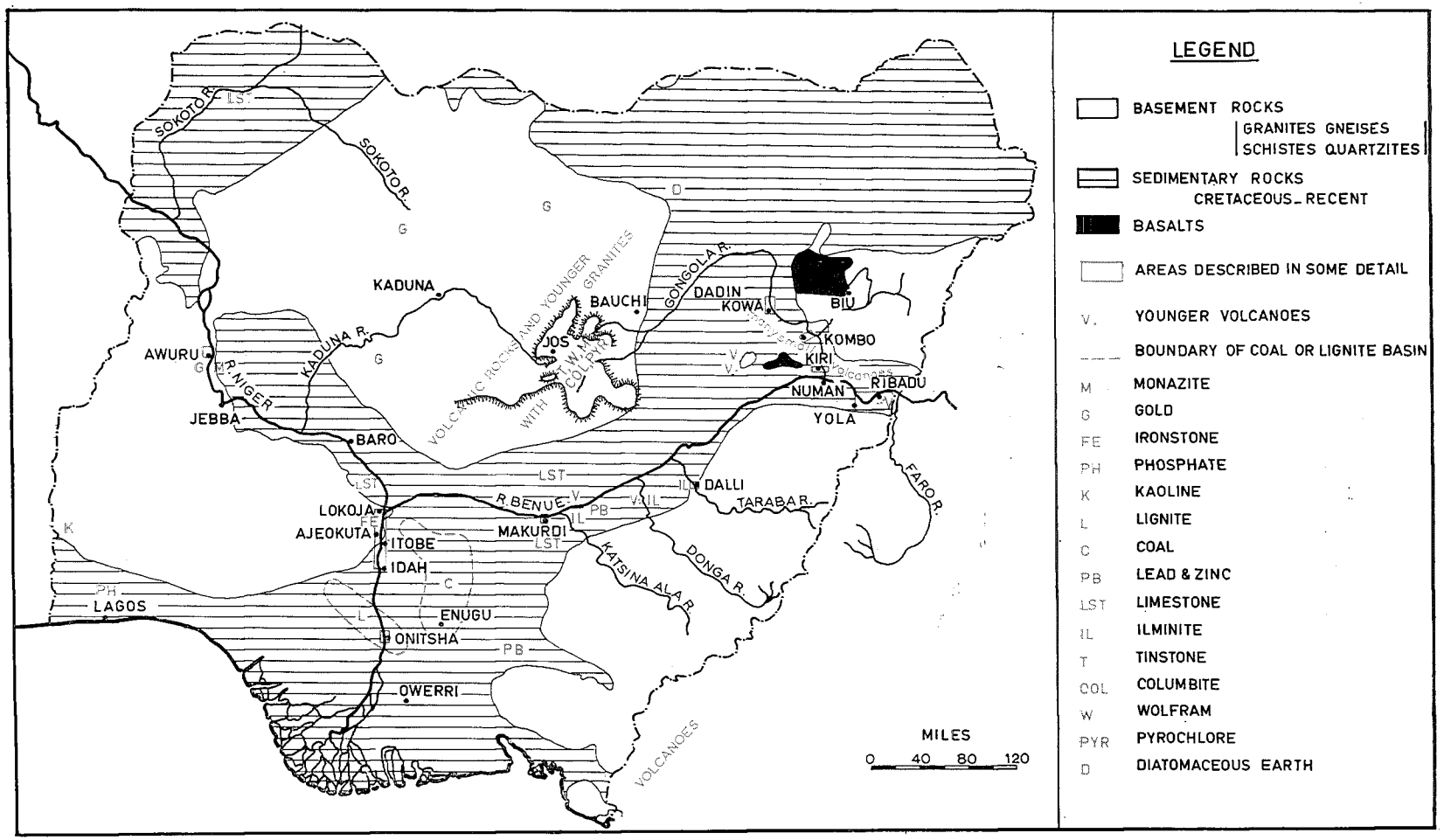


DIAGRAM 3.2.1-1

Simplified geological map of Nigeria

all of these minerals, however, have yet been found in concentrations which are of economic interest. Pegmatite veins with cassiterite and columbite have been observed in other parts of the Basement Complex. In contrast to the tinstone-bearing Younger Granites, the cassiterite mineralisation of the pegmatites is associated with tourmaline. The older Granites and schists contain also gold, ilmenite, rutile, monazite and talc. Kaoline deposits have been found near the Dahomey boundary; these are in part of a sedimentary origin and in part originated from weathered gneisses. Talc schists occur in western Kabba Province, but as far as is known the industrial quality has not yet been investigated.

Only a brief outline of mineral findings can be given here. Much exploration is being done and new findings are being regularly reported. The development of the country brings along the exploitation of an increasing number and quantity of these minerals. This feature will be briefly discussed in Section 3.3.

Ground-water is of considerable economic importance in Northern Nigeria and the Geological Survey Department of Nigeria pays much attention to ground-water investigations. As will be mentioned in Paragraph 3.4.3 sub *d*, the studies of the NEDECO Mission have led to the finding of a considerable ground-water occurrence east of Yola.

The morphological and geological features of the country already described are also of considerable importance from an agricultural point of view. The possibilities of using the land for farming or for pasture depend on such various features as relief, climate, soil types, drainage, availability of water during the dry season, and diseases of man and cattle. The details of the relief, especially near stream channels, are the result of erosion and sedimentation in recent geological times when conditions have sometimes been drier than at present and at other times more humid, as has been mentioned in an earlier paragraph. The soils on the plains are commonly derived from materials which accumulated during late Tertiary and Recent times. Man's activity at present is accelerating the geological processes of erosion and sedimentation in most areas.

Laterite soils predominate over a very large part of Nigeria. They consist partly of fossil lateritic soils with ironstone hardpans. In the hilly Basement Complex area in the Western Region, moreover, eluvial mottled clay soils occur. In Kano and Damaturu sandy desert soils cover huge areas. These soils also reflect in their features the influence of climatic changes during the Pleistocene ([1, ([2.

3.2.2. Rocks and soils along the Niger and Benue

When describing the soil conditions in the Niger and Benue Valleys, it will be necessary to indicate the areas included in these valleys. The Niger Valley, upstream of the Benue Confluence as well as from Lokoja downstream to Aboh, lies in between plateaux and hilly areas, such as for instance the Nassarawa Tableland, the Kabba and Ilorin hilly country and the plateaux and ridges of the Enugu-Owerri area. Generally bordered by escarpments, the valley consists of the flood-plains along the river-bed and some fluviatile terraces situated at various altitudes above river-level. The Benue Valley, on the other hand, is considered to cover the entire trough situated between the Jos Plateau in the north and the Cameroon Mountains in the south. This wide area includes not only the flood-plains along the Benue River, but also river terraces and plains situated at varying altitudes along the main river and several of its tributaries. In accordance with this geographical definition, the area covered by the Benue Valley is much larger than the area of the Niger Valley, and more will be said about the former than about the latter.

The River Niger between Jebba and Lokoja and also from Idah downstream is bordered

([1 VINE, 1949. GEO. 49
([2 MOHR and VAN BAREN, 1954. GEO. 30

by flood-plains and low-lying river terraces covered with soils of a varying nature and fertility. Some of the soils must be considered fossil, reflecting past climatic conditions, but others are still being formed at the present time. This, and the different geological conditions observed in several parts of the valley, explains the variety of soils found. In view of the inconvenience of regular flooding and the relatively reduced width of the valley, these soils do not play an important role in the country's economy, and the farmed areas are mainly situated in the hills and on the plateau. More detailed studies will be needed to determine the potential value of the area lying within the boundaries of the valley.

The soils of the Benue Valley are most variable in character as they have been derived from a great variety of parent materials, and their drainage conditions and age are very diverse. There are fertile soils, some of them derived from young volcanic rocks and from alluvium, but wide areas are underlaid by rock or ironstone at a shallow depth and will never make good farmland. On the whole the soils are unattractive, except over rather restricted areas, not all of which are cultivated at present. Soil deterioration is apparent in several areas.

In the higher parts of the plains red and brown shallow and pebbly soils are commonly found, which are rather compact and do not appear to be very productive. There are more fertile soils on the alluvium near the river, for instance the black clayey soils in the low-lying parts of Numan Division. Several of these areas, which in other respects have agricultural possibilities, are too swampy to provide good settlement sites and remain uncultivated.

The plains lying between the swamps alongside the Benue and the foot of the escarpment bordering the Jos Plateau to the north have an underground of variable and folded rocks and show a complicated arrangement of soils. The area is thinly populated because of lack of water in the dry season and the prevalence of diseases. Fadamas, grassy swamps and low-lying flood plains are well developed along the rivers draining the Jos Plateau. Trees occur on the alluvial banks and natural levees along the river channels, and the levees are often inhabited and farmed. The flood-water takes its course by way of low saddles in the banks over the lower lying adjacent fadama. In the fadamas, flooded for long periods during the rains, trees are unable to survive, but conditions are in many ways ideal for rice-growing. At times, no doubt, flooding of the fadamas is primarily the outcome of local run-off from adjacent slopes which cannot drain into the rivers because of the presence of natural levees, rather than a result of river flooding.

Similar conditions occur to the south of the Benue. Fadama areas, suitable for rice-growing, are found along the Lower Taraba, the Katsina Ala and the Donga Rivers.

The wide flood-plain of the Benue is dissected by a maze of channels in the same way as the Niger Valley flood-plains. Between them the micro-relief is very complicated, with sandy banks, which emerge above normal floods, alternating with swampy hollows. Black soils, rich in humus, which yield good crops of rice have been found. The main areas of fadama alongside the Benue lie between Numan and Ibi. Downstream of Ibi there is a good deal of freshwater swamp forest and in many places the banks are high. Volcanic hills occur near the river in some places. Elsewhere sandstone cliffs are found, for instance, opposite the mouth of the Katsina Ala and near Makurdi.

In the Gongola Valley conditions differ widely from those observed in the Benue Valley. South of Nafada, the Gongola Valley is about 30 miles wide, and it is crossed by anticlines and synclines. Shales underlie a large part of the valley floor on the left bank of the river, and Bima sandstones build ridges and escarpments in the south. The soils in the valley are valuable, with well-drained red sandy soils derived from the sandstones, and heavy clay soils liable to become swampy over the shales. Below Bima Hill, on the left bank, there is a wide fertile area, while on the right bank, 2 miles down-stream of Dadin Kowa, alluvial deposits rise to 30—50 feet above the river. The fertile area, about 20 miles wide and extending for about 50 miles along the river, forms one of the most productive regions of the Benue Valley.

The Gongola flows across the strike of the folds and across an outcrop of Basement Complex. Black Cotton Soils have been derived locally from the Lamja Shales in the synclines, and there are quite good soils derived from the Gombe sandstones. The shale areas are swampy during the rains and the majority of the villages seems to be situated on the margins of the sandstone outcrops, where sites are well-drained, springs and seepages close at hand, and the heavier soils within easy reach.

In Numan Division the lowlands of the Gongola Valley show a variety of soils, the most fertile of which appear to be sandy alluvial soils standing above flood-level and the Black Cotton Soils derived in some cases from volcanic material and in others from weathering of limestone and shale.

Most of the information on the soils of the Benue Valley and its tributaries has been taken from a report by A. T. GROVE ([1 where the possibilities of development of the Benue Valley are discussed, taking into account its physical geography.

3.3. EXPLOITATION POSSIBILITIES

In this Section brief mention will be made of the main exploitation possibilities of minerals, rocks and soils, as far as these possibilities bear upon shipping and energy where Niger or Benue water is involved. Building materials, at the same time, may serve to harness the rivers. Places where minerals are found are indicated on Diagram 3.2.1-1.

3.3.1. Ores and Minerals

a. *Ores*

The importance of the various ores for the Nigerian economy appears from a few production figures. For the year 1955, for instance, the following figures have been quoted ([2:

tinstone (concentrates)	11,254 longtons (about constant)
columbite (ore)	3,146 longtons (still increasing)
tantalite	16 longtons
wolfram	3 longtons
lead (ore)	16 longtons
gold	881 troy ozs.

None of these ores, or their derivates, is to any appreciable extent transported by river, though the development of the mining area influences river transport to a slight degree.

The Jos Plateau forms the principal mining area of Nigeria. Tinstone and columbite are the chief ores, tin mining having been in operation for several decades. Wolfram and tantalite are of less importance, but radio-active minerals like cryolithe and pyrochlore, rare earth and other minerals may perhaps become exploitable in the future.

There is considerable exploration activity by both the Geological Survey Department and private firms in the area. In view of the price and quantity of the ores, transportation is effected by road and by rail. The mining activity in the Jos Plateau area, however, also involves the transportation of large quantities of goods and liquid fuel to the mining district. Moreover, the mining activity and the concentration of several of the ores leads to an important consumption of electric energy.

([1 GROVE, 1956. GEN. 14
([2 La Chronique des mines d'Outremer et de la recherche minière.

Some tinstone has also been found and exploited in pegmatite veins in the older granites in other parts of Nigeria, but no development of any importance is to be expected in this field.

The lead-zinc ores are of little importance only, although the lead-ores are silver-bearing. They are mostly exploited by local inhabitants and are used for cosmetics. The exploitation possibilities of most of these restricted ore occurrences, which lie near Ameka, Nyeba and Abakaliki (east of Enugu), east of Akwana (to the east of Makurdi) and near Zurak to the north of the Benue, do not appear to be very promising. For a short period mines have been operated at Zurak and Nyeba and exploration has been resumed recently at Ameri, Abakaliki Division, where it has been possible to revise favourably the estimate of reserves.

Ironstone is widespread in Nigeria, capping many hills and plateaux. Large deposits of oolitic ironstones have been found on the Agbaja Plateau, the Koton Karifi Hills, the plateau in the western part of Igala Division of Kabba Province and Mt. Patti, all situated around the Niger-Benue Confluence. Investigations on the Agbaja Plateau have proved the existence of the following reserves:

ore averaging 50% iron	186,000,000 longtons
ore averaging 47½% iron or more	273,000,000 longtons
ore averaging 45% iron or more	383,000,000 longtons

There is considerable variation in iron content, and it would probably be impossible to mine the 50% ore selectively. It is therefore doubtful whether this deposit is of economic value unless the bulk of the ore could be cheaply handled and worked. At any rate, for the time being the iron ore is not yet economically exploitable, the transportation costs of the ores to the industrial centres abroad being too high compared with ores produced elsewhere. If the future mining of the ironstone would become economically justified, it would considerably affect shipping on the Niger River, because of the geographical location of the ore deposits.

Other ironstone deposits, totalling about 60 million tons with an average iron content of 31.9%, have been found to the west of Enugu. They are not economically exploitable.

Mention must be made of the occurrence of gold and monazite in the alluvial deposits of the Niger River upstream of Jebba, where gold has been found between Awuru and Yankade Island and monazite between Jebba and the River Oli. The investigations carried out so far (1 are not sufficient to determine whether the deposits are economically exploitable. Further investigations should be carried out, however, in connection with any proposed reservoir dam in this area, as the construction of a dam might considerably alter the exploitation conditions of the gold and monazite deposits.

b. *Coal and lignite*

Coal has been found in several places and lignite beds are widespread in Nigeria. The coal seams near Enugu have been under exploitation for a number of years. The exploitable seams stretch north-eastward until beyond Orukpa. Annual production figures amount to some 800,000 tons.

The coal reserves indicated are as follows:

Enugu (Onitsha Province)	38,000,000 tons
Ezimo (Onitsha Province)	25,000,000 tons
Orukpa (Benue Province)	41,000,000 tons
Okaba (Kabba Province)	65,000,000 tons
Odokpono and Ogboyoga (Kabba Province)	75,000,000 tons

In the Onitsha-Asaba area the lignite beds are of sufficient size to warrant exploitation both

(1 JOYCE, 1951. GEO. 23

to the east and to the west of the River Niger. Elsewhere, for instance, in the Benue and Gongola areas where lignite beds have been observed, they are not exploitable, and little hope exists that beds of economic value could be found in those areas. A thorough study has been made by the Geological Survey Department of the occurrence of coal and lignite in Nigeria and the results have been published in several of its bulletins.

c. *Crude oil*

The oil-wells, under casual exploitation since 1957, are situated in the Delta area. Full-scale development has not yet been undertaken, the reserves being still uncertain. Promising results have been obtained, however, at a number of locations. Although gas has been found in the Onitsha area and in the Enugu area, conditions do not seem to be very favourable for the occurrence of exploitable oil-bearing beds in the sedimentary basins situated along the middle course of the River Niger and in the Benue area. It is too early yet to judge about the possibilities in the Sokoto Basin and the adjoining Soudanese Niger Basin. Transportation of crude oil is not expected to take place along the Benue and Niger Rivers.

d. *Limestone for cement manufacture*

Three projects for the exploitation of limestones for cement manufacture are under discussion: near Jakura to the north-west of Lokoja, in the Sokoto area and near Makurdi. Only the sites near Jakura and Makurdi are situated near the main rivers, where shipping facilities for fuel and for the finished products are available. A cement plant is operating at Nkalaku, Abakaliki Division, while still other limestone occurrences are being investigated by the Geological Survey Department, but because of their geographical location they have been left out of this Report and its accompanying map.

e. *Diatomaceous earth*

The exploitation possibilities of the considerable deposits of diatomaceous earth known to exist in the western and south-western parts of Bornu Province and in the north of Bauchi Province will depend largely on the transportation costs.

f. *Kaoline, phosphate and other deposits*

The deposits of kaoline (found near the Dahomey boundary), phosphate occurring north of Lagos, and other minerals which occur at a far distance from the main rivers, are not taken into consideration in this account.

Summarising, bulk transport resulting from mineral exploitation under present conditions is negligible, but if all-the-year-round river transport becomes a reality, chances for transportation of iron ore, cement and fuel will be increasing. Chances for water power for exploitation purposes, however, are considered to be very moderate. Prospects for gold-winning in the Niger Valley upstream of Jebba will probably be brighter after the construction of a reservoir when exploitation by dredging would become possible.

3.3.2. Building materials

The fact that natural building materials of first quality are absent in a great part of Nigeria, including along the lower course of the River Niger, produces big problems. Rock and stone (for construction purposes and concrete manufacture) and gravel (for making concrete) in

particular are very scarce. For this reason much use is being made of the only widespread natural "stone": laterite and ironstone. Selected laterite and ironstone are used not only for road-building and similar purposes, but even as a building stone and as mix for the manufacture of low-grade concrete. These materials are unsuitable, however, for making high-grade concrete or for constructing quay walls, jetties, groynes, dams, breakwaters or similar installations.

The need has arisen, therefore, to ascertain whether rock and gravel of good quality are found along or near the Niger Valley and, if this would be the case, whether their exploitation would be warranted.

A preliminary reconnaissance has been executed of the so-called "Rocky Section" between Idah and Lokoja, where the Niger River breaks through the Basement Complex and where consequently solid rock reaches the river. Before opening quarries, however, it seems advisable to have more detailed investigations carried out in promising places, to study both the quality and the quantity of the occurrence and the requirements so that an estimate can be given of the possibilities for exploitation at a fair price per ton. It should be emphasized that the size of the quarries to be opened is entirely dependent upon the needs.

The texture of the rock and the presence and spacing of cracks, fractures, sets and systems of cleavage and joints will determine the way in which the quarry has to be worked. Furthermore, it should be kept in mind that the effects of variation in quality of the rock, the thickness of overburden and the depth of the weathering processes work out differently upon the budget (the operative costs) of a large or small quarry.

A brief reconnaissance has indicated that a number of areas appear suitable for the exploitation of sound rock, but more detailed information should be obtained to ascertain the most suitable sites to be developed with regard to the requirements.

An account of the exploration made in this Rocky Section will be given in Paragraph 3.4.3.

Between Jebba and Yelwa the River Niger has also cut its bed through the sedimentary beds into the underlying rocks of the Basement Complex, and suitable rock might be expected to exist along this part of the river. Mention should be made in this respect of the granite migmatites quarried by the Nigerian Railways for ballast 2 miles north of Gana (to the north-west of Jebba (1).

Along the Benue conditions are less favourable. With the exception of a few small outcrops of basalts situated from Makurdi onward upstream until beyond Yola, the entire wide valley is bordered and underlain by sedimentary deposits without hard rocks. To the north of the Benue River granite of a good quality is found in the Nassarawa and Akwanga areas, but quarries situated in the western part of these areas would have to be connected by road with Loko. Transportation from the eastern part of the granite outcrops towards the Benue could probably take place by canoe along a small tributary river.

Sand occurs everywhere along the main rivers in very considerable quantities, and therefore is available in abundance for all purposes. This is not the case, however, with gravel, which has been observed only in minor quantities mixed with the sand deposits in the Benue Valley and in the Lower Niger Valley. Locally the gravel has been concentrated in the river channels at place where the current is strongest. In these places dredging of relatively small amounts of gravel is possible. Some gravel has been found also near Patani in the Delta area of the Niger, even in exploitable quantity. Other gravel occurrences exist along the river terraces in the Rocky

(1 JOYCE, 1951. GEO. 23

Section downstream of Lokoja. Over most of the Benue drainage area the prevailing conditions seem to preclude the presence of large amounts of gravel in the main river and in the lower courses of its tributaries. Large quantities of gravel of good quality might be expected to occur, however, in the upper reaches of the northern tributaries in the Nassarawa and Akwanga areas and of the southern tributaries draining the Cameroon Mountain area. In the Niger Valley gravel is found in large quantities between Jebba and Yelwa, especially towards Awuru and Yelwa. Apart from the river-beds and river terraces proper some gravel is also exploited from the basal sandy clay-grit and conglomeratic beds of the Cretaceous sedimentary formations, for instance on the lower slopes of Mount Patti near Lokoja.

In several areas of Nigeria and in the Southern Cameroons building stones and aggregate of good quality have been found by the geologists of the Geological Survey Department. But detailed mention of them need not to be made here as they are located at great distances from the main navigable rivers.

Summarising, it appears that the exploitation and transportation of building materials could benefit by the presence of the river and especially if quarrying would start along the river; for instance, between Lokoja and Idah chances are considered favourable. Up to now, transportation of building materials has been limited to some insignificant dredging and the haulage of sand and gravel.

3,4. VALLEY NARROWINGS

Whereas Sections 3.1 sets out the general morphological pattern in which the rivers had to take their course, the present Section will deal with some peculiarities of this pattern, viz., the places where geological conditions caused some constriction in the natural course of the river valleys.

In Section 3.1 it has been pointed out that considerations of this kind in many cases are no longer to be considered as such. Due to wearing of the gorges, ageing of the rivers, or rising of the sea-level, in many cases these places are less stringent than at the time of their origin and the actual boundaries are no longer formed by rocks but by sediments. Very often, it is only during peak levels of the rivers that the constrictions make themselves felt, leaving as a predominant feature that at those places the river was prevented from swerving.

From this outline follow two general principles which hold good for each of the narrows considered in the next paragraphs:

(i) The narrowness of the valley is due to the firmness of its boundaries. This entails that such places are pre-eminently suitable for riverain or transriver constructions, because of reliable subsoil, shortness of access-routes and shortness of riverspan.

(ii) The uncertainty of the depth and the quality of the buried bedrock. The alluvial fill generally covers an uneven erosion pattern in the bedrock which, before any foundations are built on it, should be carefully investigated by means of boreholes or a combination of geophysical methods and boreholes. Moreover, as the bedrock often will be weathered or fissured, this problem also requires attention. In general there should be a detailed mapping of the veins, dikes, faults, fractures and lineations cutting across the site.

In the following paragraphs some ten narrow places will be geologically described, all chosen along the lower courses of the main rivers or tributaries on account of their geo-historical significance. Most of them offer opportunities for the construction of bridges or dams; in the latter case, their merits will be further explained in Chapter VI, Section 8.2. A few of them may be considered as suitable places for exploitation of building materials.

PHOTOGRAPH 3.4.1-1

Awuru site with rapids viewed upstream

3.4.1. The Niger near Awuru

In the neighbourhood of Awuru, some 50 miles upstream from Jebba, the Niger Valley shows topographical features which seem of sufficient interest to warrant a brief description. No personal observations have been made here, so the descriptions given below had to be based on statements by various authors, mainly upon the comprehensive report by JOYCE (1 which provides most useful information. The following has been taken from this report.

In a large area situated upstream of Jebba, the Niger cuts into the rocks of the Basement Complex. Near Awuru Rapids partially granitised rocks of the Basement Complex are exposed in the river banks, where fine-grained dark quartzites occur as bands with various schists. Early pegmatite veins and basaltic dikes intruded into these rocks are still recognisable in spite of the degree of alteration which they have undergone as a result of the granitisation processes.

In the area around Awuru two belts of more or less schistose rocks have been distinguished, lying on either side of the valley. Near Awuru the river roughly follows the strike of the foliation. A series of ridges, consisting of rocks of the "Awuru schistose belt", lies adjacent to the main river on the left bank. The rocks forming these ridges are rich in mica and are dominantly veined by quartz.

Along the western boundary of the Awuru schistose belt a lenticular exposure of basic rocks over a distance of about 6 miles is found. At the northern end, which lies between $1\frac{1}{2}$ and 2 miles south of Awuru Kontagora, the exposure is tongued by aplitic rocks and a marked schistosity is developed. The area underlain by these rocks is characterised by clayey soil. The rocks are of the plagioclase-hornblende type. From west to east the basic rocks of this small belt vary in mineralogical composition and in grain-size.

Small intrusive bodies of granodiorite, parallel to the foliation, have been observed at several places in the schistose belt. It is not quite excluded that similar rocks might also exist near Awuru.

Downstream of Awuru Gungu the shallow gorge of the Niger is filled with Niger alluvium, which occasionally extends for two miles west of the present river course, but is much more restricted in distribution on the left bank, where harder rocks outcrop. The dominant sediment

(1 JOYCE, 1951. GEO. 23

is a sandy silt, clay beds being very subordinate. Mechanical analysis of the silt indicate a high clay fraction and a sandy portion, the greater part of which is very fine-grained. The clays are normally stiff blue varieties. Erosion accompanying the regional uplifting movements resulted in the formation of two sets of terraces, the first 24 to 36 m (80—120 feet) above the present dry season water-level and the second between 6 m and 21 m (20 and 70 feet) above the same datum, which is about 85 m (280 feet) above Mean Sea-level. Sand and wash from 2 to 4 m (7 to 14 feet) were proved in the river channel.

Over most of the distance between the Oli River upstream of Awuru and Yankade Island midway between Awuru and Jebba the River Niger flows at slight angles to the strike of the foliation of the country rock. Harder and more resistant banks of rocks thus form a series of bars which rake the channel at low angles. Between the bars the river has eroded a series of basins, and there is consequently considerable variation in depth. For about ¾ mile below the Upper Awuru Rapids the Niger flows almost at right angles to the foliation. Between Awuru and Yankade Island the river is contained in a single channel rarely more than 100 yards wide and cuts into granitic basement rocks. These rocks between dry-season flow-level and flood-level have acquired a high degree of water polish, which seems to inhibit weathering. The actual bedrock in the channel proper is unlikely to be decomposed to a marked degree.

These facts are in accordance with the description of the same area given by FALCONER ([1]: "At Wuru (apparently as at Awuru) the channel of the Niger is occupied by a hard and coarsely-foliated epidote hornblende gneiss, much pierced by irregular veins of schistose granite and pegmatite. The foliation planes of the gneiss are vertical and strike approximately N. 20° E. On the left bank the gneiss is succeeded by thinly-bedded quartzites and quartz schists with scattered knots, lenticles and veins of quartz and finely fibrous tourmaline. Intercalations of much corrugated and wrinkled mica schist bear witness to differential movements along certain lines. The whole series, which strikes north-south and dips vertically or at high angles to the east or west, has apparently suffered a rapid and repeated folding. These rocks are followed by a series of fine-grained green and yellow quartzites and well-cleaved slaty schists with numerous quartz reefs, which pass eastward into a complex of hornblende gneisses, epidote hornblende gneisses, amphibolites and fine-grained schistose granites which disappear at Kumboli under the sandstones of Southern Kontagora".

3.4.2. Jebba Defile

Near Jebba, about 200 miles above Lokoja, the Niger is bordered by high rocks and the valley is rather narrow. In the river-bed at a number of places the bottom rock protrudes through the sand fill, thus forming a few islands. The most conspicuous of these is "Juju Rock".

The railway from Lagos to Kaduna crosses the Niger at the lower and wider part of the defile in two jumps, the middle part of the crossing being formed by an island stretch about a half mile long. Part of the bridge piers are founded on rock, part on sand, the bedrock being deeper than 25 m (80 feet) below the sand bottom.

The area immediately upstream from Jebba is particularly interesting with regard to the general topography and geology and also with a view to the navigability of the Niger (Photograph 3.4.2-1).

Detailed geological investigations of the Jebba area have been carried out with the special object of determining the feasibility of a multi-purpose dam on the Niger (joint investigation by BALFOUR BEATTY & CO. and NEDECO). The results have been mentioned in a special report on

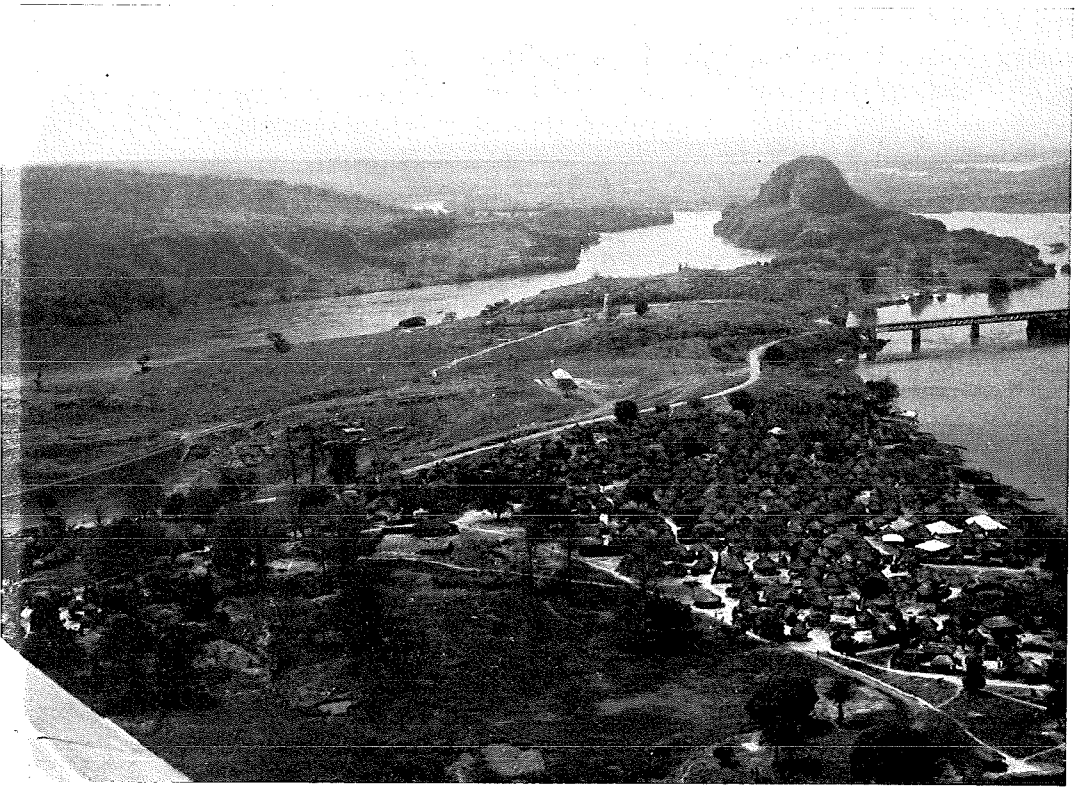
([1] FALCONER, 1911. GEO. 17

this subject. Therefore, the present Report will contain only a few general remarks on the Jebba gap.

Upstream from Jebba, between this town and the village of Ya'afu, the Niger River flows on the border between Basement Rocks (metamorphic rocks, gneisses, etc.) on the right bank and quartzites on the left bank. Near Jebba on both sides of the river quartzites are found, which are of an unknown age. They are strongly folded and commonly called "Jebba quartzites".

The underground and the valley sides of the Niger River upstream from the railway bridges are composed of Jebba quartzites, occurring in banks of varying thickness, intercalated with thin layers or soft crumbly micaschists. The strike of the beds is north-west — south-east, with a dip upstream between 40° and vertical. The quartzites show a well-developed system of fissures and joints.

The depth of the alluvial fill below the river-bed is not known. In view of the fact, however, that the major rivers and some of their tributaries at several places have deeply-entrenched and sometimes canyon-like buried valleys lying underneath their present river-bed, it may well be possible that the valley of the Niger near Jebba shows similar characteristics. On the other hand, however, mention has been made in Paragraph 3.1.2e that Jebba actually lies lower than might be expected according to its position of the longitudinal section of the main river. The conclusion drawn therefrom, that the filling up of the Niger Valley in response to a rising sea-level after the Gamblian regression was retarded in this area when compared with the rate of filling up of the Lower Niger Valley downstream of Lokoja and of the Benue Valley, leads to the assumption that the thickness of the alluvial fill consisting of sand and gravel is less near Jebba than in other parts of the main valleys.



PHOTOGRAPH 3.4.2-1

Jebba Island viewed upstream

Note saddle beyond Juju Rock

3.4.3. Niger Rocky Section

A narrowing of the Niger Valley in the so-called Rocky Section occurring below Lokoja seems worth mentioning and describing. The area is shown on Diagram 3.4.3-1.

a. *Geology*

The floor and sides of the valley are formed by rocks of the Basement Complex (coarse-crystalled to porphyric granites), with the exception of the river-bed of the modern river, and filled with medium and coarse sand.

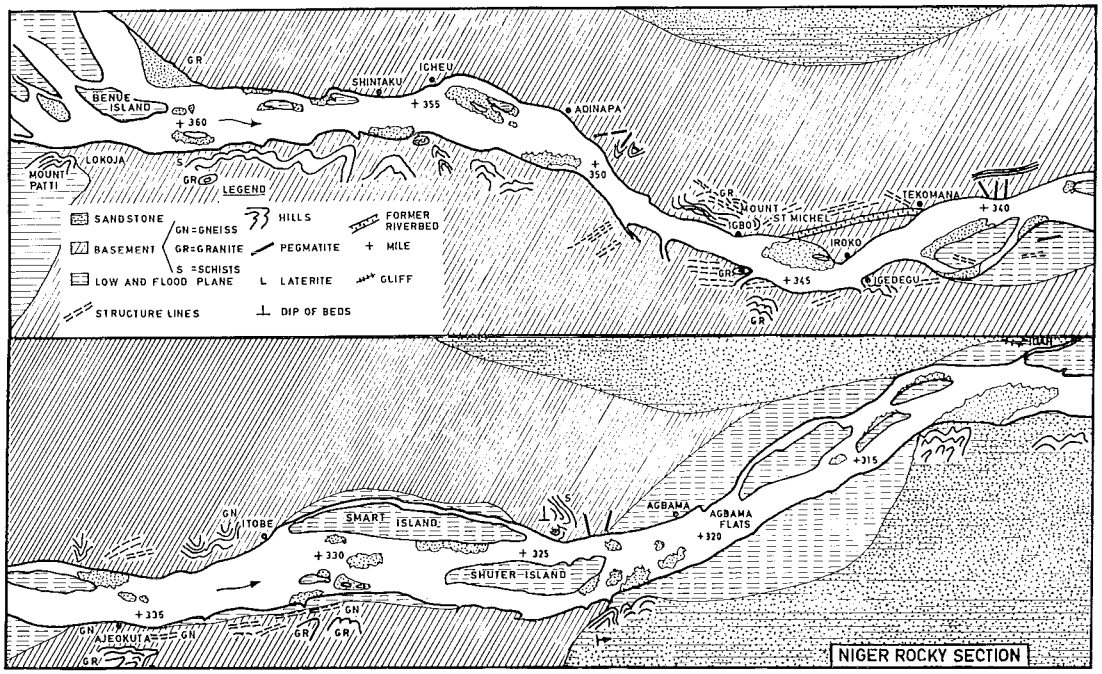


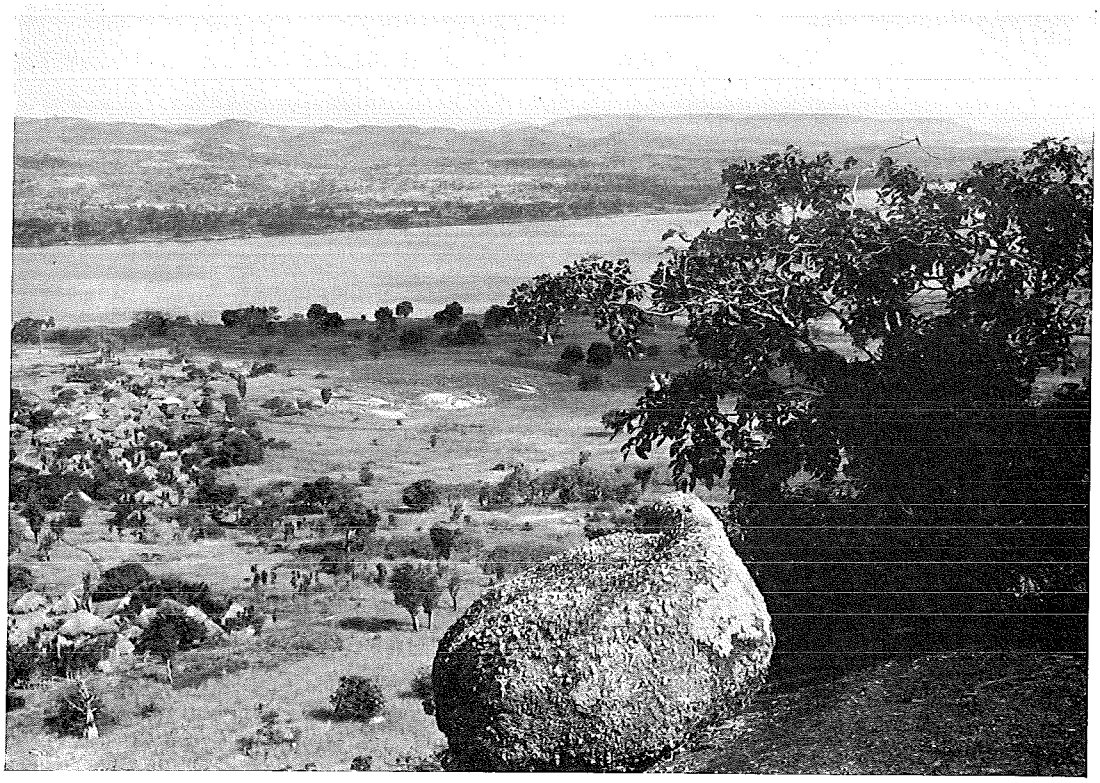
DIAGRAM 3.4.3-1

Geological map of Niger Rocky Section

The depth of the alluvial fill below the river-bed is not known. However, in view of the general geological and morphological history of Nigeria as described in Section 3.1, and from comparisons with the cross-sections studied at Onitsha and Makurdi, it is to be expected that the bottom of the valley fill will be found at a depth of approximately 80 or 90 metres (250 to 300 feet) below the present river-bed. The alluvial deposits probably consist mostly of medium to coarse sand with some gravel, being very pervious.

The Basement Complex, composed of granites, gneiss and schists, is cut by a number of pegmatite dikes and veins. Some quartz veins occur, but they seem to be of minor importance only. The granites, which are mainly of a coarse-grained and porphyric composition, show in the landscape as big rounded hills. As a result of weathering and quick changes in temperatures occurring under the present-day climatic conditions, the surface of the granite is peeling off, thus forming huge boulders and blocks which cover the hills; hence the name "Exfoliating Hills" used by FALCONER ([1] while describing the area. A pronounced cleavage of the rocks underneath the cover of blocks has generally not been observed.

([1] FALCONER, 1911. GEO. 17



PHOTOGRAPH 3.4.3-2

Niger Rocky Section viewed upstream

In front porphyric granites of east hill, western hills consisting of granites and gneisses. In far background ironstone-capped Mt. Patti above Lokoja.

b. *Building materials*

Quarrying of a massive sound rock without any cracks or fissures is rather difficult, especially when quarrying is done on a small scale and with the aid of primitive tools only. Therefore use of this type of granite will generally be restricted to the loose boulders and blocks formed as a result of the exfoliating processes, unless the (weathered) rock is of too poor a quality. The thickness of the cover of loose blocks will thus be a measure for the quantity of building material to be expected.

In places where pronounced sets of joints and fractures occur in not too narrow or too wide a network, as observed in the area of Mile 348 along the River Niger, the aspects for exploitation are more promising. The natural fissures which are found here in the solid rock under the cover of boulders facilitate further exploitation below the weathered part of the rock on the surface.

The schists have less consistency and, because of their tendency to rapid weathering, are unsuitable as building material. Schists of a poor quality have been observed to occur, for instance, at the Agbanama Flats and around Ajeokuta.

The gneisses observed in the Rocky Section, which from the point of view of strength and resistance come in between the granites and schists, often do not show pronounced systems of joints. At several places, however, it would be possible to obtain flat blocks and stones for

building purposes by using the planes of schistosity when exploiting the gneiss. The shales, sandstones, laterites and ironstones, which form the cliffs at and near Idah and which form Mount Patti near Lokoja, do not offer suitable rock for building purposes.

Sand has been found in considerable quantities. Rounded gravel is rather rare and although on the hard rock a thin layer of gravel occurs occasionally, the quantities observed were small. A gravel occurrence might be found in the pegmatite zone of Mile 340, but only more detailed investigations by way of digging pits will enable an estimate to be made of the extent of the occurrence and the quantities available.

The banks of the river from Itobe several miles upstream consist of gneisses cut by small pegmatite veins. If not too brittle rock is selected, this material can be used as rockfill for groynes. It is already being exploited by the population, though in a primitive way. Along the banks, just above highest flow-level, a thin layer of (river) gravel is found, having an average diameter between 1 and 3 cm (0.4″ to 1.2″), and of excellent quality for the manufacture of concrete. A considerable number of flat blocks of gneiss (max. size 3 × 4 m or 10 × 13 feet) is found on the eastern bank near Shintaku.

On the eastern bank of the river, north of Ajeokuta, near Mile 338, a ridge about 3 miles long is situated at some distance from the river and at an acute angle to the valley. This ridge, consisting of porphyric granite, shows pronounced joints continuing in various directions, most likely also in a horizontal direction. It could provide a considerable quantity of blocks of an average size of 2 × 3 × 4 m (6 × 10 × 13 feet). But when the granite is exploited, care should be taken to avoid the schistose inclusions which occur locally.

A number of pegmatite veins occur at the foot of the ridge at right angles to the river, some of them protruding into the river itself. They are rich in quartz and contain also white mica flakes, feldspar and a little granat. Though the pegmatite is of very poor quality for building purposes, the quartz which remains when the pegmatite has weathered may be used as coarse gravel.

A river terrace is found between the zone containing pegmatite veins at Mile 341 and the river, where blocks of quartz of a diameter of 40 cm (over 1 foot) have been observed in the gravel.

It may be expected that in Icheu material will be found similar to that which has been observed near Mile 340. It could probably be easily split into blocks for building purposes, and it is likely that rocks suitable for exploitation will be found also opposite Icheu near Iroko.

Considerable quantities of material with natural joints can be exploited near Igbo between Mile 346 and Mile 348 at 500 yards from the river on the eastern bank. As far as could be seen on the aerial photographs, conditions for exploitation seem to be favourable.

Rounded hills, composed of coarse crystalled to porphyric granite, are found opposite Igbo. They are covered by stones — the result of weathering — of the size of a house, which do not show a pronounced fissuring. For this reason they will be of little use for building purposes.

Exfoliating granite hills border the river on both sides between Igbo and Lokoja. The loose stones may be suitable for rockfill and the non-weathered ones may be used as mix for concrete. It is advisable that possibilities for exploitation be thoroughly investigated.

At Lokoja, the granites, gneisses and schists of the Basement Complex are found. Near the confluence of the Niger and Benue the granite is topped by sandstone. Mount Patti near Lokoja, which is formed by sandstone, is covered with a thick layer of ironstone, part of which may be used for filling purposes. Regarding the possibility of opening a quarry in the granites near Lokoja, the position is the same as proposed for the porphyric granites found between Igbo and Lokoja.

3.4.4. Onitsha Defile (Niger)

a. *Morphology*

Between Onitsha and Asaba a considerable narrowing of the Lower Niger Valley occurs. The area which comprises the Niger Valley and the adjacent hilly country may be subdivided into three separate regions, viz., the hill country east of the Niger River, the hill country west of the River Niger and the Niger Valley proper.

The hill country east of the river consists of a plateau with altitudes varying between 150 and 250 m (500 and 800 feet) above Mean Sea-level, cut by several small streams and brooks flowing from east to west and debouching into the Niger or into its confluent the Anambra, such as the N'kisi immediately north of Onitsha, and the Ide Mili, approximately 4 miles south of Onitsha. The flat-topped hills are capped by laterites and lateritic sandstones, the latter dipping slightly to the south-west (3—4°). The plateau surface shows the same general SW dip. The hills, representing remnants of the dissected plateau, therefore become gradually lower in a south-westerly direction.

The hill country west of the Niger River shows a marked east-west directed ridge. It lies south of the highway from Asaba to Benin, and several streams rise on its south side flowing in a south-easterly direction towards the Niger. North of the ridge the landscape with its many low hills has great resemblance to the hill area situated east of Onitsha.

The Niger Valley between Asaba and Onitsha is relatively narrow. The hills reach as far as the river or its flood-plains. Near Asaba, at the confluence of the Niger and the Anambra, the valley widens in a northerly direction. A low, very wide plain is situated between the Niger and the Anambra at a level of 21 to 23 m (69 to 76 feet) above Mean Sea-level. This plain stretching away over a long distance upstream is almost entirely flooded during the high-water period.

Along the west bank of the river, downstream of Asaba, another flood-plain is found, which widens southward. Its altitude is also at 21 to 23 m (69 to 76 feet) above Mean Sea-level. Between the flood-plain and the western hilly country lies an alluvial plain at an altitude between 23 and 25 m (76 and 84 feet) above Mean Sea-Level. This plain, which shows remnants of several ancient river arms and meanders, is flooded at periods of exceptionally high water.

Only a few narrow flood-plains occur along the east bank, south of Onitsha. Between the river-bed and the eastern hilly country several alluvial plains and former river terraces situated at varying altitudes have been observed, each one of them a few hundred metres wide and the lowest at an altitude of 30 to 35 m (100 to 115 feet) above Mean Sea-level, being 10 m (30 feet) above the highest water-level of the Niger. This lowest terrace is formed by a shallow depression, draining into the marshy pond which divides Onitsha town into two separate parts near the timber market. The pond itself, which is separated by a sand-bar from the River Niger, with which it still communicates, is situated at the same level as the river and below the level of the terrace. A second terrace lies about 30 m (100 feet) above the highest water-level of the Niger (at an altitude of about 50 m or 165 feet above Mean Sea-level). A third terrace lies at approximately 100 to 110 m (330 to 360 feet) above Mean Sea-level, about 80 m (260 feet) above the highest water-level. It has been found, for instance, near the forestry area north of Onitsha Town, overlooking the confluence of the Niger and the Anambra, and also east and south-east of Onitsha Town.

The + 21 to + 23 m flood-plains have a close relationship with the recent river. The + 23 to + 25 m alluvial plain to the west of the Niger probably represents the highest level reached by the river during the Würm period of the Quaternary after the formation and the filling of its ancient buried valley, thus corresponding to the higher sea-level which appears to have occurred about 45,000 years ago (see Table 3.1.1-1).

The + 30 to + 35 m and + 100 to + 110 m terraces are not related to the recent river systems

and represent erosion stages of the ancient Niger, mention of which has been made in Section 3.1 on the geological and morphological history of Nigeria.

The marshy pond into which the depression of the +30 m (100 feet) terrace drains is of a later formation, corresponding probably to the period of deepest erosion of the principal valley and may be compared with the deeply-entrenched valley of the N'kisi. At the time when the Niger filled its former deeply-eroded valley with sediments, the outlets of these small tributaries were also partly filled up and barred by sand deposits.

b. *Geology*

The following succession of sedimentary deposits forms the underground of the region under consideration, starting with the oldest beds (lowest layers of the succession):

(i) Fine to coarse sandstones with abundant intercalations of calcareous shale and thin shelly limestone (outcrops around Awka, about 20 miles east of Onitsha).

(ii) Coarse, loose, cross-bedded, grey-green sandstone and sandy clay (outcrops can be found from Onitsha eastward as far as Agulu).

(iii) A variable succession of clays, sands and grits in which lignite seems to occur at numerous horizons. There is marked lateral variation in lithology. The junction with the underlying beds is poorly exposed, but it is possible that a small angular unconformity exists. According to some authors (DU PREEZ) there is no evidence for other than local intraformational disconformities. These beds underlie a broad belt of hilly country from Onitsha south-eastward to Mumakia. Exposures of these beds are poor except at the heads of the deeply-incised valleys, where springs emerge above impervious beds of lignite. The rolling ridges between the streams are covered by red earthy sands.

(iv) Incoherent, yellow and white, cross-bedded and occasionally pebbly sands with some beds of grey sandy clay.

The beds mentioned under the items (i) to (iii) are mostly represented in the Onitsha area by medium-grained white and grey sand with intercalations of clay and lignite beds. The sandy deposits are compact and they form steep slopes of hills and banks of rivers. Near to the surface they are often cemented by laterite. The interbedded clays are shaly. To the west of the Niger the intercalated lignite beds are more numerous and thicker than to the east of the river.

The beds mentioned under the item (iv) consist of loose coarse-grained sands which are strongly affected by erosion. Irregular beds and lenses of gravels occur within these sandy deposits, as well as some soft reddish-brown clay and some earthy lignite.

The beds described under (i) to (iii) are in the Lignite Group, which belongs to the Eocene. The deposits described under (iv) are more recent in age, Oligocene and Miocene, and belong to the Coastal Plains Sands Group.

Sandstones showing a considerable development of laterite and ironstone are present in the east bank of the river, both north and south of Onitsha, as well as at several places in Onitsha Town. They have been observed also in the canyon of the N'kisi, where they were encountered in quarries situated at an altitude of approximately 50 m (165 feet). In these quarries the sandstones indurated by laterite and ironstone are exploited for road-making and building purposes.

In the Niger Valley proper fluviatile deposits occur, which are much more recent in age. These generally sandy deposits form the fill of the buried valley of the ancient Niger and the flood-plain deposits and river-bed deposits of the recent river. They consist mostly of medium to coarse-grained sands, with some local intercalations of argillaceous beds. Boreholes made in the valley for a bridge project revealed their thickness to be more than 45 m (150 feet) and their base to lie more than 25 m (80 feet) below the sea-level. It appears from the geological

history of Nigeria, as summarised in Section 3.1, that the depth of the sandy fill of the buried valley is possibly about 90 m (300 feet) below the present river-bed.

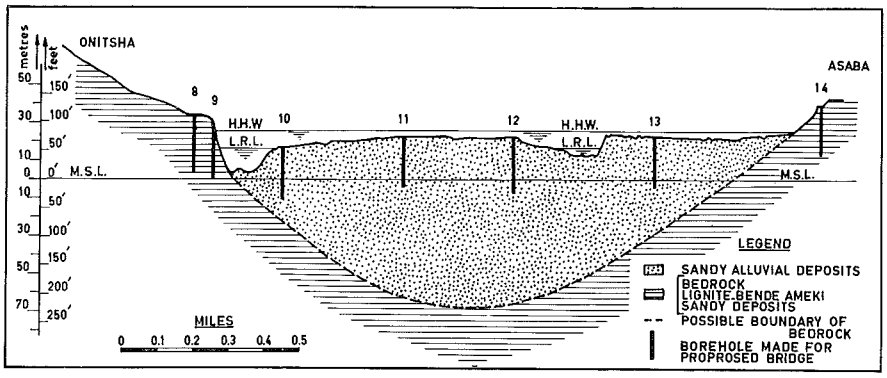


DIAGRAM 3.4.4-1

Cross-section of the Niger at Onitsha

Full details of the sediments as observed during the execution of the reconnaissance drilling and during the analyses and tests in the laboratory are given in the "Report on the practicability of constructing a bridge across the Niger near Onitsha" ([1], Annexes II and IIa, which may be referred to here.

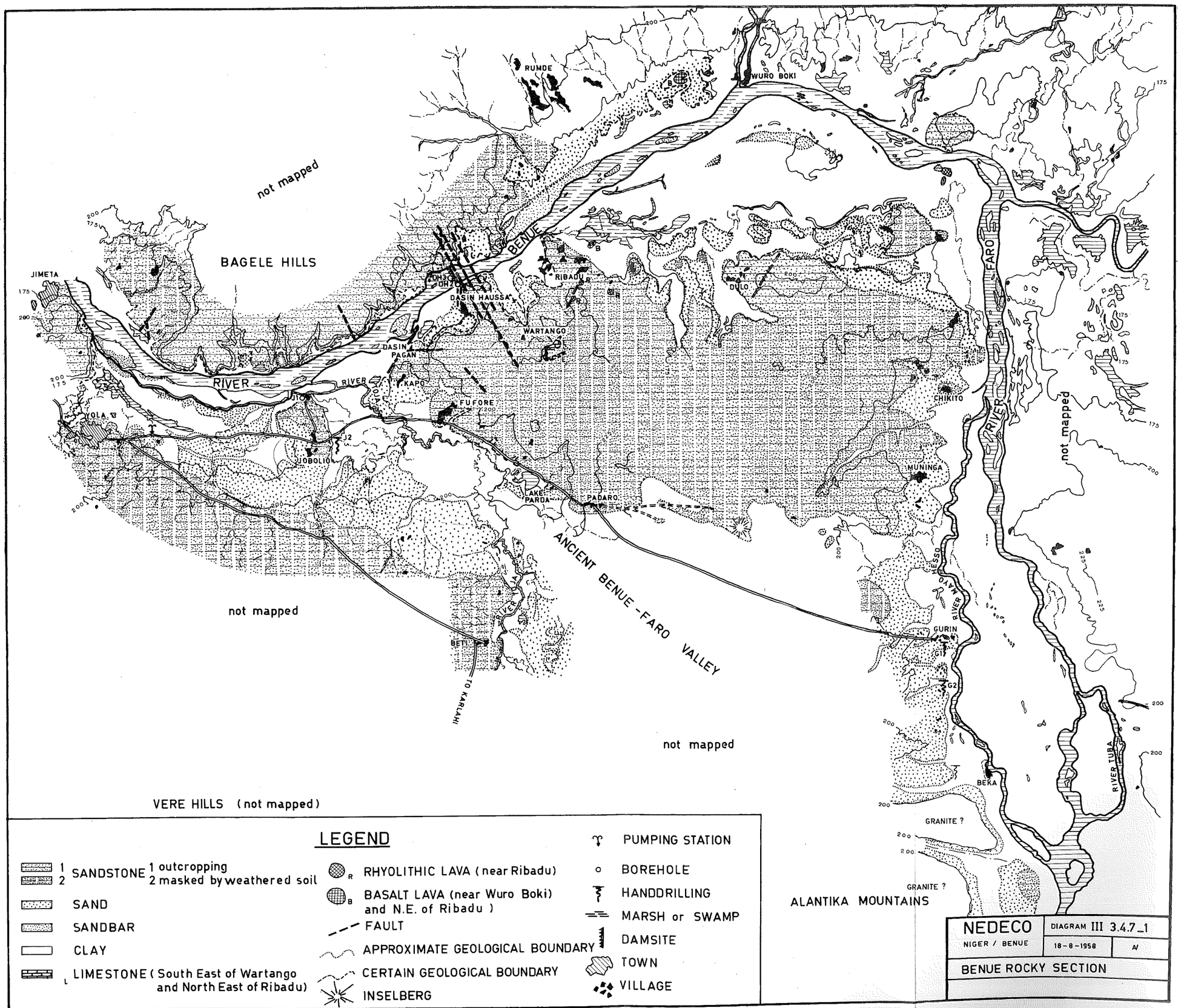
The tectonic structure was observed to be a simple one. The Eocene, Oligocene, and Miocene formations underwent some very gentle folding as a result of which the average dip of the layers in the Onitsha area is 3—4° to the south-west. Some beds, however, may locally show a gentle apparent dip in the opposite direction, due to the cross-bedded nature of these deposits.

Some faulting also occurred. Two major faults are presumed to exist in the Niger Valley area in this region, one of them with a north-south direction, running along the east banks of the Anambra and the Niger downstream of the confluence of the Anambra. The steep slope of the hills overlooking the east banks of the Anambra and the Niger at the forestry area north of Onitsha, as well as at Onitsha itself, is supposed by several authors to represent a fault scarp, connected with the north-south fault. But as far as can be learned, no proof of the occurrence of this fault has yet been given.

3.4.5. Lagdo Defile

Lagdo is the name of a village near a gorge in the Upper Benue, upstream from the confluence with the Mayo Kebi and at 40 miles above Garua. This site has been investigated by the "Commission Scientifique du Logone et du Tchad" on account of its attractiveness as a dam-site. Electrical soundings were carried out by the "Institut d'Etudes Centrafricaines" which reported in 1951 on the geophysical conditions ([2]. In 1952, Electricité de France reported about six borings carried out in that year ([3]. The gorge has a width of about 180 m (600 feet) between rocks under 30° consisting of porphyric granite, fissurised to a horizontal depth of 12 m (some 40 feet). The same material was encountered in the river-bed under 23 m (78 feet) of rather coarse sand, sometimes mixed with gravel, interchanged with two thin layers of clay.

([1] NEDECO, 1957. GEN. 22
([2] INSTITUT D'ETUDES CENTRAFIRICAINES, 1951. GEO. 21
([3] ELECTRICITÉ DE FRANCE, 1952. GEO. 15



LEGEND

- 1 SANDSTONE 1 outcropping
- 2 SANDSTONE 2 masked by weathered soil
- SAND
- SANDBAR
- CLAY
- L LIMESTONE (South East of Wartango and North East of Ribadu)
- R RHYOLITHIC LAVA (near Ribadu)
- B BASALT LAVA (near Wuro Boki and N.E. of Ribadu)
- FAULT
- APPROXIMATE GEOLOGICAL BOUNDARY
- CERTAIN GEOLOGICAL BOUNDARY
- INSELBERG
- PUMPING STATION
- BOREHOLE
- HANDDRILLING
- MARSH or SWAMP
- DAMSITE
- TOWN
- VILLAGE

NEDECO	DIAGRAM III 3.4.7_1	
NIGER / BENUE	18-8-1958	A/
BENUE ROCKY SECTION		

The geologist ROCH considered that fissures in the rocky surface would decrease gradually and stop at some 18 m (60 feet); they could be tightened easily by grouting. It is further considered that weathering of the bedrock would not be very considerable.

3.4.6. Cossi Defile

Cossi is a village on one of two hillocks causing a narrow place in the Mayo Kebi, a northern tributary which debouches into the Upper Benue some 12 miles above Garua. The site was considered by the French for the construction of a dam, the width of the Gorge being some 450 m (1500 feet).

In 1951 an exploration was made at this site by the "Institut d'Etudes Centrafricaines" ([1; by means of electrical soundings sound rock was indicated at a depth varying from 20 m (70 feet) at the banks and 60 m (200 feet) in the middle of the river-bed. The rock was found to consist gneiss, slightly weathered at the surface, with veins of fissured rhyolite at the left bank.

In 1952 a 30 m (100 feet) boring in the river-bed was made on behalf of "Electricité de France" ([2. Until that depth the bed was found to consist of coarse sand mixed with grit, and containing some silt at greater depth.

3.4.7. Benue Rocky Section (above Yola)

A little downstream of the Cameroun's border, where the Faro River joins the Benue to double its discharge, the Benue Valley narrows to a gorge some 11 miles in length, between Ribadu (Mile 908) and Jobolio (Mile 897). In view of an eventual regulation of the Benue, this narrowing of the valley represents a possible dam site; the only other possibilities along the Benue would be at Lagdo (Paragraph 3.4.5) and Makurdi (Paragraph 3.4.10). Therefore topographical and geological surveys, including some reconnaissance drilling, have been made of the river-valley between Yola and the confluence of the Faro River, as well as of part of the adjacent areas, in order to determine the possibilities for dam construction in this area ([3.

The narrowest spots of the valley occur near the villages of Jobolio (Mile 897), Dasin Pagan (Mile 901) and Dasin Hausa (Mile 904), the most favourable of which in all respects has been found near Dasin Hausa (Photograph 3.4.7-2).

It was found that not only the topographical and geological conditions at the potential dam-site had to be investigated, but that special attention has also to be paid to the possibility of considerable water losses from the reservoir itself. The actual topography and the geological and morphological history of the area shows that important water losses might be expected to occur south of the Benue and therefore the attention of the Mission has been concentrated mainly on this critical area.

The topographical data which served as a basis for this study have been obtained from a photogrammetical map scale 1 : 50,000 prepared in 1957 by KLM Aerocarto, checked and completed early in 1958 by a traverse levelled by Federal Survey Department from Jobolio to Gurin on the Faro and from Beka on the Faro to the foothills of the Alantika Mountains. The absolute altitudes have been taken from fixed points from the French river survey. These data served as a basis for the geological map of the area (Diagram 3.4.7-1).

During the period of geological field-work reconnaissance boreholes were made in combined percussion and rotary drilling and with a Banka drilling outfit. The field-work was completed with an analysis of the aerial photographs which cover most of the area under consideration.

([1 INSTITUT D'ETUDES CENTRAFRICAINES, 1951. GEO. 21
([2 ELECTRICITÉ DE FRANCE, 1952, GEO. 15
([3 Several of the geological problems and phenomena observed have been discussed with Mr. J. D. Carter of the Geological Survey Department of Nigeria. Fossils (ammonites) from the Yola region have been identified by Mr. W. Barber, paleontologist in the Department.

PHOTOGRAPH 3.4.7-2

Benue Valley viewed eastward

showing dam-site in background, with Dasin Hausa on right hand behind the shrubs

a. *Topography and morphology*

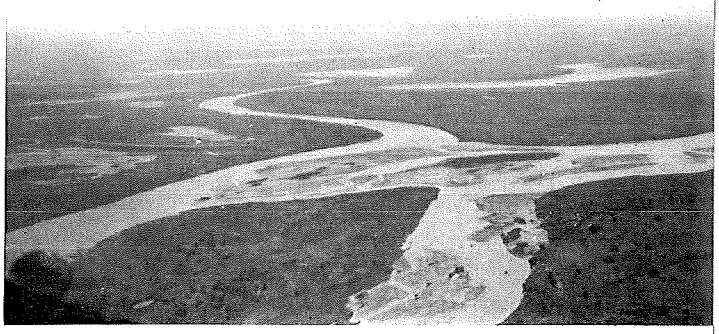
The geological survey was intended to provide basic data for an eventual dam construction. As a directive it was assumed that the maximum reservoir level would reach to the 190 or 200 m contour-line (620 or 660 feet) of the 1 : 50,000 topographical map of this region. North of the river the Bagele Hills rise to an altitude of 600 m (2,000 feet). Eastward there are the broad valley of the River Kilunga and the wide plains along the Benue which rise imperceptibly and stretch away into the French Camerouns, eventually attaining altitudes of over 200 m (600 feet). Immediately to the south of the river other hills are found, rising to an altitude of 220 m (720 feet) but they are bordered to the south by a large flat valley, which runs from Beka on the Faro to Jobolio on the Benue. South of this valley in the Vere Hills and the Alantika Mountains the ground-level rises definitely to higher altitudes. The traverses levelled proved, however, that the 190 m (627 feet) contour-line closes around the reservoir area without the occurrence of a saddle below this level. The area and the storage volume of the reservoir will be described in VI, 8.5.1.

The following features are the most prominent in the area:

(i) the plain, which is very flat and in places marshy and which stretches from the confluence of the Benue and Faro Rivers eastward until beyond Garua into the French Camerouns;
(ii) the Bagele Hills north of the Benue River;
(iii) the Dasin-Gurin ridge south of the Benue River;
(iv) a large flat valley situated between the Dasin-Gurin ridge and the Vere Hills; and
(v) the Vere Hills and further southward the Alantika Mountains.

Little is to be said about the Upper Benue plain which extends into the French Camerouns. It consists of a graben-area (1 or synclinal basin (2, filled with Cretaceous sandstones and covered with extensive flood-plain and alluvial sediments deposited by the Benue River and its tributaries (see Photograph 3.4.7-3). At several places the Cretaceous sandstones form plateau-areas rising above the plain, for instance to the north and to the south of Garua. A few small volcanoes exist, which are indicated on the French geological maps. Northward and southward the basin is bounded by Basement Rocks showing distinct ancient peneplain levels (Fali country and Namchi country (2).

(1 GAZEL, 1956. GEO. 19
(2 ROCH, 1953. GEO. 37

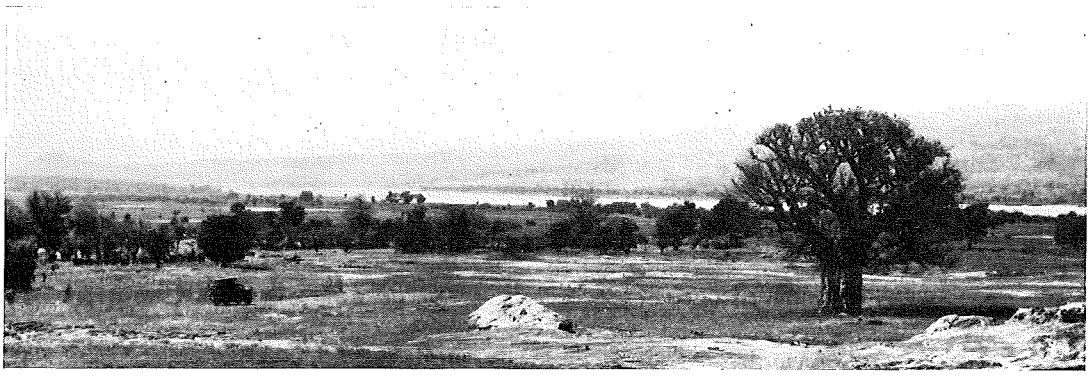


PHOTOGRAPH 3.4.7-3

The confluence of the Upper Benue (top) and the Faro (right) viewed eastward

The Bagele Hills, rising to an altitude of 600 m (2,000 feet), are formed by a broad anticline of Cretaceous sandstones. They are connected northward with the Basement Rocks by high grounds which form the Biu Plateau.

The Dasin-Gurin ridge south of the River Benue, consisting of Cretaceous sandstones, forms a promontory of the Bagele Hills, cut off from the latter by the present river-bed of the Benue (see Photograph 3.4.7-4). Near Gurin it becomes gradually lower and is dissected into separate hills by some valleys. The flat-topped ridge is a remnant of an erosion surface which originally stretched away from the Bagele Hills as far as the Vere Hills. On the Dasin-Gurin ridge this erosion surface, on which two "inselbergs" remain from a still higher and older peneplain, lies at an altitude of 220 m (720 feet). The northern footplain of the Vere Hills, which forms its southern continuation, lies at an altitude of 255 m (840 feet).



PHOTOGRAPH 3.4.7-4

Benue Valley viewed westward

showing dam site; on the left side: Dasin Hausa; beyond te river: Bagele Hills

The Vere Hills and the Alantika Mountains further southward, exceeding an altitude of 600 m (2,000 feet), consist of Basement Rocks. They continue eastward, interrupted only by the valley of the Faro River, into the Namchi Country, where the Basement Rocks also outcrop ([1.

The large flat valley situated between the Dasin-Gurin ridge and the Vere Hills takes its beginning at the Faro both north and south of Beka, a village situated on a low hill. The valley extends westward from Beka, curves north as far as Padaro, and then curves north-west to meet the Benue between Dasin Pagan and Jobolio. The valley, which is bordered by Cretaceous sand-

([1 ROCH, 1953. GEO. 37

stones, is filled to an unknown depth with sandy alluvial deposits, topped by clays. It is considered to be an ancient course of the Benue-Faro, having the same topographical and morphological features. River-blindness, tsetse and malaria cause the valley to be uninhabited. Lake Parda lies in a local swampy area; the other parts of the valley are covered with a bush vegetation.

Small streams flow into the valley. Almost all rivers situated to the east and south-east of Padaro drain towards the Faro Valley, whereas those situated west and south of Padaro drain towards the Benue near Jobolio. A very low ridge, running north-south, forms the watershed between the Benue Valley and the Faro Valley. This ridge, which is believed to be a result of tectonic movements, shows signs of active erosion by the small streams. West of Lake Parda, however, the same streams meander strongly on the flat valley bottom and only one of them shows an entrenched river-bed. These meandering streams are bordered by natural levees. Some of these features are showing on the topographical Diagram VI, 8.5.1-1.

The contact between the Cretaceous sandstones, lying south of the ancient Benue-Faro Valley, and the Basement Rocks of the Vere Hills lies somewhere below the northern footplain of the Vere Hills and passes midway between Beka and Karin, situated about 8 miles south of Beka. The plain being covered by recent deposits the contact could not be observed, but it is believed to be a boundary by faulting, in continuation of the assumed fault zone in the French Camerouns on the southern border of the Benue Graben ([1].

A flat and broad valley, through which the River Toja takes its course, stretches northward between the Vere Hills and the Alantika Mountains, and joins the ancient Benue-Faro Valley. The Toja Valley gives the impression of being much too large for the present river. In the valley, south of Beti, some low hills were observed, consisting of granites. In other parts of the valley its bottom and the banks of the river consist of cross-bedded sand-layers of silt and clay, which show some resemblance to the Chad deposits. The modern river has eroded its river-bed into these deposits.

South of Jobolio a branch of the ancient Benue-Faro Valley was observed. At present there is a low hill between the footplain of the Vere Hills and the sandstone ridge of Jobolio, which is partly covered by a thin layer of clay. It is composed of at least 4 metres (13 feet) of coarse, cross-bedded alluvial sands and is believed to be an old sand-bar of the Benue-Faro. As the aerial photographs taken do not cover the whole of the ancient valley system, full particulars about its topography cannot be given. The average slope of the ancient Benue-Faro Valley amounts to an estimated 60×10^{-5} between Beka and Jobolio, which is steeper than the slope of the Faro River (50×10^{-5}). The altitude of the watershed which crosses the valley to the east of Padaro probably exceeds the 220 m (720 feet) level. Along the footpath from Padaro to Gurin an altitude of 232 m (760 feet) has even been observed.

The Faro River flows between natural levees. Near Beka the bottom of the river-bed is situated at an altitude of 186 m (610 feet). The plain behind the natural levees, however, in the area where the ancient valley meets the present Faro Valley, lies at an altitude of only 181 m (595 feet), separated from the present river-bed of the Faro by the natural levees of this river. Inhabitants of Beka say that water of the Faro during the high-water season flows over the natural levee and into the depression west of Beka, leaving the village, which is situated in a slightly higher spot of the ridge, dry but surrounded by water.

Although the above-mentioned facts indicate that the eastern part of the former Benue-Faro Valley still acts as a flood basin during periods of very high water in the Faro River, it has become clear that flood water cannot reach Lake Parda and the Benue near Jobolio owing to the presence of a watershed across the ancient valley. Nor under present-day topographical

([1] GAZEL, 1956. GEO. 19

conditions is it possible for the Faro to be diverted into its former valley and to flow directly towards Jobolio instead of towards Wuro-Boki.

As will be explained under c. the formation of a watershed across the ancient valley, forcing thereby the Faro to abandon this valley, has been the result of tectonic movements accompanied by faulting of the Cretaceous sandstones and volcanic activity. One of the volcanoes was formed near Wuro Boki on the 170 m (560 feet) erosion surface, indicating that these tectonic movements must have occurred during a rather recent geological period.

b. *Stratigraphy*

(i) *Basement Complex*

The oldest rocks of the region under consideration belong to the Basement Complex. Rounded blocks of fine-grained, slightly-coloured granite have been found at the foot of the Vere Hills near the Yola-Karlahi road. To the south of Beti some low hills in the valley of the Toja River were observed, consisting of granites. The Vere Hills and the Alantika Mountains are composed of granites, schists and gneiss. As the occurrences of Basement Rocks are situated to the south of the area concerned they do not figure on the Geological Map 3.4.7-1. The hills situated along the footpath from Beka to Karin probably also consist of Basement Rocks. The contact between the Cretaceous Rocks and the Basement Rocks lies here about 7 km. (4 miles) south of Beka.

(ii) *Cretaceous deposits*

The Cretaceous deposits consist predominantly of sandstones, outcropping over wide areas in the Bagele Hills, the Dasin-Gurin ridge, near Jobolio and at the foot of the Vere Hills. The sandstones, which are reddish to yellow in colour, are arkosic. False bedding is a common feature. Some layers of gravel are interbedded in the sandstones which generally are fine to medium grained. Near the Vere Hills they are coarser, however, and contain layers of gravels with rounded pebbles of quartz granite and schists of the Basement Complex. The sandstones of Jobolio contain thin lenticular beds of sandy shales, which have been observed in the outcrops as well as during reconnaissance drilling. According to information provided by the Geological Survey Department, drilling near Yola and Jimeta has indicated the presence of considerable quantities of claystones and shales in between the sandstones. From this fact it may be concluded that claybeds and shales become more and more abundant in the Cretaceous series when going westward from Dasin towards Yola.

It is suggested that the sandstones were deposited originally in a delta north of the Vere Hills and the Alantika Mountains, where debris from the Basement Rocks of these hills and mountains were accumulated.

The sandstones of the Bagele Hills are considered by the Geological Survey Department to be of Lower Cretaceous age (Albian to Cenomanian), and the outcrops of most of the sandstones south of the Benue are therefore assumed to be of the same age. Some thin beds of limestone, which consist of a coquina (a shell breccia) with fragments of oysters, occur on the slope of a hill south-west of Ribadu. In these beds some ammonites have been traced, which proved to be of Lower Turonian age (Bauchioceras Nigeriense Woods and Gombeoceras Gongilense Woods, identifications made by the Geological Survey Department). These limestones, each layer of which is less than a few feet thick, are interbedded in shales or sandy shales. At the base of the shales and limestones lie the Lower Cretaceous arkosic sandstones of the Bagele Hills and of the Dasin-Gurin ridge. Other sandstones have been observed topping the shales. The latter, more recent sandstones, are light-coloured and thin-bedded at their base, but towards the top they assume the same aspect as the lower sandstones. It is possible that these more recent Turonian sandstones are present elsewhere on top of the older sandstone series, but the Lower

Turonian limestones or shales which would have enabled the boundary to be traced between the various sandstone formations were missing there.

Blocks of similar limestones and coquina beds have been found east of Ribadu on a low hill containing a very badly preserved ammonite. These limestones are accompanied by some volcanic tuff, basalt and metamorphic sandstone. Other blocks of limestone were found at an earlier date by Mr. Carter of the Geological Survey Department in the region between Ribadu and Dulo. It may therefore be assumed that these limestone beds once had a far greater extent and that they can be correlated with other limestones of the same age outcropping between Yola and Numan.

A similar sandstone series with associated volcanic rocks extends eastward into the French Camerouns as far as beyond Garua. They are attributed by the French geologists to the Upper Cretaceous. No definite information was obtained regarding the thickness of this sandstone formation which in any case is considerable near the Benue Valley. The geologists of the Geological Survey Department mention a thickness of several hundreds of metres, whilst estimates in the French Camerouns amount to as much as 700 m (2,300 feet) ([1].

The sandstones are very impermeable because of their arkosic composition, as their feldspar components on weathering form clayey products. This conclusion is corroborated by observations made in water wells and in reconnaissance boreholes made by the Geological Survey Department.

(iii) *Pliocene and Quaternary deposits*

Fluviatile and continental deposits dating from different periods of the Pliocene and the Quaternary cover wide areas. They are here subdivided into the following groups, which, however, do not represent chronological subdivisions:

1. the sediments of the ancient Benue-Faro Valley;
2. the sediments of the recent Benue Valley; and
3. other fluviatile and continental deposits.

Ref. 1. The sediments of the ancient Benue-Faro Valley.

Alluvial deposits of unknown thickness form the fill of the former Benue-Faro Valley between Jobolio-Dasin Pagan and Beka. Natural cuts in river-banks as well as shallow reconnaissance boreholes testify about the composition of the upper part of these deposits. A layer of clay or silt, which varies in thickness from 1 to 3 metres (3 to 10 feet) lies on top of coarse sandy deposits in the central part of the valley. Near its borders the top layer of clay has been found to lie in places directly on weathered beds of the Cretaceous sandstones (borehole Gurin 1). Borehole profiles are shown on Diagram 3.4.7-5 and grain-size distribution of samples taken on Diagram 3.4.7-6. The boring near Beka showed the following sequence from the surface downward:
3 m (10 feet) of brown and bluish clay;
1 m (3 feet) of sand with some gravel, and solid sandstone (Cretaceous).

The sequence observed in borehole Jobolio 2 consisted of 1 m of brown silt, followed by sand and gravel down to the bottom of the hole. The borehole was stopped at a depth of 10 m (33 feet) without the bedrock being attained.

The interpretation of the results of borehole Gurin 2 is more difficult. From the surface downward were found:
1 m of humus;
1 m of red clay containing laterite, and brown quartz-sand, slightly clayey.

It was impossible to decide whether the sand represents a much-weathered Cretaceous sandstone or a fluviatile sand (Diagram 3.4.7-5).

([1] ROCH, 1953. GEO. 37

The coarse-grained sand deposits have also been observed in the banks and the river-bed of the River Bamoi (a tributary of the Toja), of the River Toja to the west of Lake Parda, and of small streams to the east of Lake Parda. As a result of their light-coloured sandy bottom several of these streams show clearly on the aerial photographs against the surrounding dark clay deposits.

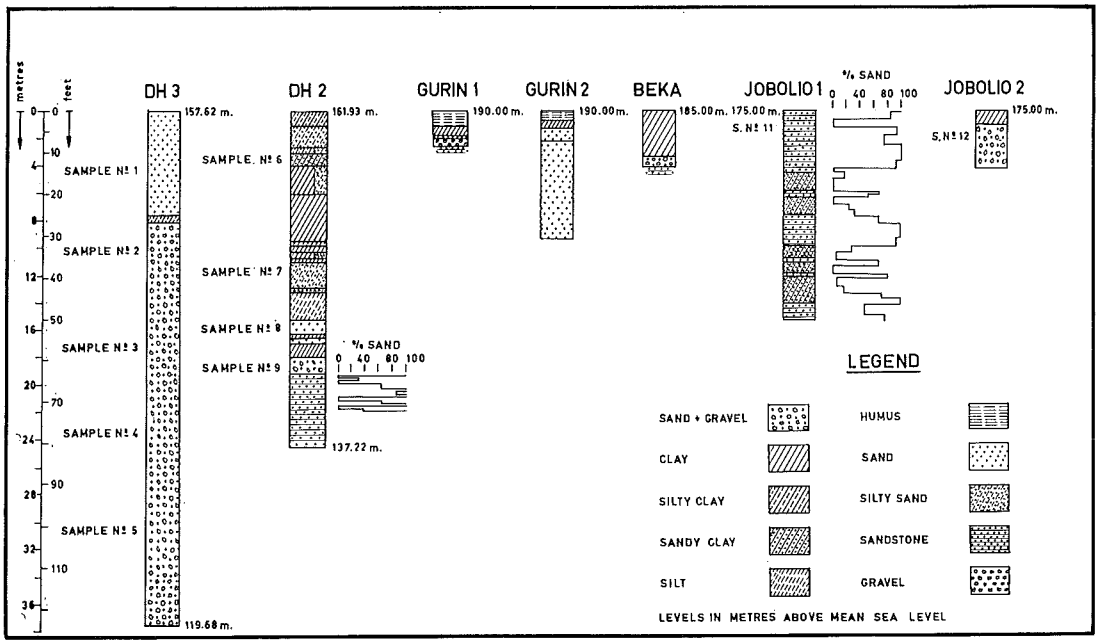


DIAGRAM 3.4.7-5

Borehole profiles

The sites are shown on Diagram 3.4.7-1

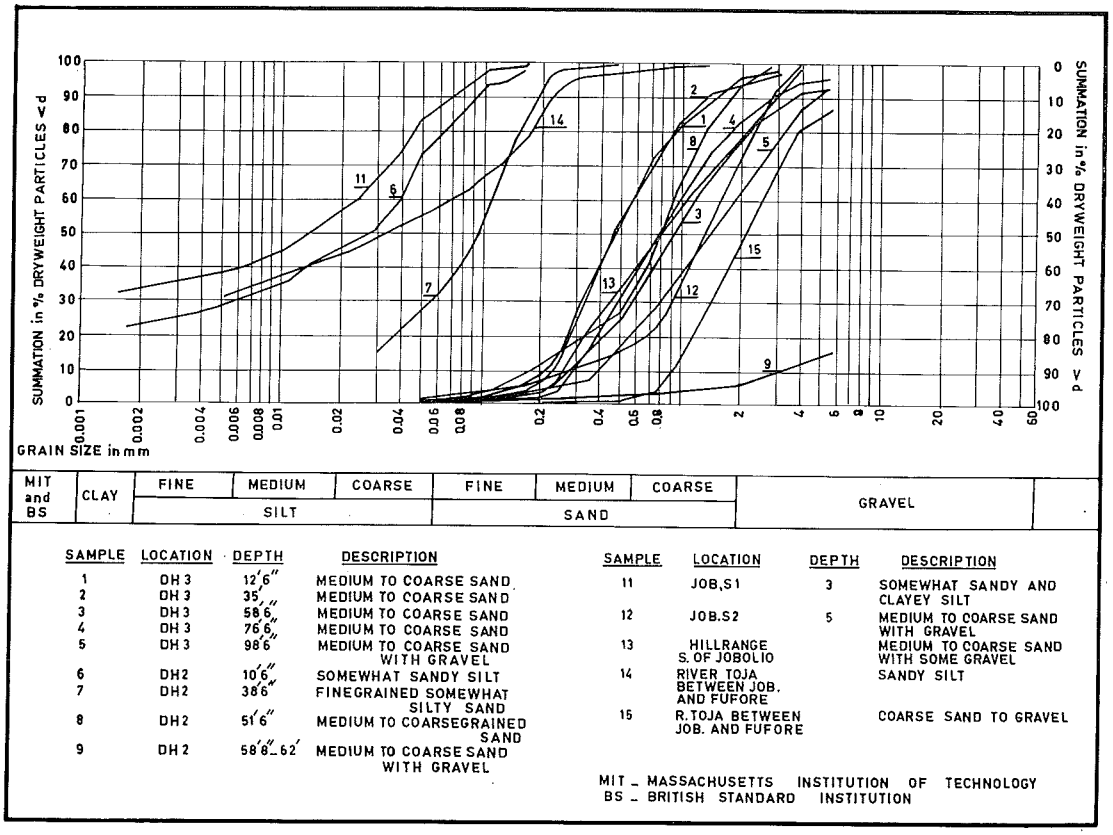
The topography of the former Benue-Faro Valley shows much resemblance to the present river-valley of the Faro System, with lower and higher islands, sand-bars and old meandersl which are less evident, however, in the dried-up valley owing to the eroding effects of rainfal, and other agents.

South of Jobolio a branch of the ancient Benue-Faro Valley was observed. At present a low hill exists between the footplain of the Vere Hills and the sandstone ridge of Jobolio, which is partly covered by a thin layer of clay. It is composed of at least 4 m (13') of coarse, cross-bedded alluvial sands and is believed to be an old sand-bar of the former river system.

In Diagram 3.4.7-6 grain-size diagrams are given of some sand and silt samples from the ancient Benue-Faro river system.

Ref. 2. The sediments of the modern Benue Valley.

In the river-bed of the Benue medium and coarse sand is found. Sand-banks and bars are a common feature (see Photograph 3.4.7-3). On the footplains clay and clayey silt has been deposited in layers much varying in thickness. In the area situated between Dulo and Ribadu the alluvial deposits have been found up to the highest flood-level. Investigations with the aid of boreholes made near Dasin Hausa proved the existence of a thick fill of coarse sands with very few and thin clayey layers underneath the present bed of the Benue. The borehole Dasin 3 has



SAMPLE	LOCATION	DEPTH	DESCRIPTION
1	DH 3	12'6"	MEDIUM TO COARSE SAND
2	DH 3	35'6"	MEDIUM TO COARSE SAND
3	DH 3	58'6"	MEDIUM TO COARSE SAND
4	DH 3	76'6"	MEDIUM TO COARSE SAND
5	DH 3	98'6"	MEDIUM TO COARSE SAND WITH GRAVEL
6	DH2	10'6"	SOMEWHAT SANDY SILT
7	DH2	38'6"	FINEGRAINED SOMEWHAT SILTY SAND
8	DH2	51'6"	MEDIUM TO COARSEGRAINED SAND
9	DH2	58'8"-62'	MEDIUM TO COARSE SAND WITH GRAVEL

SAMPLE	LOCATION	DEPTH	DESCRIPTION
11	JOB,S1	3	SOMEWHAT SANDY AND CLAYEY SILT
12	JOB.S2	5	MEDIUM TO COARSE SAND WITH GRAVEL
13	HILLRANGE S. OF JOBOLIO		MEDIUM TO COARSE SAND WITH SOME GRAVEL
14	RIVER TOJA BETWEEN JOB. AND FUFORE		SANDY SILT
15	R.TOJA BETWEEN JOB. AND FUFORE		COARSE SAND TO GRAVEL

MIT - MASSACHUSETTS INSTITUTION OF TECHNOLOGY
BS - BRITISH STANDARD INSTITUTION

DIAGRAM 3.4.7-6

Grain-size distribution of soil samples

stopped at a depth of 32.7 m (108 feet) in the sandy deposits, without the bedrock having been attained. As the depth of the valley fill near Garua proved to be 40 m (130 feet), it might be even deeper at Dasin (Diagram 3.4.7-7).

Ref. 3. Other fluviatile and continental deposits.

These deposits are of no importance to the problems at hand and therefore have not been studied here. They are, however, mentioned to complete the geological description.

The footplain north of the Vere Hills is covered with a blanket of recent alluvial deposits. Other alluvial deposits, consisting of cross-bedded sand-layers, silt and clay, which show some resemblance to the Chad deposits, have been observed in the valley of the River Toja to the south of Beti. The modern river has eroded its river-bed into these deposits.

On the southern side of the sandstone hills between Dasin and Gurin water wells show the presence of 8 m (26') of red silty sands, capped by a laterite about 1 m thick on top of the sandstones. On top of the laterite hardpan a layer of about 1 m of red lateritc soil is to be found. In some wells blocks of white sandstone were observed at the base of the laterite, underneath which the sandy deposits showed yellowish and white colours.

(iv) *Volcanic rocks*

Apart from the Cretaceous volcanic rocks found east of Ribadu together with some limestone

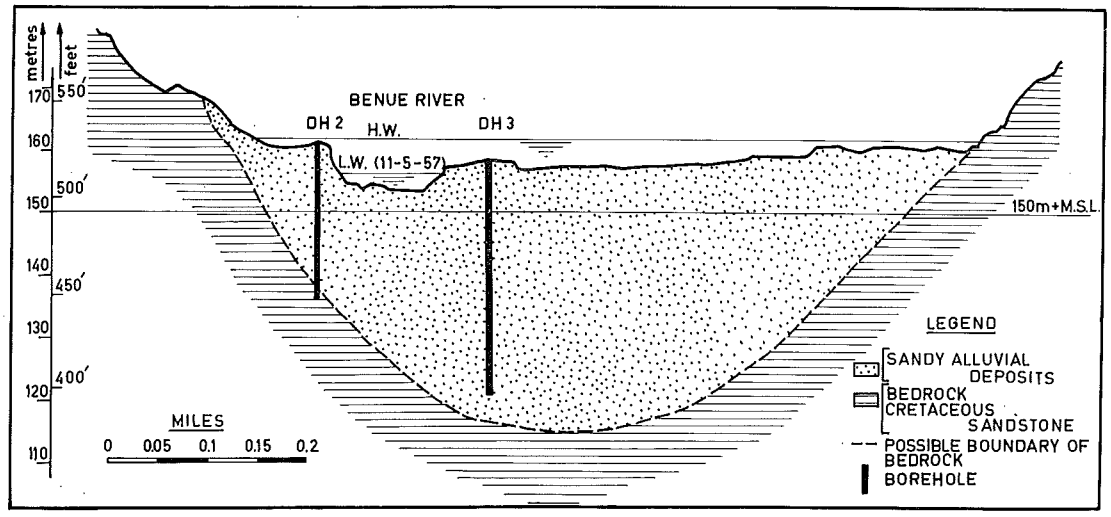


DIAGRAM 3.4.7-7

Cross-section of the Benue at dam-site, Dasin Hausa

and coquina beds, volcanic lavas were observed in the region under consideration which might be of recent or sub-recent age. Four volcanoes were found in a NNE line corresponding to a fault (see Diagram 3.4.7-1) namely,

No. 1 west of Wuro Boki, north of the Benue: a small volcano, about 25 m (80 feet), consisting of basalt. The volcano was formed on the 170 m (550 feet) erosion surface, indicating its rather recent age.

No. 2 east of Ribadu: basalt and tuff has been found, which might be a remnant of a volcano.

No. 3 south-south-west of Ribadu: a 20 m (65 feet) high volcanic cone, consisting of white rhyolithic lavas, tuffs, and metamorphic sandstone. A fault plane is visible at this place.

No. 4 at some distance south-south-west of the latter: the remnants of another volcanic cone, where similar rhyolithic lavas and tuffs were observed.

Outside the area mapped other volcanoes have been noted: for instance, near the road from Yola to Numan, where three volcanoes rise above the plain along the River Ini. Many more volcanoes are indicated on the maps prepared by the Geological Survey Department north of the Benue and west of the Gongola. The aerial photographs of the area around Kiri on the Gongola show some of these volcanoes to be situated on fault zones. Likewise the geological map of the French Camerouns indicates volcanoes with associated rhyolithic and basaltic lavas in the Benue Valley situated along faults.

(v) *Tectonic structures*

The tectonic structures observed are not complex. The sandstones of the Bagele Hills are gently folded into an anticline. In the south-eastern part of the hills, near the villages of Dasin, they show a southern dip of mostly no more than 6°. Eastward and westward the strike of the beds varies somewhat, while the dip remains gentle. The sandstones south of the Benue have the same average dip southward. Some minor secondary folding was observed but nowhere does it affect the problems investigated.

Faults were observed at several places and presumably they are present in other areas. A

major fault, hidden by recent or sub-recent deposits, has been assumed north of the Vere Hills, forming the boundary between the Cretaceous sandstones and the Basement Complex.

A few faults crossing the Benue with a NNW direction have been observed. Mirrors were found on their fault planes, on which the striae indicate movements in a horizontal direction. These faults occur in parallel groups in certain zones only, found east of Dasin Pagan, and west and east of the hills of Dasin Hausa. Another fault, NNE directed, showing also traces indicating horizontal displacements, is associated with the volcanoes found near Ribadu.

Still another fault with NNE direction was found north of the Benue opposite Dasin Hausa, resulting in the steep slope of the Bagele Hills in that place. Probably this fault continues across the valley along the steep west side of the hills of Dasin Pagan. This, however, remains to be proved. Important sets of joints and fissures were observed with an east-west direction. They end against the fault planes mentioned above, and they show no indications of displacements along them.

The major faults and fault zones are indicated on Diagram 3.4.7-1. The trends of the observed faults often show a curvature towards the north. Faults along which movements with a vertical component occurred have not been observed. The faulting probably was accompanied by a slight upwarping of part of the area along an axis with the same NNE direction. This axis of upwarping crosses the former Benue-Faro Valley, and as a result of the tectonic movements a watershed has been formed across this valley.

The latest tectonic movements must have occurred in a rather recent geological period, as they postdate the formation of the ancient Benue-Faro Valley and are accompanied by a recent phase of volcanic activity.

c. *Geological and morphological history of the Yola-Ribadu area*

The observations and features described in the foregoing pages seem to point to certain conclusions regarding the geological and morphological history of the area situated along the Benue River between Yola and Ribadu, embodied in the following description of the geological history of the area after the Pliocene.

Some diagrams have been prepared to illustrate the development of the Yola-Ribadu area and the shifting of the Benue and Faro valleys in this area.

In Diagram 3.4.7-8, Stage A illustrates the earliest stage. At one time the Upper Benue discharged into the Faro near Beka. The River Kilunga, transporting the greater part of the erosion products from the eastern part of the Bagele Hills, and a small river which descended from the 220 m (720 feet) erosion level south of the Bagele Hills in the neighbourhood of Ribadu and Dasin Hausa, joined the Upper Benue near Wuro Boki. From Beka onward the Benue-Faro River followed a course between the footplains of the Vere Hills to the south and the hills of Dasin-Gurin to the north. The River Toja debouched into this valley, taking large quantities of granitic sands into the main valley. This Benue-Faro River joined the valley of the present-day Benue between Yola and Jobolio.

Stage B shows a later period. The Benue-Faro River shifted its bed slightly eastward in the Jobolio area, flowing then between Jobolio and Furore, while the old bed south of Jobolio was obstructed by a sand-bar. During the same period an eastern confluent of the river, near Dasin Pagan, cut a valley into the 220 m (720 feet) erosion level south of the Bagele Hills, while the confluent near Wuro Boki continued the downcutting of its valley into the same hills. Faulting accompanied by volcanic activity near Dasin and Wuro Boki probably had already started, thus weakening the sandstone beds along the fault zones and thereby promoting the erosion of lateral valleys.

During the next stage, indicated as stage C, continuous tectonic movements, combined

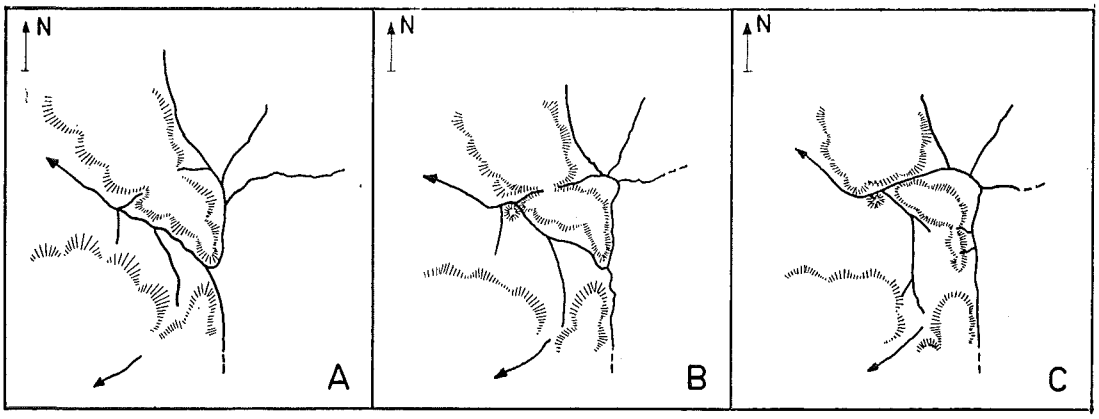


DIAGRAM 3.4.7-8

The genesis of the Faro-Benue Confluence

with a further downcutting of the valleys of the confluents of the Upper Benue between Wuro Boki and Dasin Hausa and of the Benue-Faro between Jobolio and Dasin Pagan, resulted in a capturing of the Upper Benue by the Dasin Pagan Valley, while the Benue-Faro Valley became barred to the east of Padaro by an axis of upwarping. The Benue now flowed through the canyon between Dasin Hausa and Dasin Pagan, whilst the Faro adopted the Benue Valley between Beka and Wuro Boki and flowed into the new river-bed and canyon of the Upper Benue.

This newly-established river system got deeply entrenched, as was the case with the Upper Benue Valley (for instance, near Garua and Lagdo), the Lower Benue Valley, (as indicated by the boreholes made in the valley near Makurdi) and the Lower Niger (as may be deduced from the borehole results near Onitsha). The downcutting of the Valley to a level at least 40 metres (130 feet) below the river-bed of the modern Benue River probably was related to a considerable eustatic lowering of the sea-level contemporaneous with a period of glaciation.

During this period also the River Logone was probably diverted from the Chad Basin and drained into the Upper Benue, augmenting its flow markedly.

A subsequent rising of the sea to approximately its present level caused the rivers to adjust their valleys to the new conditions, and deposition of huge quantities of sand took place in the valleys of the rivers which raised their beds until the situation of to-day was reached. In the meantime, the supply of sand by the Kilunga and most of all by the Faro River, unbalanced by the water-supply of these rivers and of the Upper Benue reduced by the loss of water draining through the Logone towards the Chad Basin, formed the broad plains around the confluence of the Benue and Faro (see Photograph 3.4.7-3). These points have been discussed more fully in 3.1.2 c. whilst the periods are indicated in Table 3.1.1-1.

d. *Groundwater development*

Although entirely out of the scope of this investigation, the results of this study quite accidentally permit some interesting observations on the possibilities of ground-water development in the Yola region. The reconnaissance drilling carried out by the Geological Survey Department in the Yola-Jimeta area shows that the authorities are concerned with this problem.

The Cretaceous sandstones, because of their poor permeability, are not very promising from the point of view of water supply. The geological constitution of the ancient Benue-Faro Valley, however, forming a very dry area with the exception of the marshes of Lake Parda, offers much

more favourable conditions. As a matter of fact, the coarse sandy deposits which fill the ancient valley below the topmost clay beds form an excellent aquifer at a shallow depth only. Considerable ground-water reserves are available because of the size of the valley. Moreover, if there should be a development of the ground-water resources of the area, a sufficient natural recharge can be counted upon by water infiltrating from the Faro River near Beka and Gurin as well as from the River Toja and other streams which have cut their courses through the clay-beds into the sands. This might be of importance if reclamation of this area, now very poorly populated for hygienic reasons, is ever planned.

3.4.8. Gongola Defiles (Dadin Kowa, Kombo, Kiri-Bobore)

a. *General geology*

During a short visit to the Lower Gongola some geological observations have been made. Much useful information has also been obtained from specially-prepared aerial photographs and from reports of the Geological Survey of Nigeria with attached geological maps, which have given the necessary background information on the main geological trends in this area. The reports ([1—7 proved to be especially valuable. Only a few pertinent data on the general geology of the Gongola Valley will be given here. The stratigraphical sequence, from recent to old is as follows:

Longuda basalt: consisting of plateau basalt (Iddingsite basalt);

Lamja sandstone: consisting mainly of well-bedded sandstones with ordinate shales;

Numanha Shale: clay-shale series with occasional nodular mudstone and sandstone bands;

Sekude Formation: limestones and shales;

Jesu Formation: blue-grey shales with interbedded mudstones and rare thin bands of crystalline limestone;

Dukul-Kanawa Formation: clay shale facies with bands of nodular, crystalline or shaly limestone forming impervious beds;

Yolde Formation (transition beds of shallow water to marine sedimentation): succession of grits, sandstone, clay shales with occasional thin impure limestones having maximal thickness near Dadin Kowa;

Bima sandstone: coarse arkosic grits with subsidiary sandstones and ironstones; and

Basement Complex: consisting mainly of granite with some subsidiary granite gneiss.

Volcanic plugs occur frequently in this area; they consist of olivine basalt, which may show columnar cleavage.

Except for the Longuda basalt, these formation are cut in by the Gongola.

The deposits mentioned above show distinct features caused by tectonic movements. The sedimentary deposits have been folded into a great number of anticlines, while considerable faulting is apparent in several places.

b. *Dadin Kowa Defile*

A little to the north of the ferry near Dadin Kowa a considerable narrowing of the Gongola Valley occurs, when the river cuts through the south-western part of the Bima Range (Photo-

([1 BARBER and TAIT, 1953. GEO. 1
([2 TAIT, 1954. GEO. 40
([3 THOMPSON, 1951. GEO. 43
([4 THOMPSON, 1951. GEO. 44
([5 THOMPSON, 1951. GEO. 45
([6 THOMPSON, 1955. GEO. 46
([7 GROVE, 1956. GEN. 14

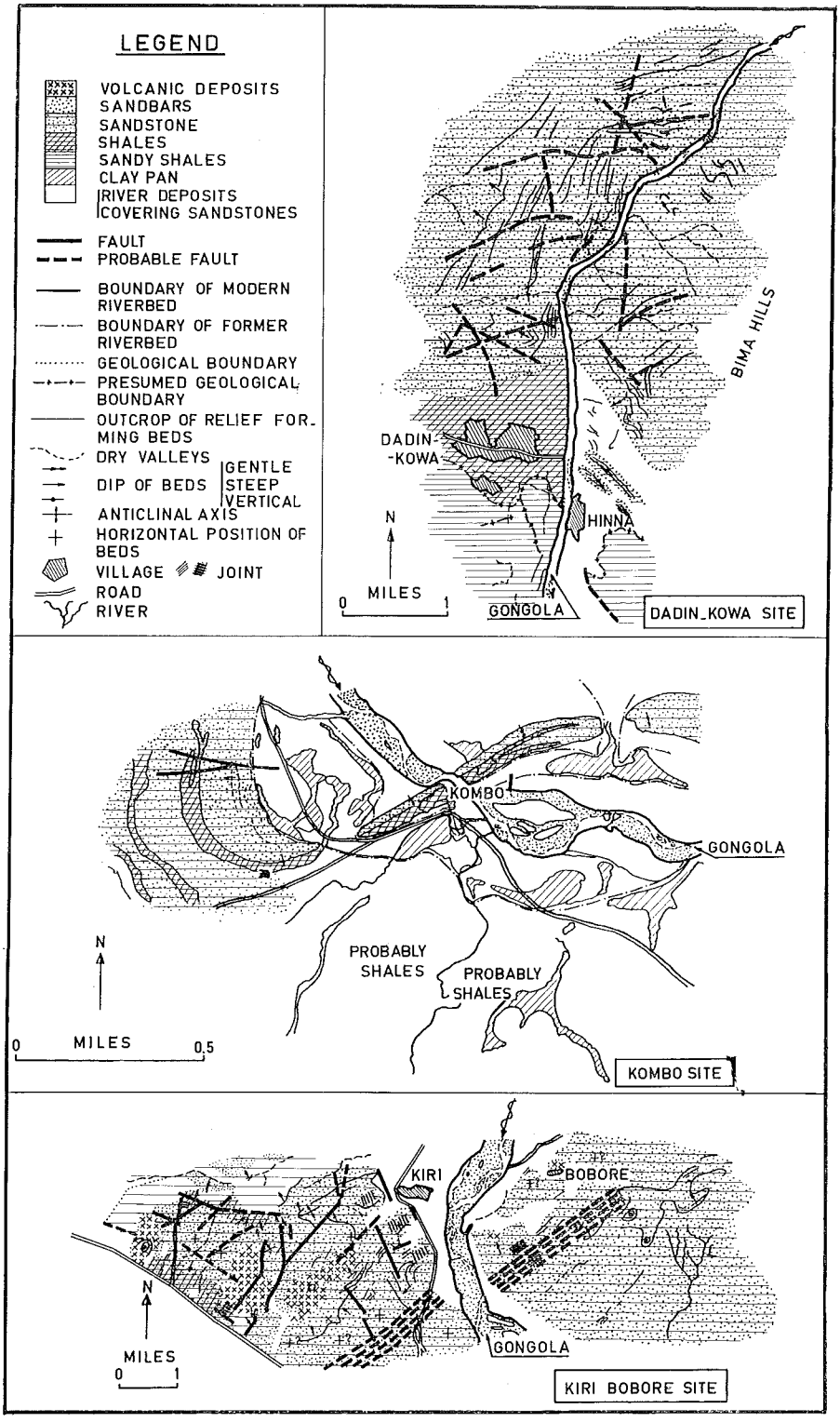
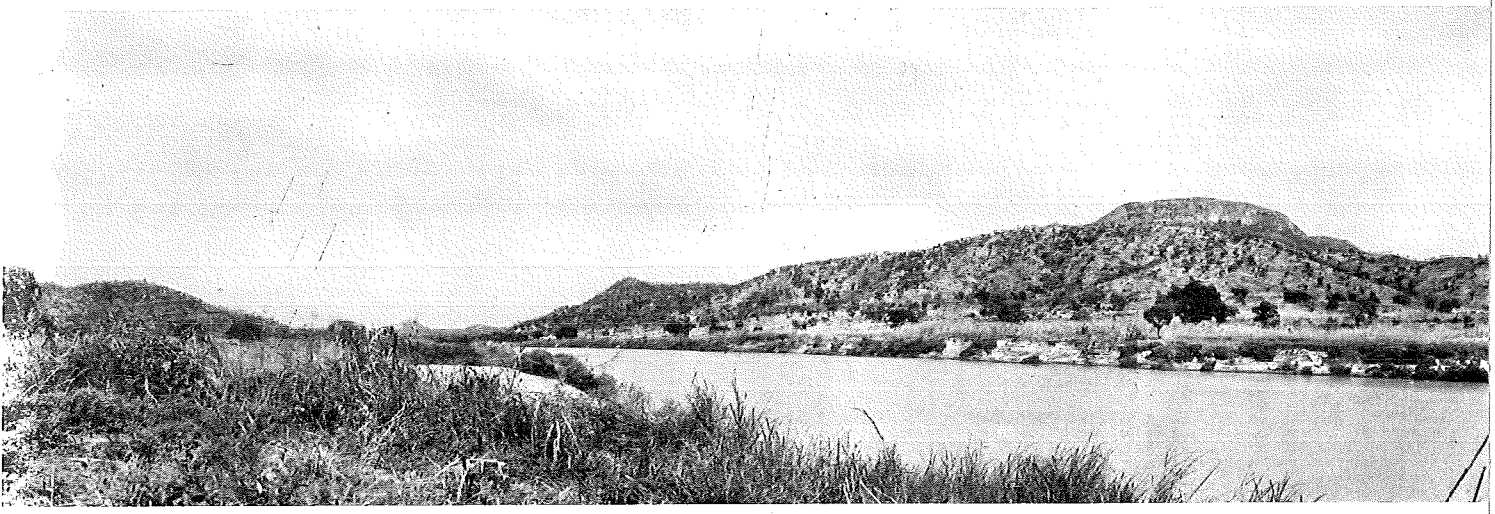


DIAGRAM 3.4.8-1

Geological maps of Gongola sites at Dadin Kowa, Kombo and Kiri-Bobore



PHOTOGRAPH 3.4.8-2

Dadin Kowa site, north of the village, viewed upstream

On right hand, Bima Hills (sandstone) with fault-scarp

graph 3.4.8-2). Upstream of the narrow gorges wide and flat, sometimes marshy, plains stretch along the River Gongola as far as Bajoga. The Bima Range being connected with the high area of the Biu Plateau and westward through an area of dissected but rising ground with the Gombe Plateau, the Gongola gorges upstream of Dadin Kowa appear to be a suitable site for a reservoir dam. The geology of the site has been indicated on the attached Diagram 3.4.8-1.

The hills adjoining the gorge are rather steep, the high-water terraces on both sides of the river do not exceed a width of 30 or 40 metres or yards, and the bottom of the valley is about 150 to 200 m (500 to 600 feet) wide.

The underground of both the valley and the bordering hills consists of banks of cross-bedded crumbly arkosic sandstone, belonging to the Bima Sandstone Formation. The layers, which vary in thickness, are intercalated with thin layers of ironstone. They are folded and, forming the northern limb of an anticline, show gentle dips upstream (north-westward). Sets of rather widely-spaced joints occur, some of them forming open fissures and others being cemented by ferruginous crusts.

The Bima and Wada ranges, situated north of Dadin Kowa and formed by these sandstones, are bordered to the south by considerable fault-scarps. Major faulting along a SW-NE direction has occurred in this area, and both in and south-east of the Bima and Wada ranges granites of the Basement Complex are found.

An important fault cuts across the Gongola Valley, in the vicinity of the ferry of Dadin Kowa, where shales, sandy shales and steeply-dipping sandstone beds, all of them belonging to the Yolde Formation, are in contact with the Bima Sandstone.

Many secondary faults occur in the Bima Sandstones, either parallel to or at an angle with the main fault zone. The drainage pattern of the small tributary valleys in the area of the sandstones has been largely determined by the faults and joints. For a discussion of the possibilities of the construction of a dam, reference is made to VI, 8.1.9.

c. *Kombo*

The following has been based primarily on field observations and on a study of aerial photographs. A geological sketch is shown on Diagram 3.4.8-1 and a view of the narrow site in Photograph 3.4.8-3.

The village of Kombo is situated where the Gongola breaks through a ridge consisting of sandstones and marls. The axis of the ridge consists of well-bedded arkosic sandstones, the total

thickness of which is only 30 or 40 metres (or yards) and standing out as a wall, considerably narrowing the valley at both sides. The gap between the protruding walls of sandstones measures approximately 200 m (650 feet). To the casual observer the site appears very suitable for the construction of a reservoir dam with the wide plains upstream of the site serving as a reservoir.

The sandstone ridge of Kombo represents the northern limb of a syncline, the layers showing a steep dip downstream. To the south they are bordered by shales with sandy intercalations and some very thin beds of limestone attributed to the Yolde Formation and to the Dukul Formation. To the north the sandstone ridge of Kombo is also bordered by soft deposits, presumably shales, into which the Gongola and its tributary streams have cut a wide plain, from which rise some hills consisting of thick-bedded sandstones belonging to the Bima Formation. The sandstones of the ridge near Kombo show some shaly intercalations which increase in thickness in a westward direction and which die out to the east of the river. At the same time, the sandstone beds thin out westward and become thicker in an eastward direction. The sandstones and shales thus form a transition zone between the Yolde Formation and the Bima Formation.

The the west of the river the ridge extends south-westward for nearly a mile as a single sandstone bar, its beds dipping steeply southward. Then it divides into a set of separate, parallel-running ridges which turn away to the north. At the same time, the strike of the beds changes from NE-SW to nearly N-S, whilst the dip becomes westward and much gentler. A small fault with an east-west direction is apparent in the thus-formed anticline. The fault probably continues eastward, crossing the Gongola at the narrows and following the river until it cuts again through a hilly ridge about $3\frac{1}{2}$ miles downstream from Kombo, where the hills show a distinct off-set on the topographical map, probably under the influence of an important east-west fault.

To the east of the river the ridge extends eastward for at least 4 miles, the beds mostly showing very steep southward dips. Locally they are vertical or even slightly overturned with very steep northward dips. North of the ridge, in the axial zone of the anticline, some steep-sided hills emerge from the plain, consisting of horizontal massive sandstone beds followed to the north and the north-east by others more rounded hills of Basement Rocks (see photograph). Well-developed sets of north-south directed joints have been observed in the sandstones.

Apart from the folded and faulted formations already mentioned, other deposits are found much more recent in age. They occur along the bottom of several valleys, some of which represent abandoned courses of the Gongola River and consist of alluvial sandy and clayey sediments.

PHOTOGRAPH 3.4.8-3

Kombo site viewed upstream

Breach in Cretaceous sandstone ridge. On right hand Basement rocks of Kwąba Hills.
Smoke from bush-fire

It appears from the geological and morphological analysis of the aerial photographs that the River Gongola has shifted its bed several times. The abandoned valleys have been indicated on Diagram 3.4.8-1. One valley crosses the ridge of Kombo nearly one mile south-west of Kombo and another crosses the ridge a little more than a mile north-east of the village. The ridge thus shows two gaps, apart from the actual river-bed of the Gongola near Kombo. In between these gaps the ridge has everywhere about the same height, rising approximately 10—12 m (30—40 feet) above the highest flood-plains of the river.

d. *Kiri-Bobore*

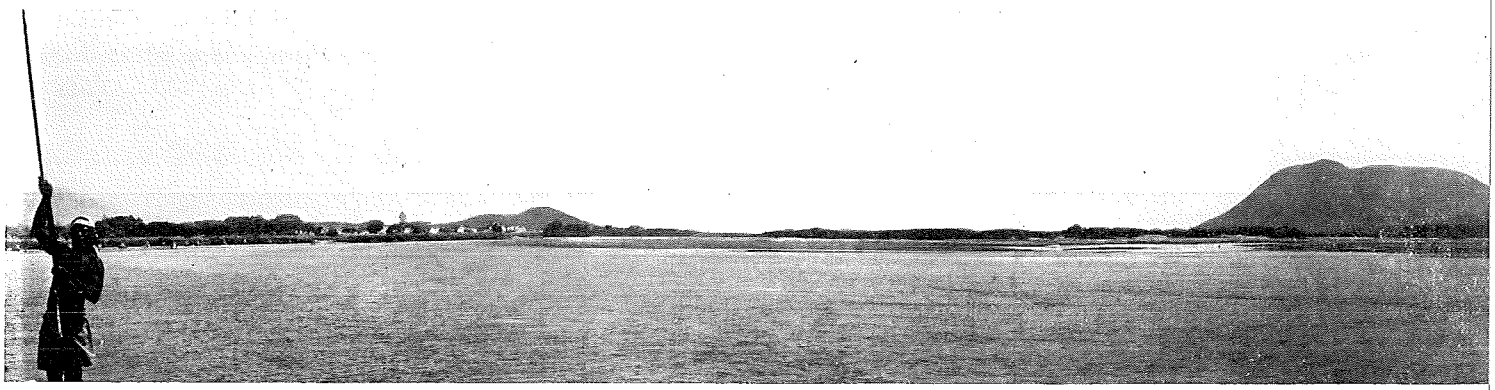
The following has been based primarily on a study of aerial photographs and on field observations. A geological sketch is shown on Diagram 3.4.8-1.

The village of Kiri is situated where the Gongola, here combined with the Hawal, breaks through a hilly area consisting of sandstones. Upstream of the relatively narrow valley, wide and flat, sometimes marshy, plains stretch along the River Gongola beyond Shellem and as far as Kombo. The hills near Bobore, east of the river, extend north-eastward for about $3\frac{1}{2}$ miles and are connected by a slowly-rising area with the Kaji Hills and the hilly country around Song. The hills near Kiri, west of the river, extend west-south-westward for about 4 miles. They are separated from the high-lying Longuda plateau by a featureless plain, which almost imperceptibly slopes southward towards Givone and the Benue near Numan. Accurate data about the altitudes of the lowest parts of the watersheds between Kiri and the Longuda plateau and between Bobore and the Kaji Hills are not yet available. The aerial photographs and the preliminary sheets of the 1 : 100,000 topographical maps at hand indicate, however, that in these watersheds some very low saddles may occur.

The geological features of the hills east and west of the Gongola near Kiri and near Bobore are illustrated on the geological sketch-map. They consist of arkosic sandstones with iron crusts, attributed to the Bima Sandstones. To the north and to the south of the hills shales are found with presumably thin beds of sandstone (Yolde Formation and probably Dukul Formation). These deposits are strongly folded and faulted, forming a distorted and deeply-eroded anticline. During a geologically recent time, when the deposits had already been strongly subjected to the erosion which resulted in the forming of deep valleys mostly along fault zones, volcanic activity took place. The volcanoes are situated on faults and faults zones, some of which might have been formed at the time of the volcanic activity, but mostly seem to be older rejuvenated faults.

Seven volcanoes are indicated on the geological sketch map, four to the west of the river and three to the east of the Gongola. They are not all of the same type. Three of them produced a considerable quantity of effusive rocks (lava, ashes and lapilli), volcanic cones came into being and in one case even a deeply-entrenched ancient valley, which extended from Kiri south-westward, was filled up. All of these volcanoes are situated west of the Gongola River. One small volcano south-south-west of Kiri and all volcanoes situated east of the river are of a very different type, resembling more or less the maares in Europe, and consisting of a low circular wall around a flat-bottomed area with a diameter of a few hundred yards. They probably originated with a single explosion, followed by a very small quantity of effusive rocks only, which now form the circular walls and cover the bottom of the structure. Sedimentary formations and volcanoes have been subjected to further erosion and in several places alluvial fans have been deposited. A considerable quantity of alluvial deposits occur also in and along the river-bed of the Gongola, with sandbanks in the river and clay-topped flood-plains.

The sandstones to the west of the river still form a massive area of steep hills with deep valleys. The sandstones, folded into an anticline, are cut by major faults and by closely-spaced sets of



PHOTOGRAPH 3.4.9-1

Dalli site viewed upstream

On both sides hills of Basement prophyric granites, covered by Cretaceous sandstones

joints. The faults are mainly running NW-SE and NE-SW, the principal set of joints being NW-SE directed. To the east of the river the more deeply-eroded sandstones form almost isolated steep-sided hills separated by undulating plains and platforms. Near the river, joints and faulted zones are still very much apparent but farther to the east the sandstones are much less disturbed, showing only gentle dips, or becoming nearly horizontal.

The Gongola Valley traverses the sandstone hills at the crossing of two major fault-zones, each of which has a width of several hundred metres (or yards). The SW-NE directed fault-zone is very clear on the aerial photographs, as an area with sandstones fractured and jointed to such an extent that on the photographs a distinction cannot be made between fractures, points and bedding planes. This zone shows a considerable throw at the site where it crosses the river-bed, indicating horizontal movements along the more recent NW-SE fault-zone. The latter is not easily perceptible, as the river-bed follows it, but it becomes apparent by its results and the accompanying parallel faults and joints.

3.4.9. Dalli Defile (Taraba)

A reconnaissance trip was made along part of the Taraba Valley to try and find sites suitable for a reservoir dam. The only narrow place on the lower course was found near Dalli, about midway between Beli and Gassol.

The cross-section of the Valley at its narrowest point is still relatively wide (about 2,000 m or 7,000 feet); the bordering hills are gently sloping. The main topographical and geological features of the area are illustrated by Photograph 3.4.9-1 and Diagram 3.4.9-2.

In contrast to the indications on the geological map of Nigeria, published by the Geological Survey Department, which in this special area proved to be not quite accurate, the subsoil of the dam-site and its surroundings consists of rocks of the Basement Complex, being mainly porphyric granites. They show several veins and dikes, as well as a distinct lineation pattern which probably represents lines of structural weakness of the rocks, such as faults or fractures. The location and the direction of the valley have obviously been determined by these structural lines, which tend to run parallel to the river and to abandoned stream channels still visible on an erosional terrace occuring west of the valley.

The floor and the sides of the valley are formed by rocks of the Basement Complex with the exception of the river-bed of the modern river, filled with medium and coarse sand. Along the banks of the river and on some of the islands and sand-bars some silty and sandy clay has been observed. The study of the aerial photographs of the site has revealed, moreover, a possible occurrence of some small and isolated outcrops of granite in the river-bed.

The depth of the alluvial fill below the river-bed is not known. In view of the fact, however,

that the major rivers and some of their tributaries at several places have deeply-entrenched and sometimes canyon-like buried valleys lying underneath their present river-bed, it may well be possible that the valley of the Taraba shows similar characteristics.

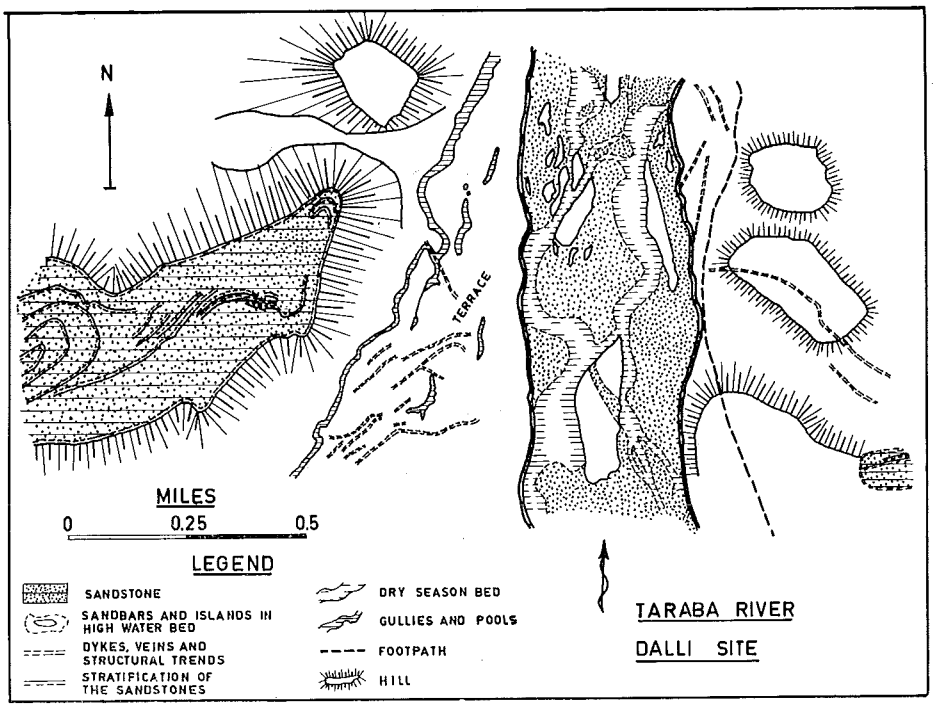


DIAGRAM 3.4.9-2

Geological map of Dalli site

Other sedimentary rocks, for instance thick-bedded sandstones belonging to the Cretaceous Formation and lying discordantly on the rocks of the Basement Complex, have been observed on top of the high hills east and west of the valley, representing the remnants of a dissected plateau with a gentle north-west dip.

3.4.10 Makurdi Defile (Benue)

In the normally very wide valley of the Benue River, with its extensive flood-plains and marshes situated on both sides, a very conspicuous narrowing is found immediately upstream of the town of Makurdi. Near the railway bridge, where it is bordered by hills, it is only 700 m or 2,200 feet wide. The site is shown on Diagram 3.4.10-1.

The River Benue has cut its course across a hilly ridge which extends from the north-east to the south-west. This ridge consists of Cretaceous sandstones, folded into a gentle anticline. The axis of the anticline shows a south-westward pitch, as a result of which the hills tend to become lower south of the Benue. About 1½ miles south-west of Makurdi railway bridge a saddle occurs in the hilly-ridge. It is doubtful whether the sandstones which are exposed near the bridge extend beyond this saddle. Some small faults and major joints might cut across the sandstones of the anticline, as would appear from the drainage pattern of the area.

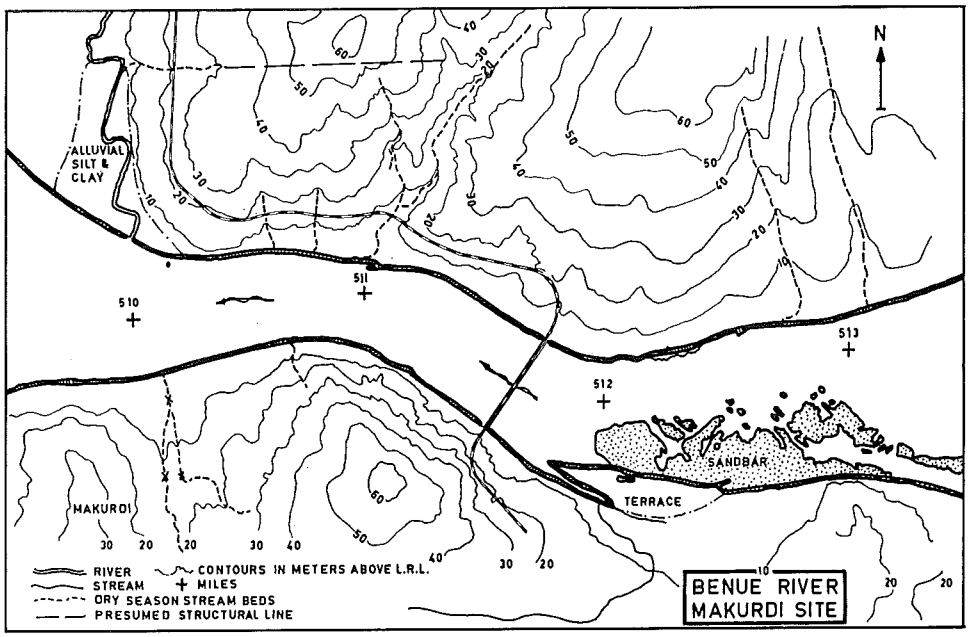


DIAGRAM 3.4.10-1

Geological map of Makurdi site

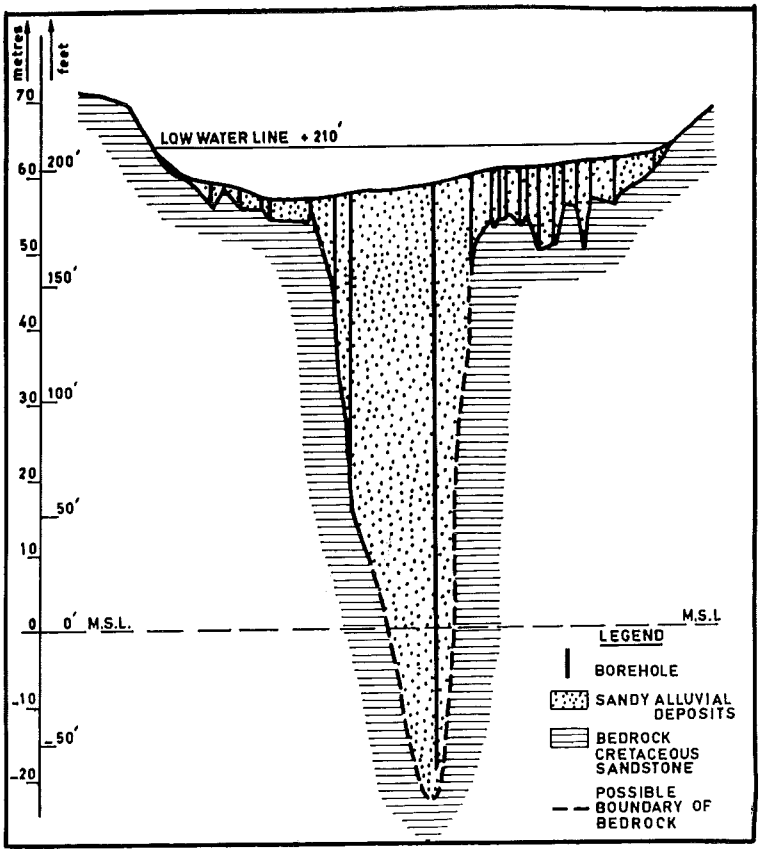


DIAGRAM 3.4.10-2

Cross-section of the Benue at Makurdi

Use has been made of some of the results of the boreholes made for the railway bridge in the years 1914—1926. On Diagram 3.4.10-2 the level at which the bedrock has been found in these boreholes is shown. These data indicate that though relatively thin underneath a great part of the river, the unconsolidated sandy fluviatile deposits form in the central part of the river the fill of a very deep, canyon-like ancient valley, the bottom of which lies at least 20 m (70 feet) below the present sea-level. The occurence of similar buried valleys had been observed earlier at two sites in Nigeria, where reconnaissance drilling has been carried out in the two main rivers of the country (near Yola in the Benue Valley and near Onitsha in the Lower Niger Valley); the depth (at least 80 m or 270 feet below present river level) and the narrowness of the valley (only 220 m or 700 feet), however, are very striking features. The ancient buried valleys near Yola and near Onitsha, exceeding 33 m (100 feet and 45 m (130 feet) in depth (in neither case was the bedrock reached in the boreholes), have the same width as the modern valley.

CHAPTER 4

HYDROLOGICAL CYCLE

4.1. PRECIPITATION

4.1.1. Yearly rainfall on the Niger Basin

Diagram 4.1.1-1 shows the mean annual isohyets over the Niger Basin. The areas with the highest rainfall are: the headwater area of the Niger in the mountainous area in South-West Guinea; the Cameroon Mountains, where the most important Benue tributaries rise; the Jos Plateau, where the Kaduna River and the Gongola rise; and the Delta region, which drains directly to the sea.

Where the Niger rises, in the south-west of Guinea, a small part of its headwater area receives annually more than 80″ rainfall, but the average yearly rainfall on the headwater area (above Kouroussa) is 65″. Towards the north-east the rainfall decreases, and on the basin above Koulikoro the average rainfall becomes 60″. The basin of the Bani, which is situated more inland than the Niger Basin above Koulikoro, receives on the average only 50″ per annum. Because of the decrease of the rainfall towards the north-east, the average rainfall on the whole basin above Mopti near the interior delta is only 50″.

The interior delta and the most northerly part of the Niger are situated in a region where the average yearly rainfall is about 10″. In the interior delta (see also 2.3.1.) a large area of free water surface exists in the form of lakes and pools, and in the wet season, when the flood from the headwater region arrives, this area is considerably increased by the flooding of adjacent land. This explains the fact that in the interior delta and the more northern part of the Niger, evaporation from water surface exceeds the inflow from the lateral basin.

Farther downstream rainfall again increases, and at the Nigerian frontier the average yearly rainfall is about 35″. The rainfall on the Niger drainage area between Malanville and Jebba is 34″ per year. In the drainage area a part of the Jos Plateau is situated where yearly rainfall becomes more than 60″.

On the headwater area of the Benue above Garua, the average yearly rainfall is 43″. The main tributary of this river above Garua is the Mayo Kebi which drains the north-eastern part of the basin. Rainfall on the basin of this river reaches an average of only 37″ per year. The Benue itself, above the confluence with the Mayo Kebi, drains an area which receives 48″ per annum. At the Nigerian frontier the Benue is joined by the Faro which comes from the south and drains an area on which the average yearly rainfall is about 55″.

Between Yola and Makurdi the average rainfall on the area drained by the Benue is 49″, although the rainfall is distributed very unequally over this area. The basin of the Gongola, a tributary from the north, receives an average rainfall of 39″, whereas the basins of the main

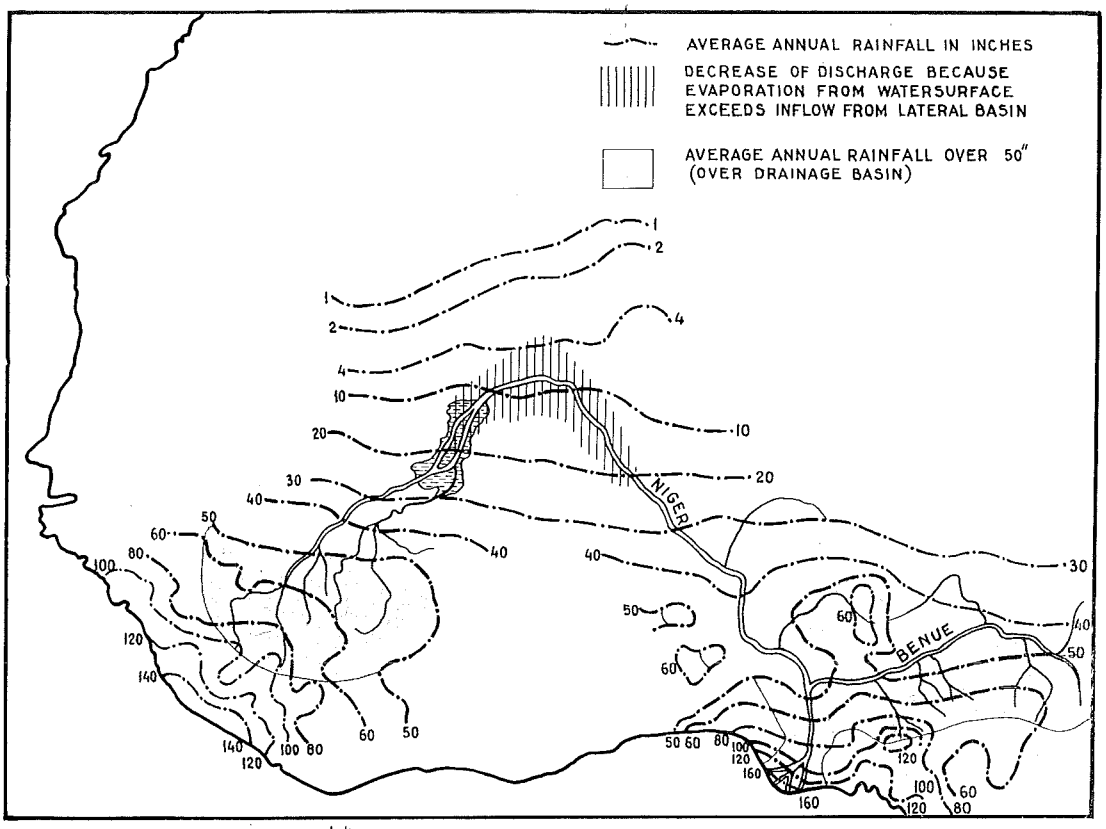


DIAGRAM 4.1.1-1

Mean annual isohyets over the Niger Basin

southern tributaries arriving from the Cameroon Mountains — the Rivers Taraba, Donga and Katsina Ala — receive respectively 50″, 57″ and 79″ rainfall.

At Lokoja the Niger is joined by the Benue, and as the river continues its flow towards the south, the rainfall on its drainage area increases. The average rainfall on the drainage area between Lokoja and Onitsha is 59″.

The average rainfall on the Niger and Benue drainage area within Nigeria is 45″.

South of Onitsha, rainfall over the Delta increases to the south from 100″ to 160″ on the coast.

4.1.2. Variation in annual, monthly and daily rainfall

a. *Annual rainfall*

Isohyets as shown on Diagram 1.3.3-1 are mean isohyets, that is, lines of equal yearly rainfall. But yearly rainfall is far from constant. Diagram 4.1.2-1 shows duration curves of annual rainfall in inches for some stations in Nigeria.

The variability of annual rainfall can be defined as $\frac{P_{25}-P_{75}}{\overline{P}}$ in which $\overline{P}$ is the mean rainfall, P_{25} is the rainfall which is exceeded during 25% of the years, and P_{75} is the rainfall which is

exceeded during 75% of the year. This variability has been computed as a percentage for a number of stations and is given in Diagram 4.1.2-2.

There is a tendency (which is, however, not strict) for the variability to be higher for stations with a low rainfall than for those with a high precipitation. The variability for the higher altitudes (Jos, Bamenda) appears to be smaller than for the lowland.

For the years 1955, 1956 and 1957 the average rainfall over several river basins has been computed by making use of annual isohyets, drawn from the rainfall figures as published by the Meteorological Service, Lagos. The results are discussed in 4.5.3.

The average area covered by one rainfall station is given in Table 4.1.2-3. Considering the large area per rainfall station, however, it is clear that great value cannot be attached to the exactitude of the computed averages.

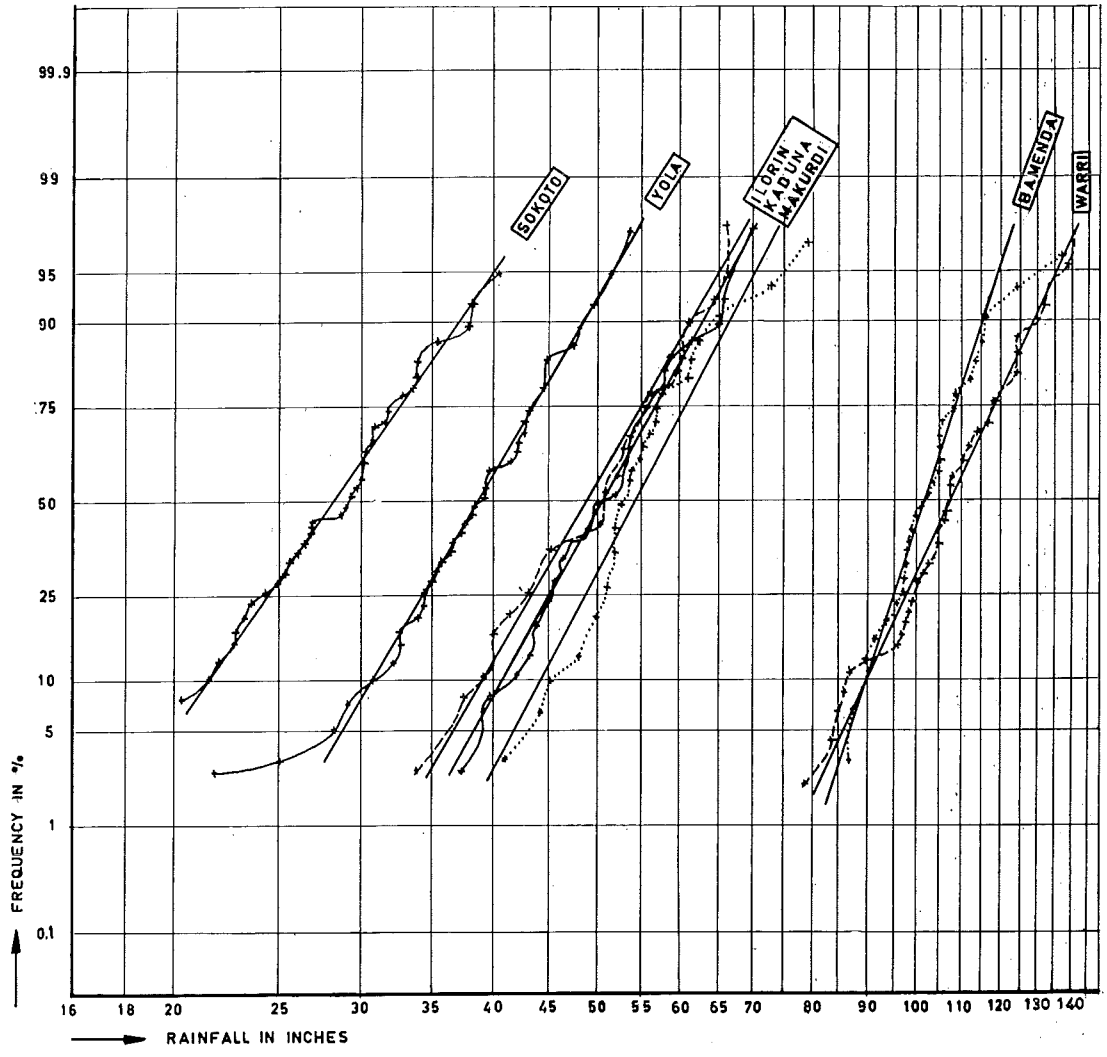


DIAGRAM 4.1.2-1

Duration curves annual rainfall

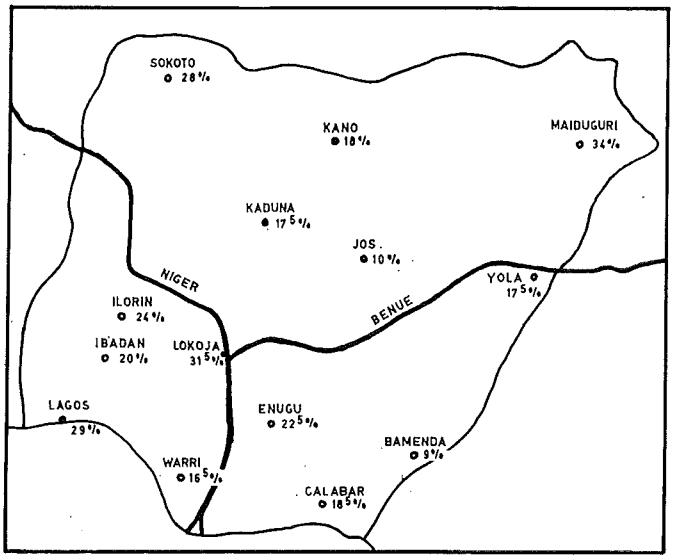


DIAGRAM 4.1.2-2

Variability of annual rainfall

$$\frac{P_{25} - P_{75}}{\overline{P}}$$

TABLE 4.1.2-3

DENSITY OF RAINFALL MEASURING STATIONS ON THE NIGER AND BENUE DRAINAGE BASIN (1956)

1 drainage basin	2 area sq. miles	3 total number of rainfall stations	4 number of rainfall stations with record fit for use	5 area per rainfall station sq. miles	6 area per rainfall station with record fit for use sq. miles
BENUE: Wuro Boki — Lokoja	89,500	137	49	650	1,800
NIGER: Jebba — Lokoja	46,000	98	34	470	1,370
NIGER: Lokoja — Onitsha	10,000	33	20	300	500

b. *Monthly rainfall*

The Meteorological Service (Lagos) has prepared charts of monthly isohyets for the years 1955 and 1956. These charts have been useful in the qualitative analysis of the discharge hydrographs, a subject discussed further in 4.3.3 and 4.5.4.

c. *Daily rainfall*

In computing average daily rainfall over a certain area, a greater number of rainfall stations is desirable than in the case of the average yearly rainfall, as many storms cover only a limited area. This is illustrated by Diagram 4.1.2-4 in which daily rainfalls during 1955 over Mbatie and Yandev (Benue Province) are plotted against each other. Although the distance between these two places is not more than 10 miles, it can be seen that very frequently rainfall occurs in one of the stations only.

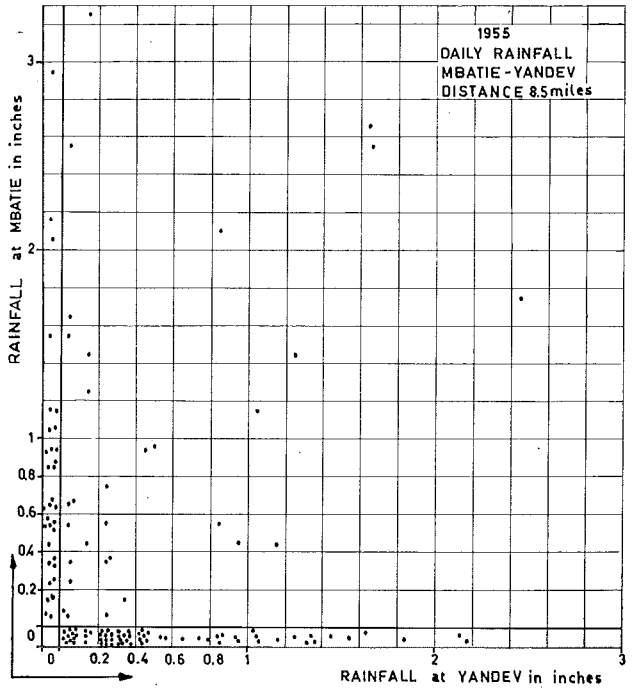


DIAGRAM 4.1.2-4

Scatter in daily rainfall

If the precipitation of a certain day over a certain station has been caused by the passing of a Disturbance Line (see 1.3.3) it can be presumed that there has been rainfall over a vast area. But if rainfall has been caused by local storms, it is not possible with the present low density of rainfall measuring-stations to compute the average daily rainfall over a certain area from the record of a few stations only.

The headwater area of the Katsina Ala River is an area with a reasonable density of rain-gauges (150 sq.miles per station). In Diagram 4.1.2-5, 5-days rainfall measured in one of the stations (Bamenda) is plotted against the average 5-days rainfall over the entire area. The curve fitted through the points is concave upwards, which means that the area covered by heavy rainfall is smaller than the area over which light rainfall occurs. The scattering of the points shows that it is not possible in this case to select a station at which the rainfall will give a fair indication of the average rainfall over the area.

4.1.3. Seasonal variation

The origin of the seasonal variation of rainfall over the Niger-Benue Basin has been described in 1.3.3. In the present paragraph the seasonal variation itself will be discussed more in detail.

The seasonal variation of rainfall within Nigeria can best be dealt with following the movement of the mean monthly isohyets, although there are in this method some disadvantages. In the first place, the choice of *monthly* isohyets, which means the choice of 30 days as interval, is arbitrary. In using this rather long interval, the occurrence of the "little dry season" will sometimes not be very well expressed. But the use of shorter periods will involve a thorough study of the synoptic situations to determine whether a certain decrease in rainfall is caused by an accidental variation or whether it is really the "little dry season". This, however, goes beyond the present study. In the second place, the use of *mean* monthly isohyets will not show the yearly variation

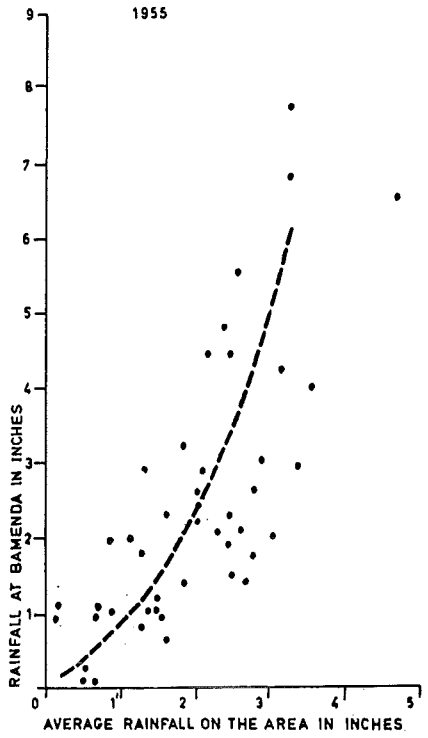


DIAGRAM 4.1.2-5

Scatter in 5-days rainfall

of the seasonal movements of the isohyets. However, to avoid the complicated configurations which occur when considering the movements of the isohyets during a particular year, mean monthly isohyets will be used.

In Diagram 4.1.3-1 the positions of the various mean monthly isohyets (12″, 10″, 8″, 6″, 4″ and 2″) have been drawn ([1]. The various isohyets will be discussed one by one. The movement inland of a isohyet is indicated by a blue colour, the movement to the south by a red colour. When rainfall over the area decreases during July—August, the isohyet is green. To make the graph less confusing, the 6″, 8″ and 10″ and 12″ isohyets have been smoothed, although the characteristic positions are maintained.

Only a small part of Nigeria receives during one or more months a mean monthly precipitation exceeding 12″. The July 12″ isohyet has about the same position as in June, but the position in August is more south than in June. The most northern position is reached in September. At the end of October the 12″ isohyet is displaced considerably southward over the Niger Delta but less in the east.

After having moved towards the north during April. May and June, the 10″ isohyet lies during July and August south of its June position. But in July rainfall over the Plateau is more than 10″, and during August the area in the north receiving more than 10″ rainfall is greater than in July. The September position of the 10″ isohyet is north of its position in June, except in the south-west, where the position remains even south of that during July. In the north the area receiving more than 10″ decreases from August to September. The southward movement during October is rather slow, but in November only a very limited area on the coast receives more than 10″.

The movement of the 8″ isohyet is complicated. In July it lies over its greater length south

([1] After Met. Services. HYD. 5

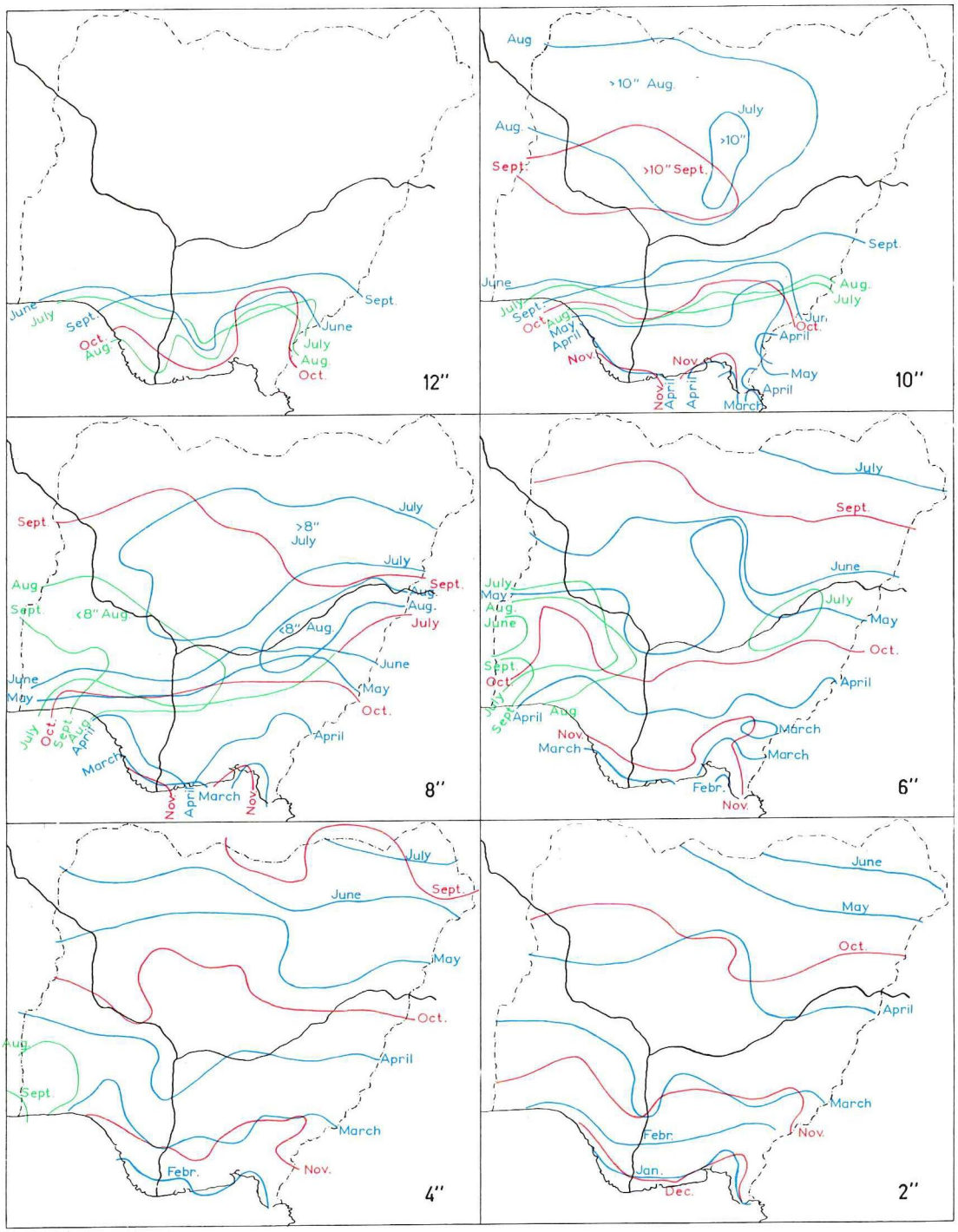


DIAGRAM 4.1.3-1

Position mean monthly isohyets

of its June position, but more in the north is a vast zone which receives more than 8″ rainfall. In August the area of the Benue Valley with a rainfall less than 8″ decreases (but rainfall over the Benue Valley does not become less than 6″). In July the whole Niger Valley above Lokoja receives less than 8″ rainfall, except the part between the Plateau and the river. In August the whole area north of the river receives more than 8″; in September rainfall over the Niger Valley is more than 8″, but the region of Sokoto receives less than 8″. The area in the south-west receiving less than 8″ is greater in August than in September and than in July. The southward movement of the 8″ isohyet during October is faster than the northward movement during the summer. In November only in the coastal area is the rainfall higher than 8″.

The 6″ isohyet does not reach its most northern position before August, when it lies north of Nigeria, but already in June the rainfall in the south-west is less than 6″, although on a rather small area. This area increases more in July and reaches its maximum during August (little dry season). In September rainfall in the north is already below 6″, but over a great area in the south-west rainfall in September is higher than in August. The decrease of rainfall during July over the Benue Valley is remarkable.

It can be seen that the 4″ isohyets at the end of the rainy season are moving south nearly twice as fast as during the northward movement early in the season. When in August the whole of the north receives more than 4″ rainfall, the precipitation in the south-west, where the "little dry season" is very distinct, becomes less than 4″.

The 2″ isohyet displaces considerably during April and May. During July, August and September the whole of Nigeria receives more than 2″ rainfall per month. It can be seen that, except along the line Jos-Onitsha, the southward movement during November is faster than the northward movement in the Spring.

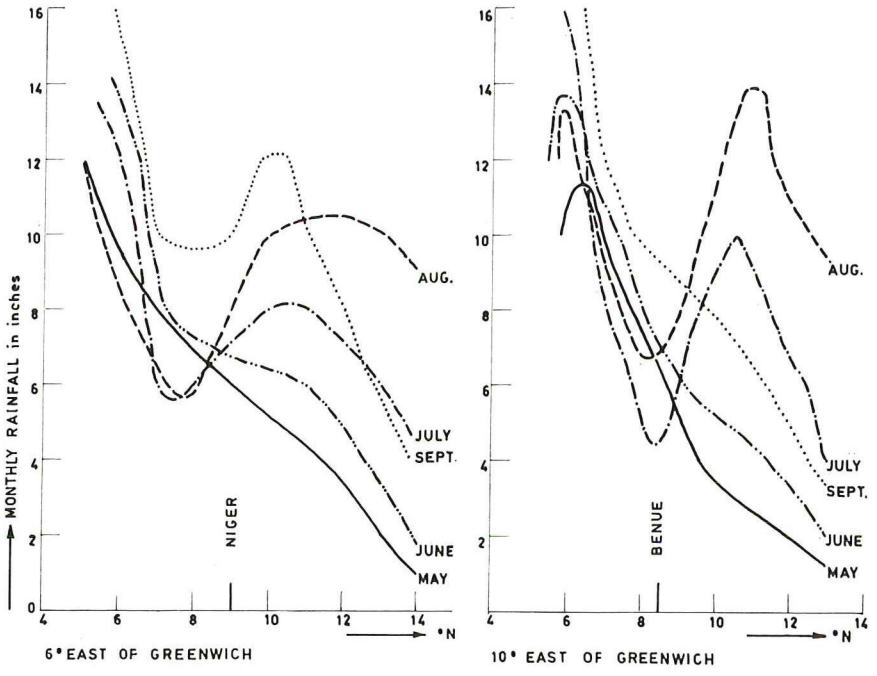


DIAGRAM 4.1.3-2

Distribution of monthly rainfall along the 6th and the 10th Meridians

To illustrate more particularly the seasonal variation of rainfall over the Niger and Benue Valleys within Nigeria, Diagram 4.1.3-2 has been drawn. This shows the mean distribution of rainfall along the 6th and the 10th meridians for the months of May, June, July, August and September, and should be compared with Diagram 4.1.3-1.

It can be seen that during May and June rainfall decreases steadily towards the north. In July there is a decrease in rainfall over the river valleys of both the Benue and the Niger, and south of the rivers. The zone in which disturbance lines occur (see 1.3.1) is situated north of the river. The orography renders the rainfall higher than when the storm zone is over the valley.

Over both the Niger and Benue Valleys rainfall north of the river is more in August than in July. But south of the river there is a difference between the two valleys: rainfall south of the Benue is more in August than in July, except in the far south, where the "little dry season" becomes perceptible. South of the Niger the rainfall is everywhere lower in August than in July because the "little dry season" covers a much greater area in the west than in the east.

At the end of the season the rainfall zone retires more quickly to the south along the 10th meridian than along the 6th.

Diagram 4.1.3-3 shows the rainfall distribution along the 14th meridian over the Benue Basin above Garua for the months June, July, August and September 1955 and 1956. It is seen that there are considerable differences between the two graphs. As has been stated earlier, rainfall distribution in individual years can differ much from the pattern drawn from mean figures. Nevertheless, some features show themselves clearly: in the south rainfall during July and August is less than in June (little dry season). There is a well-marked orographic influence, as

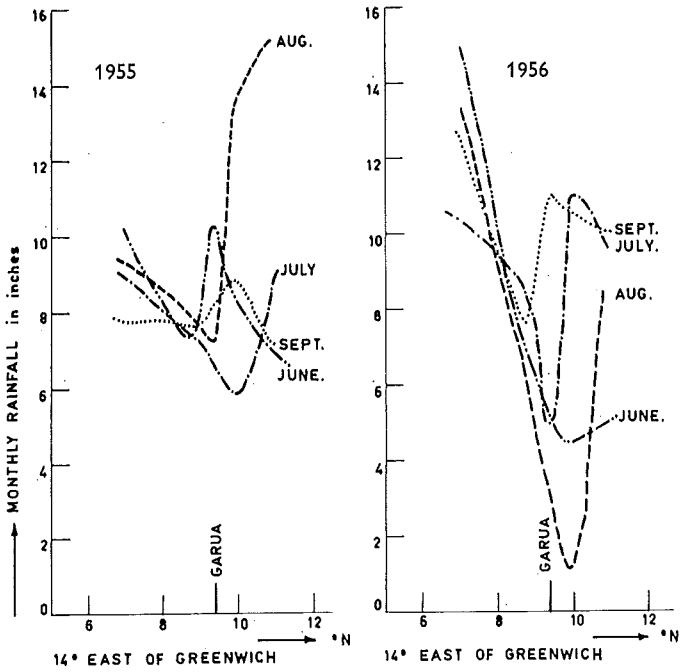


DIAGRAM 4.1.3-3

Distribution of rainfall along the 14th meridian

Data supplied by the "Service Météorologique" of the French Camerouns (Douala)

rainfall at the borders of the basin is greater than in the centre. In the north the area where rainfall is maximum in September is situated south of the area where rainfall is maximum during August. The zone with disturbance lines is already going south.

In Diagram 4.1.3-4 monthly rainfall figures of 1955 at 4 stations along the Niger above Diré (western drainage area) have been plotted against the months of the year (1. The river flows about SW—NE and the order of the stations going downstream is: Kissidougou, Kankan, Siguiri and Bamako. An analysis of the diagram shows that the characteristics of the rainfall distribution caused by the mechanism explained in 1.3.3 and illustrated for Nigeria in that paragraph are again present. Kissidougou and Kankan both show two monthly rainfall peaks, Going north, there is only one peak in Siguiri and Bamako, but in Siguiri there is not much difference between the July and August rainfall. The rainy season in Bamako is shorter than at the other stations.

However, the "little dry season" has no influence on the shape of the hydrograph at Diré and at stations along the Niger below Diré, because of the enormous storage capacity of the flood area above Diré.

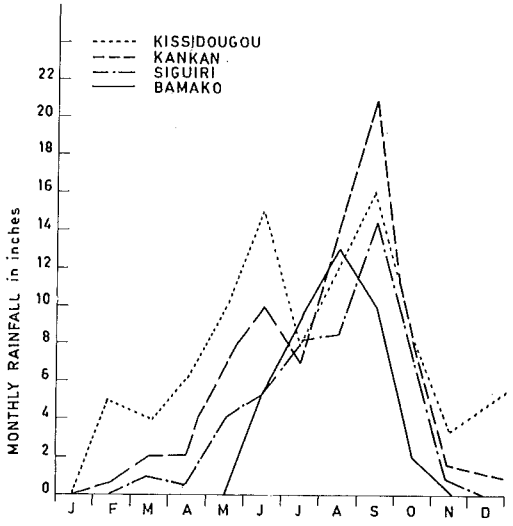


DIAGRAM 4.1.3-4

Monthly rainfall Niger Basin above Diré 1955

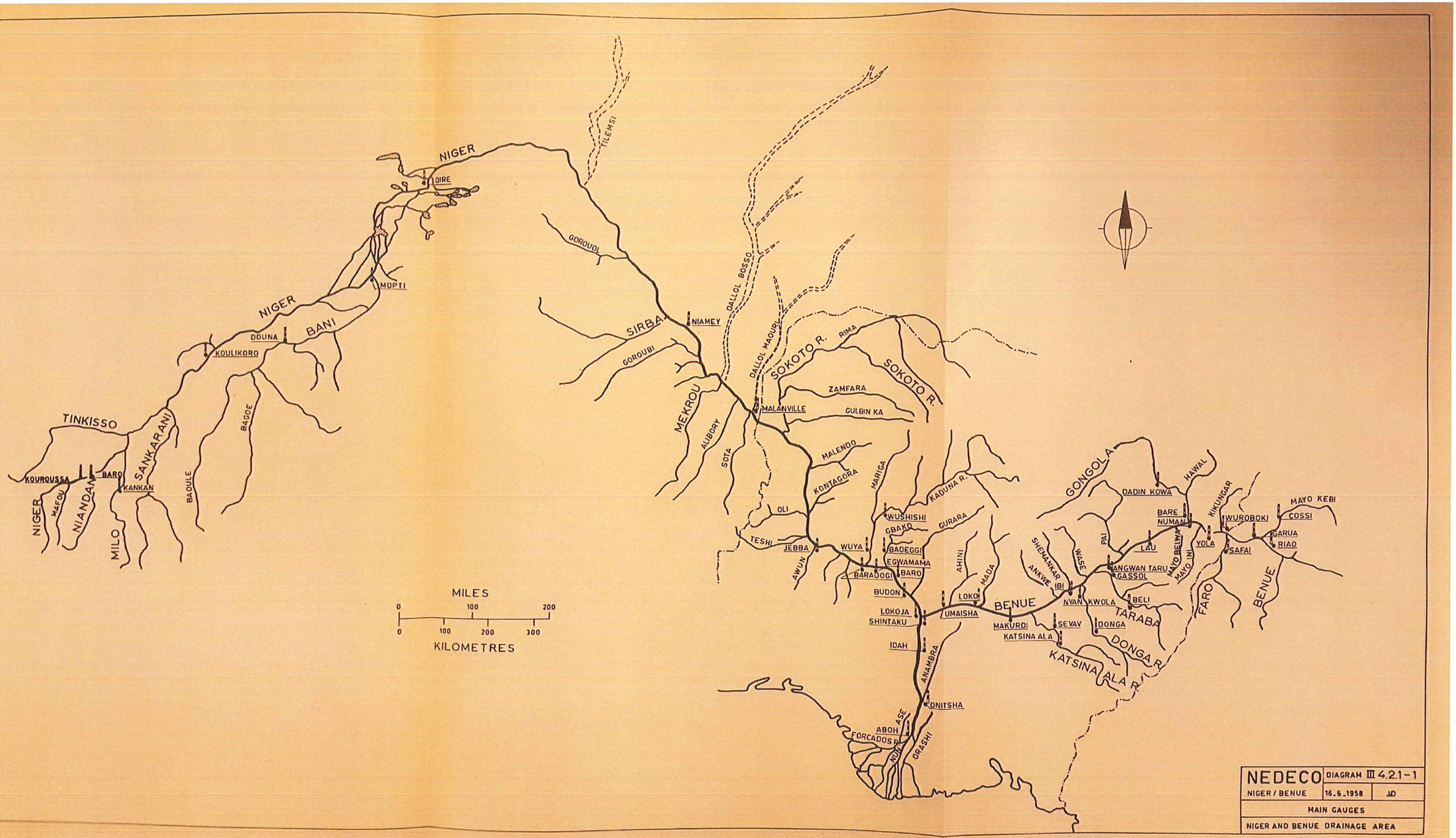
4.2. STAGES

4.2.1. River gauges

The need for water-level records of the Niger was already felt early in this century. In 1908 a gauge was erected at Jebba, in connection with the intended construction of a railway bridge across the Niger, whilst in the same year another was installed at Koulikoro. During 1910 a gauge was constructed at Kouroussa, but the observations have been lost.

Then in 1914, in the beginning of the first World War, gauges were installed by a Government

(1 Data from ORSTOM, 1955. HYD. 6



NEDECO	DIAGRAM III 4.2.1-1	
NIGER / BENUE	16.6.1958	JD
MAIN GAUGES		
NIGER AND BENUE DRAINAGE AREA		

Agency along the Niger at Baro, Lokoja, Idah, and Onitsha and along the Benue at Yola, Ibi and Makurdi. A few years after the installation, however, those at Yola and at Makurdi were no longer being read; in 1924 the readings of the gauges at Jebba and at Idah stopped (the datum of the latter gauge has now been lost); and the gauge at Ibi was abandoned after 1938 and the datum subsequently lost.

Continuous records of river stages from 1914 up to the present time are available of the gauges at Baro, Lokoja and Onitsha. Hydrological computations show that the datums of the Baro and Onitsha gauges have been changed one or more times. Readings of the gauge at Jebba are available from 1915 to 1925 and after 1948, but during these years the datum of this gauge has also been changed. Since 1948 readings were done with the help of a tape lowered from the bridge to the water-level. The records of the gauge readings of Baro and of Onitsha very often showed, during low water, readings which are unreliable. Fortunately, it has been possible to correct these readings, as well as to compute the changes of the datums of the gauges at Jebba, Baro and Onitsha by way of comparison.

Continuous records of readings of the gauge at the Makurdi railway bridge since 1931 are available. These readings are mostly weekly readings and have an accuracy of about 3″.

The shipping companies have kept records of river-stages at Yola (since 1934), Numan and Lau (since 1948) on the Benue, and at Dadin Kowa (since 1951) on the Gongola. But except for Yola, records are not continuous. In all the 4 stations just mentioned, readings were only taken during the shipping season. The datum of the Numan gauge has been lost.

Some gauges were installed on the Niger in French West Africa between 1920 and 1930, (Diré 1924; Mopti 1923; Niamey 1928), and the gauge at Malanville was erected in 1952. In the French Camerouns a gauge was installed on the Benue at Garua in 1930. Originally, readings on this gauge were only made during the shipping season, but later on this gauge was read daily during the whole year.

After 1945 a number of gauges were installed in the headwater areas of the Niger (French West Africa). In the Camerouns some gauges were erected after 1950 by the Office des Récherches Scientifiques et Techniques d'Outre-Mer (Mission Logone-Tehad) during the hydrological investigations in the headwater areas of the Benue. Some of these gauges are within Nigerian territory: Numan, Yola and Wuro Boki on the Benue, Bare on the Gongola. In the Camerouns they include Safai on the Faro, Riao on the Benue above Garua and Cossi on the Mayo Kebi.

The Irrigation Department erected several gauges after 1945, such as those at Wuya on the Kaduna River (1948), and Baradogi on the Niger.

For the purpose of collecting more detailed data NEDECO has since 1955 extended the existing system of gauges by installing new gauges on the Niger below Jebba and on the Benue and its most important tributaries within Nigerian territory. Some of these gauges have already served their temporary purposes and have been abandoned. These secondary gauges have been:
On the Niger at Ogudu, Likpata, Sunlati, Elogicepi, Elah, Gwachinko, Mogun, Kelebe, Jamata, Tjeia, Mogadya, Adama, Etikaku, Bangede, Itobe, Illushi, Asaba, Onitha-Shell, and Samabri;
on the Benue at Tepe, Gamadio, Jen, Wiwan Gogi, Katsina Ala Confluence, Abinsi, Bagana, and Ugua;
on the Hawal at Garkida; and
on the Taraba at Bakundi.

A number of tertiary gauges around the Niger-Benue Confluence has also been used.

A certain number of the above-mentioned gauges has been used to determine if there was any result of backwater conditions from an intersecting stream below the cross-section for which a stage discharge relation had to be established. The gauge at Shintaku, for example, had to be

TABLE 4.2.1-2

GAUGES ALONG THE NIGER RIVER AND TRIBUTARIES

RIVER	STATION	MILE (1	Gauge installed in:	Datum zero gauge above mean sea-level	AGENCY	PERIODS OF RECORD (up to 1957 included)	Stage-discharge rating curve established or not
Niger	Kouroussa	2,307	1910	355.375 m. (1165.92 ft.) (levelling C.F.C.N.)	Service Hydraulique (2 (Bamako)	1923—1926 1945—1957	+
Niger	Koulikoro	2,041	1908	290.083 m. (951.75 ft.) (Service Geographique)	Messageries Africaines (Bamako)	1908—1957	+
Bani	Douna	1,963	1949	270.714 m. (888.17 ft.) (I.G.N. levelling)	Service Hydraulique (Bamako)	1950—1953 1954—1957	+
Niger	Mopti	1,765	1922	260.455 m. (854.50 ft.) (I.G.N. levelling) 279.39 m. (916.79 ft.) (Levelling: Office du Niger	Service Hydraulique (Bamako)	1922—1929 1934—1936 1943—1957	+
Niger	Dire	1,574	1924	275.915 m. (905.25 ft.) (Sansanding levelling) 257.20 m. (843.83 ft.) (I.G.N. levelling)	Service Hydraulique (Bamako)	1924—1957	+
Niger	Niamey	995	1928	175.92 m. (577.17 ft.)	Service Hydraulique (Bamako)	1928—1931 1933—1935 1940—1952	
			1952	175.80 m. (577.08 ft.)	Office du Niger (Ségou)	1952—1957	+
Niger	Malanville	811	1952	155.132 m. (509.02 ft.)	Service Hydraulique (Bamako)	1952—1957	+
Niger	Jebba	556	1908	about 233 ft.	Nigerian Railways	1915—1925 1948—1957	
			1956	189.76 ft.	NEDECO I.W.D.(3 since 1.4.58	1956—1957	+
Niger	Baradogi	480	1951	about 186 ft.	Irrigation Department Northern Region (Kaduna)	1951—1957	—
Kaduna	Wushishi	570	1954	—	P.W.D. Northern Region (Kaduna)	1954—1957	—
Kaduna	Wuya	about 505	—	210.87 ft.	Irrigation Department Northern Region (Kaduna)	1948—1957	+
Niger	Egwamama	471	1956	—	NEDECO I.W.D. since 1.4.58.	1956—1957	(+)
Gbako	Badeggi	475	1955	—	Irrigation Department Northern Region (Kaduna)	1955—1957	+
Niger	Baro	434	1914	151.95 ft.	Nigeria Marine Department I.W.D.	1914—1957	+
Niger	Budon	398.5	1955	—	NEDECO I.W.D. since 1.4.58.	1955—1957	—
Niger	Lokoja	361.2	1914	106.21 ft.	Nigeria Marine Department I.W.D.	1914—1957	+
Niger	Shintaku	355.6	1957	103.40 ft.	NEDECO I.W.D. since 1.4.58.	1957	+
Niger	Idah	310	1914	Datum lost	Nigeria Marine Department	1914—1923	
			1955	88.54 ft.	NEDECO I.W.D. since 1.4.58.	1955—1957	+
Niger	Onitsha	232.3	1914	38.47 ft.	Nigeria Marine Department I.W.D.	1914—1957	+
Niger	Isara/Aboh	177.5	1954	28.10 ft.	NEDECO I.W.D. since 1.4.58.	1954—1957	—

(1 Miles from Escravos Lighthouse, measured along the river-axis.
(2 Service Hydraulique; Direction Générale des Travaux Publics de l'A.O.F. (Service Hydraulique)
(3 I.W.D.: Inland Waterways Department, Federation of Nigeria, Lagos.

TABLE 4.2.1-3

GAUGES ALONG THE BENUE RIVER AND TRIBUTARIES

RIVER	STATION	MILE(1	Gauge installed in:	Datum zero gauge above mean sea-level	AGENCY	PERIOD OF RECORDS (up to 1957 included)	Stage-discharge rating curve established or not
Benue	Riao	1,008	1950	185.80 m (609.58 ft.) (I.G.N. levelling)	P. & V.N.(2	1951—1957	+
Mayo Kebi	Cossi	1,031	1954	about 195 m (639.76 ft.)	P. & V.N.	1950—1957	+
Benue	Garua	972	1930	572,46 ft.	P. & V.N.	1930—1957	+
Faro	Safaie	983	1950	—	P. & V.N.	1950—1957	+
Benue	Wuro Boki	916	1953	530.10 ft.	P. & V.N. I.W.D. since 1.4.58	1953—1957	+
Benue	Yola	888	1934 1954	about 501.45 ft. 495.95 ft.	U.A.C. P. & V.N. I.W.D. since 1.4.58	1934—1957 1954—1957	+
Gongola	Dadin Kowa	about 935	1951	—	U.A.C. I.W.D. since 1.4.58	1951—1954 1954—1957	—
Gongola	Bare	855	1955	488.69 ft.	O.R.S.T.O.M.(3 I.W.D. since 1.4.58	1953—1957	+
Benue	Numan	846	1933 1955	Datum lost 457.29 ft.	U.A.C. NEDECO I.W.D. since 1.4.58	1933—1935 1955—1957	+
Benue	Lau	777.5	1948	386.8 ft.	U.A.C. NEDECO I.W.D. since 1.4.58	1948 1950—1953 1955—1957	+
Benue	Angwan Taru	682.5	1955	322.70 ft.	NEDECO I.W.D. since 1.4.58	1956—1957	+
Taraba	Beli	about 753	1955	—	NEDECO I.W.D. since 1.4.58	1956—1957	+
Taraba	Gassol	691	1955	355.96 ft.	NEDECO I.W.D. since 1.4.58	1955—1957	+
Donga	Donga Town	about 685	1955	373.50 ft.	NEDECO I.W.D. since 1.4.58	1955—1957	+
Donga	Nyankwola	650	1956	—	NEDECO I.W.D. since 1.4.58	1956—1957	+
Benue	Ibi	614	1914 1955	Datum lost 269.66 ft.	Nigeria Marine Department NEDECO I.W.D. since 1.4.58	1914—1938 1955—1957	+
Katsina Ala	Katsina Ala Town	about 610	1955	336.89 ft.	NEDECO I.W.D. since 1.4.58	1955—1957	+
Katsina Ala	Sevav	about 570	1955	271.99 ft.	NEDECO I.W.D. since 1.4.58	1955—1957	+
Benue	Makurdi	511.6 510.6	1914 1931 1956	Datum lost about 100.6 ft. 194.55 ft.	Nigeria Marine Department Nigerian Railways NEDECO I.W.D. since 1.4.58	1914—1916 1932—1957 Railway gauge 1956—1957	+
Benue	Loko	454	1955	—	NEDECO I.W.D. since 1.4.58	1955—1957	—
Benue	Umaisha	400.5	1955	—	NEDECO I.W.D. since 1.4.58	1955—1957	+

(1 Miles from Escravos Lighthouse, measured along the river-axis
(2 P. & V.N.: "Ports et Voies Navigables", Douala.
(3 O.R.S.T.O.M.: "Office de la Recherche Scientifique et Technique Outre-Mer, Paris.

maintained because the water-levels at the Lokoja gauge are during low stages affected by backwater conditions.

At the following stations primary gauges were maintained by NEDECO up to the end of the investigations and were handed over to the Nigerian Government in April, 1958:
Jebba, Egwamama, Budon, Shintaku, Idah and Isara-Aboh on the Niger;
Wuro Boki, Yola, Numan, Lau, Angwan Taru, Ibi, Makurdi, Loko and Umaisha on the Benue;
Dadin Kowa and Bare on the Gongola;
Beli and Gassol on the Taraba;
Donga and Nyankwola on the Donga; and
Katsina Ala and Sevav on the Katsina Ala River.

The gauges at Baro, Lokoja and Onitsha on the Niger have always been maintained, firstly by the Nigeria Marine Department and afterwards by the Inland Waterways Department.

On Diagram 4.2.1-1 the position of the main river-gauges in the Niger-Benue drainage system are indicated, whilst Tables 4.2.1-2 and 4.2.1-3 give some information about these gauges and their records.

The elevation of every gauge is known relative to benchmarks erected on the shore, so that damaged or washed-away gauges can be replaced in their original positions.

The result of a Geodetic Levelling executed by the Federal Survey Department on behalf of the NEDECO Niger and Benue Investigation became available in the course of 1957. By means of this levelling the elevation of the benchmark and thus of the zero point of most of the primary gauges in the Niger-Benue Basin within Nigeria has been given (see Tables 4.2.1-2 and 3).

When not stated otherwise, the data of the zero points refer to the elevation above mean sea-level. This is the Mean Sea Level at Kribe near Douala in the French Camerouns. The result of the Nigerian Geodetic Levelling has been connected with the Mean Sea Level at Kribe via a benchmark at Pitoa, in the neighbourhood of Garua.

A register of water-level records was kept up to date at NEDECO headquarters in Lokoja and was handed over to the Inland Waterways Department in April, 1958.

4.2.2. Gauge readings 1955—1957

The curve obtained by plotting water-levels observed on a river-gauge against the time at which they occurred is called a water-level hydrograph. Diagrams 4.2.2-1, 4.2.2-2 and 4.2.2-3 show for the period 1955—1957 the water-level hydrographs of the most important gauges along the Niger and the Benue and their tributaries within Nigeria. They also show the water-level hydrographs of Diré, situated on the Niger in French West Africa, of Garua on the Benue, and of Safaie on the Faro. The latter two stations are situated in French Camerouns.

The hydrographs show clearly that there is a remarkable seasonal variation in river-stages.

Along the Benue (Diagram 4.2.2-1) stages are rising from May to October, although the hydrographs are not going upwards smoothly. During July or August, there may be a temporary fall.

The hydrographs of the Benue tributaries are drawn on Diagram 4.2.2-2. The general trend of the shape of these hydrographs is the same as for the Benue, with the exception of the Gongola graphs (Dadin Kowa and Bare), when river-stages show their maximum during August or September.

On Diagram 4.2.2-3 are shown the water-level hydrographs of stations along the Niger, as well as the hydrograph of Wuya on the Kaduna River which joins the Niger between Jebba

1955 | 1956 | 1957 | 1958

APR MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR.

GARUA
WURO-BOKI
YOLA
NUMAN
LAU
ANGWAN TARU
IBI
MAKURDI & LOKO
UMAISHA

GA. WB. YO. NU. LA. AT. IB. MA. LO. UM.

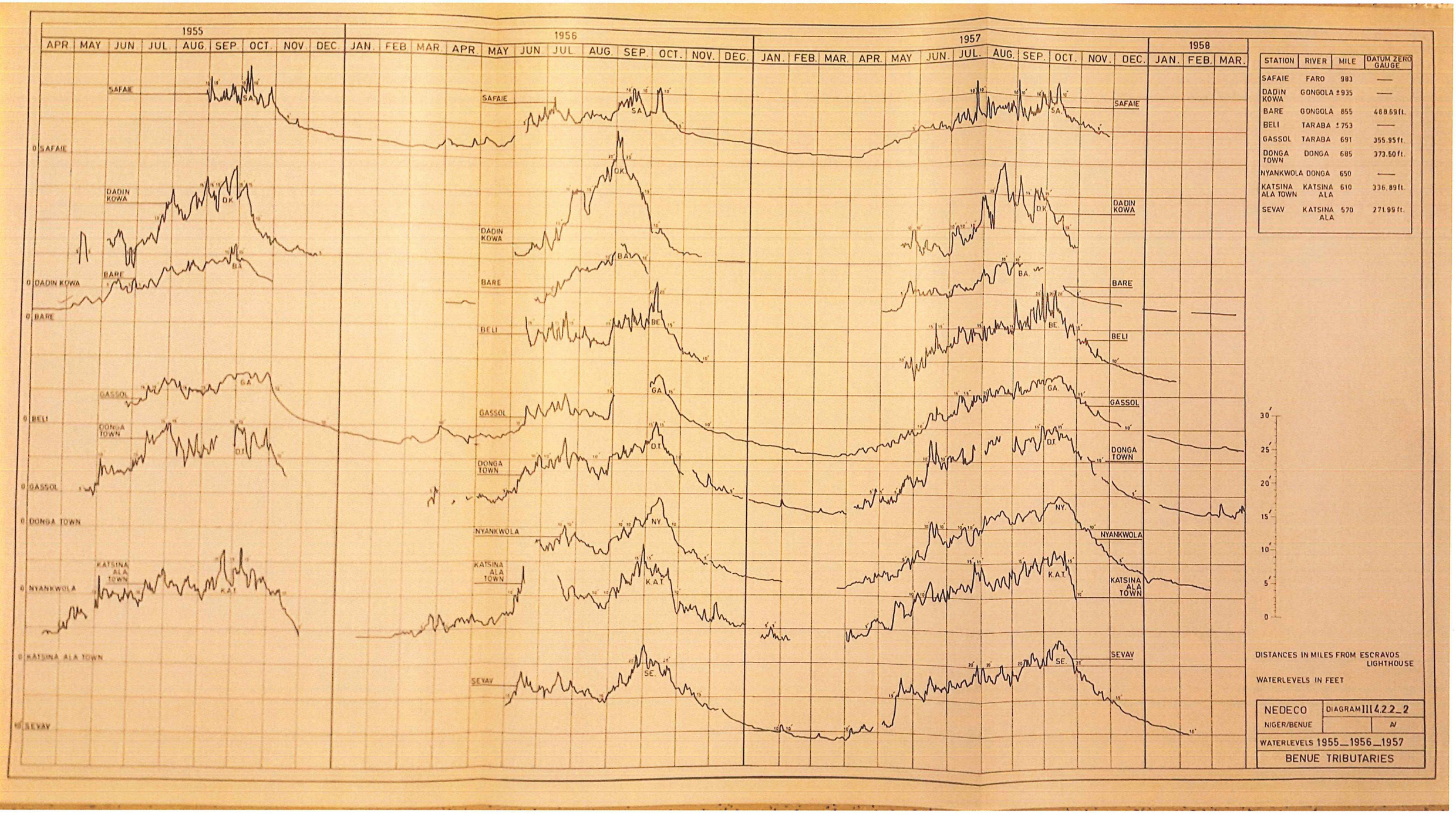
STATION	RIVER	MILE	DATUM ZERO GAUGE
GARUA	BENUE	972	572.46 ft.
WURO-BOKI	BENUE	916	530.10 ft.
YOLA	BENUE	888	495.95 ft.
NUMAN	BENUE	846	457.29 ft.
LAU	BENUE	777.5	386.80 ft.
ANGWAN TARU	BENUE	582.5	322.70 ft.
IBI	BENUE	514	288.66 ft.
MAKURDI RAILWAY-GAUGE	BENUE	511.6	± 199.4 ft.
LOKO	BENUE	454.1	——
UMAISHA	BENUE	400.5	——

30 25 20 15 0 5 0

DISTANCES IN MILES FROM ESCRAVOS LIGHTHOUSE

WATERLEVELS IN FEET

NEDECO	DIAGRAM III 4.2.2._1	
NIGER/BENUE		A/
WATERLEVELS 1955 _ 1956 _ 1957		
BENUE		



STATION	RIVER	MILE	DATUM ZERO GAUGE
SAFAIE	FARO	983	—
DADIN KOWA	GONGOLA	± 935	—
BARE	GONGOLA	855	488.69 ft.
BELI	TARABA	± 753	—
GASSOL	TARABA	691	355.95 ft.
DONGA TOWN	DONGA	685	373.50 ft.
NYANKWOLA	DONGA	650	—
KATSINA ALA TOWN	KATSINA ALA	610	336.89 ft.
SEVAV	KATSINA ALA	570	271.99 ft.

DISTANCES IN MILES FROM ESCRAVOS LIGHTHOUSE

WATERLEVELS IN FEET

NEDECO NIGER/BENUE	DIAGRAM III 4.2.2_2	AV
WATERLEVELS 1955_1956_1957		
BENUE TRIBUTARIES		

1955 | 1956 | 1957 | 1958

APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR.

DI. JE. DIRE JEBBA WU. WUYA BA. BU. BARO MA. LO. BUDON ID. ON MAKURDI AB LOKOJA IDAH ONITSHA ABOH

0 DIRE
45 JEBBA
0 WUYA
0 BARO
0 BUDON
0 MAKURDI
0 IDAH & LOKOJA
0 ABOH
0 ONITSHA

STATION	RIVER	MILE	DATUM ZERO GAUGE
DIRE FWA	NIGER	1574	± 840 ft.
JEBBA	NIGER	556	189.76 ft.
WUYA	KADUNA	505	210.87 ft.
BARO	NIGER	434	151.95 ft.
BUDON	NIGER	398.5	——
MAKURDI RAILWAY GAUGE	BENUE	511.6	± 199.4 ft.
LOKOJA	NIGER	361.2	106.21 ft.
IDAH	NIGER	310	88.54 ft.
ONITSHA	NIGER	232.3	38.47 ft.
ABOH	NIGER	177.5	28.10 ft.

30′ 25′ 20′ 15′ 10′ 5′ 0

DISTANCES IN MILES FROM ESCRAVOS LIGHTHOUSE

WATERLEVELS IN FEET

NEDECO | DIAGRAM III 4.2.2_3
NIGER/BENUE | A

WATERLEVELS 1955 — 1956 — 1957

NIGER AND TRIBUTARIES

and Baro. To mark the influence of the Benue upon river-stages on the Niger, the hydrograph of Makurdi has been drawn in addition.

Along the Upper Niger, from Jebba to Baro, the water-levels are rising due to the local rains from July to early October, when the annual peak-level is reached. The river then falls until December, when the fall is balanced by the second flood which has travelled from the head-water area in French West Africa after having been retarded in the swamp area south-west from Timbuctu. This Black Flood (as it is called because its waters are clearer than those of the silt-laden local White Flood) results in a period of sustained water-levels until March or April, when there is a further fall, continuing until June.

Along the Lower Niger the influence of the Benue is noticeable, as the continued Benue fall is superimposed on the Black Flood, and the Benue rise causes the Lower Niger water-levels to rise from May or June onwards.

Whether or not the river-stages during the 1955—1957 period have been normal or exceptional will be discussed in 4.2.4 and 4.3.4.

4.2.3. Frequencies of water-levels

The knowledge of water-level frequencies is very useful, especially for navigation and agriculture, so it was thought desirable to compute water-level frequencies for several stations along the Niger and the Benue. The lengths of the daily water-level records available and fit for the computation of frequencies are given in Table 4.2.3-1.

For Yola (Benue) readings made by one of the shipping companies have been used, but on the frequency diagrams the water-levels are given in relation to the zero level of the newly-installed gauge.

For Makurdi (Benue) the water-level record made by the Nigerian Railway has been used, and on the frequency curve water-levels are given as read on the gauge at the Railway Bridge.

TABLE 4.2.3-1

PERIOD OF RECORDS FOR FREQUENCY CURVES

River	Station	Period of record used for the computed frequency curves
Benue	Yola	1934—1957
Benue	Makurdi	1932—1957
Niger	Baro	1915—1957
Niger	Lokoja	1915—1956
Niger	Onitsha	1925—1944 1949—1956

On the frequency diagrams for Baro (Niger) water-levels are given in relation to the zero point of the present gauge. A discussion of the datums of the various gauges preceding the present one can be found in 4.5.4.

For Lokoja (Niger) the readings made by the Nigeria Marine Department have been used.

To compute frequencies of the water-level for Onitsha (Niger) use has been made of the records kept by the Nigeria Marine Department. But as there were reasons to distrust the records of the period from 1916 to 1925 (see II, 4.4.2) and of the period from 1945 to 1948, these records have not been used.

Given the records of daily gauge readings, there are two ways in which the frequencies of water-levels can be considered. Firstly, the variation of the water-levels which occur on the same day, say June 13, during a number of years, and secondly, the variation of the number of days per year during which water-levels are lower (or higher) than a certain given water-level.

The first method has been used in establishing Diagrams 4.2.3-2 to 6 inclusive, which give the frequency curves of the water-level for every day of the year for the stations as mentioned in Table 4.2.3-1. From these diagrams can be read for every day of the year which water-level has not been reached during a certain part of the period over which records are available. For instance, Diagram 4.2.3-6 shows that the water-level at Onitsha gauge on June 1 has been lower than 9'8" during 25% of the years. Another example, seen from Diagram 4.2.3-4, is that on June 10 the water-level at Baro has been lower than 6' as read on the gauge during 75% of the years of record. This means that during 25% of the years the water-level on June 10 has been over 6'. As for June 10 the water-level has been lower than 6' during 75% of the years, and lower

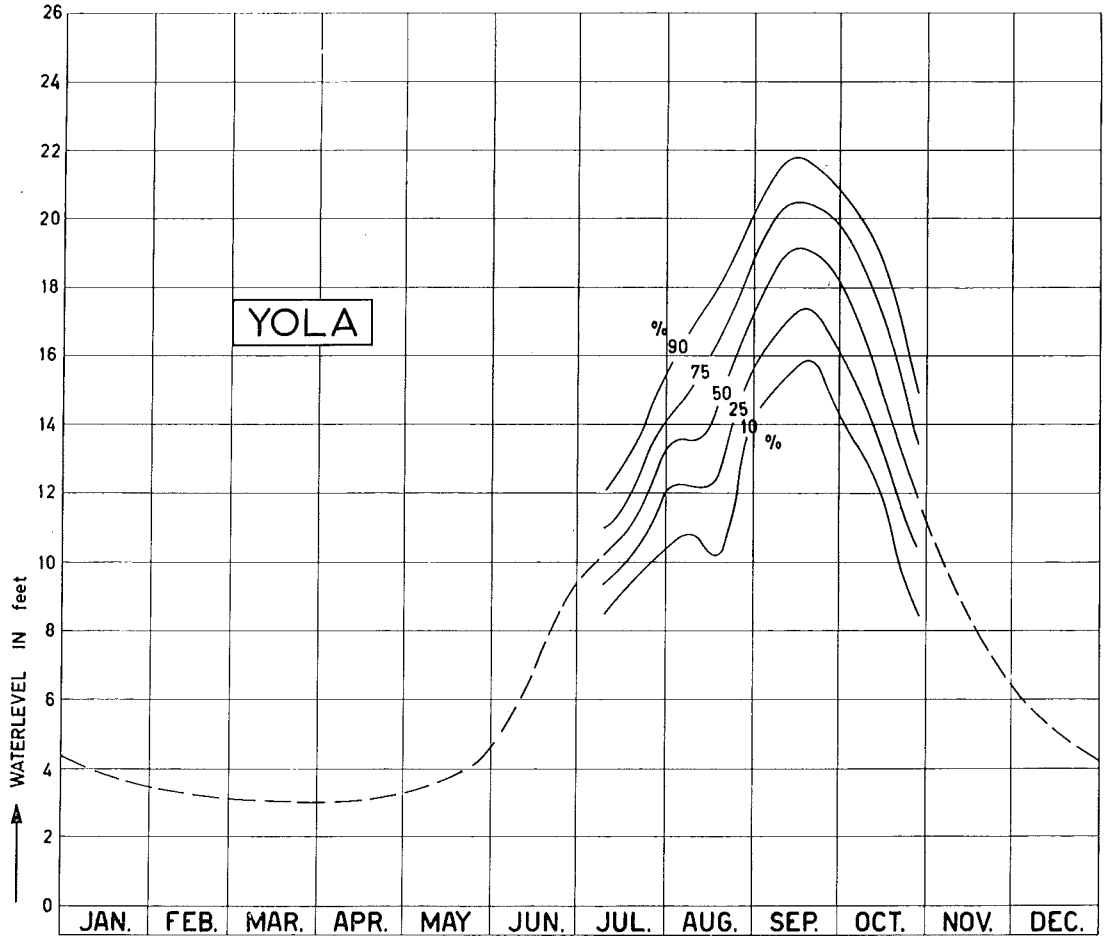


DIAGRAM 4.2.3-2

Frequencies of river-stages at Yola (Benue) for a fixed day

than 3′ during 25% of the years, it follows that during 50% (75% — 25%) of the years, the water-level at Baro on that date has been between 6′ and 3′.

On Diagrams 4.2.3-7 to 11 inclusive are drawn for the various stations the frequency curves which result from considering the number of days per year during which the water-level has been lower than a certain river-stage. For instance (see Diagram 4.2.3-10): During 75% of the number of years of record the water-level at the Lokoja gauge has been lower than 9′ during 165 days or more. This means that during the same 75% of the years the water-level has been higher than 9′ during 200 days or less (365 — 165). Another example (Diagram 4.2.3-7) is: The water-level as read at the gauge at Yola has been for 50% of the number of years of record lower than 10′ during 250 days or more. Hence, during 50% of the number of years, the water-level has been higher than 10′ during 115 days or less (365 — 250).

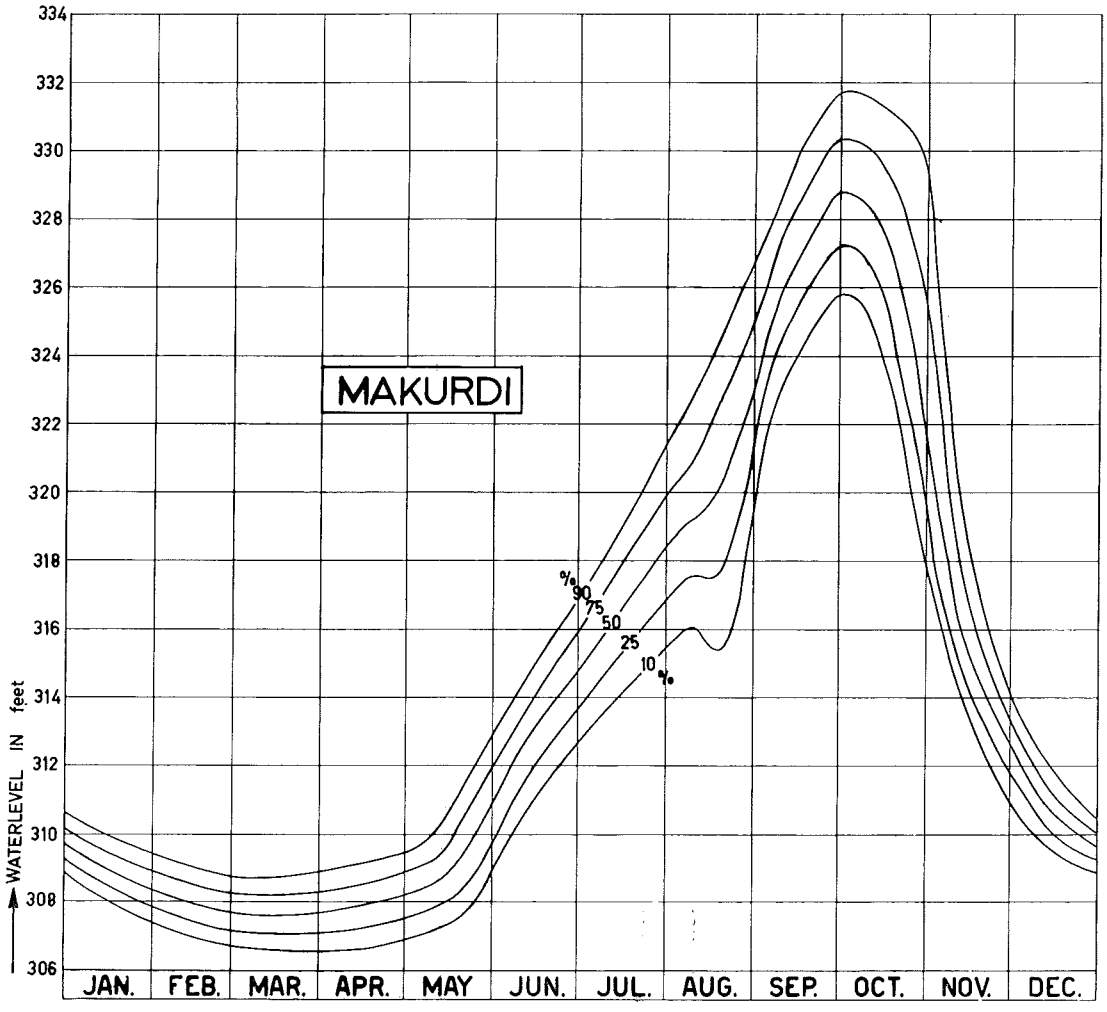


DIAGRAM 4.2.3-3

Frequencies of river-stages at Makurdi (Benue) for a fixed day

A difference between the results of vertical frequencies (Diagrams 2 to 6) and horizontal frequencies (Diagrams 7 to 11) may be observed. For example, Diagram 2 shows that on September 15 the Yola water-level was in 10% of the years less than 15′ 9″ and in 90% less than 21′9″. But Diagram 7 shows that the water-level during 364 days per year was lower than 17′9″ in 10% of the years and 23′9″ for 90%. The explanation is that the September 15 levels of Diagram 2, viz: 15′9″ (10%) and 21′9″ (90%), have not necessarily been peak levels with respect to previous or subsequent days. The lines of Diagram 2 do not represent individual years but only connect water-levels with equal frequencies.

Diagrams 4.2.3-12 to 16 inclusive show the average frequencies of water-levels of the stations of Table 4.2.3-1. An example (Diagram 15) of the interpretation of these diagrams is: the water-level at Lokoja has been lower than 12′ as read on the gauge during — on the average — 229 days per year. These curves are not identical with the 50% curves of the Diagrams 7 to 11. The latter curves indicate the *minimum* number of days during which the water-level has been lower than a certain river-stage during 50% of the years of record. The curves of the Diagrams

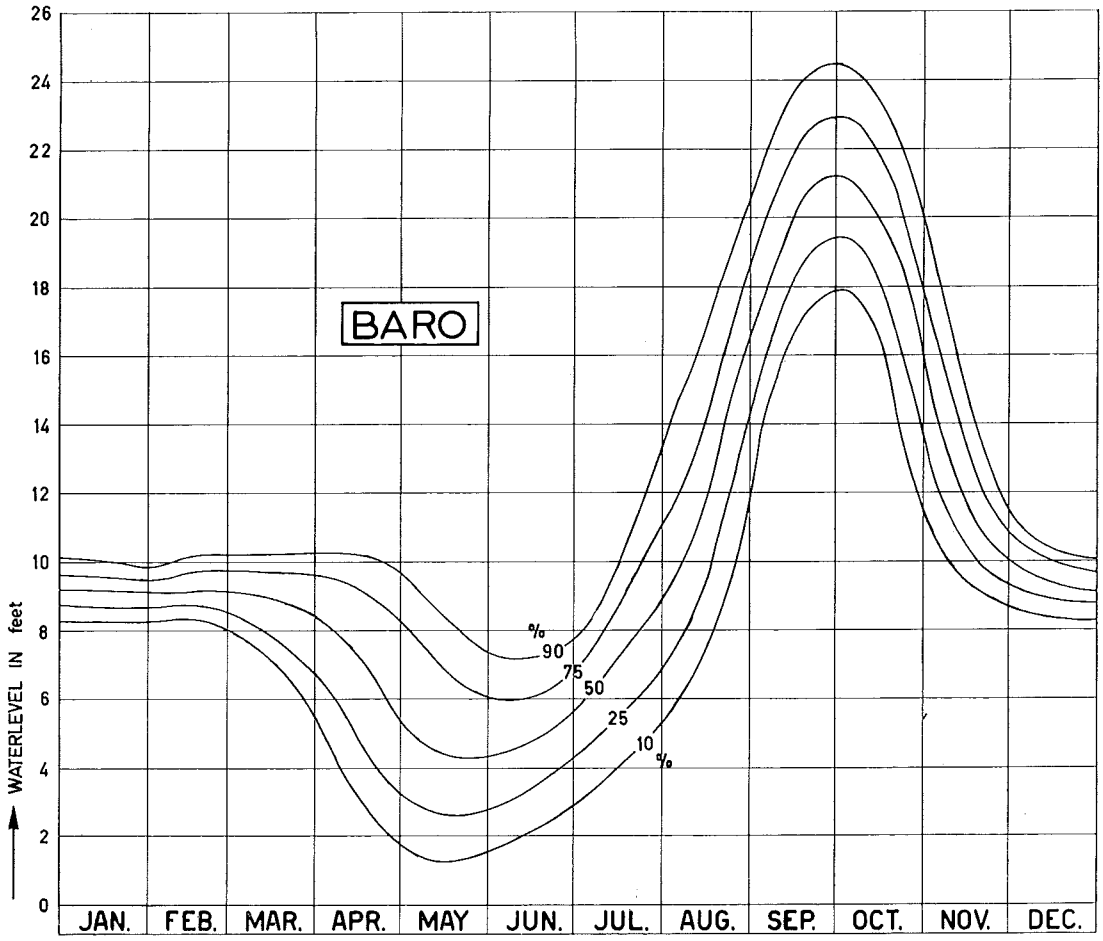


DIAGRAM 4.2.3-4

Frequencies of river-stages at Baro (Niger) for a fixed day

12 to 16 indicate the *average* number of days per year during which the water-level has been lower than a certain river-stage.

Diagrams 7 to 11 have been used to compute numbers of days during which navigation, not exceeding a certain draught, is possible on the various river-stretches. Diagrams 12 to 16 have been used for instance for computations on sand-transport.

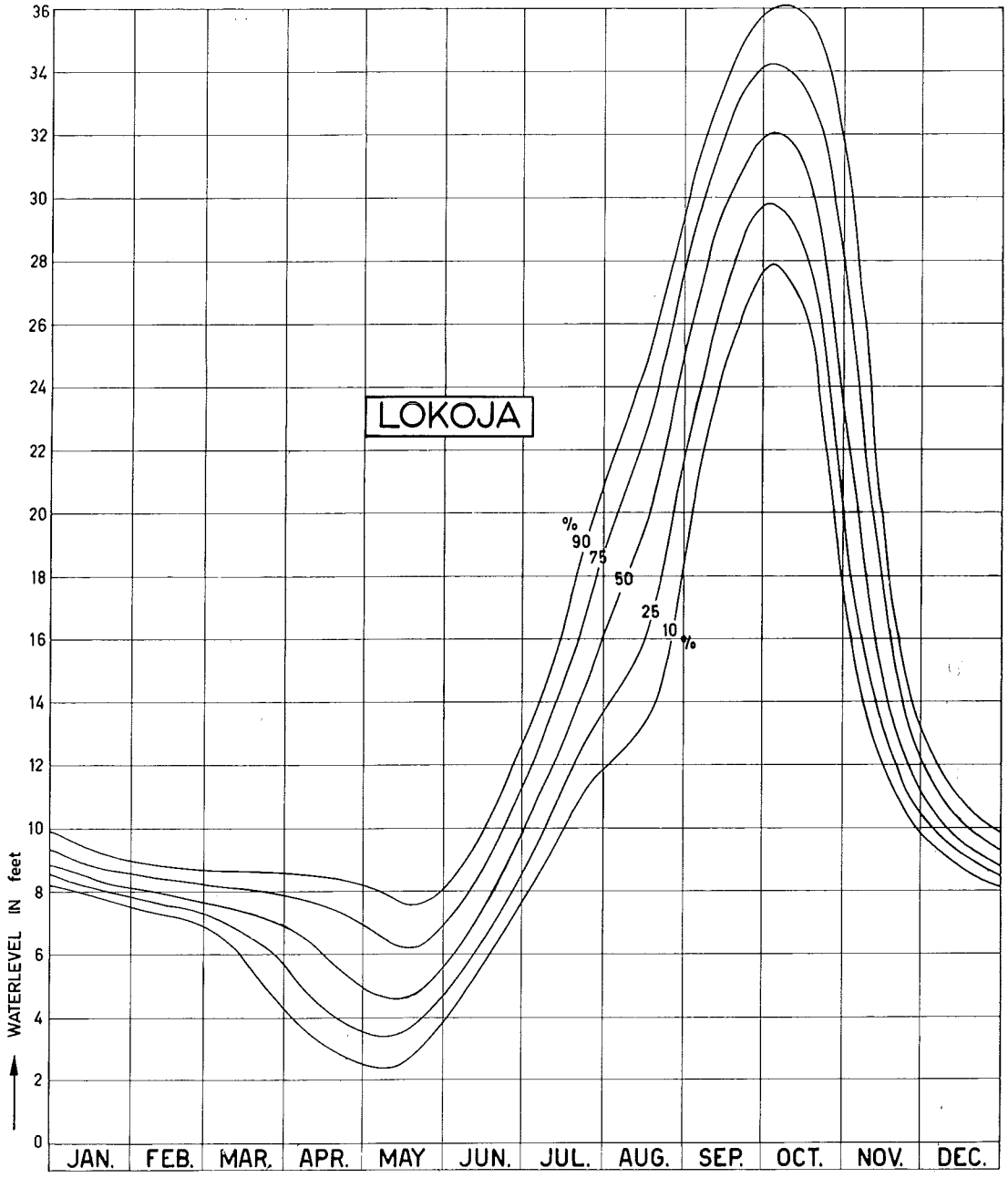


DIAGRAM 4.2.3-5

Frequencies of river-stages at Lokoja (Niger) for a fixed day

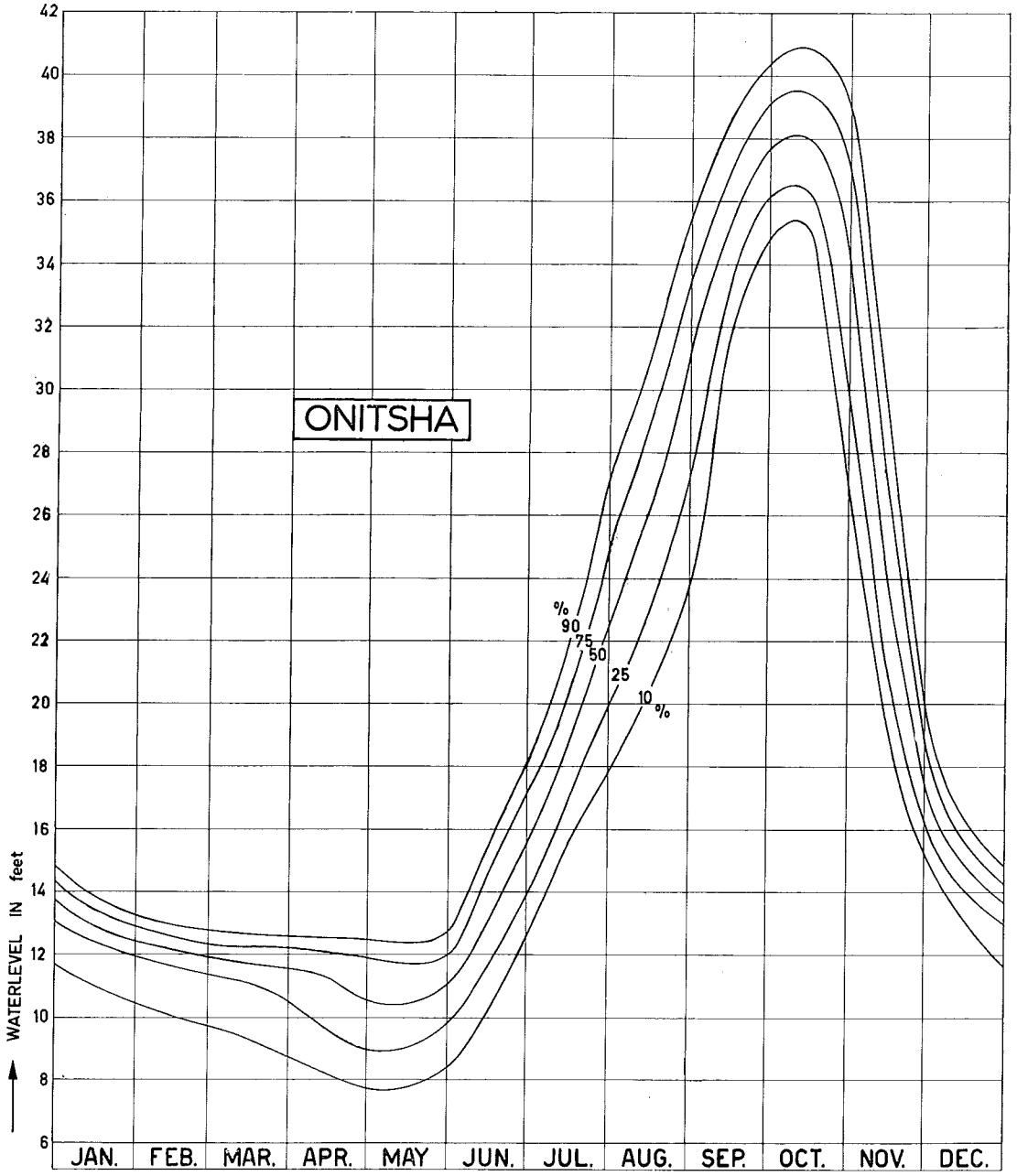


DIAGRAM 4.2.3-6

Frequencies of river-stages at Onitsha (Niger) for a fixed day

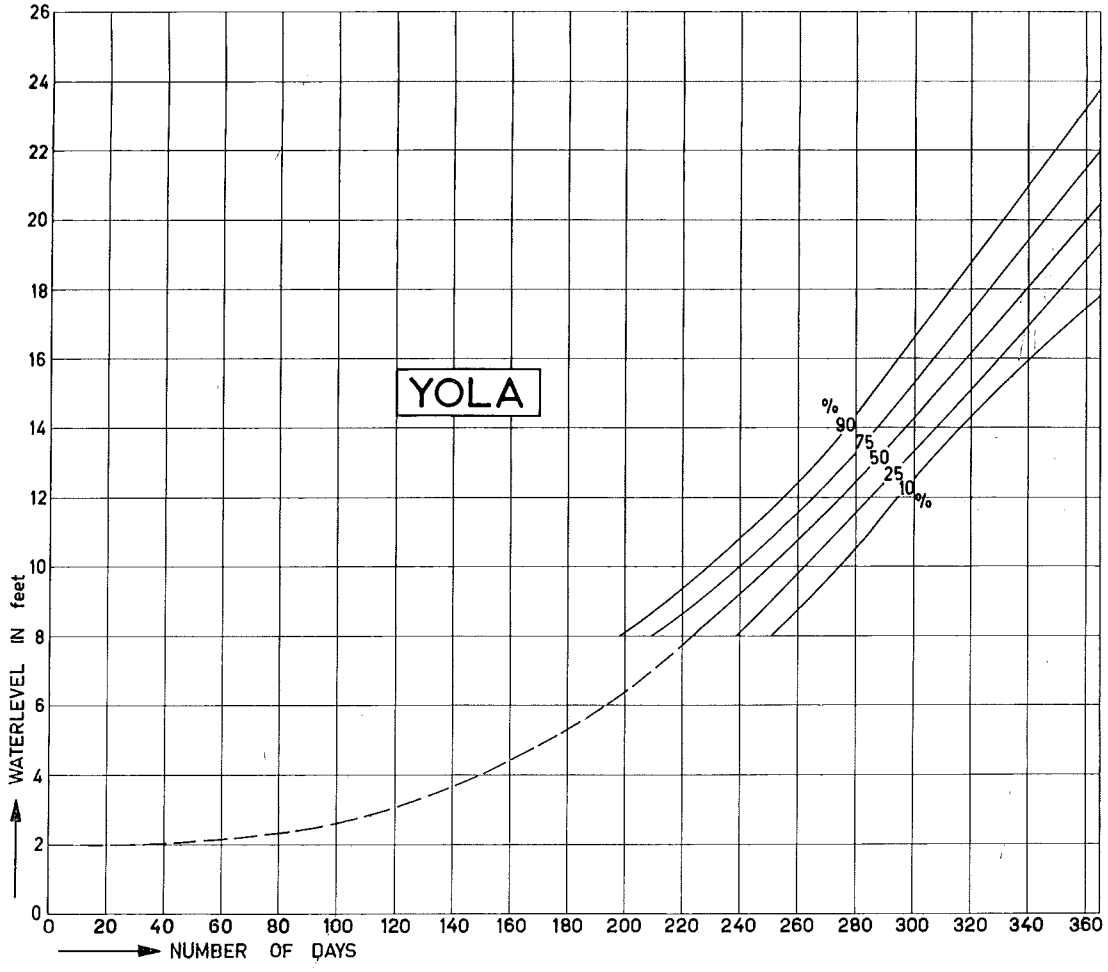


DIAGRAM 4.2.3-7

Duration curves of water-levels at Yola (Benue)

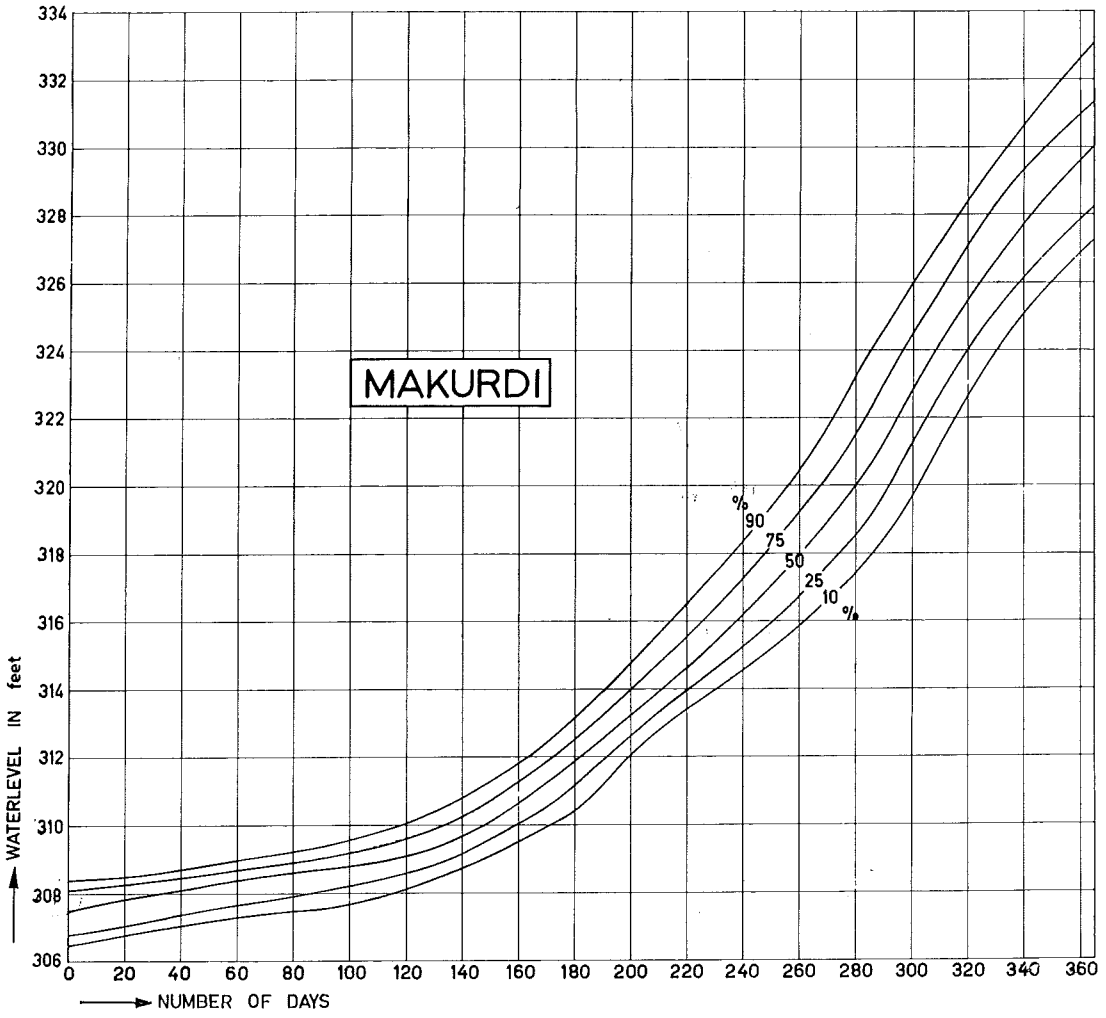


DIAGRAM 4.2.3-8

Duration curves of water-levels at Makurdi (Benue)

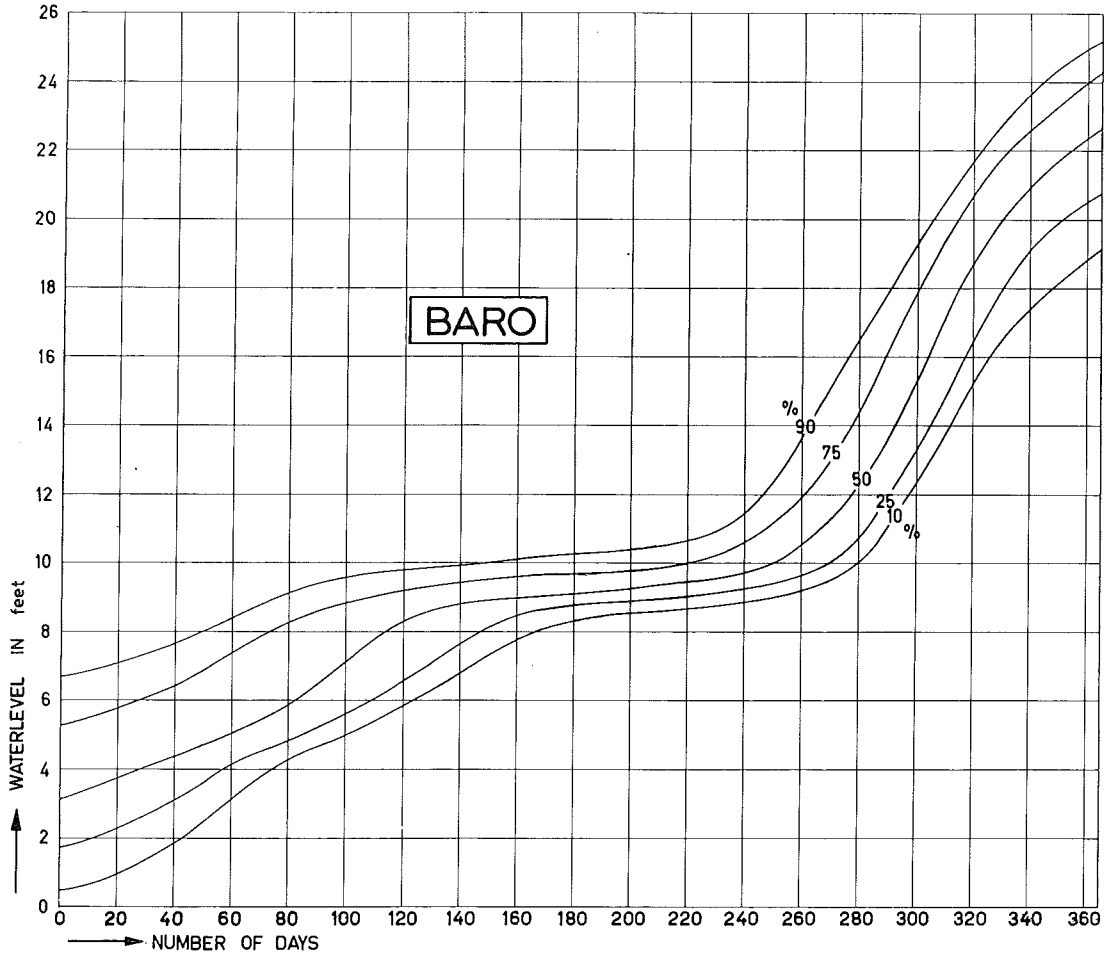


DIAGRAM 4.2.3-9

Duration curves of water-levels at Baro (Niger)

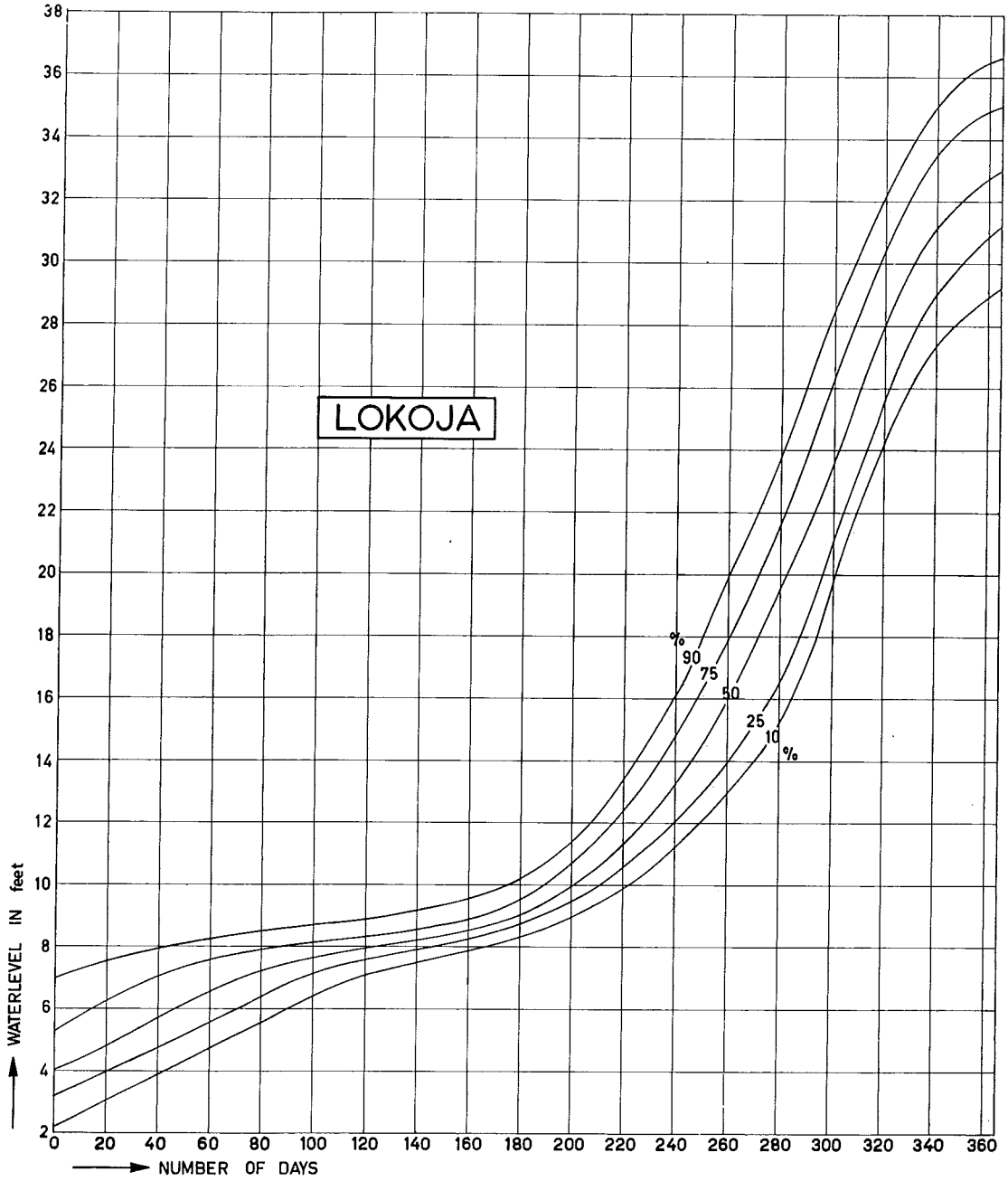


DIAGRAM 4.2.3-10

Duration curves of water-levels at Lokoja (Niger)

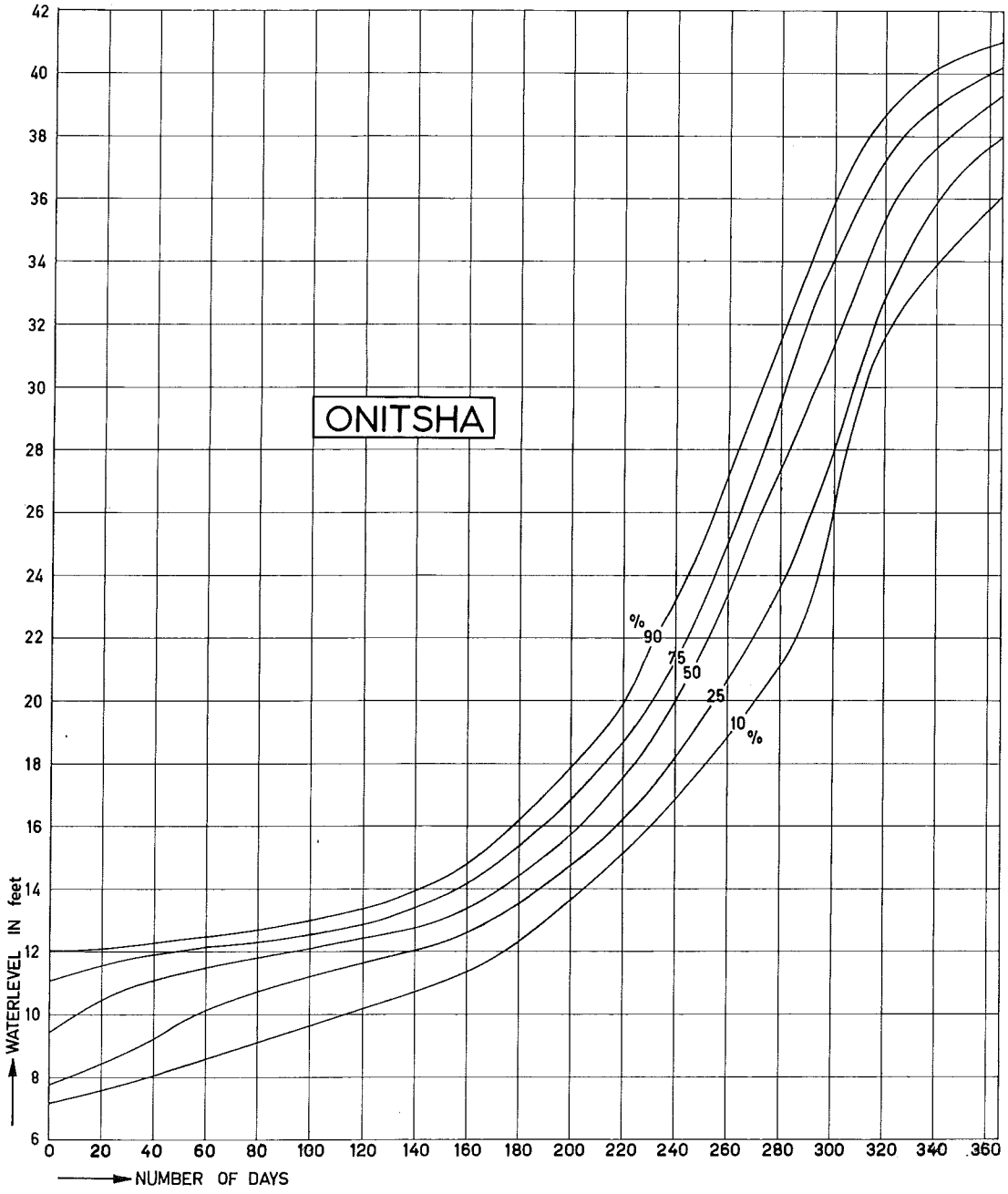


DIAGRAM 4.2.3-11

Duration curves of water-levels at Onitsha (Niger)

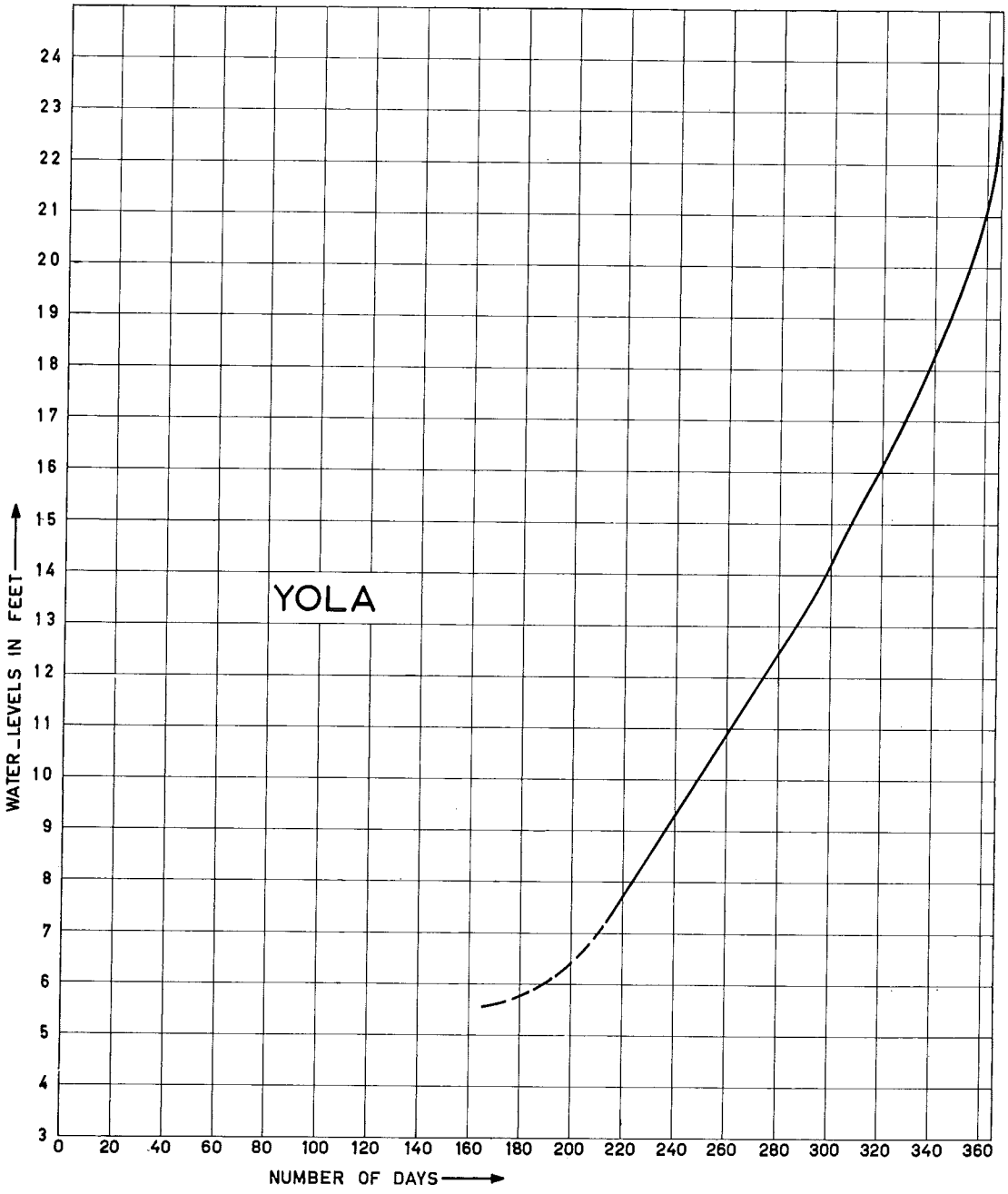


DIAGRAM 4.2.3-12

Average frequencies of water-levels at Yola

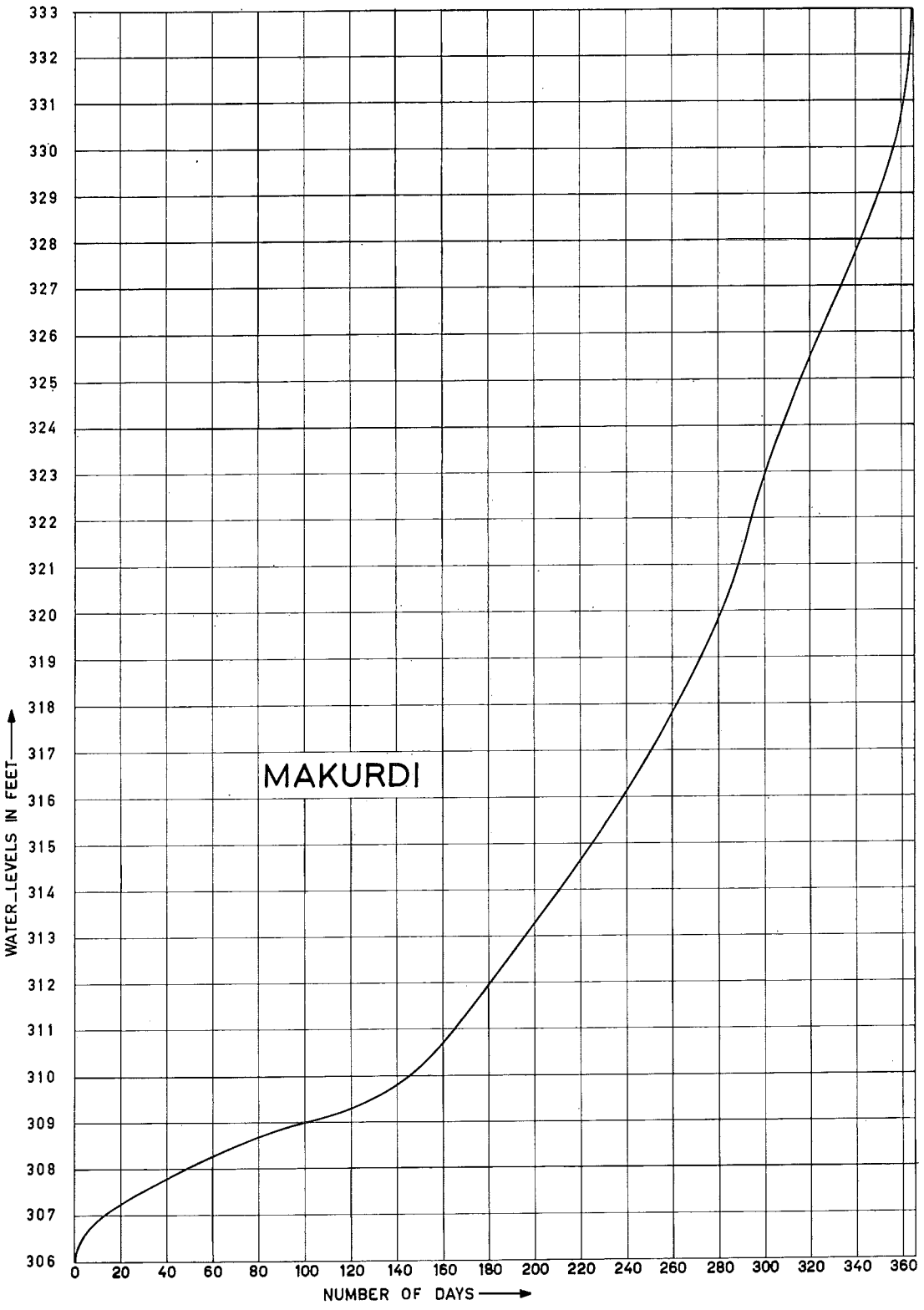


DIAGRAM 4.2.3-13

Average frequencies of water-levels at Makurdi

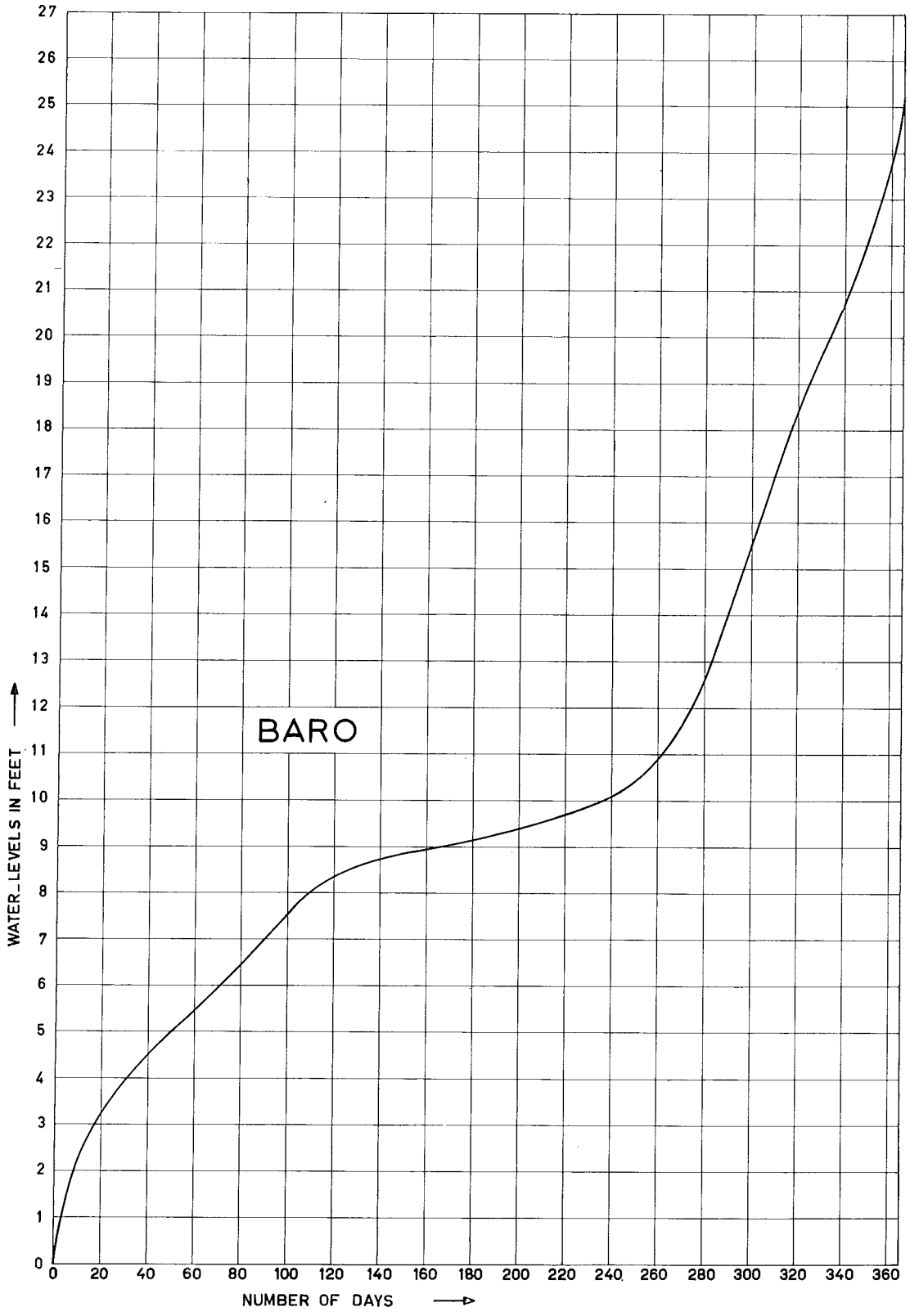


DIAGRAM 4.2.3-14

Average frequencies of water-levels at Baro

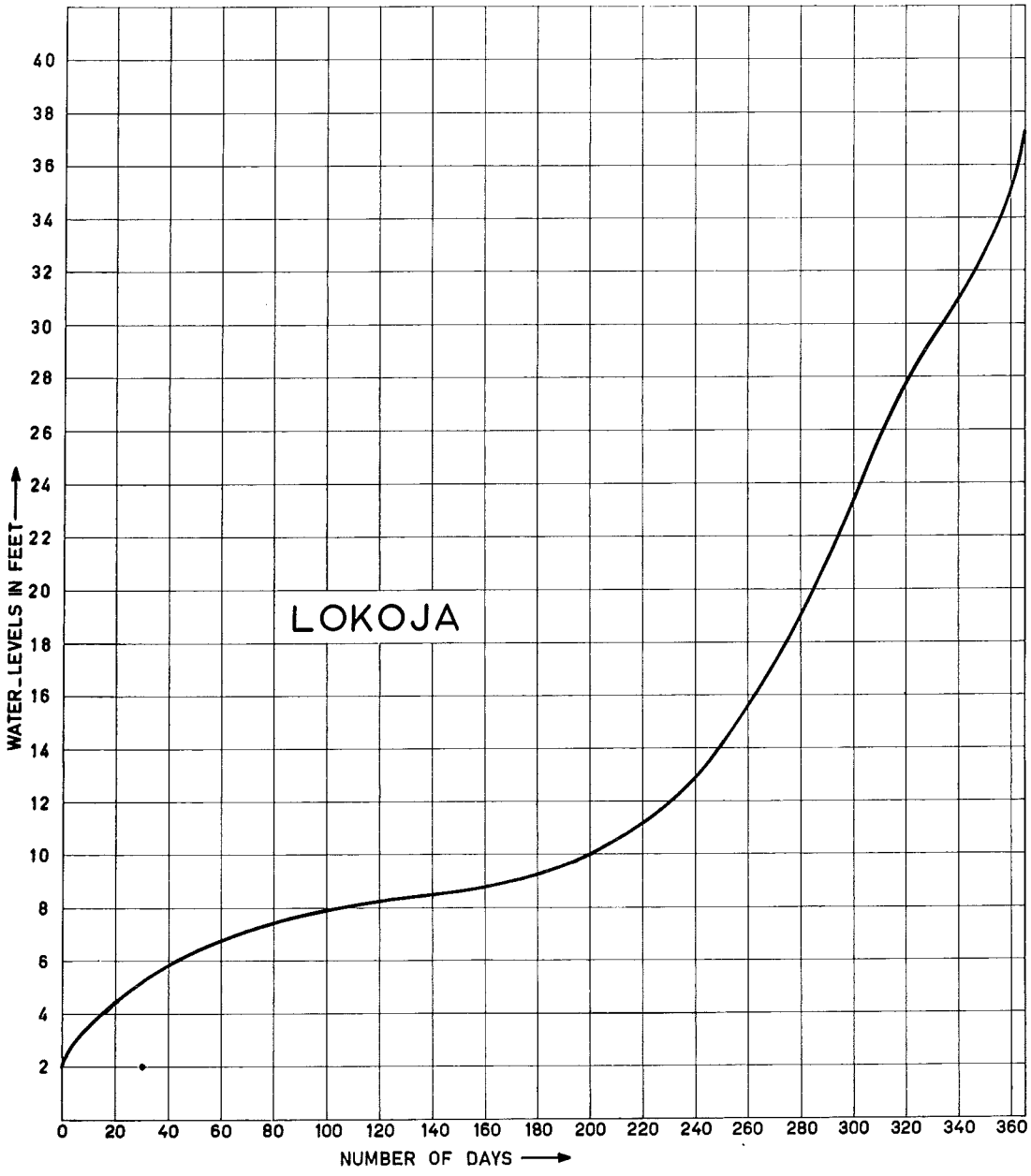


DIAGRAM 4.2.3-15

Average frequencies of water-levels at Lokoja

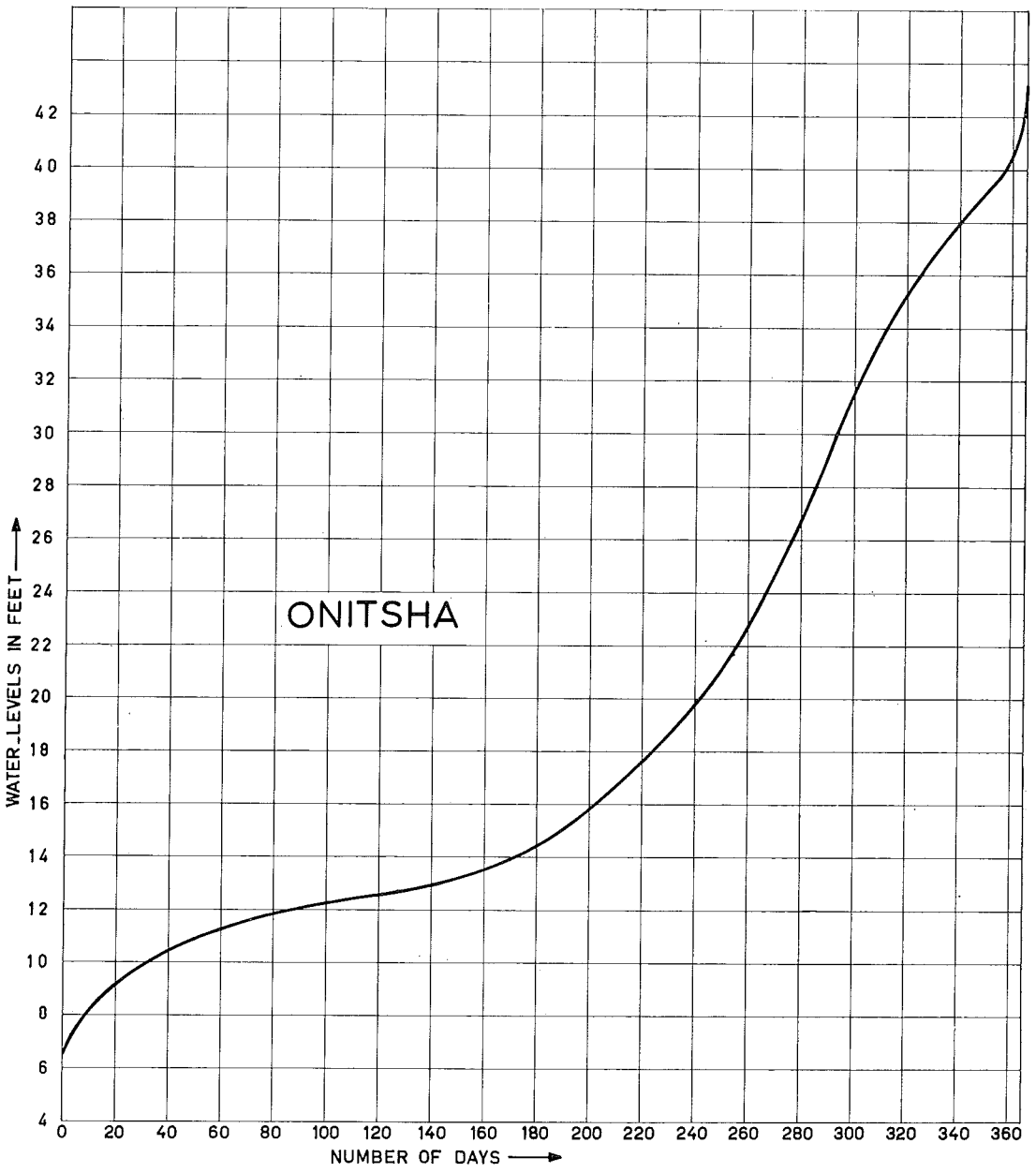


DIAGRAM 4.2.3-16

Average frequencies of water-levels at Onitsha

TABLE 4.2.4-1

ANNUAL HIGHEST AND LOWEST WATER-LEVELS ALONG THE NIGER AND BENUE.

RIVER	NIGER														BENUE							
STATION	DIRÉ			JEBBA			BARO			LOKOJA			ONITSHA			GARUA			YOLA		MAKURDI	
year	highest water-level			highest water-level		lowest water-level	highest water-level		lowest water-level	highest water-level		lowest water-level	highest water-level		lowest water-level	highest water level			highest water-level		highest water-level	lowest water-level
	m	ft	in	ft	in	ft in	ft	in	ft in	ft	in	ft in	ft	in	ft in	m	ft	in	ft	in	ft in	ft in
1914	4.95	16	3																			
1915	5.50	18	½	61	5	48 7	21	4	0 10	30	9	1 7	36	8	5 2	—	—		—		—	—
1916	5.47	17	11	64	9	49 0	24	10	1 4	38	9	1 7	40	0	7 10	—	—		—		—	—
1917	5.57	18	3	65	5	49 7	25	1	0 6	35	9	2 8½	38	4	8 1	—	—		—		—	—
1918	5.63	18	6	62	5	49 5	22	2	2 3	34	6	4 6	37	6	10 2	—	—		—		—	—
1919	5.48	18	0	57	11	48 8	19	5	1 8	32	4	4 3	34	8	9 3	—	—		—		—	—
1920	5.35	17	7	61	11	47 5	24	1	0 3	35	9	3 0	38	5	6 11	—	—		—		—	—
1921	5.12	16	9½	62	8	48 9	23	7	0 4	34	11½	4 0	37	10	10 4	—	—		—		—	—
1922	5.59	18	4	62	5	48 6	22	10	0 3	31	2	2 10	34	9	8 2	—	—		—		—	—
1923	5.40	17	9	61	1	51 2	21	0	5 0	34	8	6 9	37	6	8 11	—	—		—		—	—
1924	5.80	19	0	65	5	49 9	25	0	3 0	37	7	4 6	39	11½	5 1	—	—		—		—	—
1925	5.87	19	3	—		—	23	1	5 3	34	4	4 3	37	10	10 8	—	—		—		—	—
1926	5.32	17	5½	—		—	21	3	7 0	32	7	5 10	36	10	11 3	—	—		—		—	—
1927	5.78	18	11½	—		—	24	7	3 3	34	0	3 4	37	9	7 6	—	—		—		—	—
1928	5.87	19	3	—		—	24	1	5 7	34	0	7 8	37	11	11 8	—	—		—		—	—
1929	5.92	19	5	—		—	25	3	5 11	35	9	6 0	39	2	10 6	—	—		—		—	—
1930	5.86	19	3	—		—	24	10	7 0	33	3	5 3	37	7	11 7	—	—		—		—	—
1931	5.70	18	8½	—		—	22	0	6 4	31	6	5 5	37	2	11 7	—	—		—		—	—
1932	5.77	18	11	—		—	18	0	3 5	32	3	4 0	37	3	10 1	7.15	23	5	—		333 0	306 6
1933	5.77	18	11	—		—	23	5	5 4	30	6	3 5	38	1	9 7	7.60	24	11	—		329 0	307 3
1934	5.49	18	0	—		—	26	6	4 1	35	10	4 11	38	3	9 3	7.35	24	1	18	6	329 0	307 4
1935	5.67	18	7	—		—	24	6	2 10	36	4	3 6½	38	8	7 6	7.85	25	9	20	9	331 9	308 3
1936	5.85	19	2	—		—	21	9	3 8	35	0	5 1	38	0	9 2	7.44	24	5	22	3	333 6	308 0
1937	5.42	17	9	—		—	21	8	3 0	28	8	4 9	33	9	9 6	—	—		16	6	326 6	308 0
1938	5.70	18	8½	—		—	22	1	0 10	31	6	3 7½	36	0	7 11	7.76	25	6	20	0	330 0	307 9
1939	5.52	18	1	—		—	24	11	4 6	33	6	5 0	37	3	8 7	6.26	20	7	20	6	327 9	308 0
1940	5.16	16	11	—		—	19	7	3 0	28	1	3 7½	32	6	7 5	—	—		20	0	327 9	308 0
1941	5.26	17	3	—		—	21	11	3 6	30	2	3 8	35	3	7 5	7.54	24	9	21	6	329 0	309 0
1942	5.07	16	8	—		—	16	6	2 7	28	10	3 0	34	2	7 0	7.16	23	6	20	6	330 0	308 3
1943	5.39	17	8	—		—	21	7	1 10	31	3	2 3	36	4	6 11	7.23	29	9	25	0	330 6	308 0
1944	5.10	16	9	—		—	19	3	1 7	28	5	3 3	—		—	5.71	18	9	18	3	326 9	308 0
1945	5.53	18	2	—		—	23	0	0 10	31	4	2 0	—		—	7.36	24	2	20	7	329 0	306 3
1946	5.67	18	7	—		—	21	9	2 4	29	0	3 2	—		—	7.84	25	9	19	10	327 0	307 0
1947	5.26	17	3	65	10	—	25	3	3 7	34	6½	4 2	—		—	7.22	23	8	22	0	329 9	306 6
1948	5.50	18	½	60	4	51 5½	21	6	2 9	34	8	3 9	—		—	8.60	28	2	23	6	333 9	307 0
1949	5.40	17	9	59	9	48 9	20	9	—	32	6	3 4	—		—	6.70	22	0	20	0	330 9	—
1950	5.80	19	0	—		—	20	3	2 8	28	7	2 11	35	7	8 0	6.45	21	2	19	4	327 9	306 6
1951	6.01	19	9	—		—	23	6	3 5	32	11	4 10	38	9	8 1	6.64	21	9	21	0	329 9	306 9
1952	5.98	19	7½	—		—	23	3	4 8	30	8	7 10	37	5	12 3	6.52	21	5	20	6	327 6	306 6
1953	6.06	19	10½	63	0	50 6	23	5	5 9	31	6	7 2	38	0	11 3	6.58	21	7	18	0	328 3	307 0
1954	6.13	20	1	64	9	51 0	25	0	5 3	36	9	7 6	41	8	12 0	7.14	23	4	21	3	332 6	307 0
1955	6.12	20	1	64	6	52 2	25	5	4 0	37	0	7 2	41	8	12 1	7.38	24	3	23	4	332 0	307 8
1956	5.65	18	6½	63	6	50 8	20	4½	5 0	34	0	6 3	37	10	10 4	7.20	23	7	21	11	330 0	307 9
1957	6.11	20	0	66	1	51 2	26	7	4 1½	36	2½	5 0	41	0	8 4	6.94	22	9	21	2	330 10	306 0

4.2.4. Frequencies of high-water and low-water levels

Table 4.2.4-1 gives yearly peak stages for several stations along the Niger and the Benue. For some of these stations low-water records were also available.

To see whether or not the highest and the lowest water-levels of a particular year have been exceptional, the data of the table have been plotted on normal probability paper. Through the plotted points straight lines have been drawn (Diagrams 4.2.4-2, 3 and 4).

It is seen, for example, that the peak water-level of 1955 at Diré has been rather high. The table states that this level was 20'1", and it can be read from Diagram 2 that in only 7% of the years did a peak level occur which is higher. In that year peak levels on the Benue have also been high. The highest water-level at Makurdi in 1955 was 332'0", and from Diagram 3 it is read that in only 18% of the years did a peak level occur which is higher than 332'.

In 1955 also the minimum water-levels have been rather higher. During this year the minimum river-stage at, for example, Makurdi was 307'8", and from Diagram 4 it is read that during 70% of the years the minimum water-level is lower than this figure.

The range of the water-levels at a station can be defined as the difference between the peak level which is surpassed by 50% of the yearly maximum and the low-water level which has such a magnitude that 50% of the yearly minimum water-levels are lower. From the diagrams it can be read that this range is at Baro 19.5', at Lokoja 28.5' and at Onitsha 28'.

It is remarkable that generally peak levels along the Niger and the Benue do not vary much from year to year. At Baro, for example, the difference between the yearly peak level which is surpassed by 25% of the yearly maxima (24,5') and the yearly peak level which is surpassed by 75% of the yearly maxima (21.25') is only 3.25' on the range of 19.5' (see above). For both Yola and Garua along the Benue this difference is 3.0', and at Makurdi it is 3.25' (with a range of 22'). For both Lokoja and Onitsha the difference is 4', whilst at these stations the range is some 28'. At Diré in French West Africa the variation is only 1.5'. This is caused by the very large flood-land upstream from this place, which flattens every high peak (see 2.3.1 and also 4.5.2).

The variation of the yearly minimum water-levels is smaller than that of the yearly maxima. At Makurdi this variation (defined as the difference between that 25% surpassed and that 75% surpassed) is 1.25'. At Baro on the Niger, this figure is 2.75', and at Lokoja and Onitsha it is 2.50'.

4.2.5. Water-level gradients

The water-level gradient or slope of a river-stretch is a dimensionless quantity which is obtained by dividing the drop of the water-level by the river-length over which this drop takes place. This slope is a basic characteristic of a river-section and plays an important part in most flow phenomena.

When a river is flowing in an alluvial bed, the gradient generally decreases when going downstream (see Section 2.5).

Where the difference between high-water stages and low-water stages (usually called "range") is greater at downstream parts of the river than at upstream parts, the gradient during high river-stages will be smaller than during low river-stages.

On the other hand, the form of the river-bed will also affect the gradient at the various river-stages. The low-water bed of both the Niger and the Benue has generally a meandering axis, whilst the high-water bed is mostly rather straight. So the low-water stream channel will be longer than the high-water channel. The difference between these two lengths can be expressed by their ratio, termed meander-coefficient (see Table 6.3.3-1, Channel sinuosity). This means that if over a certain river-stretch the same drop would occur during high water and during low

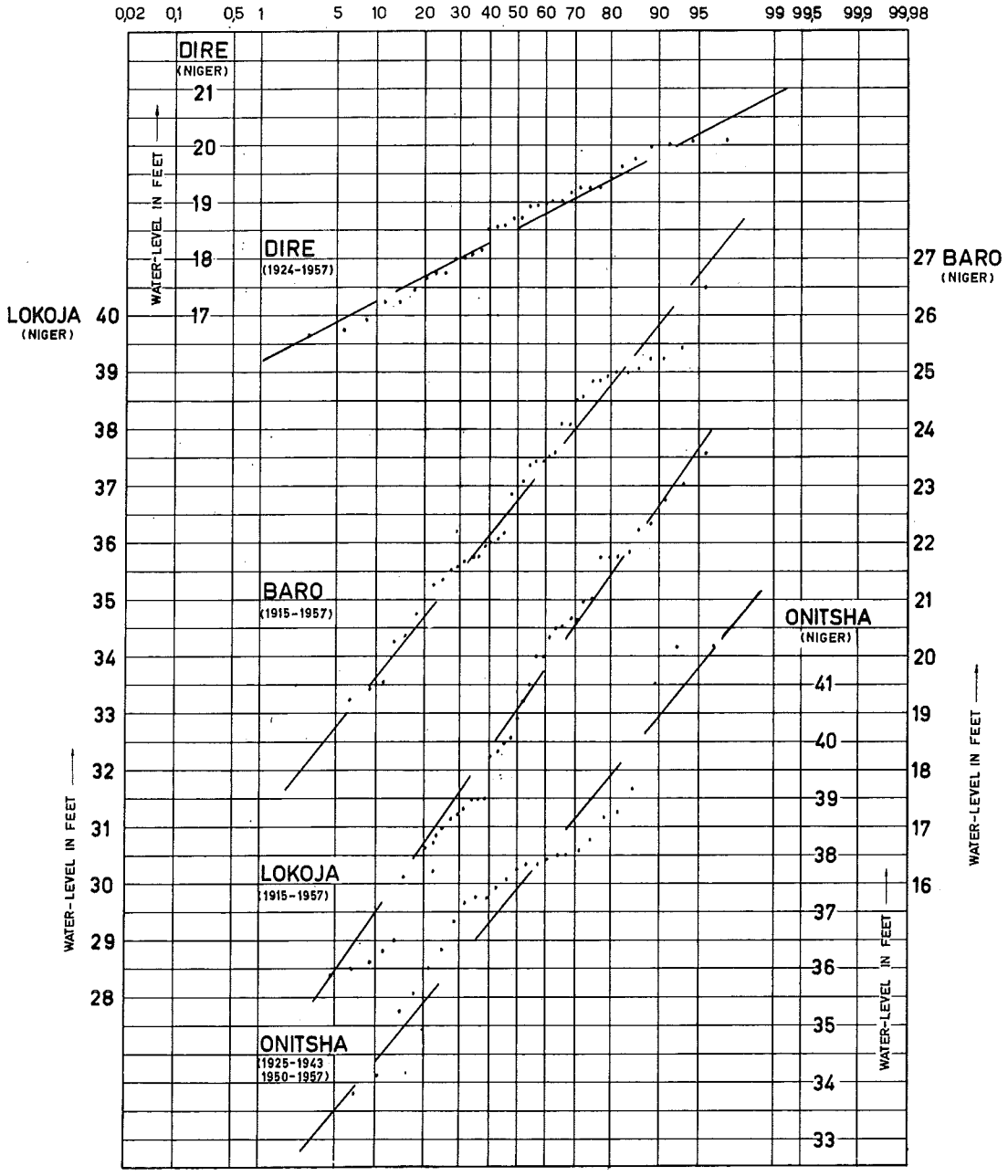


DIAGRAM 4.2.4-2

Frequencies of annual peak water-levels along the Niger

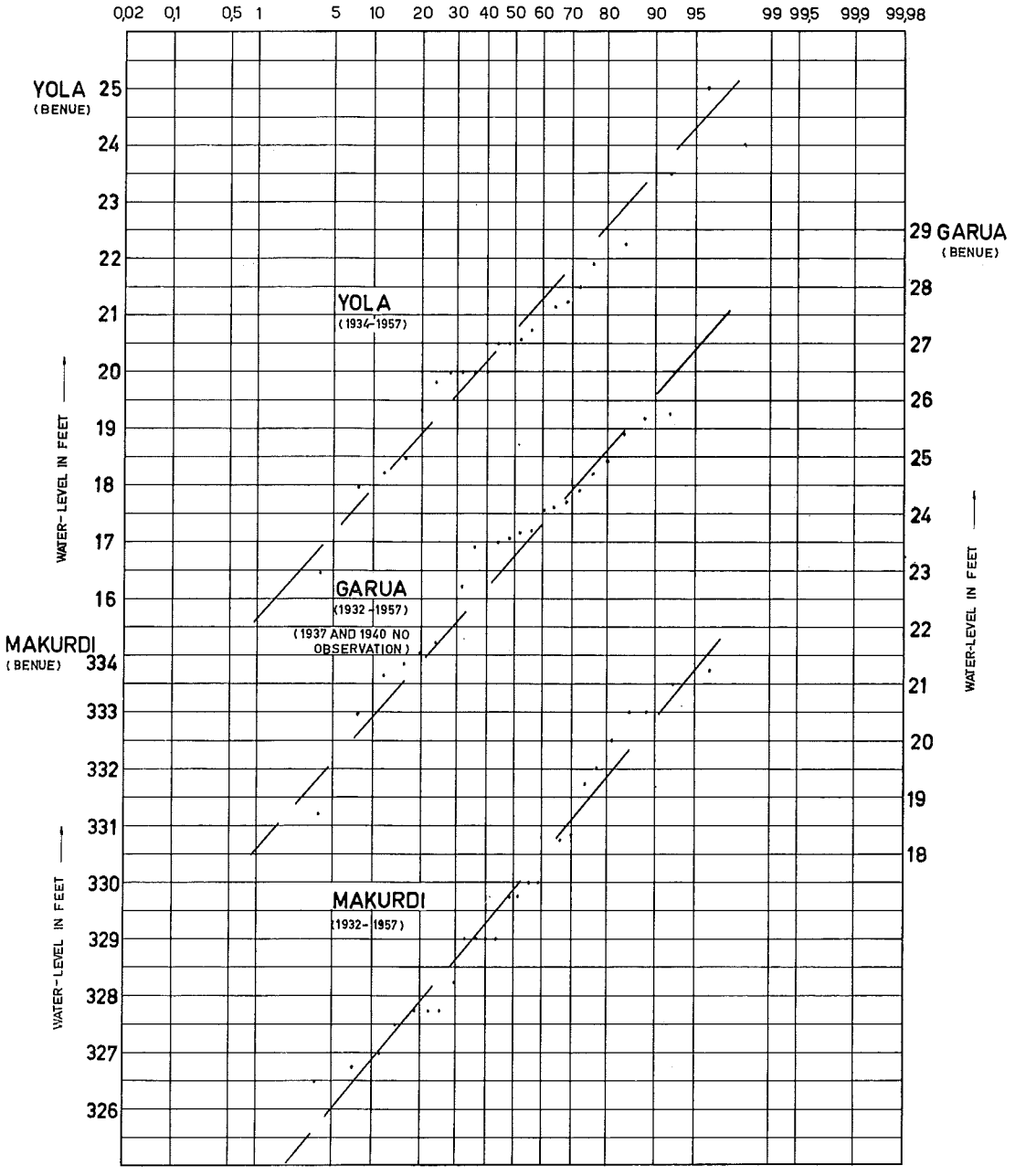


DIAGRAM 4.2.4-3

Frequencies of annual peak water-levels along the Benue

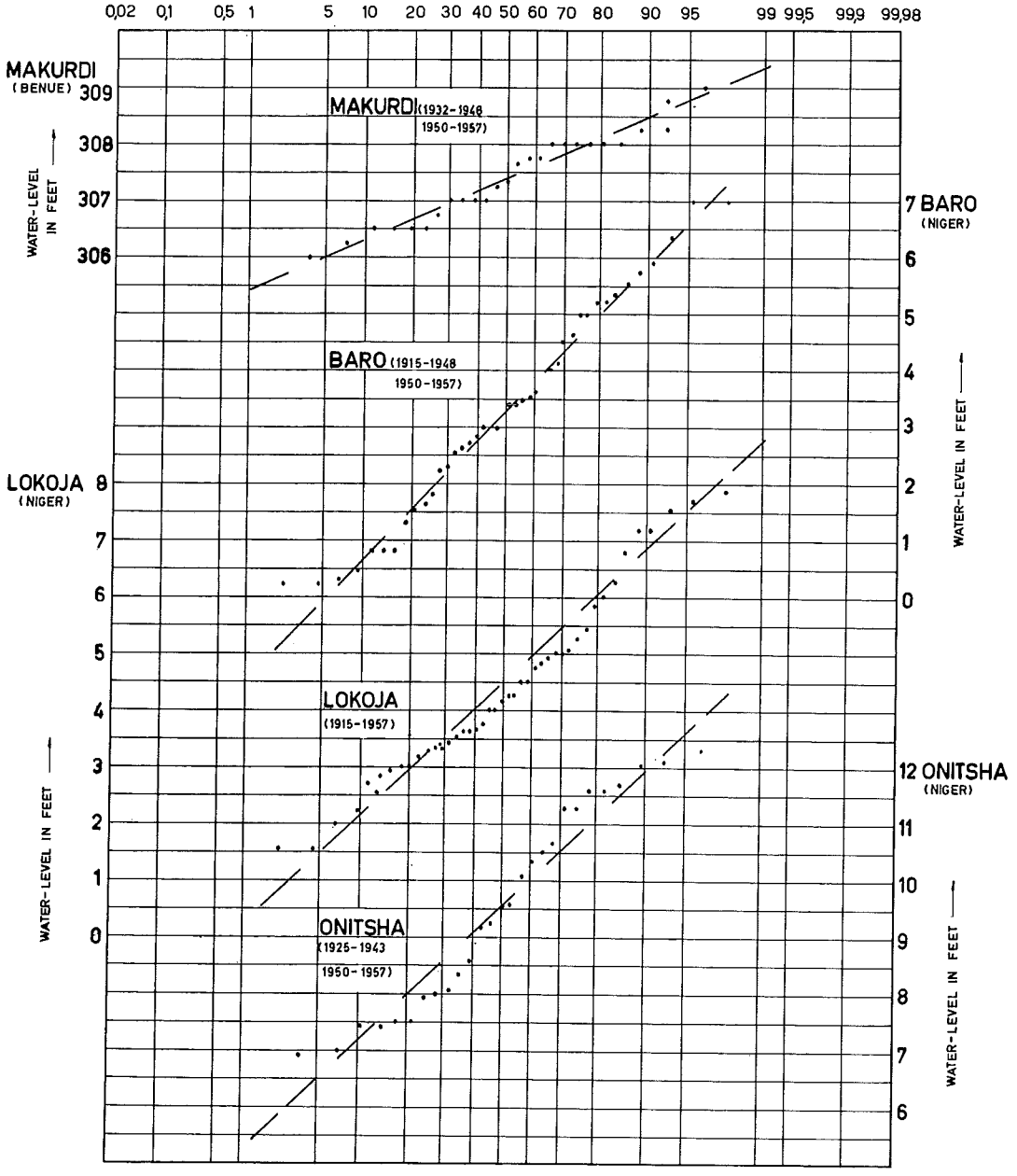


DIAGRAM 4.2.4-4

Frequencies of annual lowest water-levels along Niger and Benue

water, the gradient during this high-water stage will be greater than during the lower stages. This effect may eliminate or even exceed the change of gradient caused by the increase of range when going downstream.

It is common practice to express the slope in units of 10^{-5}. A gradient of 1×10^{-5} equals one centimetre per kilometre (0.053 foot per mile), or 1 foot per mile equals 18.9×10^{-5}. Most alluvial rivers show slopes between 5×10^{-5} and 50×10^{-5}. In their lower courses these may decrease to between 0.5 and 5×10^{-5}.

Diagram 4.2.5-1 shows the water-level gradients (in units of 10^{-5}) of the Niger and the Benue within Nigeria for high, medium and low-water stages. To prepare this diagram use has been made of the datums of the various gauges as resulting from the geodetic levelling executed by the Federal Survey Department (see 4.2.1, and also II, 4.5) and of water-level readings obtained during the period 1955—1957. The lengths of the various river-stretches have been determined with the help of the river charts (see II, 4.1.2). The lengths on the diagram are those of the low-water channel as indicated on the appended Book of River Charts. To find the lengths during high water, the coefficients of Table 6.3.3-1 (Channel sinuosity) have been used.

Gradients shown are average gradients over the fairly long river-stretches (30—100 miles) of which at each end water-level data were available. This means that within the river-stretch the slope may deviate from the average. Especially during the lower stages can the difference between the gradient over a crossing and the gradient between two crossings become considerable (see 6.4.2).

Where slopes are indicated by a number in brackets river-lengths or water-level elevations are not accurately known.

Slopes near a confluence of two rivers depend on the discharges arriving from both rivers. Slopes at a confluence as indicated on the diagram (for example, Benue-Katsina Ala R.) are to be considered as averages. Slopes at the Niger-Benue Confluence are dealt with in detail in 4.2.6 (see in particular Diagram 4.2.6-17).

Slopes on the Niger between Jebba and Malanville are known only for low stages.

Where the Niger flows into the sea, the water-level slope depends also on the tide, as shown on the diagram.

Diagram 4.2.5-2 shows river slopes of the Niger during low water above Malanville, which is situated near the Nigerian frontier. The data were obtained from the "Bureau de Coordination des Etudes Hydrauliques, Dakar".

On the same diagram are drawn the low-water slopes of the Benue above Garua in French Camerouns. The data for this graph were taken from the "Electricité de France", Office des Recherches Scientifiques et Techniques d'Outre-Mer, Paris.

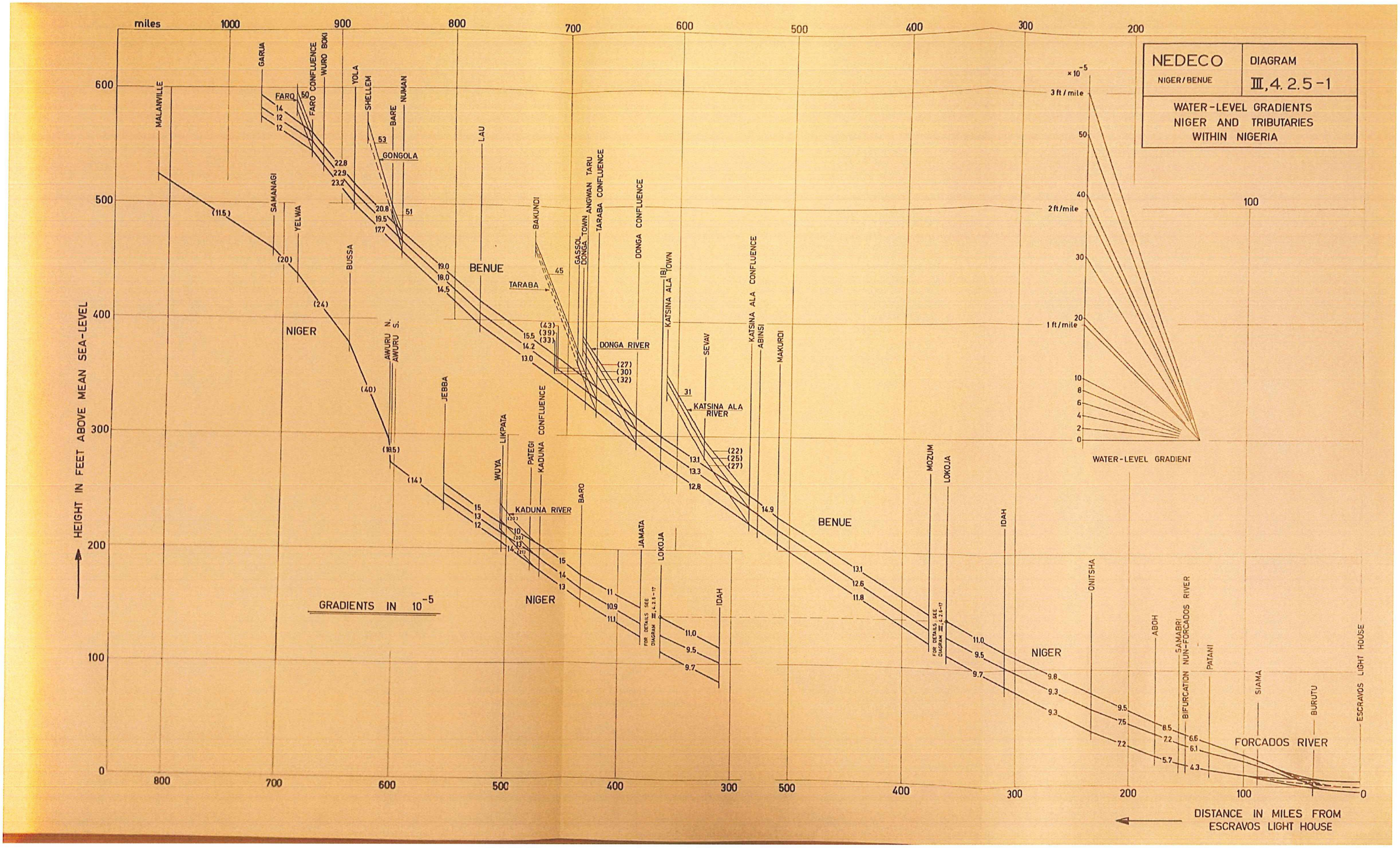
4.2.6. Backwater curves

A river in its most simple form has its water-line parallel to the bottom. As the main factors determining the slope, namely, the ratio sand-transport to water discharge and the diameter of the grains, do not vary, the slope would be constant and the water-line a straight line.

Such an ideal circumstance never occurs. Disturbances in the straight line can be effected by various causes, whilst distinction must be made here between causes within the river's own system, such as increase of resistance by shallows, change of width, shortcuts, etc., and causes from outside. An example of the latter can be found in a large tributary affecting the water-level at the confluence and consequently in the whole section of the main river immediately upstream of the confluence.

NEDECO	DIAGRAM
NIGER/BENUE	III, 4.2.5-1

WATER-LEVEL GRADIENTS
NIGER AND TRIBUTARIES
WITHIN NIGERIA



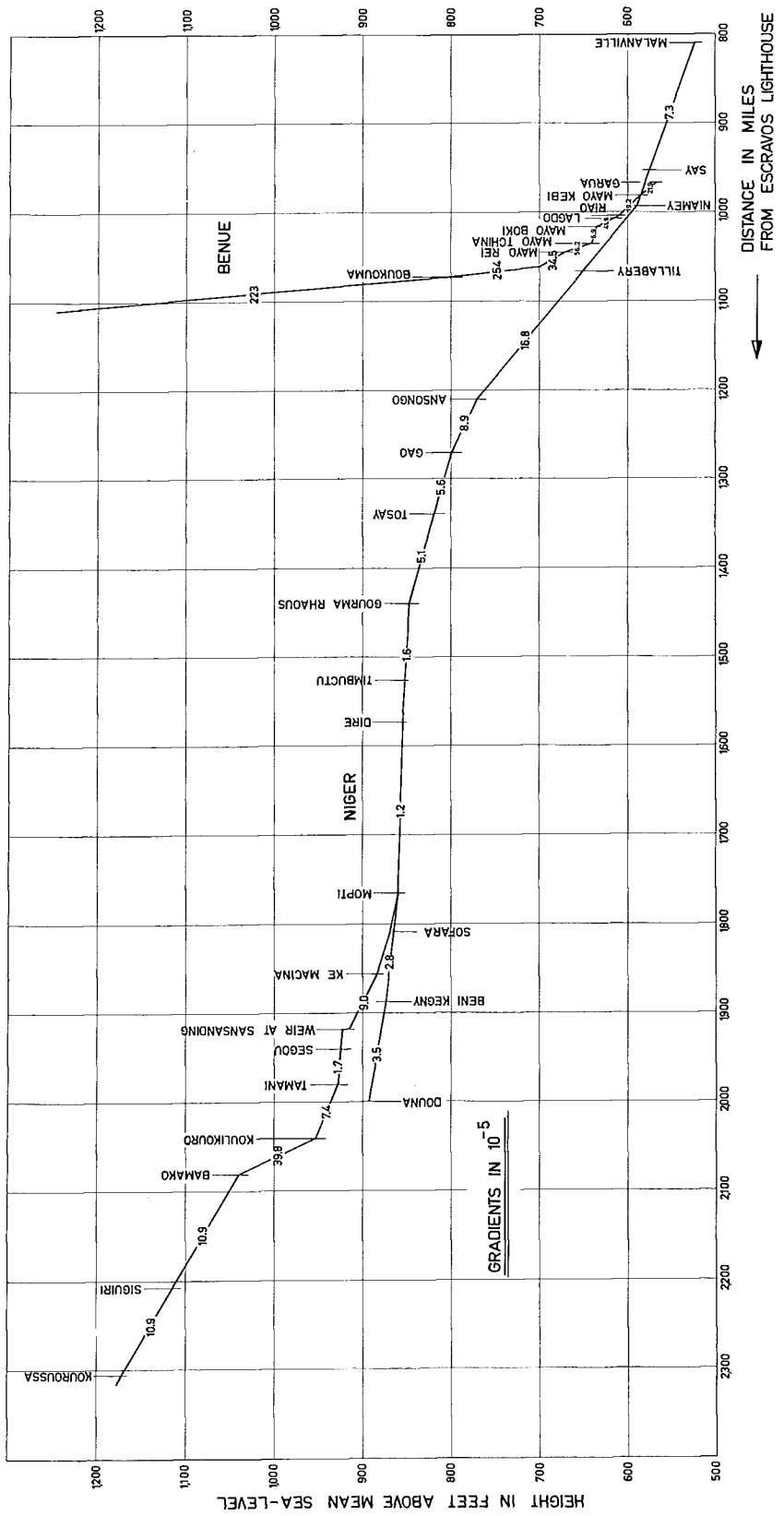


DIAGRAM 4.2.5-2

Water-level gradients of Niger and Benue outside Nigeria

a. *Causes within the river's own system*

Disturbances of the first group, originating within the river's own system, are all fully determined by the water-discharge being the only independent variable. Any steady discharge Q brings about a specific equilibrium, solely determined by Q under the condition that no scour and no accretion occurs. At this equilibrium the water-line adjusts itself, and the slope shows variation only with respect to the shape and size of the cross-section. With a high Q, still being steady, this variation can be approximated as zero and the equilibrium shows a straight water-line. At a low steady discharge, however, the slope depends on the depth. A deep (and consequently narrow) river-section has a relatively gentle slope.

The discharge Q, being the basis of the consideration, can be expressed when using the formula of De Chezy (see 4.3.1)

$$Q = bCa^{\frac{3}{2}} i^{\frac{1}{2}} \quad \ldots\ldots\ldots \quad (1)$$

Obviously, Q is constant for the whole length of the river-section.

Equilibrium condition (no scour and no accretion) is found in the equation

$$ba^{\alpha} = \text{constant} \quad \ldots\ldots\ldots \quad (2)$$

since a variation in the term ba^{α} immediately results in a scour or accretion (see 5.4.2). Here, α is a coefficient depending on the so-called "drag" ρgai (see 5.2.1). It appears to vary between $1\frac{1}{2}$ at very high water to a little above 1 at very low water.

Now,
$$Q = Cba^{\alpha} a^{\frac{3}{2}-\alpha} i^{\frac{1}{2}} = \text{constant}$$

When it is accepted that the coefficient C is a constant, it then follows

$$a^{\frac{3}{2}-\alpha} i^{\frac{1}{2}} = \text{constant} \quad \ldots\ldots\ldots \quad (3)$$

which is the equilibrium equation for steady discharge. It appears that for very high water, with $\alpha = 3/2$, the equation leads to the conclusion

$$i = \text{constant}$$

which means that the water-line is a straight line.

With low water, however, let it be assumed that $\alpha = 1.2$. Equation (3) is then

$$a^{0.3} i^{\frac{1}{2}} = \text{constant}$$

from which follows that a deep river-section has a gentle slope, and a shallow river-section a steeper slope.

In a natural river the discharge changes continuously. However, it is stated (5.2.4) that somewhere in the range a specific value for Q exists which, flowing constantly and continuously, would have the same effect upon the bed (i.e., the cross-section) as the varying Q ultimately takes; this specific discharge is called the dominant discharge Q_b. It appears that the Q_b on the Niger and Benue is reasonable high. Hence, with a value for the coefficient α not far from 3/2, the water-line is almost a straight line. Within the term ba^{α} both b and a could change. A narrow river-section must be deep, a wide be shallow; but in all these cases the water-line at $Q = Q_b$ is nearly straight.

With a little rise or fall the situation is different. Generally speaking, with a discharge $Q \neq Q_b$ the cross-section no longer follows Equation (2) and the above-mentioned derivation is not applicable. Differentiating Equation (1), and assuming that the width of the river does not depend on change of stage, it is concluded that

$$\Delta a_2 = \Delta a_1 \left[\frac{a_2}{a_1}\right] \quad \ldots\ldots\ldots \quad (4)$$

which means that in a shallow river-section the fall or rise in water-stage is smaller than in a deep river-section. Equation (4) can also be written as follows:

$$\Delta a_2 = \Delta a_1 \left[\frac{b_1}{b_2}\right]^{1/\alpha} \quad \ldots\ldots\ldots \quad (5)$$

which means that in a wide river-section the fall or rise in water-stage is smaller than in a narrow river-section.

The slope, being originally straight or nearly straight at $Q = Q_b$, is now affected by changes in width and depth. Diagram 4.2.6-1 shows how, starting from a straight water-line for $Q = Q_b$, the water-level would run in cases of a wide (Diagram 1A) and a narrow (Diagram 1B) river-section respectively. The depth, of course, is dependent on the width and determined at $Q = Q_b$.

There is, for instance, the case of a wide section with a discharge $Q < Q_b$. The fall in water-stage on the original river, Δa_1, is greater than the fall on the section concerned, Δa_2, which causes a relative higher water-level in the wider section. This "raise" is extended gradually upon the section immediately upstream of the widening, and results in a so-called "backwater curve". At the end of the widened section also a backwater curve occurs, since the water-level must go back down to the original height. This type of curve is a "draw-down".

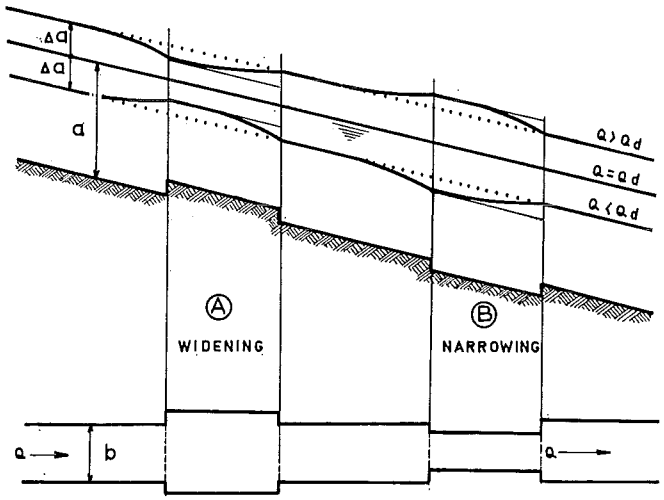


DIAGRAM 4.2.6-1

Behaviour of water-level at variation in width

Distinction is made here between "rise" and "raise". "Rise" means a higher water-level while the slope remains unchanged. This could occur, for instance, by an increase of Q or a decrease of the width. The situation still is in equilibrium; the water-line can be straight. "Raise" is caused by a disturbance upon this equilibrium; the slope differs from the original value and the water-line is curved. The disturbance propagating upstream is gradually losing its influence.

A backwater curve is called positive when (as in this case on the upstream side of the widening) it is caused by a raise in water-stage; negative when it is caused by a draw-down. The shape of the curve is dependent on various factors, the theory on which is given in general hydraulic literature.

The above-mentioned phenomenon of a backwater curve caused by a narrow section in the river is clearly recognised in the river-section below Lokoja, known under the name "Rocky Section". Diagram 4.2.6-2 shows how the width in this 20-mile section is reduced by a chain of rocks, while Diagram 4.2.6-3 gives the water-lines at three different stages: a raise at very high water and a draw-down at low water is the result, analogous to Diagram 1 B.

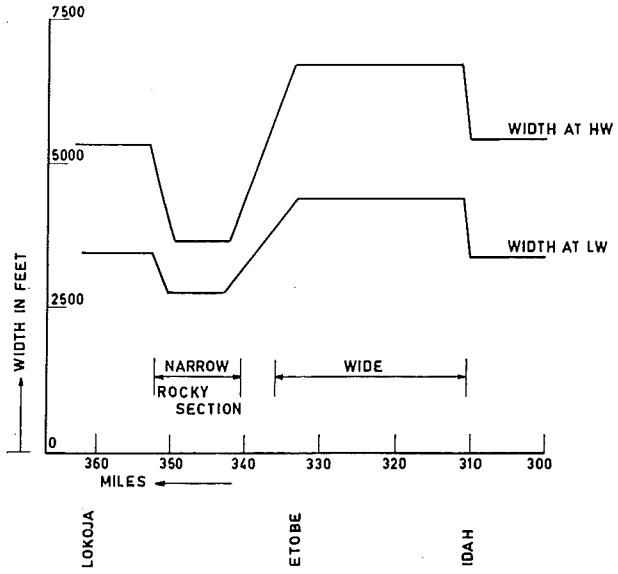


DIAGRAM 4.2.6-2

Variation in width of the Niger below Lokoja

Here the width gives primary restriction and the depth adjusts itself to it. The reverse is the case at a "crossing" (6.4.2) involving an increase in width by curvature of the stream-lines. It appears that at a normal crossing during high water both cross-sections 1 and 2a have almost equal depth. Such has been drawn in Diagram 4.2.6-4 where the depth is 14′. At low water cross-section 1 has 16.8′ and 2b only 6′. A raise at L.W. results, as in Diagram 1A.

To complicate matters, the length of the crossing is so small that the raise in water-stage cannot fully develop itself. The negative backwater curve (draw-down) at the end of the shallow section affects the water-level over the entire length. The result is a smaller raise, but a steeper

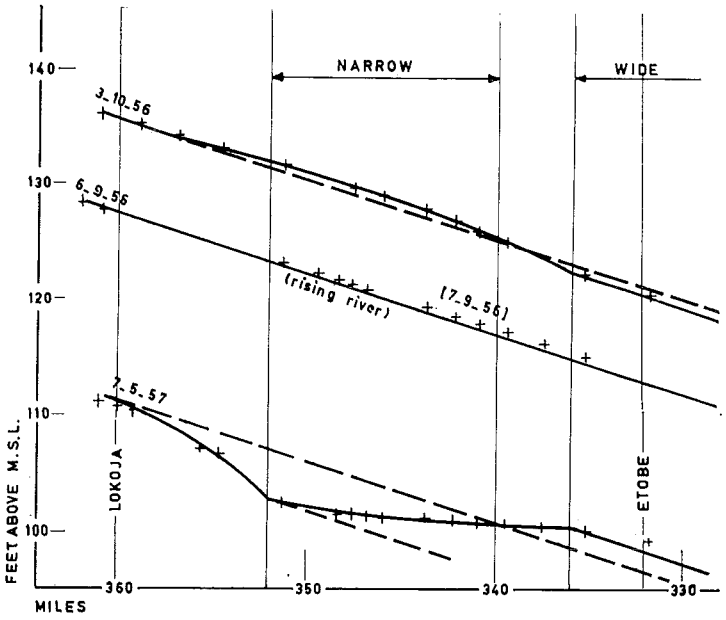


DIAGRAM 4.2.6-3

Observed water-line of the Niger below Lokoja

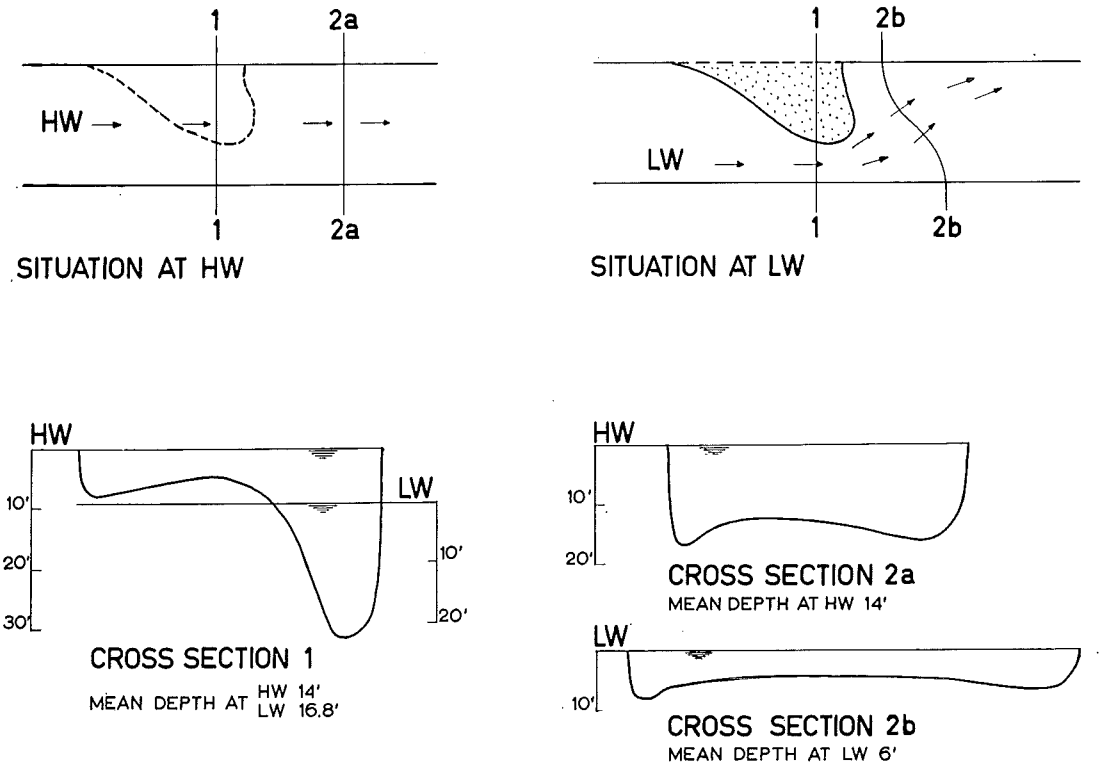


DIAGRAM 4.2.6-4

Variation in depth of various cross-sections at a crossing

slope over the crossing, as shown in Diagram 4.2.6-5. At H.W., however, no disturbance at all occurs, because of the equality of depth in cross-sections 1 and 2a. These specific low-water disturbances occur very frequently over the full length of the river. An example is given in Diagram 4.2.6-6.

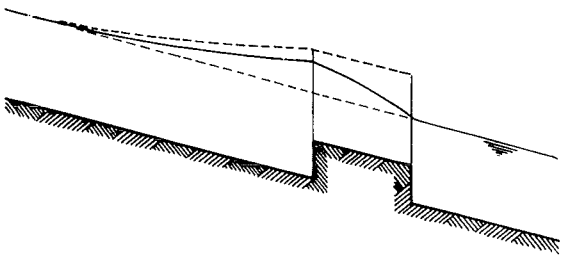


DIAGRAM 4.2.6-5

Water-line over a crossing at low water

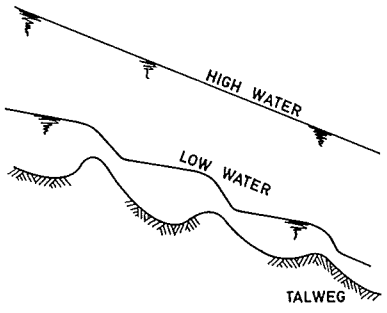


DIAGRAM 4.2.6-6

Local variations in the slope during low water

b. *Causes from outside*

As the second cause of disturbance onto a straight water-line — the cause coming from outside the river's own system — a large tributary has been mentioned affecting the water-level and slope of the river-section immediately upstream of the confluence.

Let it be assumed that a specific circumstance is possible where both rivers have straight water-lines. No influence exists from one river on the other. The two water-lines meet at the confluence and the discharging capacity of the lower river is just sufficient to maintain the water-level (see Diagram 4.2.6-7).

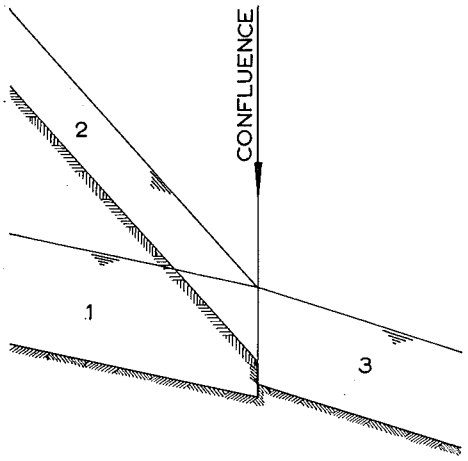


DIAGRAM 4.2.6-7

Equilibrium at two joining rivers

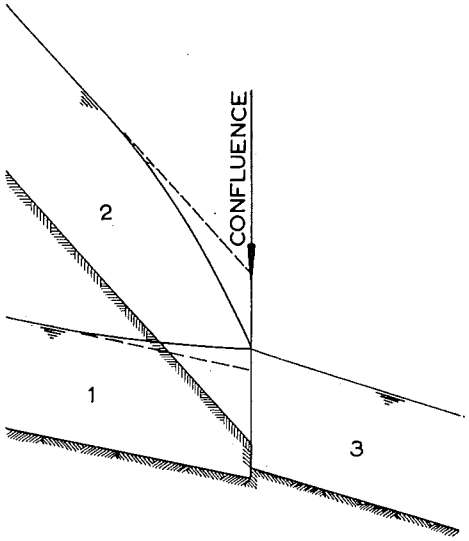


DIAGRAM 4.2.6-8

Disturbed equilibrium at confluence by a rise of one river

A small rise on one of the rivers would disturb the whole situation. Its water-line, extended downward as a straight line, does not meet the water-line of the other river. Since jumps of water surface are not possible, the two water-lines must bend towards one another to effect the meeting at the fixed point of confluence. Now the water-line is not straight, but clearly influenced by this effect (see Diagram 4.2.6-8). Generally speaking, a rise in river 2 will effect a raise on river 1, and a draw-down on itself.

The water-level in the lowest section of river 1 depends not only on its own discharge Q_1, but also on the discharge of river 2, Q_2. Between the discharges Q_1 and Q_2 no correlation exists. Obviously the water-level in river 1 can vary even with steady discharge Q_1, contrary to a disturbance of the first group (mentioned under a), where Q_1 was the only independent variable.

The straight extension to the water-line of the upper river over its lowest section, however it is raised or drawn down, will be used as datum for expressing the magnitude of raise in the considerations on the following pages.

Attention is drawn to the fact that this straight extension is by no means a natural equilibrium. Since river 2 affects the water-level and slope of river 1, it will also affect the sand-transporting capacity S (see 5.2.1) and hence the river-bottom. Generally the temporal-average influence of river 2 upon river 1 will not be a straight line. From DE CHEZY's formula it is concluded that the surface line (only straight when the bottom line is also straight and parallel to the surface) cannot possibly be straight.

However, no better datum approaching a natural possibility has been found. For reason of more simple mathematical derivations the above-defined datum appeared to be most efficient.

The deviation of water-level from datum at any distance x from the point of confluence is called the raise z_x; the raise at the point of confluence itself is symbolised as z_0.

Since the river-bottom of river 1, the main river, being continuously influenced by the tributary (river 2), does not necessarily follow a straight line, here too the extension from the upper stretches of the river is drawn. A jump in the bottom-line at the confluence seems unavoidable, as in the lower river different conditions cause a different slope and depth. The bottom jump is called A (see Diagram 4.2.6-9).

Equilibrium is defined as the situation where $z_0 = 0$, which does certainly not involve $z_x = 0$. Condition for equilibrium is derived from Diagram 4.2.6-9:

$$a_{e_1} = a_3 + A$$

a formula which, with the law of DE CHEZY already mentioned, can be reduced to the simple

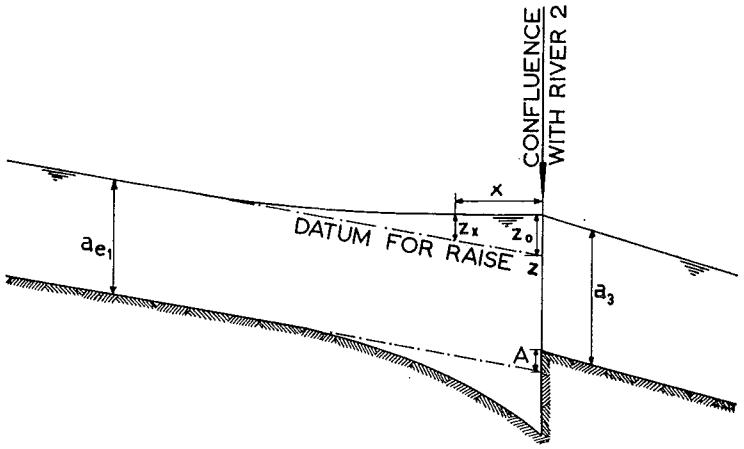


DIAGRAM 4.2.6-9

Definitions of symbols used in considerations about the phenomenon of raise at confluences

equilibrium-condition

$$Q_1^{\frac{2}{3}} = Lh_3 + K \qquad \ldots\ldots\ldots (6)$$

where Q_1 = discharge of the river concerned (river 1),
h_3 = gauge reading at the point of confluence, and
L,K constant coefficients.

This condition expresses a function between the discharge Q_1 and the water-level at point of confluence; the latter is influenced also by the discharge Q_2 of the tributary.

The discharge in river 1 has been used here, and not the water-level, because the latter is variable without change of discharge. The discharge, however, is independent and not influenced by outside sources.

It must be kept in mind that by Q_1 in the formula is meant the discharge immediately upstream of the confluence. It is equal to the discharge of the upper river at a specific site situated far enough upstream to be independent of the influence from the tributary if
(i) the river is steady, or the time-lag (4.2.7) between the site and the confluence is taken into account; and
(ii) lateral inflow, storage, evaporation, etc., between the site and the confluence is zero.

The discharge at such a site is solely determined by the water-level h_1 (f.i., a daily read river gauge). When these conditions are not satisfied, the discharge from the upper river has to be corrected.

Equation (6), thus reduced to a function between h_1 and h_3, makes it possible to calculate the daily raise or draw-down z_0 at the confluence as the difference between the actual water-level and the equilibrium water-level.

A fine example for this phenomenon is the confluence of the Niger and Benue at Lokoja.

The water-level at Lokoja depends on the discharges from the Niger and Benue together. Rating curves (1 (uniquely determined where the concerned site is situated in a river-section not influenced by causes from outside) have been constructed for three sites, Makurdi in the Benue, Baro in the Upper Niger and Shintaku in the Lower Niger, the latter being related to the gauge in Lokoja. On the assumption of satisfaction to the condition (ii), the discharge at Shintaku can be found simply by adding the discharges of Makurdi and Baro, but taking into account the time-lag Baro—Lokoja and Makurdi—Lokoja.

With the rating curve of Shintaku (related to the gauge at Lokoja) this total discharge can be transformed into water-stage at Lokoja, called the theoretical water-level since the condition (ii) is supposed to be satisfied. The theoretical Lokoja level follows immediately from the water-levels of Makurdi and Baro. Diagram 4.2.6-10 makes a quick and easy calculation possible.

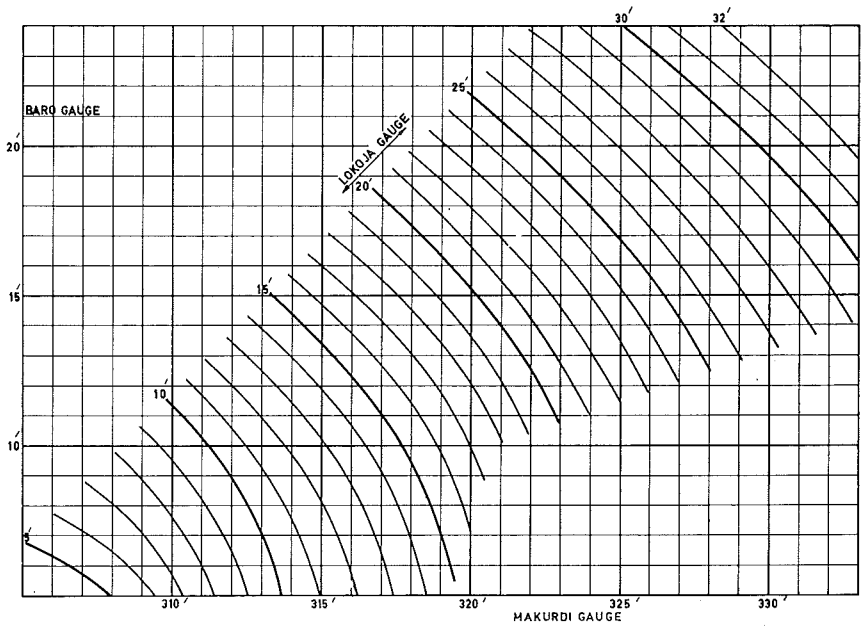


DIAGRAM 4.2.6-10

Lokoja gauge reading as a function of gauge readings at Baro and Makurdi on the assumption of lateral inflow and storage being zero

The actual reading on the gauge at Lokoja will probably show a deviation from this theoretical value, caused by the fact that the condition (ii) is actually not satisfied. This deviation of water-level Δh can be transformed (with the help of the rating curve for Shintaku-Lokoja) into a difference of discharge ΔQ, which is the correction mentioned above over both rivers together.

To arrive at ΔQ_1 for the Niger only, or ΔQ_2 for the Benue, this total correction ΔQ must be partitioned. Investigations about the influence of the Niger upon ΔQ with estimation of the storage and with consideration of the discharge measurements on the Niger just upstream from the confluence in relation to the discharge at Baro, did not lead to any valuable conclusion. Therefore it is assumed that, since the length of river between Baro and Lokoja is about one-half the distance Makurdi—Lokoja, by taking 1/3 of ΔQ as the cause of the Niger and 2/3 from the Benue, the acquired result Q_1 is approximated with sufficient accuracy.

The discharge Q_1, now known, can be used for derivation of the condition for equilibrium.

(1 see 4.3.2

Mutual levelling of gauges along the Niger permits a consideration of water-lines. It is concluded that Lokoja water-level h_3 fulfilled the condition of equilibrium $z_0 = 0$ on June 21, 1956, on November 3, 1956, and on November 16. 1957. From water-lines on other dates the slope between Baro and Kelebe appears fairly constant at 11.5×10^{-5}, while below Kelebe the water-line spreads out, sometimes upward (raise), sometimes downward (draw-down), as shown in Diagram 4.2.6-11.

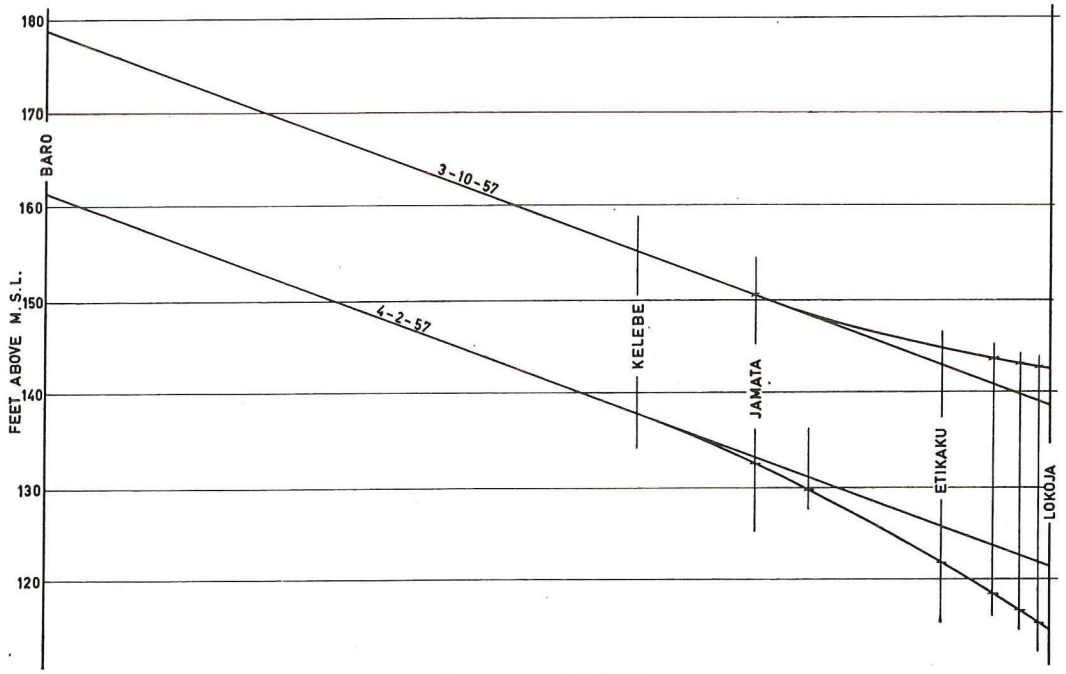


DIAGRAM 4.2.6-11

Observed water-lines on the Upper Niger for high water and for the Black Flood period

In Equation (6) for equilibrium condition

$$Q_1^{\frac{2}{3}} = Lh_3 + K$$

is

$$L = (b_1 C_1 \sqrt{i_1})^{\frac{2}{3}}$$

Observations in the Upper Niger show that the term

$$C_1 \sqrt{i_1}$$

is fairly constant over the whole river-stretch between Baro and Lokoja, and is about independent of the water-stage. On November 3, 1956, the average width of the river-section was roughly 700 m. It is computed that

$$L = 13.6$$

when Q is expressed in m^3/sec and h_3 in feet.

Using the status of equilibrium on November 3, where $h_3 = 19.15'$ and $Q_1 = 3680$ m^3/sec, it follows that

$$K = -22,$$

thus giving the condition of equilibrium for the Niger:

$$Q_1^{\frac{2}{3}} = 13.6\, h_3 - 22$$

with Q_1 in m^3/sec, and h_3 in feet.

For each value of h_3 a specific value for Q_1 can be calculated. With again the assumption of $\Delta Q = 0$, Q_1 can be transformed into a water-level at Baro with the help of the rating curve of Baro. Equilibrium can thus be drawn (stroke-line in Diagram 4.2.6-12) as a function between h_1 and h_3.

The Niger is raised when plot A of observation (for example, as in Diagram 12 fixed by the gauge readings 16'8" at Baro vertically and 325'9" at Makurdi horizontally plotted) is situated on the right side of the line for equilibrium. With steady discharge in the Niger, and thus constant Baro level, the Benue must fall in order to transfer the plot A horizontally to A' onto the equilibrium line. It appears that the Benue originally had a too high stage. A' shows the hypothetical situation with equilibrium on the Niger. Both A and A' have a corresponding theoretical Lokoja level (A 25'5", A' 22'9"). The difference of 2'8" is the raise of the Niger at Lokoja.

Conversely, a point of observation situated on the left side of the equilibrium line corresponds to a draw-down on the Niger, the size of which is read with respect of the curved lines of equal Lokoja level in the diagram.

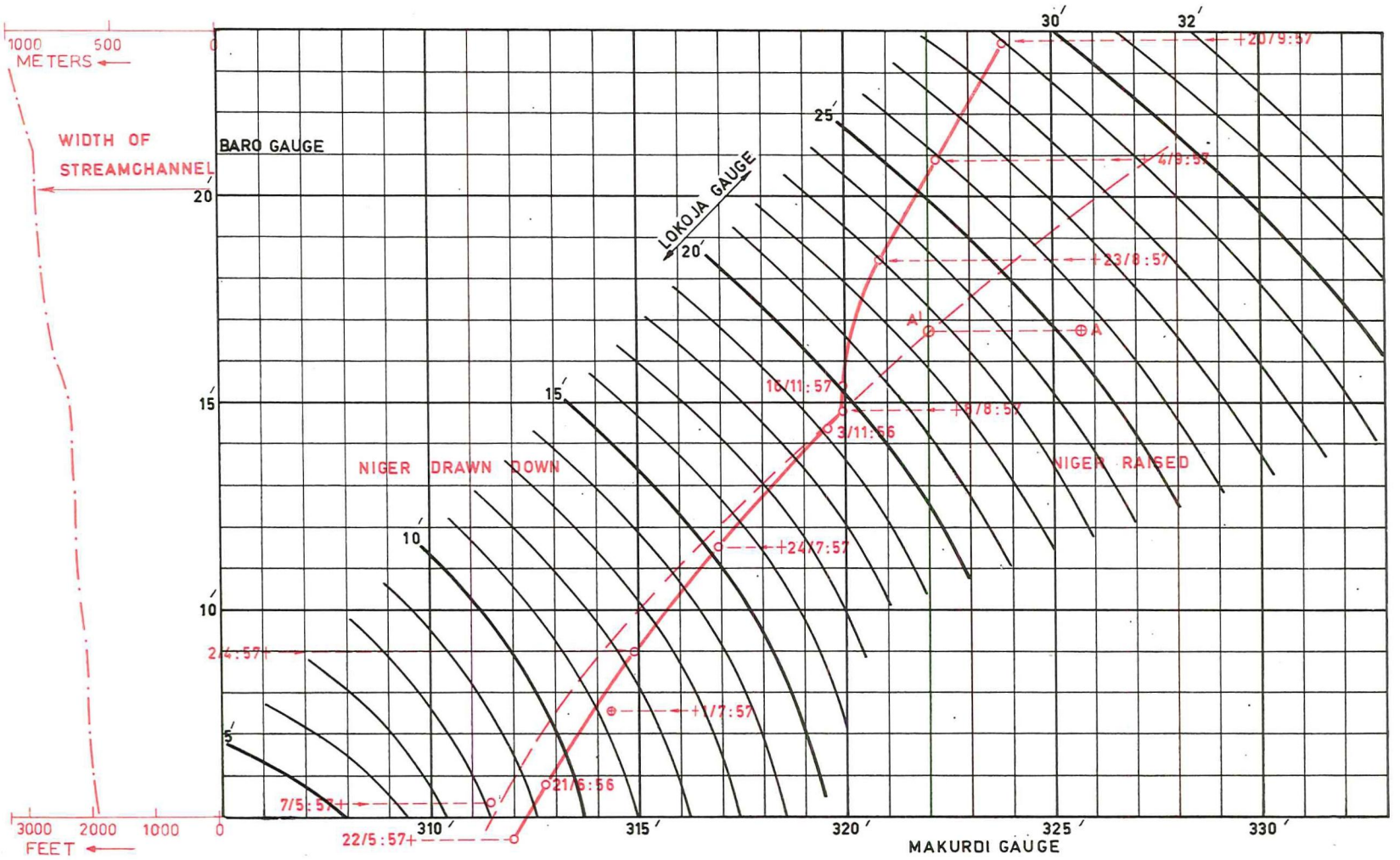


DIAGRAM 4.2.6-12

Equilibrium on the Upper Niger

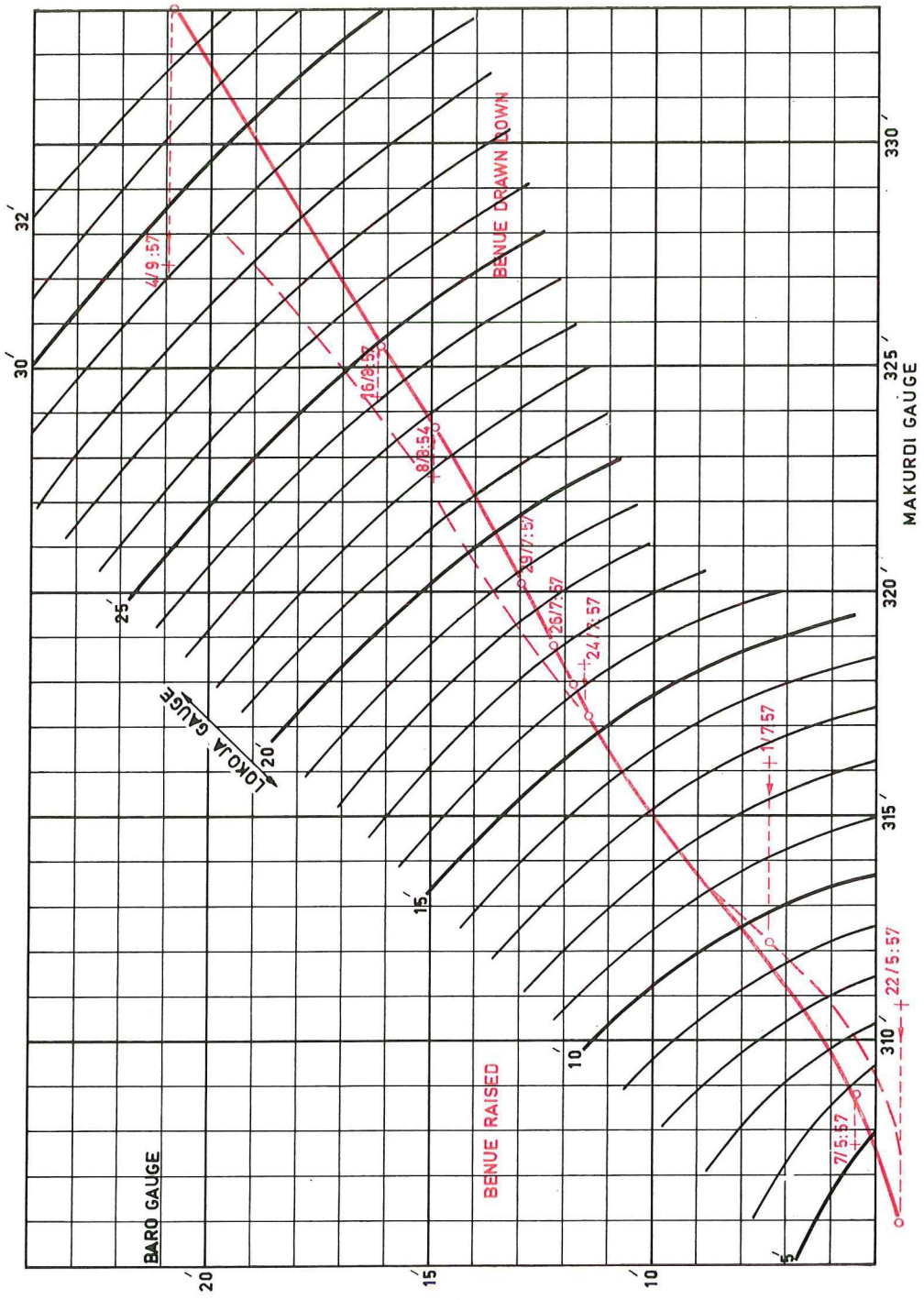


DIAGRAM 4.2.6-14
Equilibrium on the Benue

The line of equilibrium has been calculated on the assumption of constant width. The mistake made with this assumption is considerable.

It is also possible to determine experimentally a line for equilibrium. For various days the water-line between Baro and Lokoja can be plotted (as result of the mutual levelling of gauges along the river), and thus the raise of the Niger be graphically computed. In Diagram 12 various observations are plotted and horizontally transferred over a distance corresponding to the magnitude of raise (or draw-down). The connection of these experimental points is the full line in the diagram.

The deviation between both lines (stroke line and full line) is caused by change of width. It appears possible

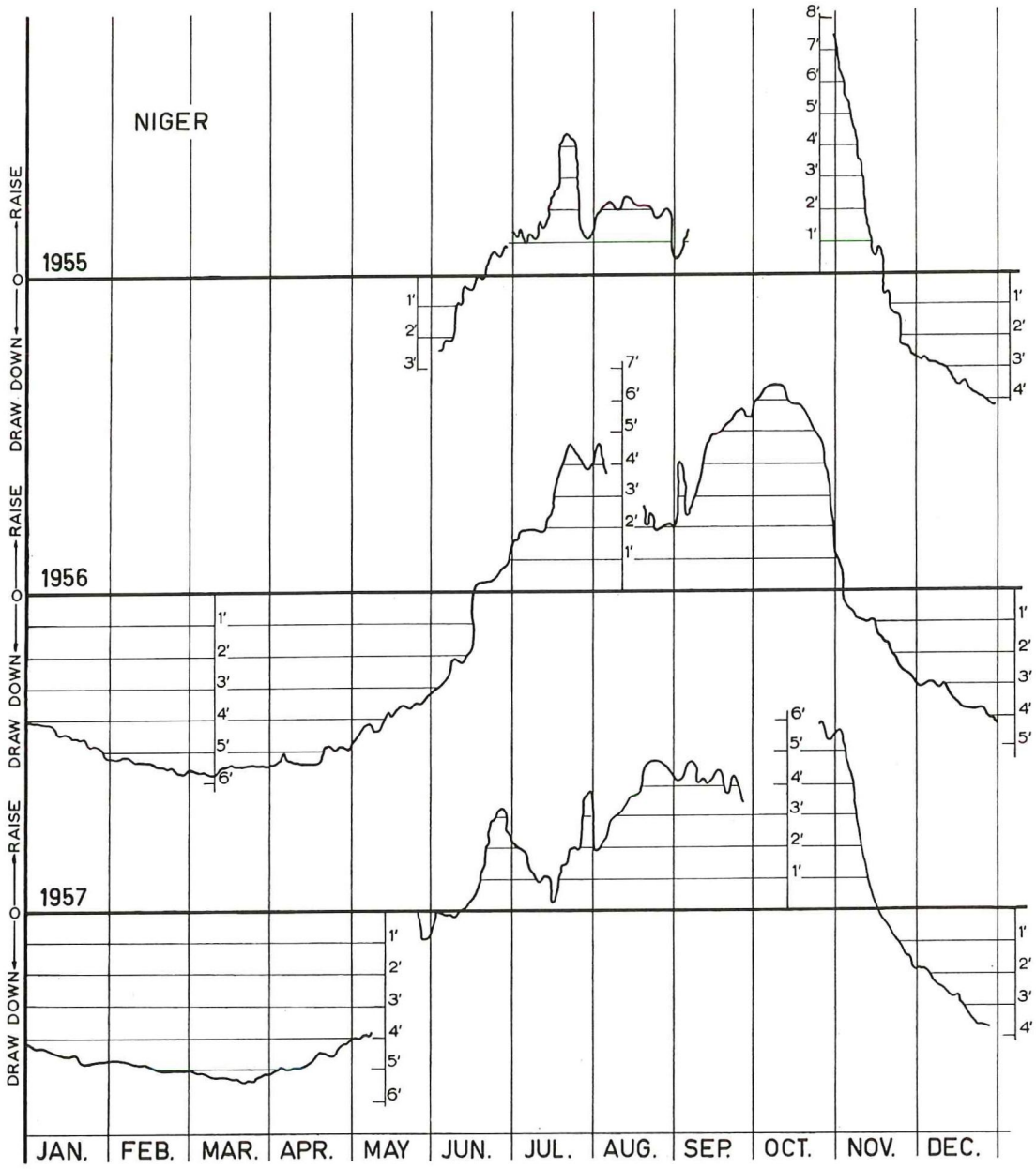


DIAGRAM 4.2.6-13

Daily raise on the Upper Niger, 1955—1957

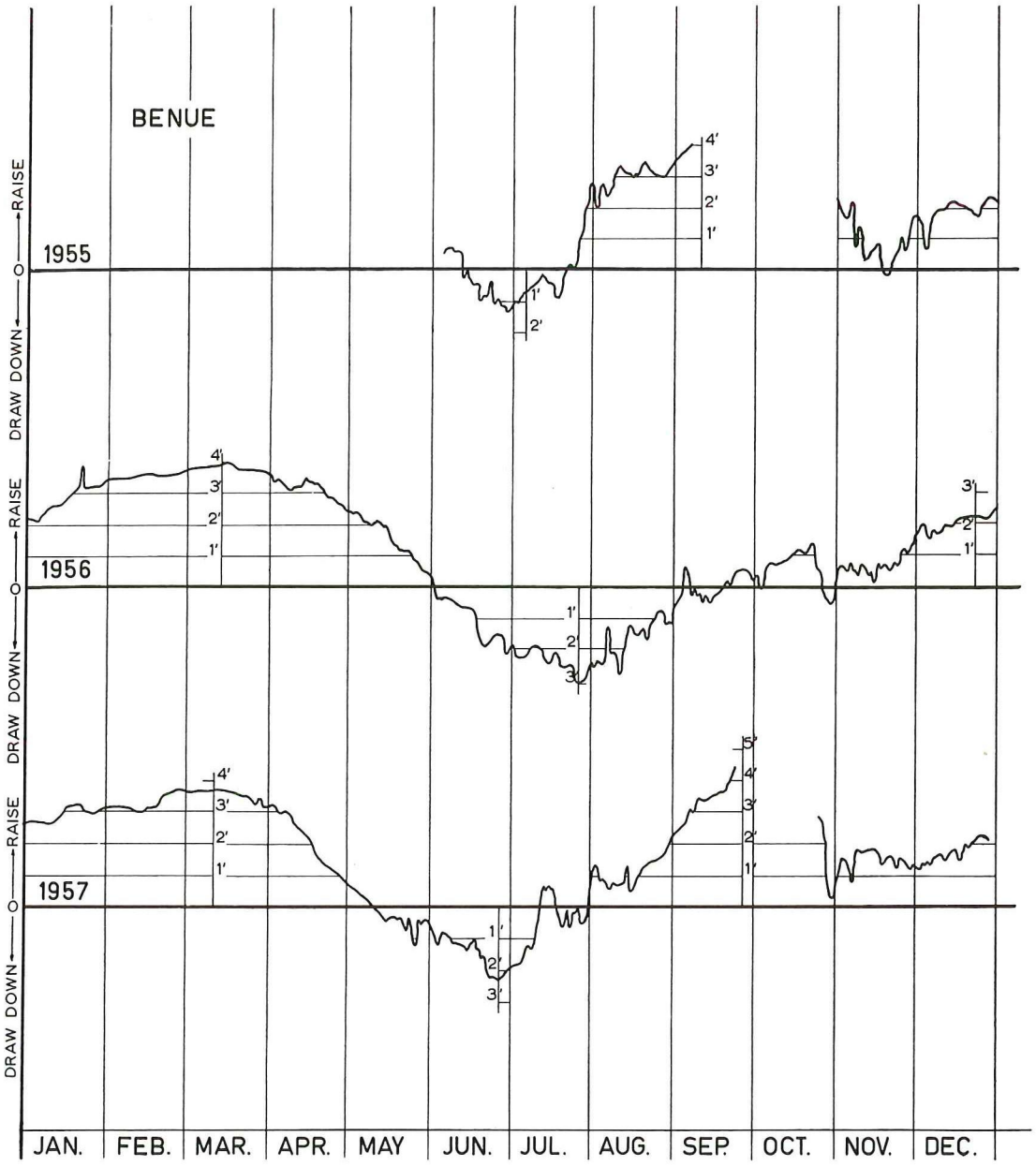


DIAGRAM 4.2.6-15

Daily raise on the Benue, 1955—1957

to compute the actual width from the deviation; results are plotted at the left side of the diagram. A sudden increase of width occurs at a level of 15′ (on the Baro gauge), probably caused by overflowing banks and sand-banks. It is notified that the width found here is not the full width of the inundated area, but of the actual discharging part of the river.

It is concluded that the full line in Diagram 12 marks the circumstance for equilibrium on the Niger. The line is an experimental one, but is explained theoretically.

With its help it is possible to compute the daily raise z_0 on the Niger. First, with the assumption of $\Delta Q = 0$ still valid, the observations on the gauges of Makurdi and Baro (with their respective time-lag taken into account) are plotted in Diagram 12, and from here the theoretical level of Lokoja and the theoretical raise (in relation to the experimental equilibrium line) are determined. Now the deviation of the theoretical water-level from the practical, Δh, is caused partly by the Benue and partly by the Niger. Obviously the part from the Niger does not cause any raise in the Niger, but only a rise of water-level gradually between Baro and Lokoja. The part from the Benue, however, does cause a raise in the Niger. Therefore, 2/3 of Δh is added to the theoretical raise and the result is the actual raise of the Niger at Lokoja, z_0.

The same methods are used for the computation of the raise of the Benue. The line for equilibrium is drawn in Diagram 4.2.6-14.

The daily raise (draw-down) of the Niger at Lokoja, derived by the above-mentioned methods, is plotted in Diagram 4.2.6-13 over the period June 1955 to December 1957. Diagram 4.2.6-15 shows the same concerning the Benue.

One problem still remains to be solved: the size of the bottom-jump A (see Diagram 4.2.6-9). From the derivation of Formula (6) it is concluded that

$$\frac{K}{L} = A + D$$

where A is the bottom-jump and D is the difference in height between the zero of the gauge at the confluence and the average bottom height. Observations at Lokoja lead to the estimation of D:

$$D = -2'$$

Hence, A can be computed as

$$A = \frac{K}{L} + 2'$$

With the magnitudes for L and K substituted, it is concluded that for the Niger the bottom-jump $A = +5''$ and for the Benue $A = -3''$. As drawn in Diagram 4.2.6-16, the Niger shows a jump upward, the Benue downward. Both jumps are calculated in relation to the straight extension of the bottom-line from the upper river.

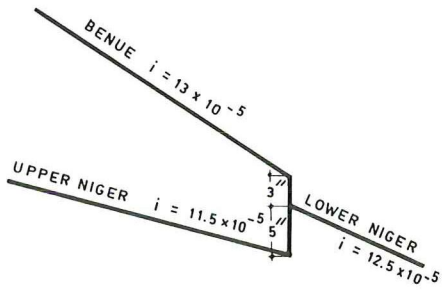
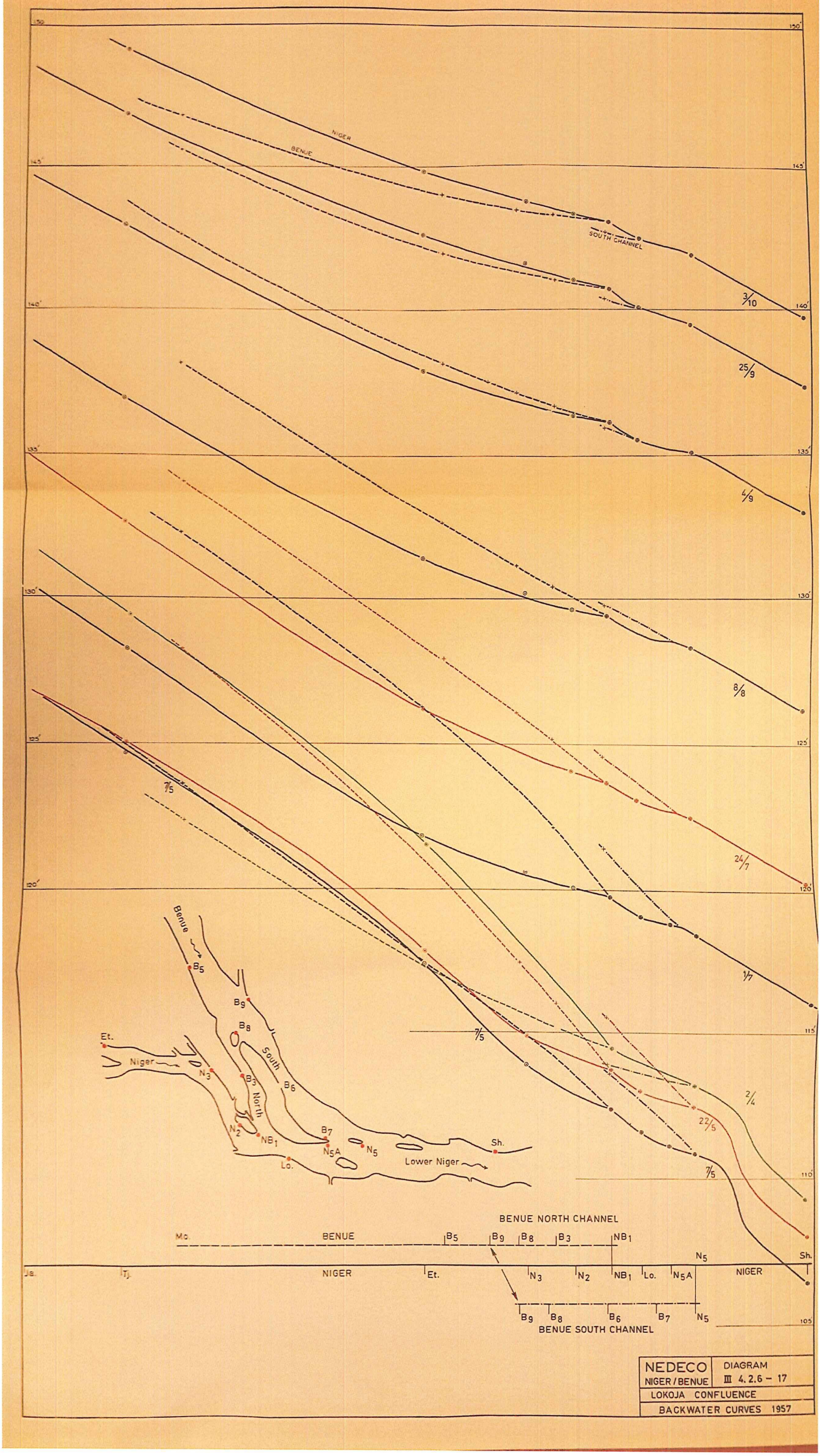


DIAGRAM 4.2.6-16

Computed bottom-jump at Lokoja Confluence


150'
145'
140'
135'
130'
125'
120'
115'
110'
105'
NIGER
BENUE
SOUTH CHANNEL
3/10
25/9
4/9
8/8
7/5
24/7
1/7
7/5
2/4
22/5
7/5
Benue
B5
B9
B8
B3
B6
B7
N5
Sh.
Et.
Niger
N3
N2
NB1
N5A
Lo.
South
North
Lower Niger
BENUE NORTH CHANNEL
Mo.
BENUE
NIGER
Et.
N3
N2
NB1
Lo.
N5A
NIGER
N5
Sh.
Ja.
Tj.
B9
B8
B6
B7
N5
BENUE SOUTH CHANNEL
NEDECO
NIGER / BENUE
DIAGRAM
III 4.2.6 – 17
LOKOJA CONFLUENCE
BACKWATER CURVES 1957

The magnitude is very small, but the rivers differ only on a very small scale as far as their basic determinants are concerned. The average slope of the Lower Benue is 13×10^{-5}, while the Niger has 11.5×10^{-5} with a mutual difference of only 11%. The same could be said about the size of grains: the mean diameter in the Niger is roughly 0.5 mm and in the Benue 0.7 mm.

Finally, to complete this subject of backwater curves around the Lokoja Confluence, Diagram 4.2.6-17 shows various water-lines for various days.

A striking difference in these lines appears for the situation on April 2, 1957, with a very low Benue and a moderate Niger, and on June 1, 1957, when the Benue was rising considerably and the Niger had a fairly low stage.

Another conspicuous fact is shown by the S-shaped water line of the Niger on May 7, 1957. The river, although drawn down on the whole, showed a raise in the lowest few miles. The explanation is found in a severe erosion in the lowest section of the Niger causing a considerable lowering of the river-bottom, as described in 6.5.8. The river-bottom takes the greatest effect upon the water-line when the level is at its lowest stage, as was the case on May 7. Its influence is negligible at higher water-stages of the Niger; therefore the S-shape is only seen during the short low-water period in May and June.

It is also concluded from Diagram 17 that both the Niger and Benue Rivers are raised simultaneously at high water. This is probably a result of the relative narrow (and deep) section along Lojoka between the gauges NB1 and N5, disturbing the water-line as described under a of this para. Consequently a draw-down of both rivers occurs at low water (May 7, 1957).

Shallow flats immediately below the confluence cause at low water a raise in the river-section along Lokoja with a relative steep slope over the flats. With higher water this local influence disappears gradually.

The second half of the mentioned river-section along Lokoja between gauges NB1 and N5 is disturbed by the confluence with the South Channel. This disturbance is smaller than the one at the confluence with the North Channel, since the difference of discharges varies less here (near gauge N5) than there (near gauge NB1).

The confluence of the Niger with the South Channel has a variable location. At low water the two rivers meet below gauge N5, as the opening between N5 and N5A is closed by sand-banks. A rising water-level causes the intersection of the two streams to move upward till at very high water the Benue island is flooded, and the confluence takes place above N5A.

The gauge readings in Diagram 17 are plotted without respect to the variation in velocity-head $v^2/2g$. It is, for instance, apparent that during H.W. the gauge at Lokoja reads too low, as the velocity v in its narrow cross-section is relatively high. The deviation of gauge N3 from the line is caused by transversal slope due to bended streamlines (see 6.1.2).

4.2.7. Propagation of floods: relations between gauge readings

In any river-stretch, discharges passing the downstream end of the stretch are the combined result of discharges entering the stretch and the inflow from the drainage basin along the river-stretch. It will be assumed that at every point along the river only one discharge corresponds to a certain water-level, whether the water-level is rising or falling. A change of discharge (which includes a change in water-level) at the upstream end will after a certain time — here called the time-lag — affect the discharge and the water-level at the lower end. The velocity of propagation is found by dividing the length of the stretch by the time-lag.

For a prismatic channel (including a prismatic adjacent flood-plain) the velocity of propagation can be computed by:

$$c = \frac{1}{b}\frac{dQ}{dH} \qquad \ldots\ldots\ldots \quad (1)$$

in which: c = velocity of propagation,

$\frac{dQ}{dH}$ = the change of discharge per change of river-stage,

b = the width at the surface of the water.

By applying De Chezy's formula (4.3.1), formula (1) can be written as:

$$c = \tfrac{3}{2} v \qquad \ldots\ldots\ldots \quad (2)$$

in which v = mean velocity of the stream.

When the river inundates the lateral flood-land, Equation (1) must be written as:

$$c = \tfrac{3}{2} \frac{(b_1 v_1 + b_2 v_2)}{B} \quad \ldots\ldots\ldots (3)$$

in which: b_1 = width of the stream-bed
v_1 = velocity of the stream in the stream-bed
b_2 = mean width of the flood-land
v_2 = velocity of the stream over the flood-land
$B = b_1 + b_2$ = surface width of storage.

Combining (2) and (3) and ignoring v_2 gives:

$$b_1 = \frac{2}{3v} \frac{dQ}{dH} \quad \ldots\ldots\ldots (4)$$

In the derivation of (1) the friction has been neglected. This friction will flatten the flood-wave. The value of c, when computed by using (1), will be greater than in Nature.

Assuming no lateral inflow and a prismatic channel and flood-plain, the relation between river-stages at the upstream and downstream ends of a river-stretch and the time-lag can be established, even without knowledge of the discharges, by plotting the water-levels read at the upstream gauge against those simultaneously read at the downstream gauge.

An example which illustrates the principles of this method is found in Diagram 4.2.7-1. Simultaneous water-levels for August (rising water) and October (falling water-levels) are plotted.

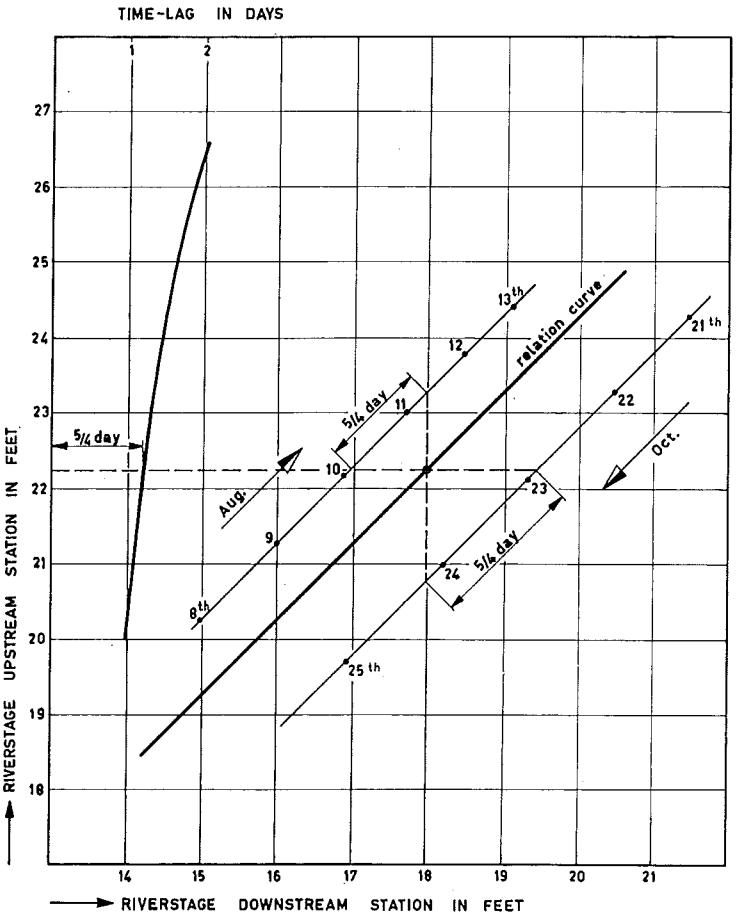


DIAGRAM 4.2.7-1

Graphical procedure for establishing the relation between river-stages

On August 10 and on October 22 a water-level of 22.25′ at the upstream gauge is passed. After a certain time (the time-lag required for propagation) which must be equal for both cases, a certain corresponding water-level at the downstream station has to occur. After one full day, the downstream gauge shows 17.8′ during the rising stage, and 18.4′ during the falling stage. After two full days, these figures are 18.5′ and 17.0′ respectively. Evidently the time-lag is between one and two days. By trial and error it is found that after $1\frac{1}{4}$ day the water-level at the downstream gauge is 18′ both for rise and fall. In this way one point of the relation curve and one point of the curve for the time-lag are found. By constructing more points, the whole curves can be drawn.

Another graphical method of finding the water-level relation and the time-lag is that described by BANCHET (1, which is illustrated in Diagram 4.2.7-2. River-stage hydrographs are plotted for the stations between which a relation has to be established. To every river-stage at the upstream station A there is a corresponding river-stage at the downstream station B and one length of time-lag, irrespective of whether the water is falling or rising. Let it be supposed that the water-level h_a at the station A and at the time t_1 corresponds with the water-level h_b at the station B at the time t_3. The time-lag is $t_3 - t_1$. Similarly, the water-level h_a at the upstream station A at the time t_2 corresponds with the water-level h_b at the downstream station B at the time t_4. The timelag is $t_4 - t_2$ and equals $t_3 - t_1$, from which it follows that $t_a = t_b$. By measuring t_a and by determining h_b in such a way that t_b equals t_a, the water-level relation and the time-lag can be established.

The first described method is preferred because the occurrence of lateral inflow (preventing the procedure) is discovered more easily. The ordinates can be used immediately to plot the relation curve, which is an additional advantage.

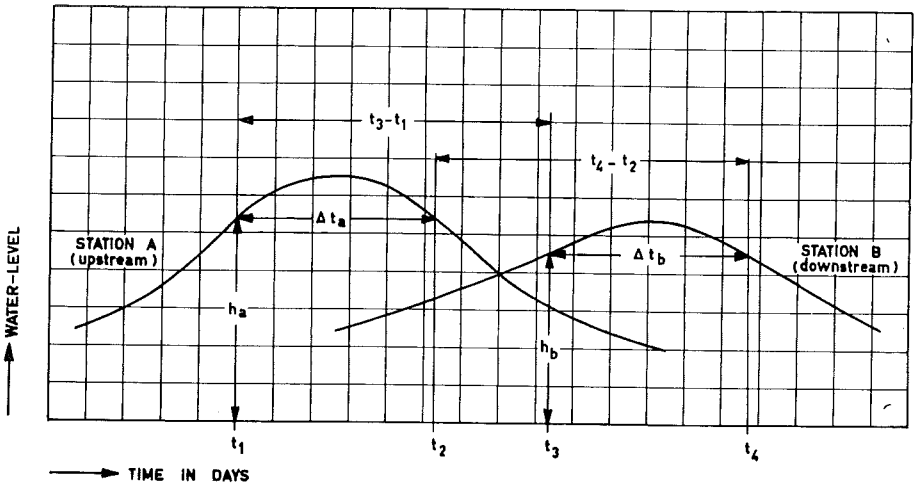


DIAGRAM 4.2.7-2

Graphical procedure to establish the relation between river-stages, after Banchet

The assumption of a prismatic stream-bed will generally hold well, but a prismatic flood-plain does not always occur. This is the case, for example, when adjacent lakes are filled during high river-stages by a narrow connection with the main stream; and then the above-mentioned formula (1) can no longer be used. In the case, however, when the inflow into the lake from the river during rising stages and the outflow from the lake into the main stream during falling stages depend only on the river-stage itself, it is still possible to establish empirical relations between the hydrograph at the upstream end and at the downstream end of the river-stretch (see VI, 3.6.2).

(1 REFFAY, 1948. HYD. 9

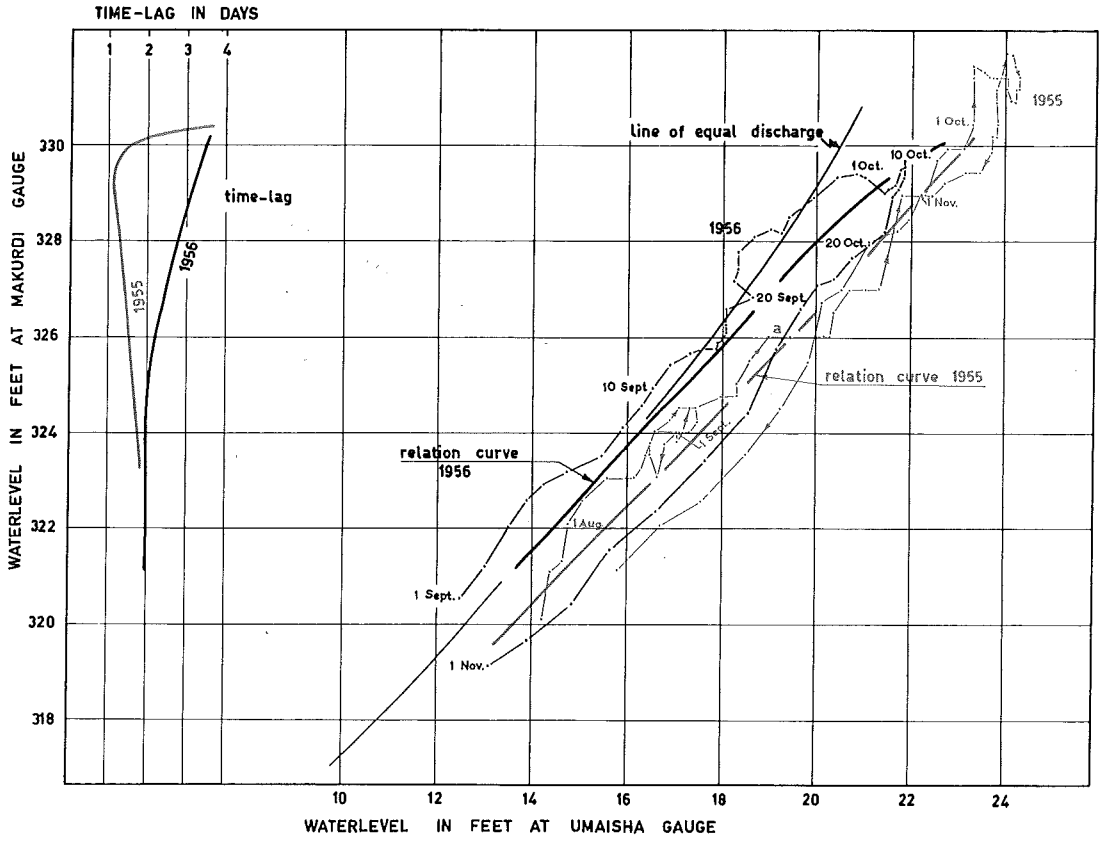


DIAGRAM 4.2.7-3

Relation of river-stages along the Benue: Makurdi—Umaisha

When lateral inflow between the upper and the lower ends of the stretch becomes important, the establishment of relationships becomes more complicated and the above-mentioned graphical methods cannot be applied. This can be seen by considering the Benue between Makurdi and Umaisha, where an area of 11,400 sq.miles, of which the Mada River and the Ahini River carry the run-off from 7,400 sq.miles, drains towards this river-stretch. On Diagram 4.2.7-3 have been plotted the simultaneous river-stages at Makurdi and Umaisha for the higher stages of 1955 and 1956. Relation curves established by the above explained graphical method have been constructed, as well as the curve for the time-lag. It is seen that at *a* on the graph (September 15, 16, 17 and 18, 1955) the river-level at Umaisha is rising while the Makurdi river-stage is steady. This is due to lateral inflow, originating from heavy rainfall north of the Benue between Makurdi and Umaisha. It explains why the time-lag at this river-stage in 1955 seems to be smaller than in 1956: the lateral inflow causes the Umaisha water-level to rise before the effect of a rise at Makurdi is due to occur at Umaisha. In this way the time-lag is seemingly shortened.

By comparing the relation curve with the line of equal discharge, it will be seen that for the lower stages in 1956 (Sept. 1—8) the lateral inflow has been just great enough to replenish the decrease in discharge by storage. Over this period the relation curve coincides with the line of equal discharge.

For similar water-levels at Makurdi in 1955 (July 30—August 8) water-levels at Umaisha

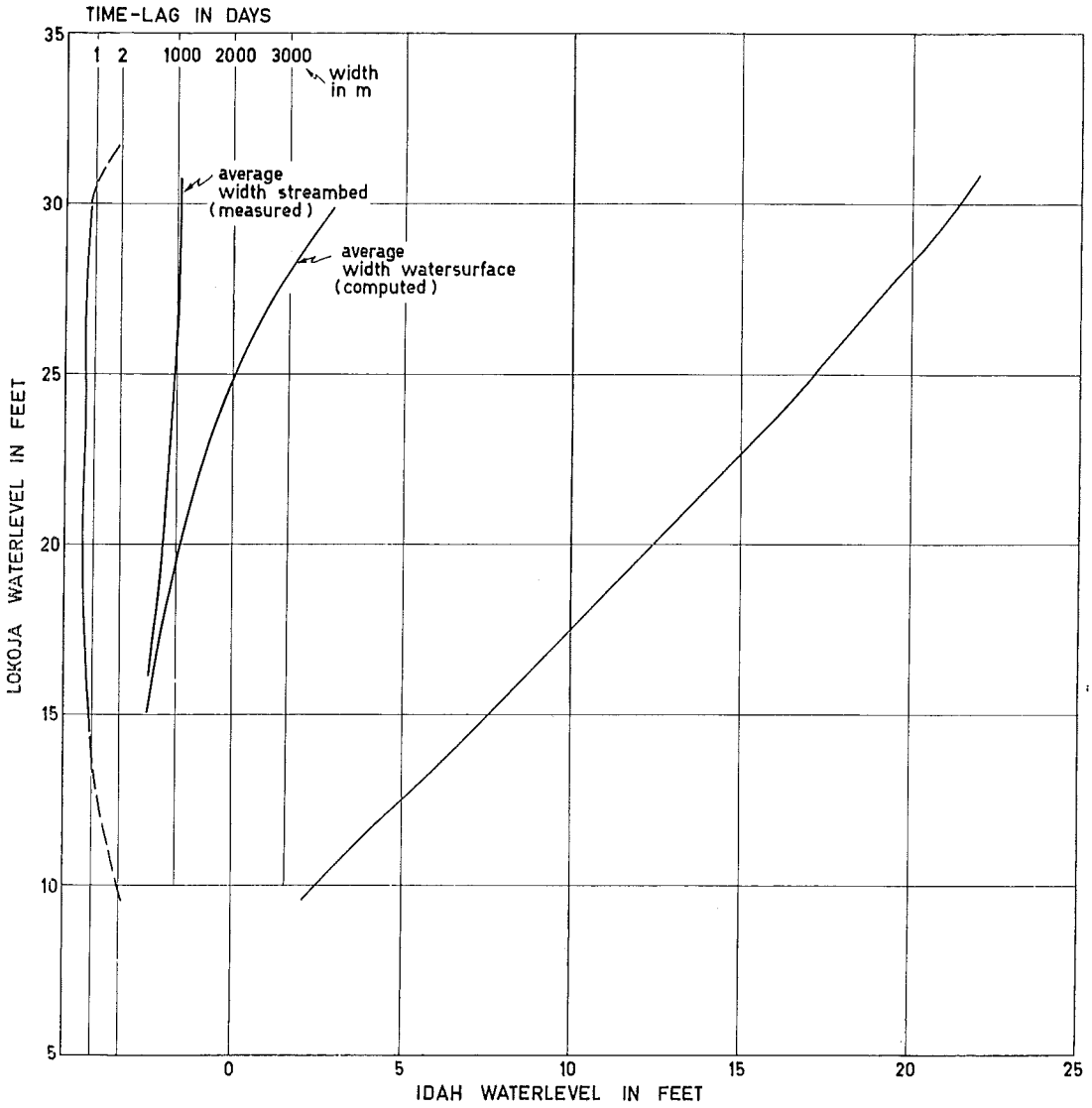


DIAGRAM 4.2.7-4

Relation of river-stages along the Niger: Lokoja—Idah

have been more than one foot higher than in 1956. Apparently the lateral inflow exceeded the storage. In the region of a water-level of 15′ at the Umaisha gauge, which occurs in the period here discussed, a difference of one foot involves a difference in discharge of about 750 m^3/sec (26,500 cusec).

To make it possible to establish a relationship between water-levels along stretches where lateral inflow is important, either a good knowledge of the storage or all data concerning lateral inflow must be available. This would involve, however, the collection by fieldwork of a considerable body of data.

The variation of lateral inflow into the Niger between Lokoja and Idah is relatively small.

TABLE 4.2.7-5.

COMPUTATION OF WIDTH AT WATER SURFACE ON THE NIGER BETWEEN LOKOJA AND IDAH.

Lokoja water-level	Idah water-level	time-lag	velocity of propagation	$\frac{dQ}{dH}$ Lokoja	$\frac{dQ}{dH}$ Idah	$\frac{dQ}{dH}$ average	computed width of storage	average stream velocity at Lokoja	average stream velocity at Idah	average stream velocity Lokoja-Idah	computed width of streambed	width of streambed from survey
feet	feet	days	m/sec	m^3/sec/ft	m^3/sec/ft	m^3/sec/m	m	m/sec	m/sec	m/sec	m	m
28'2''	20'0''	1.5	0.955	1,110	1,250	3,850	4.050	1.46	1.26	1.36	1,820	2,000
24'2''	16'7''	1	1.28	920	1,100	3,650	2,850	1.31	1.18	1.24	1,880	1,960
15'11''	8'6''	1	1.28	625	590	1,870	1,450	1.00	1.01	1.00	1,240	1,440

TABLE 4.2.7-8.

COMPUTATION OF WIDTH AT WATER SURFACE ON THE BENUE BETWEEN WURO BOKI AND YOLA.

Wuro Boki water-level	Yola water-level	time-lag	velocity of propagation	$\frac{dQ}{dH}$ Wuro Boki	$\frac{dQ}{dH}$ Yola	$\frac{dQ}{dH}$ average	computed width of storage	average stream velocity at Wuro Boki	average stream velocity at Yola	average stream velocity Wuro Boki-Yola	computed width of streambed	width of streambed from survey
m	m	days	m/sec	m^3/sec/m	m^3/sec/m	m^3/sec/m	m	m/sec	m/sec	m/sec	m	m
3.00	3.15	0.5	0.93	720	400	560	600	0.70	0.67	0.68	540	585
4.00	4.35	0.45	1.02	1,160	1,120	1,140	1,115	1.00	0.88	0.94	800	740
5.00	5.50	0.5	0,93	1,600	1,570	1,585	1,710	1.24	1.09	1.15	910	780
6.00	6.60	0.9	0.51	2,050	1,920	1,985	3,900	1.46	1.35	1.40	935	780

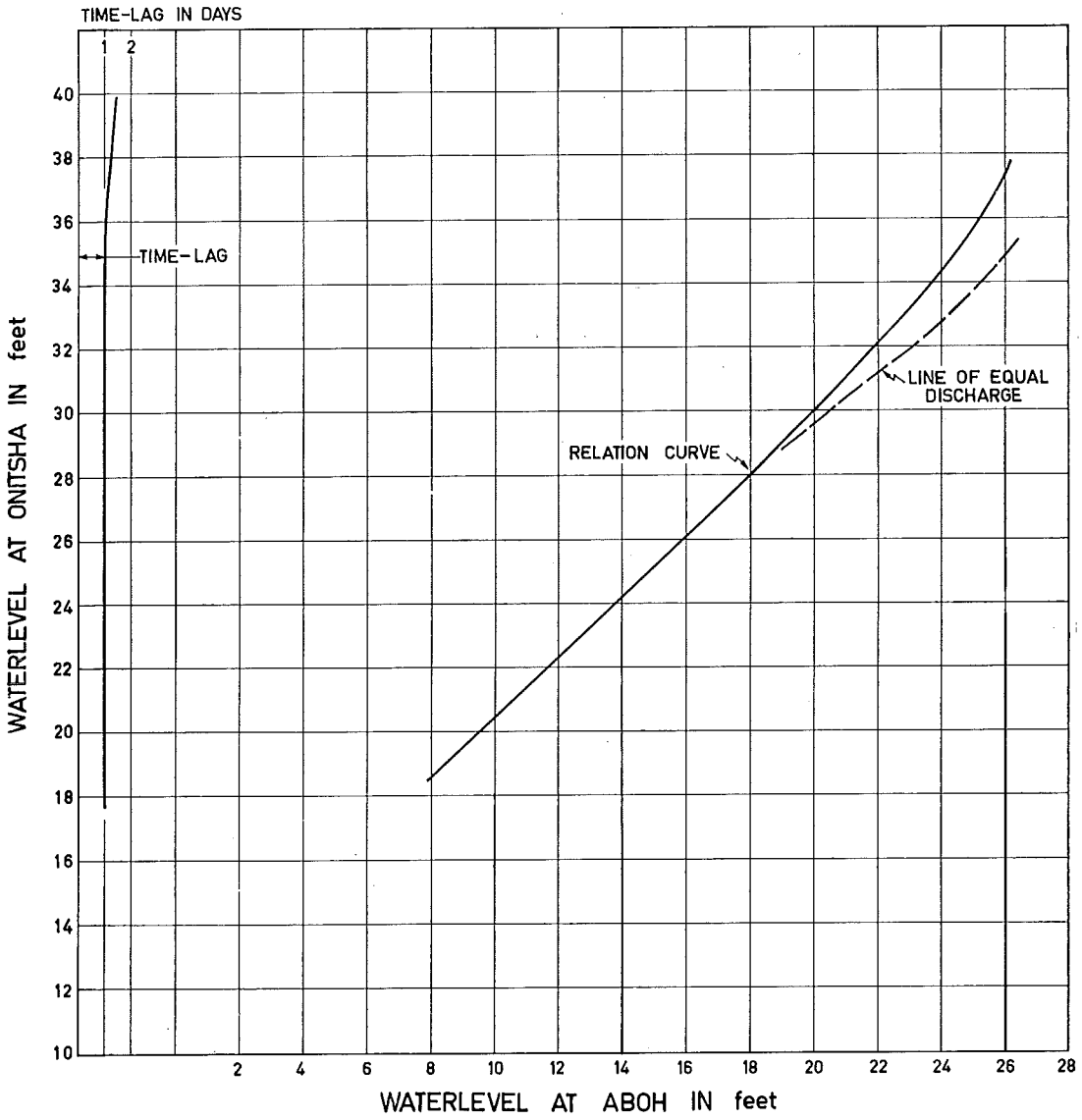


DIAGRAM 4.2.7-6

Relation of river-stages along the Niger: Onitsha—Aboh

Diagram 4.2.7-4 shows the relation between water-levels at the Lokoja gauge and those at the Idah gauge, as well as the time-lag. From the time-lag the velocity of propagation can be computed, as the stage-discharge rating curve for both Lokoja and Idah are known (see Diagram 4.3.2-4); $\frac{dQ}{dH}$ can also be determined.

By using Formula (1) the width at the water surface, B, is computed (Table 4.2.7-5). The average width of the surface of the stream-bed for the various stages is known from survey. It appears that both widths are equal for the lower stages, but during higher water-levels the total width of the water surface, which means including the flood-land, increases considerably, as can only be expected. Making use of Formula (4), the width of the stream-bed has been

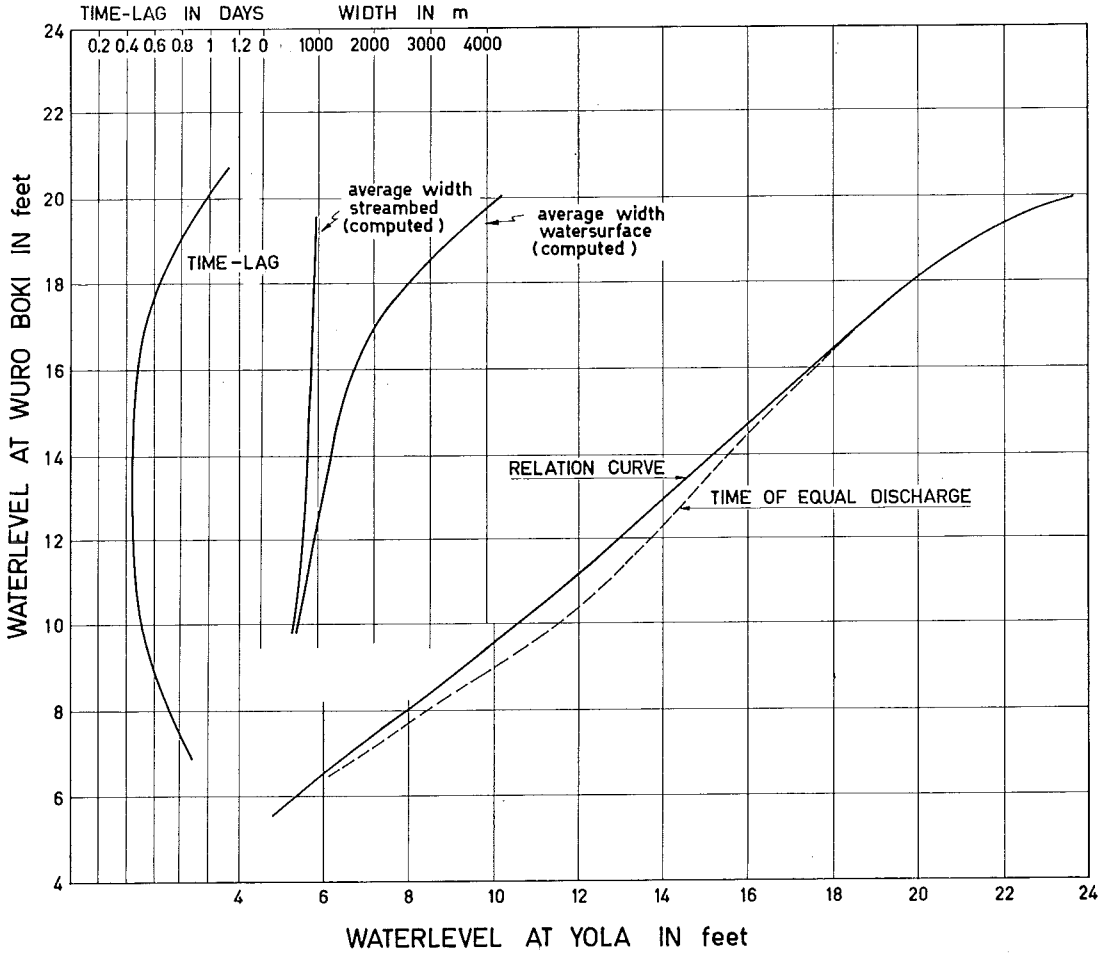


DIAGRAM 4.2.7-7

Relation of river-stages along the Benue: Wuro Boki—Yola

computed as well, and the magnitude was found to correspond satisfactorily with the width as ascertained by survey.

This example illustrates the interconnection and the applicability of the formulae and observations which have been used.

On the stretch of the Niger between Onitsha and Aboh the lateral inflow is negligible, but a certain amount of water flows during the higher stages toward the Orashi River and the Ase River, which run towards the sea more or less parallel to the Niger. The amount of flow leaving the Niger depends practically only on the height of the water-level on the main river. Hence the discharge at Aboh will depend only on the river-stage at Onitsha, taking into account the time-lag. Diagram 4.2.7-6 gives the relation curve of water-levels at Onitsha and Aboh, together with the time-lag. The line of equal discharge, which has also been drawn, shows that at a water-level of 28′ at the Onitsha gauge, the Niger starts losing flow to the two parallel rivers.

Between Wuro Boki and Yola on the Benue there is little lateral inflow. The form of the hydrograph at these two stations is rather irregular. This is because the stations are situated at a short distance from the headwater area in the French Camerouns.

On Diagram 4.2.7-7 top stages at the Wuro Boki gauge are plotted against top stages at the Yola gauge, as far as a top stage at Yola could be traced back to having its origin in a top stage at Wuro Boki. By comparing the time at which a top water-level occurred at these two stations, a time-lag is found. Both for Yola and Wuro Boki the rating curves are known. Applying Formulae (1) and (4), the width of the streambed and the width of storage are computed (Table 4.2.7-8), the curves for both of which are drawn in the diagram.

The line of equal discharge, also drawn, shows that during the peak of a flood-wave discharges at Yola are smaller than at Wuro Boki. This is because the flood-wave flattens out as a result of friction. During the higher discharges the difference between peak discharges at Wuro Boki and those at Yola becomes smaller. As these discharges occur during the height of the rainy season, this may be caused by flow entering the river between Wuro Boki and Yola.

4.2.8. Significant water-levels and datums of soundings

In order to be able to compare soundings of a certain river-stretch made at various river-stages, they must be reduced to the same datum.

The datum of a sounding is an imaginary plane which may be horizontal, or inclining more or less parallel to the water-level of the river. In the latter case, its height above the bed of the river is determined by readings on the various gauges along the river. As for the purpose of navigation the depth below a water surface is of more interest than the elevation of the river-bottom above, for example, Mean Sea Level, a plane of reduction more or less parallel to the river-bottom has been used here.

To determine the position of this plane the water-level readings on the various gauges must be chosen. The choice can be based on certain frequencies of water-levels or discharges, or on water-levels which possess a certain property in connection with the navigation; for example, when river-stages occur below these water-levels, navigation with a certain draught is not possible.

On the Benue it is not possible to determine the position of the reduction-plane with the help of water-level frequencies because long enough periods of records are only available for Makurdi and Yola and between these two stations the river is joined by several important tributaries which makes it inadmissible to interpolate.

As a relation between water-levels and depths available for the navigation was not known at the beginning of the investigation, the position of the reduction-plane has been chosen arbitrarily (see Table 4.2.8-1 column 2).

On the Niger long water-level records are available for Baro, Lokoja and Onitsha. On this river water-levels during the so-called Black Flood (November to March) determine the length of the shipping season as they affect the form of the river-bed during low stages.

In the beginning of the investigation the reduction-plane used was the water-surface of what was thought the average Black Flood. The water-levels used to determine the position of that reduction-plane (Low River Level or L.R.L.) are given in Column 5 of Table 4.2.8-1. Later it was discovered that there had been changes of the zero point of the river-gauges at Baro and at Onitsha (see II, 4.4.2) during the period of record.

It seems better to use reduction-planes on both the Niger and the Benue which are defined in the same way. As it is not possible to define the position of the reduction-plane of the Benue with the help of water-level frequencies, the following definition is proposed:

Soundings are reduced to depth below a plane, connecting readings at the various gauges along the river below which navigation with a draught exceeding 5′ is generally not possible in the present natural state of the rivers. To facilitate the reduction, the above-mentioned readings are rounded off to whole numbers of feet.

With the help of observations of least available depths during the three years of the survey, relations between these depths and water-levels could be established (see 6.4.3).

The water-levels corresponding to the proposed reduction-plane are indicated in Columns 3 and 6 of Table 4.2.8-1. Water-levels as mentioned in the last two columns of the table will generally not occur simultaneously, so the reduction-plane corresponds only with an imaginary river-surface.

TABLE 4.2.8-1

DATUMS OF SOUNDINGS

BENUE			NIGER		
1	2	3	4	5	6
STATION	gauge reading corresponding to reduction-plane used during 1955—1957	gauge reading corresponding to proposed reduction-plane	STATION	gauge reading corresponding to reduction-plane (L.R.L.) used during 1955—1957	gauge reading corresponding to proposed reduction-plane
Wuro Boki	11′ 6″	12′	Baro	11′	9′
Yola	11′ 2″	12′	Lokoja	9′	8′
Numan	8′ 10″	11′	Idah	0′ 6″	0′
Gamadio	15′	— (1	Onitsha	13′	12′
Lau	15′ 6″	17′	Aboh	2′	1′
Ibi	17′ 8″	13′ (1			
Makurdi	313′	312′ (1			

(1 it is advised to reconsider these figures

4.3. DISCHARGES

4.3.1. Measuring-sites and stage-discharge relations

By relating every measured discharge to the river-stage as read during the measurement at a gauge in the neighbourhood of the measuring-site, stage-discharge relation curves, or rating curves, have been obtained for a number of stations within Nigeria. The choice of the site of the measuring-section in relation to the location of a certain gauge must, of course, be such that no ungauged flow will enter the river between the two places.

Other conditions which may determine the choice of a measuring-section are that the flow should be uniform and rectilinear, that the cross-sectional profile should be roughly rectangular with about a constant depth, and that there should not be an appreciable over-bank flow during high stages, as this would complicate the measurements. It will be clear that for untrained alluvial rivers as the Niger and Benue and their tributaries these conditions are difficult to satisfy completely and the selected measuring-section will usually be a compromise.

In the last column of Tables 4.2.1-2 and 3 there is indicated for which main gauges of the Niger and its tributaries rating curves now exist. In the same table the mileage of the location of the various measuring-sites within Nigeria is given.

As a rule discharges have been measured by using the Pendulum Current Meter (for a description of this instrument, see II, 3.4). In the very few cases where this was not practicable, floats have been used instead.

Factors determining the relation between the river-stage and the discharge are: gradient of the river-bed, water surface gradient, rise of water-level per unit of time, area and shape of the cross-section, and the hydraulic roughness of the river-bed. For steady uniform flow, the river-bed gradient equals the gradient of the water surface, and the rise of water-level per unit of time is zero. When these conditions are present, only one discharge corresponds with a certain river-stage.

The configuration of an alluvial river may change with time through erosion of the bed and of the banks, or through accretion. This will influence the stage-discharge relation. The discharge measurements have shown that, for the middle and the higher river-stages, the change in bed configuration has not been large enough to create an appreciable change in this relation during the period of survey (3 years). The low-water bed, however, is changing very much from year to year because of the shifting of the sand-banks during the high-water stages. The influence of this phenomenon on the stage-discharge relations is very remarkable on the tributaries, because on these rivers the discharges become very small during the dry season. On the Niger the discharges during the dry season remain moderate because of the so-called Black Flood (see 4.5.4). Thus it is not possible to establish stage-discharge relations for the lower stages on these tributaries which would remain valid during several years. The so-called recession curves, however, will make it possible to compute daily discharges during the lower stages on these rivers (4.3.7), but it will need several years of measurements before these curves can be established.

When flow is steady and uniform, the mean depth of the river is called normal depth. The most frequently used discharge formulae ([1 are:

$$Q = A\ C\ R^{\frac{1}{2}}\ i^{\frac{1}{2}} \quad \text{(DE CHEZY)} \qquad \ldots\ldots\ldots \quad (1)$$

$$Q = A\ \frac{1}{n}\ R^{\frac{2}{3}}\ i^{\frac{1}{2}} \quad \text{(MANNING)} \qquad \ldots\ldots\ldots \quad (2)$$

where: Q = discharge
A = cross-sectional area
i = slope
R = hydraulic radius, which is defined as $R = \frac{A}{P}$ in which
P = perimeter of the zone of contact between the solid boundary (river-bed) and fluid (river-water)
C = coefficient of de Chezy
n = Manning's coefficient

As for most rivers the width is very great in comparison with the mean depth a, P can often be replaced by b, and R by a.

Since A = ba, the above formulae become:

$$Q = C\ b\ a^{\frac{3}{2}}\ i^{\frac{1}{2}} \quad \text{(DE CHEZY)} \qquad \ldots\ldots\ldots \quad (3)$$

and

$$Q = \frac{1}{n}\ b\ a^{\frac{5}{3}}\ i^{\frac{1}{2}} \quad \text{(MANNING)} \qquad \ldots\ldots\ldots \quad (4)$$

in which the value for C has the dimension $m^{\frac{1}{2}}$/sec. If the feet-system is used, the dimension for C would be $feet^{\frac{1}{2}}$/sec, the mutual relation between these two ways of expression being

$$C_f = 1.82\ C_m \qquad \ldots\ldots\ldots \quad (5)$$

where C_f is the value for C expressed in the feet-system, and

C_m is the value for C expressed in the metric system.

([1 THIJSSE, 1949. HYD. 12

The value for n, Manning's coefficient, is for various circumstances and various conditions listed in the metric unit and given by many hydraulic manuals. The above formula (4) concerns, therefore, the metric system only. In order to be able to use the same values for n in the feet-system, the formula must be slightly modified. It then becomes

$$Q = \frac{1.49}{n} b a^{\frac{5}{3}} i^{\frac{1}{2}} \quad \text{(MANNING)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The values for C and n depend on the shape of the cross-section, on the size of the sand grains forming the river-bed, and on the size and shape of the sand ripples on the river-bottom. As far as the morphology of the channel-bed is concerned, C could be calculated from

$$C = 5.75 \sqrt{g} \log 12 \frac{R}{k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which k is the roughness of the bed (see 6.3.4).

Strickler has found the relation:

$$\frac{1}{n} = \frac{\varepsilon}{k^{\frac{1}{6}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

in which ε was originally supposed to have a constant value. Combining (3), (4), (7), and (8), it can be shown that

$$\varepsilon = f\left[\frac{a}{k}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

It appears that for the rivers dealt with in this Report, the value of ε varies between 20 and 22.

Since the presence of ripples has a great influence on the roughness of the bed, the values of C have to be computed by measuring Q, A, i, and R, and applying (1) or (3). The value of C for the Niger and the Benue varies between 30 and 60 $m^{\frac{1}{2}}$/sec or 55 and 110 $feet^{\frac{1}{2}}$/sec (see 6.3.4).

The hydrographs (see Diagrams 4.2.2-1, 2 and 3) show that river-stages are frequently changing. As the water surface gradient during subsiding water is less than during rising stages' it can be expected that for the same river-stage the discharge is greater during a rise than during a fall. Computations and observations, however, have proved that the difference in discharge during falling and rising stages (for the same water-level) lies within the accuracy of the result of discharge measurements as far as the present gauges are concerned. This means that at every cross-section for which a discharge rating curve is established, only one curve will serve all practical purposes. An exception is the stage-discharge relation at Diré (French West Africa) where the river-bed gradient is extremely small (about 1.5×10^{-5}) and variations of the slope therefore have a relatively greater influence. This curve is shown on Diagram 4.3.2-2.

The ratio of the discharge during rising or falling water-levels and the discharge during steady uniform flow can be expressed as:

$$\frac{Q_a}{Q_m} = \sqrt{1 + \frac{\frac{dh}{dt}\frac{1}{c}}{i_m}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

in which: h = water-level
t = time
c = velocity of propagation of the flood-wave
i_m = water-level slope for steady uniform flow; i_m equals the river-bed gradient
Q_m = discharge during steady flow
Q_a = discharge during rising or falling water-stages

Apparently the ratio increases with the speed of change of river-stage, and decreases with the increase of propagation velocity of the flood and the increase of the river-bottom gradient.

From Table 4.3.1-1, showing extreme values of $\frac{Q_a}{Q_m}$, it follows that the difference between the discharge during rising stages and that during falling stages, both for the same river-stage, becomes in extreme circumstances 5—6% of the discharge during steady flow.

TABLE 4.3.1-1

INFLUENCE OF RISING STAGES ON STAGE-DISCHARGE RELATION

$\frac{dh}{dt}$ ft/day	c ft/sec	i_m $\times 10^{-4}$	$\frac{Q_a}{Q_m}$
3.3	3.3	2.4	1.025
1.0	1.6	1.5	1.023
7.0	3.3	4.0	1.03

4.3.2. Stage-discharge rating curves

On Diagrams 4.3.2-1 to 4 inclusive the stage-discharge rating curves for various stations along the Niger and its tributaries have been constructed.

The curves for Garua (Benue) and Safaie (Faro) in the French Camerouns have been established by the "Mission Bénoué" (Office des Recherches Scientifiques et Techniques Outre-Mer, Paris) and the "Service d'Annonce des Crues at Garua" (Ports et Voies Navigables, Douala). The curve for Diré (Niger) in French West Africa has been established by the "Service Hydraulique" of the "Direction Générale des Travaux Publics de l'A.O.F." (Bamako). For the stage-discharge relations of Bare (Gongola), Wuro Boki, Yola and Numan (all on the Benue), use has been made both of NEDECO measurements and those made by the "Mission Bénoué". For the curves of the other stations, only NEDECO measurements have been used.

Table 4.3.2-5 gives the numbers of the diagrams on which the various stage-discharge rating curves can be found.

In the above-mentioned diagrams linear scales are used for both the discharges and the water-stages. The relation between the discharge and the water-level appears generally as a curved line, which becomes often rather straight at the higher discharges. For some rivers in other

TABLE 4.3.2-5

DISCHARGE RATING CURVES OF DIAGRAMS III, 4.3.2-1, -2, -3 and -4.

Diagram 4.3.2-1		Diagram 4.3.2-2		Diagram 4.3.2-3		Diagram 4.3.2-4	
river	**station**	**river**	**station**	**river**	**station**	**river**	**station**
Benue	Garua	Niger	Diré	Gongola	Bare	Niger	Baro
Faro	Safaie	„	Jebba	Taraba	Beli	Benue	Ibi
Benue	Wuro Boki	Kaduna River	Wuya	„	Gassol	„	Makurdi
„	Yola			Donga	Donga Town	„	Umaisha
,	Numan			„	Nyankwola	Niger	Lokoja
„	Lau			Katsina Ala	Katsina Ala Town	„	Idah
„	Angwan Taru			„	Sevav	„	Onitsha
						„	Aboh

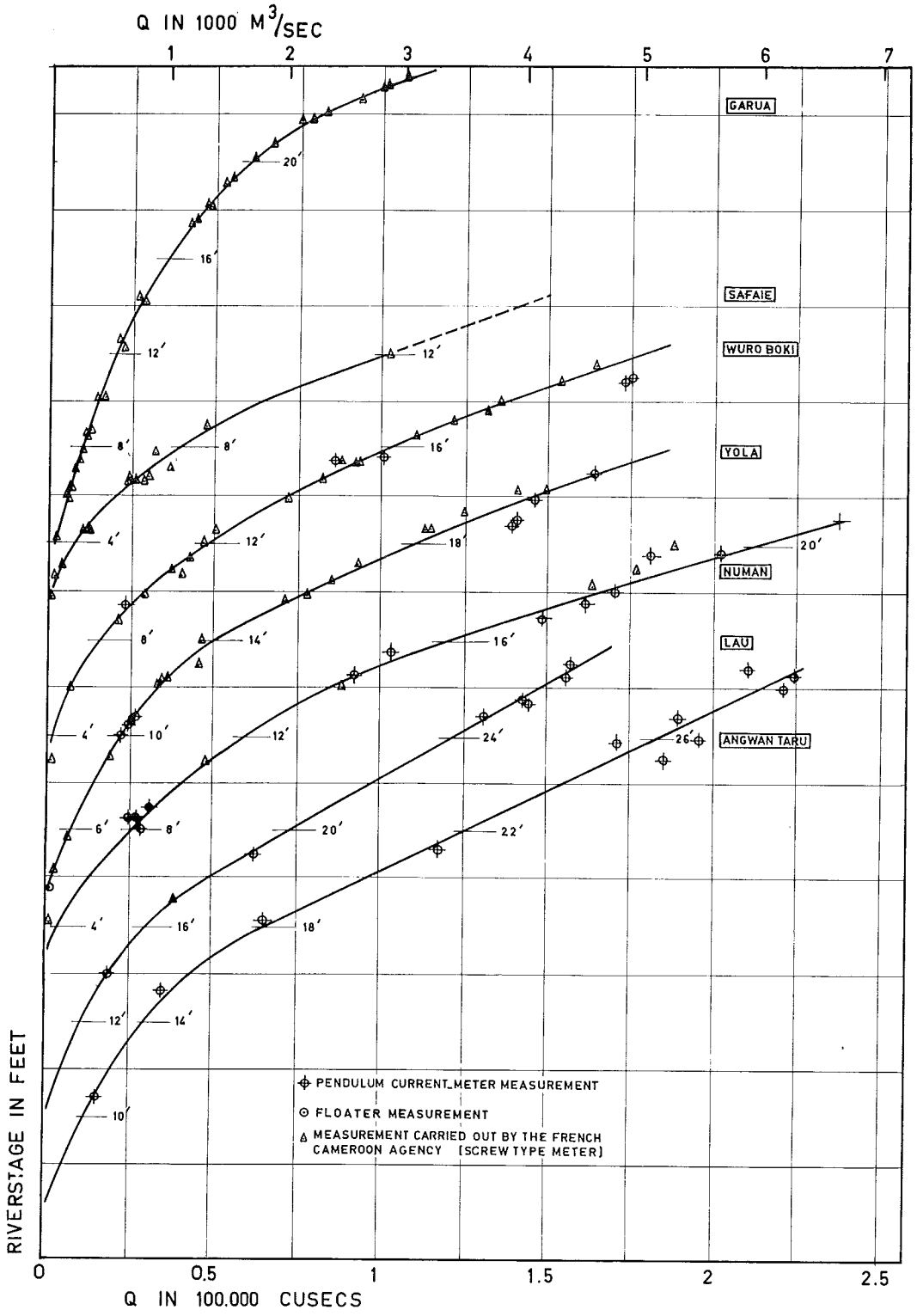


DIAGRAM 4.3.2-1

Discharge-rating curves for the Benue above Ibi

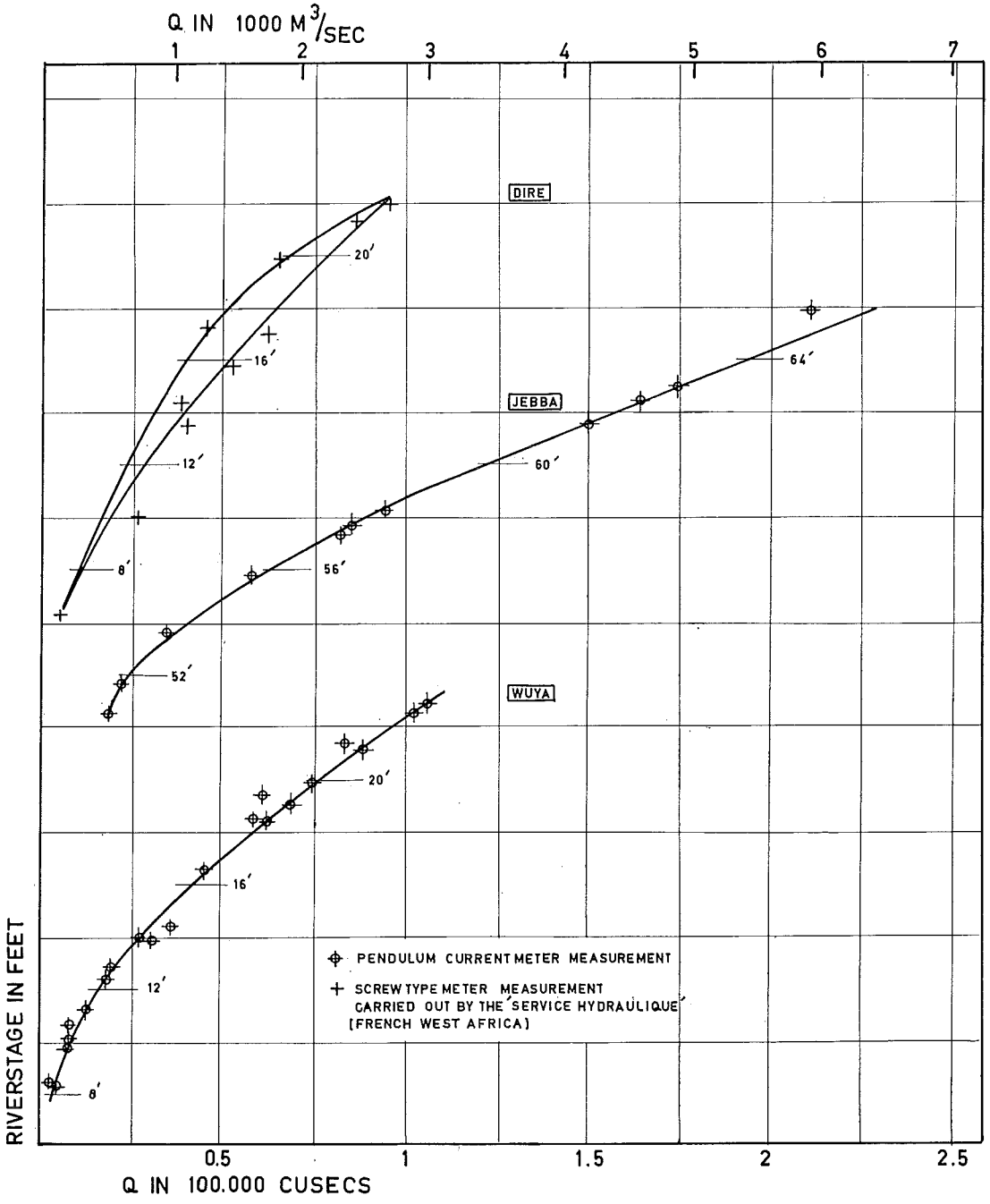


DIAGRAM 4.3.2-2

Discharge-rating curves for Diré and Jebba (Niger) and for Wuya (Kaduna River)

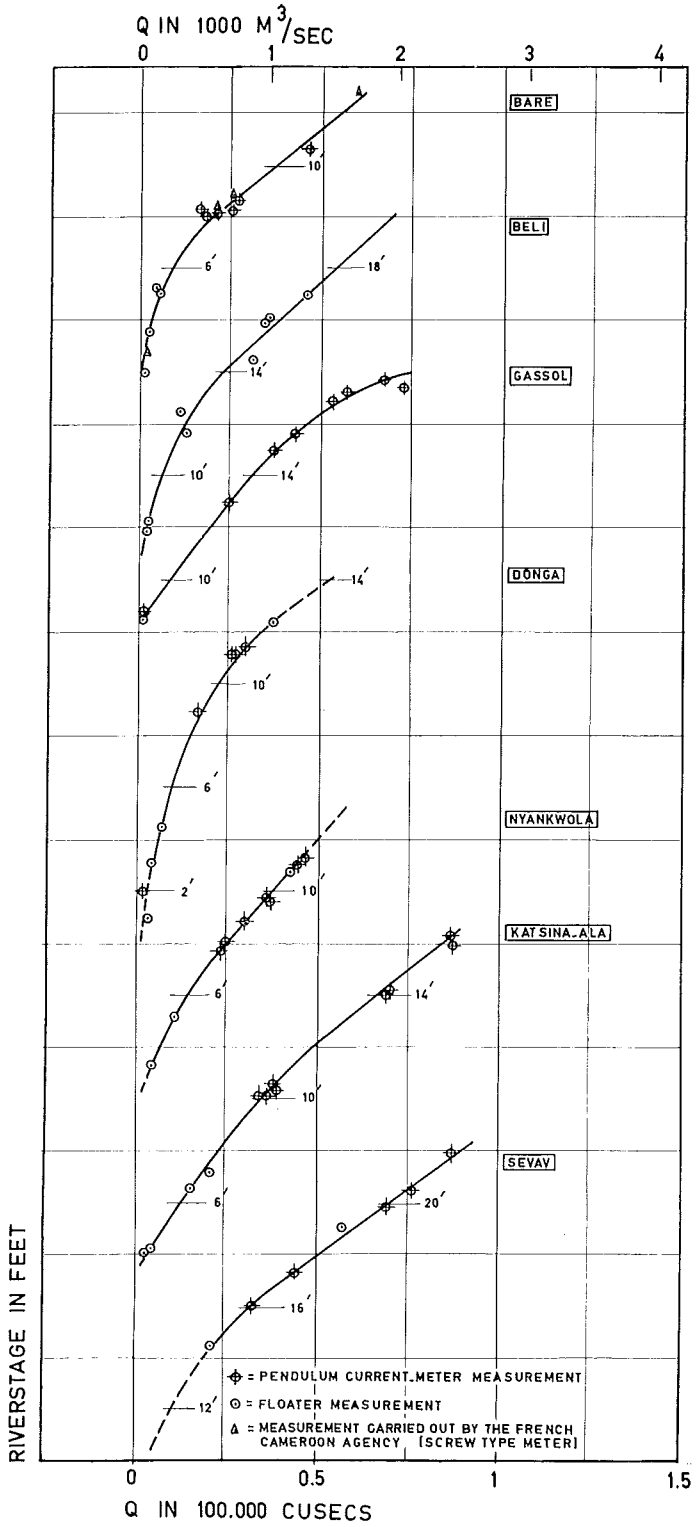
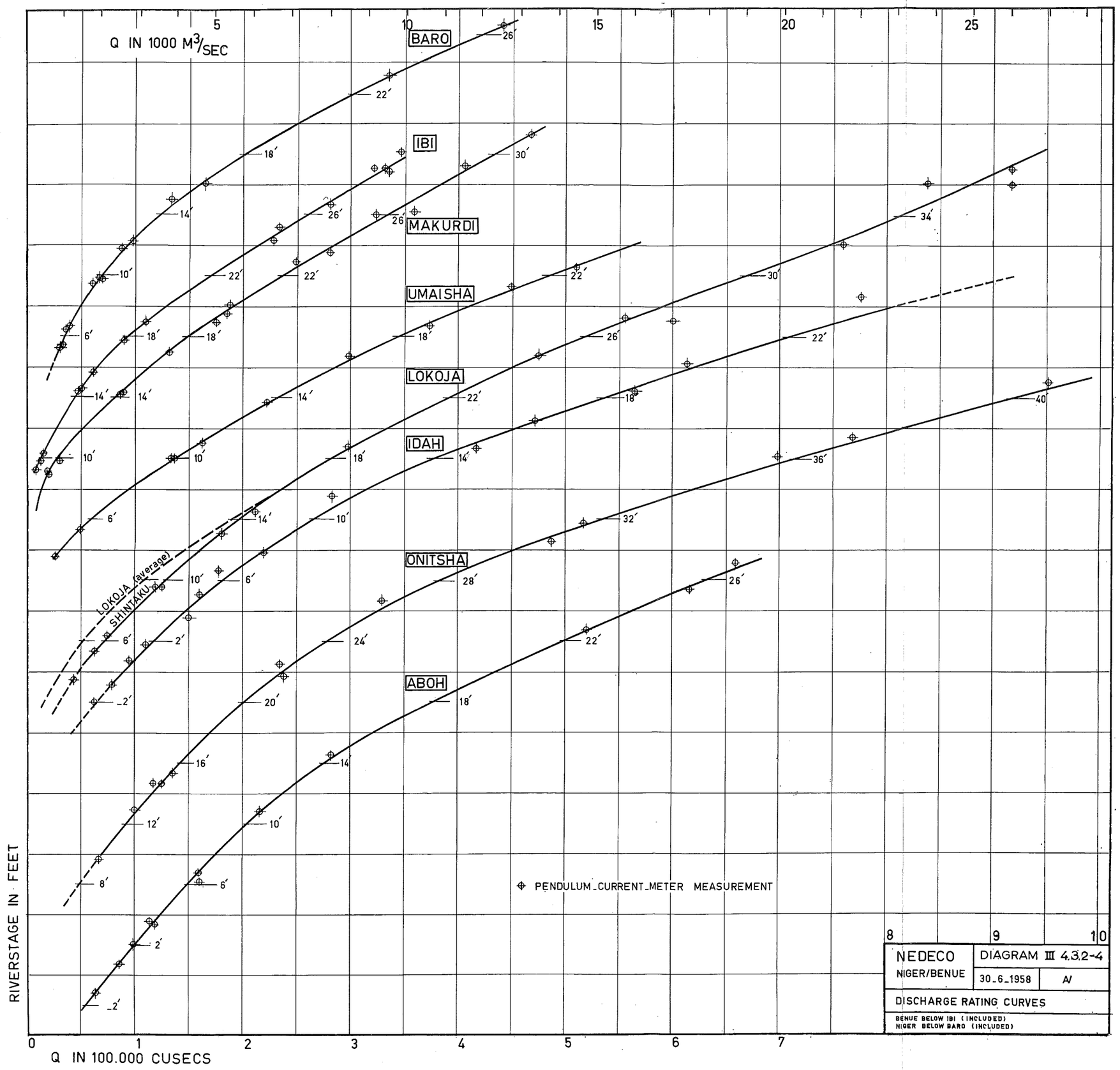


DIAGRAM 4.3.2-3

Discharge-rating curves for the Benue tributaries


Q IN 1000 M³/SEC
5
10
15
20
25
BARO
IBI
MAKURDI
UMAISHA
LOKOJA
IDAH
ONITSHA
ABOH
LOKOJA (average)
SHINTAKU
26′
22′
18′
14′
10′
6′
2′
-2′
30′
34′
36′
40′
32′
28′
24′
20′
16′
12′
8′
PENDULUM-CURRENT-METER MEASUREMENT
RIVERSTAGE IN FEET
Q IN 100.000 CUSECS
0
1
2
3
4
5
6
7
8
9
10
NEDECO
NIGER/BENUE
DIAGRAM III 4.3.2-4
30-6-1958
A/
DISCHARGE RATING CURVES
BENUE BELOW IBI (INCLUDED)
NIGER BELOW BARO (INCLUDED)

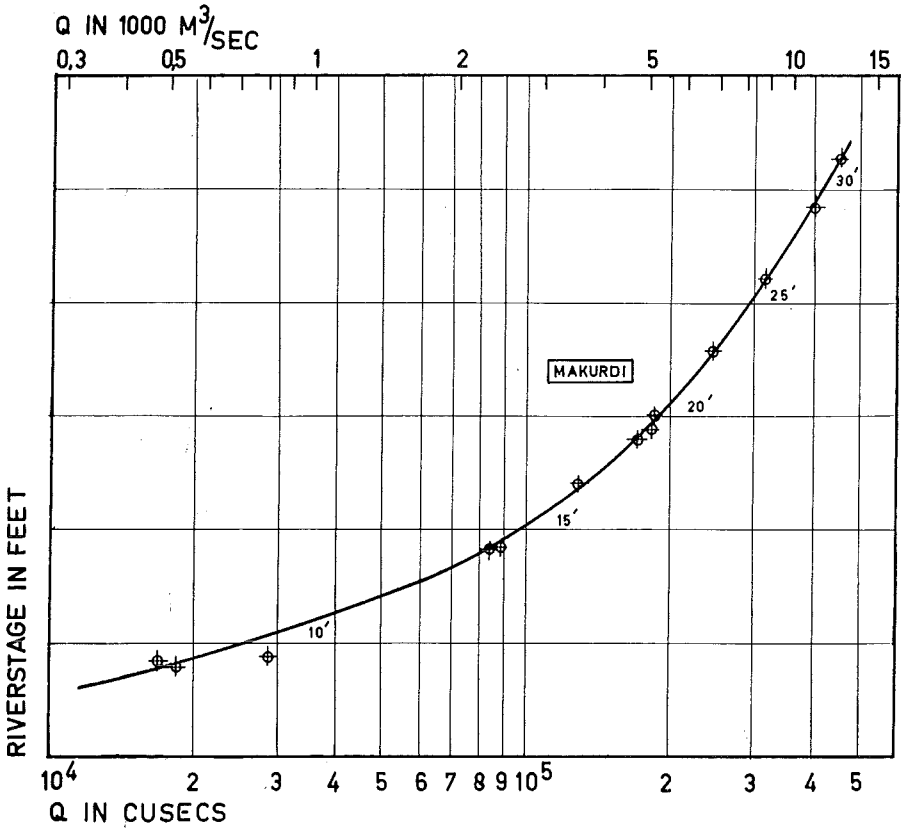


DIAGRAM 4.3.2-6

Discharge-rating curve of Makurdi (Benue) with logarithmic discharge scale

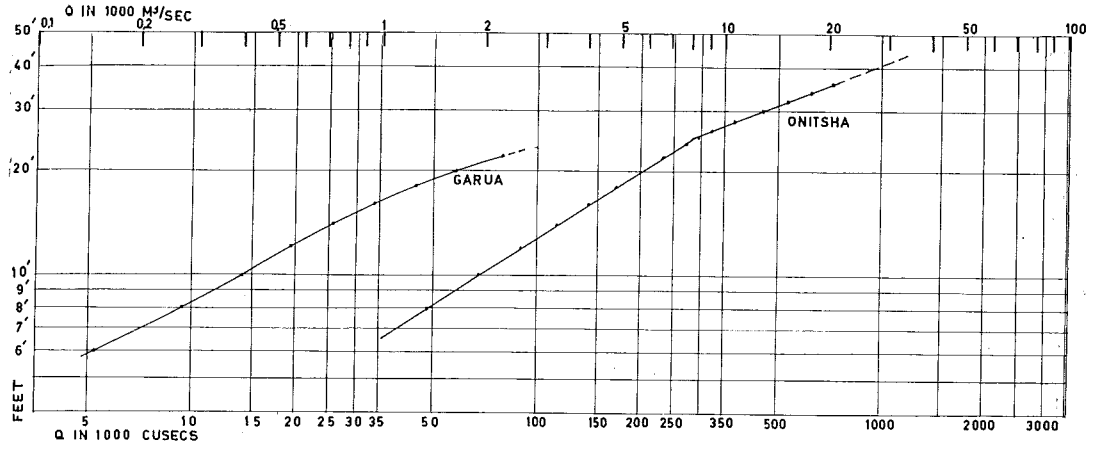


DIAGRAM 4.3.2-7

Discharge-rating curves of Garua (Benue) and Onitsha (Niger) with logarithmic scales of discharges and river-stages

parts of the world, a logarithmic scale for the discharge is used to obtain a straight or almost straight line. A straight line as the expression of the stage-discharge relation is desirable, because this can make the extrapolation above the highest measured discharge less liable to subjective judgment. It proved, however, that when results of observations were plotted in this way, the stage-discharge relation curves for the Niger and its tributaries still remained curved. An example is given in Diagram 4.3.2-6

Generally, stage-discharge relation curves will become more or less straight lines when the scales of both the river-stages and the discharges are logarithmic. Diagram 4.3.2-7 shows this for Garua (Benue) and for Onitsha (Niger). When necessary, this kind of line has been used for the extrapolation of the stage-discharge relation curve. But as in 1955 very high river-stages occurred during which measurements were taken, extrapolation has been necessary only in a few cases (shown in broken lines) and then only over a few feet.

Diagrams 8, 9 and 10 make it possible to read immediately the discharge belonging to a certain river-stage.

4.3.3. Discharges 1955—1957

Diagrams 4.3.3-1, -2 and -3 give the discharge hydrographs 1955—1957 of those stations for which a discharge rating curve has been established (see 4.3.2).

At the onset of the wet season discharges along the Benue (Diagram 4.3.3-1) below Angwan Taru start to increase earlier than upstream from this station. Below Angwan Taru the Benue is joined by three important tributaries, viz., the Taraba River, the Donga River, and the Katsina Ala River, all three of which rise in the Cameroun Mountains where rainfall begins earlier than elsewhere on the Benue Basin.

In their turn the discharges above Angwan Taru and below Wuro Boki (this latter station included) start to increase earlier than the discharge of the Benue at Garua. A few miles above Wuro Boki, the Benue is joined by the Faro which arrives from the northern part of the Cameroun Mountains. Rainfall over this area starts before it begins over the Benue head-water area.

Discharges keep increasing during June and the beginning of July, but during July—August the discharge remains constant (see August 1955, at Wuro Boki and Garua) or may decrease (Ibi, August, 1955). This is called the "August fall", although the phenomenon may also start in July. An explanation of this has been given in Section 1.3. The hydrographs of 1957 illustrate that this August fall does not occur every year in the same measure. During that year it occurred only slightly upstream from Lau, and it is hardly perceptible in the hydrographs below Angwan Taru.

The phenomenon of flood propagation (see 4.2.7) finds a good illustration in the 1956 hydrographs. The influence of flood peaks of the Benue tributaries on the discharges of the Benue itself is seen by comparing Diagram 4.3.3-1 with Diagram 4.3.3-2.

Garua—Wuro Boki:

The June peak on the Faro (at Safaie) is seen at Wuro Boki. The rather high July peak has been greatly flattened out because of its short duration.

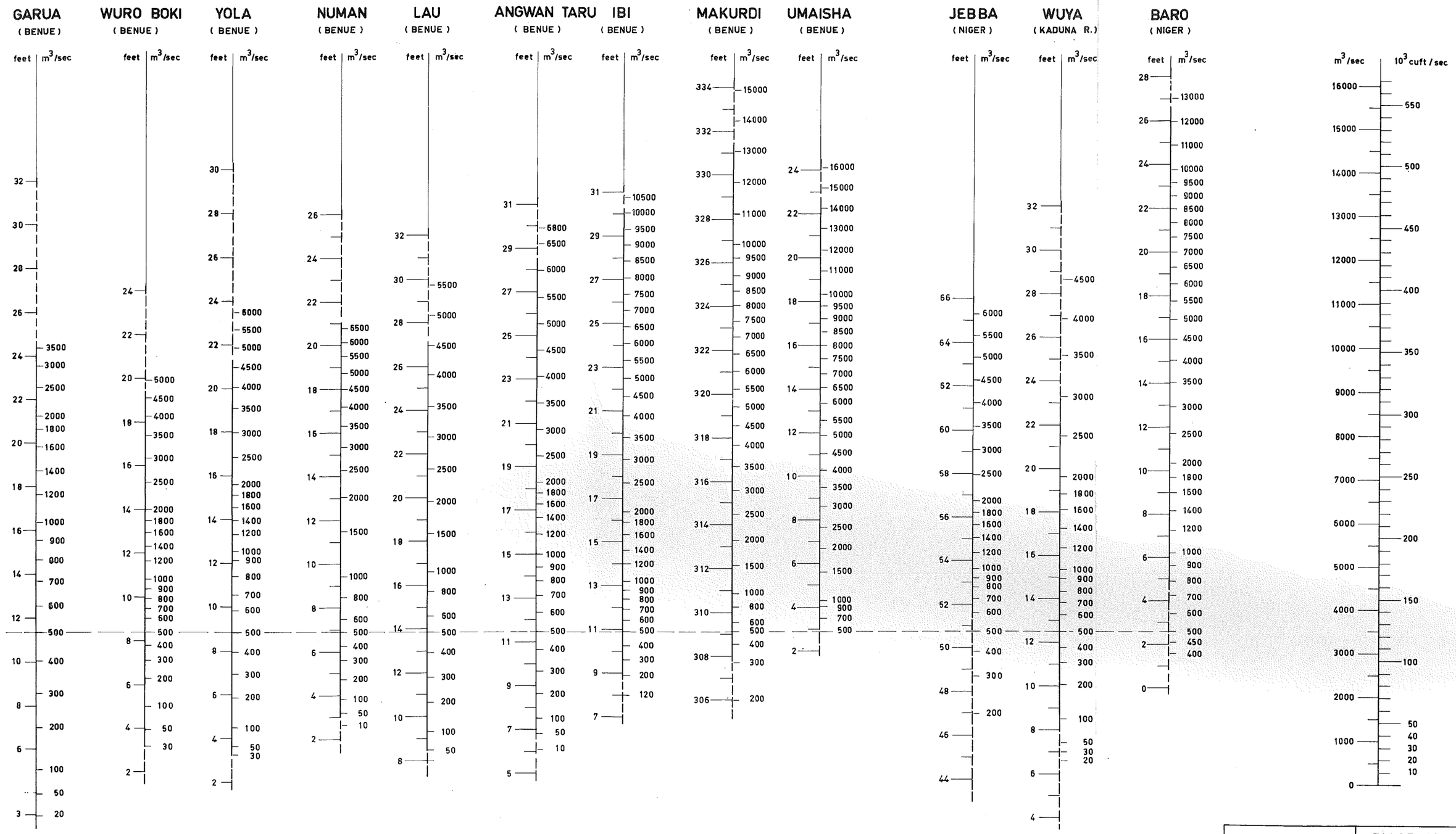
During August, September and October there are simultaneously three conspicuous peaks on the Faro at Safaie and on the Benue at Garua. Apparently, the storm which caused these flood peaks has covered both the Faro and the Benue headwater area. On the Wuro Boki hydrograph for October it is seen that the Faro peak reached this station earlier than the Benue peak. The Faro peak, early in September, is recognisable at Wuro Boki.

Wuro Boki—Yola:

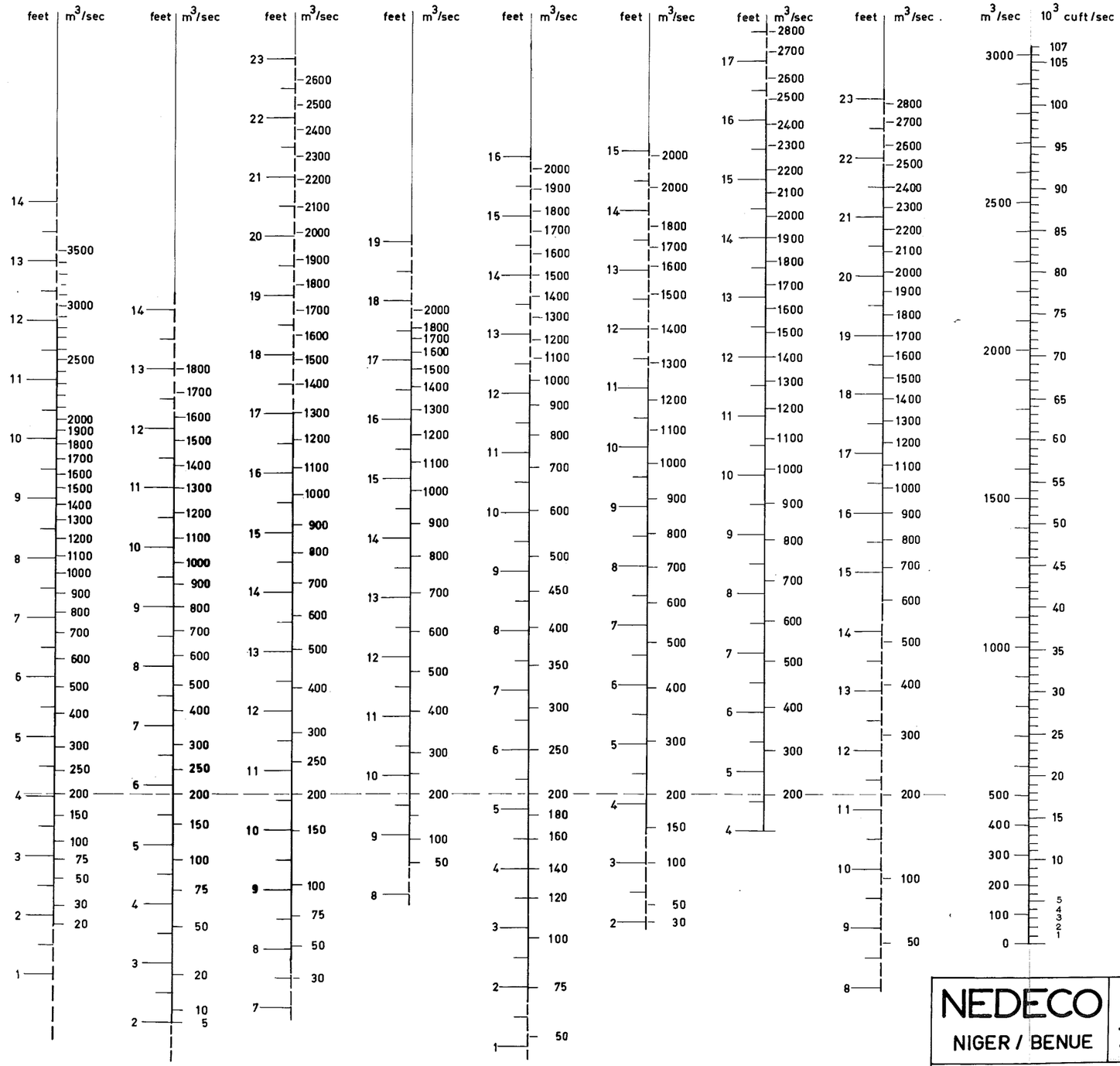
The shape of the hydrograph at Yola is quite analogous to that of the Wuro Boki hydrograph.

Yola—Numan:

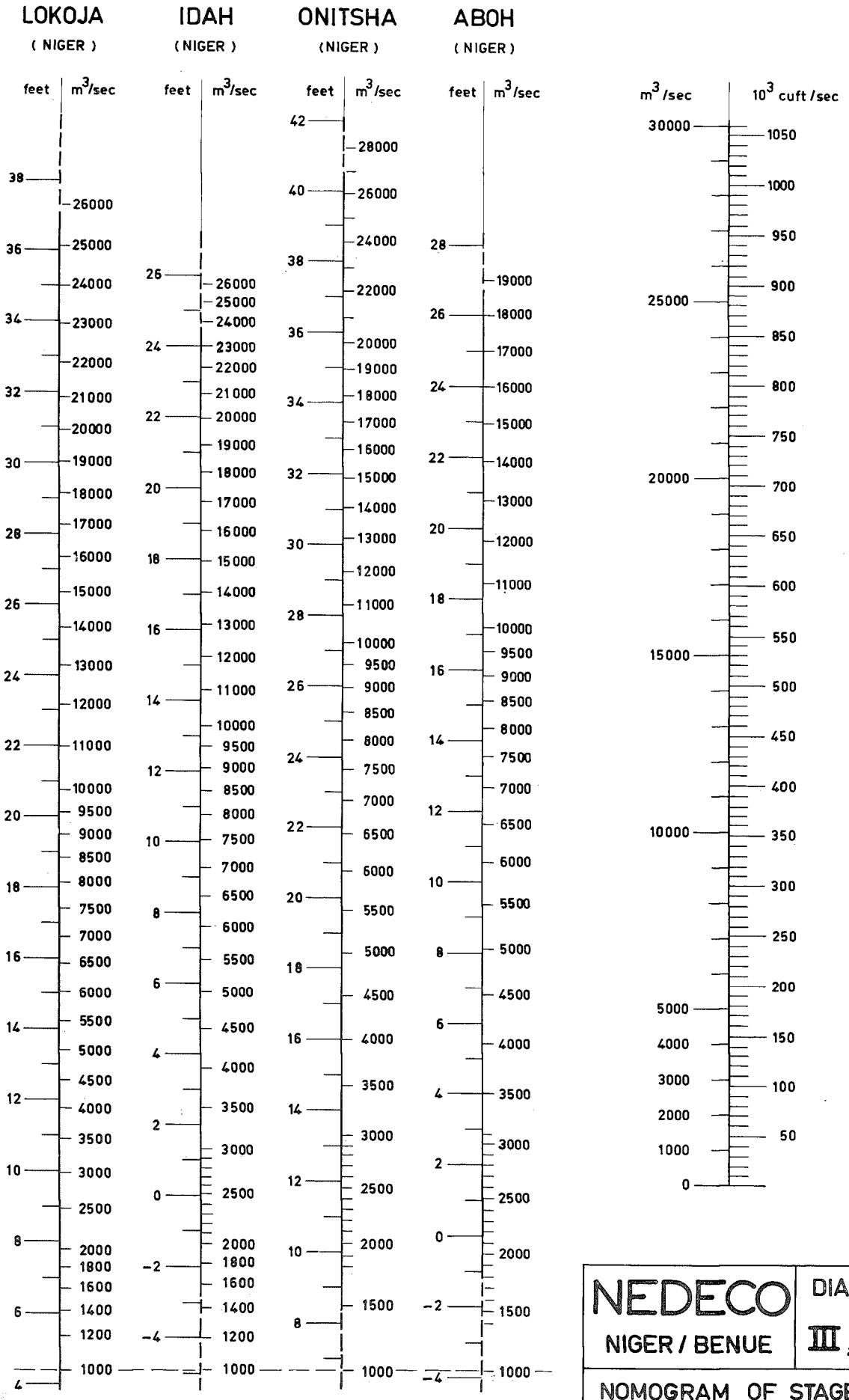
Between these two stations the Benue is joined by the Gongola. The discharge hydrograph for Bare situated on this river is found in Diagram 4.3.3-2. At the end of August, the discharge at Yola is decreasing, although



NEDECO NIGER / BENUE	DIAGRAM III, 4.3.2-8
NOMOGRAM OF STAGE – DISCHARGE RELATIONS	
BENUE AND NIGER ABOVE LOKOJA	



NEDECO NIGER / BENUE	DIAGRAM III, 4.3.2-9
NOMOGRAM OF STAGE-DISCHARGE RELATIONS	
BENUE TRIBUTARIES	



NEDECO NIGER / BENUE	DIAGRAM III, 4.3.2-
NOMOGRAM OF STAGE–DISCH RELATIONS	
NIGER BELOW LOKOJA	

not that at Numan, because the discharges on the Gongola are increasing. The Gongola peak in early September shows its effect on the Numan hydrograph.

Numan—Lau:

No important tributaries join the Benue on this river-stretch. The shape of the hydrograph at Numan corresponds with that of the hydrograph at Lau, although during the greater discharges differences between peaks and troughs are more marked at Numan than at Lau. This is the result of storage: great areas of land are covered with water during the height of the season, which flattens the flood peaks.

Lau—Angwan Taru:

Also along this river-stretch much land is flooded during the higher river-stages. The three peaks which are still perceptible at Lau during September and October are scarcely visible at Angwan Taru.

Angwan Taru—Ibi:

Between Angwan Taru and Ibi the Benue is joined by the Taraba and the Donga Rivers. For the Taraba, hydrographs are given of Beli, which is situated in the headwater area, and of Gassol near the confluence with the Benue. Along the Donga are situated Donga Town and Nyankwola, respectively in the middle course of the river and at the lower end. The hydrographs for these two stations are also given.

Comparing the hydrographs for Beli and Gassol, it is seen that although the latter is more flattened, they closely correspond.

All the crests and troughs of the hydrographs of Donga Town can be found again on the hydrograph of Nyankwola.

But the hydrographs of Gassol (Taraba) and Nyankwola (Donga River) can also be compared mutually, and show a marked resemblance. Most of the larger peaks occurring on the Taraba correspond with simultaneous peaks on the Donga River, which means that the storms causing these peaks have covered the headwater area of both rivers at the same time.

It is interesting to note that some high peaks occur simultaneously with peaks on the Faro (the peak of mid-July and that of the beginning of October). So the area covered by the same storm may be considerable (see also 1.3.1).

That the shape of the hydrograph at Ibi only roughly corresponds with that of the hydrograph at Angwan Taru is due to the fact that the two major tributaries join the Benue between these stations. The Ibi peaks of the second half of July, the last week of September and about mid-October can be found back on the hydrographs of these tributaries. In June the Ibi hydrograph starts to rise before the discharge at Angwan Taru is increasing. As can be seen on Diagram 4.3.6-1, the combined discharge of the Taraba and the Katsina Ala Rivers during June, 1956, was about 70% of the Benue discharge at Ibi.

During the second half of August, the Angwan Taru hydrograph is still rising, but Ibi discharges are practically constant. This is explained by the decrease of flow on the tributaries.

Ibi—Makurdi:

Between Ibi and Makurdi the Benue is joined by the Katsina Ala River, which rises in the Cameroun Mountains. The discharge hydrographs of Katsina Ala Town and of Sevav, two stations along this river, are drawn on Diagram 4.3.3-2. Sevav is situated downstream from Katsina Ala Town, and the two hydrographs resemble each other, as could be expected.

The general trend of the Katsina Ala River hydrograph corresponds with the trend of the Faro, Taraba and Donga River hydrographs but not all peaks occur simultaneously.

The decrease of discharge at Makurdi during the second half of August, while the Ibi discharge remains about constant, is caused by the decrease of flow on the Katsina Ala River. The peak, early October at Makurdi, is not the effect of the Ibi peak at the end of September, but is caused by a Katsina Ala River peak. The effect of the Katsina Ala River peak at the end of October is seen on the Makurdi hydrograph. The small peak on the Ibi hydrograph in December occurs also on the Makurdi hydrograph.

Makurdi—Umaisha:

The hydrographs of these two stations correspond also in a general way. Storage in the river-stretch causes the October peaks of Makurdi to flatten out before reaching Umaisha. The same phenomenon occurs during June and July. The small peak on the Makurdi hydrograph in December is seen on the Umaisha hydrograph as well.

On Diagram 4.3.3-3 are drawn the discharge hydrographs for Diré on the Niger (French West Africa) and for the main gauges along the Niger within Nigeria; the hydrographs of Wuya along the Kaduna River and of Makurdi along the Benue are also given. These two rivers are the most important tributaries of the Niger within Nigeria.

The distance between Diré and Jebba is about 1,000 miles, and so a considerable time-lag can therefore be expected. The peak of the flood at Diré is generally in December. On its way downstream the peak passes Jebba in February or March, 4 or 5 months after the local flood caused by rain in the basin within and near Nigeria has occurred. The propagation of the Diré flood (in Nigeria called the Black Flood) is examined more in detail in 4.5.4.

After the dry season, discharges at Jebba do not generally increase before the end of July or the beginning of August. But at the end of the wet season, in November, discharges do not

fall to very small values as on the Benue, because of the effect of the Black Flood. During January and February a small increase of the discharge takes place, and a second maximum discharge occurs in February or March. The effect of this second maximum can be followed downstream along the Niger, sometimes down to Aboh.

Jebba—Baro:

Between Jebba and Baro the Niger is joined by the Kaduna River which rises on the Jos Plateau. After the dry season, discharges on the Kaduna River start to increase later than on the Benue tributaries which arrive from the Cameroun Mountains. Sometimes peaks on the Kaduna River may coincide with those on the Niger at Jebba (see the hydrographe of 1955), but this is certainly not always the case.

The effect of flood peaks on both the Niger at Jebba and the Kaduna River at Wuya can be seen on the Baro hydrograph.

Baro—Lokoja:

At Lokoja the Niger is joined by the Benue, and the hydrograph at this station will reflect the shape of those of both rivers.

In 1956 the Baro discharge started decreasing after the first week of April, with the minimum discharge occurring at the end of July. As is seen on the Makurdi hydrograph, the Benue discharge shows a minimum during the third week of May. The result was that the Lokoja discharge became minimum during the last days of May.

The peak at Makurdi during the end of July reveals its effect on the Lokoja hydrograph. At the end of August, when Makurdi discharges are decreasing, the discharge at Lokoja remains constant, because the Niger discharges at Baro are rising. During the higher stages in September and October the Lokoja hydrograph is more smooth than those of Baro and Makurdi, because of the effect of storage.

The small rise at Makurdi during December, 1956, is still visible at Lokoja.

Lokoja—Idah:

The shape of the hydrograph at Idah reflects clearly that of the hydrograph at Lokoja.

Idah—Onitsha:

The hydrographs of these two stations also correspond closely, as could be expected.

Onitsha—Aboh:

For the small and the medium discharges these two hydrographs correspond very considerably.

As explained in 4.2.7, a part of the discharge at Onitsha at higher stages flows overland towards the Ase and the Orashi Rivers which run parallel to the Niger to the south. This is the reason why the Aboh hydrograph does not reach the same peak discharge as that of Onitsha.

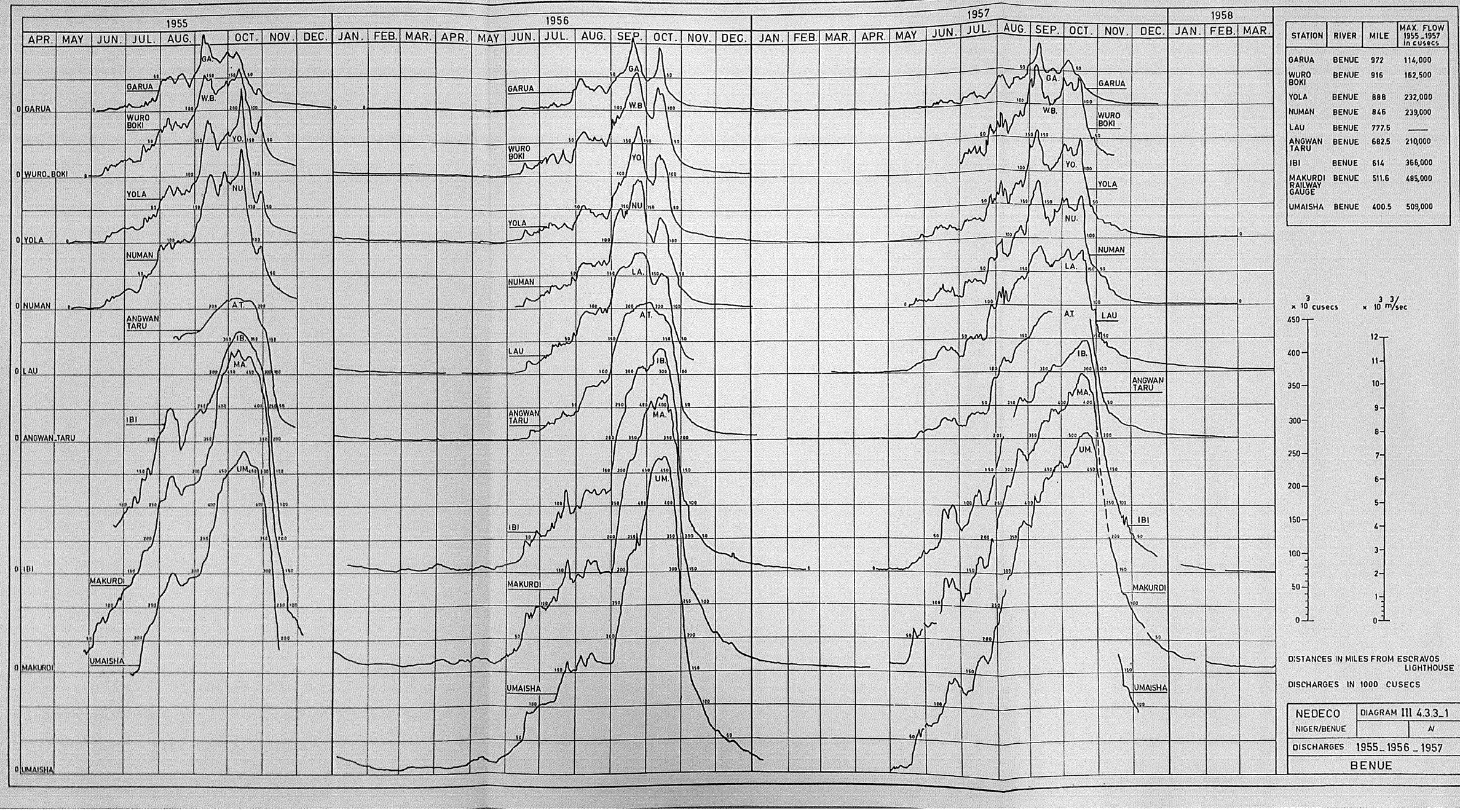
A comparision of the discharge hydrographs of 1955, 1956 and 1957 shows that, generally speaking, the discharges during 1956 were lower than during 1955 and 1957. Whether they have been exceptional or not will be discussed in 4.3.4.

4.3.4. Frequencies of discharges

Making use of the stage-discharge relation curves (4.3.2), the water-level frequency curves as given in 4.2.3 can be converted into discharge frequency curves.

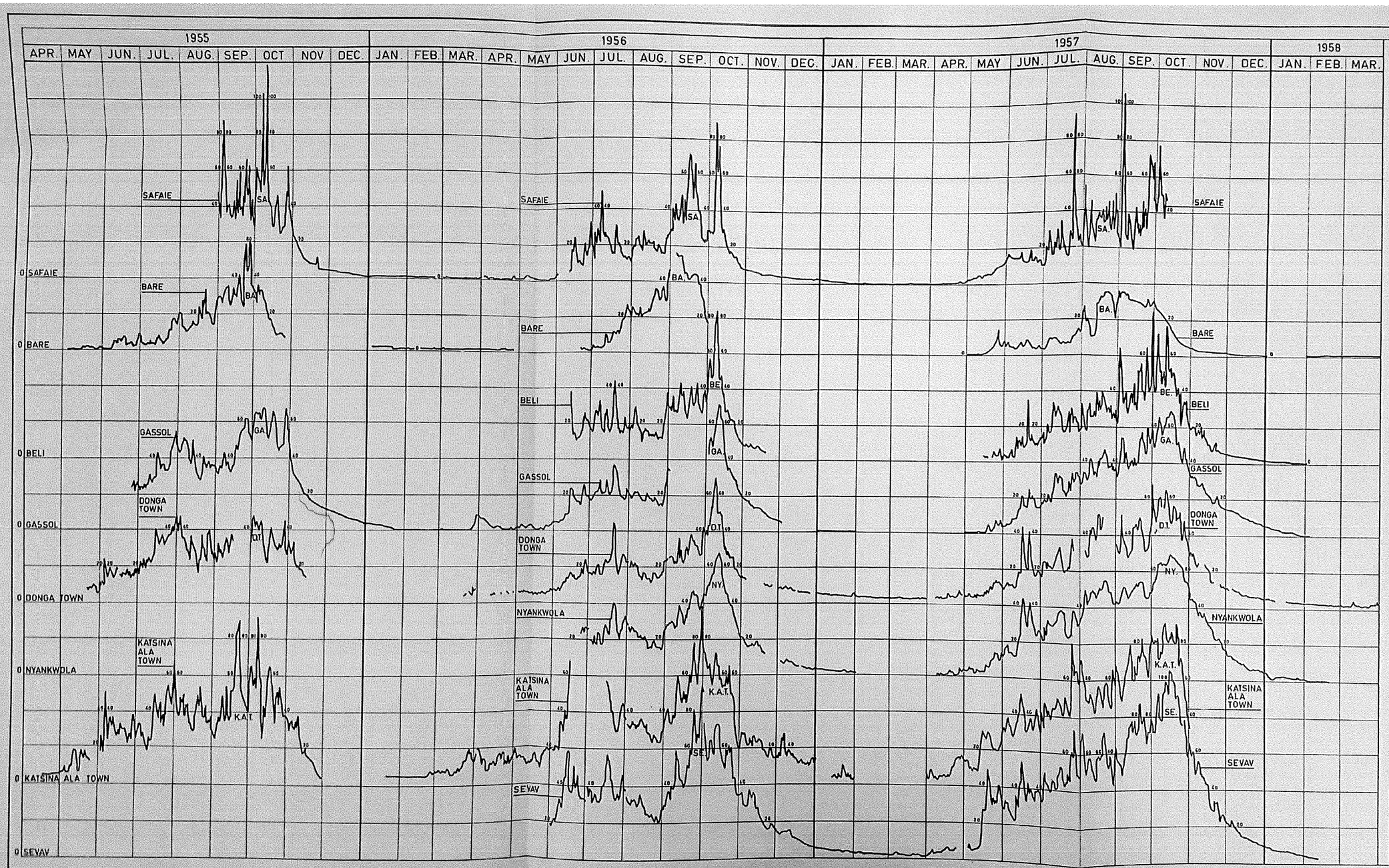
As explained in 4.3.1, the stage-discharge relation depends on several factors. The most important cause of a gradually changing stage-discharge relation can be the scouring or aggrading of the river-bottom. But in computing the frequency of the discharges, it has been assumed that conditions determining the discharge rating curve have not changed during the period of record. This assumption introduces some uncertainty in the frequencies of discharges computed in this way, as rating curves of 1955—1957 have to be applied on water-level records dating as far back as 1914. Unfortunately there are no other means of establishing the required frequencies of discharges, nor is there a check on the rating curves for previous years, as practically no discharge measurements have been carried out before 1955.

The result of the "translation" of the frequency curves of Diagrams 1 to 10 of 4.2.3 into discharge frequency curves is shown on Diagrams 4.3.4-1 to 10 inclusive. The interpretation of the diagrams is analogous to that of the diagrams of 4.2.3. For instance (Diagram 4.3.4-1),



STATION	RIVER	MILE	MAX. FLOW 1955_1957 in cusecs
GARUA	BENUE	972	114,000
WURO BOKI	BENUE	916	162,500
YOLA	BENUE	888	232,000
NUMAN	BENUE	846	239,000
LAU	BENUE	777.5	——
ANGWAN TARU	BENUE	682.5	210,000
IBI	BENUE	614	366,000
MAKURDI RAILWAY GAUGE	BENUE	511.6	485,000
UMAISHA	BENUE	400.5	509,000

NEDECO NIGER/BENUE	DIAGRAM III 4.3.3_1	A/
DISCHARGES	1955_1956_1957	
BENUE		



STATION	RIVER	MILE	MAX. FLOW 1955_1957 in cusecs
SAFAIE	FARO	983	118,500
DADIN KOWA	GONGOLA	± 935	—
BARE	GONGOLA	855	59,300
BELI	TARABA	± 753	—
GASSOL	TARABA	691	71,400
DONGA TOWN	DONGA	± 685	70,000
NYANKWOLA	DONGA	650	—
KATSINA ALA TOWN	KATSINA ALA	± 610	98,000
SEVAV	KATSINA	± 570	—

3 × 10 cusecs

100 80 60 40 20 0

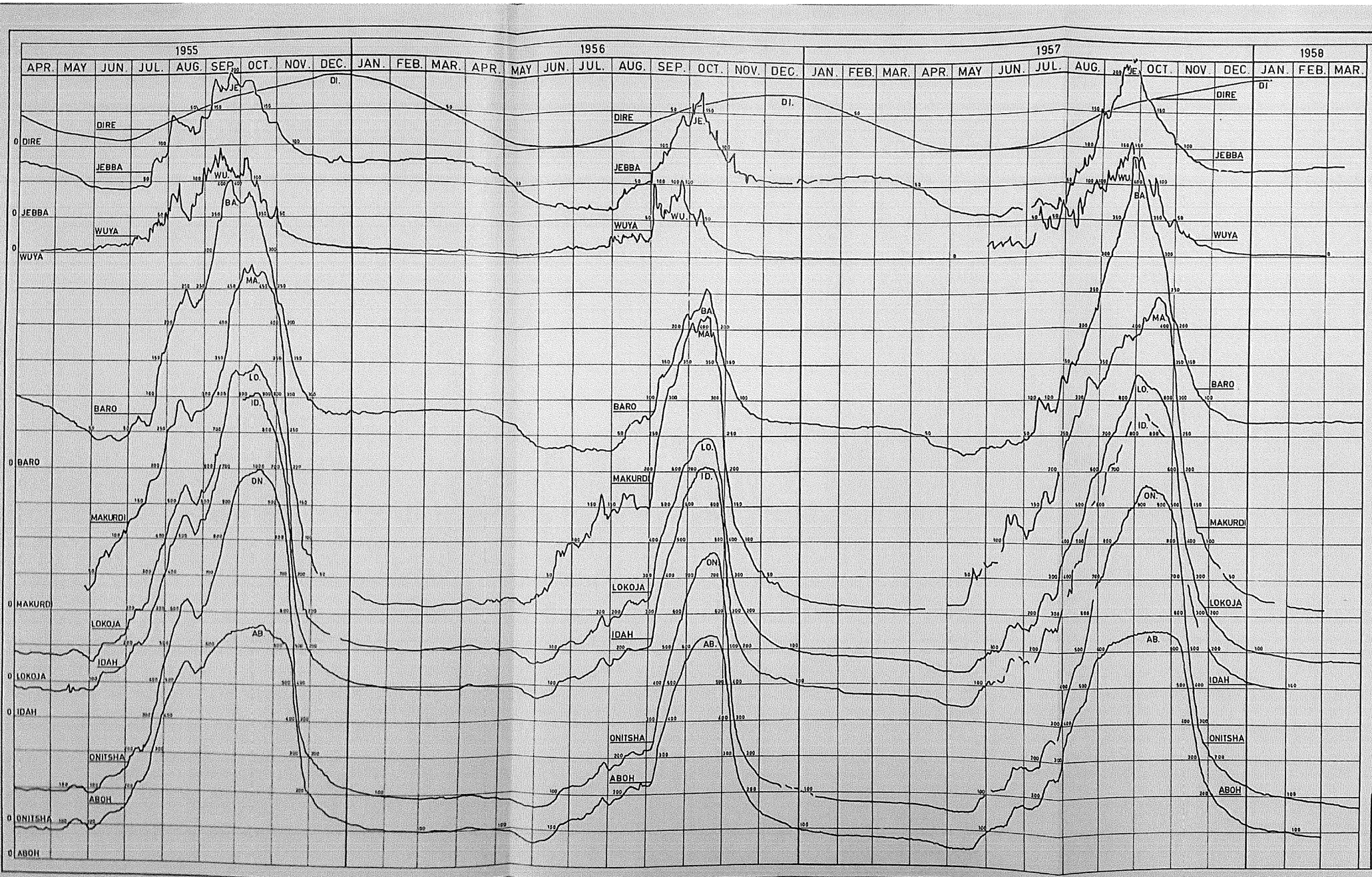
3 3/sec × 10 m/sec

2.8 2.4 2.0 1.6 1.2 0.8 0.4 0

DISTANCES IN MILES FROM ESCRAVOS LIGHTHOUSE

DISCHARGES IN 1000 CUSECS

NEDECO NIGER/BENUE	DIAGRAM III 4.3.3_2	A/
DISCHARGES 1955 _ 1956 _ 1957		
BENUE TRIBUTARIES		



STATION	RIVER	MILE	MAX. FLOW 1955–1957 in cusecs
DIRE (F.W.A.)	NIGER	1574	96,500
JEBBA	NIGER	556	223,000
WUYA	KADUNA	505	157,000
BARO	NIGER	434	439,000
BUDON	NIGER	398.5	—
MAKURDI RAILWAY GAUGE	BENUE	511.6	484,000
LOKOJA	NIGER	361.2	888,000
IDAH	NIGER	310	911,000
ONITSHA	NIGER	232.3	996,500
ABOH	NIGER	177.5	663,000

× 10^3 cusecs: 450, 400, 350, 300, 250, 200, 150, 100, 50, 0 — 900, 800, 700, 600, 500, 400, 300, 200, 100, 0

× 10^3 m^3/sec: 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0 — 24, 22, 20, 18, 16, 14, 12, 10, 8, 6, 4, 2, 0

DISTANCES IN MILES FROM ESCRAVOS LIGHTHOUSE

DISCHARGES IN 1000 CUSECS

NEDECO NIGER/BENUE	DIAGRAM III 4.3.3_3 AV
DISCHARGES	1955_1956_1957
NIGER AND TRIBUTARIES	

the discharge of the Benue at Yola on August 15 has been lower than 70,000 cuft/sec during 75 % of the period of record. And (see Diagram 4.3.4-6) during 25 % of the number of years of record, the discharge of the Benue at Yola has been less than 30,000 cuft/sec during 280 days or more.

Diagrams 4.3.4-11 and 12 give the frequency curves of the average monthly discharges for Garua (Benue River, French Camerouns) over 1930—1956, and for Diré (Niger River, French West Africa) over 1924—1955 ([1]. An example of the interpretation of these two diagrams is (see Diagrams 4.3.4-11): The average October discharge of the Benue at Garua has been lower than 56,000 cuft/sec during 90 % of the years of record.

It is of interest to compare the discharge hydrographs of a certain year with the frequencies of Diagrams 2, 3, 5 and 6, for which purpose Diagrams 4.3.4-13 to 16 have been drawn. On the first one it is seen that at Yola, on the Benue, discharges during 1956 have generally been rather high. Even during the so-called August fall (see 4.3.3) they are oscillating between the 50 %

([1] ORSTOM, 1955. HYD 6

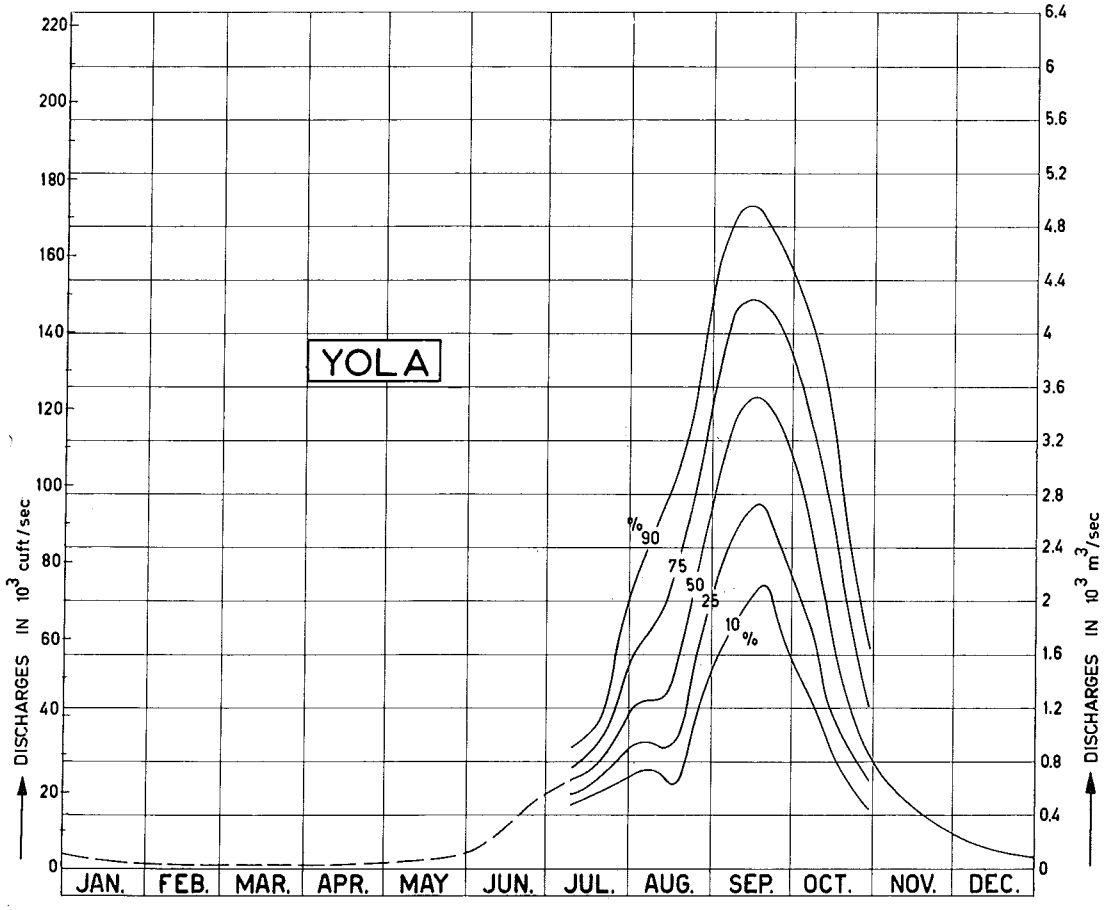


DIAGRAM 4.3.4-1

Frequencies of discharges at Yola (Benue) for a fixed day

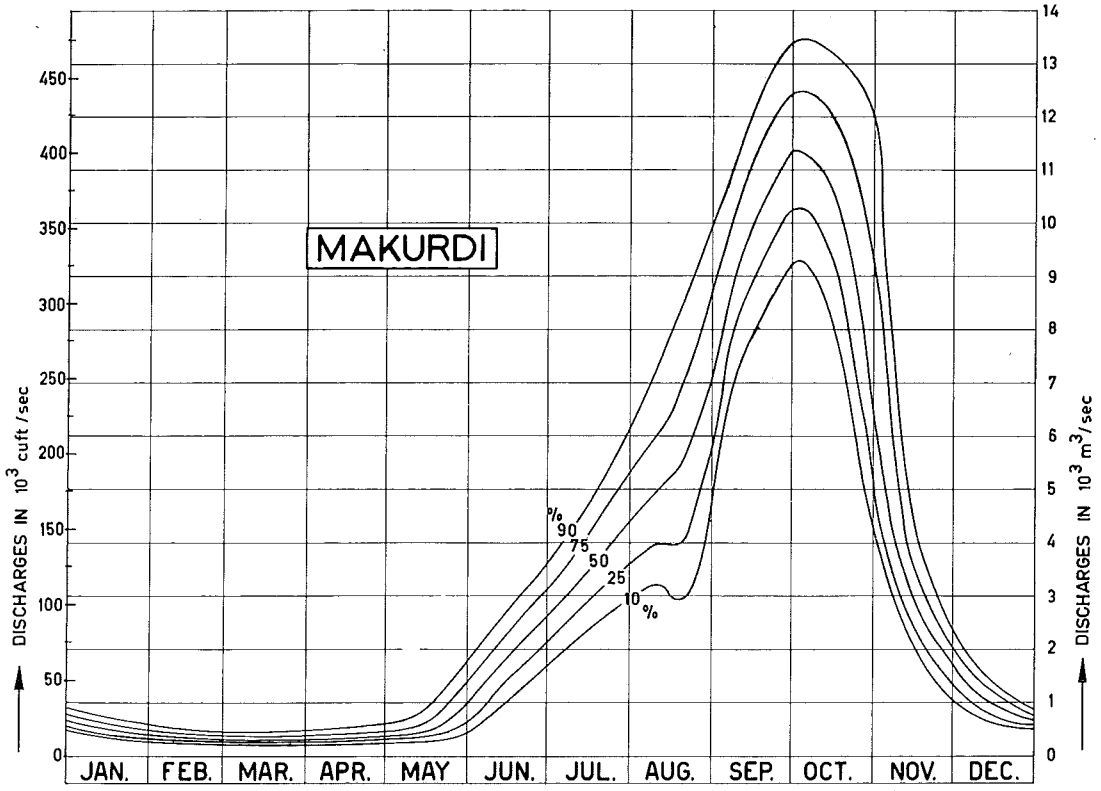


DIAGRAM 4.3.4-2

Frequencies of discharges at Makurdi (Benue) for a fixed day

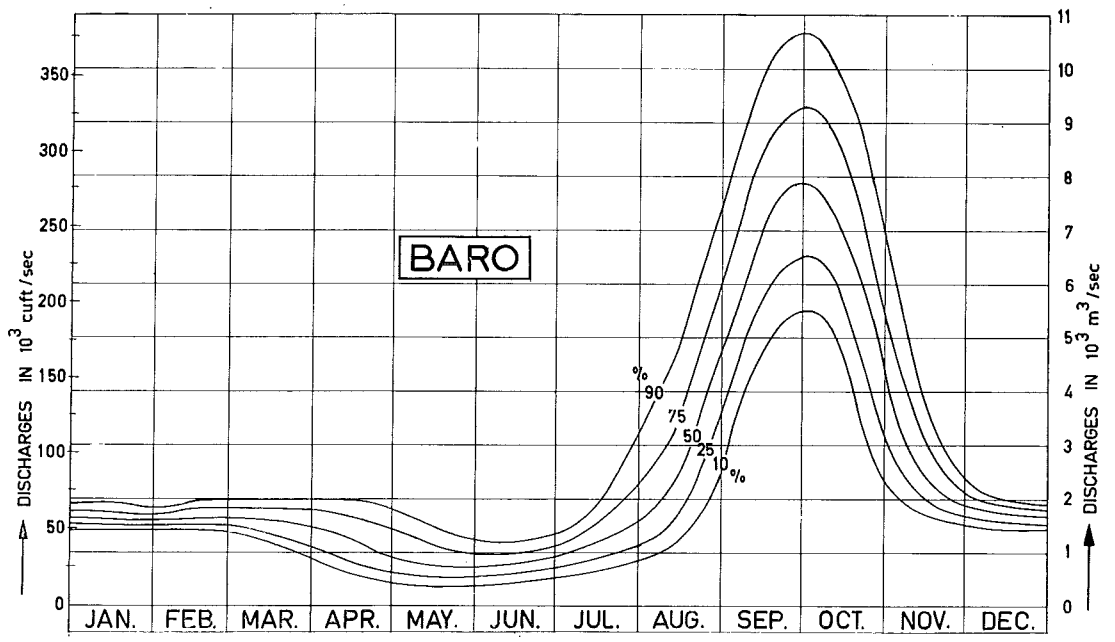


DIAGRAM 4.3.4-3

Frequencies of discharges at Baro (Niger) for a fixed day

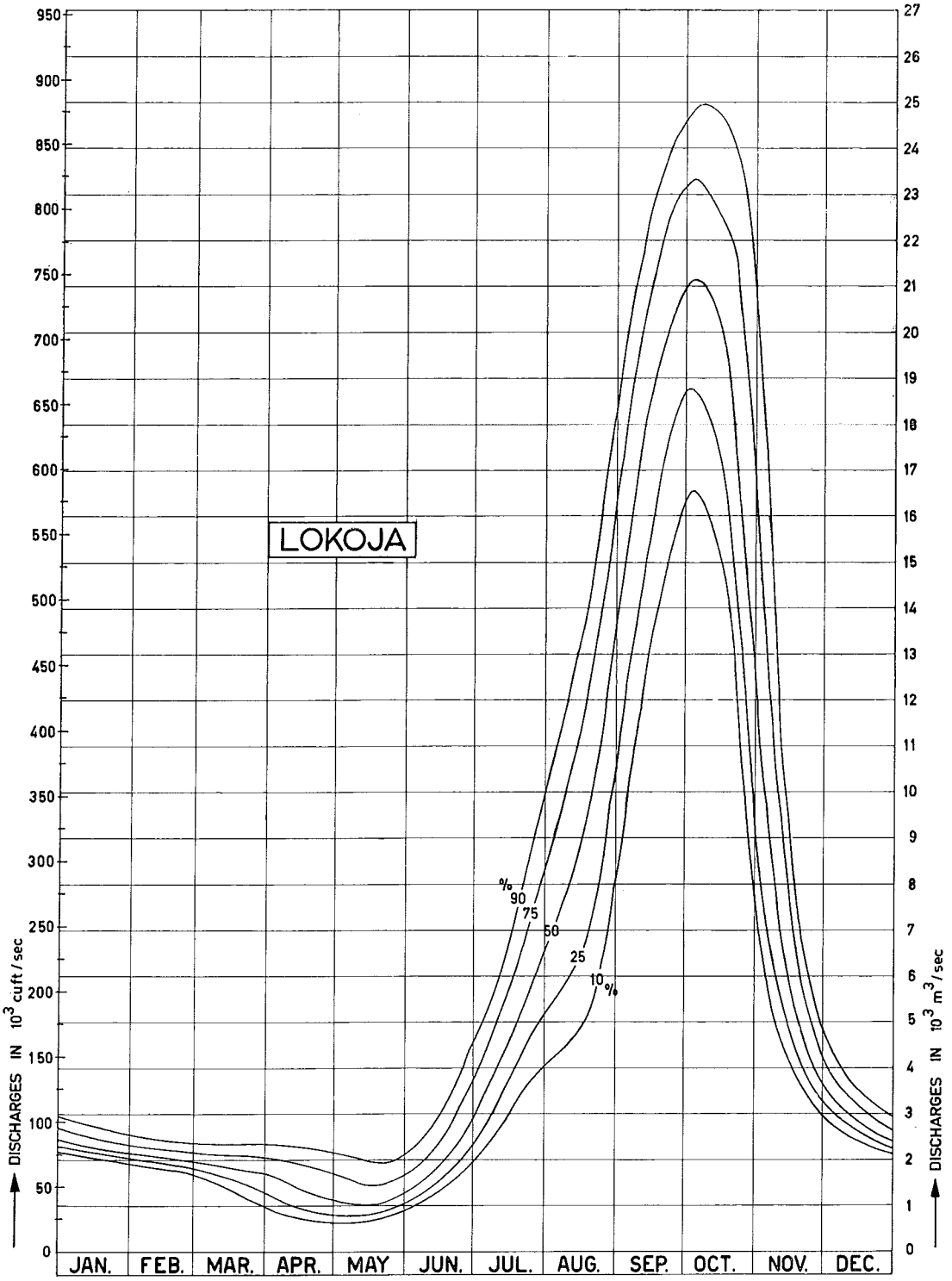


DIAGRAM 4.3.4-4

Frequencies of discharges at Lokoja (Niger) a fixed day

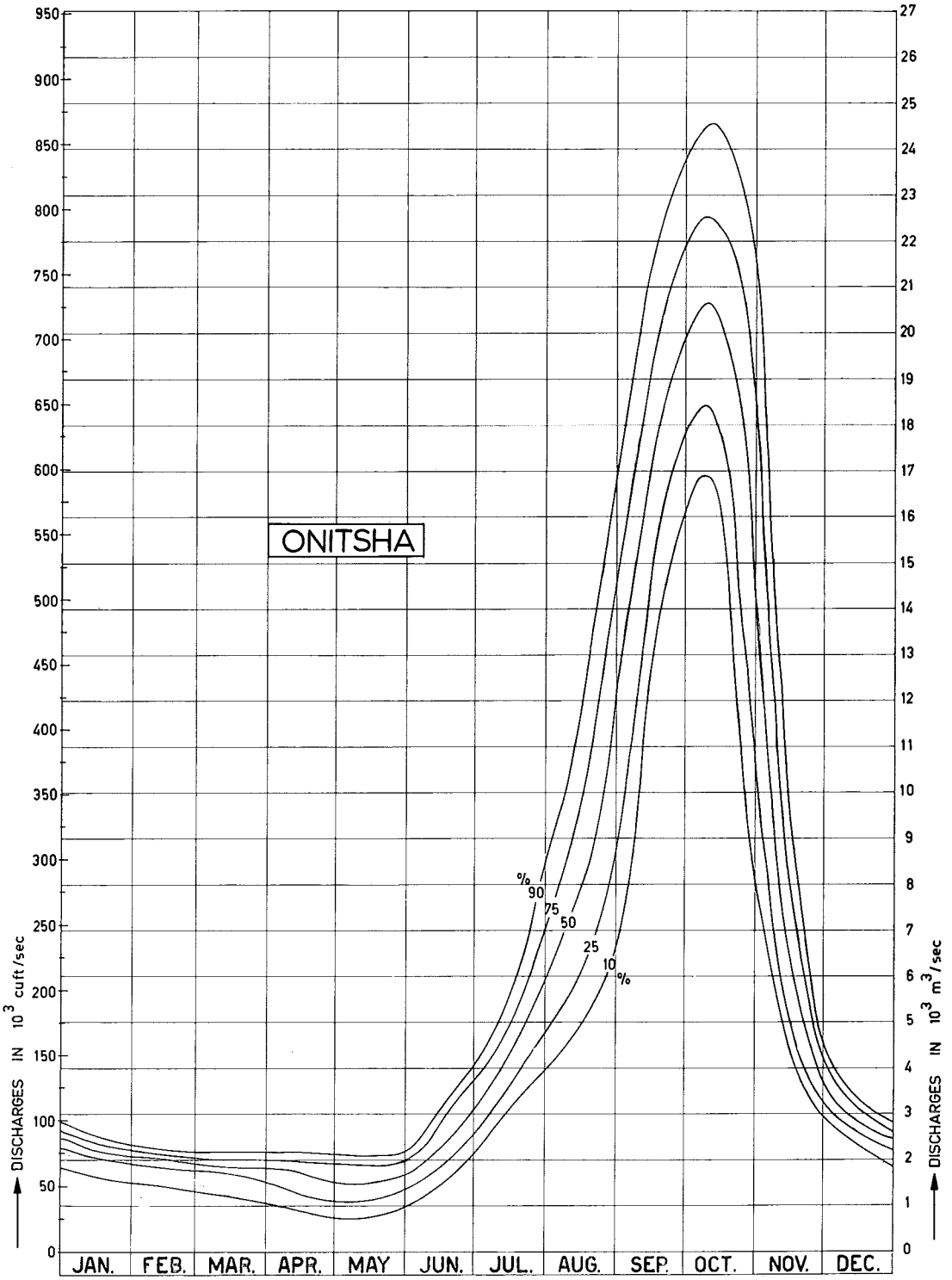


DIAGRAM 4.3.4-5

Frequencies of discharges at Onitsha (Niger) for a fixed day

and the 90% curve. In the middle of October discharges have been extremely high. On the other hand, discharges during 1956 have been rather small, except during the second half of September and the middle of October.

Also at Makurdi (Diagram 14) discharges during 1955 have been high and those during 1956 rather low. During the latter year, discharges oscillate between the 50% and the 10% lines during August and September; during October they are between the 50% and the 75% lines; and in November they follow the 50% curve. It is not by accident that in both 1955 and 1956 the November hydrographs are practically parallel to the frequency curves. As will be explained in 4.3.7, discharges during the fall on successive days are closely correlated, and this finds its expression in the frequency curves as well. It is, however, not very well seen on the Yola hydrographs, as these have been disturbed by high peaks occurring after the fall had already started (an effect analogous to that illustrated in Diagram 4.3.7-1, examples of recession-curves).

For the Niger, the discharge hydrographs of Baro and of Lokoja for 1955 and 1956 have

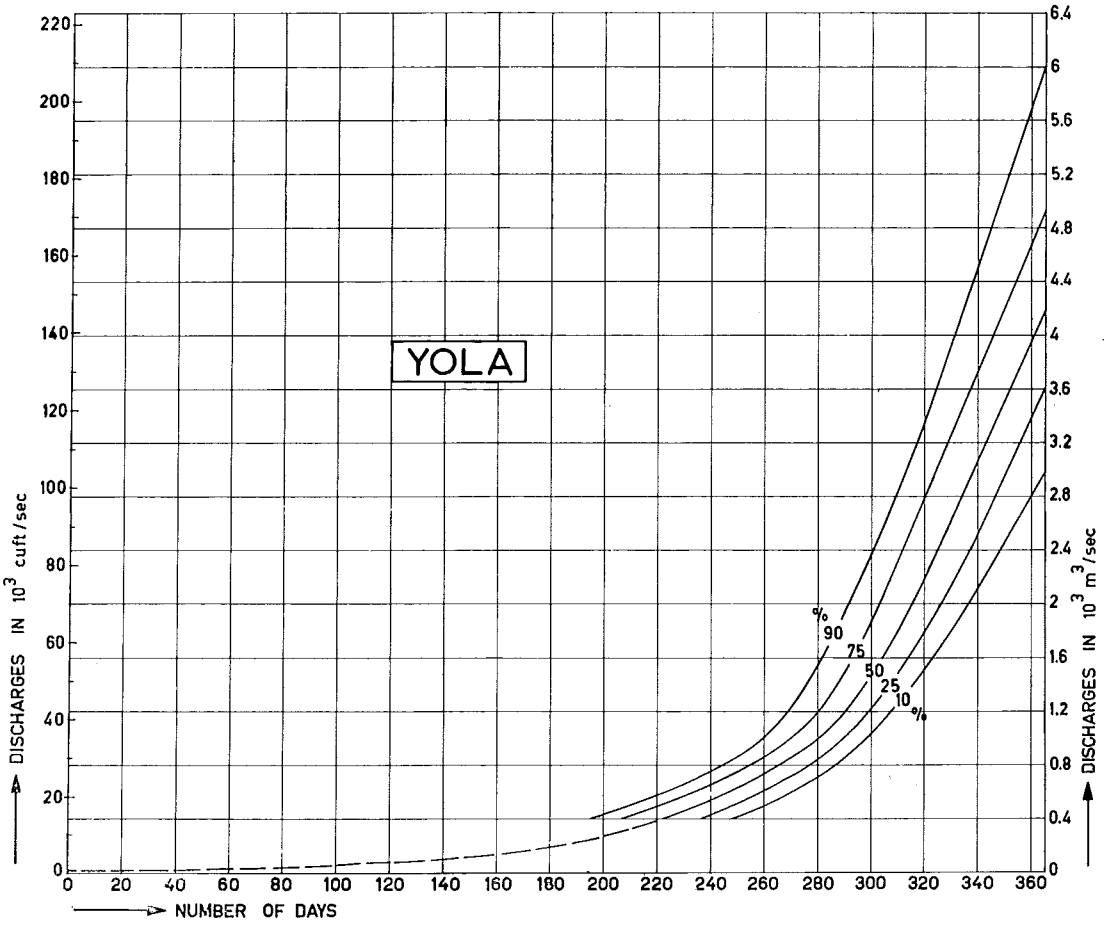


DIAGRAM 4.3.4-6

Duration curves of discharges at Yola (Benue)

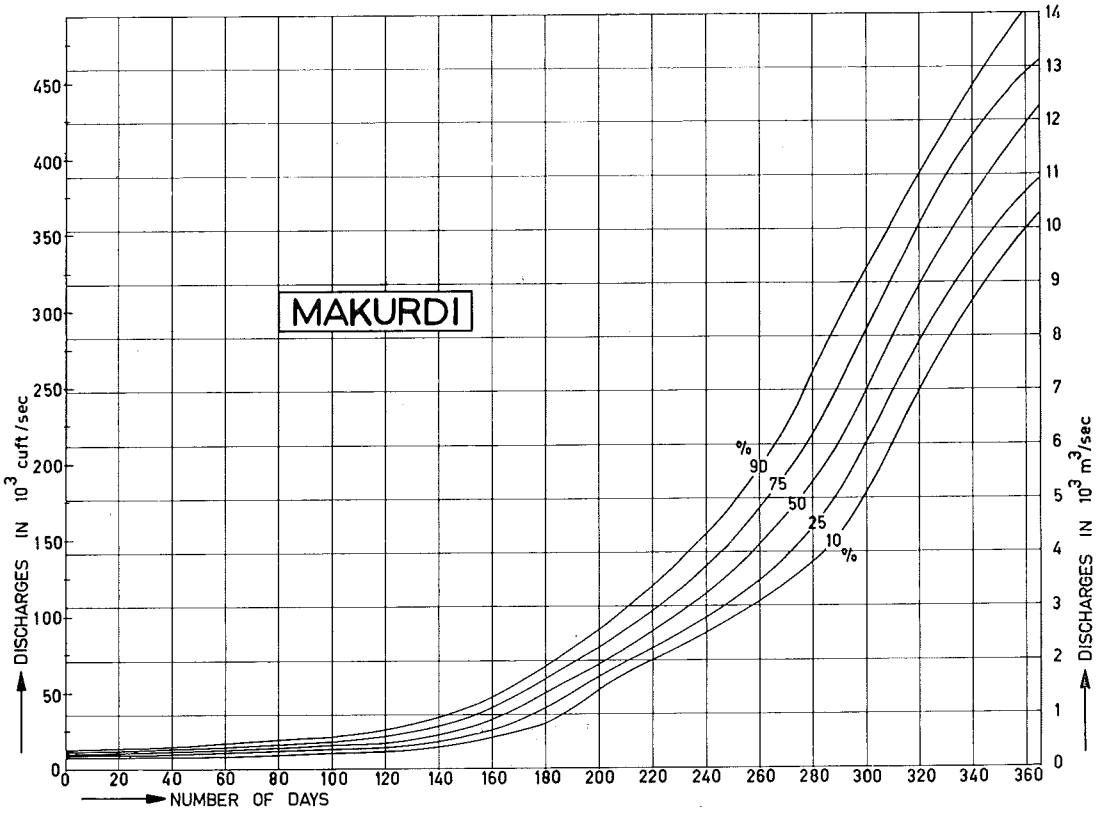


DIAGRAM 4.3.4-7

Duration curves of discharges at Makurdi (Benue)

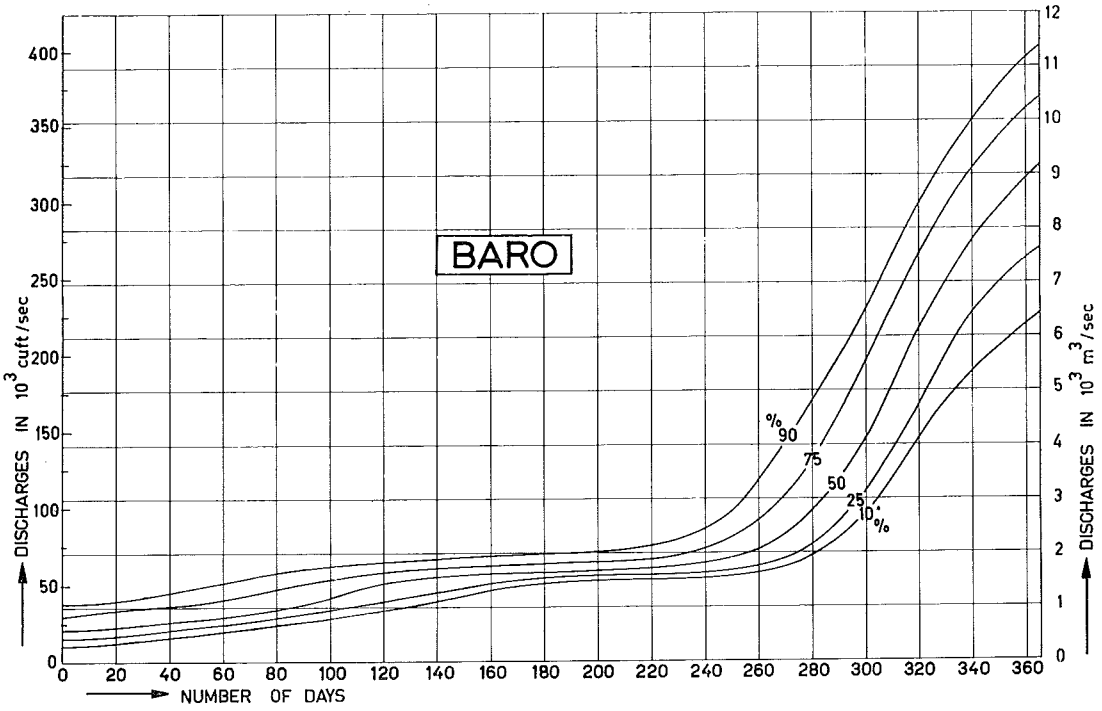


DIAGRAM 4.3.4-8

Duration curves of discharges at Baro (Niger)

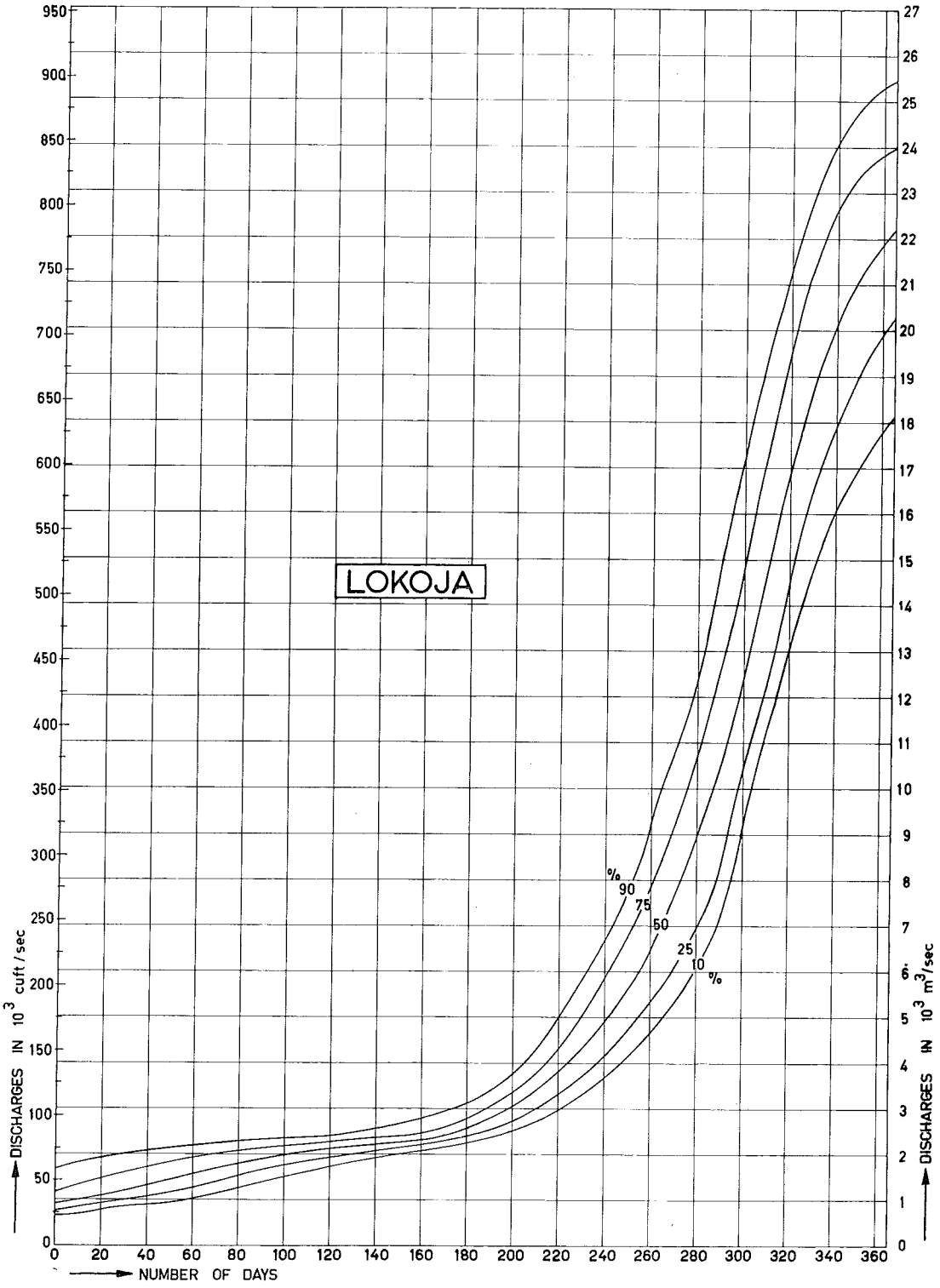


DIAGRAM 4.3.4-9

Duration curves of discharges at Lokoja (Niger)

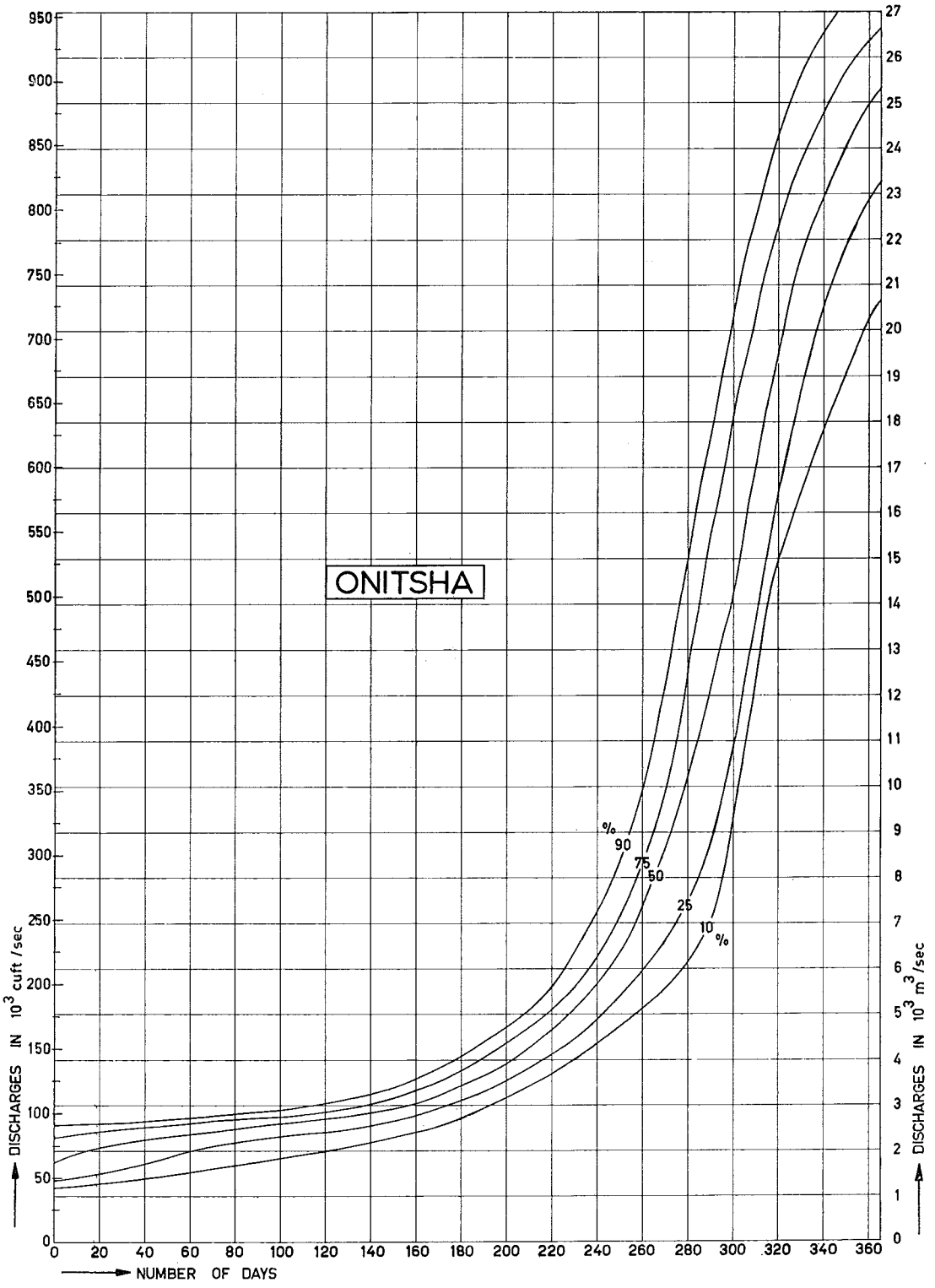


DIAGRAM 4.3.4-10

Duration curves of discharges at Onitsha (Niger)

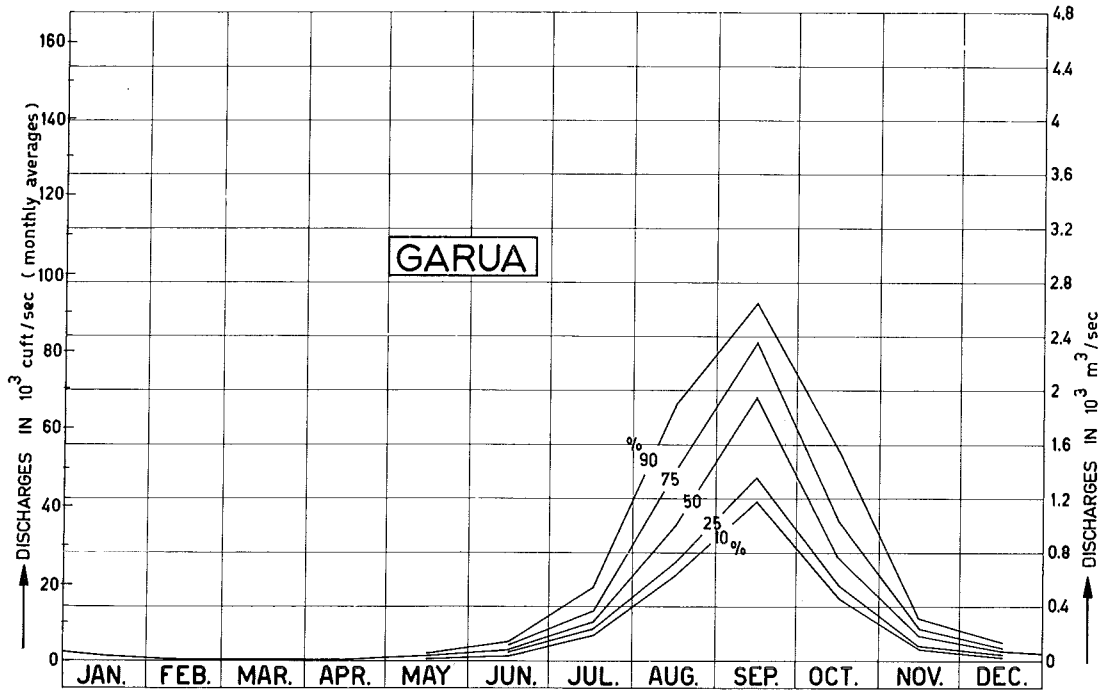


DIAGRAM 4.3.4-11

Frequencies of monthly discharges at Garua (Benue) for a fixed day

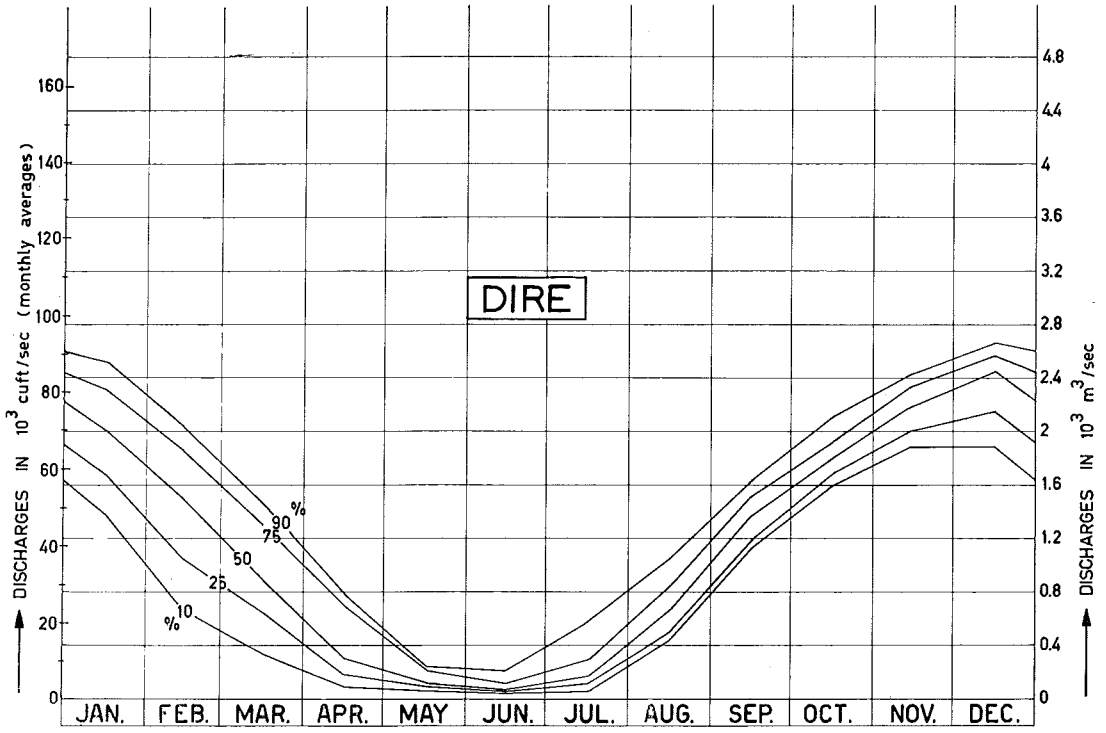


DIAGRAM 4.3.4-12

Frequencies of monthly discharges at Diré (Niger) for a fixed day

been drawn in Diagrams 4.3.4-15 and 4.3.4-16. Again it is seen that discharges in 1955 have been high and during 1956 low. The discharges in the beginning of 1956, however, were very high for the time of the year, but they originate in French West Africa, and form the Black Flood which is a result of the 1955 rains in French West Africa (see also 4.5.4). During the fall of the river, in October and November, the hydrographs follow again the frequency curves.

Diagrams 4.3.4-13 to 16 illustrate well the differences which can be expected between frequencies of discharges computed from a long record and discharges as occurring in individual years. In particular, it should be stressed that there is only little correlation between the discharges at a certain moment and those several weeks later. An extreme example, indeed, is given by the 1956 Benue discharges which early in September were still below the 10% frequency curve but rose to above the 90% frequency at the end of September (Yola) or to the 75% frequency (Makurdi). In general it can be stated that a late rise need not promise a late or an early fall of the discharges, or a low maximum.

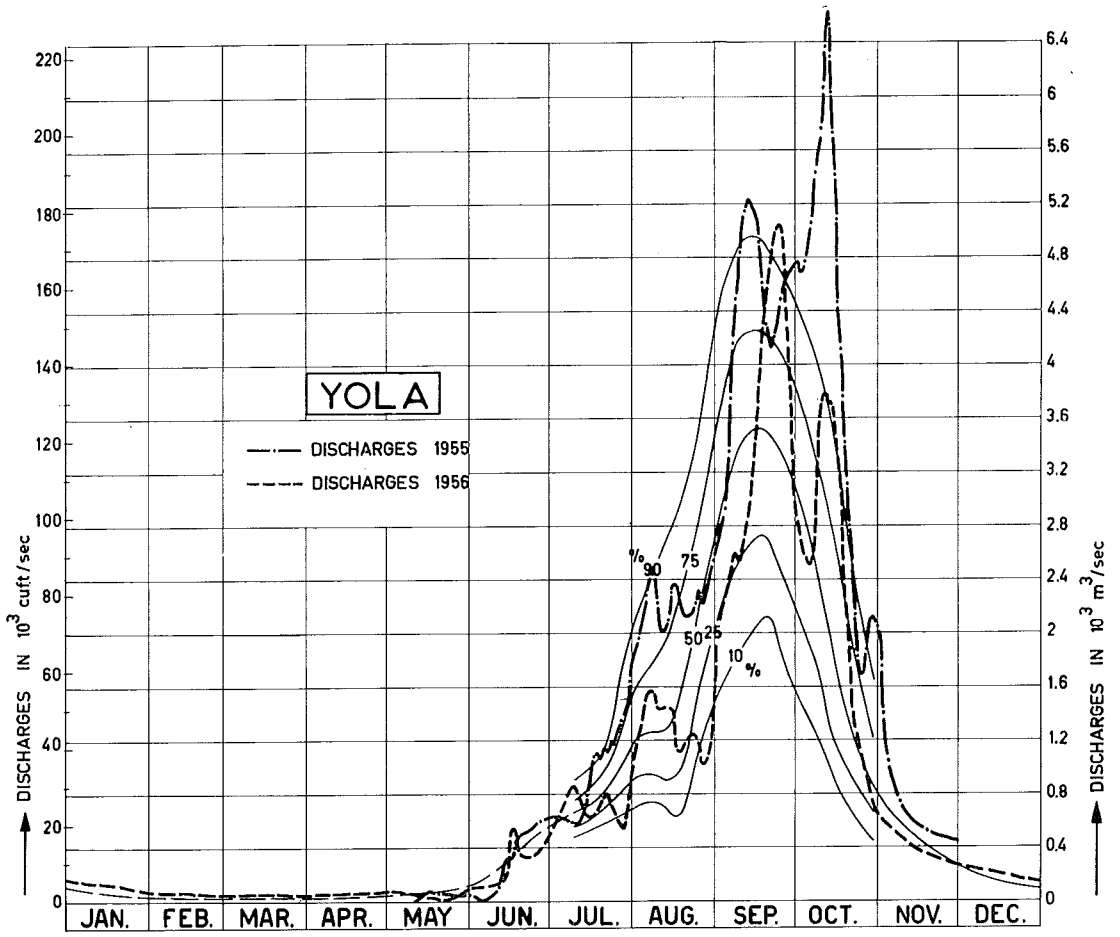


DIAGRAM 4.3.4-13

Discharge hydrographs at Yola (Benue) for 1955 and 1956 compared with discharge frequencies

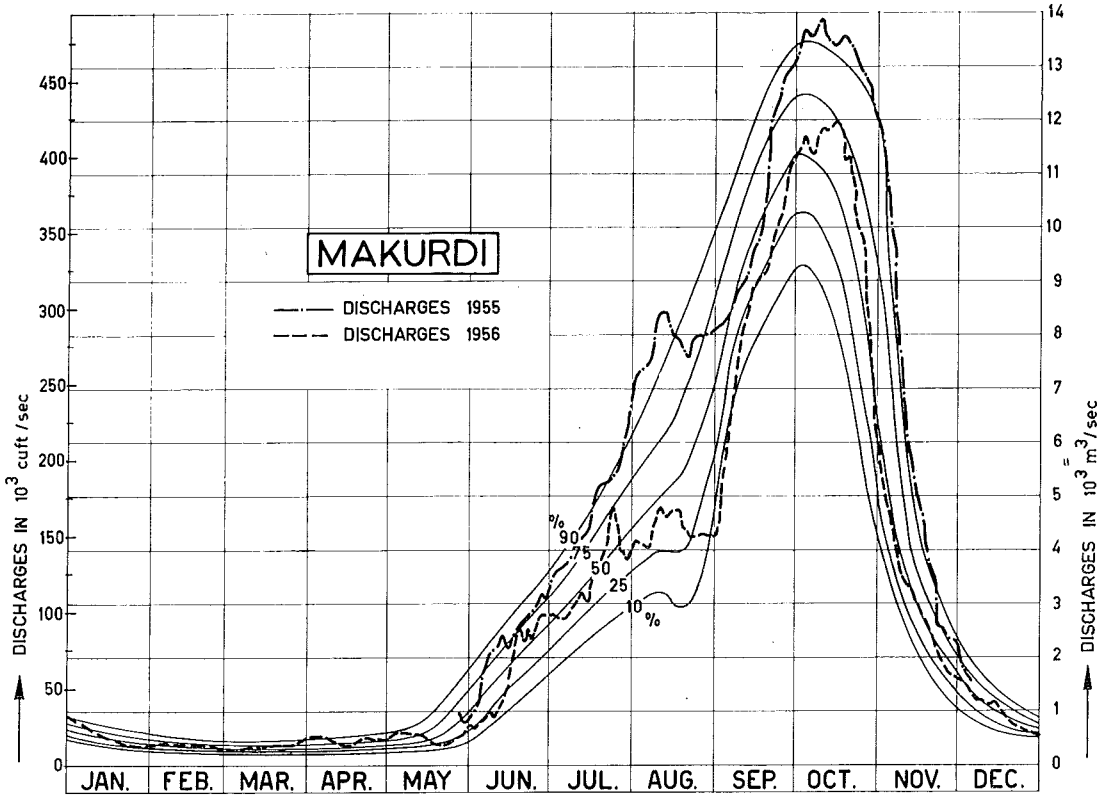


DIAGRAM 4.3.4-14

Discharge hydrographs at Makurdi (Benue) for 1955 and 1956 compared with discharge frequencies

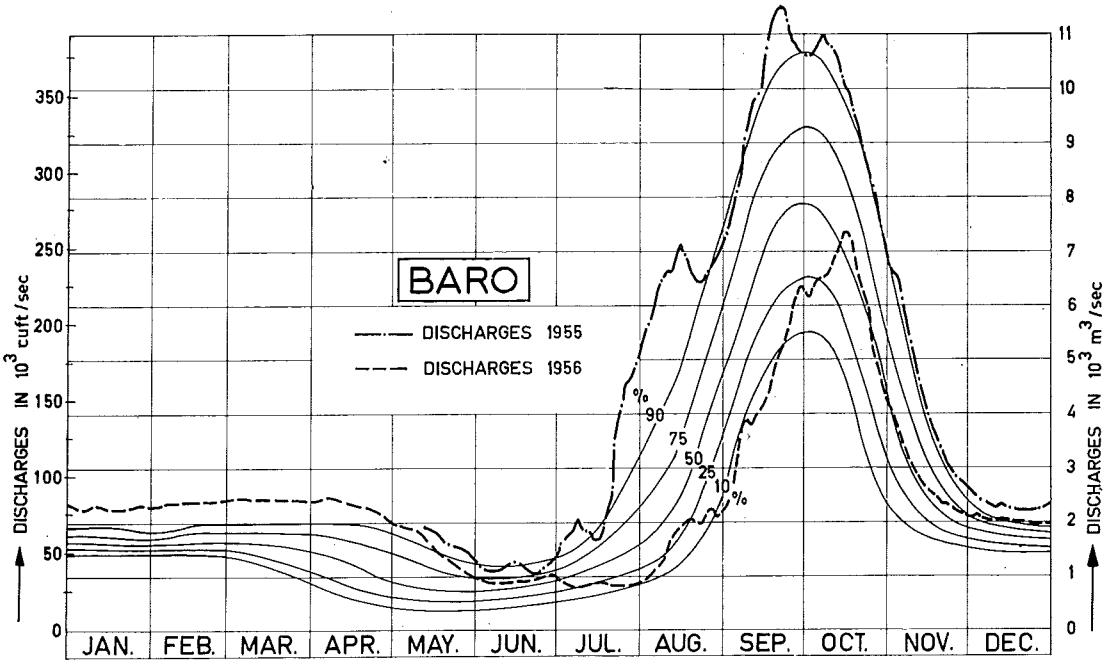


DIAGRAM 4.3.4-15

Discharge hydrographs at Baro (Niger) for 1955 and 1956 compared with discharge frequencies

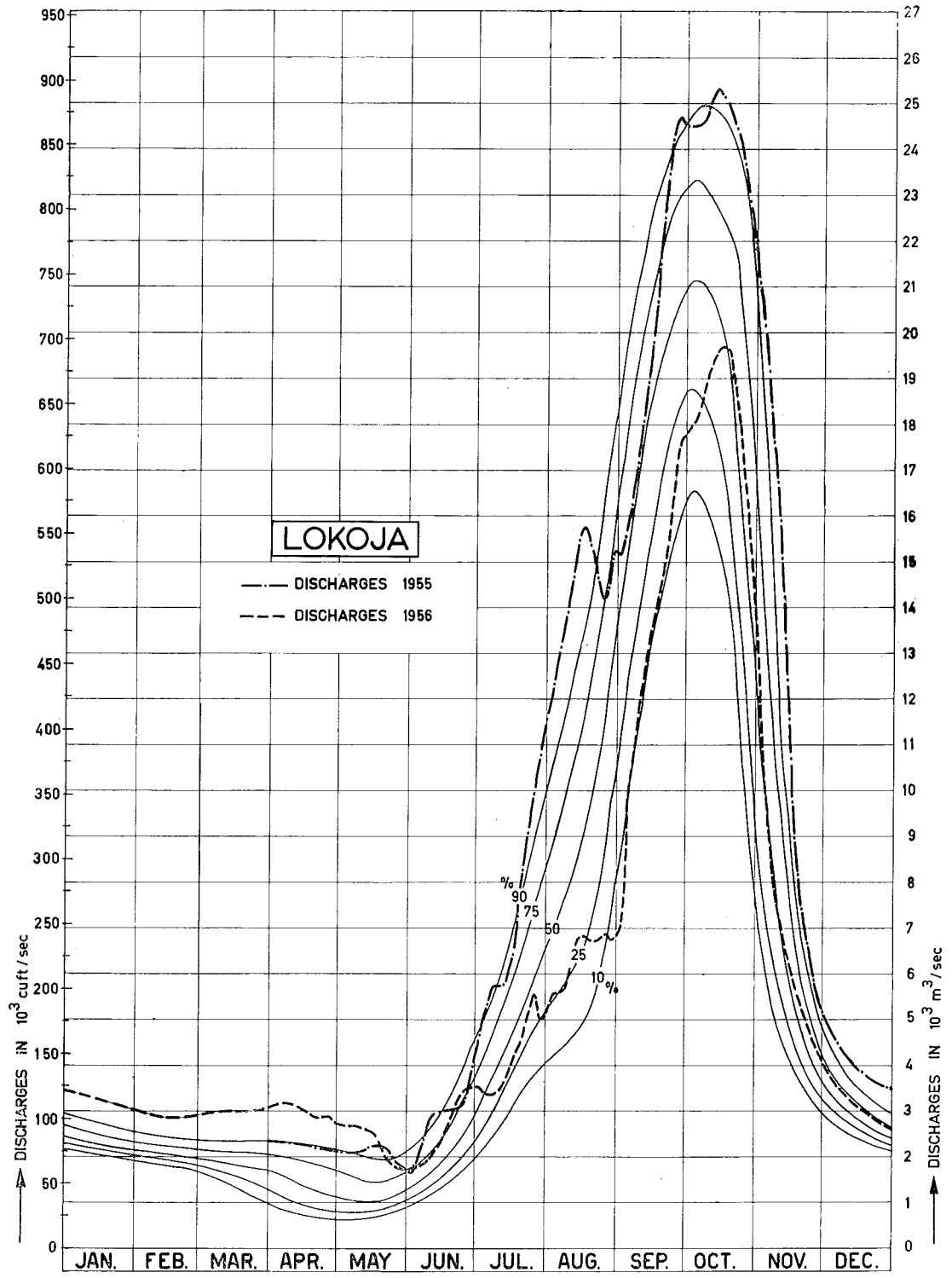


DIAGRAM 4.3.4-16

Discharge hydrographs at Lokoja (Niger) for 1955 and 1956 compared with discharge frequencies

4.3.5. Frequencies of annual discharges

Table 4.3.5-1 gives the yearly average discharges in m^3/sec and in cuft/sec at those stations along the Niger and the Benue of which a long record is available.

The discharges of the Niger at Diré are computed with the help of data received from the "Service Hydraulique", Bamako (French West Africa). The figures for the stations within Nigeria have been obtained by using the water-level records available (see 4.2.1 and 4.2.3) and the discharge rating curves established by NEDECO during 1955—1957. In 4.3.4 it has already been stated that the stage-discharge relation of a river at a certain place may change slowly because of scouring or aggrading of the river-bed. In preparing the figures of the Table it has been supposed that there has been no change in this relation during the period of record.

Table 4.3.5-2 shows the averages over the period of record of some of the stations. No figure has been computed for Jebba as the period of record is rather short. For Onitsha no record-average has been computed because the record shows a gap of several years and the data before 1925 are considered to be suspect.

TABLE 4.3.5-2

AVERAGE DISCHARGES

RIVER	STATION	PERIOD	AVERAGE DISCHARGE	
			m^3/sec	10^3 cuft/sec
Niger	Diré	1924/25—1926/27 1928/29—1947/48 1949/50—1956/57	1,115	39.4
Niger	Baro	1915/16—1956/57	2,525	89
Benue	Yola	1934/35—1957/58	740	26
Benue	Makurdi	1932/33—1957/58	3,150	111
Niger	Lokoja	1915/16—1957/58	6,100	215

The data of Table 1 are chronologically plotted on Diagram 4.3.5-3. It is seen that there is a general trend for the discharges to increase after 1945, not only for Diré and Baro which is situated downstream of Diré, but also for the Benue at Makurdi. Between 1925 and 1945 the general trend has been a decrease of the yearly discharges. The period of records is, however, not long enough to speak of a cycle.

On Diagram 4.3.5-4 successive averages of yearly average discharges are plotted against the last year of the period over which the average is computed. For example: the first year over which a record for Baro is known is 1915, so against 1915 is plotted the average discharge of that year, viz., 2,490 m^3/sec; against 1916 the average discharge of 1915 and 1916 is plotted; against 1917 the average discharge of the period 1915, 1916, and 1917; etc.

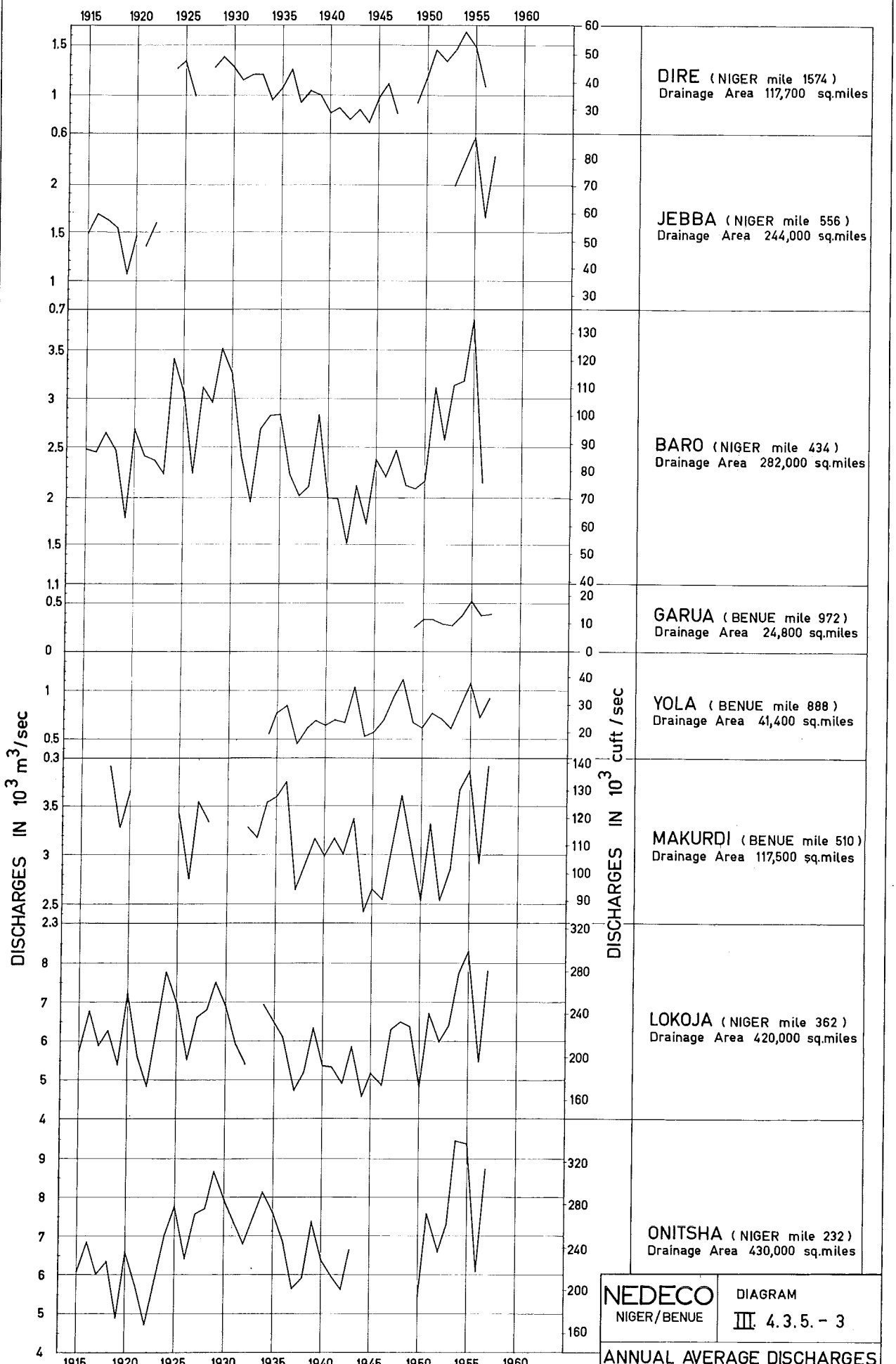
It is seen that after some years the difference between the average of these years and the figure obtained for the whole period of record (the last figure plotted against 1956 or 1957) already becomes rather small. Parallel to the time axis two lines are drawn which deviate + 10 and — 10 % from the ultimate average.

TABLE 4.3.5-1

AVERAGE YEARLY DISCHARGES

	DIRE (2		JEBBA (2		BARO (2		YOLA (1		MAKURDI (3		LOKOJA (1		ONITSHA (1	
	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec	m^3/sec	10^3 cuft/sec
1914/15	—	—	—	—	—	—	—	—	1,910	67.4	—	—	—	—
15/16	—	—	1,485	52.4	2,490	87.9	—	—	2,630	92.9	5,730	202.2	6,080 (4	214.6 (4
16/17	—	—	1,680	59.3	2,460	86.8	—	—	—	—	6,770	239.0	6,860 (4	242.2 (4
17/18	—	—	1,630	57.5	2,660	93.9	—	—	—	—	5,890	207.9	6,030 (4	212.9 (4
18/19	—	—	1,545	54.5	2,480	87.5	—	—	3,920	138.2	6,290	222.0	6,370 (4	224.9 (4
19/20	—	—	1,065	37.6	1,780	62.8	—	—	3,290	116.1	5,410	191.0	4,890 (4	172.6 (4
1920/21	—	—	1,480	52.2	2,700	95.3	—	—	3,670	129.4	7,260	256.3	6,630 (4	234.0 (4
21/22	—	—	1,365	48.2	2,420	85.4	—	—	—	—	5,610	198.0	5,800 (4	204.7 (4
22/23	—	—	1,610	56.8	2,380	84.0	—	—	—	—	4,840	170.9	4,710 (4	166.3 (4
23/24	—	—	—	—	2,240	79.1	—	—	—	—	6,430	227.0	5,790 (4	104.4 (4
24/25	1,260	44.5	—	—	3,420	120.7	—	—	—	—	7,780	274.6	7,100 (4	250.6 (4
25/26	1,340	47.3	—	—	3,070	108.4	—	—	3,420	120.7	6,990	246.7	7,790	275.0
26/27	980	34.6	—	—	2,220	78.4	—	—	2,760	97.4	5,510	194.5	6,440	227.3
27/28	—	—	—	—	3,140	110.8	—	—	3,650	125.2	6,650	234.7	7,590	267.9
28/29	1,270	44.8	—	—	2,980	105.2	—	—	3,350	118.2	6,820	240.7	7,710	272.2
29/30	1,380	48.7	—	—	3,520	124.3	—	—	—	—	7,540	266.2	8,670	306.1
1930/31	1,280	45.2	—	—	3,280	115.8	—	—	—	—	6,880	242.9	8,050	284.2
31/32	1,145	40.4	—	—	2,440	86.1	—	—	—	—	5,940	209.7	7,490	264.4
32/33	1,200	42.3	—	—	1,950	68.8	—	—	3,290	116.1	5,410	191.0	6,830	241.1
33/34	1,205	42.6	—	—	2,790	95.3	—	—	3,190	112.7	4,920 (4	173.7 (4	7,560	266.9
34/35	940	33.2	—	—	2,840	100.3	545	19.2	3,550	125.2	6,950	245.3	8,160	288.0
35/36	1,060	37.4	—	—	2,850	100.6	760	26.8	3,610	127.2	6,540	230.9	7,610	268.6
36/37	1,270	44.8	—	—	2,240	79.1	840	29.7	3,760	132.7	6,080	214.6	6,790	239.7
37/38	915	32.3	—	—	2,020	72.0	450	15.9	2,650	93.5	4,740	167.3	5,620	198.4
38/39	1,040	36.7	—	—	2,120	74.8	610	21.5	2,940	103.8	5,170	182.5	5,900	208.3
39/40	1,000	35.3	—	—	2,840	100.3	685	24.2	3,170	111.9	6,390	225.6	7,360	259.8
1940/41	810	28.6	—	—	2,000	70.6	645	22.8	2,990	105.6	5,350	188.9	6,380	225.2
41/42	860	30.35	—	—	1,990	70.3	695	24.5	3,180	112.2	5,310	187.4	5,960	210.4
42/43	740	26.1	—	—	1,520	53.6	670	23.7	3,010	106.3	4,910	173.3	5,630	198.7
43/44	840	29.65	—	—	2,140	75.6	1,030	36.4	3,380	119.3	5,860	206.9	6,630	234.0
44/45	712	25.15	—	—	1,730	61.0	515	18.2	2,420	85.4	4,560	161.0	—	—
45/46	960	33.9	—	—	2,390	84.4	575	20.3	2,660	93.9	5,200	183.6	—	—
46/47	1,110	39.2	—	—	2,220	78.4	695	24.5	2,550	90.0	4,870	171.9	—	—
47/48	795	28.05	—	—	2,480	87.5	925	32.7	3,110	109.8	6,300	222.4	—	—
48/49	—	—	1,460	51.5	2,110	74.5	1,110	39.2	3,620	127.8	6,500	229.5	—	—
49/50	904	31.9	—	—	2,090	73.8	680	24.0	3,130	110.4	5,890	207.9	—	—
1950/51	1,160	40.9	—	—	2,160	76.2	615	21.7	2,540	89.6	4,810	169.8	5,420	191.3
51/52	1,450	51.2	—	—	3,110	109.8	770	27.2	3,310	117.0	6,720	237.2	7,560	266.9
52/53	1,340	47.3	—	—	2,580	91.1	715	25.2	2,530	89.3	5,950	210.0	6,450	227.7
53/54	1,450	51.2	1,990	70.2	3,160	111.5	610	21.5	2,860	100.9	6,400	225.9	7,280	257.0
54/55	1,640	57.9	2,240	79.1	3,200	113.0	845	29.8	3,690	130.2	7,720	272.5	9,460	333.9
55/56	1,500	52.9	2,485	87.7	3,830	135.2	1,070	37.8	3,880	137.0	8,300	293.0	9,400	331.8
56/57	1,070	37.8	1,615	57.0	2,140	75.6	725	25.6	2,920	103.1	5,470	193.1	6,090	215.0
57/58	—	—	2,285	80.7	—	—	915	32.3	3,910	138.0	7,800	275.3	8,730	308.2

(1 1 Jan.—1 Jan.
(2 1 June—1 June
(3 1 April—1 April
(4 probably not correct



NEDECO
NIGER/BENUE

DIAGRAM
III. 4.3.5. - 3

ANNUAL AVERAGE DISCHARGES
NIGER-BENUE

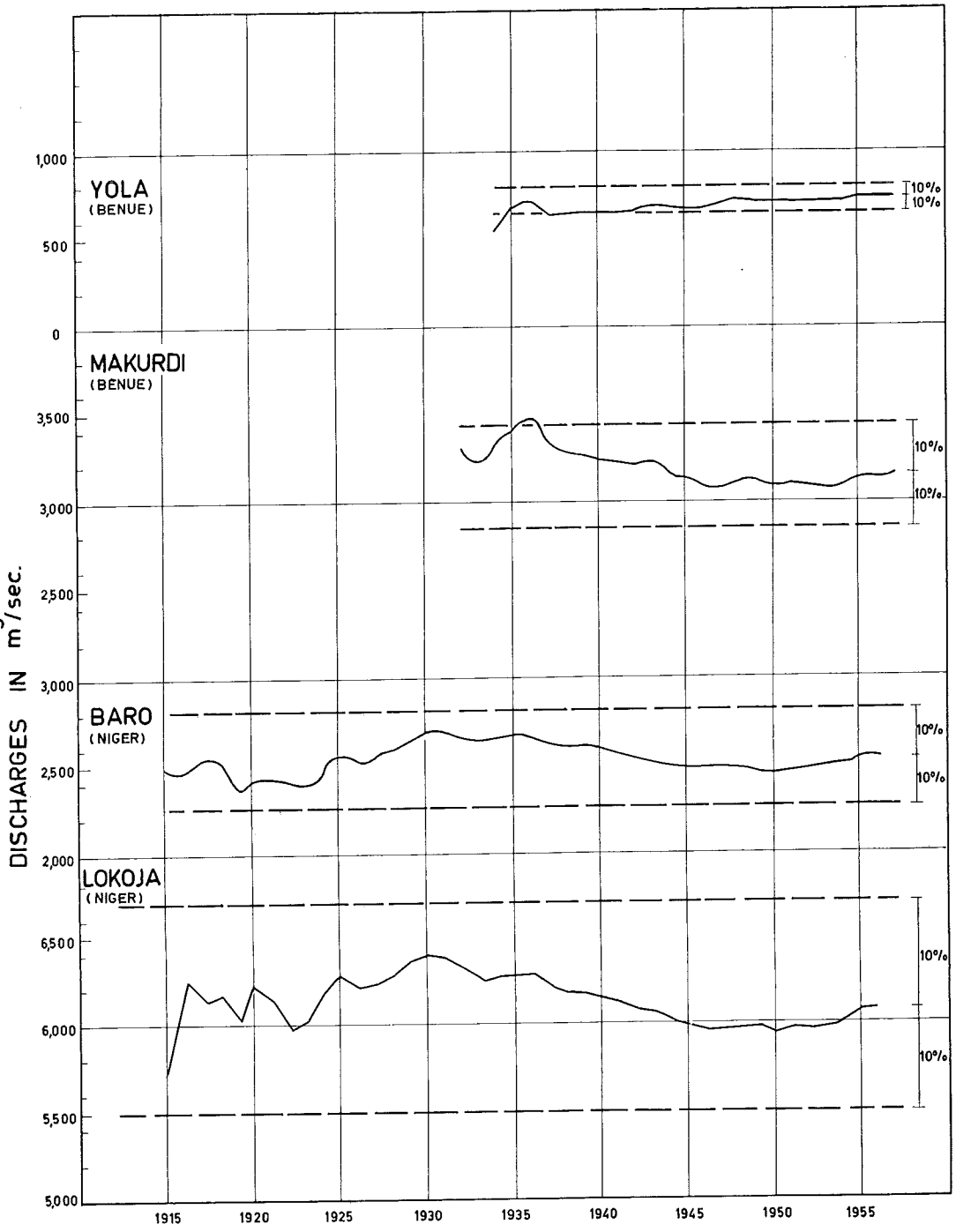


DIAGRAM 4.3.5-4

Successive averages of yearly average discharges

If it is allowed to neglect the change in the stage-discharge relation since 1915, it is concluded from the above that the average of the record available is a fair estimate of the "true" average, barring climatic changes. From Diagram 3, however, it is seen that the discharge of individual years may deviate considerably from the long-run average. To get a clear picture of this deviation, the frequencies of yearly average discharges are plotted on probability paper, of which the discharge axis has a logarithmic scale (Diagrams 4.3.5-5 and -6). As a measure of the variation can be taken $\frac{R_{25} - R_{75}}{R_{50}}$, in which R_{25} is the yearly discharge which is surpassed by 25 % of the years of record. The value of this variation for Yola is 33 %, for Makurdi 22 %. For Baro this figure is 31 % and for Lokoja 24 %.

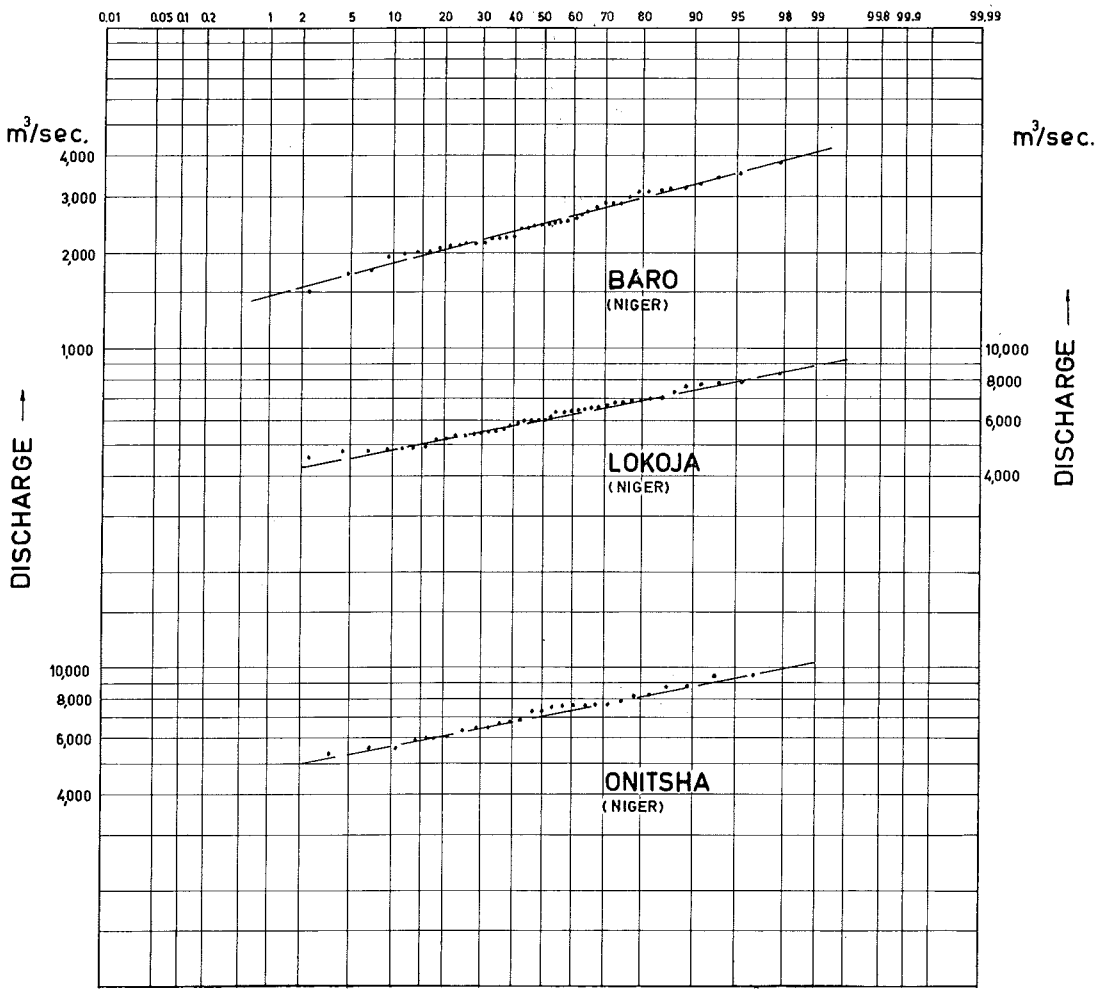


DIAGRAM 4.3.5-5

Frequencies of yearly average discharges along the Niger

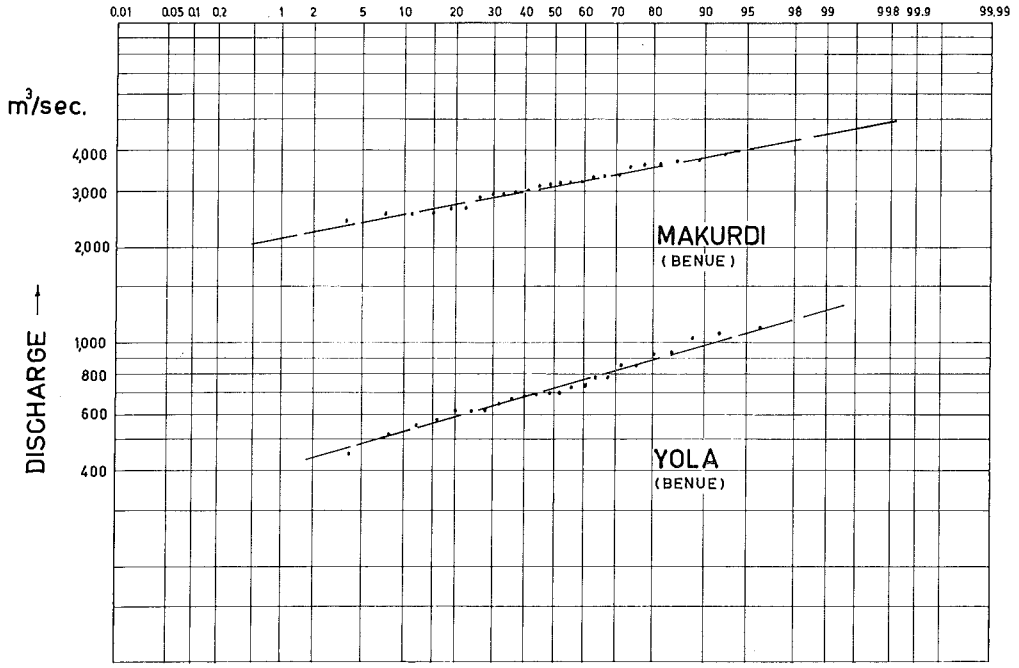


DIAGRAM 4.3.5-6

Frequencies of yearly average discharges along the Benue

4.3.6. Comparison of average and specific discharges

To illustrate the contributions of the various parts of the Niger and Benue Basin to the discharge of these two rivers, Diagrams 4.3.6-1 and 4.3.6-2 have been constructed.

In these diagrams ratios of monthly discharges of tributaries to monthly discharges of the main river are shown, as well as ratios of monthly discharges at stations situated upstream along the main rivers to monthly discharges at stations situated more downstream. Similar ratios are given for yearly discharges. The data available concern the years 1955, 1956 and 1957; they are not complete, but where possible an estimate has been made to fill the gap in the readings. When the gap in the gauge readings has been more than 10 days, no monthly figure is used; but when there were less than 10 days without a reading, the water-level readings have been estimated by the assumption of a shape of the hydrograph more or less analogous to that of a station upstream or downstream. Estimated values are shown in a dotted line in the graph.

As for Diagram 4.3.6-1, the upper two graphs show that both the Benue at Garua and the Faro at Safaie contribute about 50 % of the yearly discharge of the Benue at Wuro Boki, although it is seen that in September a greater part of the Wuro Boki discharge is flowing along Garua than along Safaie, whilst early in the season most of the flow is arriving from the Faro. This can be explained by noting that rains start earlier over the Faro Basin than over the Benue Basin above Garua. The higher rainfall and the greater run-off coefficient compensates the smaller drainage area of the Faro (see 4.5.3).

The third graph shows that the Gongola contributes only a small part of the Benue discharge at Numan.

The lower three graphs show that early in the season the contribution to the discharge of the lower part of the Benue of the tributaries coming from the Cameroon Mountains (Taraba,

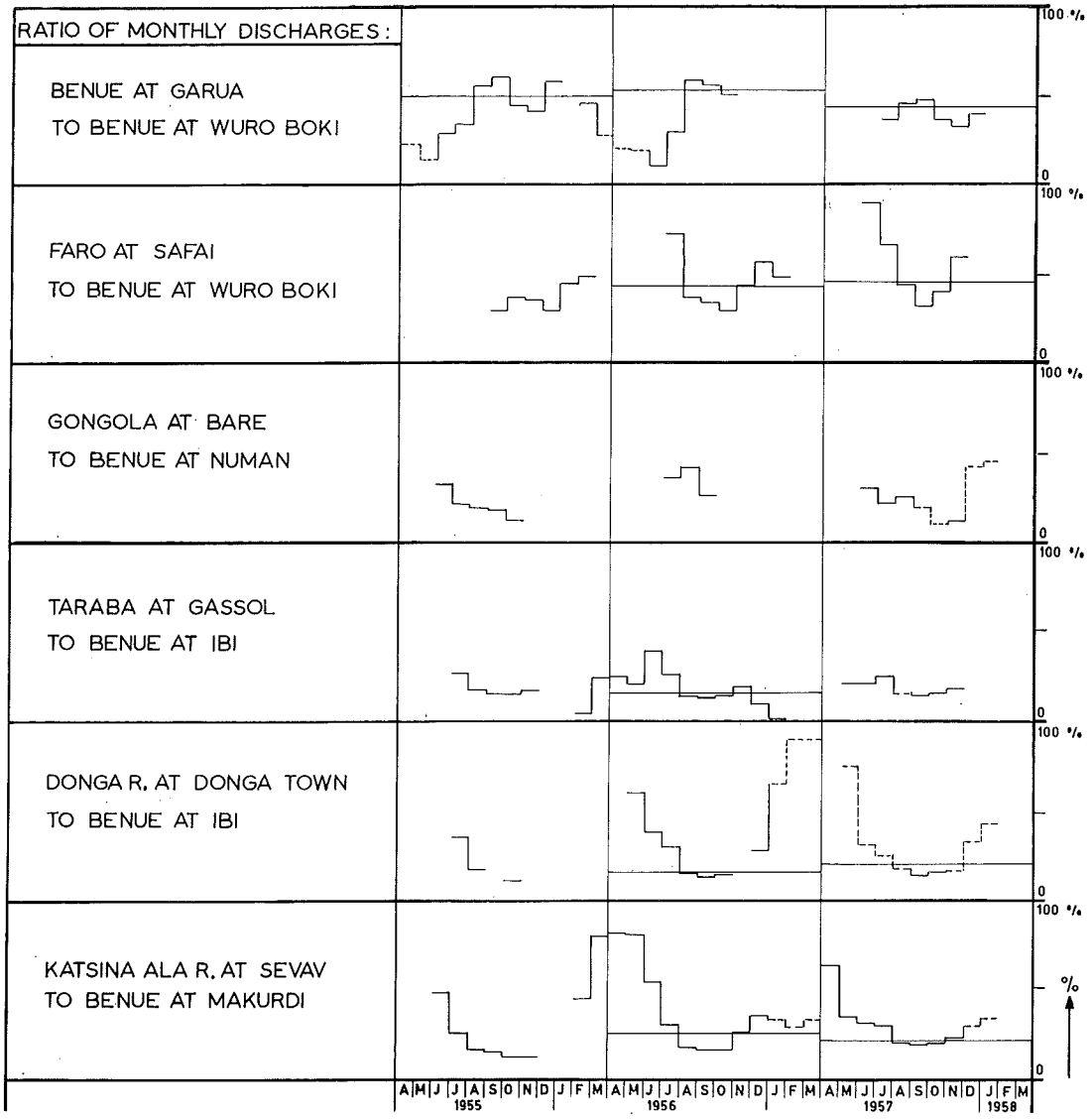


DIAGRAM 4.3.6-1

Ratios of monthly and yearly discharges of Benue tributaries to those of the Benue

Donga and Katsina Ala) is relatively important. This is caused by the earlier starting of the rains over these mountains. In 1956 the Taraba and the Donga contributed together about 15 % of the Benue discharge at Ibi. The Katsina Ala contributes annually 20 to 25 % of the water passing Makurdi, but in the middle of the dry season (December and January) 30 % of the Makurdi discharge arrives from the Katsina Ala.

Regarding Diagram 4.3.6-2, the upper graph shows that the water yearly flowing along Yola at the Benue is not more than about 25 % of the discharge passing Makurdi. The percentages for the month of September is at a maximum about 35 %. For Angwan Taru and for Ibi these figures become respectively about 40 % maximum 55 %, and 70 % maximum 75 %. Hence,

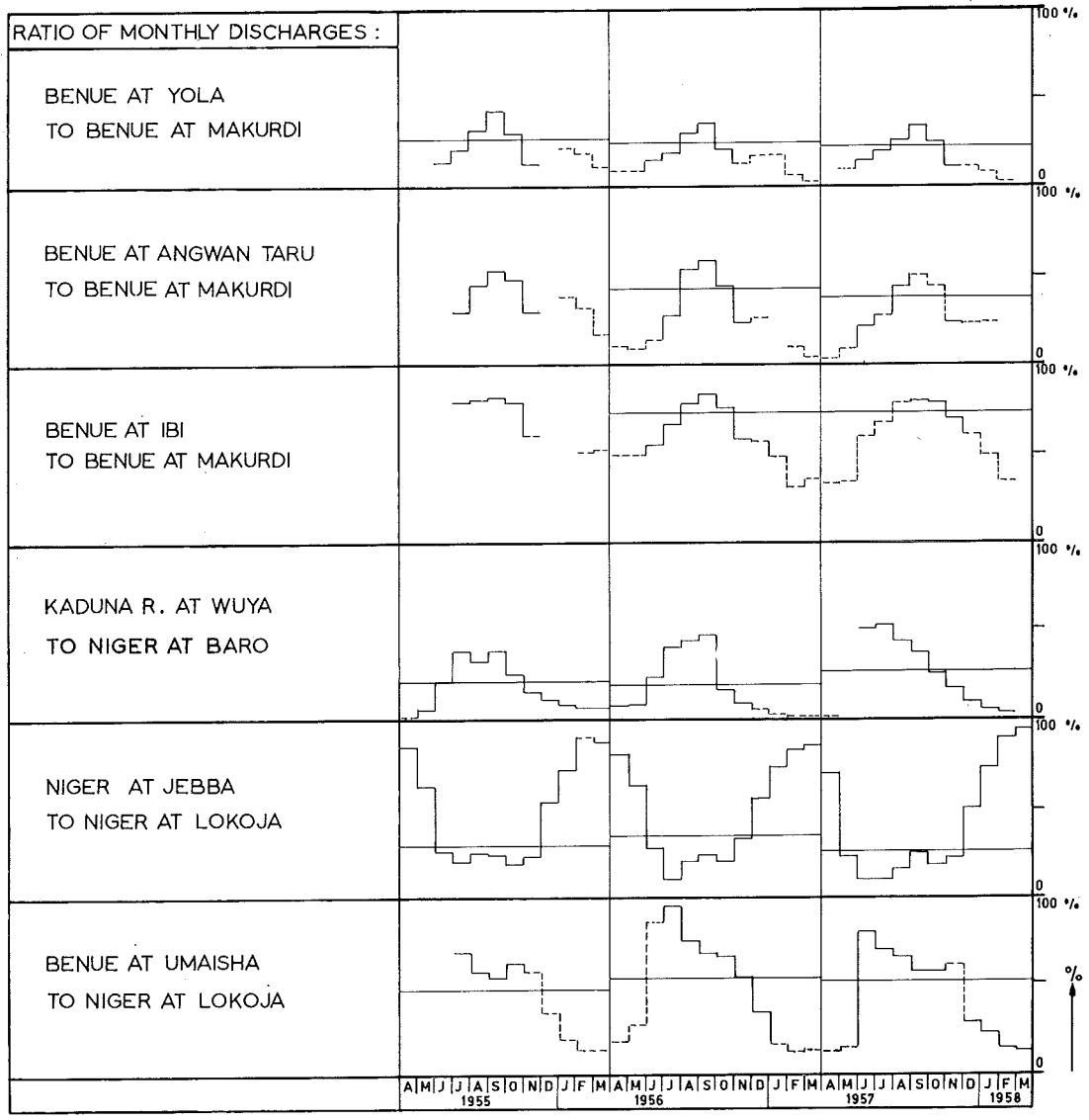


DIAGRAM 4.3.6-2

Ratios of monthly and yearly discharges along Niger and Benue

although during the height of the rainy-season precipitation over the Katsina Ala Basin remains greater than over the remainder of the Benue Basin, the total run-off contributed to the Benue by the latter part becomes then, because of its size, about three times as great as the run-off from the Katsina Ala Basin.

The fourth graph from the top of Diagram 4.3.6-2 shows that the yearly contribution of the Kaduna River to the discharge of the Niger at Baro is comparatively large, viz., about 20 %. This is rather high, taking into account that the area drained by the Kaduna is less than 10 % of the drainage area of the Niger above Baro. The Kaduna River is draining a part of the Jos Plateau which is receiving rain earlier than the remaining part of the Niger Basin between Niamey and Baro. As is explained in 2.3.1 and 4.2.2, rain over the western drainage area of the Niger

(above Tosay) does not affect water-levels at Baro during the wet season because of the very great time-lag. This explains why in July and August the discharge of the Kaduna River becomes even 40 % of the Niger discharge at Baro (50 % in June, 1957).

The two bottom graphs of Diagram 4.3.6-2 show the ratio of the Niger discharge at Jebba to the Niger discharge at Lokoja, and the ratio of the Benue discharge at Umaisha to the Niger discharge at Lokoja (i.e., below the confluence of the Niger and Benue). As far as concerns the yearly figures, both ratios are just under or over 50 %. The seasonal variation of the monthly ratios, however, is considerable.

Early during the wet season, in June and July, discharge at Umaisha reaches to 80 to 85 % of the Niger discharge at Lokoja. It has already been seen that most of this flow arrives from the Cameroon Mountains via the Katsina Ala. In August, with the real onset of rains over the Niger Basin above Jebba, the ratio of the discharge at Jebba to that at Lokoja increases. After the end of the rainy season over Nigeria, the contribution of the Benue decreases more than that of the Niger at Jebba. During January, February, March and April, more than 70 % of the discharge at Lokoja has passed Jebba. This flow originates from the rainfall in the preceding wet season (June—October) over the western drainage area of the Niger in French West Africa and, as has already been pointed out, is called the Black Flood (see 4.2.2).

Run-off from different basins can be compared by computing the specific discharge which is defined as the run-off per unit of time per unit of area. It is mostly expressed in liters/sec/km^2 or cuft/sec/sq.mile.

Rainfall is generally more abundant in the neighbourhood of watersheds than in the centre of a river basin, because of the cooling of the air when forced upward (orographic rains). This, combined with a lower temperature which lessens the evaporation and with steeper surface slopes which give less opportunity to infiltration, will cause the specific discharge generally to be higher in a headwater area than in the adjacent plains.

Table 4.3.6-3 gives for a number of stations the average discharges for separate years and for periods of years, as well as the specific discharges. It should be noted, however, that the periods for which average figures are computed are not all equal.

Rivers of the Niger system in French West Africa with a rather high value of the specific discharge are: the Niger at Kouroussa (1.37 cuft/sec/sq.mile), the Niandan at Baro (1.92), and the Niger at Koulikoro (1.18).

No great value can be attached to the computed specific discharge of stations below Diré as the area of the drainage basin is rather vague.

Tributaries of the Benue with a high specific discharge are: the Faro at Safaie (1.26), the Taraba, the Donga and the Katsina Ala. For the year 1956 the specific discharges of these three last-mentioned rivers have been respectively 1.53, 2.92, and 4.03 cuft/sec/sq.mile. The measuring-station along the Taraba, Gassol, however, is situated far away from the headwater area of this river. A comparison of the figures for 1957 shows that the specific discharges of the Katsina Ala Basin is greater than that of the Donga Basin which, in its turn, exceeds the figure of the Taraba Basin above Beli, which is situated in the foot-hills of the Adamawa Mountains. This decrease of specific discharge from the Katsina Ala to the Taraba is caused not only by a decrease of rainfall to the north but also by a decrease in run-off coefficients (see 4.5.3).

The Gongola at Bare shows a very low specific discharge. Both the rainfall over this basin and the run-off coefficient are low.

Considering the figures of the specific discharges for the very rainy year 1957 when going along the Benue from Garua downstream, the effect of important tributaries is apparent. At Garua the value of the figure is 0.56 cuft/sec/sq.mile, but at Yola the value is 0.77. This is caused

TABLE 4.3.6-3

SPECIFIC DISCHARGES

RIVER	STATION	DRAINAGE AREA sq. miles [1]	AVERAGES					YEARLY AVERAGE DISCHARGE cuft/sec				YEARLY SPECIFIC DISCHARGE cuft/sec/sq.mile			
			Discharge		Specific Discharge		Period	1954—55 [3]	1955—56 [3]	1956—57 [3]	1957	1954—55 [3]	1955—56 [3]	1956—57 [3]	1957
			m^3/sec	cuft/sec	l/sec/km^2	cuft/sec./sq. mile [2]									
Niger	Kouroussa [4]	7,000	270	9,550	15.0	1.37	1923—1955	10,000	—	—	—	1.44	—	—	—
Niandan	Baro [4]	4,950	270	9,450	21.0	1.92	1947—1955	11,100	—	—	—	2.27	—	—	—
Niger	Koulikoro [4]	47,000	1,550	54,600	12.9	1.18	1908—1955	74,300	—	—	—	1.58	—	—	—
Bani	Douna [4]	39,650	830	29,400	8.1	0.74	1950—1955	32,500	—	—	—	0.82	—	—	—
Niger	Mopti [4]	108,500	1,120	39,200	4.0	0.37	1915—1955	49,500	—	—	—	0.46	—	—	—
,,	Dire [4]	117,700	1,095	38,600	3.3	0.30	1924—1955	44,800	49 500	35,300	—	0.38	0.42	0.30	—
,,	Malanville [4]	170,000	1,520	53,500	3.5	0.32	1952—1956	54,300	57,000	—	—	0.32	0.34	—	—
,,	Jebba	244,000	—	—	—	—	—	—	90,500	57,200	74,000	—	0.36	0.23	0.30
Kaduna	Wuya	25,300	755	26,600	11.5	1.05	1955—1957	—	32,300	15,000	33,000	—	1.25	0.59	1.31
Niger	Baro	282,000	2,525	89,000	3.4	0.31	1915—1957	112,500	135,000	75,500	124,000	0.40	0.48	0.27	0.43
,,	Lokoja	420,000	6,100	215,000	5.6	0.51	1915—1957	—	287,000	189,000	282,000	—	0.70	0.44	0.66
,,	Onitsha	430,000	—	—	—	—	—	—	340,000	208,000	314,000	—	0.77	0.48	0.72
Mayo Kebi	Cossi [4]	10,000	83	2,930	3.2	0.29	1950—1956	—	4,200	—	—	—	0.42	—	—
,, ,,	Famou [4]	11,600	84	2,960	2.8	0.25	1951—1952	—	—	—	—	—	—	—	—
Benue	Riao [4]	12,000	260	9,200	8.6	0.77	1950—1956	9,800	—	—	—	0.82	—	—	—
,,	Garua [4]	24,800	380	13,600	6.0	0.54	1930—1956	13,400	18,500	13,400	13,800	0.55	0.75	0.55	0.56
Faro	Safaie [4]	9,800	350	12,350	13.9	1.26	1950—1953	—	—	11,100	14,900	—	—	1.14	1.53
Benue	Yola	41,400	740	26,100	7.0	0.63	1934—1957	29,600	38,100	25,800	31,900	0.72	0.92	0.63	0.77
Gongola	Bare	21,500	—	—	—	—	—	—	—	—	8,700	—	—	—	0.38
Benue	Lau	69,600	—	—	—	—	—	—	—	38,200	49,500	—	—	0.55	0.71
,,	Angwan Taru	79,500	—	—	—	—	—	—	—	43,700	51,000	—	—	0.55	0.64
Taraba	Beli	4,200	—	—	—	—	—	—	—	—	14,500	—	—	—	3.48
,,	Gassol	8,240	—	—	—	—	—	—	—	12,700	18,700	—	—	1.53	2.25
Donga	Donga Town	4,600	—	—	—	—	—	—	—	13,400	19,200	—	—	2.92	4.19
Benue	Ibi	99,500	—	—	—	—	—	—	—	76,600	99,100	—	—	0.77	1.00
Katsina Ala	K'Ala Town	6,450	—	—	—	—	—	—	24,200	25,800	30,900	—	(3.75)	4.03	4.75
Benue	Makurdi	117,500	3,100	110,200	10.3	0.94	1934—1957	—	136,700	104,000	137,000	—	1.17	0.90	1.17
,,	Umaisha	128,860	—	—	—	—	—	—	—	109.000	—	—	—	0.87	—
,,	Yola-Makurdi	76,100	2,400	84,100	12.2	1.12	1934—1957	101,000	90,000	79,000	104,000	1.33	1.18	1.04	1.37

[1] 1 sq.mile = 2.59 km^2

[2] 1 cuft/sec/sq.mile = 11 liter/sec/km^2

[3] Hydrological year

[4] Data from „Annuaire hydrologique de la France d'Outre-Mer" published by the „Office de la Recherche Scientifique et Technique Outre-Mer", Paris.

by the Faro which flows into the Benue some miles above Yola. Towards Lau and Angwan Taru no affluents abounding with water enter the Benue, and consequently the specific discharge decreases (Angwan Taru: 0.64 cuft/sec/sq.mile). At Ibi the value has become 1.00, because of the inflow from the Taraba and the Donga. At Makurdi, below the Katsina Ala Confluence, the specific discharge has become 1.17 cuft/sec/sq.mile.

4.3.7. Recession curves

The part of the hydrograph after the crest of a flood wave has passed is called the recession curve (see Diagram 4.3.7-1a). River-stages fall because the amount of water entering the river decreases. This, in its turn, is caused by a decrease of rain.

Let it be supposed that the whole drainage basin above a certain point along the main river has been subject for a long time to a constant precipitation, equally distributed over the basin. Early in this period a great part of the rain has entered into the soil, and from there into the dry sub-soil. The remainder of the rain has flowed over the surface into the small water-courses and rivers which all join, either directly or indirectly, the main river. After some time the soil and the sub-soil become more or less saturated, and a smaller part of the rain will enter into these layers. As far as the elevation of these layers is higher than the water-level in adjacent streams, water will enter into the stream from these layers. The amount of flow will partly depend on the properties of the soil.

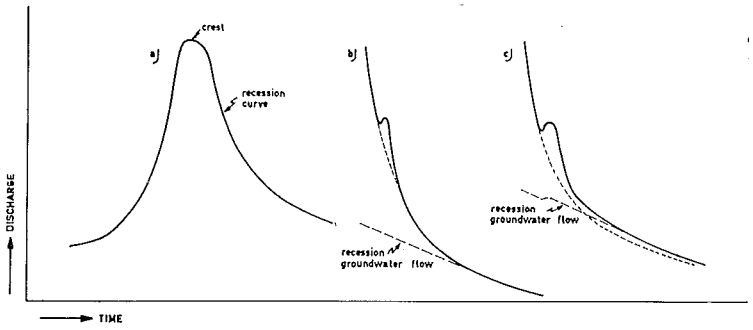


DIAGRAM 4.3.7-1

Examples of recession curves

After a certain time of constant precipitation, an equilibrium will be reached: the amount of water leaving the drainage basin per unit of time will equal the precipitation per unit of time (less evaporation from open-water surfaces and vegetation).

A certain amount of water will be stored in the basin. The water stored in the rivers is called the channel storage, whilst the water stored in the soil and sub-soil is called the ground-water storage. This storage has, as an effect, that when the rain stops suddenly, the discharge in the river at the lower end of the basin will not decrease to zero immediately, but the basin will empty itself gradually. Water-levels will fall slowly.

The shape of the recession curve depends on several factors, the most important of which are:

(i) the shape of the drainage basin;
(ii) the average slope of the basin;
(iii) the storage capacity of the rivers, and of the soil and sub-soil;
(iv) the permeability of the soil layers; and
(v) the state of the vegetation.

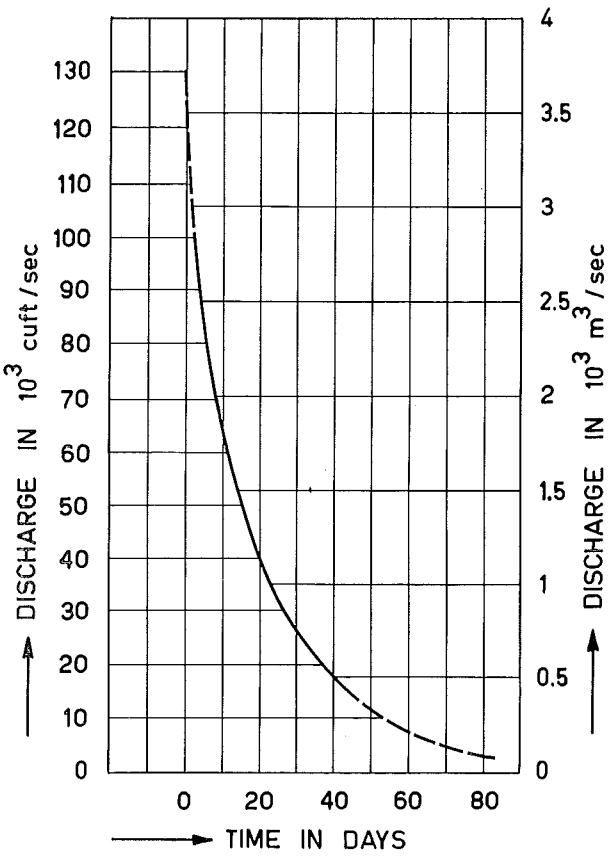


DIAGRAM 4.3.7-2

Recession curve of the Niger at Baro

When conditions are as assumed above (equally distributed rainfall during a period long enough to saturate the sub-soil) the shape of the recession curve is determined by the above-mentioned properties of the basin. But these conditions will not occur very often in Nature. Actually rainfall distribution will vary for each period of rain and not always will the saturation of the sub-soil layers be reached. It can be said generally that the distribution of rainfall over the area of small basins will vary less from year to year than that over large basins.

Usually precipitation does not stop at once. After the height of the rainy season local storms still occur, and even a big storm covering a large area may occur. Rainfall from these storms may induce a change in the shape of the recession curve, as illustrated in Diagram 4.3.7-1 b and c. In the case of the curve b, the groundwater storage did not receive any supply, but all the precipitation flowed almost immediately into the river. In the case where the curve c occurred, a part of the precipitation flowed to the deeper layers and increased the groundwater storage. The recession curve has been displaced over its lower part parallel to itself.

As the shape of the recession curve depends very much on the physical properties of the drainage basin, several formulae have been proposed to depict the form of curve mathematically. These formulae generally contain several coefficients, the value of which must be determined for every basin. The knowledge of the value of these coefficients may be useful when comparing run-off properties of basins, but for the present purpose this knowledge has not been thought necessary.

By analysing the actual recession curves of a number of flood waves for a particular station it is possible to establish an ideal curve which would occur if, after the crest of a flood wave has passed, no precipitation on the basin is observed. To eliminate the effect of an unequal rainfall distribution, for each river-stage only that recession curve has to be used which shows the steepest

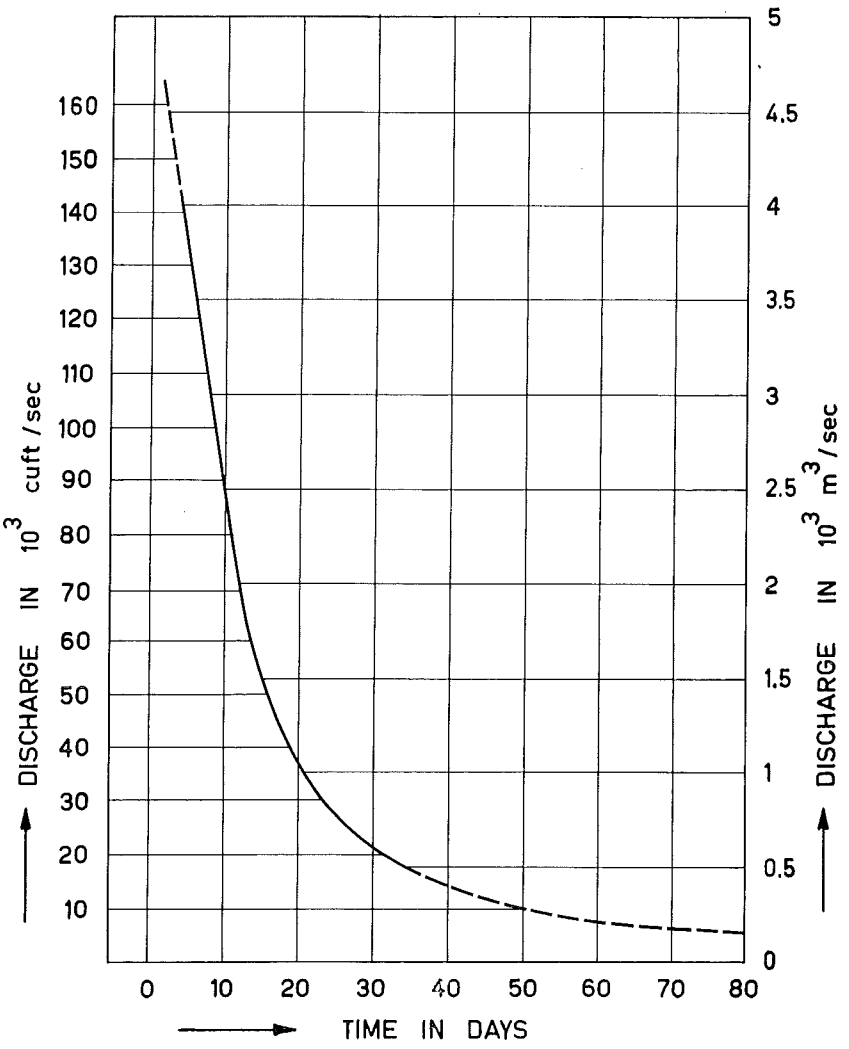


DIAGRAM 4.3.7-3

Recession curve of the Benue at Yola

inclination at this river-stage. But it must be assured that this steep inclination is not caused by an effect as in Diagram 4.3.7-1 b.

The so-established recession curve can be used to determine, a certain time beforehand, the water-levels which will occur during the period of falling river-stages. Water-levels, of course, might appear to be higher than predicted because of rainfall. The distribution of rainfall over the basin during the rainy season may also cause the water-levels to be higher than predicted. Hence the predicted water-levels must be considered as minimum water-levels.

The actual recession curve will mostly deviate from the established curve at the higher and the lower river-stages. For the higher river-stages this is caused by the distribution of the channel storage over the streams draining the basin, which depends very much on the rainfall distribution over the basin during the last rains. Only if the recession curve is expressed in water-levels, and not in discharges, may an important deviation during the lower stages be expected. This is because the stage-discharge relation for the lower river-stages is not a permanent one, but depends

very much on the configuration of the sand-banks in the river over some distance downstream from the river gauge.

Diagram 4.5.4-8 shows the recession curve of the Niger at Diré (F.W.A.). Above Diré are found the remnants of an old interior delta, consisting of a great number of lakes and pools, and a large area of flood-land (see 2.3.1). Each year this great natural reservoir of water will empty itself at the end of the rainy season, while river-stages will follow the same recession curve. The form of the upper part of the recession curve depends on the height of the crest of the flood. But an equal height will result in an equal form of the recession curve.

Diagram 4.3.7-2 shows the recession curve of the Niger at Baro, as far as this discharge does not find its origin in the Black Flood which arrives from the western drainage area of the Niger (see 4.5.4). This curve has been found by analysing the shape of the hydrographs which arise when the discharge at Baro is reduced by the Black Flood discharge. The Black Flood discharge at Baro has been found by making use of the procedure described in 4.5.4.

Diagram 4.3.7-3 gives the recession curve of the Benue discharges at Yola. As only a limited number of hydrographs during October and November were available, this curve is given here with some reserve. Particularly the lower part of the curve might be variable from year to year.

The recession curve of the Benue discharge at Makurdi is given in Diagram 4.3.7-4.

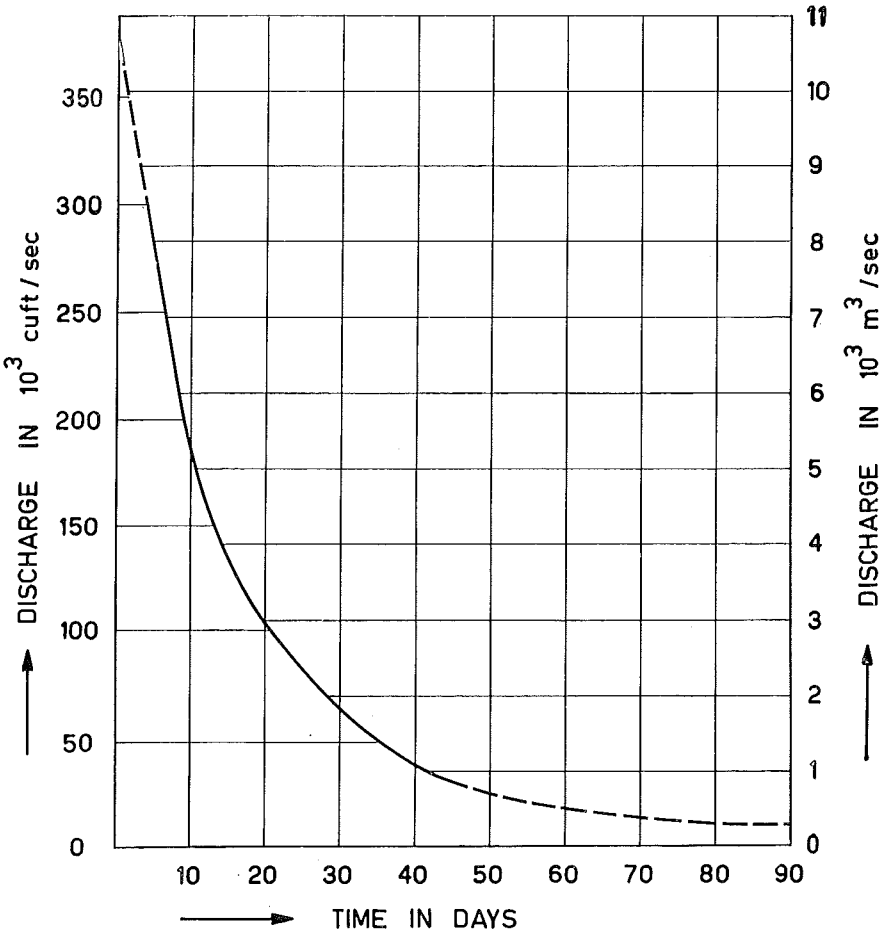


DIAGRAM 4.3.7-4

Recession curve of the Benue at Makurdi

4.3.8. Confluences, bifurcations, midstream islands

As has been explained under 4.2.6, the water-level and the slope of a river upstream from the intersection by a tributary are strongly influenced by the stage of the tributary, being drawn down or raised by backstage. On the other hand, the discharge cannot possibly be affected, unless temporarily, by varying storage during change of stage in the tributary. But as soon a equilibrium is restored, the discharge is constant again, wherever it is taken.

Islands too can affect the water-level and slope and also the river-bottom, but very definitely not the discharge. The distribution, however, of the discharge over the two branches on each side of an island may vary highly and depends on various factors, such as the stream resistance in each of the two branches and the topography of the river-bottom above the island.

As far as the latter is concerned, a single sand-bank which happens to block the entrance of one of the two branches may change the whole situation. The water-level below the sand-bank in the blocked branch is low because of the small discharge, but is raised by backstage from the down-end of the island (see 6.6.4). With a short island this backstage keeps the water-level in the blocked channel so high that the drop over the sand-bank is very small. Since the discharge over the sand-bank, as over a submerged broad-crested weir, is dependent on this drop of water-level, the result is a small discharge through the blocked branch. With a longer island, the backstage does not affect the water-level so far upstream. The drop increases and consequently the discharge grows. When the island is so long that influence from backstage is not felt at all at the location of the blocking sand-bank, the drop is maximum and the discharge high, as long as the "weir" is submerged, as is the case at high-water (Diagram 4.3.8-1). At low-water, however, free overfall ([1] over the sand-bank would cause a maximum discharge without any dependency on the level downstream from the sand-bank. Here the length of the island would not have any influence upon the discharge through the blocked channel.

([1] ROUSE, 1950, p. 219. HYD. 11.

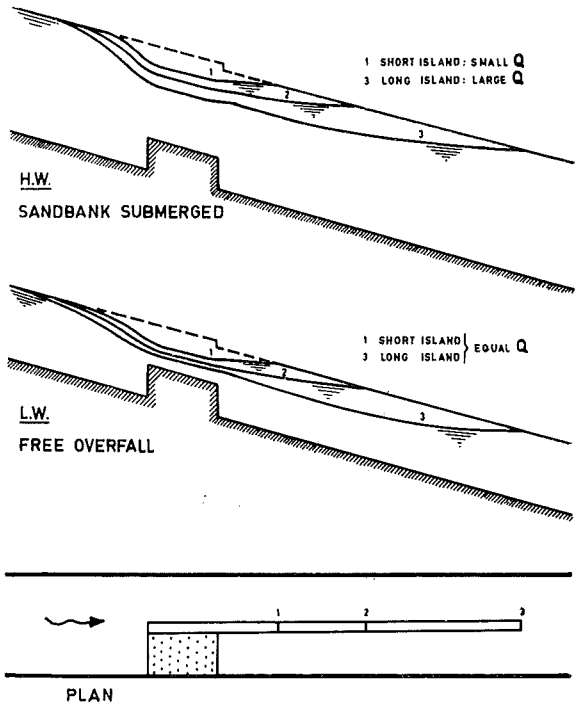


DIAGRAM 4.3.8-1

Influence of the length of an island upon the distribution of discharge

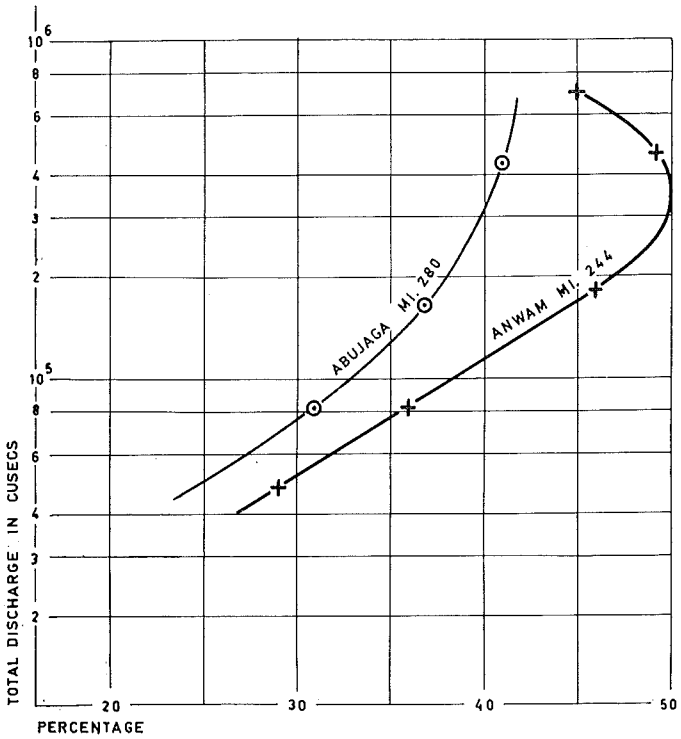


DIAGRAM 4.3.8-2

Observations on discharge distribution for two examples in the Lower Niger

It is concluded that the influence of the sand-bank upon the distribution of discharge around the island is greatest at low water; at high water the influence is great in case of a short island and small with a long one. In the latter case, the resistance of the whole channel from fork to junction takes relatively high effect.

Most islands in the Niger and Benue are "short", and therefore the blocking sand-bank plays an important rôle in the distribution of discharge.

Such a distribution is shown in Diagram 4.3.8-2. Here, out of the measurements of discharge distribution around islands, two examples of the Lower Niger are chosen. The first concerns an island near Anwam (Mile 244, see sheet 11 of the Book of River Charts). The percentage of discharge flowing through the western channel is plotted against the total discharge of the whole river. Obviously this percentage decreases with the falling river, because of a sand-bank blocking the entrance. Decrease of percentage in the very high water-stages is caused by a natural diversion in the left bank, consuming large quantities of water and thus attracting the current towards the left bank.

The second graph has been drawn for the bifurcation at Abujaga (Mile 280, see sheet 12 of the Book of River Charts). No secondary influences affect this distribution except the sand-bank in the western branch.

From the observations on the Niger, the impression was gained that, generally speaking, the main channel used by navigation is the branch with the highest discharge percentage. However, on the Upper Niger above Lokoja some remarkable exceptions have been observed, as for instance the narrow branch near Jamata (Miles 381—382, see sheet 17 of the Book of River Charts). Here, indeed, at low-water stages the major part of discharge passes through this narrow

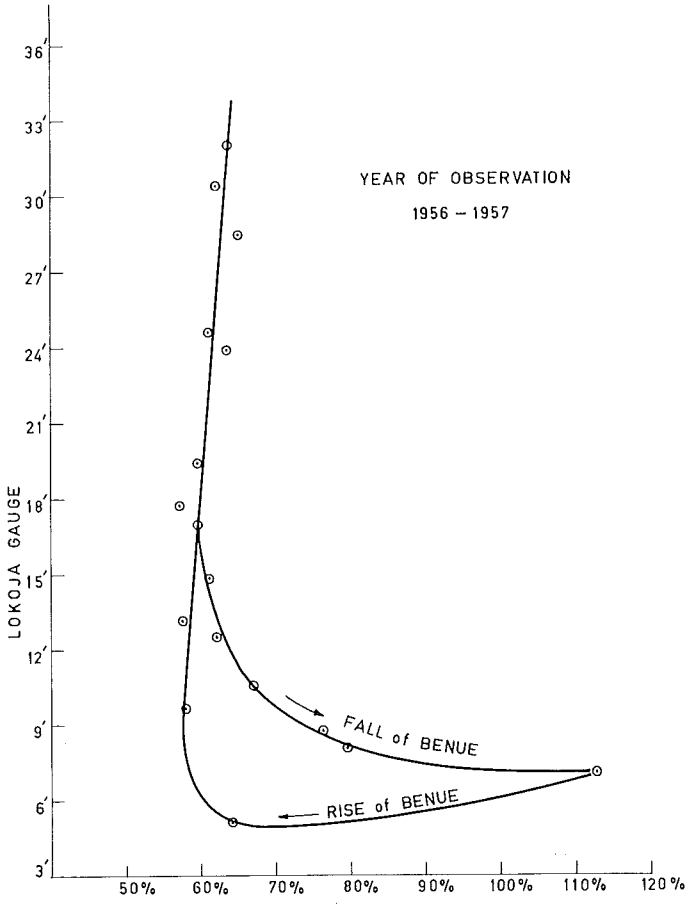


DIAGRAM 4.3.8-3

Discharge distribution around the Benue island near Lokoja

creek, but at high-water the wide eastern branch attracts the highest percentage. The exception to the above-mentioned general rule might be caused by the rocky inerodible western bank (see 6.1.5).

Another example of distribution of discharge around an island is shown in Diagram 4.3.8-3, viz., the Benue Island in the lowest section of the Benue near Lokoja, the situation of which is given in Diagram 4. Here, a second influence from outside, namely the backstage from the Niger, is exerted upon the distribution. Out of the two factors, Benue-discharge and backstage from Niger (between which no correlation exists), the water-level at the confluence is chosen as parameter against distribution. As even this does not fully comprehend both influences, the graph shows a difference for fall and rise of the Benue, and would probably also differ from an analogous line for a different year of observation. However, it appears that the percentage of discharge flowing through the South Channel is almost constant at 60 %, except for the low-water stage where the North Channel is blocked by a huge sand-bank at its entrance. Only a narrow creek remains to feed it (see Diagram 4.3.8-4).

It will be seen in Diagram 4.3.8-3 that the percentage exceeds 100 at one observation point. At this time the Benue was very low while the Niger maintained a moderate discharge. The raise of the Benue by the backstage of the Niger was so great that the slope of the North Channel was reversed and the flow went from the Niger through the North Channel in to the South Channel, as shown by the arrows in Diagram 4.3.8-4. Thus the discharge through the South Channel was greater than 100 % of the total Benue discharge.

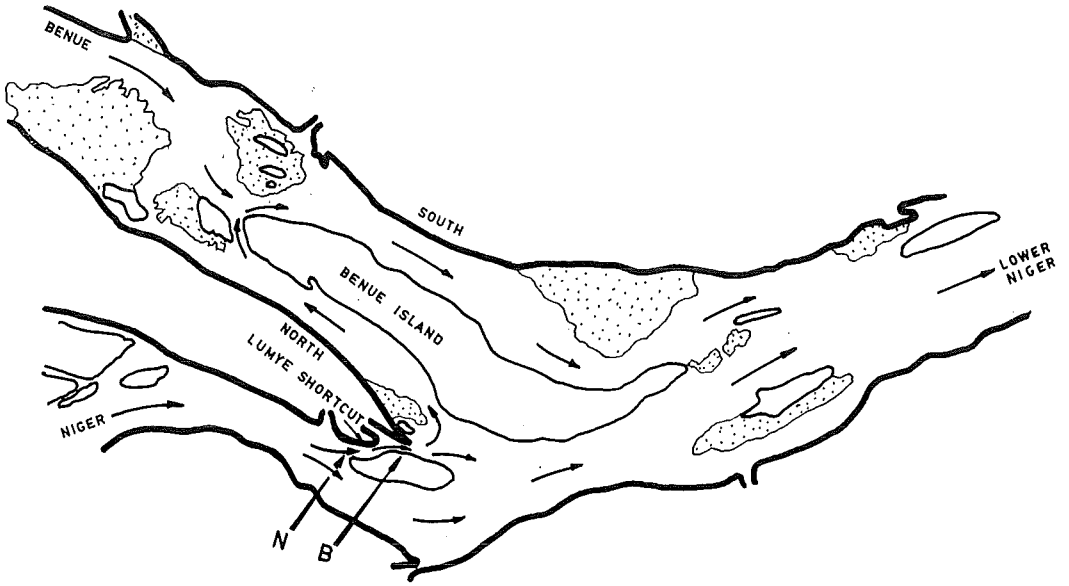


DIAGRAM 4.3.8-4

Direction of flow around the Benue Island on April 6, 1957

Finally, a third bifurcation calls for attention: through the landspit between the Niger and Benue a 200-feet wide short-cut exists. It is called the "Lumye short-cut" and originates from bank erosion along the Niger, beheading a small creek originally belonging to the Benue system (see Diagrams 4.3.8-4 and 6.5.8-5). The discharge passing this short-cut depends totally on the difference in height of water-level at both ends N and B of the creek. Mostly it flows towards the Benue. During the dry season when the Niger discharge is moderate and the Benue is low (Diagram 4.3.8-5), it may take over 12 % of the Niger discharge. In May and June, however, when the Niger is low and the Benue rising (Diagram 4.3.8-6), in the short-cut the current is reversed, and then the discharge may amount up to 10 % of the discharge from the Benue.

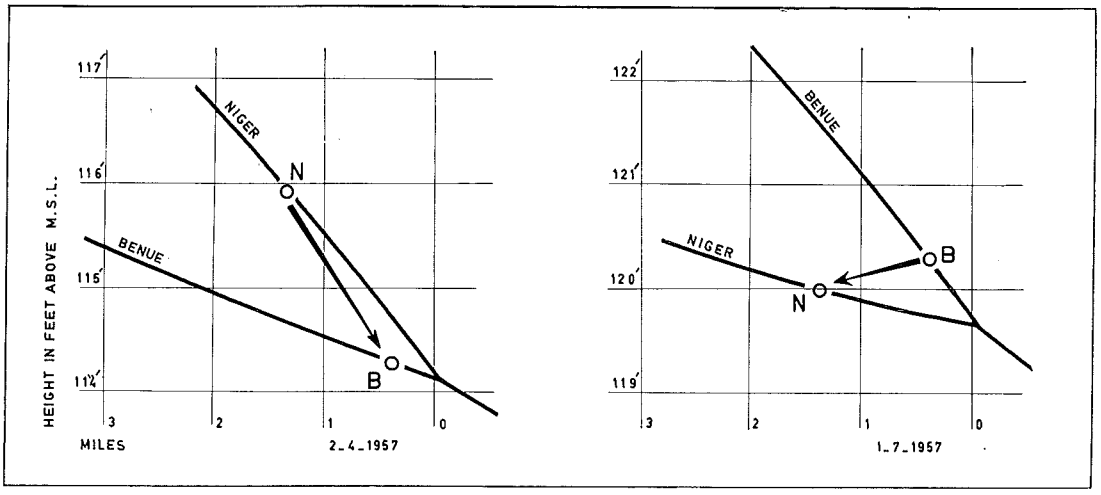


DIAGRAM 4.3.8-5 DIAGRAM 4.3.8-6

Direction of flow through Lumye short-cut depending on the elevation of the water-levels of Upper Niger and Benue

The examples considered above all concern "short" islands. Long islands do not exist in the Niger and Benue, but the phenomenon of a long island may be considered to occur at the downstream end of the Lower Niger, where it ramifies into various delta rivers. Here, an accidental sand-bank in the entrance of one of these rivers, for example the Nun (see sheet 6, Book of River Charts) has at high-water only a minor effect on the distribution of discharge. The resistance of the entire downstream river is determinant for the distribution. At low-water, according to the above theories, the blocking sand-bank would effect a free overfall and consequently would have large influence. This, however, is a temporary affair of a very short duration, if not completely absent, due to forces towards compensation of the extra resistance in the entrance. The steep slope over the sand-bank will doubtless effect locally a great velocity and consequently scour, and thus produce an increase of discharge in the course of time. Moreover, it is probable that the sand-bank, moved forward and brought into its blocking position by high water, will leave a more or less narrow but deep channel, since the power of the distributary branch (the Nun River) to attract a certain amount of discharge resists complete blocking more strongly than in the case of a bifurcation by a short island. However, it is true that, due to the sand-bank in the entrance, minor differences in the distribution of discharge at low water over the two distributaries might occur from year to year.

There is, however, another phenomenon which must have an important influence on the distribution of discharge over the two distributaries, viz., the distribution of sediment load. As will be mentioned later (6.1.2), the sand carried down by the river follows the convex side of a bend, while the water flow tends towards the concave bank. If the division is situated in a bend, which is mostly the case, and certainly with respect to the Nun, the main part of the sediment therefore finds its way into one distributor (the one on the inside of the bend). In the example it is the Nun receiving more sand than the Forcados. Since this effect is due to the curvature of the stream and therefore dependent on the situation at the division, it is liable to changes caused by erosion of banks and movement of sand-bank.

These changes, however, are very slow; a tendency of increasing sediment supply into one distributary may therefore last a very long period, and affect the resistance of the whole down-

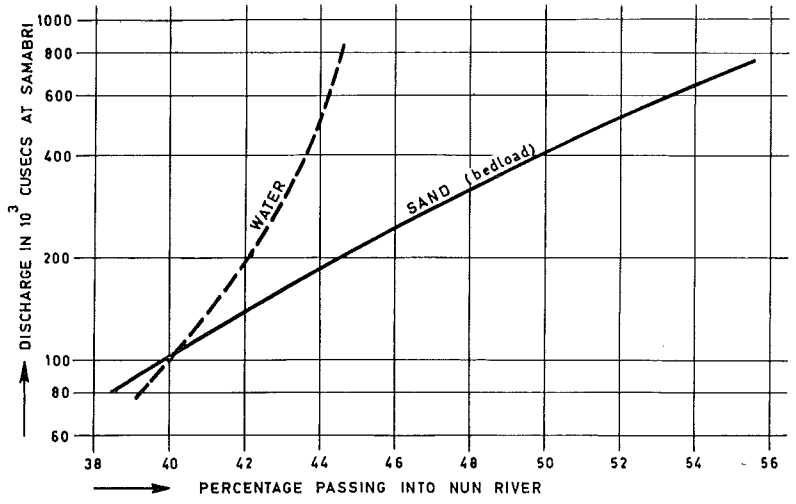


DIAGRAM 4.3.8-7

Distribution of discharge of water and sand from the Niger over the Nun and the Forcados Rivers

stream river. It is possible that the Nun, formerly a good navigation route, has received a greater sand supply since then, and has gradually so far increased its resistance that also the water discharge distribution has been modified in favour of the Forcados.

Diagram 4.3.8-7 shows the distribution of water and sediment discharge from the Niger over the Nun and the Forcados as computed from observations in 1953/54 ([1].

4.4. EVAPORATION

4.4.1. Measurements

In Nigeria long-period records of measurements of evaporation from open water surfaces do not exist.

The knowledge of evaporation is of great interest, because it constitutes an important phase of the hydrological cycle. Especially in connection with the management of reservoirs, a good estimate of the evaporation to be expected from the surface is necessary.

Recently the British West African Meteorological Services, Lagos, have installed a number of tank evaporimeters, and Diagram 4.4.1-1 gives the locations of those at present in use.

Table 4.4.2-1 (first column) gives the results of the evaporation measurements at Yola Met. Station (Airport). To compute the monthly evaporation from the tank, use has been made only of the records for those days on which no rain has been observed. This has been done because rain is very frequently accompanied by strong winds which cause a loss of water over the rim of the tank.

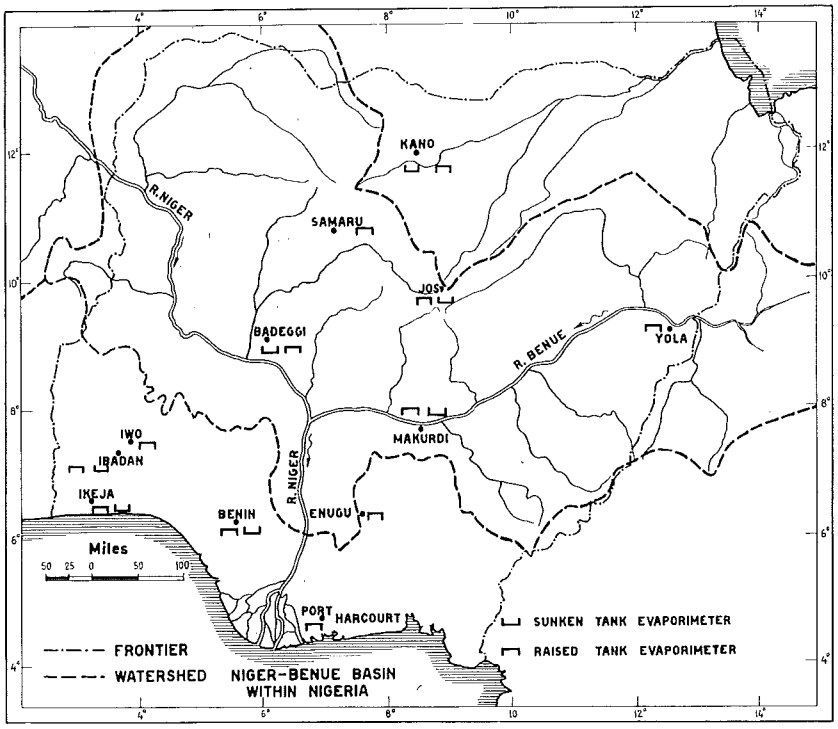


DIAGRAM 4.4.1-1

Tank evaporimeters in Nigeria

([1] NEDECO, 1954. GEN. 23.

4.4.2. Computations

Many formulae have been proposed to compute evaporation from meteorological data, but to get as soon as possible an estimate of the evaporation to be expected from the surface of a reservoir in the neighbourhood of Yola, use has been made of DALTON's formula, which reads

$$E = K (F - f)$$

in which: E = evaporation in mm,
K = a coefficient,
F = saturation vapour pressure (mm. mercury),
f = actual vapor pressure (mm. mercury).

The value of K, which depends partly on the wind velocity over the water surface, has to be determined by local experiments. As such experiments were not available, data from experiments at Bamako (French West Africa) ([1 have been used. At Bamako monthly K values were computed for the year 1952, with the help of records of evaporation from a floating tank, although these values are not given for every month of the year. As the given figures do not vary very much, the average value of 0.45 has been used throughout the entire year-cycle. From the monthly mean of daily maximum and minimum temperatures and monthly mean of daily maximum and minimum relative humidity of the period 1943—1947 ([2, and a value of K of 0.45, monthly values of E have been computed for Yola. They are given in column 2 of Table 4.4.2-1.

TABLE 4.4.2-1

MONTHLY TANK EVAPORATION AT YOLA AND GARUA

	1 monthly evaporation measured in tank evaporimeter at Yola (1957—1958)		2 monthly evaporation computed with E = K (F — f) (1943—1947)		3 monthly evaporation measured in tank evaporimeter at Garua (1955—1956)		4 monthly values of K at Garua (1955—'56)
	mm.	inches	mm.	inches	mm.	inches	
Aug.	139.7	5.50	71.3	2.8	142	5.6	0.46
Sep.	127.0	5.00	66.0	2.6	132	5.2	0.43
Oct.	120.0	4.73	93.0	3.7	192	7.6	0.45
Nov.	158.0	6.22	186.0	7.3	276	10.9	0.42
Dec.	207.8	8.18	244.9	9.6	276	10.9	0.38
Jan.	214.4	8.44	266.6	10.5	263	10.4	0.37
Feb.	252.5	9.94	277.2	10.9	296	11.7	0.41
Mar.	414.5	16.32	356.5	14.0	295	11.6	0.40
Apr.	309.9	12.20	294.0	11.6	345	13.6	0.46
May	232.2	9.14	189.1	7.5	313	12.3	0.43
Jun.	143.5	5.65	96.0	3.8	219	8.6	0.38
Jul.	139.7	(5.5) (*	77.5	3.1	211	8.3	0.47
year	2459.2	96.82	2218.1	87.4	2960	116.7	0.42

(* no record, estimated.

([1 RODIER AND TOUCHEBEUF, 1954. HYD. 10.
([2 BUCHANAN AND PUGH, 1955. GEN. 3.

Evaporation measurements with a sunken pan made by the "Service Météorologique du Cameroun" at Garua during 1955—1956 have given the values of K as shown in column 4. The average of these values is 0.42, a figure which is rather close to the value of 0.45 measured at Bamako.

Experiments all over the world have shown that evaporation from a tank is always higher than from a lake surface. This is mainly caused by:
(i) the increase of moisture in the air when moving over the water surface; and
(ii) as a lake is deeper than a tank, the same amount of sunshine will increase the temperature of the water in the tank more than the water in the deeper lake.

The following reduction factors are often used to arrive at a figure for lake evaporation:
raised land pan 0.7
sunken land pan 0.8
floating pan 0.8

The factor 0.7 is applied to the tank measurements at Yola, and the factor 0.8 to the value of the evaporation as computed with the help of K = 0.45 and K = 0.42; the results are given in Table 4.4.2-2. The concordance between the figures of the last column is certainly satisfying.

TABLE 4.4.2-2

EVAPORATION FROM A LAKE AT YOLA

	inches	reduction factor	evaporation from lake (inches)
Measured at Yola	96.82	0.7	67.5
Computed for Yola K = 0,45	87.4	0.8	69.5
Computed for Yola K = 0,42	81.5	0.8	65

Diagram 4.4.2-3 illustrates the monthly evaporation in inches as measured in Yola and as computed for Yola, as well as the monthly evaporation measured in Garua, whilst Diagram 4.2.2-4 gives the monthly tank evaporation as a percentage of the annual total. Considering the assumptions used, the two curves for Yola are in good concordance.

When examining possible regulation programmes for a reservoir in the neighbourhood of Yola, evaporation from an open water surface has to be considered (see VI, 8.5.3). For this purpose, the tank evaporation as computed for Yola has been reduced by a factor 0.9. This gives a value of 87.4 × 0.9 = 78.5″ per year. The comparison of the computed tank evaporation made in 1956 with data of the period 1943—1947 with the result of the measurements of 1957—1958 shows that the values of evaporation used for the regulation programmes are certainly not too small. It is expected that further experiments will enable the more exact computation of the evaporation which is to be expected. Collection of the necessary meteorological data will make it possible to use for this purpose more modern formulae than the DALTON's formula, mentioned above.

4.4.3. Main evaporation areas

During the higher river-stages great areas along the river are flooded. This phenomenon is explained by the vertical and horizontal displacements of the river-bed.

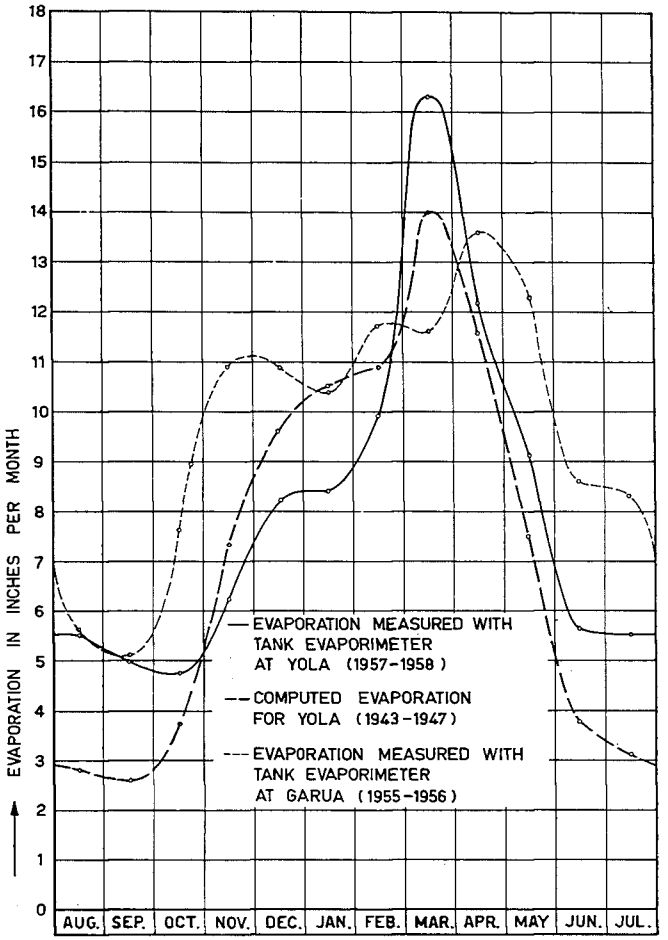


DIAGRAM 4.4.2-3

Tank evaporation at Yola and Garua

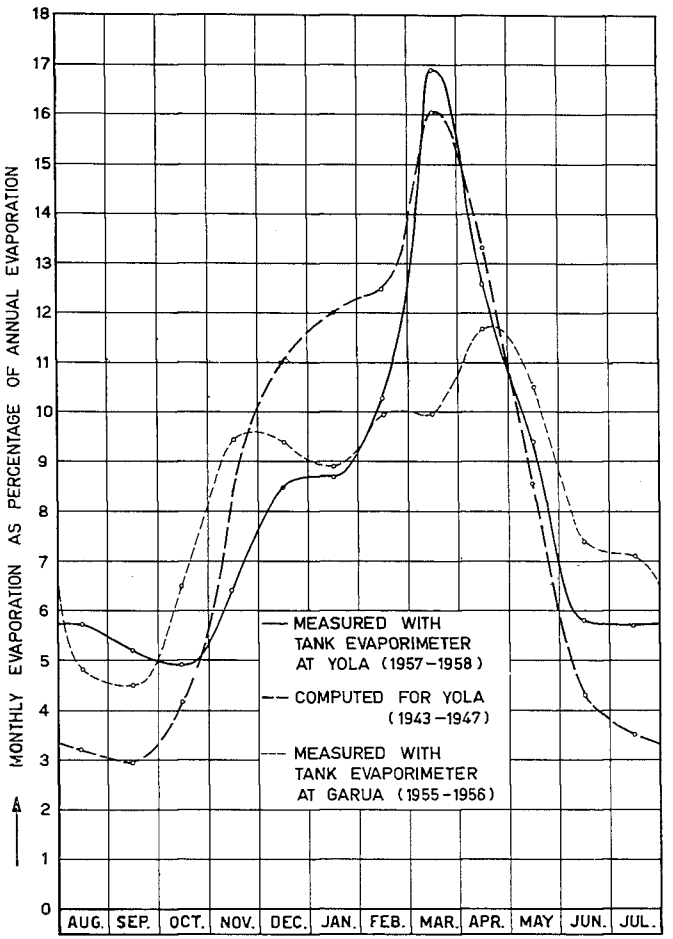


DIAGRAM 4.4.2-4

Monthly tank evaporation as a percentage of annual total

When the river-bed is aggrading (Niger, Interior Delta above Diré; Benue between Garua and Lau) river-stages will rise in the course of time, although the discharge frequencies remain constant. A horizontal displacement of the river is illustrated by the former river-branches which are found in the flood-plain along the river. These old branches will, in the course of time, be filled up with silt and sand, but this can take many decades. So the bed of these branches will remain for a long time below the higher water-stages, and thus be subject to flooding.

In the Interior Delta of the Niger in French West Africa (see Diagram 4.1.1-1), some 6,000 to 10,000 sq.miles may be flooded in the period between July and January. REFFAY (1 shows that 55 to 65% of the yearly run-off from the Niger Basin above Diré is lost in this interior delta by evaporation and infiltration. He divides this loss into:

(i) evaporation from water surfaces which are from July to January in open connection with the river	15%
(ii) infiltration during rising river-stages:	45 to 55%
(iii) storage which does not return to the river after the fall:	40 to 30%

The storage (iii) disappears eventually by evaporation from the water surface during the period January to July, by transpiration from aquatic plants, and by infiltration.

An example of the evaporation from the surface of the lakes in the Interior Delta is given in Diagram 1.2.4-4 which shows successive stages of Lake Faguibine from 1924 to 1941. The supply of water to this lake depends on the height of the flood on the Niger. When the Niger flood is low, the lake does not receive very much water, but evaporation continues.

Along the Niger in Nigeria rather large areas between Baro and Lokoja and also some regions between Yelwa and Bussa (Foge Island) may be flooded during high river-stages. Evaporation will also take place from these areas, but it is not expected that this is great in comparison with the yearly Niger discharge. The computed water-balance (see 4.5.3) does not permit an estimate of the value of this evaporation, nor are there direct measurements of it.

Along the Benue, the water-stages are being raised by backwater between Garua and the Faro Confluence, while the river-bed between the Faro and Lau is aggrading. This explains why between Garua and the confluence with the Taraba River considerable areas are flooded during the wet season by the Benue or by small rivers flowing towards the Benue but which are dammed up by the natural levees of this river. The flooding of the riverain lands (flood-plain) by the Benue has a noticeable flattening effect on the shape of the hydrographs at Lau and Angwan Taru (see also 4.3.3). After the Benue flood has passed, water stays in the pools behind the natural levees and in former river-branches which are no longer in connection with the main river. Evaporation during the dry season will lower the water-level, but at the end of the dry season there is still water in some pools. Data at present available do not allow the exact computation of the loss of yearly discharge by evaporation from the water surface over the flood-land, as the area of this surface is not known. Roughly estimated, however, this evaporation will be in the order of 2 to 3 $\times$ 10^9 m^3 per year, which is 2 to 3% of the yearly discharge at Makurdi.

These losses can be reduced by a regulation of the discharges which aim at a flattening-out of the peak discharges. Consequently the peak stages which cause the greatest flooding will be reduced, thus decreasing the evaporation and increasing the total volume of water discharge by the river. On the other hand, evaporation from the surface of the reservoir at Yola (VI, 8.5.3) will amount to about 1 $\times$ 10^9 m^3. So the final result will be an increase of from 1 to 2% of the yearly discharge at Makurdi.

(1 REFFAY, 1948, p. 232. HYD. 9.

4.5. HYDROLOGICAL BALANCE

4.5.1. Run-off, evapotranspiration and ground-water

The general circulation of water from the seas to the atmosphere, to the ground and back to the sea again is called the hydrological cycle. A simplified scheme of it is given in Diagram 4.5.1-1. Under certain circumstances a part of the water vapour in the air will condense and may cause precipitation on the surface of the earth as snow, hail or rain. The water vapour may also condense directly on the earth surface, when it is known as dew. As snow and dew are not important for the purpose of this Report, only the rainfall will here be dealt with.

Part of the rain falls in the ocean and part on the continent. The latter part is the more interesting as it feeds the rivers, either directly or indirectly. It will therefore be considered in some detail.

During a shower some rain will fall on the leaves of the vegetation; a part of this will in turn fall from the leaves upon the ground, whilst the remainder will stay on the leaves and evaporate when the rainfall ceases. The rain which reaches the soil surface will partly stay in puddles and pools and later evaporate, and some, called the surface run-off, flows over the surface into small water-courses and streams. A third part will enter into the soil (infiltration) and form the soil-moisture. The vegetation satisfies its need of water from this soil-moisture, the water taken being partly kept within the organism and partly transpirated by the leaves into the air. Some of the infiltrated water evaporates from between the grains which constitute the soil. This, together with the transpiration from thevegetation, is called the evapotranspiration.

The moisture may flow in the soil itself. When this moisture leaves the soil and enters the stream through the banks, it is said that interflow takes place. When from the soil-moisture some water enters into deeper layers and joins the ground-water, percolation occurs.

The ground-water may flow towards the rivers, and in Nigeria this is the most important source of river flow during the dry season (see also 4.3.7). By capillary rise, however, a part of the ground-water may return to the soil-moisture and serve the vegetation.

The river flow which originates from a supply from the adjacent land is increased by rainfall on the water surface and reduced by evaporation.

From the above considerations the following equation for a river basin can be set up:

$$P = E + \Delta S + R \qquad \ldots\ldots\ldots \quad (1)$$

in which: P = precipitation on the basin during a time Δt
E = evapotranspiration + evaporation during Δt
S = storage, which is the quantity of water contained by the soil and the rivers
ΔS = change in storage before and after Δt and
R = run-off during the time Δt.

P can be computed from rainfall measured during Δt at a number of stations spread over the basin. This can be done, for example, by drawing isohyets. R can be obtained by measuring the discharge at the lower end of the basin. It is, however, rather difficult to find correct values for E and ΔS.

Several formulae ([1] have been proposed to compute the potential evapotranspiration, E_p, which is the evapotranspiration which would occur in a region completely covered by vegetation if an unlimited supply of soil-moisture were available. The amount of evapotranspiration then becomes dependent only on climatic factors, and can be computed with the help of climatic

([1] GARNIER, 1956. HYD. 2.

WATER VAPOUR IN THE ATMOSPHERE

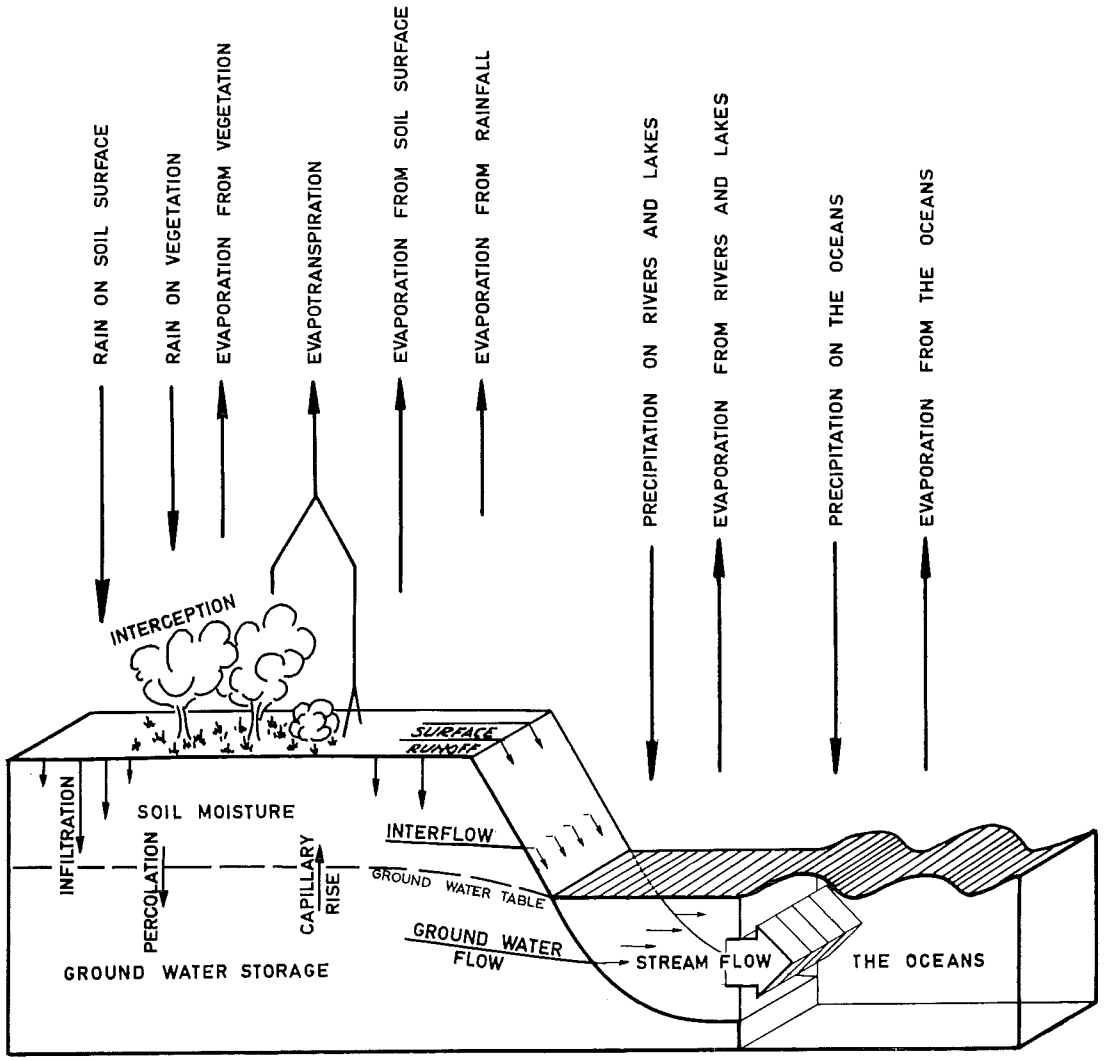


DIAGRAM 4.5.1-1

Simplified scheme of the hydrological cycle

observations. The Niger-Benue Basin does not possess a complete vegetation cover, and moreover the supply of soil-moisture during the dry season is certainly not unlimited. So the potential evapotranspiration will exceed the actual evapotranspiration, and it would not be allowed to substitute a computed value of it in Formula (1).

The evaporation from that part of the basin which is covered by open water surface could be computed (see 4.4.2), but generally this open water surface covers only a very small part of the basin.

The Equation (1) could be solved if ΔS were known. The variation of the water storage in the basin can be divided into the variation of soil-moisture, the variation of ground-water storage and the variation of storage in the river channels. The variation of the soil-moisture could be determined by examining soil samples; the variation of the ground-water storage could be computed by observing the variation of the ground-water level, although a knowledge of the porosity over the basin is then necessary; and the variation of the river storage could be learned by making a hydrographic survey of the rivers in the basin.

The problem becomes, however, more simple if the hydrological year is chosen as the unit of time over which Equation (1) has to be solved. The regime of the rivers in Nigeria is generally characterised by two periods: one during which much the greatest part of the yearly run-off takes place, and the other during which the discharge becomes very small. At the end of the latter period (dry season) the discharges will reach a minimum. The hydrological year is the period of one year between two points of minimum discharge. Depending on the onset of the rainy season, there are, of course, slight variations from year to year of the moment at which discharges reach a minimum, but for the present purpose it can be taken that the hydrological year of the Niger between Diré (French West Africa) and the coast runs from June 1 to May 31, and that the hydrological year on the Benue is between April 1 and March 31.

When applying this conception of a hydrological year, it can be assumed that the content of moisture in the soil is about the same at the beginning and the end of the period. For both moments are preceded by 2 to 4 months in which scarcely any rain has fallen, and the soil has dried up. This involves that during the dry season the only source of the river water is the ground-water storage.

It has been explained in 4.3.7 that the shape of the hydrograph during the dry season depends only on the physical properties of the basin. For a particular basin the actual discharge will then be determined only by the amount of ground-water storage. If for this basin one dry season discharge equals the discharge during another dry season, it can be taken that the amount of ground-water storage at the two considered moments has been the same. So, if at the beginning and at the end of the hydrological year the discharge is the same, the variation of ground-water storage can be taken as zero.

For the river storage the same reasoning as for the ground-water storage can be adopted.

Therefore for a hydrological year, Equation (1) can be solved. This will be done for several basins in the Niger-Benue system in 4.5.3.

4.5.2. Storage and overbank spill

The storage of water within a river basin can be divided into:

(i) channel storage,
(ii) flood-plain storage, and
(iii) ground-water storage.

Channel storage is the amount of water which is found between the banks of the river. Flood-plain storage is the amount of water beyond the river-banks and over the flood-plain.

Channel storage and flood-plain storage together is called valley storage. Flood-plain storage can be divided into that part which will return to the river during falling stages and into that which will stay behind in pools which do not have an open connection with the river during lower stages. Both parts are of interest for the prediction of water-levels during rising stages, but only the first part is of use for the prediction during falling stages. Ground-water storage is the amount of water stored in the ground below the ground-water table.

The valley storage capacity has an important effect on the propagation of floods. The propagation speed of the flood wave will decrease with the increase of the storage capacity. The peak discharge of the flood will diminish when going downstream (see also 4.2.7).

This effect of the storage capacity on the propagation of a flood-wave is very well illustrated in the propagation of the Niger flood through the interior delta, which is dealt with in detail in 4.5.4. Another example is shown by the hydrographs of Lau (Mile 777.5) and Angwan Taru (Mile 682.6) along the Benue (Diagram 4.2.2-1). During the high stages the Lau hydrograph shows three peaks which can be clearly distinguished from each other. But at Angwan Taru the hydrograph is flattened out and shows a broad crest. This is caused almost entirely by the storage over the wide flood-plain along the Benue between Lau and Angwan Taru.

The valley storage will increase with the river-stage. It is, however, generally rather difficult to establish a relation between the two, and for the Niger and the Benue certainly more data will be necessary for this than could be obtained during the three years of survey. The knowledge of such a relation, however, is important for the stage prediction (see also VI, 3.6.1).

During the dry season, when rain over the Niger-Benue Basin is very rare, the discharges of these rivers find their origin in ground-water (except for the so-called Black Flood in the Niger, see 4.5.4). During this time the discharge in a river can be considered to be a function of only the ground-water storage as explained in 4.5.1. This would enable a computation of the ground-water storage to be made, but for this more data will be necessary than are now available.

Some idea about the amount of water that can be stored in the Benue Basin might be obtained by considering the Makurdi discharge hydrograph (Diagram 4.3.3-1). After peak stages have passed, discharges are decreasing rapidly, because rainfall over the basin above Makurdi has practically finished. So all over the discharge passing Makurdi during the time between the moment of peak discharges and the beginning of the next rainy season originates in storage. This discharge may vary between 20 and 35 milliard m^3 (16 to 28 million acre-feet), or between 20% and 30% of the yearly discharge. It is estimated that about one-half of this amount finds its origin in ground-water storage, the remaining part originating in the returning valley storage.

4.5.3. Run-off coefficients

The run-off coefficient of a river basin as used here is the ratio of the year run-off (R) from that basin to the amount of precipitation (P) over the basin during the same period. To compute these coefficients for various basins, precipitation and run-off data over the hydrological year have been used. For reasons explained in 4.5.1, the hydrological year has been taken instead of the calendar year.

The run-off coefficient is a function of the physical properties of the basin and of the climate, but also of the precipitation. Steep surface slopes, a small permeability of the soil, little vegetation and low temperatures (which means a low value of the potential evapotranspiration) will increase the coefficient. On the other hand, a basin with a sub-horizontal surface, a sandy soil, a well-developed vegetation cover and a hot climate will have a small run-off coefficient.

When the soil is saturated with water, a greater part of the precipitation will become run-off than when the soil is dry. So it can be expected that the run-off increases with the rainfall. Of

TABLE 4.5.3-1

RUN-OFF COEFFICIENTS

RIVER	STATION	DRAINAGE AREA (sq. miles)	rainfall (inches)			run-off (inches)			run-off coefficient (%)			AVERAGE			
			1955—56 (1	1956—57 (1	1957	1955—56 (1	1956—57 (1	1957	1955—56 (1	1956—57 (1	1957	Period	Rainfall (inches)]	Run-off (inches)	Run-off Coeff. (%)
Niandan	Baro (2	4,870	84	—	—	35	—	—	42	—	—	1949—55	79.5	28.5	34
Niger	Koulikoro (2	47,000	65	—	—	21.5	—	—	33	—	—	1949—55	65	19	29
Kaduna	Wuya	25,300	56	39.5	57.3	17	7.9	17.8	30	20	31	1955—57	51	14.2	27
Mayo Kebbi	Cossi (2	10,000	40.5	—	—	6.2	—	—	15.3	—	—	—	—	—	—
Mayo Kebbi	Famou (2	11,600	—	—	—	—	—	—	—	—	—	1951—52	37	3.5	9.5
Benue	Riao (2	12,000	52	—	—	15.5	—	—	30	—	—	1950—55	40.5	9.9	24
Benue	Garua (2	24,800	47	—	—	10.5	—	—	22	—	—	1949—55	42	6.7	16
Faro	Safai (2	9,800	—	—	—	—	—	—	—	—	—	1953	52	18.5	35.5
Gongola	Bare	21,500	—	—	39	—	—	5.2	—	—	13	—	—	—	—
Taraba	Beli	4,200	—	—	(80)	—	—	47.	—	—	(59)	—	—	—	—
Taraba	Gassol	8,240	(67.5)	(68)	(70)	—	20 8	30.5	—	(30.6)	(43.5)	—	—	—	—
Donga	Dongatown	4,600	74	69.3	—	—	39.6	56.8	—	57	—	—	—	—	—
Katsina Ala	Katsina Ala Town	6,450	86.5	77	87	(59.0)	54.	64.5	(59)	71	74	1956—57	82	59	72
Benue	Yola-Makurdi	76,100	59	50.5	54	18.2	14.5	19.4	31	29	36	1955—57	54.5	17.4	32

(1 Hydrological year for Baro (Niandan), Koulikoro and Wuya is from 1 June to 31 May. For all other stations it is from 1 April to 31 March.

(2 Data from: "Annuaire Hydrologique de la France d'Outre-Mer", published by the "Office de la Recherche Scientifique et Technique Outre-Mer", Paris.

a heavy shower a greater percentage will be discharged as run-off than when rain-intensity is low.

Table 4.5.3-1 gives run-off coefficients for several parts of the Niger-Benue Basin. Values from this table are plotted on Diagram 4.5.3-2. For those parts of the Niger Basin situated in French West Africa or in the French Camerouns, the data have been obtained from the "Annuaire Hydrologique de la France d'Outre-Mer" (1. For the Nigerian parts of the Basin, precipitation has been computed by plotting on a map rainfall data obtained from the West Africa Meteorological Services and then drawing the isohyets. Discharge has been computed by using the daily water-level readings and discharge rating curves.

The diagram shows that the run-off coefficient is generally increasing with the precipitation.

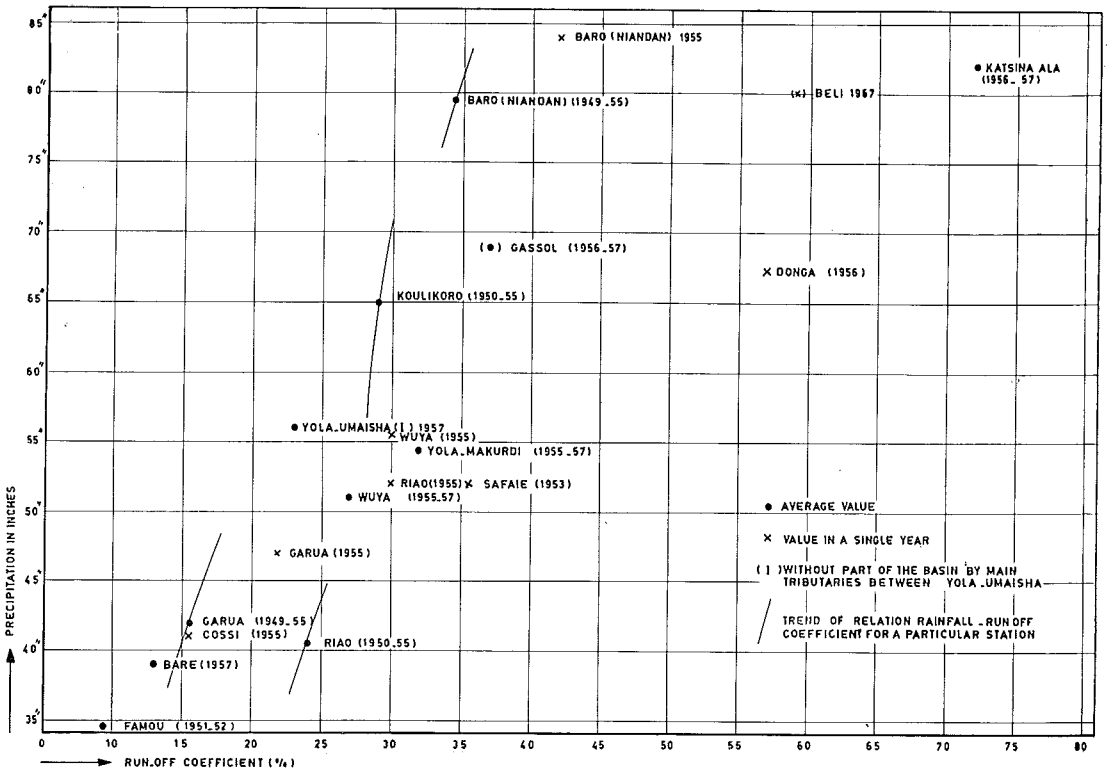


DIAGRAM 4.5.3-2

Run-off coefficients as a function of the precipitation

The basins above Garua, Cossi, Bare and Riao are receiving almost equal rainfall, but the coefficient of the Benue Basin above Riao is higher than those of the other basins. This finds its explanation in the rather steep slopes of that part of the former basin which is situated in the eastern part of the Adamawa Mountains and of that part which drains the Poli Plateau. The whole basin of the Faro above Safaie is surrounded by mountains which have steep slopes: Alantika Mountains, Adamawa Mountains, and the Poli Plateau (2. Hence, although rainfall on the Benue Basin above Riao in 1955 has been the same as on the Faro Basin above Safaie in 1953, the run-off coefficient of the latter has been greater than that of the former.

The coefficients of the basins above Beli, Katsina Ala Town and Donga are rather high,

(1 ORSTOM, 1949—1955. HYD. 6.
(2 ORSTOM, 1953. HYD. 7.

which finds its explanation in a high rainfall on a mountainous area (Cameroon Mountains). The figure given for Beli might be incorrect, as because of the very small number of rainfall stations in the basin above this place, the rainfall has been estimated rather than computed by extrapolating isohyets over the area of which no precipitation was known.

No run-off coefficients have been computed for stations along the Niger below Koulikoro. These would have been meaningless, as a great amount of water is lost in the interior delta above Diré and the area of the drainage basin between Diré and Malanville is not exactly known (see also 2.2.2).

The diagram shows that the increase of the run-off coefficient with rainfall is somewhat smaller for a particular basin than the increase of this coefficient with rainfall not regarding individual basins.

4.5.4. Relations and predictions

Making use of the considerations of the preceding sections of this Chapter, a general picture of the connections and inter-relations between the discharges downstream and those upstream — the time-lag being taken into account — can be now obtained.

a. *Within Nigerian Territory*

Diagram 4.5.4-1 gives such relations in the Niger-Benue Basin within Nigeria. This diagram can best be explained by following a certain discharge passing Wuro Boki and Yola on the Benue on its way downstream, as indicated by a dotted line on the diagram.

On June 14, 1957, the water-level at Yola at 1800 hrs. was 10′7″. From the discharge rating curve for Yola, which is drawn at the left top corner of the diagram it is seen that a discharge of 25,500 cusecs corresponds with this river-stage.

The time-lag Yola—Numan for the various discharges is indicated by figures written along the discharge rating curve of Numan. For the discharge of 25,500 cusecs, this time-lag is about 0.6 days.

The water-level at Numan, 12 hours after 1800 hrs. on June 14, 1957, that is, 0600 hrs. on June 15, was 8′11″, corresponding with a discharge of 34,000 cusecs. Of this discharge, 25,500 cusecs arrived from the region above Yola.

Just upstream from Numan the Benue is joined by the Gongola, of which a discharge rating curve is known for the station of Bare. The time-lag Bare—Numan is about 2 hours, a period which can be neglected for the present purpose. At 0600 hrs. on June 15, the water-level at the Bare gauge was 5′3″, to which belongs a discharge of 4,750 cusecs.

The difference between the sum of the discharges at Yola and Bare (25,500 + 4,750 = 30,250 cusecs) and the discharge at Numan (34,000 cusecs) is considered to be due to lateral inflow between these stations, less the storage. The storage is deducted because, as water-levels were rising, the amount of water in the river channel increased, and some water may have left the stream-bed and be stored over the flood-plain.

Along the Yola rating curve are drawn lines for inflow less storage between Yola-Bare and Numan. The value of this being computed, the dotted line connecting the Yola and Numan rating curves could be drawn.

The time-lag Numan—Lau is about 1 day (see the figures written along the rating curve of Lau). One day after June 15 (0600 hrs.), that is, 0600 hrs. on June 16, the water-level at the gauge at Lau was 16′10″, corresponding with a discharge of 37,500 cusecs. The difference between this discharge and that at Numan one day before (3,400 cusecs) is again the lateral inflow less storage (see the lines along the Numan rating curve).

When the water-level at Lau is 17′, the time-lag Lau—Angwan Taru is about 2 days. So two days after the water-level of 16′10″ occured at the Lau gauge, which means 0600 hrs. on June 18, the water-level at the Angwan Taru gauge was 14′1″, giving a discharge of 31,000 cusecs, which is less than the discharge at Lau. The difference is due to storage, which exceeds in this case the lateral inflow between the two stations.

When river-stages become still higher, a considerable area along the river between Lau and Angwan Taru becomes flooded. This causes the time-lag to increase to even 5 or 6 days during the high stages.

Below Angwan Taru the Benue is joined by the Taraba and the Donga Rivers. Of the Taraba, a discharge rating curve has been established for Beli in the headwater area and for Gassol, 10 miles from the confluence with the Benue. The latter is used in this diagram, and has been drawn in the same way as for Bare on the Gongola. Of the Donga River, rating curves for Nyankwola, and more upstream for Donga Town, have been established, but only the stage-discharge relation for Nyankwola has been drawn here, in the same way as for Bare and Gassol.

The first station along the Benue below the confluence with the Donga River for which a discharge rating curve is known is Ibi. As both Gassol and Nyankwola are situated rather close to the Benue, the time-lag over the river-stretch between each of these stations and Ibi depends on Benue discharge. The discharge at Ibi is the result of the discharges at Angwan Taru, Gassol and Nyankwola and the inflow less storage between these stations.

For river-stages considered here, the time-lag Angwan Taru—Ibi is about $1\frac{1}{2}$ days. The water-level at Ibi $1\frac{1}{2}$ days after June 18 at 0600 hrs. (the time of the water-level at Angwan Taru, considered here), which means 1800 hrs. on June 19, was 17′8″, corresponding with a discharge of 87,000 cusecs. The time-lags Gassol—Ibi and Nyankwola—Ibi are at this river-stage about $1\frac{1}{4}$ days. The river-stage at Gassol $1\frac{1}{4}$ days before 1800 hrs. on June 19, namely 1200 hrs. on June 18, was 11′6″. The line which gives the discharge at Gassol for this river-stage can be found by interpolating between the line for 10′ and the one for 12′. The river-stage at Nyankwola was 9′10″ at 1200 hrs. on June 18 and the discharge belonging to this stage is found by interpolating in the same way as for Gassol.

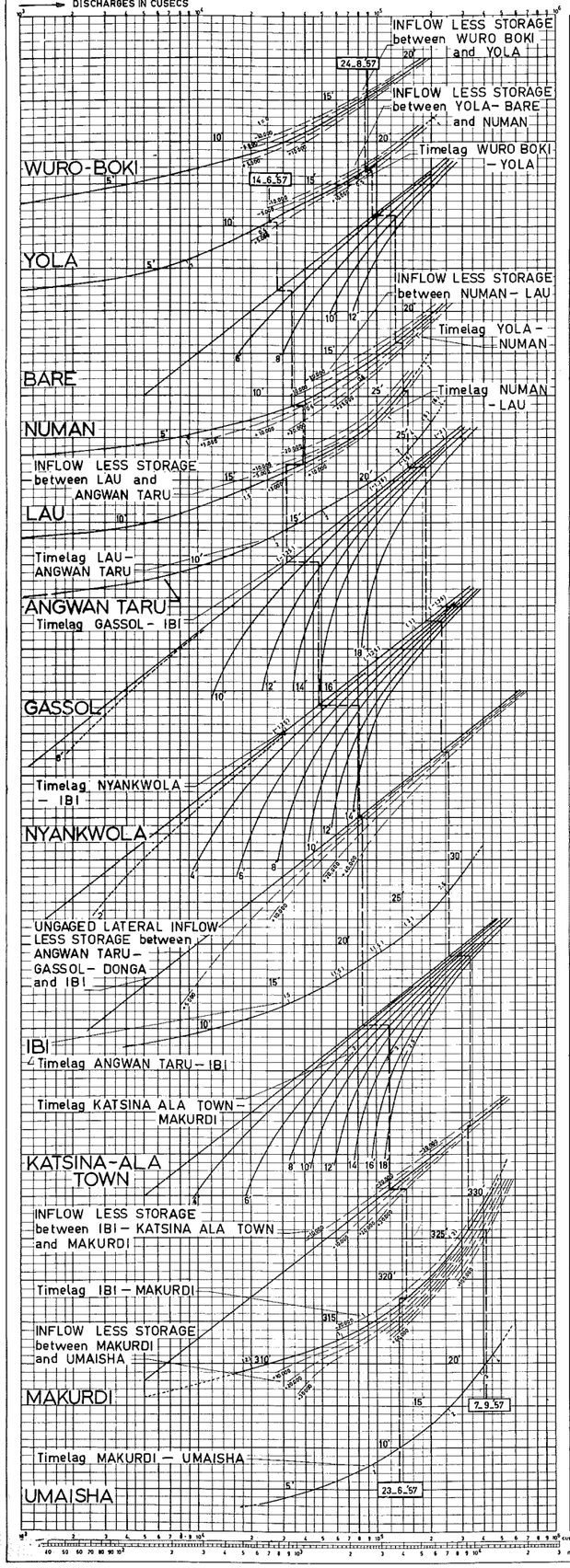
So, going from Angwan Taru to Ibi, the dotted line connecting the river-stages can be drawn, and the diagram shows that there has been only little inflow less storage between Angwan Taru—Gassol—Nyankwola and Ibi (5,000 cusecs).

Below Ibi, and only 26 miles above Makurdi, the Benue is joined by the Katsina Ala River. Along this river discharge rating curves are known for Sevav and for Katsina Ala Town. The latter is used here in the same form as used for Bare, Gassol and Nyankwola.

The distance between Katsina Ala Town and the confluence of the Katsina Ala River with the Benue is about 75 miles. Comparing this distance with the distance between the confluence and Makurdi (25 miles), it is concluded that the time-lag Katsina Ala Town—Makurdi depends for practical purposes only upon the river-stage at the former station. In the diagram the time-lag is, therefore, written across the lines of equal discharge of Katsina Ala Town.

The time-lag Ibi—Makurdi is written along the Makurdi rating curve and, for the water-levels as considered here, this is about $1\frac{1}{2}$ days. So $1\frac{1}{2}$ days after 1800 hrs. on June 19 (the last used time at Ibi) the water-level at Makurdi was 317′8″ as read on the gauge at the Railway Bridge (0600 hrs. on June 21). Two days before, the water-level at Katsina Ala Town was 9′6″. By drawing the dotted line between Ibi and Makurdi, it is seen that the inflow less storage into the river-stretch between Ibi—Katsina Ala Town and Makurdi has been considerable (30,000 cusecs).

For river-stages described here, the time-lag Makurdi—Umaisha is about 2 days. At 0600 hrs. on June 23 the Umaisha water-level was 10′0″. From the lines drawn along the Makurdi



WURO - BOKI mile 916
Area Drainage Basin between WURO - BOKI and YOLA : 900 sqmiles

YOLA - BENUE mile 888.2
Area Drainage Basin between YOLA - BARE and NUMAN : 3,100 sqmiles

BARE - GONGOLA mile 852
Drainage Area : 21,500 sqmiles Timelag BARE - NUMAN about 2 hours

NUMAN - BENUE mile 846.3
Area Drainage Basin between NUMAN and LAU : 3,600 sqmiles

LAU - BENUE mile 777.5
Area Drainage Basin between LAU and ANGWAN TARU : 9,900 sqmiles

ANGWAN TARU - BENUE mile 682.6
Drainage Area : 79,500 sqmiles

GASSOL - TARABA mile 690
Drainage Area : 8,240 sqmiles
Timelag GASSOL - IBI depends on IBI discharge

NYANKWOLA - DONGA R. mile 650
Drainage Area : 7,650 sqmiles
Timelag NYANKWOLA depends on IBI discharge

Area Drainage Basin between ANGWAN TARU - GASSOL - NYANKWOLA and IBI : 4,100 sqmiles

IBI - BENUE mile 614
Drainage Area : 99,500 sqmiles

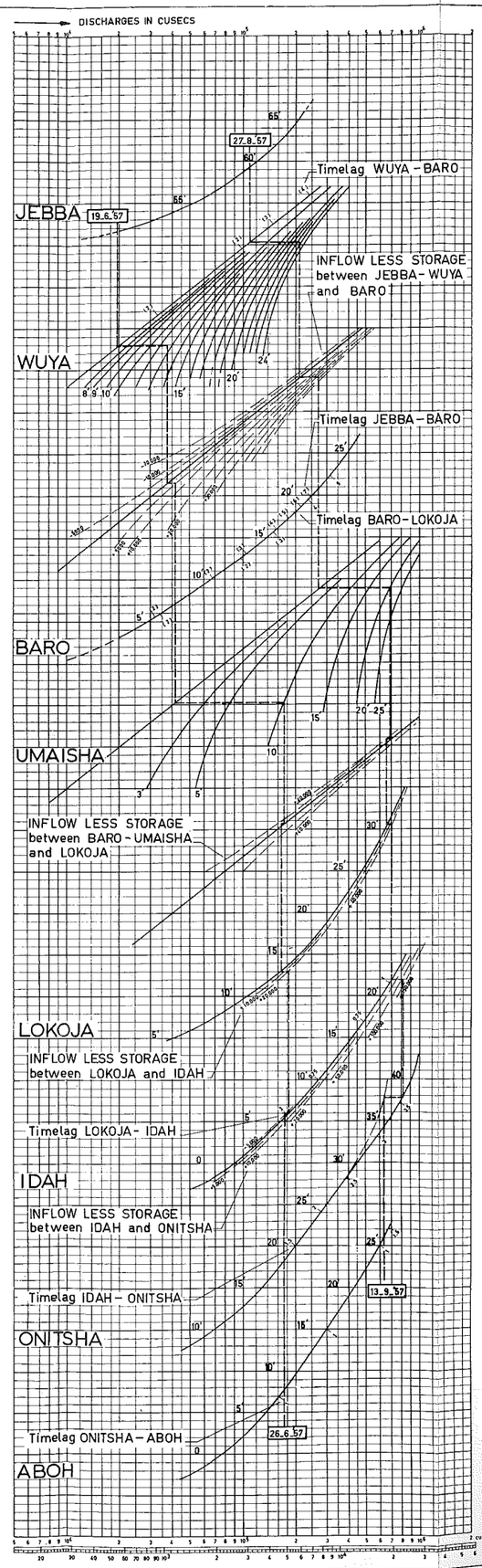
KATSINA-ALA TOWN - KATSINA-ALA R.
Drainage Area : 6,450 sqmiles

Area Drainage Basin between IBI - KATSINA-ALA TOWN and MAKURDI : 11 500 sq.miles

MAKURDI - BENUE mile 511.6 (Railway Gauge)
Drainage Area : 117,500 sqmiles
Area Drainage Basin between MAKURDI and UMAISHA : 11,400 sqmiles

UMAISHA - BENUE mile 400.6
Drainage Area : 128,900 sqmiles

TIMELAG in DAYS
STORAGE less INFLOW in cuft / sec.



JEBBA - NIGER mile 556

WUYA - KADUNA RIVER mile 515
Drainage Area 25,300 sqmiles Timelag WUYA - BARO depends on BARO discharge

Area Drainage Basin between JEBBA, WUYA and BARO 12,700 sqmiles

BARO - NIGER mile 434

UMAISHA - BENUE mile 400.6
Drainage Area 128,900 sqmiles Timelag UMAISHA - LOKOJA about half a day

Area Drainage Basin between BARO, UMAISHA and LOKOJA 9,100 sqmiles

LOKOJA - NIGER mile 362
Area Drainage Basin between LOKOJA and IDAH : 3,000 sqmiles

IDAH - NIGER mile 310
Area Drainage Basin between IDAH and ONITSHA : 7,000 sqmiles

ONITSHA - NIGER mile 232
During river stages higher than 28' ONITSHA gauge, a part of the NIGER discharge flows towards the ORASHI and ASE river.

Lateral inflow between ONITSHA and ABOH is negligable

TIMELAG in DAYS
STORAGE less INFLOW in cuft / sec.

NEDECO NIGER/BENUE	DIAGRAM III, 4.5.4-1
DISCHARGE RELATIONS NIGER-BENUE BASIN WITHIN NIGERIA	

rating curve and indicating inflow less storage, it is seen that at this moment the storage exceeded the inflow into the river-stretch between Makurdi and Umaisha by 10,000 cusecs.

The time-lag Umaisha—Lokoja is about $\frac{1}{2}$ day. At 1800 hrs. on June 23 the water-level at Lokoja was 13′0″.

For river-stages on the Niger above Lokoja, which occurred during the period here considered, the time-lag Jebba—Lokoja is about 4 days. To follow discharges from Jebba downstream, a start will be made with the Jebba water-level at 0600 hrs. on June 19 when it was 51′8″, corresponding with a discharge of practically 20,000 cusecs. The time-lag Jebba—Baro at this river-stage is about 2 days.

Between Jebba and Baro the Niger is joined by the Kaduna River, an important tributary which arrives from the Jos Plateau. A stage-discharge relation for Wuya, a station some 30 miles above the confluence, is known. For river-stages as considered here the time-lag Wuya—Baro will be about 2 days. On June 19 the water-level at Wuya was 12′6″. Adding the corresponding discharge to the Jebba discharge, and comparing the sum with the Baro discharge 2 days later (water-level 7′2″ and discharge 41,500 cusecs), it is found that the inflow less storage between Jebba-Wuya and Baro has been about 5,000 cusecs.

At Lokoja the Niger and the Benue join. To find the inflow less storage between Baro-Umaisha and Lokoja, the discharge at Lokoja 2 days after the Baro gauge read 7′2″ must be reduced by the discharges at Baro and at Umaisha, taking the time-lags into account. At 0600 hrs. on June 23 the Lokoja gauge-reading was 13′0″, from which there follows a discharge of 167,000 cusecs. The Benue is a tributary of the Niger, and analogous again to the stage-discharge relation of the Gongola at Bare, this relation has been drawn on the diagram in the form of a number of lines of equal discharge. The result of connecting the Baro rating curve via the curves for Umaisha with the Lokoja rating curve by the dotted line, is that the inflow less storage between Baro-Umaisha and Lokoja can be considered to have been about 10,000 cusecs.

For a Lokoja water-level of 13′, the time-lag Lokoja—Idah is 1 day. The water-level at Idah, 1 day after 0600 hrs. on June 23, namely 0600 hrs. on June 24, was 6′0″, corresponding to a discharge of 185,000 cusecs. From the graph it can be read that the inflow less storage has been 18,000 cusecs.

The time-lag Idah—Onitsha is at these water-levels about $1\frac{1}{2}$ days. At that time later at Onitsha the water-level was 18′7″, producing a discharge of 177,000 cusecs. From the diagram it follows that the storage between Idah and Onitsha exceeded the inflow by 8,000 cusecs.

The time-lag Onitsha—Aboh is 1 day at the river-stages discussed here, and at 1800 hrs. on June 26 the Aboh reading was 7′10″. The area which drains towards the Niger between Onitsha and Aboh is very small and the lateral inflow is negligible. From the diagram it follows that for the lower and medium stages the discharge at Aboh is practically equal to the discharge at Onitsha, the time-lag being taken into account.

The above discussion of the dependency of water-levels on those more upstream started for the Benue with the river-stage at Yola on June 14, 1957. Following the water-levels going downstream, the Niger was reached on June 23, so the time-lag Yola—Lokoja was 9 days. It has already been shown that the time-lag Jebba—Lokoja for the discussed water-levels was about 4 days. As Aboh has been reached on June 26, the time-lag Lokoja—Aboh was 3 days.

Analogous to the dotted line, which starts on June 14 at Yola, another line has been drawn to show how during higher river-stages water-levels downstream depend on those upstream. This line starts with the water-level of 15′5″ at Wuro Boki (Benue River) on August 24, 1957. Following this line, it is seen that on certain river-stretches the lateral inflow exceeds the storage,

where the converse had been the case during the June water-levels which have been considered above (Lau—Angwan Taru, Makurdi—Umaisha, Lokoja—Idah).

The other way round happens as well (Ibi—Katsina Ala Town—Makurdi). But generally it cannot be stated beforehand for a particular river-stretch which of the two, storage or inflow, will exceed the other. Mostly the storage at a certain river-stage depends only on the physical properties of the adjacent flood-plain, but the inflow is due to the occurrence of storms over the area draining into the river-stretch.

An exception to this takes place along the river-stretch Onitsha—Aboh. The area draining into the Niger along this stretch is very small, which makes the lateral inflow negligible. On the other hand, during the higher stages much water is flowing away towards the Ase and the Orashi, two rivers which run to the sea more or less parallel to the Niger (see Diagram 2.2.2-1). The amount of water leaving the Niger and going to these two rivers can be expressed as a function of the discharge at Onitsha. So, to one discharge at Onitsha belongs only one discharge at Aboh. At the upper end of the Onitsha rating curve on the diagram is indicated the amount of water with which the Onitsha discharge has to be reduced to find the Aboh discharge. The time-lag must, of course, be taken into account.

The second dotted line passes Yola on August 24, 1957, and arrives at Lokoja on September 7. So at these higher stages the time-lag Yola—Lokoja is 14 days. For the Niger the line starts at Jebba on August 27, which shows the time-lag between Jebba and Lokoja to be about 11 days. As the dotted line ends on September 15 at Aboh, the time-lag Lokoja—Aboh has been 6 days for the river-stages here discussed.

The importance of this diagram, apart from reconstructing the propagation of flood waves, is that it forms a basis for predictions of water-levels and discharges (see VI, 3.6).

b. *Outside Nigeria*

Discharge relations upstream from Wuro Boki have been established by the French investigators (see VI, 3.6.3). Discharge relations on the Niger upstream from Jebba as far as the Timbuctu area and their connection with the discharge at Baro will now be discussed.

The Black Flood in Nigeria (as already mentioned in 2.3) has a narrow relation with the discharge of the Niger in the interior delta. As the crest of this flood passes Baro during the months of January up to April inclusive, it creates good possibilities for the navigation on the Niger, which would in this period be just as dry as the Benue but for this second flood. Thus it seems worthwhile to establish relationship between the water-levels of the Niger at Diré and those at Baro, together with a definite time-lag between these two stations.

For this purpose the behaviour of the Black Flood for the period 1914—1958 has been studied. The available basic data are:

(i) The average annual discharge of the Niger at Koulikoro, approximately 450 miles upstream from Diré, for the period 1914—1956, except for a gap of two years 1946-47 and 1947-48;

(ii) the yearly maximum water-levels at Diré since 1923;

(iii) the yearly maximum discharges of the Black Flood at Niamey, approximately 600 miles downstream from Diré, for 22 years out of the period under consideration: and

(iv) the water-level readings at Baro since 1914.

In Diagram 4.5.4-2 the yearly maximum water-levels at Diré are plotted against the average yearly discharge of the Niger at Koulikoro and a graph has been drawn. With the use of this graph the maximum water-levels at Diré for the period 1914—1923 have been estimated from the available data at Koulikoro.

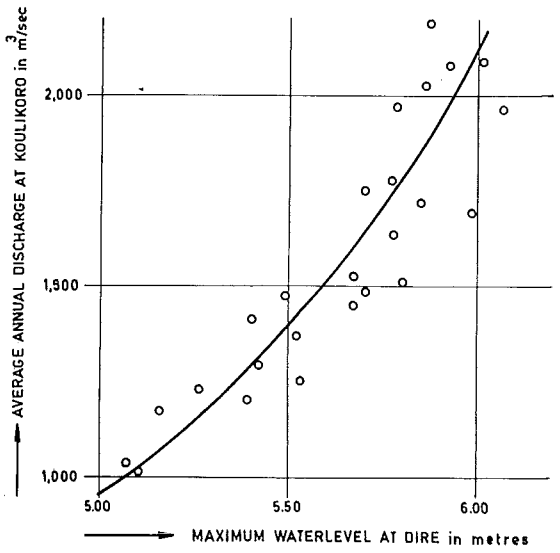


DIAGRAM 4.5.4-2

Yearly maximum water-levels at Diré as a function of the average yearly discharge of the Niger at Koulikoro

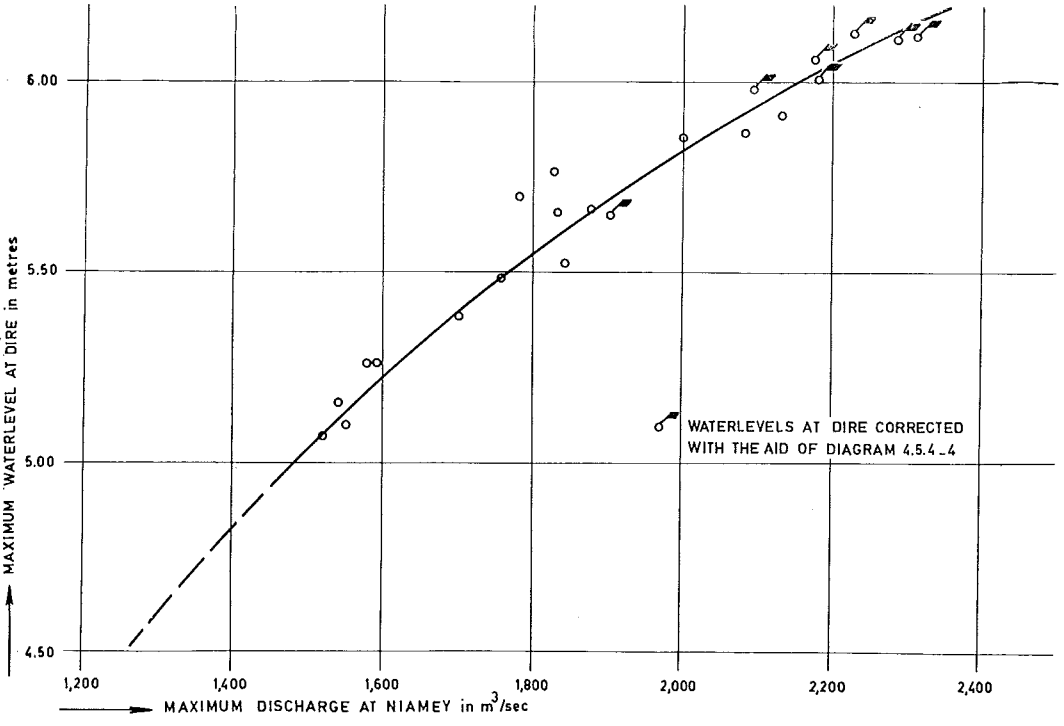


DIAGRAM 4.5.4-3

Maximum black flood discharges at Niamey as a function of maximum water-levels at Diré

By comparing the maximum water-levels at Diré with the maximum discharges of the Black Flood at Niamey, a relation is obtained in Diagram 4.5.4-3 between them, and with this graph the missing maximum discharges at Niamey have been determined. It must be understood, however, that the maximum water-levels at Niamey, derived from the estimated maximum water-levels at Diré for the period 1914—1923, are less accurate, because of the double approximation, than those calculated directly with water-level records of Diré.

In 1952 the gauge at Niamey was replaced by the M.E.A.N. (1 by another one and when comparing the readings over the rather short period during which both gauges were read, it is found (Diagram 4.5.4-4) that the water-level on the new gauge rises faster than on the old one.

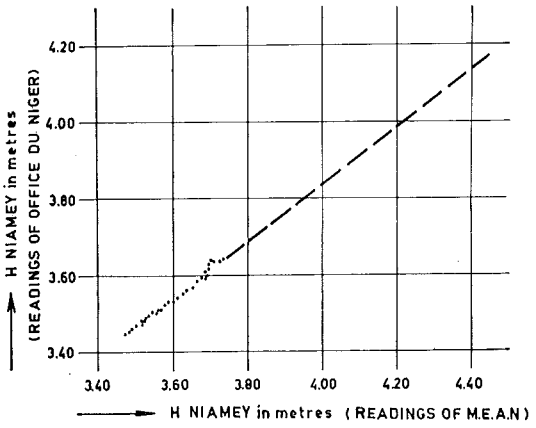


DIAGRAM 4.5.4-4

Relation between water-levels as observed on the old and new gauges at Niamey

To prevent a discrepancy in the comparison of data originating from two gauges, the maximum readings at the new gauge have been converted into those as would have been read at the old gauge with the use of Graph 4.5.4-4. To determine the maximum discharge from these converted water-levels of Niamey, the original discharge rating curve of Niamey published by REFFAY (2 has been used.

The gauge readings at Baro, put together with the discharge rating curve as determined by NEDECO, gives the maximum discharges of the Black Flood at Baro.

The results of the above-mentioned computations are given in Table 4.5.4-5, columns 1—5, while in column 6 the differences between the maximum discharges of the Black Flood at Niamey and Baro respectively are given.

From this tabel at first sight 4 periods can be observed, namely,

(i) 1914/15—1921/22 inclusive during which the average of col. 6 = + 70 m^3/sec

(ii) 1922/23—1933/34 inclusive during which the average of col. 6 = — 140 m^3/sec

(iii) 1934/35—1954/55 inclusive during which the average of col. 6 = + 170 m^3/sec

(iv) 1955/56—1957/58 inclusive during which the average of col. 6 = — 125 m^3/sec

(1 Mission d'Etudes et Aménagement du Niger
(2 REFFAY, 1948. HYD. 9

TABLE 4.5.4-5.

CALCULATION OF CORRECTION ON BARO GAUGE READINGS

(1) year	(2) average discharge at Koulikoro m³/sec	(3) maximum water-level at Diré m	(4) maximum discharge at Niamey m³/sec	(5) maximum discharge at Baro m³/sec	(6) col. (5) minus col. (4) m³/sec	(7) average of col. (6) m³/sec	(8) corrected discharge at Baro m³/sec	(9) col. (8) minus col. (4) m³/sec	(10) average of col. (9) m³/sec	
1914/15	920	(4.95)	((1,450))	1,550	+ 100		1,360	− 90		
1915/16	1,400	(5.50)	((1,765))	1,810	+ 45		1,600	− 165		
1916/17	1,365	(5.47)	((1,740))	—	—		—	—		
1917/18	1,485	(5.57)	((1,810))	1,835	+ 25	+ 70	1,620	− 190	− 135	I
1918/19	1,555	(5.63)	((1,850))	1,940	+ 90		1,710	− 140		
1919/20	1,380	(5.48)	((1,750))	1,760	+ 10		1,560	− 190		
1920/21	1,240	(5.35)	((1,670))	1,700	+ 30		1,510	− 160		
1921/22	1,035	(5.12)	((1,540))	1,720	+ 180		1,530	− 10		
1922/23	1,505	(5.59)	((1,825))	1,720	− 105		—	—		
1923/24	1,550	(5.40)	((1,700))	1,640	− 60		—	—		
1924/25	2,250	5.80	(1.980)	1.930	− 50		—	—		
1925/26	2,400	5.87	(2,040)	1,860	− 180		—	—		
1926/27	1,685	5.32	(1,650)	1,620	− 30		—	—		
1927/28	1,975	5.78	(1,965)	1,830	− 135	− 140	—	—		II
1928/29	2,190	5.87	2.080	1,830	− 250		—	—		
1929/30	2,080	5.92	2,130	1,900	− 230		—	—		
1930/31	2,030	5.86	2,000	1,760	− 240		—	—		
1931/32	1,750	5.70	1,780	1,830	+ 50		—	—		
1932/33	1,780	5.77	(1.960)	1,710	− 250		—	—		
1933/34	1,635	5.77	1,825	1,650	− 175		—	—		
1934/35	1,475	5.49	1,755	1,830	+ 75		1,560	− 195		
1935/36	1,450	5.67	1,830	1,890	+ 60		1,600	− 230		
1936/37	1,720	5.85	(2,025)	1,960	− 65		1,660	− 365		
1937/38	1,295	5.42	(1,710)	1,750	+ 40		1,490	− 220		
1938/39	1,485	5.70	(1,900)	1,900	0		1,610	− 290		
1939/40	1,370	5.52	(1,775)	1,900	+ 125		1,610	− 165		
1940/41	1,175	5.16	1,540	1,760	+ 220		1,495	− 45		
1941/42	1,230	5.26	1,590	1,740	+ 150		1,480	− 110		
1942/43	1,025	5.07	1,515	1,650	+ 135		1,405	− 110		
1943/44	1,200	5.39	1,700	1,910	+ 210		1,620	− 80		
1944/45	1,010	5.10	1,550	1,830	+ 280	+ 170	1,560	+ 10	− 135	III
1945/46	1,250	5.53	1,840	—	—		—	—		
1946/47	1,530	5.67	1,875	2,050	+ 175		1,735	− 140		
1947/48	—	5.26	1,580	1,900	+ 320		1,610	− 130		
1948/49	—	5.50	(1,770)	1,950	+ 180		1,650	—		
1949/50	1,412	5.40	(1,700)	1,950	+ 250		1,650	− 50		
1950/51	1,510	5.80	(1,985)	—	—		—	—		
1951/52	2,093	6.01	2,180(1	2,420	+ 240		2,050	− 130		
1952/53	1,693	5.98	2,090(1	2,420	+ 330		2,050	− 40		
1953/54	1,966	6.06	2,170(1	2,445	+ 275		2,080	— 90		
1954/55	2,061	6.13	2,225(1	2,480	+ 255		2,110	− 115		
1955/56	2,064	6.12	2,310(1	2,225	− 75		—	—		
1956/57	—	5.65	1,900(1	1,830	− 70	125	—	—		IV
1957/58	—	6.11	2,285(1	2,050	− 235		—	—		

(1 Niamey water-levels corrected with Diagram 4.5.4-4.
( ) derived from basic data.
(( )) estimated from a derived figure.

To explain these discontinuities, it is necessary to study the history of the gauge at Baro.

Between September 26, 1922 and October 7, 1922, no readings of the gauge at Baro are available. As this period coincides with the H.W.-period of the Niger, the gauge was probably damaged by the Flood and it is quite possible that while re-erecting the gauge a change of the zero-mark occurred.

According to correspondence in old Marine files, there was in 1934 a difference of opinion between the Divisional Marine Officer at Lokoja and the U.A.C. agent at Baro about the correct zero-mark of the gauge at Baro, after the gauge had been repainted.

Observations of the Divisional Marine Officer led to the conclusion that the concrete base on which the gauge is placed corresponds with a reading of six feet. The U.A.C. agent, on the contrary, maintained that this base corresponded with five feet, and that all the readings of the previ us years had been based on this level.

The Divisional Marine Officer requested to base all future readings (i.e., after a certain date somewhere in 1934) on his observation.

Here lies the possibility of a difference of one foot in the readings before and the readings after 1934.

The gauge at Baro as used by the survey of NEDECO has been levelled in 1955 to a benchmark probably established in 1952. According to this benchmark, the zero-mark of the gauges at Baro is situated 33'6" below the benchmark.

This benchmark makes it difficult to explain the discontinuity between the second and the third periods, as the gauge during both periods is said to be based on the same benchmark.

The only possibility lies in an error of 1 foot during the establishment of the benchmark in 1952, the levelling of NEDECO being beyond doubt, because of the frequent re-levelling of the gauge at Baro in the course of the routine check-up of the gauges.

As the levelling from the benchmark to the old gauge in 1952 gives a reading of 33'6" on the gauge, it is quite possible that there has been a mistake of one foot. Diagram 4.5.4-6 shows how a reading of 34'6" on the gauge can be easily misinterpreted as a reading of 33'6" on the levelling instrument. This kind of mistake occurs quite often, especially with a reading of some feet and about *six* inches.

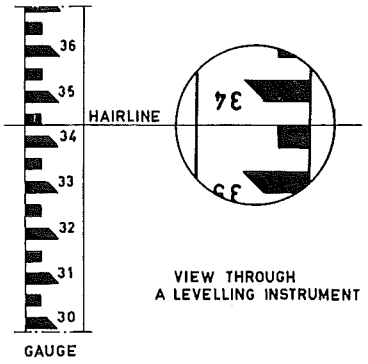


DIAGRAM 4.5.4-6

34'6" on the gauge at Baro

As a basis for further calculations it is assumed that over the third period, i.e., 1934/35—1954/55 inclusive, one foot is to be subtracted from all readings on Baro gauge to make them comparable with those of the second and fourth periods.

In Table 4.5.4-5 the maximum discharges of the Black Flood at Baro and Niamey are compared when this correction is applied (columns 8, 9 and 10) and the average difference of — 135 m³/sec over the third period is in accordance with the average differences found over the second and and fourth periods.

TABLE 4.5.4-7.

WATER-LEVELS AT DIRÉ FROM WHICH CERTAIN WATER-LEVELS AT BARO ORIGINATE.

(1) water-level at Baro feet	(2) discharge at Baro m³/sec	(3) discharge at Niamey m³/sec	(4) water-level at Diré m	(5) discharge at Diré m³/sec
7'0"	1,145	1,280	4.63	1,450
8'0"	1,355	1,490	5.01	1,710
9'0"	1,600	1,735	5.45	2,030
10'0"	1,885	2,020	5.85	2,400
10'6"	2,050	2,185	6.03	2,620

Explanation:

Column (1) → (2) discharge rating curve of Baro.

Column (3) = column (2) + 135 m³/sec (columns (7) and (10) of Table 4.5.4—4)

Column (3) → (4) with Diagram 4.5.4-2

Column (4) → (5) discharge rating curve of Diré.

To find an acceptable correction over the first period it is assumed that the said difference also has to be — 135 m³/sec This leads to a correction of minus 9 inches for all readings before the H.W.-period of 1922.

In the foregoing all relations are between maximum water-levels and maximum discharges of the Black Flood. If it is assumed that these relations are also valid when they do not concern the maxima, Table 4.5.4-7 gives the water-levels at Diré from which certain water-levels at Baro originate.

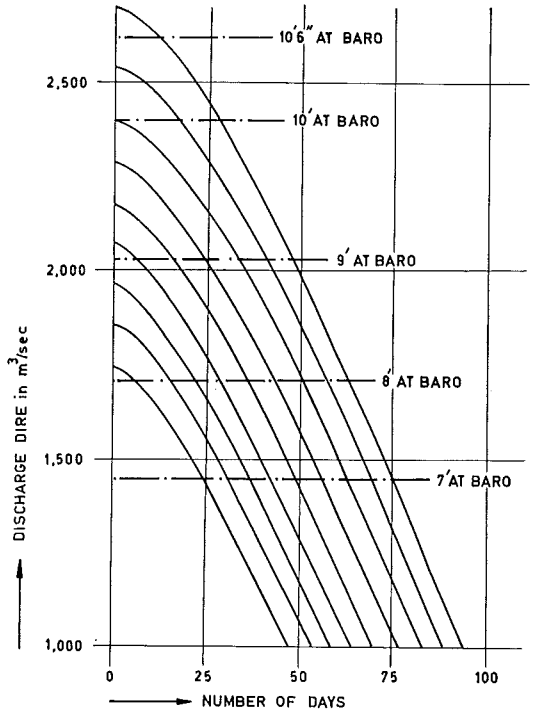


DIAGRAM 4.5.4-8

Recession curves for Diré

As the fall of the discharge at Diré is rather uniform and is found to be a function of the maximum discharge, the discharges at Diré, as mentioned in the last column of Table 4.5.4-7, can be linked to the maximum discharge at Diré with the use of Diagram 4.5.4-8. From this graph the time-lag between a certain maximum water-level at Diré and the discharge at Diré, which is the origin for a certain water-level at Baro, can be concluded. By subtraction of this time-lag from the time which elapses between the moment of maximum water-level at Diré and the occurrence of the said water-level at Baro, the time-lag of the phenomenon itself (i.e., discharge Diré linked to water-level Baro) can be determined. Such calculation has been carried out in Table 4.5.4-9.

Some of these readings, however, are disturbed by an early rainfall in Nigeria, thus giving a false picture of the time-lag. The discharge at Baro in that case is not completely due to the Black Flood only and the figures of those years are to be omitted. Another source of inaccuracy lies in comparing a water-level to a discharge which occurs very near to the top level of a certain

TABLE 4.5.4-9

RELATION BETWEEN WATER-LEVELS AT DIRÉ AND BARO

(1) year	(2) H max. at Diré in metres	(3) date of H max. at Diré	(4) date of H Baro = 10 ft	(5) col(3) minus col(4)	(6) timelag from graph 7	(7) col(5) minus col(6)	(8) date H Baro = 9 ft	(9) col(3) minus col(8)	(10) timelag from graph 7	(11) col(9) minus col(10)	(12) date H Baro = 8 ft	(13) col(3) minus col(12)	(14) timelag from graph 7	(15) col(3) — col(14)	(16) date H Baro = 7 ft	(17) col(3) minus col(16)	(18) timelag from graph 7	(19) col(17) minus col(18)
1924/25	5.80	1- 1-'25	—	—	—	—	4-5-'25	123	30	93 (1	11-5-'25	130	48	82 (1	20-5-'25	139	60	79 (1
1925/26	5.87	10- 1-'26	—	—	—	—	13-5-'26	123	35	88 (1	29-5-'26	139	52	87 (1	—	—	—	—
1926/27	5.32	19-12-'26	—	—	—	—	10-3-'27	81	—	81	27-3-'27	97	20	77	5-4-'27	106	34	72 (
1927/28	5.78	10- 1-'28	—	—	—	—	6-5-'28	116	29	87 (1	17-5-'28	127	47	80 (1	8-6-'28	149	59	90 (1
1928/29	5.87	5- 1-'29	—	—	—	—	2-5-'29	117	35	82	13-5-'29	128	52	76	21-5-'29	136	64	72
1929/30	5.92	6- 1-'30	—	—	—	—	1-5-'30	115	39	76	13-5-'30	127	55	72	24-5-'30	138	67	71
1930/31	5.86	20-12-'30	—	—	—	—	12-4-'31	113	36	77	16-5-'31	147	52	95 (1	28-5-'31	159	64	95 (1
1931/32	5.70	14-12-'31	—	—	—	—	19-3-'32	95	22	73	8-4-'32	114	41	73	15-4-'32	121	54	67
1932/33	5.77	5- 1-'33	—	—	—	—	10-4-'33	95	28	67	26-4-'33	121	46	75	4-5-'33	129	58	71
1933/34	5.77	29-12-'33	—	—	—	—	30-3-'34	91	28	63	21-4-'34	112	46	66	29-4-'34	120	58	62
1934/35	5.49	23-12-'34	—	—	—	—	—	—	—	—	30-3-'35	96	28	68	8-4-'35	105	42	63
1935/36	5.67	26-12-'35	—	—	—	—	25-3-'36	89	20	69	7-4-'36	102	39	63	14-4-'36	109	52	57
1936/37	5.85	30-12-'36	—	—	—	—	12-4-'37	103	34	69	23-4-'37	114	51	63	30-4-'37	121	63	58
1937/38	5.42	23-12-'37	—	—	—	—	—	—	—	—	17-3-'38	84	25	59	28-3-'38	95	39	56
1938/39	5.70	26-12-'38	—	—	—	—	—	—	—	—	7-4-'39	102	41	61	19-4-'39	114	54	60
1939/40	5.52	30-12-'39	—	—	—	—	17-3-'40	77	8	69	9-4-'40	100	30	70	18-4-'40	109	43	66
1940/41	5.16	19-12-'40	—	—	—	—	—	—	—	—	9-3-'41	80	11	69	21-3-'41	92	28	64
1941/42	5.26	14-12-'41	—	—	—	—	—	—	—	—	11-3-'42	87	17	70	22-3-'42	98	32	66
1942/43	5.07	3-12-'42	—	—	—	—	—	—	—	—	22-2-'43	81	5	76	5-3-'43	92	24	68
1943/44	5.39	11-12-'43	—	—	—	—	25-2-'44	76	—	76	18-3-'44	97	24	73	24-3-'44	103	37	66
1944/45	5.10	6-12-'44	—	—	—	—	—	—	—	—	28-2-'45	84	7	77	8-3-'45	92	25	67
1945/46	5.53	24-12-'45	—	—	—	—	—	—	—	—	4-4-'46	101	30	71	10-4-'46	107	44	63
1946/47	5.67	25-12-'46	—	—	—	—	6-4-'47	102	20	78	16-4-'47	112	39	73	23-4-'47	119	52	67
1947/48	5.26	11-12-'47	—	—	—	—	25-2-'48	76	—	76	10-3-'48	89	17	72	16-3-'48	95	32	63
1948/49	5.50	20-12-'48	—	—	—	—	17-3-'49	87	7	80	25-3-'49	95	29	66	4-4-'49	105	42	63
1949/50	5.40	15-12-'49	—	—	—	—	—	—	—	—	17-3-'50	92	24	68	25-3-'50	100	37	63
1950/51	5.80	1- 1-'51	—	—	—	—	unreliable	—	—	—	unreliable	—	—	—	unreliable	—	—	—
1951/52	6.01	5- 1-'52	—	—	—	—	unreliable	—	—	—	unreliable	—	—	—	unreliable	—	—	—
1925/53	5.98	1- 1-'53	19-4-'53	109	19	90	30-4-'53	120	43	77	7-5-'53	127	58	69	14-5-'53	134	70	64
1953/54	6.06	27-12-'53	20-4-'54	103	25	78	4-5-'54	127	48	79	10-5-'54	133	61	72	15-5-'54	138	73	65
1954/55	6.13	7- 1-'55	unreliable	—	—	—	unreliable	—	—	—	unreliable	—	—	—	unreliable	—	—	—
1955/56	6.12	3- 1-'56	24-4-'56	111	30	81	9-5-'56	126	50	76	14-5-'56	131	63	68	21-5-'56	138	75	63
1956/57	5.65	26-12-'56	—	—	—	—	31-3-'57	95	19	76	13-4-'57	108	38	70	17-4-'57	122	51	71
1957/58	6.11	11- 1-'58	3-5-'58	112	29	83	17-5-'58	126	49	77	21-5-'58	130	63	67	29-5-'58	138	75	63
					Average	83				76				70				65

(1 Disturbed by an early rainfall in the catchment area of Baro

year. A difference of one inch, or some tens of m^3/sec, may give a difference of 10 or more days in the time-lag; these figures also are to be omitted.

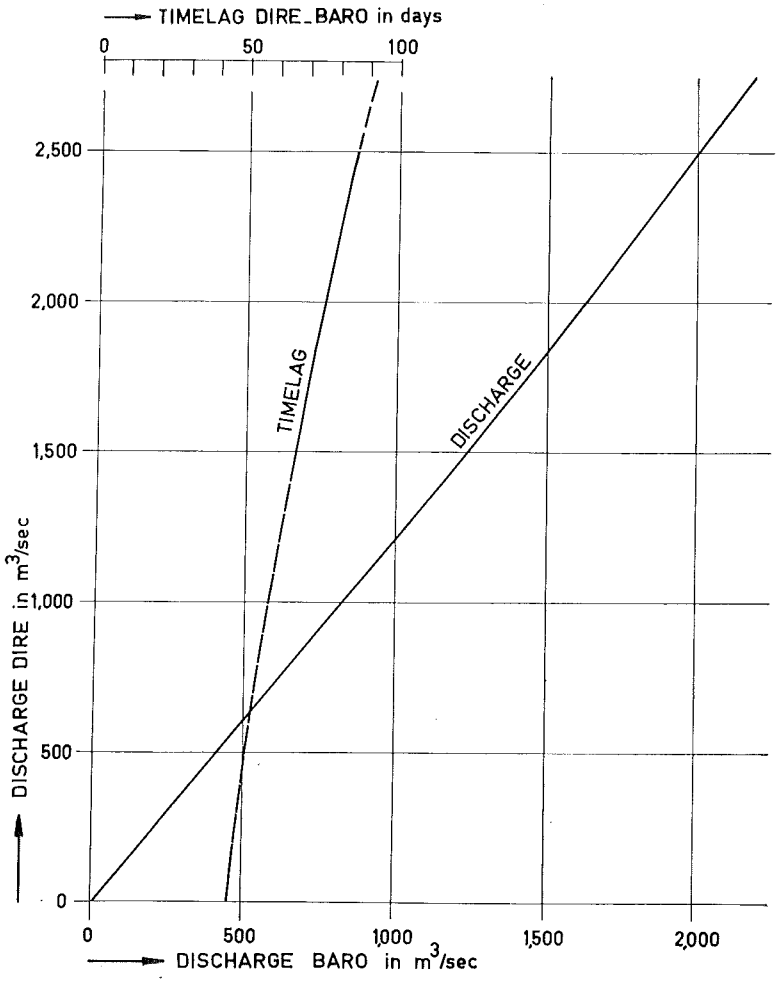


DIAGRAM 4.5.4-10

Relation and time-lag of discharges at Diré and Baro

The divergence of the average of the time-lag is about one week, which is only about 10% of the total time-lag. This result makes it possible to produce a rather accurate prediction of the water-levels at Baro, during the Black Flood period, from the maximum water-levels at Diré two to four months ahead (see VI, 3.6.2).

The results as found in Table 4.5.4-9 are plotted in Diagram 4.5.4-10 which shows how, from a given discharge at Diré, a certain discharge results at Baro after a definite number of days.

CHAPTER 5

TRANSPORT OF SEDIMENTS

5.1. SEDIMENTS

5.1.1. Solids carried by the flow

Insight into and knowledge of the water discharge in a river, its mechanism and the variation of its pattern is undoubtedly essential for various purposes, but the formation and deformation of the river-bed cannot be considered without a study of sediment transport, as that is the main factor determining the behaviour of the bed and the boundary conditions.

Sediment is a major problem in the control of a river. Every man-made intervention in natural conditions of the system will be followed by changes of sediment transport, scour or deposition. Qualitative and quantitative knowledge of the mechanism of sediment transport will lead to an insight into the expected results of artificial intervention and will decrease the chance of failures, of which there have been so many in history.

Sediment originates in erosion of the drainage basin. Every year the rains which fall on the earth's surface carry soil particles down into the river. The major part of the sediment comes from the mountain areas with their torrent streams and severe erosion. Geologically, no mountain will stand the continuous attack of water, and the ultimate result is a peneplain with a drainage system of very slowly flowing rivers without any sediment transport.

But it is not only the mountains; for the greater part of the country with its more or less hilly landscape is affected by erosion. Gulleys, expanding swiftly in all directions, destroy farmlands and endanger roads and bridges. And when the finest particles of the top layer of the land have been washed away, there remains a poor structure without much fertility and with no capacity to retain the rain-water. Shortly after the rains have stopped, the soil becomes dry again, the vegetation encounters hard circumstances and the productive capacity of the ground will be small in both quality and quantity.

Determinant causes of erosion include:

(i) burning the country by which all rotting vegetable remainders, normally making a good mould, disappear into smoke; whilst young vegetation, very useful for preventing the rain from beating the earth's surface and from demolishing the structure of the soil, cannot grow but is killed by the fire;

(ii) cutting forests over large areas; and

(iii) injudicious ploughing, with furrows not running along the horizontal contour lines, and instead forming artificial rivulets with an extra easy discharging capacity of the rain-water.

So far, however, the damage done to the country in Nigeria is still small, and activities on soil conservation could undoubtedly prevent serious extension of the erosion.

Sediment transport has been subject to investigation for many centuries, but only recently have modern hydraulics given a proper scientific background to the experiments.

Distinction is now made between three different kinds of transport.

Firstly, there is *suspended load*, where the solids are continuously supported by the water and do not sink down because their weight is compensated by the upward directed force of the turbulence of the stream. Consequently the size of the solids must be relatively small. This transport is measured by an instrument called "Delft Bottle DF_1", as described under II, 3.5.3.c. Suspended load is dealt with in 5.3.1.

The second way of transport concerns the solids of a slightly larger size. These grains cannot remain in suspension because their weight takes them down onto the bottom; occasionally, however, great turbulence vortices exert sudden forces in such a way that the solids more or less jump up and down, although finally returning normally to the river-bed. This form of transport is termed here *saltation-load*, and is measured by a "Delft Bottle DF_2" as described under II, 3.5.3.b which comprehensively covers the layers between 4 and 16 inches above the bed, where it is assumed that the majority of saltation-load takes place.

Finally, there are the larger grains of the material carried by the river which roll and slide over each other but do hardly rise from the bottom. Their movement is extended some distance into the bottom, with an exchange of grains from different layers. This *bed-load* is measured by the Bed-load Transport Meter "Arnhem", BTMA, as described under II, 3.5.3. The size of the grains can extend up to that of boulders, depending on the transporting capacity of the stream. Saltation-load and bed-load are dealt with under 5.2.

Generally in a river the size of the solids decreases gradually in a downstream direction, due to exchange of grains between river-bed and valley, to wear of the grains by friction and to disintegration by weathering. This decrease normally, according to YATSU (1, discontinues at the size of about 4 mm, where a sudden decrease to 1 to 2 mm takes place, which may be explained by petrographical considerations. In tropical regions, however, the composition of the drainage basin is such that occurrence of grains of a size larger than the 2 mm is not very probable in the alluvial courses of a river, so that the discontinuity mentioned does not come into consideration. The sizes of the grains met in the Nigerian rivers are, indeed, mostly smaller than 2 mm.

In this investigation samples have been taken from the yield of the instruments DF_1, DF_2 and BTMA of nearly every sand measurement. In addition, along the total length of the Niger from Jebba to Burutu and along the Benue from Garua to Lokoja, bottom samples (which are samples of the material composing the river-bed) have been collected with the grab or scraper (see II, 3.5.1) at specific intervals, mostly three samples in one cross-section, viz., left, middle and right.

BTMA and bottom samples were transferred into small gunny bags. Where the amount caught was too large, the reduction method of square partition was carried out. The quantities of sand from the DF_1 and DF_2 were always rather small, and were carefully collected in glass tubes. All samples were taken to Lokoja, where the laboratory undertook sieving after the sample had been dried in a stove. To avoid any personal influence upon the result, a sieving machine was used which shook the set of sieves constantly for a period of five minutes. The sieves in use had openings of respectively 11.2, 5.6, 2.8,1.4, 0.6, 0.3, 0.15, 0.09, 0.075 and 0.06 mm (1 mm = 0.04 inches).

Weighing of the partitioned quantities was done on a scale with an accuracy of 0.1 gram. The percentage of each part compared with the total quantity of the whole sample was computed and plotted on semi-logarithmic paper, as shown in Diagram 5.1.1-1.

(1 YATSU, 1955. MOR. 33

The total number of samples taken by NEDECO during the three years of investigation was about 3,000. This may seem very high, but when compared, for instance, with the Rhine in the Netherlands, it is very small. Table 5.1.1-2 shows that the average number of samples per mile river-length for the Niger and Benue is only about 2.7, whilst the Rhine below Lobith has been

RECEIVED	19-7-'57	SIEVE OPENING	WEIGHT REMAINING ON SIEVE	% REMAINING ON SIEVE	% PASSING THROUGH SIEVE.
DRIED	2-8-'57				
DISH Nº	3	11.2	0	0	100
SIEVE	5-8-'57	5.6	1.5	1.2	98.8
L.N.-ANWAM 1-7-'57 position II 180 m from L.O. BTMA.		2.8	6.1	4.7	95.3
		1.4	20.3	15.8	84.2
		0.6	45.7	35.6	64.4
		0.3	98.2	76.5	23.5
		0.15	127.0	98.8	1.2
		0.105	128.2	99.8	0.2
		0.09	128.3	99.9	0.1
		0.075	128.4	99.9	0.1
		0.06	128.5	100	0
		less	128.5	100	0
		TOTAL	128.5	100	

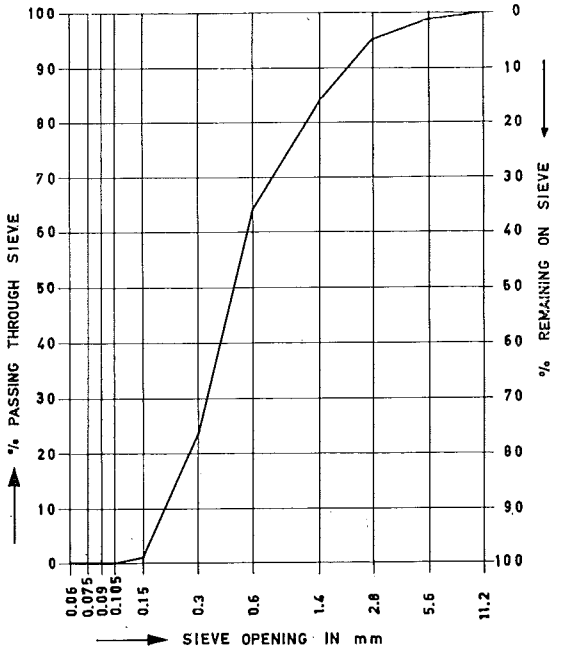


DIAGRAM 5.1.1-1

Example of analysis of a sediment sample

sampled with a frequency of some 500 samples per mile river-length. But it was not, of course, possible even to try to equal this frequency with the two rivers now under survey, if only because of the short period available.

It is, however, strongly advisable to continue the collection of data about the size of grains in the Nigerian rivers on the same or even on a higher production scale, because the spread of

TABLE 5.1.1-2

NUMBER OF SAMPLES TAKEN

	TOTAL MILEAGE	number of samples per mile	1955	1956	1957	1958	TOTAL
Upper Niger Jebba-Lokoja	190	5.0	305	402	131	111	949
Lower Niger Lokoja-Burutu	320	2.8	201	331	253	117	902
Upper Benue Garua-Ibi	360	1.8	193	190	279	—	662
Lower Benue Ibi-Lokoja	250	1.8	125	243	92	—	460

the few figures is too great to provide an accurate result, and the grain-size as a basic information about the river will be used in calculations on many subjects.

5.1.2. Grain-sizes

The sieve-curve, an example of which is given in Diagram 5.1.1-1, as a whole gives a good picture of the sediment material, composed of various fractions with different grain-sizes. However, it is not possible to represent the mixture by a single figure. A proper indication of the composition can only be shown by three or four figures, each of which gives the size of opening of a hypothetical sieve through which a certain weight-percentage of the mixtures passes. The figures in use are d_{10}, d_{50}, and d_{90}, and sometimes also d_{60}, all expressed in mm. The index indicates the passing percentage. In Diagram 5.1.2-1 a sieve-curve has been drawn and the corresponding figures for d_{10}, d_{50} and d_{90} computed.

Obviously, d_{50} represents a useful grain-size of the mixture. However, as the range of the diameters and the shape of the sieve-curve do not have any influence upon the magnitude of this figure, a so-called "mean-diameter" is therefore used, d_m, defined with

$$\frac{1}{d_m} = \frac{1}{100} \sum \frac{\Delta p}{d}$$

where Δp = interval in percentage

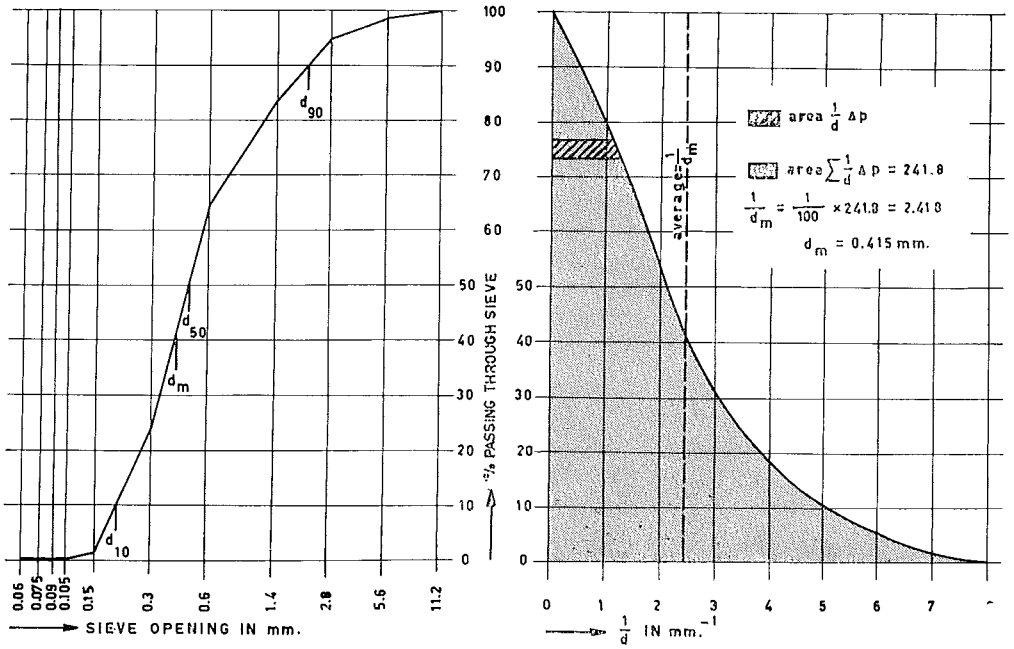


DIAGRAM 5.1.2-1

Computations with a sieve-curve

This mean diameter has been calculated in the right-hand section of Diagram 5.1.2-1.

It appears that d_m does not normally differ greatly from either d_{50} or sometimes d_{60}. Since calculating d_m takes much time, it is thought to be of sufficient accuracy to use in hydrological computations either d_{50} or d_{60} instead of d_m. In a later stage, when more precise data and infor-

mation about the river have been collected in the course of many years of investigation, it might be necessary to change over to the use of d_m, but for the present, this is not advisable.

From the sieve-curves of the 3,000 samples mentioned, grain-sizes have been derived.

In accordance with Paragraph 5.1.1, distinction is made between four groups of grains: samples from the bottom, from the BTMA, from the DF_2 and from the DF_1. A fifth group of material, the silt, has been dealt with in 5.3.2.

a. *Bottom samples* have been taken along the entire length of the river, and Table 5.1.2-2 shows where, when and with what frequency they have been taken.

After sieving, the characteristic figures d_{10}, d_{50}, d_{60} and d_{90} have been determined and collected in Table 5.1.2-3, giving the average for these figures per river stretch. Division in stretches on the Benue and on the Upper Niger has been based upon the occurrence of tributaries which affect the grain-size below their confluences with the main river; whilst on the Lower Niger division has been made on the basis of differences of boundary conditions (width, composition of the banks, etc.).

TABLE 5.1.2-2

COLLECTION OF BOTTOM SAMPLES ALONG THE RIVERS

riverstretch	mileage	sampled in	every	location in cross-section
Niger				
Jebba—Baro	562—434	Oct. 1955	10 km	M
Baro—Lokoja	434—360	Jan. 1956	5 km	M
		July 1956	5 km	LMR
Lokoja—Idah	360—310	Jan. 1956	5 km	M
		Feb. 1958	5 km	LMR
Idah—Aboh	310—178	Jan. 1956	5 km	LMR
Aboh—Samabri	178—157	Jan. 1956	5 km	LMR
		Apr. 1958	3 miles	LMR
Samabri—Burutu	157— 40	Apr. 1958	3 miles	LMR
Benue				
Garua—Faro	972—925	occasional samples		
Faro—Gongola	925—846	July 1955	15 km	LMR
Gongola—Taraba	846—673	June 1955	20 km	LMR
Taraba—Donga	673—632	June 1955	20 km	M
Donga—K'Ala	632—537	July 1955	20 km	LMR
		Sept. 1956	5 km	M
K'Ala—Lokoja	537—361	July 1955	20 km	LMR
		Sept. 1956	5 km	M
Tributaries		occasional samples		

L = left sample
M = middle sample
R = right sample

Diagram 5.1.2-4 shows exclusively all the data concerning the grain-sizes of bottom samples. It appears that while on the Upper Niger and on the Benue no systematic variation of size can be concluded, there is a more or less sinuous curvature in the average line on the Lower Niger

(black stroke-line on the graph). This might possibly have been caused by historic periods of relatively great importance of the Niger in comparison with the Benue, with consequently a greater transport of sediment from the Niger than from the Benue. However, as the number of samples is too small for reliable or definite conclusions, for the present no special meaning has been given to this accidental phenomenon. The full line on the graph is supposed to give the average tendency of grain-size. A more detailed investigation into this matter might lead to interesting results.

TABLE 5.1.2-3

AVERAGE GRAIN-SIZES OF BOTTOM MATERIAL

RIVER	MILEAGE	GRAIN-SIZES in mm			
		d_{10}	d_{50}	d_{60}	d_{90}
Upper Niger	562—479	0.22	0.48	0.75	1.27
	479—395	0.23	0.47	0.56	1.35
	395—361	0.23	0.51	0.61	1.65
Benue	972—925	0.26	0.61	0.73	1.78
	925—846	0.25	0.81	1.09	3.88
	846—673	0.22	0.55	0.68	2.42
	673—632	0.24	0.61	0.75	2.88
	632—537	0.29	0.69		3,11
	537—361	0.30	0.74		3.07
Lower Niger	356—336	0.30	0.83	1.06	3.19
	336—306	0.29	0.70	0.94	2.18
	306—271	0.21	0.56		2.13
	271—232	0.21	0.46		1.29
	232—178	0.25	0.52		1.62
	178—153	0.25	0.61		2.70
	153— 90	0.20	0.39	0.46	1.14
	90— 40	0.18	0.32	0.38	0.85
Kaduna	(480)*)	0.27	0.59	0.70	4.93
Faro	(925)*)	0.30	0.74	0.94	5.40
Gongola	(846)		0.58	0.70	1.70
Taraba	(673)	0.49	1.18	1.63	5.30
Donga	(632½)	0.30	0.74	0.90	2.38
Katsina Ala	(537)	0.34	0.78	0.93	2.17

1 mm = 0.04 inch
*) mileage of confluence with main river between brackets

b. *Samples from BTMA* have been collected at every sand-transport measurement in the main rivers and tributaries. As these were all taken at specific selected sites, the results, therefore, only concern those sites, and certainly not a river-section.

The grain-size of the transported material at a certain site is not constant. A great discharge corresponds with a great turbulence which can be understood to have the power of bringing larger particles into motion. Therefore the grain-size is plotted against the discharge, as shown in Diagram 5.1.2-5, from which it can be concluded that this theory does not always come true. Mostly, the variation of the size is not clearly a function of the discharge, but is due

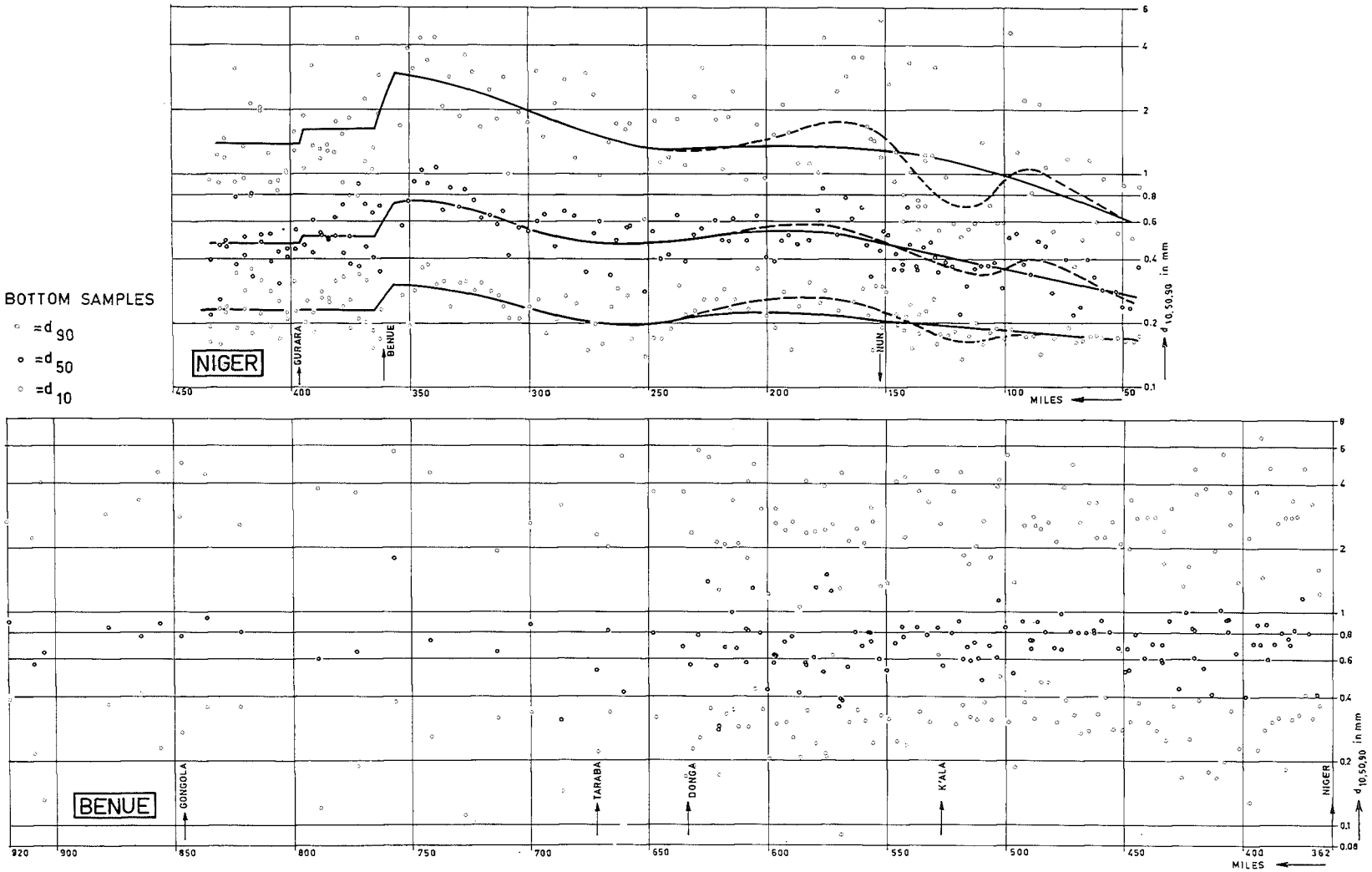


DIAGRAM 5.1.2-4

Observations on grain-sizes from bottom samples of Niger and Benue

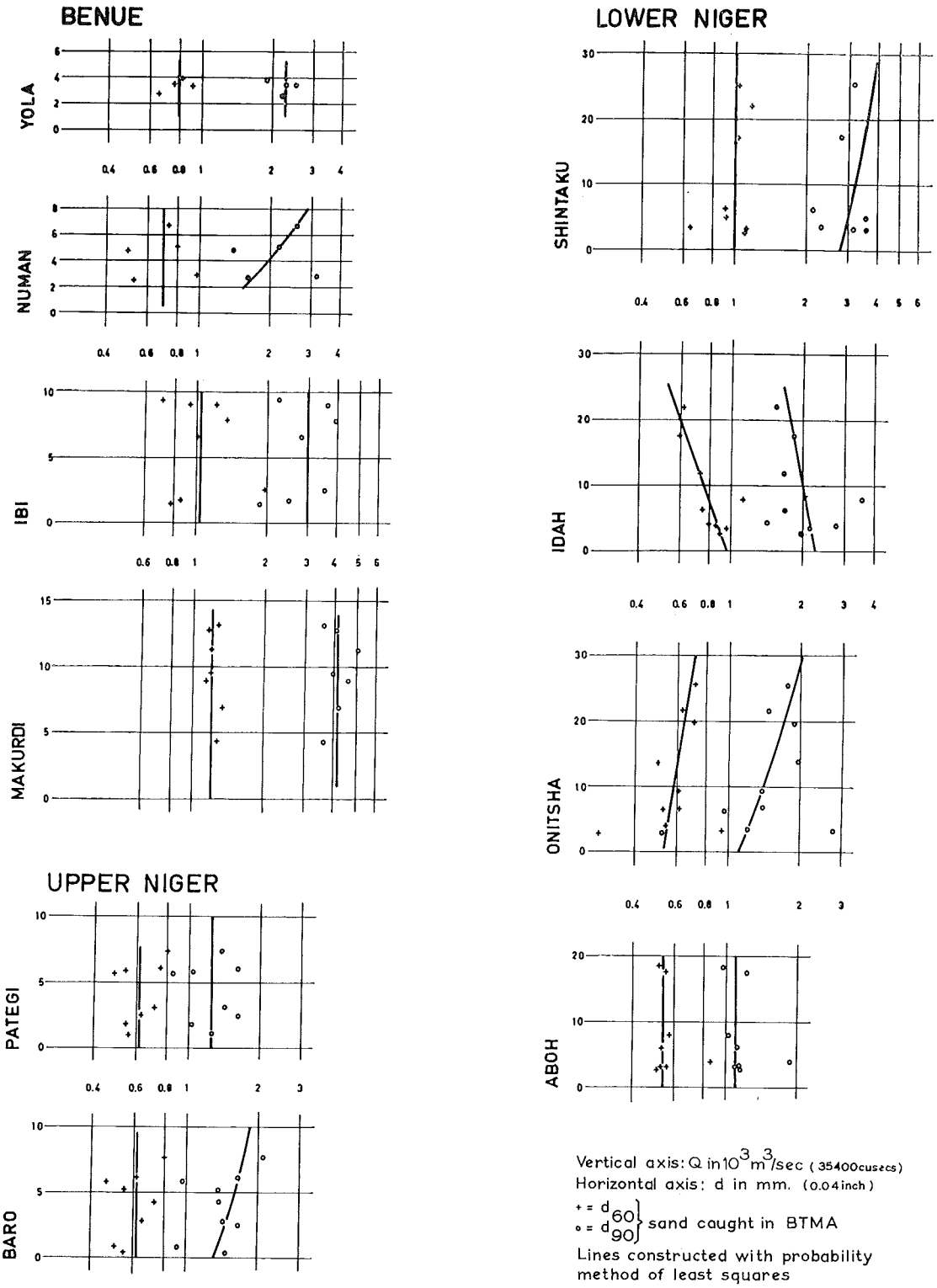


DIAGRAM 5.1.2-5

Observed grain-sizes of catch by BTMA

to irregularities of local origin. From this it seems possible to work with a constant value of grain-size, d_{50}, d_{60} and d_{90}. These averages are collected in Table 5.1.2-6.

TABLE 5.1.2-6

AVERAGE GRAINSIZES OF CATCH BY BTMA AND DF

figures in mm

STATION	BTMA			DF_2			DF_1		
	d_{50}	d_{60}	d_{90}	d_{50}	d_{60}	d_{90}	d_{50}	d_{60}	d_{90}
Benue									
Yola	0.66	0.80	2.3	0.32	0.39	0.71	0.21	0.23	0.42
Numan	0.56	0.71	2.2	0.30	0.36	1,4	0.22	0.24	0.42
Gamadio	0.53	0.66	2.1	0.32	0.39	0.93	0.14	0.17	0.29
Ibi	0.85	1.05	3.0	0.41	0.58	1.5	0.18	0.21	0.49
Makurdi	1.04	1.22	4.3	0.63	0.80	1.7	0.22	0.23	0.69
Upper Niger									
Pategi	0.54	0.62	1.3	0.28	0.30	0.56	0.18	0.20	0.37
Baro	0.52	0.62	1.6	0.23	0.27	0.55	0.21	0.24	0.40
Lower Niger									
Shintaku	0.78	1.0	3.3	0.23	0.27	0.75	0.15	0.17	0.31
Idah	0.67	0.72	2.0	0.22	0.25	0.48	0.15	0.17	0.29
Onitsha	0.52	0.60	1.8	0.20	0.23	0.43	0.13	0.15	0.25
Aboh	0.49	0.54	1.1	0.15	0.16	0.31	0.11	0.12	0.18
Gongola									
Bilachi	0.81	1.1	3.7	0.36	0.43	1.1	0.16	0.20	0.39
Faro									
Kossel	0.75	0.95	2.8	0.55	0.68	1.9	0.16	0.19	0.34
Taraba									
Sendirdi	0.82	1.0	3.1	0.68	0.87	2.3	0.21	0.25	0.46
Donga									
Nyankwola	0.88	1.1	2.2	0.42	0.51	0.8	0.13	0.15	0.23
K'Ala									
Confluence	0.85	1.0	2.7	0.50	0.55	1.7	0.27	0.32	0.77

1 mm = 0.04 inch

c. The average of grain-sizes of *saltation-load*, caught in the DF_2, and of *suspended load*, measured by the DF_1, are also collected in the same Table 5.1.2-6. No attempt has been made to analyse an eventual relationship between the diameter and any other basic characteristic.

5.1.3. Mineral composition

A few samples of sand derived from various parts of the rivers have been examined by the Delft University Mining Laboratory in order to obtain some idea of the mineralogical composition of the sediment. The results of the analysis of the heavy minerals are given in Table 5.1.3-1, the figures representing numbers of counted grains as a percentage of the heavy fraction after separating the transparent opaque grains.

Although the number of samples was limited, some elementary conclusions may be drawn for the various river sections.

a. *Upper Niger (Baro—Lokoja)*: The samples are characterised by the presence of sillimanite, disthene and staurolite, the sillimanite occurring in a high percentage. These minerals are formed in metamorphised rocks (meso and kata zone) such as gneisses and schists. Tourmaline, found in percentages varying between 5 and 7 %, occurs often in the Older Granites in high temperature veins associated with cassiterite, and in granite pegmatites. Andalusite, which has also been found, occurs in the same veins as the tourmaline, as well as in sheared metamorphic rocks. Rhombic pyroxene occurs in the Gurara River.

TABLE 5.1.3-1

MINERAL COMPOSITION AS A PERCENTAGE OF THE TOTAL HEAVY MINERAL FRACTION AFTER SEPARATION OF OPAQUE

	UPPER NIGER			BENUE			DRAINAGE AREA						LOWER NIGER					
	mile 434	mile 372	mile 363	Benue mile 930	R. Deo	Upper Faro	Lower Faro	Benue mile 923	Lower Gongola	Benue mile 843	Lower Taraba	Benue mile 512	mile 350	mile 339	mile 313	mile 296	mile 227	mile 146
Opaque	36	76	63	50	25	47	39	11	42	37	28	48	56	36	28	42	50	42
Amphibole (green)	37	25	33	30	55	62	38	63	48	45	45	19	43	41	41	37	37	34
Amphibole (brown)	—	—	—	—	6	3	11	11	2	4	4	1	2	4	—	5	3	3
Epidote.....	15	21	21	52	20	10	18	10	9	35	34	22	37	26	41	21	19	33
Zircon	2	13	12	5	4	9	9	5	17	4	5	4	6	16	4	11	21	5
Garnet	5	6	—	2	5	6	11	2	7	5	5	—	2	3	3	5	4	3
Titanite	—	3	—	4	4	3	6	2	2	—	1	—	—	—	1	—	—	—
Apatite	—	1	1	4	5	5	5	3	4	4	2	4	1	4	3	2	1	2
Sillimanite	26	7	14	1	—	1	—	1	1	—	1	2	3	1	1	6	4	3
Disthene	2	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—
Staurolite	5	7	8	1	—	—	—	—	—	1	1	—	2	—	1	3	4	1
Andalusite	2	4	3	—	—	—	—	—	—	—	—	—	—	1	—	1	1	3
Augite	—	—	—	—	—	—	—	1	7	—	—	2	—	1	—	1	—	—
Rhomic pyroxene	—	2	—	1	—	1	1	2	—	1	1	—	1	1	1	1	2	1
Titane augite	—	—	—	—	1	—	—	—	—	—	1	—	—	—	—	—	1	—
Tourmaline	5	7	7	—	—	—	—	—	2	—	—	2	1	1	2	4	3	2
Rutile	2	1	—	—	—	—	—	—	1	1	—	—	—	1	—	3	1	1
Spinel	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—
Topaz	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—
Orthite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
total percentage	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Orthoclase	very abundant	abundant	very abundant
Quartz	very abundant	very abundant	very abundant
Microline	less abundant	few	less abundant
Plagioclase	less than 10%	more than 20%	less than 10%

b. *Upper Benue (above Gongola)*: Metamorphic minerals are very scarce, but the samples contain the highest percentages observed of titanite and amphiboles (in large part brown amphiboles). The mineral association indicates the presence of acid instrusive rocks as well as of basic volcanics in the drainage area of the river.

c. *Gongola*: The zircon percentage is rather high, and the augite percentage very high. Tourmaline has also been observed.

d. *Taraba*: Its mineral association corresponds more or less to the average for the whole Benue River. Brown amphiboles (from basic volcanic rocks) are present.

e. *Lower Benue (downstream from the Taraba Confluence)*: Few brown amphiboles, no garnets and no titanites, almost no metamorphic minerals. Apatite occurs in a higher percentage in this sample, as in all Benue samples, than in the Niger River upstream from Lokoja.

f. *Lower Niger (between Lokoja and Idah)*: From the Niger drainage area upstream from Lokoja the percentage of metamorphic minerals has become relatively low because of the admixture of Benue sand with its brown amphiboles.
g. *Lower Niger (downstream from Idah):* The percentage of metamorphic minerals has become higher again (probably from the Basement Rocks of the Rocky Section). There are also many more zircons, possibly washed out of the sandstone formations.

The main distinction between the Niger sands and the Benue sands consists of the presence of metamorphic minerals in the former and of volcanic minerals (apatite, epidote, brown amphiboles, titanite and augite) in the latter. The Niger upstream from Lokoja and its most important affluents show considerable outcrops of Basement Rocks in their drainage areas, whereas the Benue and several of its tributaries drain areas where much basic volcanic rock occurs.

5.2. BED-LOAD

5.2.1. Formulae and measuring stations

Bed-load is the transport of sand where the grains roll and slide over one another. Grains of the bottom are not necessarily in continuous motion, but remain quietly in position most of the time. Occasional movement with frequent exchange of particles in a layer several centimetres deep is the modern conception of the way the transport of bed-load takes place.

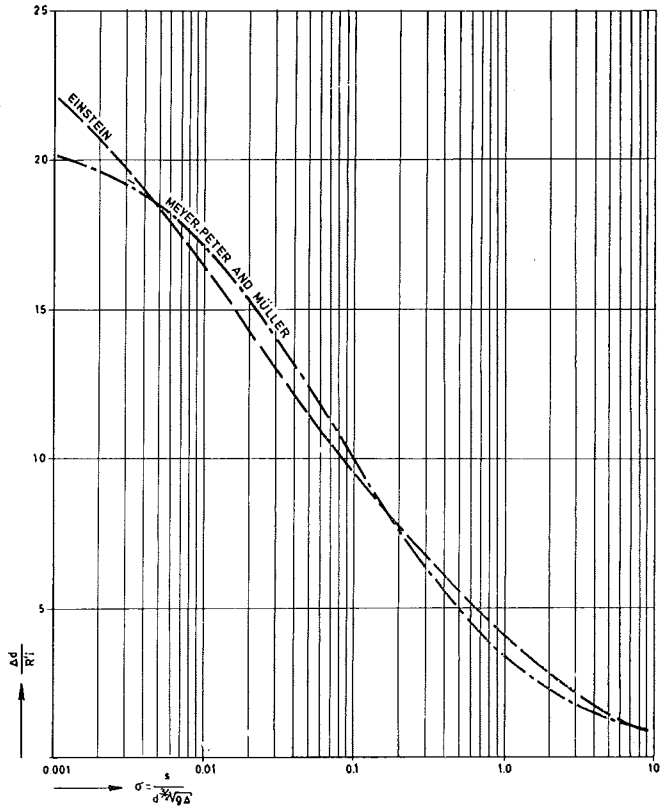


DIAGRAM 5.2.1-1
Sand-transport formulae of Einstein and of Meyer-Peter and Mueller

Usually bed-load and saltation-load together are considered to be determinant for the formation and deformation of the river-bed. KALINSKE (1 and EINSTEIN (3 state after laboratory experiments that saltation-load is not a specifically distinguishable kind of transport. Now it is true that small-scale models of water-courses do not show particles jumping higher than 2 inches, but in a river on a natural scale the turbulence is such that saltation-load does undeniably occur. In the recent formulae for bed-load, this saltation-load is considered to be included. There are three important formulae, viz., those of KALINSKE (1, MEYER-PETER and MUELLER (2 and EINSTEIN (3.

FRIJLINK (4, comparing the three, states that they lead to similar results with only minor differences, as shown in Diagram 5.2.1-1 where the formulae of Einstein and of Meyer-Peter and Mueller have been drawn. Both can be modified into a form where along one axis the dimensionless term for sand-transport

$$\frac{s}{d^{\frac{3}{2}}\sqrt{\Delta g}}$$

is plotted against

$$\frac{\Delta d}{R'i}$$

which is also dimensionless. In these terms, R′ is a reduction of R, the hydraulic radius, considered later in this paragraph, s = sand-transport per unit width and Δ = relative density = 1.68.

The formula of Kalinske is based upon slightly different terms, and could not clearly be plotted in the same diagram; but this formula also gives almost equal results for s.

A clear decision on which formula is correct cannot be given, but the measurements of NEDECO in the Nigerian rivers appeared to follow the formula of Meyer-Peter and Mueller satisfactorily, and therefore it is this easily applicable formula which has been used throughout this Report.

This formula, henceforth briefly denoted as the formula of M.P.-M., concerns the sand-transporting capacity of a river. It is generally accepted that an alluvial river has an actual sand-transport (bed-load plus saltation) always equal to its transporting capacity. A smaller transport than the transporting capacity would immediately involve supply of sand by local erosion from bottom or banks. It is therefore not possible to speak of a stream unsatiated with sand. Variation in sand-transporting capacity will immediately result in scour or deposition to such an extent that at every location the sand-transport satisfies the transporting capacity.

The principal moving force of the flowing mass of water upon the grains on the bottom is the component of the weight of the water mass directed along the bottom into the x-axis, which is termed the "drag", ρgai. It must exceed a minimum value, termed "critical drag", in order to effect actual sand movement.

However, the bottom configuration also influences the magnitude of the sand-transport. Frijlink introduces in his (above-mentioned) paper the "ripple factor" μ as a measure for the bed roughness, defined by

$$\mu = \frac{R'}{R}$$

where R′ and R are, as used by Einstein, respectively the hydraulic radii for the two circumstances that:

(i) the bottom is flat with a roughness only depending on the grain-size of the bottom material, R′;

(1 KALINSKE, 1947. MOR. 15
(2 MEYER-PETER and MUELLER, 1948. MOR. 23
(3 EINSTEIN, 1950. MOR. 5
(4 FRIJLINK, 1952. MOR. 10

(ii) the ripples on the bottom cause a much higher roughness with the result of a greater water-depth, and thus a greater hydraulic radius (see 6.3.4), R.
It appears that:

$$\mu = \left[\frac{C}{5.75\sqrt{g}\log 12\,R/k_s}\right]^{\frac{3}{2}}$$

where C = de Chezy's coefficient from $v = C\sqrt{Ri}$;
R = hydraulic radius as actually occurs, with ripples; for a normal (wide and shallow) river R is equal to the depth a;
k_s = sand roughness = d_{90} of the bottom material.

The formula of M.P.-M. can then be written

$$s = 6.5\, d^{\frac{3}{2}}\sqrt{\Delta g}\left[\frac{\mu ai}{\Delta d} - 0.047\right]^{\frac{3}{2}} \qquad \ldots\ldots\ldots \quad (1)$$

where s = transport of sediment per unit width, and
d = mean diameter of the transported sediment.

The original value of the coefficient (6.5) as given by Meyer-Peter and Mueller was 8, based upon the results of experiments in their laboratory in Zürich as well as of observations on European rivers; the deviation is probably due to a difference in temperature of the river-water. European rivers have an average temperature of 55° F in summer-time (and most of the observations are taken during the summer), while the Niger and Benue have approximately 82° F throughout the year. This involves, in the first instance, a decrease in kinematic viscosity from 13×10^{-6} ft²/sec for the European rivers to 8.7×10^{-6} ft²/sec for the Niger and Benue. As the fall velocity of sand particles in water with less viscosity is greater, saltating solids fall back onto the river-bottom quicker in Nigeria than in Europe, and consequently the distance of travelling during one jump is smaller. Obviously the transporting capacity of the warmer stream is smaller. Investigations on this subject are scarce. LANE ([1] observed the phenomenon in the Colorado River in U.S.A., and gave a trial for quantitative conclusions. It seemed that the coarser particles were not affected by temperature variation, but the mechanism is not clearly understood. The coefficient 6.5 as used here has been obtained experimentally from the sand measurements of NEDECO.

The formula of M.P.-M. in the form of Equation (1) might be useful for calculations in general, and indeed will be used as such in the following sections of this Report (see a.o. 6.1.2; 6.5.8; 6.6.4). However, for the purpose of determining the quantity of transported sediment it appears difficult to arrive at correct and accurate values for μ and i. The ripple factor cannot be measured, but only calculated indirectly, while the slope changes from place to place and measurement is only possible as an average over a certain distance. Therefore modifications of the formula are carried out by means of the two equations:
(i) for the ripple factor as given in 6.3.4,

$$\mu = \left[\frac{k_s}{k_r}\right]^{\frac{1}{4}}$$

(ii) for the mean velocity as used by STRICKER and mentioned under 4.3.1,

$$v = 21\, k_r^{-\frac{1}{6}}\, a^{\frac{2}{3}}\, i^{\frac{1}{2}}$$

k_r being the total channel roughness.

([1] LANE, 1949. MOR. 19

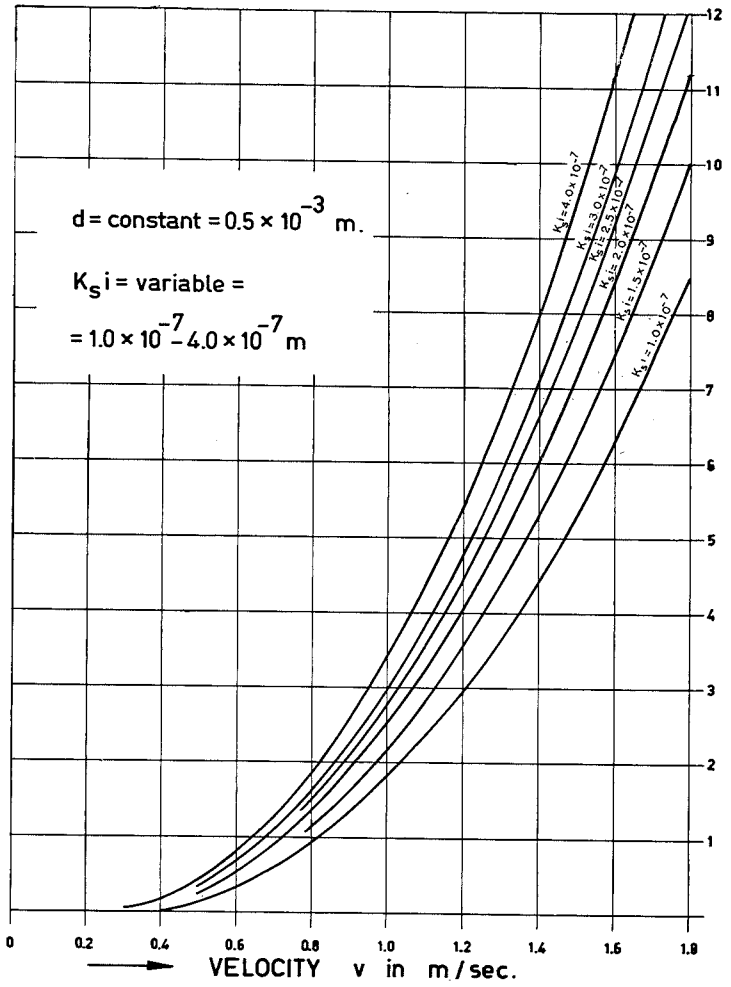


DIAGRAM 5.2.1-2

Influence of the term ki *upon the calculated sand-transport*

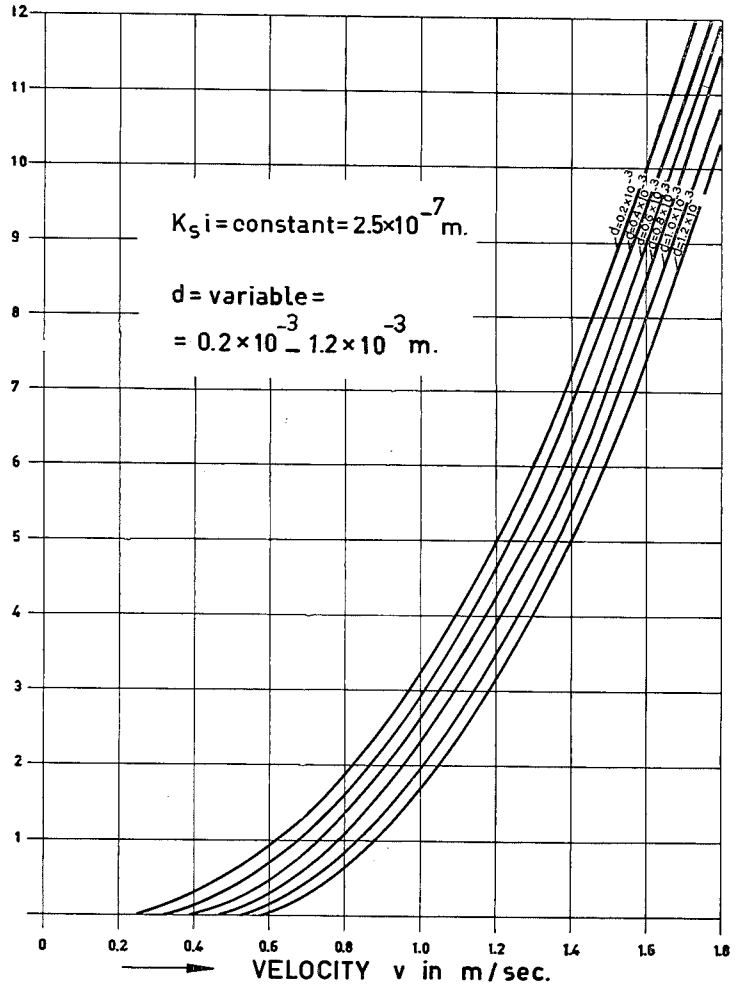


DIAGRAM 5.2.1-3

Influence of the d *upon the calculated sand-transport*

It follows from a combination of these two equations that

$$\mu ai = \left[\frac{v}{21}\right]^{\frac{3}{2}} (k_s i)^{\frac{1}{4}} \quad (1$$

which, substituted in Equation (1), leads to a modified form of the sediment transportation formula of M.P.-M.

$$s = 6.5\, d^{\frac{3}{2}} \sqrt{\Delta g} \left[\frac{v^{\frac{3}{2}} (k_s i)^{\frac{1}{4}}}{96 d \Delta} - 0.047\right]^{\frac{3}{2}} \quad \ldots\ldots\ldots \quad (2)$$

Here, v and d can be found by direct observation in the river. Also k_s of the factor $k_s i$ can be measured: the sand roughness is taken to be equal to the value for d_{90} of the bed material (see 5.1.2). Only the slope i must still be estimated, which might lead to errors. However, since the term $k_s i$ bears the power $\frac{1}{4}$, the error will not be excessive. To illustrate this, Dagram 5.2.1-2 shows the influence of $k_s i$ upon the ultimate result of the transport s.

In the foregoing it has been stated that d can be measured by direct observation. Indeed, sampling the bed material could lead to the desired result. However, the sediment concerned is the transported material, and not the bottom sand. Although intensive exchange between the particles from the bottom and from the bed-load takes place, a difference between bottom sand and bed-load sand might occur. Moreover, the correct value of d is the mean diameter d_m, defined as under 5.1.2. The computation of d_m takes much time and therefore in practice d_{50} is used instead of d_m, introducing a small error. But the error of both approximations upon the ultimately calculated sand-transport is negligible, as appears from Diagram 5.2.1-3.

It is concluded that Equation (2) gives a good basis for calculations of sand-transport at the various measuring stations along the rivers. In the next paragraph the calculation has been carried out for the following stations:

along the Niger : Baro, Shintaku, Idah, Onitsha, Aboh;
along the Benue : Garua, Yola, Numan, Wuro Boki, Ibi, Makurdi:
along the Faro : Kossel; and
along the Gongola: Bilachi.

5.2.2. Relation curves of water and sand discharges

The relation between bed-load S (including saltation-load) and water discharge Q is shown in Diagram 5.2.2-1 for the Niger and for the Benue with its tributaries Faro and Gongola, where the results of the sand-transport measurements for each station have been plotted against the corresponding water discharge, both on a logarithmic scale. A linear relationship between log S and log Q seemed to fit into the picture of the measurements and could be used as a rough approximation. This idea led to construction of the relation curves as given in the Interim Report, 1957. The lines were computed by the probability method of least squares to provide the best fit.

A more theoretical approach, however, is to be preferred. Computations have, therefore, been carried out with the help of the formula of M.P.-M., as given by Equation (2) of the previous paragraph. In this formula, S can be determined after the magnitudes for v, $k_s i$, d and b have been fixed. These data should not be the averages of the river-stretch in which the measuring station is situated, but the local data in the measuring cross-section itself, so as to arrive at the best possible comparison between measurements and computations. The data have been obtained by direct observation at the stations. However, in two of the cross-sections, viz., Baradogi on the Niger (Mile 480) and Angwan-Taru on the Benue (Mile 676.5) the river-stage appeared

(1 FRIJLINK, 1952, p. 100. MOR. 10

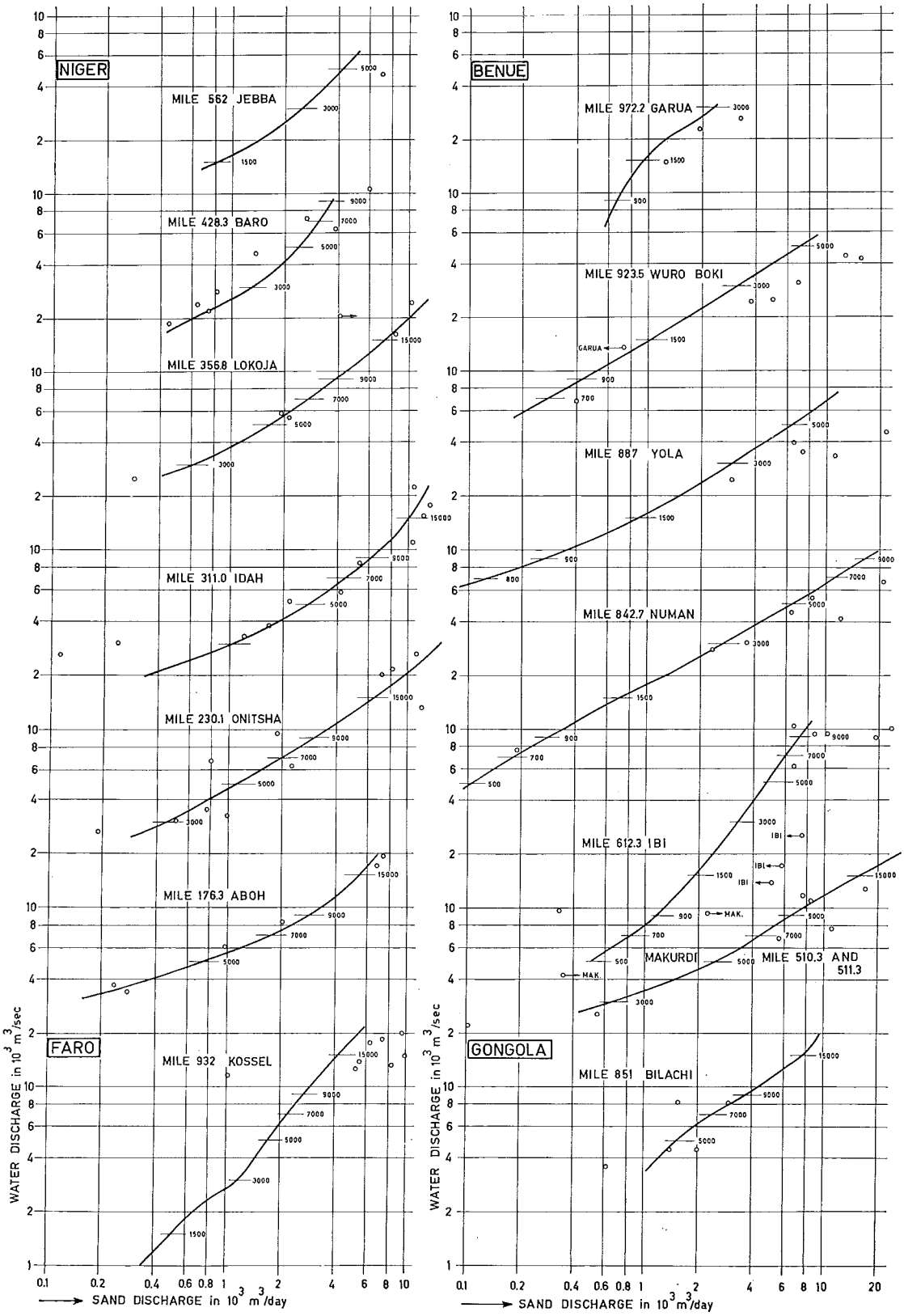


DIAGRAM 5.2.2-1

Relation curves for discharges of water and sand on the Niger and Benue

to be affected by backstage from the tributaries Kaduna and Taraba respectively. It therefore was impossible to establish uniquely the values for v, $k_s i$, d and b as functions of h; whilst it is thought that the sand-transport under such conditions might be influenced by the backwater.

However, the sand-transport measurements as published in the Interim Report of 1957, — plotted against the directly measured water discharge — appear to yield a reasonable linear relationship between log S and log Q. The graphs given in Diagram 5.2.2-1A are copied from this Interim Report.

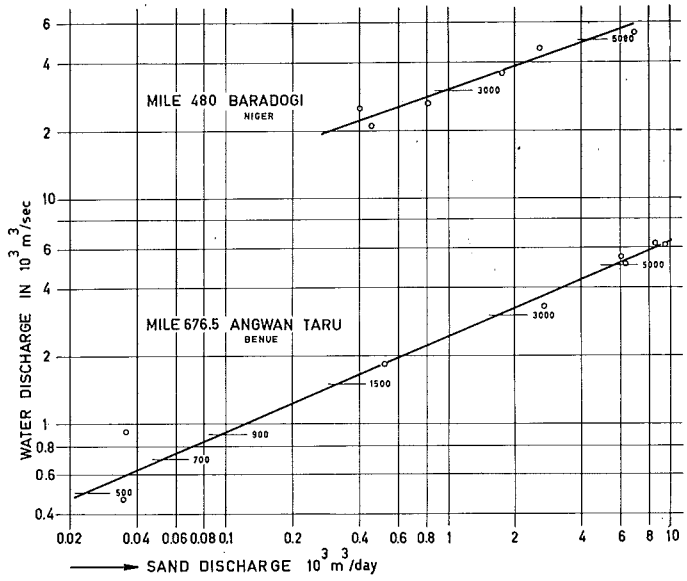


DIAGRAM 5.2.2-1A

Relation curves for discharges of water and sand for Angwan-Taru and Baradogi

For the other stations the relation between Q and S has been computed from the said basic data v, i, d, k_s and b.

Determination of these data is as follows:

$d = d_m$ *or* d_{50} *of the transported sediment.* This subject has been dealt with in Section 1 of this Chapter. The values for d as have been used in the computations are given in Table 5.2.2-2.

$k_s = d_{90}$ *of the bed material.* In the Niger, a reasonable number of bottom samples have been taken in the measuring site, and where these were not sufficiently available, samples from nearby positions within a maximum distance of two miles were included. In the Benue, however, bottom samples were rather scarce. Since the spread of the observed grain-sizes is too wide for a reliable determination of k_s from a small number of samples, d_{90} of the many observations of bed-load sediment is used instead. This is justified by the intensive mutual exchange of grains between bottom and bed-load. The values for k_s as used in the computations are also given in Table 5.2.2-2.

b = *sand-transporting width of the river.* Rectangular cross-sections (as at Baro, Shintaku, Onitsha and Makurdi) do not present problems. For triangular cross-sections (as at Idah, Aboh and Ibi) the width at about two feet below the water-level has been used. The velocity, and consequently the bed-load, in the shallow parts with a depth of less than two feet are assumed to be negligible. Where the direction of flow appears to be not perpendicular to the measuring cross-section, a corrective factor must be applied to the width.

$v = Q/A$ = *average water velocity in the measuring cross-section.* Out of the many discharge measurements, the relation between v and Q can be determined with considerable accuracy. When, however, the water-level rises above the banks, the average discharge and velocity of the main channel only are taken into account, because the sediment transport in the main channel only has been measured. Moreover, bed-load on the flood-plains is not very probable. Spiral flow might have the capacity to lift sand upward over the banks on top of the flood-plains, but ordinary transport parallel to the axis of the river does not occur. High-water branches with very low velocity are supposed to have no bed-load either.

i = *the local energy gradient in the x-direction.* This slope is not necessarily equal to the slope of the water

surface or to the average slope over a stretch of several miles. Normally, the slope can only be measured as an average over such a stretch. Although the influence of an eventual error in the determination of i upon the result of computation is not excessive (Diagram 5.2.1-2), yet it is sufficiently important to find this local slope as closely as possible. Therefore, in those cross-sections where the local slope was thought to differ largely from the average one, considerations were set up with the help of the bed roughness k_r, defined and described under 6.3.4. Based upon the assumption that k_r would grow with the increase of discharge Q, or at least remain constant but certainly not diminish, an insight into the relation between Q and i could be obtained by application of the Equations

TABLE 5.2.2-2

VALUES OF d_{50} AND k_s WHICH HAVE BEEN USED FOR COMPUTATION OF Q—S RELATION

expressed in mm

STATION	MILE	d_{50}	k_s
Niger			
Baro	428	0.36	1.2
Shintaku	356	0.50	3.0
Idah	311	0.50	2.8
Onitsha	230	0.42	2.3
Aboh	176	0.35	2.5
Benue			
Garua	972	0.6	2.1
Wuro Boki	923	0.6	2.5
Yola	886	0.5	2.3
Numan	843	0.5	2.2
Ibi	613	0.7	3.0
Makurdi	509	0.9	3.5—4.3
Faro			
Kossel	932	0.7	2.8
Gongola			
Bilachi	852	0.7	3.1—5.2

1 mm = 0.04 inch

6.3.4-(5) and 6.3.4-(6). It has been realised that the assumption about k_r is contestable; therefore the results have been submitted to a thorough consideration of the possibility and probability. In most cases the slope appears to be greater at high water than at low water, which is in complete accordance with the circumstance that most measuring stations are situated in narrowings. In two cases, viz., Wuro Boki an Makurdi, the Q-i relation could be determined from several observations; here the assumption of k_r not to diminish with growing Q appeared actually to come true. Diagram 5.2.2-3 shows the relation found with this method between, on one side, the water-level h as read on the gauge, and on the other side Q, v, a and i for those cross-sections where these calculations have been found necessary.

The formula of M.P.-M. gives the transport of sediment per unit of width. This means that for every part of the cross-section where one of the factors v, d or $k_s i$ changes, a separate computation is needed. To simplify such laborious calculation, the averages for the whole cross-section have been used. This simplification will hardly change the result where in the fairly rectangular cross-section v, d and $k_s i$ are practically constant along the width of the cross-section. However, in a triangular-shaped cross-section these factors may vary appreciably, and since the factors have a non-linear relation with the sand-transport s, the result of computations would be erroneous.

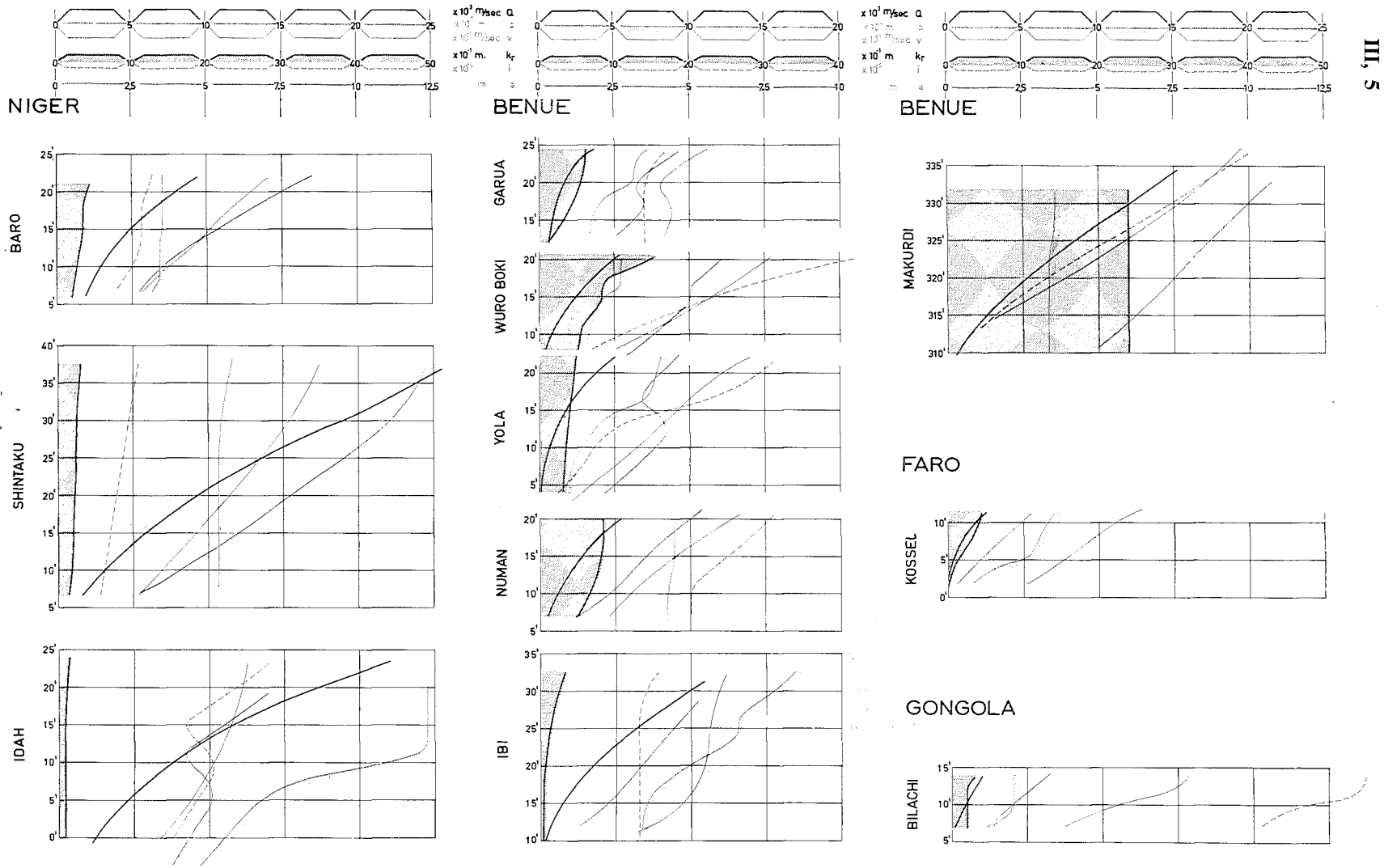


DIAGRAM 5.2.2-3

Relation curves of Q, v, a, i *and* k_r *against the water-level* h *for some measuring stations*

If p is the average magnitude of one of these factors, and Δp is its local deviation, while n is the power to which p must be raised in the computation of s, the corrective factor on the computed result should be

$$\alpha = \frac{\int_0^{b_1} (p + \Delta p)^n \, db}{p^n \, b_1}$$

where b_1 is the total width and b is the distance of any point of the cross-section to the bank.

As an example, a transversal variation of the velocity in a triangular cross-section will be considered here. For high discharges, the formula of M.P.-M. could be simplified as

$$s = \varphi \, v^{\frac{9}{4}} \, (k_s i)^{\frac{3}{8}}$$

or more roughly: s is proportional to the square velocity:

$$s :: v^2$$

In the triangular cross-section the local depth is proportional to the distance from the bank:

$$a :: b$$

Hence the local velocity u, which is proportional to the square root of the depth if the slope i is approximated to be constant, is

$$u = \vartheta \sqrt{b} = (v + \Delta v)$$

where v = mean velocity = Q/A.

The function has been drawn in Diagram 5.2.2-4

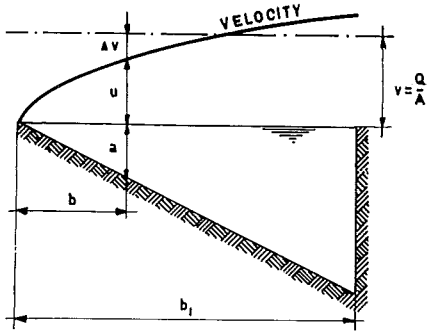


DIAGRAM 5.2.2-4

Transversal variation of velocity in a triangular cross-section

The corrective factor can now be calculated as

$$\alpha = \frac{\int (\vartheta \sqrt{b})^2 db}{v^2 \, b_1} = \frac{\vartheta^2 \int b \, db}{v^2 \, b_1} = \tfrac{1}{2} b_1 \left[\frac{\vartheta}{v}\right]^2$$

Now when

the total width b_1 = 900 m,

the local velocity at the right bank u_r = 1.50 m/sec,

the depth at the right bank a_r = 9 m,

it follows that

$$\vartheta = 0.05$$

and

$$v = 1.20 \text{ m/sec}$$

from which it is concluded that

$$\alpha = 0.78$$

This means that the computed sand-transport would be 22% too high: the sand-transport is actually less than follows from the simplified calculation. Fortunately, however, the transversal variation of the velocity in the measuring stations is not pronounced to such an extent as has been assumed in this example.

However, the transport of sand in alluvial rivers is such a complex problem that even the formulae, though theoretical in approach, bear an experimental character in their final form. Moreover, sand is not transported as a continuous and even movement, but occurs with pulsations, widely varying in time. Momentary measurements may easily differ by a factor 2 from the calculations, while mutual differences of the results under seemingly the same circumstances can be even more, partly due to imperfection of the measurements. Bearing this in mind, the simplified method of computation has been preferred. In view of the limited number and accuracy of the available data, a more precise method of computation would only raise a false idea of accuracy.

On the Niger, both relation curves, the one as given in the Interim Report of 1957 constructed by the probability method of least squares directly from the measurements, and the one as computed with the formula indirectly from basic data, coincide very satisfactorily. As for the Benue, only in a few measuring stations does the observed transport not correspond with the calculations. However, it must be stated that the sand-transport measurements in the Benue have not always been made in special measuring cross-sections, but at occasional places in the vicinity of the station, depending on the water-level. This was partly due to difficulties inherent in the very low stages at low water and to the completely different stream-pattern with the current crossing the site at non-constant angles at high water. Mostly, the basic information data for use in the formula of M.P.-M. had to be determined from observations in various cross-sections, and although the mutual distance was not great, differences were considerable.

Nevertheless, the accordance between observations and computations is striking and yields confidence in this application of the formula of M.P.-M. The formula is considered to be of great value in cases where sand-transport measurements are lacking, and for the extrapolation to extreme river conditions, or even to attain an insight into the sand-transport after artificial intervention in the regime of the natural river.

5.2.3. Year-transports

In Table 5.2.3-1, the total year-transports of bed-load have been collected for the various stations. It is not possible to draw conclusions from a comparison of the figures concerning a single year only. As has been already stated, sand-transport is a slow phenomenon; the magnitude of transport varies from year to year and from place to place. The state of equilibrium in a river is not disturbed by an accidental or occasional difference in the year-transport at one single place, as is made clear by distinguishing between local and through sand-transport (see 5.4.2).

Strictly speaking, even a Q—S relation-curve for this year will have lost its validity next year, because the boundary conditions and basic data at the measuring-site vary. The velocity v and the slope i both largely depend upon the shape, size and roughness of the cross-section, upon the location of the cross-section in the meandering pattern of the river, upon local disturbances below the cross-section, and possibly upon many more factors.

However, calculation of the average year-transport has been undertaken as the combination of the Q—S and Q—h relation-curve for the years of observation 1956/57 with the frequency diagram of water-levels h, as read on the gauge of the station during a long period of many years. The results are given in the table.

Some conclusions may be drawn. Apparently the sand-supply from the Benue is larger than that from the Niger. This might be the reason why the grain-size immediately below the Lokoja Confluence is almost equal to that of the Benue. It seems probable that in previous times this

relation between the Benue and the Niger was the opposite, because some 150 miles further downstream the grain-size is about equal to that of the Upper Niger (see 5.1.2).

TABLE 5.2.3-1

YEAR TRANSPORTS OF BED-LOAD (in 10^6 m^3)

Station	1956	1957	AVERAGE YEAR	
			transport	period
Niger				
Baro	0.29	0.44	0.31	1914—1957
Shintaku	0.72	1.2	0.88	1915—1956
Idah	1.1	1.6		
Onitsha	0.76	1.3	1.0	1925—1957
Aboh	0.45	0.75		
Samabri	0.70	1.1	1	1919—1949*)
Benue				
Garua	0.10	0.10		
Wuro Boki	0.23	0.27		
Yola	0.20	0.28	0.20	1934—1957
Numan	0.29	0.36		
Ibi	0.71	0.93		
Makurdi	0.57	0.86	0.61	1932—1957
Faro				
Gassol	0.40	0.50		
Gongola				
Bilachi	0.34	0.24		

*) From information, given in the report on the Western Niger Delta, NEDECO, 1954

The year-transport along Shintaku is smaller than those along Baro and Makurdi together, but the average deviation is only 5 %, which is less than the assumed accuracy of these figures. The difference between Idah and Shintaku, however, cannot be denied. Although there is hardly any contribution of water or sediment from tributaries on the Lower Niger between Lokoja and Onitsha, the transport at Idah is about 40 % more than that of Shintaku and 30 % more than the transport along Onitsha. A similar comment could be made concerning Aboh, where the sand-transport is lower than that along Onitsha as well as at Samabri. In this stretch of the river, at high water the Rivers Ase and Orashi withdraw large quantities of water from the Niger, while sediment could also be carried off via many small bifurcating creeks. But the amount of sand lost in this way cannot reach 40 %, such as would appear from the figures in the table. It therefore seems probable that the deviations of Idah and Aboh originate in local circumstances. Whether they are temporary phenomena, or whether they really indicate a tendency of change of the river-bed, cannot be said.

The year-transport at Samabri has been determined with the help of data from the Western Niger Delta Report of NEDECO, 1954 ([1]. A loss of sand between Onitsha and Samabri at the rate of about 10 to 20 %, as follows from the figures, does not seem impossible. Moreover, the river is gradually and continuously raising its bed, due to the building out of the delta into the sea (see 2.4 and 2.5). In the upper reaches, where lateral inflow of sand complicates the

([1] NEDECO, 1954. GEN. 23

sediment balance, it would be hard to trace such deposits; but here, without sediment contribution, deposition would be more pronounced. However, remarks about sand balance must be made only with strict reserve, since a three-years' investigation is certainly not sufficient to draw reliable conclusions on this subject.

As for the Benue, the inaccuracy of the measuring results, which did not produce satisfaction (see 5.2.2), is again expressed in the year-totals. The figures for Wuro Boki (immediately below the Faro Confluence) and Numan (below the Gongola Confluence) are apparently too low, since deposition of such large quantities of sand between the confluence of these tributaries and the closely-located measuring stations below them is hardly possible. This is in accordance with the fact that the results of the measurements are greater than the calculated relation would involve. The cause of the deviation is not understood. Deposition of sand, however, between the Faro Confluence and Yola, some 30 miles more downstream, is very probable, as this river-stretch would be raising its bed and steepening its slope, according to 5.4.5. The year-total of Yola can, therefore, be low again.

A deposition and raise of river-bed between Ibi and Makurdi could be concluded from the table, but no further proof for this has been found.

Again it must be emphasised that a sand balance is a very delicate thing to make. It may be given as an example that on the River Rhine, even after more than 25 years of investigation, still no proper sand balance has been made.

5.2.4. Dominant Discharge

Determination of the effect by sand-transport upon any artificial intervention in the natural river system can be carried out with the help of the above formula for sand-transport. On a river with a constant discharge Q this will be a simple calculation; but normal rivers in general and the Benue River in particular have a highly variable discharge. It is always a problem in such a case what discharge should be chosen as a basis of computations.

Originating from this consideration the conception of the so-called Dominant Discharge (D.D.) or Dominant Water-stage (D.W.) has been born. The definition for this conception will be considered under 6.1.1. It can be determined for a measuring station along the river as the centre of gravity of a figure obtained when against the stage along the vertical axis is plotted the quantity

$$\frac{nS'}{a\ da}$$

along the horizontal axis. For the meaning of these symbols reference is made to 6.1.1-b.

After the relation between the discharges of water and sand Q and S and between Q and the depths a in the measuring site have been determined by a series of observations, eventually combined with calculations, the only remaining unknown factor is the frequency n. Of course, it is possible to make the computations with a frequency obtained from a one-year hydrograph. Sand-movement, however, is a slow phenomenon; scour must cover a long period before it really takes effect. The D.W. as it follows from a one-year hydrograph will, therefore, have no physical meaning. The frequency which must be used in the calculations should be derived from observations of water-levels over a period of many years.

Such long-term observations of water-levels are available for Baro, Lokoja and Onitsha on the Niger and for Yola and Makurdi on the Benue. For these stations the Dominant Water-level and the corresponding Dominant Discharge have been calculated. Diagram 5.2.4-1 and Table 5.2.4-2 show the results.

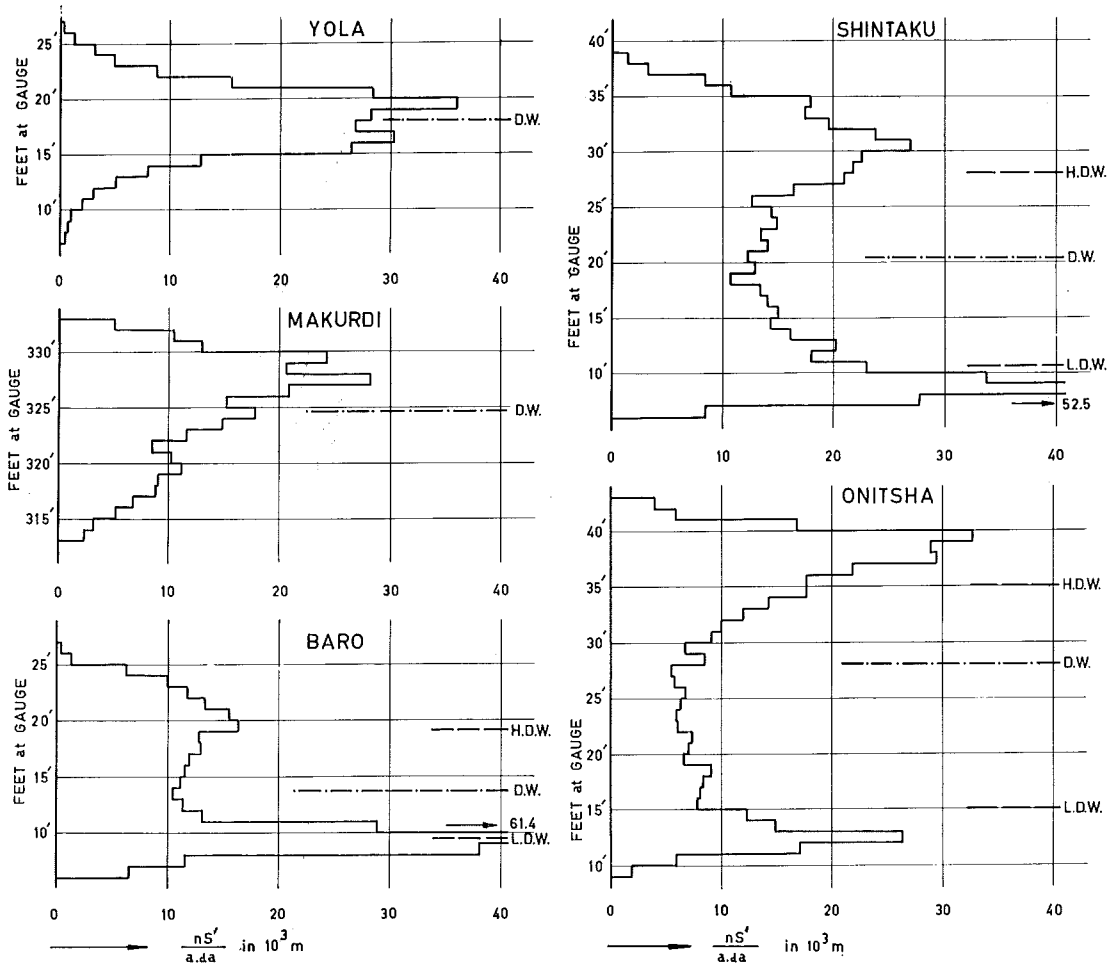


DIAGRAM 5.2.4-1
Dominant water-stages

TABLE 5.2.4-2
DISCHARGES CORRESPONDING WITH THE DOMINANT WATER-STAGES

station		waterlevel at gauge h	water discharge Q		bed-load S	
		feet	m³/sec	cusec	m³/day	cuft/day
Baro	D.W.	13′9″	3,370	119,000	1,500	53,000
	H.D.W.	19′2″	6,410	226,300	2,900	102,400
	L.D.W.	9′6″	1,730	61,100	500	17,700
Yola	D.W.	18′	3,000	105,900	2,500	88,300
Makurdi	D.W.	324′9″	8,520	300,800	5,900	208,300
Shintaku	D.W.	20′4″	9,670	344,500	4,200	148,300
	H.D.W.	28′0″	16,700	589,500	7,300	257,700
	L.D.W.	10′6″	3,280	115,800	700	24,700
Onitsha	D.W.	28′1″	10,800	381,200	4,000	141,200
	H.D.W.	35′0″	19,100	674,200	9,000	317,700
	L.D.W.	15′0″	3,630	128,100	600	21,200

Apparently the Benue has a simply built diagram with only one peak. The D.W. is a rather high one. The stream-bed has been adapted to this high water-stage and a channel system has been developed which is suitable to discharge a great mass of water. During the dry season the configuration of the bottom does not correspond with the (low) discharge, and consequently a very shallow, and non-navigable, channel then exists.

A different picture is seen on the Upper Niger, where the existence of the Black Flood (see 4.5.4) exerts great influence upon the height of the D.W. The diagram for the station at Baro appears to have two peaks, one at a rather high water-stage and one somewhere around L.R.L. The general centre of gravity has been determined and drawn in the diagram, but this D.W. does not solve the problem satisfactorily. It would be much better to divide the figure into two parts, one composed of the Black Flood only and one composed of the normal water discharge originating from the rains occurring within Nigeria. In this way two dominant water-stages are obtained, a high D.W. and a low D.W. Obviously, the stream-bed of the Upper Niger hesitates constantly between the two systems. During the rainy season it aims at adaptation to H.D.W., but some few months later it is changed into adjustment toward L.D.W. As a result, the previously made low-water channel is destroyed almost totally during high water, while the Black Flood will be capable of scouring a new low-water channel as soon as it has had time to take sufficient effect. The month of December, being the transition between the two systems, must consequently give a shallow channel with poor possibilities for navigation.

On the Lower Niger, the situation is a combination of the Benue and Upper Niger together. Here, the high peak is relatively greater than the low peak (judged according to the area of the diagram).

5.3. SUSPENDED LOAD AND SILT

5.3.1. Suspended load

In the previous paragraph the bed-load (including saltation-load) has been considered and it appeared that this type of transport exerts great influence upon the river-bed.

Suspended load has a completely different appearance. It has not yet been possible to derive a mathematical law for it as in the case of bed-load. The flowing stream is not necessarily satiated with sand-grains, but the amount of transport depends mainly on the supply of sediment into the river from outside (riparian lands; tributaries). The total transporting capacity of the river is often much higher than the actual transport.

It is indeed true that there is no sharp boundary between the two kinds of transport. Grains from the bottom might occasionally jump so high that they become more or less mixed with the higher water layers belonging entirely to the suspended load. An example of this phenomenon can be seen frequently in the Niger and Benue during high water. Downstream from a ripple, where the steep bottom gradient causes a vertical vortex in the water, the strong turbulence and the upward-directed velocity bring many sand-grains into suspension. Such a heavily-laden rolling mass of water periodically comes loose from the bottom, and is carried off by the flow. It reaches the surface some distance below the top of the ripple and looks like a boiling bubble of mud. There, temporarily and locally, the concentration of suspended particles is great, while most of them originate from the bed material. On the other hand, particles actually belonging to the suspended load might be deposited on the bottom and remain there for some time, till a turbulence vortex lifts them and brings them into the suspension zone again.

Generally speaking, however, it is possible to make distinction between bed-load and sus-

pended load, the latter being transport of grains which do not sink down onto the bottom but remain in suspension for a very long time.

It is clear that suspension must be some function of turbulence and velocity of the water, for no suspended load exists in a lake with zero velocity. Consequently, owing to the general aspect of decreasing slope, velocity and turbulence in downstream direction of the river (see 2.5), there might be a tendency to deposition of suspended particles while going downstream. This means a transfer from suspension into bed-load, and such is the effect of the suspended load upon the characteristics of the river-bed. The average grain-size of the suspension as well as of the bed material would decrease in a downstream direction, due to this deposition of the coarsest fraction of the suspension onto the bed. An example can be seen in Diagram 5.1.2-4: the said decrease in the Niger clearly takes place from Mile 170 downward.

The greater part of the suspended load, however, is carried off to the sea or is deposited on the flood-plains and no major influence upon the river-bed is probable. It might be possible that some minor effects exist due to mutual resistance of suspended solids, but an analysis of this condition has not been made as it is believed to be negligible. Various authors state that the energy consumed by the transport of sediment forms only a small portion (some 3 to 5 %) of the total energy spent by the flow. It is not likely that discharge of suspended sand-grains would consume more energy than the bed-load with its jumps and heavy mutual collisions between the inert particles.

The transported amount of suspended sand, however, is great; usually greater than that of bed-load. For the measuring station at Baro the ratio of these transport in 1957 was 1.87; suspended load was nearly twice as great.

Efforts have been made by various scientists to approach the determination of the quantity theoretically and empirically, and several formulae exist; but none of these seems to cover the phenomenon exhaustively. EINSTEIN (1, who developed an apparently sound method, also concludes with an unknown factor, the magnitude of which must be determined by measurements. It thus does not yet appear possible to calculate the quantity of transport from the basic river data only. Determination of the suspended load in the Niger and Benue, therefore, has been worked out directly from measurements on these rivers.

The measurements have been taken with the Delft Bottle DF_1, as described under II, 3.5.3. With this instrument the actual transport is measured and not the concentration of sand in the water. The latter method, used for example in the U.S.A., would appear to give less accurate results, as it is not known whether the solids travel with the same velocity as the water particles: differences in specific gravity of water and sand will undoubtedly lead to a non-homogeneous motion of the water-sand mixture, where water velocities are not necessarily equal to sand velocities.

Not caught in the DF_1 is the sediment with such a small grain-size that it does not settle easily and is carried off out of the instrument together with the water. Such sediment is called "wash-load". Suspended sand-load might at a certain location be transferred into bed-load, due to decrease of turbulence and velocity; but wash-load never settles in a normal river-stretch. It has no direct influence upon the characteristics of the stream-bed, but it may be deposited on the natural levees and the flood-plains, where vegetation plays an important role. However, wash-load affects the composition of the banks and therefore indirectly the erodibility, which indeed is an important factor of influence upon the behaviour of the river. The bulk of the wash-load, however, is carried off into the sea, where it settles as the main delta-building material (see 2.4). Wash-load is composed mainly of silt and clay, and possibly also partly of very fine sand, the quantity of which is probably negligible. The amount of wash-load in the water depends

(1 EINSTEIN, 1950. MOR. 5

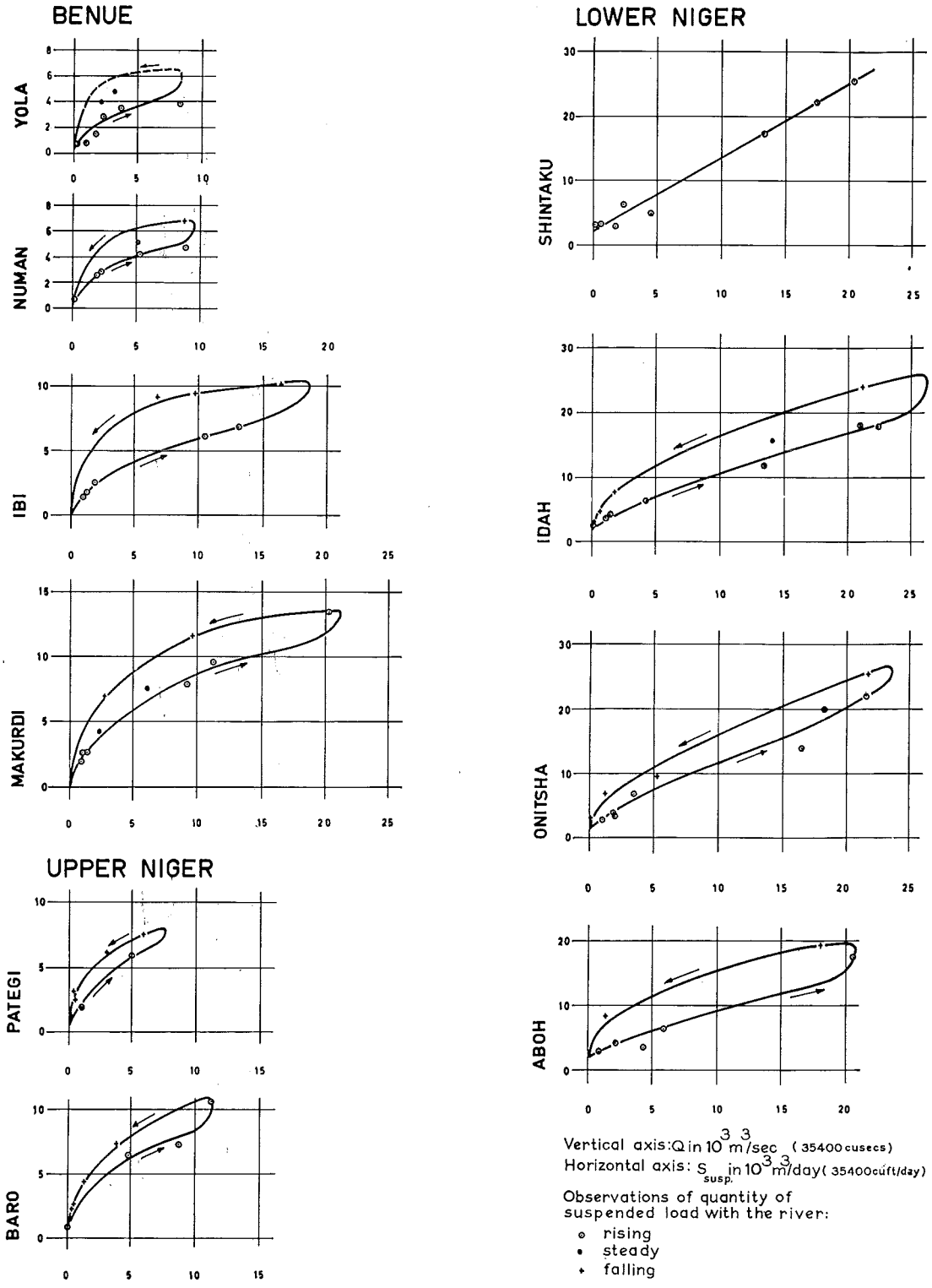


DIAGRAM 5.3.1-1

Relation between suspended load and water discharges

only on the supply into the river from outside and it can only be measured by determination of the concentration. Wash-load is dealt with in the next paragraph, and will henceforth be termed silt.

The measurements of the suspended load of the Niger and Benue have been taken in the measuring stations already mentioned in 5.2.1. The results are plotted against the water discharge Q, as some relationship is believed to exist. From Diagram 5.3.1-1 this appears to be a hysteresis curve: at a certain discharge Q the transport of suspended sand is larger during rise than during fall. When after the long dry season the top layer of the land has been affected by weathering (sun and wind), bush-fire, cultivation, animal life, etc., the sudden heavy rains will beat the soil to such an extent that sheet erosion supplies large quantities of fine sediment. However, after the loose particles have been washed away by the first rains, a solid soil remains and the removal of particles is reduced. A hysteresis curve in the relationship between discharge Q and suspended load is therefrom qualitatively explained.

The measurements are based on the assumption that a distinct boundary between bed-load (saltation-load included) and suspended load can be fixed at a certain height above the river-bottom. Of course, this is more a transition zone, the height of which depends on several factors, the velocity gradient in the vertical being one of them. It would, however, be too complicated to vary the height correspondingly at every separate measurement, while it is even doubtful whether the relationship between the height and the several factors mentioned could be analysed. The boundary has, therefore, been fixed at a constant height above the bottom, viz., 0.40 m (16 inches) which is based upon wide experience on sand-transport observations on the Rhine in the Netherlands.

With the help of the relation-curves between suspended load and water discharge of Diagram 5.3.1-1, a discharge-frequency diagram (see 4.3.4) can be translated into a suspension-frequency diagram, from which the total year-transport of sediment in suspension can be determined. Such calculations lead to the results which are collected in Table 5.3.3-1.

5.3.2. Silt

The Rivers Niger and Benue do not discharge large amounts of silt. There are other rivers in the world which have a much higher silt concentration with corresponding problems. A well-known example is the Yellow River (Hwang Ho) in China, which constantly heightens its bed, mainly by the very large amounts of silt. The river is then at a higher level than its valley, breaches in its dykes occur very frequently, and vast areas are inundated.

Another notorious problem concerning silt is the decrease of reservoir capacity by deposited silt. The Colorado in the United States of America brings yearly 170 million m^3 (6 milliard cuft) of silt into Lake Mead, and thus the storage capacity of this lake has been reduced by over 10 % of its original magnitude. In the Elephant Butte reservoir (Rio Grande del Norte) 530 million m^3 (19 milliard cuft) of silt have been deposited in 27 years.

To give an idea of the relative importance of the silt discharge of the Niger and Benue, the silt concentrations of various rivers have been collected in Table 5.3.2-1.

In order of magnitude of average concentration, the Niger and Benue are placed very low: only a little higher than, for instance, the Rhine, which appears to have no problems concerning its silt discharge, although it flows through a highly-developed area and its water is used for various purposes. It is supposed that the silt of the Niger and Benue does not cause any problem either, as it is mainly carried off into the sea and forms a large part of deltaic sediment. Only a relatively small portion remains in the river valley. High water leaves a thin layer of clayish mud on the natural levees and the floodlands, where silt could deposit in more or less stagnant

water. Poor drainage of inundated areas into the main river and grass vegetation play a role in this connection.

TABLE 5.3.2-1

Silt concentration in various rivers of the world

RIVER	COUNTRY	Place of sampling or calculation	SILT CONCENTRATION *) kg/m³		
			max.	yearly average	min.
King Ho (trib. of Wei Ho)	China	Changchiaschau	300	150	
Rio Puerco (trib. of Rio Grande del Norte)	U.S.A.			144	
Yungting (trib. of Hai)	China	San Che Tien	557		
Wei Ho (trib. of Hwang Ho)	China		540		
Hwang Ho	China	Shenhsien	460	44	1.1
Great Fish River	South-Africa	Lake Arthur		33.5	
Isser	Algerie	Tablat		20.0	
Sundays River	South-Africa	Lake Mentz		18.5	
Rio Grande del Norte	U.S.A.	Butte		17.0	
Colorado	U.S.A.	Grand Cañon		11.7	
Missouri (trib. of Mississippi)	U.S.A.	Kansas City		2.97	
Kosi (trib. of Ganges)	Nepal	Chatra		2.86	
Nile	Egypt			1.97	
Yang Tze	China	Chihkiang	5.61	1.86	0.015
Tigris	Iraq	Bagdad		1.57	
Durante	France			1.50	
Ganges	India	Faracca	1.0		0.05
Amazon	Brazil			0.8	
Irrawaddy	Burma	Prome		0.57	
Mississippi	U.S.A.	Robertsville		0.41	
Po	Italy	Ponte Lagoscuro		0.28	
Ohio (trib. of Mississippi)	U.S.A.			0.20	
Mekong	Cambodja	Kratie	0.3	0.16	
Parana	Argentine	Corrientes		0.15	
Rhône	France	Lyon		0.15	
Danube	Hungary	Budapest		0.14	
Danube	Austria	Vienna		0.10	
Congo	Central-Africa			0.04	
Rhine	Netherlands	Nijmegen		0.04	
Benue	Nigeria	various places	0.4		0.06
Niger	Nigeria	various places	0.5		0.06

*) Results obtained mainly from calculation; only occasionally from actual observation of silt concentration. Calculation is possible f.i. by considering the total amount of silt deposited yearly in reservoirs in connection with the total annual water discharge.
Figures for this table are extracted from ECAFE: flood control series no 1, 1950.
PARDÉ: Sur les valeurs de la turbidité des rivières, 1952.

From the standpoint of navigability within the scope of the investigation by NEDECO, it was not essential to obtain accurate figures about the silt. However, to have a general insight into the magnitude of the silt discharge with a special view to the rate of deposition in eventual storage reservoirs, and into its corresponding factors of influence upon the river, a few measurements have been made. Samples were taken with an ordinary bottle, in most cases near the left bank, in the middle and near the right bank, each at a depth of at least 3 feet below the surface. In this way the particular influence of wind, rain, sun or any other source of disturbance affecting the silt concentration over a thin upper layer only was avoided.

On the Benue, samples were taken 3 feet below the surface, near the river-bottom, and halfway between the surface and the bottom. Any particular tendency, however, could not be concluded from these figures: the average of 25 surface samples differed less than 10 % from the average of the corresponding bottom samples, which was fully in accordance with the thought that turbulence of the water mass was so great that an even distribution in the vertical of the very small silt particles can be accepted.

Turbulence, however, means a continuously changing water velocity and a corresponding exchange of water particles in a direction normal to the average flow. Consequently also the silt concentration varies in the course of time. Diagram 5.3.2-2 shows the result of a series of

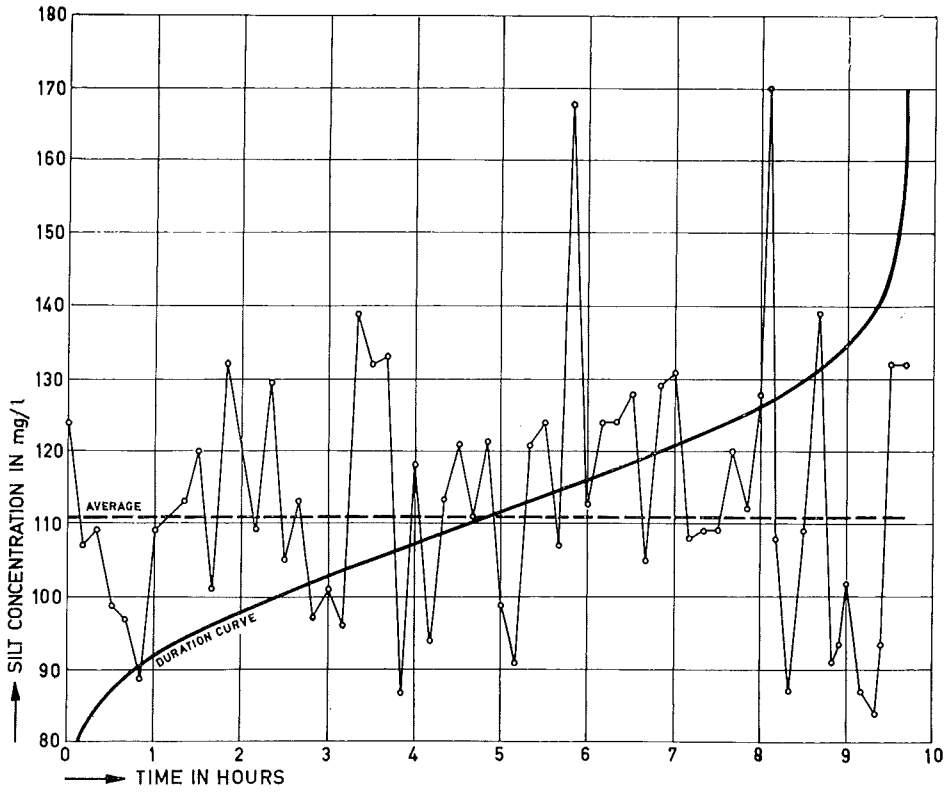


DIAGRAM 5.3.2-2

Variation of silt concentration over a period

series of observation on 28.4.58 Niger, Mile 363, 400′ from left bank (1

observations by which the silt concentration in a single place has been determined every 10 minutes. Although the extreme observations show deviations of + 53 % and — 24 % respectively, the standard deviation of the series amounts to only 16 % of the mean value for the silt concentration. From this it is concluded that three samples taken in one cross-section will give a reasonably reliable result.

(1 executed by I.W.D. on behalf of NEDECO

TABLE 5.3.2-3

OBSERVATIONS OF SILT CONCENTRATION ON NIGER AND BENUE

TOWN	MILE	DATE	Qm³/sec		SILT CONCENTRATION			
					left	middle	right	average
NIGER								
Jebba	562	11.10.56	4,400	s	*30*	*125*	*90*	**80**
Likpata	509	10.10.56	4,400	s	*45*	*50*	*50*	**50**
Pategi	480	11.10.56	5,900	s	*220*	*100*	*15*	**110**
Pategi	480	27.11.56	2,000	s	60	45	60	**60**
Egwamama	428	27.11.57	2,100	s	60	70	70	**70**
Gwachinko	428	11.10.56	6,000	s	*45*	*20*	*100*	**60**
Gwachinko	428	28.11.57	2,800	s	100		70	**90**
Kelebe	389	7. 8.57	4,000	s	*900*	*450*	*180*	**510**
Kelebe	389	8.11.57	4,900	s	*110*	*45*	*30*	**80**
Lokoja-up	362.5	17. 4.58	1,970	s	80	130	200	**140**
Lokoja-up	362.5	24. 4.58	2,050	s	160	190	200	**180**
Lokoja-up	362.5	9. 5.58	1,910	s	140	130	140	**140**
Lokoja-up	362.5	23. 5.58	1,330	s	130	150	90	**120**
Confluence	358.5	17. 4.58	2,150	s	105	230	90	**140**
Confluence	358.5	24. 4.58	2,220	s	90	190	160	**150**
Confluence	358.5	9. 5.58	2,180	s	100	160	110	**120**
Lokoja-down	358	23. 5.68	1,920	s	120	140	110	**120**
Shintaku	357	28.11.57	6,140	s	80	120	110	**100**
Idah	310	29.11.57	6,220	s	50	120	90	**90**
Idah	310	22. 1.58	2,980	s	50	50	50	**50**
Idah	310	1. 5.58	2,380	s	160	150	110	**140**
Anwam	244	18. 1.58	2,960	s	60		60	**60**
Anwam	244	18. 1.58		s	70		70	**70**
Onitsha	231	30. 4.58	2,510	s	160	170	110	**150**
Aboh	178	28. 4.58	2,530	s	120	130	120	**120**
KADUNA								
Nupeko	483	9.10.56	1,900	s		*600*		**600**
GURARA								
Gerinya	400	11.10.55		s		*3,300*		**3,300**
ORASHI								
—		21.11.57		s		*80*		**80**

TOWN	MILE	DATE	Qm³/sec		SILT CONCENTRATION			
					left	middle	right	average
BENUE								
Jimeta	894	19. 9.57	2,920	s	350	290	330	
				m	310	*110*	*200*	
				b	280	420	330	
				a	**310**	**355**	**330**	**330**
Jimeta	884	26. 9.57	3,240	s	290	260	*170*	
				m	*110*	330	*100*	
				b	270	350	330	
				a	**280**	**310**	**330**	**310**
Jimeta	884	22.10.57	2,210	s	270	280	*65*	
				m	220	250	*110*	
				b	230	350	390	
				a	**240**	**295**	**390**	**310**
Jimeta	884	23.10.57	2,040	s	190	330	210	
				m	280	310	230	
				b	250	*110*	150	
				a	**260**	**320**	**195**	**260**
Numan	846	24.10.57	2,240	s	160	140	840	
				m	190	250		
				b	*170*	250		
				a	**175**	**215**	**840**	**410**
Numan	846	31.10.57	1,510	s	260	*140*	300	
				m	*80*	320	*160*	
				b	270	*130*	690	
				a	**265**	**320**	**445**	**340**
Lau	777	3.11.57	1,630	s	*280*	*110*	*160*	
				m	*160*	*180*	330	
				b	350	330	*170*	
				a	**350**	**330**	**330**	**340**
—	647	6.11.57	2,530	s		90	*40*	
				m		190	260	
				b		150	250	
				a		**145**	**255**	**200**
Ibi	614	20.10.56	8,200	s	*100*	*160*	*160*	**140**
Ibi	614	6.11.57	5,110	s	200	210	230	
				m	150	220	260	
				b	110	160	250	
				a	**155**	**200**	**245**	**200**
Makurdi	511.6	9.11.57	6,130	s	110	310	220	
				m	120	270	250	
				b	60	280	280	
				a	**95**	**285**	**250**	**210**
Akpanaya	502	22.10.56		s		*200*		**200**
Umaisha	400	10.11.57	8,200	s	70	160	200	
				m	80	190	190	
				b	90	220	165	
				a	**80**	**190**	**185**	**150**
Lokoja	N. 364.8	17. 4.58	180	s	85	85	60	**80**
Lokoja	S. 364.8	17. 4.58		s	110	110	105	**110**
Lokoja	N. 364.8	24. 4.58	170	s	70	90	90	**80**
Lokoja	S. 364.8	24. 4.58		s	80	60	70	**70**

TOWN	MILE	DATE	Qm³/sec		SILT CONCENTRATION			
					left	middle	right	average
GONGOLA								
Dadinkowa	935	7.11.57	100	s	580	680	1150	
				m	470	1040	840	
				b	940	900	630	
				a	**665**	**875**	**875**	**810**
Kombo	897	6.11.57	100	s	640	760	650	
				m	970	780	780	
				b	600	700	430	
				a	**735**	**745**	**620**	**700**
Confluence	848	1.11.57	120	s	400	500	*250*	
				m	380	*160*	460	
				b	*190*	*140*	500	
				a	**390**	**500**	**480**	**460**
TARABA								
Beli	753	30.10.57	730	s	70	150		
				m	100			
				b	90	80		
				a	**85**	**115**		**100**
Gassol	691	7. 8.57	850	s	*200*	*46*	*185*	**140**
Confluence	673	5.11.57	940	s	*160*	220	280	
				m	110	190	80	
				b	130	250	230	
				a	**120**	**220**	**195**	**180**
DONGA								
Nyakura	649	19.10.56	1,200	s	*130*	*200*	*120*	**150**
—		8. 8.57	1,230	s	*80*	*80*	*80*	**80**
—		21. 9.57	1,560	s		*150*		**150**
Confluence	637	6.11.57	1,130	s	220	*180*	105	
				m	*170*	240	200	
				b	420	*250*	*100*	
				a	**320**	**240**	**155**	**240**
KATSINA ALA								
Sevav	570	12.10.56	2,100	s	*110*	*210*	*180*	**170**
Confluence	538	29. 7.57	1,420	s	*80*	*80*	*80*	**80**
Confluence	538	7.11.57	1,607	s	110	110	90	
				m	90	100	70	
				b	80	90	80	
				a	**95**	**100**	**80**	**90**

s = surface-sample
m = middle-sample
b = bottom-sample
a = average

In total, 261 silt samples have been taken, distributed over the rivers as follows:

Niger	72
tributaries of Niger	3
Benue	111
tributaries of Benue:	
Gongola	27
Taraba	17
Donga	16
Katsina Ala	15

These samples were taken to Lokoja, where the actual silt concentration was determined. Initially this was executed by means of a balance after the silt had settled and the water finally evaporated in an oven. But owing to the very long period necessary for the evaporation process, a turbidimeter (see II, 3.5.3-d) was later put to use. A comparison of the two methods led to the conclusion that the turbidimeter gives much more accurate results than the weighing method. In Table 5.3.2-3, figures are collected of silt concentration for all samples taken. In this a normal type of print is used for the results obtained with the turbidimeter, and italic type for the weighing method. Averages have been calculated for the vertical (in the Benue and Benue tributaries only) as well as for the total cross-section, and are printed in bold type.

From these data it appears that the main Rivers Niger and Benue have a reasonably low silt concentration. The maximum measured cross-sectional average amounts only to 0.5 kg/m^3 during high water, while at low water the concentration is less than 0.1 kg/m^3. In February the Benue has even very clear water with less than 0.002 % silt, but this has not been sampled.

However, the tributaries Gongola, Kaduna and Gurara show a strikingly higher concentration. These rivers drain the Jos Plateau, which apparently loses much soil into the river. Consequently, immediately below the intersection of these tributaries with the main river, the silt concentration of the main river is not evenly distributed. In Numan, below the Gongola, the sample near the right bank once showed a concentration nearly five times as high as the sample from the left side.

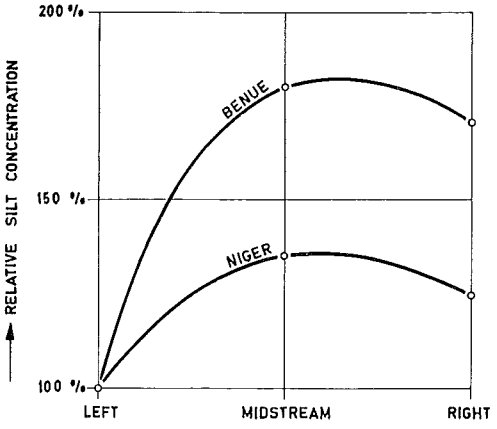


DIAGRAM 5.3.2-4

Variation of silt concentration in a cross direction

In Pategi, below the Kaduna, this ratio was even over 10, and in Kebele, below the Gurara, again a ratio of five occurred. It appears, however, that going downward this uneven distribution cannot continue owing to the turbulence with its exchange of water and silt particles in a transverse direction. In Lau, some 70 miles downstream from Numan, nothing is left from the influence of the Gongola. The same is true for Gwachinko, 43 miles below Pategi. On the other hand, the tributaries with relatively clear water also influence the distribution of silt in the main river.

The Rivers Taraba, Donga and Katsina Ala, all flowing from the left-hand side of the Benue, effect a black strip of water with a low silt concentration along the left bank of the Benue below their confluences.

Omitting those samples which have been taken immediately below affluents, there is yet a general tendency of variation in concentration in a transversal direction. The ratio of concentration right to left and middle to left, expressed in percentage, has been calculated for some 20 samples in both the Niger and Benue. The average of these figures is shown in Diagram 5.2.3-4.

Apart from the influence of tributaries, as mentioned above, this tendency to a higher silt concentration on the right side of the river might also be attributed to the influence of the acceleration of CORIOLIS (see 6.1.4), although this is not certain.

Comparison of the silt figures for the various stations along the Benue resulting from samples taken in the first half of November, 1957, leads to the conclusion that no important amount of silt is deposited in the river valley. In Table 5.3.2-5 these total amounts of silt, expressed in kg/sec, have been calculated from the silt concentration (measured) and the total water flow Q.

TABLE 5.3.2-5

SILT DISCHARGES IN THE BENUE, NOV. 1957

STATION	TRIBUTARY	date (1957)	WATER DISCHARGE m³/sec.		SILT CONC. mg/liter	TOTAL AMOUNT OF SILT kg/sec.	
			affluent	main river		affluent	main river
Jimeta		1.11		890	250		24.8
	Gongola	1.11	120		450	4.6	
	drainage area		*620*		—	—	
			+—			+—	
Lau		3.11		1,630	210		29.4
	Taraba	5.11	930		170	14.3	
	Donga	6.11	1,130		240	23.5	
	drainage area		*1,420*		*275*	*38.8*	
			+—			+—	
Ibi		6.11		5,110	200		106.0
	Katsina Ala	7.11	500		90	3.9	
	drainage area		*520*		*25*	*1.1*	
			+—			+—	
Makurdi		10.11		6,130	210		111.0
	drainage area		*1,570*		—	—	
	loss of silt				—	*-4.5*	
			+—			+—	
Umaisha		11.11		7,700	160		106.5

normal type: observed
italic type: computed

The tributaries have also been included in this calculation. Missing data about the flow from local drainage areas and its corresponding silt concentration could be computed from the measured figures with the help of the continuity condition. These computations have been printed in italic type. From the table it would follow that only in the stretch between Makurdi and Umaisha is a certain amount of silt deposited, the magnitude of which is only about 4 %. Of course, any intervention in the natural state of the river, such as by building a dam with an arti-

ficial reservoir, will cause a change in silt deposition, the maximum depositing amount being the annual silt discharge. Since the silt samples are few in number, this figure can only be roughly estimated.

For the Benue, it has been possible to compose Table 5.3.2-6 in a rather extensive form with satisfactory results. The computations are based upon the observations of silt concentration in relation with the water discharge Q. With the help of these (rough) relation-curves the silt discharge over the whole of 1956 has been found (bold print). The average concentration is determined as the quotient of the annual silt and water discharges, while in the last column of the table the average degradation of the total drainage area has been calculated as the quotient of the annual silt discharge and the area of the drainage basin, taking the weight of one cubic

TABLE 5.3.2-6

YEAR DISCHARGE OF SILT ON THE BENUE

Year of computation 1956

RIVER	STATION	DRAINAGE AREA	annual flow Q	SILT		average degradation of total drainage area
				annual silt disch.	average silt conc.	
		km^3	10^9 m^3	10^6 ton	gr/m^3	mm/100 years
Benue	Yola	107,000	23	**6.0**	260	3
Gongola	Bare	55,500	6.4	**4.3**	670	4
Taraba	Gassol	21,300	12	**1.7**	140	4
Donga	Nyankwola	19,800	13	**1.1**	85	3
K'Ala	Sevav	22 000	23	**1.4**	60	3
extra (local dr. area)		*78,400*	*16*	*4.6*	*280*	*3*
Benue	Makurdi	304,000	93	**19.1**	200	$3\frac{1}{2}$

metre of silt as two tons. Obviously these figures are negligible in comparison with, for example, the Hwang Ho, which discharges annually 1,890 million tons and has a corresponding average degradation of 150 mm per 100 years. An eventual reservoir in theB enue near Yola with a capacity of, say, 10 milliard m^3 would, according to these figures of Table 6, be reduced by less than 1 % of its capacity during a period of 25 years.

In the absence of additional data, the Niger can be said to have a silt discharge of something like 7 million tons per year at Jebba and between 8 and 10 million tons at Baro. Some additional observations by I.W.D. in 1958 have been taken into account for this estimation.

Although from the standpoint of navigation silt in the Niger and Benue does not form a problem, it might be interesting to collect more data on silt and silt concentration. The mineralogical composition of the silt as a natural fertiliser of the flood-plains is important for the agricultural development of the country. The silt concentration affects the quality of the river-water for purposes of human and industrial consumption. High concentrations also mean severe erosion of parts of the drainage area, and loss of great quantities of soil might give rise to activities on local soil conservation. Since in future the river authorities will be expected to have adequate information on every aspect of the river, the silt should be a subject of further detailed study.

5.3.3. Total quantities of sediment

In the foregoing, all the different kinds of sediment transport by the flowing stream have been considered and analysed. Observations were translated into figures giving actual quantities of the sand and silt discharges and their corresponding grain-sizes. Between the three groups of transport — bed-load, suspended load and wash-load — great differences exist; differences in origin and mechanism as well as in effect upon the river and the river-bed. There is, indeed, hardly any relationship between them.

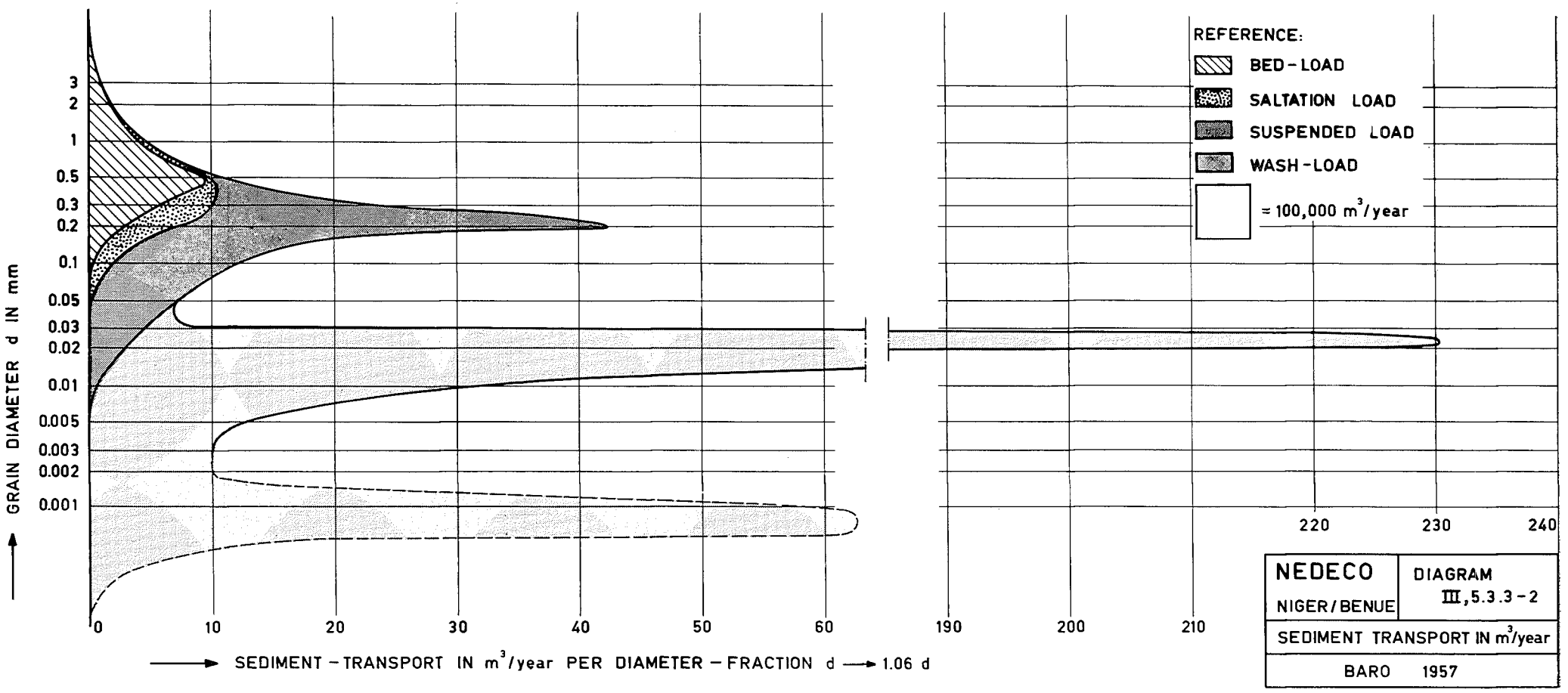
Determinant for the behaviour of the river-bed, and therefore most important in the scope of this Report, is the bed-load. As the rivers are alluvial, the quantity of bed-load always equals the transporting capacity. Extra supply of sand means deposition and increase of river-slope; reduced supply may, on the contrary, cause scour and decrease of slope.

Notwithstanding its importance, bed-load forms only a very small fraction of the total transport, the great bulk of sediment being wash-load. This appears clearly from Table 5.3.3-1.

TABLE 5.3.3-1

YEAR TRANSPORTS OF SEDIMENT ON NIGER AND BENUE

STATION	YEAR	BED-LOAD (incl. salt. load)			SUSPENDED LOAD			WASH-LOAD			TOTAL	
		10^6 m^3	10^6 cuft	% of total	10^6 m^3	10^6 cuft	% of total	10^6 m^3	10^6 cuft	% of total	10^6 m^3	10^6 cuft
Upper Niger												
Baro	1956	0.29	10	8	0.29	10	8	3	100	84	3.6	120
	1957	0.44	16	7	0.82	29	13	5	180	80	6.3	220
	average 1915—1957	0.31	11	6½	0.55	19	11	4	140	82½	4.9	170
Benue												
Yola	1956	0.20	6.9	6	0.17	6.0	5	3.0	110	89	3.3	120
	1957	0.28	10	6	0.24	8.5	5	4.2	150	89	4.7	170
	average 1934—1957	0.20	7.2	6	0.17	6.0	5	3.0	110	89	3.3	120
Makurdi	1956	0.57	21	5	0.87	31	8	9.5	340	87	11	390
	1957	0.86	31	5½	1.3	47	9	13	470	85½	15	540
	average 1932—1957	0.61	22	5	0.95	34	8	10	370	87	12	420
Lower Niger												
Shintaku	1956	0.72	26	5	1.0	36	7	*13*	*460*	88	*15*	*520*
	1957	1.2	42	5½	1.8	65	9	*18*	*640*	85½	*21*	*750*
	average 1915—1957	0.88	31	5	1.3	46	8	*15*	*530*	87	*17*	*610*
Onitsha	1956	0.76	27	5	1.2	44	8	*14*	*500*	87	*16*	*570*
	1957	1.3	47	6	2.2	79	10	*19*	*670*	84	*22*	*800*
	average 1925—1957	1.0	36	5½	1.7	59	9	*16*	*570*	85½	*19*	*660*


REFERENCE:
BED-LOAD
SALTATION LOAD
SUSPENDED LOAD
WASH-LOAD
= 100,000 m³/year
GRAIN DIAMETER d IN mm
3
2
1
0.5
0.3
0.2
0.1
0.05
0.03
0.02
0.01
0.005
0.003
0.002
0.001
0
10
20
30
40
50
60
190
200
210
220
230
240
SEDIMENT-TRANSPORT IN m³/year PER DIAMETER-FRACTION d → 1.06 d
NEDECO
NIGER/BENUE
DIAGRAM
III,5.3.3-2
SEDIMENT TRANSPORT IN m³/year
BARO 1957

Here the figures printed in italic type have been roughly estimated, as sufficient observations in these stations for a reliable computation have not been available.

The situation is more impressively shown in Diagram 5.3.3-2 where the 1957 year-transport at Baro has been plotted against the corresponding grain-diameter, the area of each figure being a measure of the magnitude of transport. Two peaks are shown to exist, which is in complete accordance with the normal phenomenon on many other rivers in the world. The existence of a possible third peak in the region of very small grain-sizes has not been proved conclusively nor could it be physically explained.

5.4. PARTICULAR PHENOMENA

5.4.1. Scour and deposition

As has been stated in the previous sections of this Chapter, bed-load is determinant for the behaviour of channels in an alluvial river. Consequently, scour and deposition in these channels entirely depend on this type of sediment load. It seems very obvious that scour takes place where the downward transport of sand exceeds the supply of sand from upstream.

Nevertheless, this has been frequently mistaken. Even in recent publications, scour has sometimes been stated to depend on the velocity of the flow: with a velocity greater than the so-called "pick-up velocity" scour is said to take place, whilst a velocity smaller than the critical value would involve deposition.

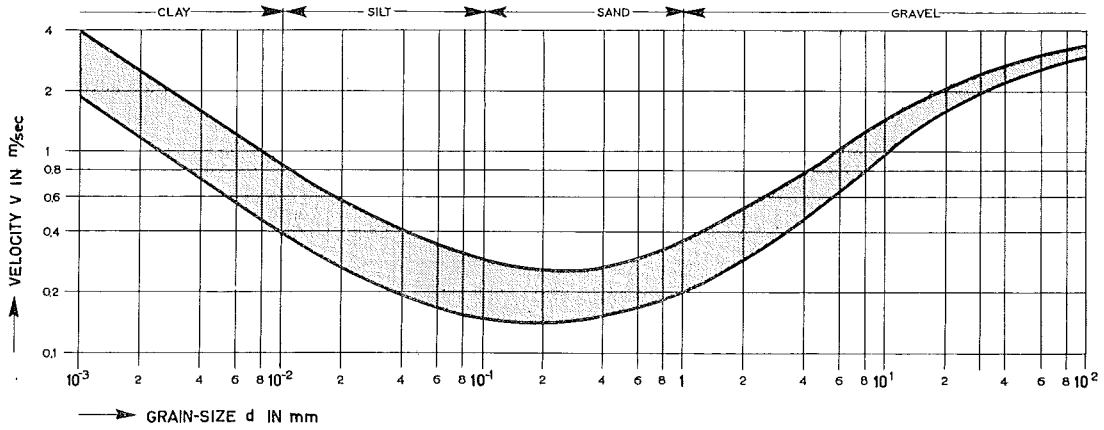


DIAGRAM 5.4.1-1

Pick-up velocity as a function of the grain-diameter d

The pick-up velocity itself has a good physical meaning where it concerns sand-grains brought into motion in a stream without original sand-transport. It thus indicates the starting-point of the phenomenon of sand-transport, analogous to the constant term 0.047 mentioned in the formula of M.P.-M. under 5.2.2. In this respect, the theory of scour depending on the velocity is indeed valid for channels without sand-transport as, for instance, irrigation channels designed with such a cross-section that the channel is stable and would not be affected by any influence of the flow.

According to HJULSTRÖM ([1] this pick-up velocity depends on the grain-size, the function given in Diagram 5.4.1-1.

([1] HJULSTRÖM, 1935. MOR. 12

However, a sand-transporting stream does not follow this simple conception of scour and deposition. Sand-grains are in continuous movement, involving formation and deformation of its very unstable channels. Although the velocity of the flow is nearly always greater than the pick-up velocity, deposition of sand might take place. Such deposition or scour is only possible where the total sand-transport along the axis of the river varies.

Sideward exchange of material might occur as a result of the sand-transporting capacity being non-uniformly distributed over consecutive cross-sections (see also the next paragraph 5.4.2 about local and through transport); but the entire section as a whole undergoes scour only

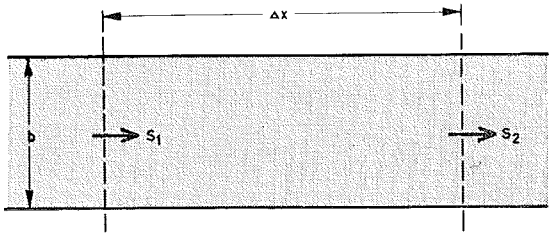


DIAGRAM 5.4.1-2

Principle of a river-section under scouring effect: $S_2 > S_1$

when the transport at the downstream end S_2 exceeds the supply at the upstream end S_1. It follows from Diagram 5.4.1-2 that

$$\text{scour} = N = \frac{\text{change in bottom height}}{\text{unit of time}} = \frac{\Delta z}{\Delta t} = \frac{S_2 - S_1}{b\,\Delta x} = \frac{\Delta S}{b\,\Delta x}.$$

When Δx is considered to be infinitesimally small, scour appears to be proportional with the differential of sand-transport:

$$\text{scour} = N = \frac{1}{b}\,\frac{dS}{dx}$$

which means that scour takes place when $\frac{dS}{dx}$ is positive and deposition when $\frac{dS}{dx}$ is negative.

The question whether scour or deposition occurs is important for the study of the behaviour of channels. In this Report it has been used, for instance, for the determination of the Dominant Discharge (see 6.1.1) and for considerations about the equilibrium state of the river-bed near confluences (4.2.6). In the present paragraph it will be investigated how this scour criterion $\frac{dS}{dx}$ can be modified into a utilisable form.

For this purpose it is assumed that the river has a steady flow with a constant discharge Q. For the calculation of the differential dS the sand-transport formula of M.P.-M. is used (see 5.2.2):

$$s = 6.5\, d^{\frac{3}{2}} \sqrt{g\Delta} \left[\frac{\mu a i}{\Delta d} - 0.047 \right]^{\frac{3}{2}}$$

which for a uniform material can shortly be denoted as

$$s = (A\mu a i - B)^{\frac{3}{2}} \qquad \ldots\ldots\ldots \quad (1)$$

where A and B are constant for the entire river-section. The total sand-transport over the full width of the cross-section is then:

$$S = sb = b\,(A\mu a i - B)^{\frac{3}{2}}$$

Differentiating this gives

$$\frac{dS}{dx} = \frac{db}{dx}\,(A\mu ai - B)^{\frac{3}{2}} + \tfrac{3}{2}b\,(A\mu ai - B)^{\frac{1}{2}} A\mu \left[i\frac{da}{dx} + a\frac{di}{dx} \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Also valid is the formula of DE CHEZY

$$Q = Cb\, a^{\frac{3}{2}}\, i^{\frac{1}{2}} = \text{constant}$$

which leads to

$$\frac{dQ}{dX} = C\left[\frac{db}{dx} a^{\frac{3}{2}} i^{\frac{1}{2}} + \tfrac{3}{2} a^{\frac{1}{2}} b\, i^{\frac{1}{2}} \frac{da}{dx} + \tfrac{1}{2} b\, a^{\frac{3}{2}}\, i^{-\frac{1}{2}} \frac{di}{dx} \right] = 0$$

when the coefficient C is assumed to be constant over the entire length of the concerned river-section. It appears that

$$\frac{db}{dx} ai + \tfrac{3}{2} bi \frac{da}{dx} + \tfrac{1}{2} ba \frac{di}{dx} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Generally speaking, the width b is variable with changing water-level h in the same cross-section and is also variable along the river-axis with constant discharge. The first variability is not considered here, since the discharge is assumed to be constant; hence

$$b = f(x).$$

The depth a is a function of x, h and the time t. However, when the change in bottom height as a result of scour or deposition is small in quantity compared with the water-depth a and its variation along the river-axis $\frac{da}{dx}$, the dependency of the depth from time can be neglected. Again, with the above-mentioned assumption h = constant, it remains that

$$a = \varphi(x).$$

From these two functions it follows that

$$\frac{db}{dx} = \frac{db}{da}\frac{da}{dx} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Combination of the Equations (2), (3) and (4) and modification of the result leads to

$$\frac{dS}{dx} = \frac{ba \dfrac{di}{dx} (A\mu\, ai - B)^{\frac{1}{2}}}{\dfrac{db}{da}\, ai + \tfrac{3}{2}\, bi} \left[\frac{db}{da} (A\mu\, ai + \tfrac{1}{2}B) + \tfrac{3}{2} bA\mu\, i \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Scour takes place with $\frac{dS}{dx} > 0$, deposition with $\frac{dS}{dx} < 0$. The state of transition is $\frac{dS}{dx} = 0$, which could be realised by the following possibilities:

(i) $\frac{di}{dx} = 0$;

(ii) $A\mu ai - B = 0$; and

(iii) $\frac{db}{da}(A\mu ai + \tfrac{1}{2}B) + \tfrac{3}{2} bA\mu i = 0.$

(i) $\frac{di}{dx} = 0$ substituted in Equations (3) and (4) leads to the conclusion that the width b and the depth a are both constant for all consecutive cross-sections of the river-section. The channel is prismatic, and at no time does scour or deposition take place, sideward exchange of material not considered.

(ii) $A\mu ai - B = 0$ substituted in Equation (1) shows that the sand-transport S is zero. It is obvious that in a river without sand-transport scour or deposition cannot occur.

(iii) The remaining possibility is actually the condition for stability in a sand-transporting and non-prismatic river. The further considerations are based upon this condition.

It follows from the condition (iii) that

$$\frac{db}{da} = - \frac{\frac{3}{2} b A\mu i}{A\mu ai + \frac{1}{2}B} \quad \ldots\ldots\ldots (6)$$

For simplicity's sake only, let it be that

$$\frac{B\ C^2}{A\ Q^2} = P \quad \ldots\ldots\ldots (7)$$

which is constant over the entire river-section. This and the formula of DE CHEZY give

$$Ai = \frac{B}{b^2\ a^3\ P}$$

which modifies Equation (6) into

$$\frac{db}{da} = - \frac{\frac{3}{2} b\mu \frac{B}{b^2\ a^3\ P}}{a\mu \frac{B}{b^2\ a^3\ P} + \frac{1}{2}B} = - \frac{b}{a} \frac{3}{2 + \frac{b^2\ a^2\ P}{\mu}}$$

Finally, if it is written that

$$\frac{3}{2 + \frac{b^2\ a^2\ P}{\mu}} = \alpha \quad \ldots\ldots\ldots (8)$$

the Equation becomes very simple, namely,

$$\frac{db}{da} = - \frac{b}{a}\ \alpha \quad \ldots\ldots\ldots (9)$$

which can be modified into

$$\frac{d\,(ba^\alpha)}{da} = ba^\alpha \ln a \frac{d\alpha}{da} = \vartheta\, ba^\alpha \quad \ldots\ldots\ldots (10)$$

From Equation (8) the differential quotient $\frac{d\alpha}{da}$ can be derived. This, multiplied with ln a gives

$$\vartheta = \ln a \frac{d\alpha}{da} = - \tfrac{2}{3} \alpha\, (3 - 2\alpha)\, (\tfrac{9}{8} - \alpha) \frac{\ln\ a}{a}$$

the value of which ranges between $- 0.03$ and $+ 0.02$, depending on the magnitudes for α and a.

Differentiation of Equation (8) gives

$$\frac{d\alpha}{da} = - 3 \frac{1}{\left[2 + \frac{b^2 a^2 P}{\mu}\right]^2} \left[\frac{2ba^2P}{\mu} \frac{db}{da} + \frac{2b^2 aP}{\mu} - \frac{b^2 a^2 P}{\mu^2} \frac{d\mu}{da}\right] =$$

$$= - \tfrac{2}{3} \alpha^2 \frac{3 - 2\alpha}{\alpha} \left[\frac{1}{b} \frac{db}{da} + \frac{1}{a} - \frac{1}{2\mu} \frac{d\mu}{da}\right] \quad \ldots\ldots\ldots (11)$$

It has been assumed that C = constant. Consequently, according to the Formula 6.3.4-(6)

$$C = 5.75 \sqrt{g}\ \log 12 \left[\frac{a}{k_r}\right] = \text{constant}$$

hence a :: k_r, and while

$$\mu = \left[\frac{k_s}{k_r}\right]^{\frac{1}{4}} \quad \text{(see 6.3.4)}$$

it is concluded that

$$\frac{1}{2\mu}\frac{d\mu}{da} = -\frac{1}{8a} \qquad \ldots\ldots\ldots (12)$$

Now the Equations (9) and (12) are substituted in (11) which gives

$$\frac{d\alpha}{da} = -\tfrac{2}{3}\alpha\,(3 - 2\alpha)\,\frac{1}{a}\,(\tfrac{9}{8} - \alpha)$$

as has been stated above.

Equation (10) then becomes

$$\frac{d(ba^{\alpha})}{da} = \vartheta\, ba^{\alpha}$$

or

$$\frac{d\,(ba^{\alpha})}{ba^{\alpha}} = \vartheta\, da.$$

Integrated

$$\ln\,(ba^{\alpha}) = \int \vartheta + \ln\varepsilon$$

or

$$ba^{\alpha} = e^{\int \vartheta\, da}\,\varepsilon \qquad \ldots\ldots\ldots (13)$$

where ε is constant.

In practice the depth a will normally vary only gradually, and with ϑ being sufficiently small the first factor on the right-hand side of this equation can be approximated to be constant.

The integration of $\int \vartheta\, da$ can be made if the variation of α is assumed to be negligible:

$$\int \vartheta\, da = -\tfrac{2}{3}\,\alpha\,(3 - 2\alpha)\,(\tfrac{9}{8} - \alpha)\int \frac{\ln a}{a}\,da = \zeta \int \frac{\ln a}{a}\,da$$

It then follows that

$$\int \vartheta\, da = \tfrac{1}{2}\,\zeta\,(\ln a)^2$$

or

$$e^{\int \vartheta\, da} = e^{\frac{1}{2}\zeta\,(\ln a)^2}$$

where ζ varies between -0.06 and $+0.08$, depending on the value for α, the first figure occuring at $\alpha = 1.3$ and the latter at $\alpha = 1$. If the first value is considered, while the depth a is supposed to decrease, for example, from 10 to 6 m going from one cross-section to the other, it appears that

$$\text{for cross-section 1:}\quad e^{\int \vartheta\, da} = 0.85, \text{ and}$$

$$\text{for cross-section 2:}\quad e^{\int \vartheta\, da} = 0.91.$$

Between these results a mutual difference of only 6% exists even under such a sudden change in the shape of the cross-section. For a decrease in the depth from 10 to 6 m corresponds with the considerable widening of the river at the ratio of about 1 : 2. Yet the error in the approximation is only 6%. This percentage is for $\alpha = 1$ slightly larger, viz., 10%, which is still small enough to allow it to be neglected.

Equation (13) is thus approximated to

$$ba^{\alpha} = \text{constant} \qquad \ldots\ldots\ldots (14)$$

which is the condition for stability in a sand-transporting and non-prismatic river, as mentioned under (iii) above. Modification of Equation (5) leads to

$$\frac{dS}{dx} = -\left[2s + 3B\,s^{\frac{1}{3}}\right] a^{-\alpha}\,\frac{d\,(ba^{\alpha})}{da}\,\frac{da}{dx} = -E\,\frac{d\,(ba^{\alpha})}{dx} \qquad \ldots\ldots\ldots (15)$$

where the factor E is always positive, which involves that, with the term ba^{α} decreasing in consecutive cross-sections, the total sand-transport S must consequently increase and erosion takes place in the stretch between the two cross-sections. Conversely, an increasing ba^{α} involves deposition.

The magnitude of α can be derived from Equation (8) which also can be written as

$$\alpha = \frac{3s^{\frac{2}{3}} + 3B}{2s^{\frac{2}{3}} + 3B} \qquad \ldots\ldots\ldots (16)$$

indicating that α is a direct function of the sand-transport per unit width s, while the constant term B includes the grain-diameter d, which is assumed to be non-variable over the entire river-section. The coefficient α varies from 1 with zero sand-transport to 1.5 with very large sand-transport.

The magnitude of the actual scour or deposition depends on the variability of the term ba^{α}, but also on the value of the factor E in Equation (15). This factor E can be written as

$$E = [2s + 3Bs^{\frac{1}{3}}]\, a^{-\alpha} \qquad \ldots\ldots\ldots (17)$$

Summarising all these considerations, the term ba^{α} can be used as a scour criterion, on the assumption that

(i) the channel is sand-transporting and non-prismatic;
(ii) the flow is steady;
(iii) the coefficient of DE CHEZY C is constant; and
(iv) the composition of the river-section concerned is of uniform material.

And with the approximation that

(a) the change in bottom height as a result of scour is small compared with the depth a and its variation along the river axis $\frac{da}{dx}$; and

(b) the variation in the term $\int \vartheta\, da$ of Equation (13) is neglected.

Scour occurs when ba^{α} decreases in consecutive cross-sections, whereas deposition takes place when ba^{α} increases.

Here b = width of the river

a = depth

α = a coefficient, depending on the quantity of sand-transport per unit width as expressed by Equation (16); it varies between 1 for zero sand-transport as a minimum to 1.5 for very large sand-transport as a maximum.

As an example, the stretch between a bend and a crossing (see 6.4.2) could be mentioned. During H.W. the sand-bank situated in the bend makes a large part of the cross-section rather shallow and consequently the value for ba^{α} is considerably reduced; whilst on the crossing the depth is more or less uniformly distributed over the full width and the magnitude of ba^{α} is relatively large. The result is a deposition of sand on the crossing. During L.W., however, the channel in the bend remains deep and the wide cross-section on the crossing is very shallow. The scour criterion, therefore, is greater in the bend than on the crossing, and scour occurs.

5.4.2. Local and through transport

Many writers make a distinction between local and through transport of sand. Among others FRIEDKIN ([1], when considering the behaviour of the transport of sand in a meandering river, discusses the source, path of travel and location of deposition of sand, and concludes:

([1] FRIEDKIN, 1945. MOR. 9.

"Within a meandering river the source of the sand is the caving banks and the sand only travels over relatively short distances to the first convex bar downstream, and the deposited sand is replaced by sand from caving banks. There is more or less continuous trading of sand along a river, deposition on bars and replacement from caving banks. The rate of trading varies, depending upon the rate of bank caving. It is particularly important to note that in practically all cases the bed-load which enters the bend from upstream tends to travel along the convex bar side of the talweg where it either deposits or passes through to the next bend."

The local transport of sand might be defined as the movement of sand which causes the sideward shifting of the meandering channel.

According to VAN BENDEGOM ([1], who considers a theoretical bend with a horizontal bottom configuration, the angle λ between the direction of the average flow line and the direction of the movement of a sand particle, when based on the theories of the spiral flow (6.1.2), follows from the Equation

$$\tan \lambda = 8\frac{a}{r} \qquad \ldots\ldots\ldots \quad (1)$$

and if the width of the river is small in relation to the radius of the bend, tan λ and thus λ is constant over the cross-section.

The assumption of a horizontal bottom configuration can only be held true if the outer bend is sufficiently erodible. In the case of a non-erodible bank the cross-section in a bend will show a transversal gradient as described in 6.1.2.

From Equation (1) the length of the river needed to enable a sand particle to cross over from the outer bend to the inner bend can be derived and is

$$l = \frac{br}{8a}$$

With b = 1,000 m (3,300 feet) and a = 5 m (16 feet) this length becomes

$$l = 25\ r$$

which means that the river has to go round nearly four times a full circle before the crossing-over of a sand particle can be achieved.

Looked on from the other side: in a bend of 90° the sand particle moves across over a width of

$$y = l \tan \lambda = \tfrac{1}{2} \pi r \frac{8a}{r} \approx 12a$$

With a depth of 5 m (16 feet), y becomes 60 m (200 feet), which is not very much in relation to the total width of the river.

The above is in full concordance with the findings of Friedkin, already mentioned, that the sand particles never cross over from one side of the river to the other.

The part of the sand passing through depends, according to Friedkin, on the rate of erosion of the river banks. Rapidly eroding banks will yield much local transport and hardly any through transport, while in the case of stabilised banks all sand movement would be through.

The movement of sand across the river, s_y, is closely related to the tan λ mentioned before, namely,

$$s_y = s_x \tan \lambda = s_x\, 8\frac{a}{r}$$

(still on the assumption that the bottom configuration is horizontal). This sand-transport s_y comes from the caving bank, and as this bank erodes over a height a, the erosion e_y amounts to

$$e_y = \frac{s_y}{a} = 8\frac{s_x}{r}$$

([1] VAN BENDEGOM, 1947. MOR. 1.

When r = 3,000 m (10,000 feet) and s_x = 600 m³/m/year (6,500 ft³/ft/year), then is

$$e_y = \frac{8 \times 600}{3{,}000} = 1.8 \text{ m/year } (6 \text{ ft/year})$$

which is a rather low value of erosion. If local erosion would be larger than this calculated one, the result would be caused by a local increase of s_x, and not result from the sideward shifting by s_y as generated by the spiral flow. The amount of sand eroded from an outer bend by a local increase in sand-transporting capacity will not cross the river, as follows from the discussion above, but will stay on the same side of the river.

When discussing the bed-load in Section 5.2, special emphasis was put on the fact that a river has a certain sand-transporting capacity and that the actual sand-transport will always equal this transporting capacity. This means that a smaller transport than the transporting capacity will immediately involve supply of sand from local erosion and that if the river is over-satiated with sand deposition will occur.

Also a certain continuity of the sand-transport is taken as a base of the theories of sand movement. A local increase of sand-transporting capacity at one spot would mean a local decrease of it at another spot. So an increase of sand-transport in the outer bend involves a decrease of sand movement somewhere else in the cross-section, for instance, in the inner bend.

This conception of sand-transport and sand-transporting capacity seems to be in concordance with the findings of Friedkin. As soon as a sand particle is taken from the concave side of a river-bend, the sand-transporting capacity is compensated by depositing another particle on the opposite sand-bank, which results in the sideward shifting of the meandering channel at a greater rate than the spiral flow could make. The actual transport of sand, however, is hardly affected by the sideward shifting, however fast it may be, and does not depend on the erodibility of the banks.

As long as the flow is constant and the cross-sections of the river have reached their equilibrium shape corresponding with this steady discharge — which results in the sand-transporting capacity being the same for each cross-section — the afore-mentioned picture of local and through transport can be used to describe the transversal movement of sand in a meandering river.

However, in normal rivers the flow will vary considerably and each discharge will have its own equilibrium shape of the river-bed, which results in a transversal exchange of sand within the cross-section. Also the relation between discharge and sand-transporting capacity of the consecutive cross-sections will be different, resulting in temporary erosion compensated by temporary deposition at another season, or conversely as the case may be.

The movement of sand thus becomes very complex, and not only the banks, which are the source of sand, but also the bottom of the river play very important rôles in this matter. For instance, during high water the relatively narrow and deep bends will erode and sand will be deposited on the wide crossings, while at low water the reverse will take place. Also a low-water channel which is scoured through a shallow crossing will be levelled out when the water rises, partly by the just-mentioned tendency to deposition of sand on the crossing during the high-water period and partly by transversal movement of sand.

It has been stated that in a natural river all movement of sand at all times and in all cross-sections satisfies the sand-transporting capacity. When leaving out the irregularities of this capacity as a function of the time, it can be said that every time a sand particle deposits in a given cross-section, another one is moved away from this cross-section. The distribution of the sand-transporting capacity within the cross-section and the variation of this distribution in consecutive cross-sections will determine from which place the particle will be put in motion

and where it will stop moving. Therefore, the net transversal transport over the cross-section is for only a small part due to actual sand movement in a transversal direction, and is caused for the greater part by this variation of the distribution of transporting capacity over consecutive cross-sections.

5.4.3. Bed-ripples

The major part of the sand-transport along the bottom occurs through the movement of the bed-ripples, but these undulations, which are to be found on every river with a sandy bottom, have always been one of the most intricate problems of hydraulic science. Many model tests have been carried out to find the factors influencing the formation, propagation and dimensions of the ripples, and also a great number of field observations have been studied in various parts of the world.

However, these investigations have led only to a few indications of what might have an influence on bed-ripples.

Since the character of the transport of sand as a whole is dependent on the sedimentary material and the tractive force, the character of the ripples also depends on these factors. According to SCHIELDS ([1], the controlling factor can be described as

$$\frac{\tau_c}{\Delta\rho d} = \left[\frac{ai}{\Delta d}\right]_{cr}$$

in which τ_c = critical tractive force
$\Delta\rho$ = submerged density of the particle
d = diameter of the particle.

Also the ratio $\frac{d}{\delta}$, in which δ is the thickness of the laminar film, has some influence, but this ratio will only have effect when observing small-scale model tests, as in Nature all rivers can be considered to have a turbulent flow with a comparatively thin laminar film.

When the velocity v increases, the size of the ripples also increases, but the height and sharpness of the ripples approach a maximum when the flow is near its critical value, i.e., when $v = \sqrt{ga}$. If v becomes larger than $\sqrt{ga}$ (shooting current), the undulations are less rugged and finally disappear (STRAUB) ([2]. In the case of shooting flow the ripples seem to move upstream but in fact the body of the ripple is moving down. This phenomenon is caused by the erosion on the downward side of the ripple exceeding the supply of sediment from upstream.

Another important observation from model tests is that the movement of sand through the movement of ripples seems to be essentially intermittent. The particles will move along the gently-sloping upstream side of the ripple, but after falling down its steep downstream slope they will remain there and be buried under the oncoming ripple, until the latter has passed and the particle starts to move again. Generally a particle travels only one ripple length, but due to local turbulence and the occurrence of a horizontal vortex behind a ripple it may saltate on to the upstream slope of the next ripple and move on immediately.

Finally, there is a most interesting theoretical approach to the problem by EXNER ([3 showing that an accidental local irregularity of the river-bed must eventually take a shape as represented in Diagram 5.4.3-1. This mathematically calculated shape is in rather good concordance with that of the sand-ripples found in many rivers in the world, including the Niger and Benue.

([1 SCHIELDS, 1936. MOR. 27.
([2 STRAUB, 1935. MOR. 29.
([3 EXNER, 1928. MOR. 6.

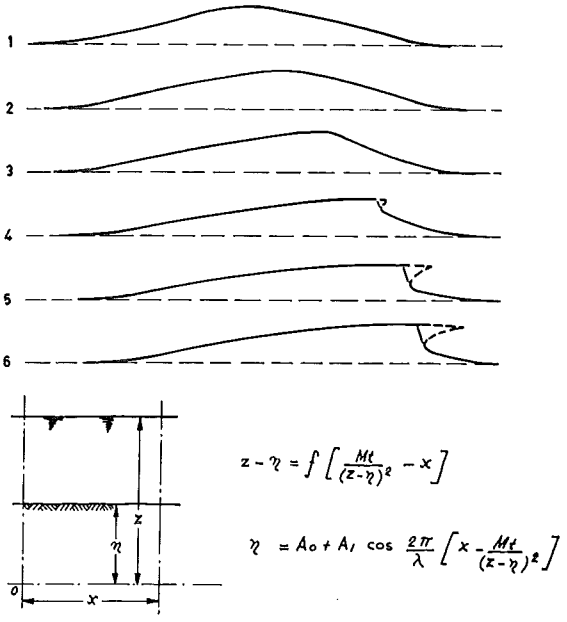


DIAGRAM 5.4.3-1

Exner's mathematically derived ripple profile

During the investigations of NEDECO on the Niger and Benue Rivers, the following observations were made on this subject:

Firstly, it appeared, when observing a certain location, that during the H.W.-period the ripples were more dominating than during the lower stages, but that there was a marked retardation in the adaptation of the ripples to the actual flow of the river. This resulted in fair-sized ripples which sometimes hampered shipping considerably when the water-level had dropped and the ripples were still high.

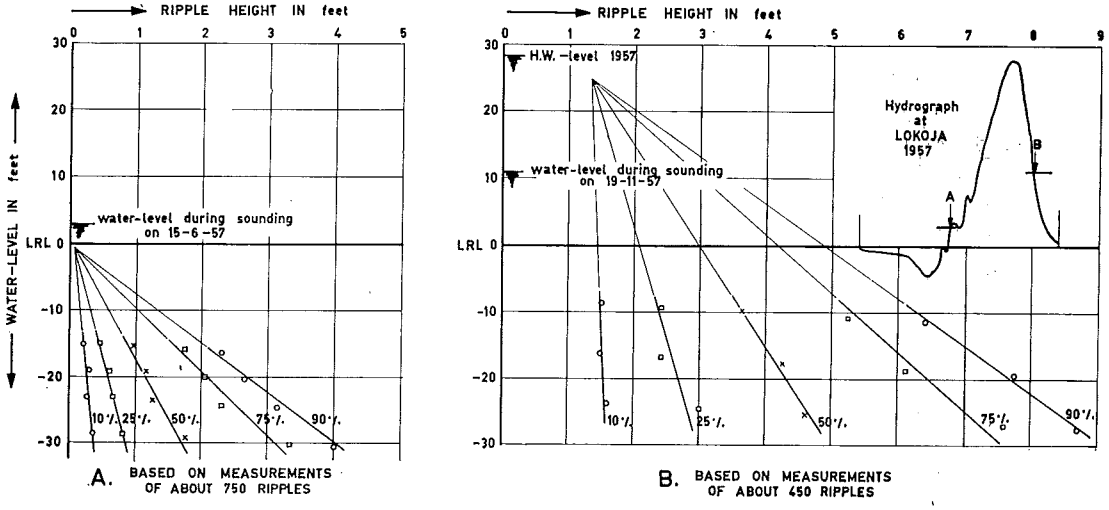


DIAGRAM 5.4.3-2

Frequencies of ripple heights on the Niger at L.W. and at H.W., as a function of the depth

Secondly, it has been found that with a certain flow the height of the ripples increases with an increasing depth of the river.

Both these phenomena can be seen from Diagram 5.4.3-2 in which the ripple height as measured at two longitudinal soundings between Mile 335 and Mile 360 on the Lower Niger have been plotted against the local mean depth of the river. So a ripple of 4 feet, ranging from 21 to 25 feet below the water-level, has been plotted against a depth of 23 feet. In this Diagram, not only have the average ripple heights been plotted but also the distribution from small to large ripples has been introduced, the lines representing a certain percentage of frequency.

Whether the fact that the lines of the graphs seem to converge to one point has any physical significance is an interesting problem for further studies, but it is striking that the converging points from both graphs coincide with a water-level which occurred some time before the day of observation. This might find its origin in the fact that the adjustment of the bed-ripples to the actual flow is lagging behind and the measured ripples possibly belong to the water-stage on this earlier date.

5.4.4. Sand-banks

In general a sand-bank is a sandy part of the river-bed which has its top-level in the range between the H.W.-level and the L.W.-level of the river. The highest limit can also (and perhaps even better) be defined as the transition-level between vegetation and no vegetation, because that part of the river-bed which is covered by vegetation can be considered as the river-bank or as an island, as the case may be.

From this definition it will be clear that the occurrence of many sand-banks has a large influence upon the flow pattern of the river, in particular during L.W., while conversely the L.W.-stage, apart from some local erosion, has hardly any effect on the location and shape of the sand-banks.

As the higher water-stages cover the sand-banks, sand movement over these banks will take place, resulting in the formation, deformation and propagation of the various sand-banks in the river. It will depend on the height of the sand-bank which water-stage will be dominant for its existence. Similar to the theories of the Dominant Discharge for the river-bed, always being below the water-level, a Dominant Discharge can be envisaged for the various levels of a sand-bank, and it will be obvious that a high sand-bank will have a high Dominant Discharge as low-water levels cannot exercise any influence upon its formation.

An exact calculation of these Dominant Discharges cannot be made, because the transversal distribution of the water-discharge and the sand-transport are not exactly known for any given irregularly-shaped cross-section with a sand-bank in it. It can be stated, however, that the cross-section of a river in a bend shows a distinct tendency to form a sand-bank in the inner part of the bend (as discussed in 6.1.2), and it will depend on local circumstances, such as the composition of the sand, the radii of the flow-lines at different water-stages and the total width of the cross-section, whether this sand-bank will be high or low, large or small.

The propagation of the sand-banks, which is clearly noticeable on the Niger and Benue, amounts to between 100 m and 300 m annually (sometimes even more). A rough comparison of the position of about 40 sand-banks on a stretch of the Lower Niger from the aerial surveys of 1955 and 1957 respectively shows that about 25 sand-banks moved between 100 m (330 feet) and 150 m (450 feet), averaging 130 m (400 feet), while 15 sand-banks moved between 220 m (600 feet) and 400 m (1,200 feet) averaging 250 m (750 feet) per year. A certain correlation was found between slow-moving and high sand-banks (about L.R.L. + 8′) as well as between fast-moving and low sand-banks (about L.R.L. + 4′).

In order to calculate the amount of sand moved in propagating these sand-banks, the average depth of the river in a crossing is estimated to be L.R.L. — 6′. To move a high sand-bank over 130 m (400 feet) in one year, 400 × (8 + 6) = 5,600 cuft/ft/year (550 m^3/m/year) of sand has to be transported over this sand-bank. For a low sand-bank this figure is 750 × (4 + 6) = 7,500 cuft/ft/year (750 m^3/m/year).

As the average annual sand-transport on the Lower Niger varies between 6,000 and 7,000 cuft/ft (600 and 700 m^3/m), it seems that the amount of sand needed to move the sand-banks is of about the same magnitude. This would entail that the sand-transporting capacity of the river in the area just below the sand-bank drops nearly to zero, and if a certain continuity of the sand movement is accepted, this would have to be counterbalanced by an increase of the sand-transporting capacity somewhere else in the cross-section, resulting in an erosion of the river-bottom downstream from the deeper channel which lies along the sand-bank. This is a quite acceptable conclusion, as this channel has to keep step with the moving sand-bank.

Locally, however, a single sand-bank might propagate much faster than the average, possibly due to particular boundary conditions.

During the detailed investigation of the crossing near Kelebe on the Upper Niger (Mile 369), as described in 6.4.2, the movement of the sand-bank upstream from this crossing has also been studied, and over the period of this investigation in 1957 this sand-bank moved about 2,000 feet in a downward direction. The sand-bank here gradually enters a narrowed river-section, more or less comparable with a funnel, and this might be the cause of the high speed at which the sand-bank moves.

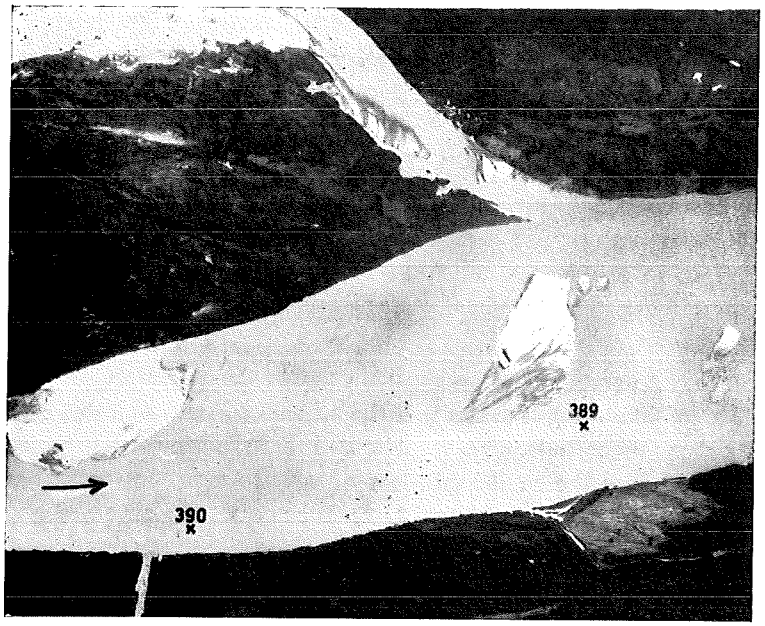
It is assumed that the propagation of a sand-bank is proportional to the water-depth a to the power $\frac{3}{2}$ (based on a simplification of the formula for sand-transport, 5.2.1) and proportional to the time t during which the propagation of the sand-bank is flooded. The propagation of the sand-bank is then $A \times a^{\frac{3}{2}}$ from which A can be calculated and was found to be 1.1 $foot^{-\frac{1}{2}}$ day^{-1} for 1957. With this value for A applied to the hydrographs of 1954, 1955 and 1956, a total movement of the sand-bank of about 4,000 feet can be calculated. In fact, the movement was only slightly less, as can be seen in the Photograph 5.4.4-1, which shows the position of the sand-bank in May 1954, December 1954 and December 1956 respectively.

The sand-transport needed to move this particular sand-bank of about L.R.L. + 4′ through an area which was situated at about L.R.L. — 7′, over a maximum distance of 2,000 feet in one year, amounts to 1,000 m^3/m/year (10,000 cuft/ft/year) taking the shape of the sand-bank into account. This is more than double the average annual sand movement near Kelebe.

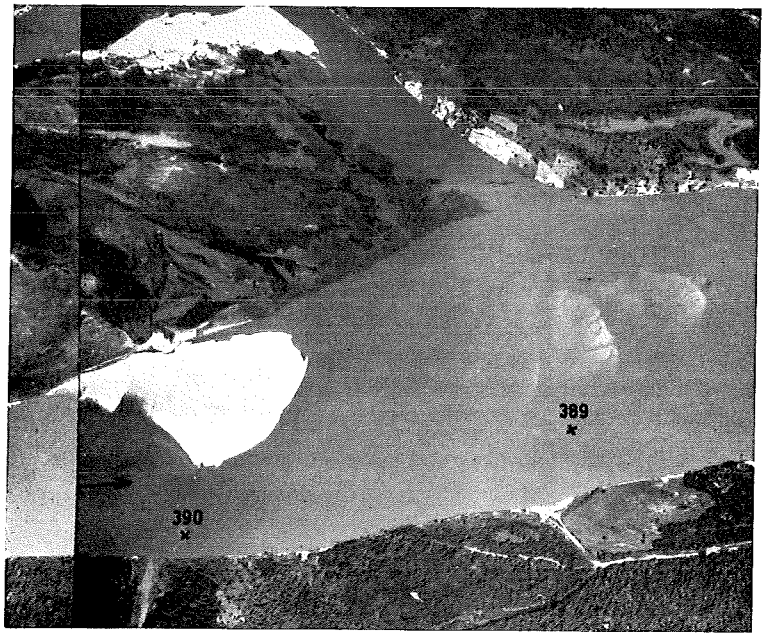
Although it is quite possible that during H.W.-stages the slope of the water-level over the sand-bank is larger than in the deeper channel along it, while also the sand-bank may be smoother than this channel resulting in larger sand movements over the sand-bank, calculations with the use of the sand-transport formula show that, even with an increased slope, smoother surface and smaller grain-sizes on the sand-bank, the figure of 1,000 m^3/m/year (10,000 cuft/ft/year) cannot be reached. This leads to the conclusion that sand must be moving from the deep channel along the sand-bank to the area downstream from the sand-bank, which means that a transversal movement of sand takes place. This transversal transport cannot be brought about only by the effect of the spiral flow as described in 6.1.2, but must find its origin in an eddy with a horizontal axis which exists directly below the edge of the sand-bank.

Such local eddies in turbulent water are by no means a rare phenomenon. They exist everywhere, but their magnitude and direction change from place to place and from time to time and their ultimate influence (averaged over the full cross-section and over a certain period of time) is zero. Only where the eddies in certain directions dominate and result in a net transversal

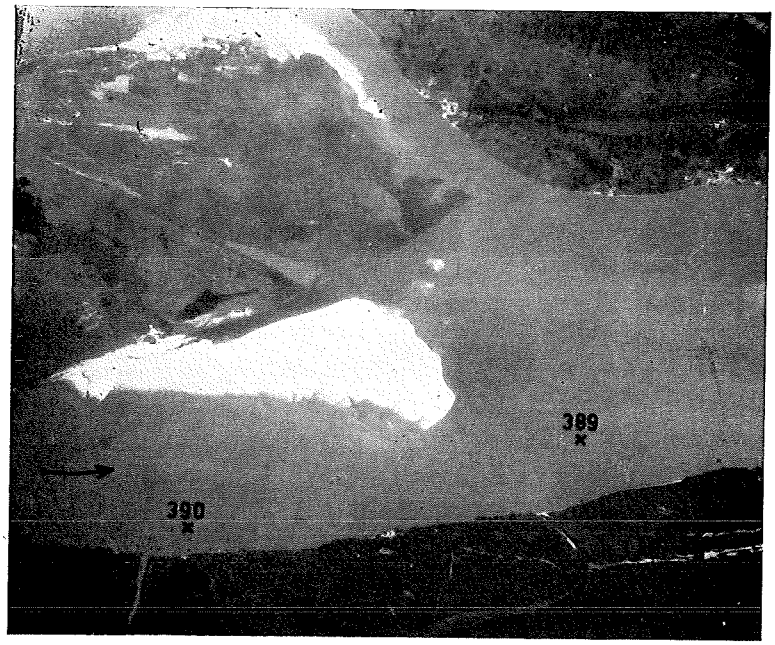
May 1954



December 1954



December 1956



PHOTOGRAPH 5.4.4-1

Propagation of the sand-bank on the Niger near Kelebe, Mile 389

sand-transport, can a particular phenomenon be spoken of. Such a condition occurs, as already stated, below the edge of a sand-bank.

Based on observations of such small eddies in the Mimi River near Lokoja, the transversal water velocity in the eddy is estimated to be 0.2 m/sec (0.65 ft/sec) during the H.W.-stages (Diagram 5.4.4-2). Behind the sand-bank at Kelebe a water depth of about 4 metres (13 feet) will occur during H.W. and when the length of the eddy is about three times this depth, it brings

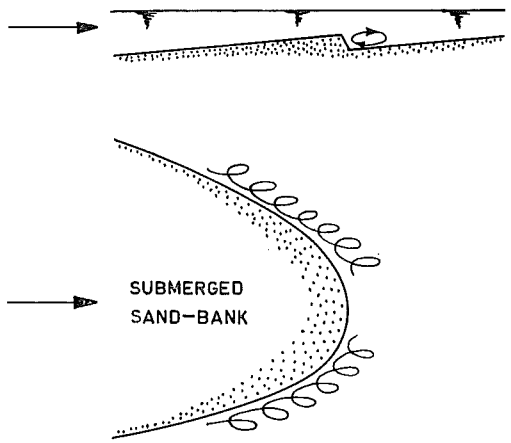


DIAGRAM 5.4.4-2

Eddy below a sand-bank

the water-flow capacity of the eddy to 8 m^3/sec (280 cusecs), which is about 700,000 m^3 (25×10^6 cuft) per day. As the sand-bank is 300 m wide and an additional movement of sand of about 500 m^3/m/year is needed to arrive at the observed propagation of the sand-bank, 150,000 m^3 of sand has to be moved by the eddy during a H.W.-period of about one and a half months. This brings the sand-concentration in the eddy to

$$\frac{150{,}000 \text{ m}^3 \text{ sand}}{45 \times 700{,}000 \text{ m}^3 \text{ water}} = 0.5\%$$

This value of sand concentration is rather high for a normally flowing river, but taking the additional turbulence in the eddy into account, this local figure lies within the possibilities.

Summarising, it can be said that:

(i) The amount of sand per unit width needed for the propagation of an average sand-bank is of the same magnitude as the average sand-transport per unit width of the river.

(ii) The amount of sand moved over the sand-bank is not always sufficient to account of the propagation of the sand-bank. Firstly, because the transport of sand per unit width over the sand-bank does not always reach the average value, and secondly, because the sand-bank sometimes propagates much faster than the average one, due to local conditions.

(iii) The existence below the sand-bank of an eddy with a horizontal axis plays an important role in the local sand movement downstream from a sand-bank, a movement which can be of the same magnitude as the average sand-transport of the river.

It can thus be concluded that the total movement of sand per unit width below a sand-bank can vary from very small to twice the average sand-transport per unit width of the river.

5.4.5. Accumulation of sand near tributaries

Where a tributary flows into the main river, the equilibrium conditions of the main stream are disturbed under the influence of various causes. The most important one is whether or not the tributary and main stream are "in phase", provided, of course, that the tributary is not too small to have any influence upon the main river. Other causes of effect include:
the ratio of the sand supply (by the tributary and the main river together) to the sand-transporting capacity below the confluence, taken as an average over the whole year;
the size of grains of the tributary in relation to those of the main river; and
the angle of confluence and the situation of confluence (in an outer bend of the main stream, or not).

Of these different causes only the two first-mentioned will be considered here, as the other factors call for no general remarks.

a. *Difference in phase*

When two rivers have their respective high-water crests arriving at the confluence simultaneously, the mass of sediment brought down from the tributary into the main flow will in general be easily carried away by the latter. If, however, the tributary supplies a large amount of sand during a low-water period of the main river, this sand will probably accumulate at or immediately below the confluence, as the lower main river has no power to transport sand in large quantities.

The river-sections above the confluence are also affected. The river with the highest water-level will backstage the lower, but will be drawn down itself (see also 4.2.6).

In Diagram 5.4.5-1 the main river (river 1) is raised. Raise by backstage decreases the slope and consequently decreases the sand-transporting capacity and accretion is the result. On the

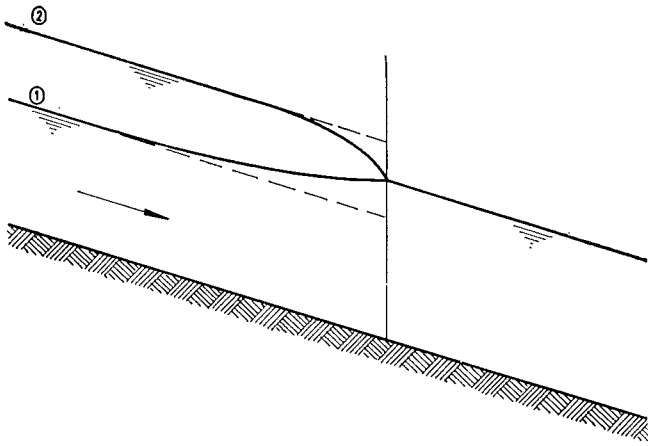


DIAGRAM 5.4.5-1

Raise and draw-down on two joining rivers

other hand, draw-down in river 2 (the tributary) causes a considerable increase in slope and as a result the river carries large masses of sand downward, made available by erosion of the affected river-section. This situation of raise in river 1 and draw-down in river 2 is reversed in another season, as the high-water crest of river 1 may arrive at the confluence somewhat later than that of river 2 while the latter has already fallen. Sand deposition in river 2 will then partly compensate earlier erosion. The picture is complicated by the fact that raise propagates further upstream

than draw-down. Close to the confluence, the severe erosion exceeds the deposition, while locations at great distances are affected by deposition during the raise only.

An example of this phenomenon is the River Niger above the confluence with the Benue near Lokoja. The Niger, as stated in Paragraph 4.2.6, is raised by backstage during the high-water period, but drawn down by the very low Benue during the dry season. Computations (see Paragraph 6.5.8) show that in the longitudinal section of the Niger upstream from the confluence (see Diagram 5.4.5-2) the deviation from a straight bottom figuration is explained by the above-mentioned sand deposition and erosion.

Difference in phase can be the result of difference in climate or in composition of soil and vegetation of the respective drainage areas. Normally these differences are small, and consequently there is a tendency for the tributary to be in phase with the main river. However, in comparison with the main river, the tributary normally has a small drainage area, located closer to the confluence, a smaller valley width and mostly a steeper slope. The tributary will, therefore, discharge its rain much more quickly than the main river and the time-lag between the rain and

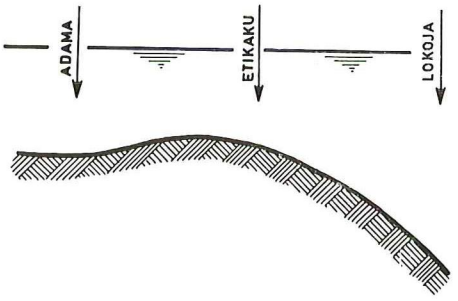


DIAGRAM 5.4.5-2

Observed bottom figuration of the Upper Niger above Lokoja

the arrival at the confluence of the high-water crest caused by this rain is small. Thus in general the tributary (even when the high-water crests of both rivers meet at the confluence simultaneously) shows a more drastic fall of its water-stage and consequently a quick decrease in sediment load. Accretion of its lower bed is the result. On the other hand, however, a small catchment area is liable to undergo an immediate influence from local rains. When, after the rainy season, the water-level of the main river is falling rapidly, the tributary can show a sudden considerable rise as a result of a late local rain in its drainage area. The large main river is not affected by this late rain because it is short in duration and small in extent. Consequently the lowest section of the tributary is drawn down, resulting in a rapid increase of sediment transport, erosion of this section and formation of a delta in the main river immediately outside the mouth of the tributary.

A complication of this general picture is that the river-bed of the tributary will probably debouch into the main river above the level of the river-bed of the main river. Thus draw-down of the tributary possibly also occurs during the low-water period, even without a late rain in the drainage area of the tributary. The formation of the delta into the main river is consolidated by this influence.

A typical example of this phenomenon is the Mimi River, debouching into the Niger some few miles downstream from Lokoja. The most downstream part of its low-water bed is severely worn out by erosion, while a distinct delta protrudes into the Niger during December and January,

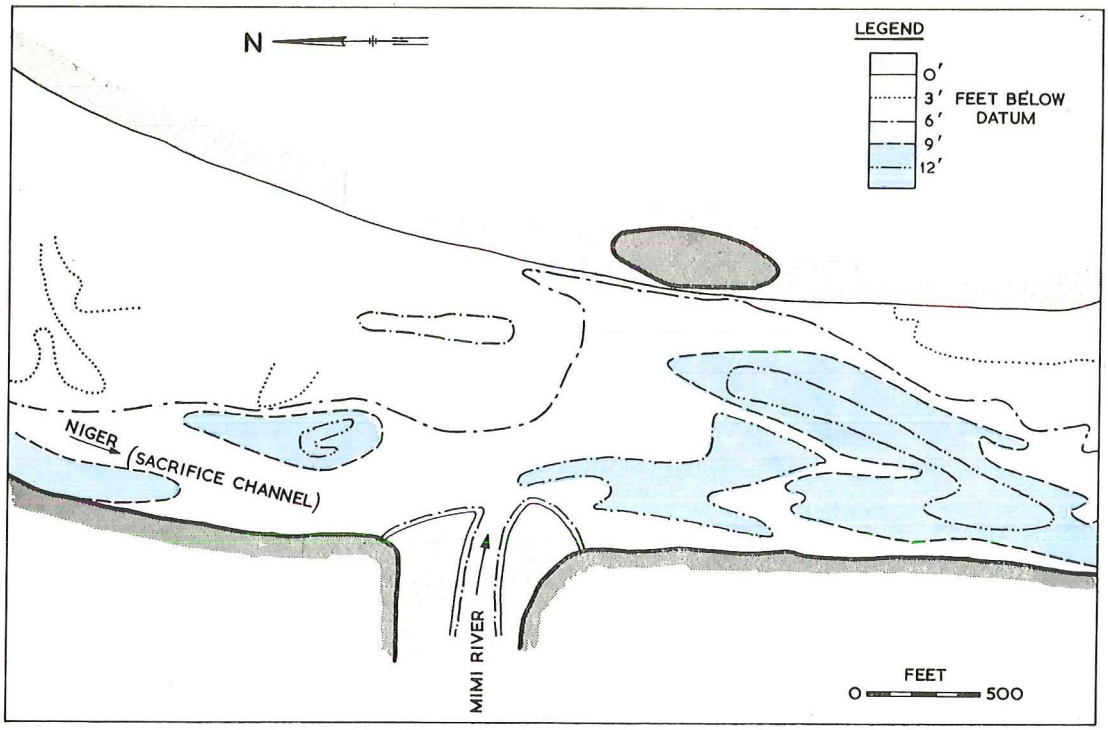


DIAGRAM 5.4.5-3

The Mimi Delta in the Niger, as sounded on February 13, 1958

which is then gradually scoured by the Niger during its Black Flood period. Only a small part of the delta remains until it is dragged away by the high water in September and October. Diagram 5.4.5-3 shows a map of the situation on February 13, 1958; the Photograph 5.4.5-4 was taken about one month earlier.

Whether such a delta-formation in the main river will cause any difficulties in the shipping channel depends on the nature of the main river. In the case described above, the Mimi River causes no difficulty in the Niger because the latter still has a great sand-transporting capacity and does not allow the delta to block its channel, due to the Black Flood phenomenon. The

PHOTOGRAPH 5.4.5-4

The Mimi Delta, seen from the western bank of the Niger, January 1958

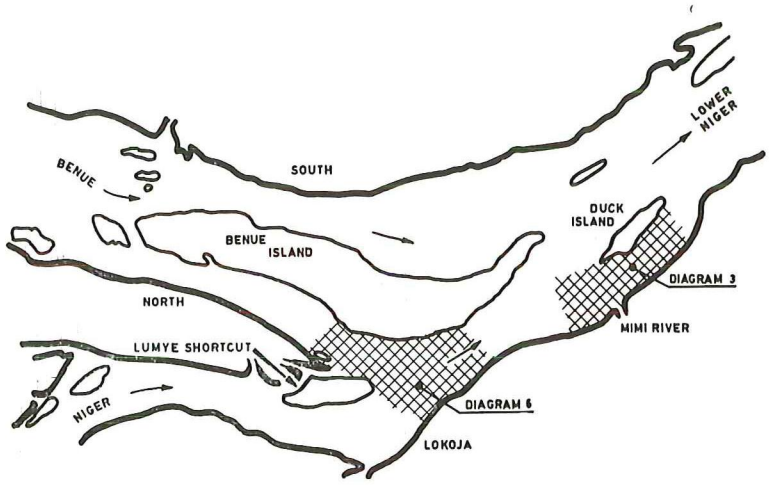


DIAGRAM 5.4.5-5

Situation of the Lumye short-cut at the Lokoja confluence

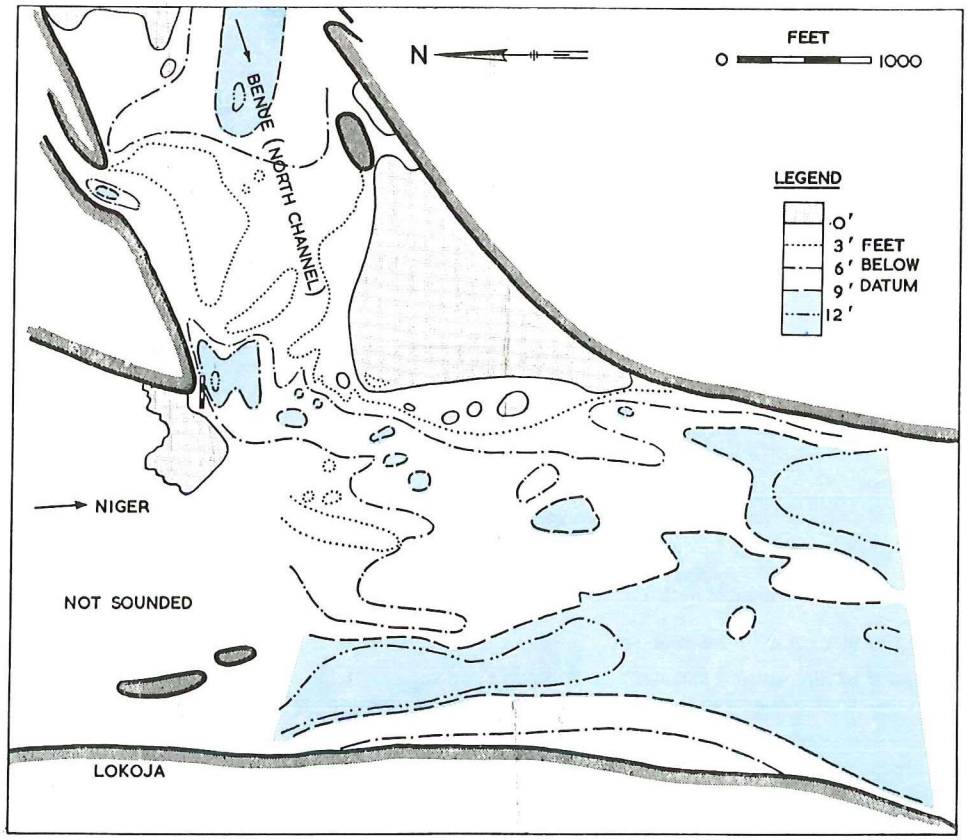


DIAGRAM 5.4.5-6

Deposition of sand brought from the Niger via Lumye short-cut into the Benue

situation is different for the Benue where, after the high-water crest, the water-level falls so far that transporting capacity is completely out of the question. Sand from tributaries brought into the Benue after the high-water crest has passed will be deposited and possibly cause shallow water.

For example, the flow through the small short-cut between the Niger and Benue near Lokoja, situated as shown in Diagram 5.4.5-5, is so swift that not only is a large amount of bed-load carried, but also a relatively high suspended load. This very high velocity is caused by the great difference of water-height in the two rivers, especially from December until April, when the Benue is very low and the Niger has its Black Flood period with a reasonably high water-level. All the sand carried down from the Niger through the short-cut is brought into the wide, backstaged and slowly-flowing Benue, and consequently deposited immediately (see Diagram 5.4.5-6).

Leaving aside other causes of formation of a Benue Bar (see V, 3), this accumulation results in a very shallow Benue Entrance, and the barrier cannot be scoured before a considerable rise in the Benue brings about some transporting capacity.

Sand deposition of the kind just described is of a temporary nature, provided the transporting capacity of the lower main river suffices to carry the sand away sooner or later. Determinant for this condition is the second cause mentioned at the start of this paragraph, namely,

b. *The ratio of sand supply upstream from the confluence to the sand-transporting capacity downstream from the confluence*

If this ratio is great, sand deposition in the main river takes place, sometimes even during high water. Accumulation goes on and on as long as the sand-transporting capacity of the lower river does not increase. Thus large quantities of sand are deposited at and immediately below the confluence, building up a kind of buffer stock of sand. The equilibrium is restored only when the sand-transporting capacity of the lower main river so increases that the sand supply

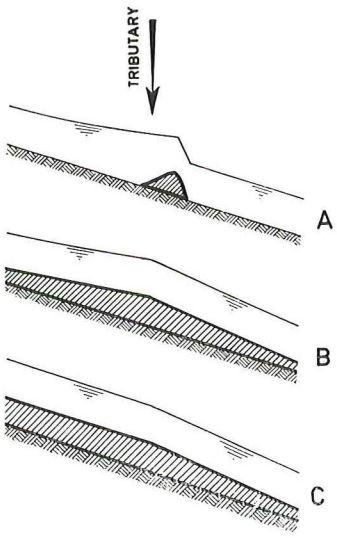


DIAGRAM 5.4.5-7

Development of a buffer stock of sand at the confluence with a tributary

from both the main river and the tributary equals the transporting capacity downward, thus making the ratio = 1. The only possibility for this purpose is an increase in slope in the lower main river, resulting from a raise of water-level upstream from the buffer stock: a backstage caused by the "barrier" in the discharging channels of the river (Diagram 5.4.5-7A).

Due to this raise, accumulation spreads from the original location over a longer area, while the steeper slope carries off more sand from the front side of the buffer stock, thus causing a propagation of this front downward. Ultimately the steeper slope exists over a considerable length down from the actual confluence to where another disturbance (for instance, another tributary) affects the regime again (Diagram 5.4.5-7B). Above the confluence the slope is gentle, but increases in course of time by accretion of its total bed from the confluence upward into the upper reaches. Ultimate equilibrium of the upper main river will show a slope equal to the original one (Diagram 5.4.5-7C). It should be realised that this accretion of the river-bed of the entire upper main river takes place very slowly and needs for its completion a period of time on a geological scale. The occurrence of the phenomenon is, therefore, a proof of a change in either the main river or the tributary during geologically recent times, such as, for example, is the case with the confluence of the Faro and Benue. Original equilibrium of the confluence has at some historic time been disturbed by a change in the regime of either the Upper Benue (possibly a beheading by the Logone) or the Faro, or both. From then on the yearly sand supply from the Faro could not be carried off downward and consequently a steep slope developed below the confluence (25×10^{-5}), while the Upper Benue was raised by backstage and shows a gentle slope (13×10^{-5}) (see Diagrams 2.5.2-3 and 4.2.5-1). Thus equilibrium is restored locally, although a very slow propagation of the influence downward beyond the river-section now affected (Mile 926 to 906) might be possible. This, however, has not been observed.

CHAPTER 6

CHANNELS

6.1. CROSS-SECTIONS

6.1.1. Cross-sections of a straight river

The shape and size of a cross-section is determined by the inflow of water and sediment on the one side and their outflow on the other side of a riversection. The inflow of water is characterised by the supply Q_{in} in m^3/sec (or in cusecs). The inflow of sediments is characterised by the quantity S_{in} in m^3/day and by the peculiarities of the sediment, of which the grain-size d is the most important. The outflow of both water and material have long been put into partly empirical formulae, expressed as

$$Q_{out} = f_1 \text{ (b,a,i, roughness, shape of cross-section)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$S_{out} = f_2 \text{ (b,a,i, roughness, shape of cross-section, characteristics of the material)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Combination of Q_{in} and S_{in} with the respective equations of continuity gives Q_{out} and S_{out}.

In the first instance, considerations are simplified by assuming a condition of steady and uniform flow on the river, while in a later stage of the development the theories are extended to the circumstances of a variable Q.

a *With a steady and uniform flow*

For a uniform flow and a uniform sediment transport (varying neither in time nor place, $Q_{in} = Q_{out}$ and $S_{in} = S_{out}$, hence

$$Q_{in} = Q_{out} = f_1 \text{ (b,a,i, roughness, shape of cross-section)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$S_{in} = S_{out} = f_2 \text{ (b,a,i, roughness, shape of cross-section, characteristics of the material)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

These two equations have many variables and more equations will be necessary when the variables have to be determined.

But in the first instance some simplifications as to the various terms are made, namely,
(i) the shape of the cross-section is rectangular, troughlike and therefore determined by the width b and the depth a only;
(ii) the characteristics of the material are condensed in one figure, the grain-size d; and
(iii) the roughness of the bed and the banks is put into one figure for which the equivalent sand roughness of NIKURADZE may be taken, symbolised by k_r.

The equations are then simplified into

$$Q = f_1 \text{ (b,a,i,}k_r\text{)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$S = f_2 \text{ (b,a,i,}k_r\text{,d)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

But even when the discharge Q, the sediment load S and the grain-size d are given, the determination of the other four variables is still impossible with only two equations.

The roughness k_r, when put into a form of a coefficient of DE CHEZY (C) or in a coefficient of MANNING (n) (see 4.3.1), may be estimated, thereby reducing the variables to three.

When, by means of regulation works such as groynes or dikes, or by rocks or other solid boundary, also the width of the river is given, the equations can be solved and the slope i and depth a calculated. NING CHIEN ([1 has put the various manipulations into useful graphs.

However, the cross-sections of alluvial rivers do not have a fixed boundary because of the erodibility of the banks, and the two equations are insufficient to calculate the cross-section or, for instance, the effect of increased discharge on a given cross-section.

The experience of irrigation engineers who were confronted with the design of channels carrying water and sediment have been put into formulae by LACEY ([2. These purely empirical formulae, derived from observations on rather small channels, however, cannot be applied to large rivers without careful checking (see also LEOPOLD and MADDOCK ([3). On this point NING CHIEN ([4 remarks: "For other than conditions in India and Pakistan, f_{VR} (a silt factor in Lacey's formulae) depends also on the hydraulic characteristics of the channel. This makes the general application of Lacey's regime theory extremely difficult. It is not just the question of whether one has the proper training or experience in estimating the value of silt factors, but rather that the experience gathered in Northern India and Pakistan may fail to apply when the conditions are substantially different from those existing in that area."

The only way out of the difficulty is to search for a *third condition* applicable to alluvial rivers in order to calculate the cross-section of that river and consequently to foresee the changes that may occur in that cross-section when one of the fundamental factors (for instance, the discharge) is changed.

On a certain stretch of river from A to B the uniform discharge and sediment load is given by Q and S (with grain-size d) respectively (see Diagram 6.1.1-1), whilst the roughness k_r is also assumed to be known. According to the Equations (5) and (6), an infinity of possibilities exists, every one with another slope i and another cross-section (determined by a and b).

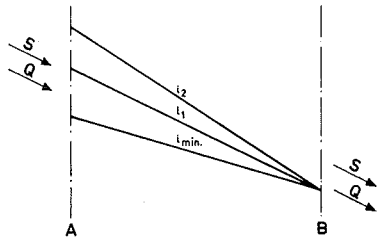


DIAGRAM 6.1.1-1

An infinite number of possible slopes

There appears to be a minimum slope i_{min}, however, under which the total inflow of material S can no longer be transported, irrespective of the cross-section ensuing from the equations. This cannot be proved with formulae in the general form of Equations (5) and (6), but the equations have to be written out in full. The equation of the discharge reads (see 4.3.1)

$$Q = b\, a^{\frac{3}{2}}\, C\, i^{\frac{1}{2}} \qquad \ldots\ldots\ldots \quad (7)$$

([1 NING CHIEN, 1955. MOR. 24.
([2 LACEY, 1930, 1933, 1946. MOR. 16, 17, 18.
([3 LEOPOLD and MADDOCK, 1933. MOR. 20.
([4 NING CHIEN, 1955. MOR. 25.

while for the sediment-transport the formula of MEYER-PETER and MUELLER can be used (see 5.2.1)

$$S = 6{,}5\ b\ d^{\frac{3}{2}}\ \Delta^{\frac{1}{2}}\ g^{\frac{1}{2}} \left[\frac{\mu a i}{\Delta d} - 0{,}047\right]^{\frac{3}{2}} \quad \ldots\ldots\ldots \quad (8)$$

The combination of (7) and (8) gives:

$$\frac{C}{6{,}5\ d^{\frac{3}{2}}\ \Delta^{\frac{1}{2}}\ g^{\frac{1}{2}}}\ \frac{S}{Q} = \frac{\left[\frac{\mu a i}{\Delta d} - 0{,}047\right]^{\frac{3}{2}}}{i^{\frac{1}{2}}\ a^{\frac{3}{2}}} \quad \ldots\ldots\ldots \quad (9)$$

in which C = coefficient of DE CHEZY (in $m^{\frac{1}{2}}/sec$)

d = grain-size; generally used d_{50} (in m)

$\Delta = \frac{\rho_{sand} - \rho_{water}}{\rho_{water}} = 1.68$ (dimensionless)

S = transported material (in m^3/sec)

Q = discharge of water (in m^3/sec)

a = depht (in m)

i = slope (dimensionless)

μ = "ripple factor" $= \left[\frac{k_s}{k_r}\right]^{\frac{1}{4}}$ (dimensionless) (see 6.3.4)

k_s = sand-roughness of the grains (in m)

k_r = equivalent sand roughness of the bed (in m)

For a certain discharge Q and sediment-transport S Equation (9) is a function of the depth a and the slope i when the other factors are taken as being constant.

Differentiation of (9) gives the minimum slope:

$$i_{min} = \frac{\Delta\ C}{8 g^{\frac{1}{2}}\ \mu^{\frac{3}{2}}}\ \frac{S}{Q} \quad \ldots\ldots\ldots \quad (10)$$

It should be noted that the minimum slope apparently is independent of the grain-size.

The water-depth corresponding with this minimum slope is ∞ (infinitely large) and consequently the width $b = 0$, according to the Equations (7) and (8). It will be seen later that when C and μ are taken into account as being functions of a and i, the depth becomes finite.

The assumption has been made that the river is alluvial, flowing through its own sediment, and capable of eroding or building up its banks. Neither the width nor the depth is restricted; both are determined by the river characteristics. Rocks are assumed to be absent.

From the above it follows that the river-stretch from A to B might be as drawn in Diagram 6.1.1-2 (first sketch) in which a bottom-line by steps seems to be possible (slopes $i \geqq i_{min}$). In Nature, however, an alluvial river never has this appearance when secondary influences such as the succession of deeps and shallows in bends and on crossings are left out. If a river is straight (straight in the horizontal plane), its slope both of water and of bottom has to be straight (straight in the vertical plane). This hypothesis put into a mathematical form will serve as the third condition.

The only possible way in which the stepped bottom of Diagram 6.1.1-2 could be evened out to a smooth line is when the transport of material on the parts with the steeper slopes exceeds the transport in the sections with the more gentle slopes. On the upstream end of the steep-sloping part the transported material then exceeds the incoming load and erosion takes place, whereas on the upstream end of the gentle-sloping part the incoming load cannot be transported because of the smaller slope, resulting in deposition as shown in Diagram 6.1.1-2 (second situ-

ation). The ultimate result would be a bottom-line as drawn in the third situation. However, when the slope of this bottom exceeds i_{min}, the transport of sediment on this stretch exceeds the incoming load because by definition Q and S can just be carried off at the minimum slope,

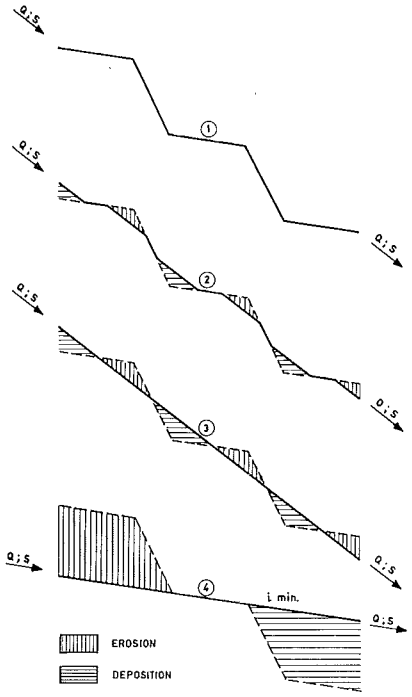


DIAGRAM 6.1.1-2
Development of a stepped bottom into a smooth one

whereas it has been proved by the third condition that always at a steeper slope more sediment is transported. It will be clear that, instead of the bottom-line of situation 3, the bottom-line according to the minimum slope (situation 4) will be the equilibrium state. Thus the condition that if a river is rectilinear the slope both of its water-level and of its bed has to be straight, has been transformed into one that the slope of a river is minimum when the river is in equilibrium, that is, when the steady incoming discharge Q and sediment load S are carried through without being affected.

An implication of the condition of the minimum slope is that the sand-transport is maximum. For any other value of the slope i the corresponding shape and size of the cross-section would imply a smaller sand-transport. This follows from the fact that the river has adjusted itself to the slope at which the incoming amount of sediment can just be transported downstream in combination with the fact that on smaller slopes the sediment-transporting capacity decreases.

Summarising, the third condition, to be used in conjunction with Equations (5) and (6), reads: Of an alluvial river-stretch in equilibrium, the slope is the least possible slope at which the incoming load can be transported downstream, and the cross-section then enables a transport of sediment which is, for that slope, the maximum possible amount.

For the determination of the cross-section three equations are now available:

(i) the discharge formula of DE CHEZY:

$$Q = ba^{\frac{3}{2}} Ci^{\frac{1}{2}} \quad \ldots\ldots\ldots \quad (7)$$

(ii) the bed-load formula, which is in its general form

$$S = b d^{\frac{3}{2}} \Delta^{\frac{1}{2}} g^{\frac{1}{2}} f\left[\frac{\Delta d}{\mu a i}\right] \qquad (1 \quad \ldots\ldots\ldots (11)$$

(iii) the third condition: minimum slope i $\ldots\ldots\ldots (12)$

The combination of these three equations (7), (11) and (12) gives the following differential equation:

$$f \frac{\Delta d}{\mu a i}\left[1.5 + \frac{7.8}{C}\left(1 - \frac{a}{k_r}\frac{dk_r}{da}\right)\right] + \frac{\Delta d}{\mu a i} f' \frac{\Delta d}{\mu a i}\left[1 - \tfrac{1}{4}\frac{a}{k_r}\frac{dk_r}{da}\right] = 0$$

$\ldots\ldots\ldots (13)$

in which $f'\left[\frac{\Delta d}{\mu a i}\right] = \frac{\partial f\left[\frac{\Delta d}{\mu a i}\right]}{\partial\left[\frac{\Delta d}{\mu a i}\right]}$

Derivation of this equation is as follows: Elimination of b in (7) and (11) gives

$$\varphi = \frac{S}{Q\, d^{\frac{3}{2}} \sqrt{\Delta g}} = \frac{f(\psi)}{i^{\frac{1}{2}} a^{\frac{3}{2}} C} \qquad \ldots\ldots\ldots (14)$$

where $\psi = \frac{\Delta d}{\mu a i}$.

For a given discharge Q and a given bed-load S with grain-size d, φ is a constant whilst i, a, μ and C are variables. Differentiation of Equation (14) gives

$$0 = \frac{\partial \varphi}{\partial a} + \frac{\partial \varphi}{\partial i}\frac{di}{da} + \frac{\partial \varphi}{\partial C}\frac{dC}{da} + \frac{\partial \varphi}{\partial \mu}\frac{d\mu}{da} \qquad \ldots\ldots\ldots (15)$$

The first term in this equation, $\frac{\partial \varphi}{\partial a}$, reads

$$\frac{\partial \varphi}{\partial a} = -\, i^{-\frac{1}{2}} C^{-1} a^{-\frac{5}{2}}\left[1.5\, f(\psi) + f'(\psi)\right] \qquad \ldots\ldots\ldots (16)$$

in which $f'(\psi) = \frac{\partial f(\psi)}{\partial \psi}$

The second term in Equation (15),

$$\frac{\partial \varphi}{\partial i}\frac{di}{da} = 0 \qquad \ldots\ldots\ldots (17)$$

because of the third condition.

Of the third term, $\frac{\partial \varphi}{\partial C}\frac{dC}{da}$ is:

$$\frac{\partial \varphi}{\partial C} = -\, i^{-\frac{1}{2}} C^{-2} a^{-\frac{3}{2}} f(\psi) \qquad \ldots\ldots\ldots (18)$$

Now

$$C = 7.8 \ln 12 \frac{a}{k_r} \qquad (2 \quad \ldots\ldots\ldots (19)$$

which gives

$$\frac{dC}{da} = \frac{7.8}{a}\left[1 - \frac{a}{k_r}\frac{dk_r}{da}\right] \qquad \ldots\ldots\ldots (20)$$

(1 At this stage it is not yet necessary to use one of the formulae in which the function f is specified, such as for instance Equation (8).
(2 see 6.3.4.

hence is the third term in Equation (15)

$$\frac{\partial \varphi}{\partial C}\frac{dC}{da} = -7.8\, i^{-\frac{1}{2}} C^{-2} a^{-\frac{5}{2}} f(\psi)\left[1 - \frac{a}{k_r}\frac{dk_r}{da}\right] \quad \ldots\ldots\ldots (21)$$

Of the fourth term in Equation (15), $\frac{\partial \varphi}{\partial \mu}\frac{d\mu}{da}$, is

$$\frac{\partial \varphi}{\partial \mu} = -\, i^{-\frac{1}{2}} C^{-1} a^{-\frac{3}{2}} f'(\psi)\, \mu^{-1} \quad \ldots\ldots\ldots (22)$$

Now

$$\mu = \left[\frac{k_s}{k_r}\right]^{\frac{1}{4}} \quad \text{(1} \quad \ldots\ldots\ldots (23)$$

which gives

$$\frac{d\mu}{da} = -\tfrac{1}{4}\,\mu\, k_r^{-1}\frac{dk_r}{da} \quad \ldots\ldots\ldots (24)$$

hence is the fourth term of Equation (15)

$$\frac{\partial \varphi}{\partial \mu}\frac{d\mu}{da} = +\tfrac{1}{4}\, i^{-\frac{1}{2}} C^{-1} a^{-\frac{5}{2}}\, \frac{a}{k_r}\frac{dk_r}{da} f'(\psi) \quad \ldots\ldots\ldots (25)$$

Substitution of (16), (17), (21) and (25) into Equation (15) leads to Equation (13).

To proceed with the modification of Equation (13) it is necessary to describe the roughness. Among other terms, the roughness appears in the term

$$\frac{a}{k_r}\frac{dk_r}{da}$$

which term can be simplified by application of a fourth condition:
(iv) the equivalent sand roughness k_r can approximately be described as

$$k_r = \vartheta\, a^{\beta}\, \chi\,(i,d) \quad \ldots\ldots\ldots (26)$$

which is a generally valid approximation for a limited zone of any function when neither k_r nor a are negative, which is obviously true. In this equation β and ϑ are constants, while χ denotes a function.

Combination of (iv) and (iii) gives

$$\frac{a}{k_r}\frac{dk_r}{da} = \beta \quad \ldots\ldots\ldots (27)$$

Substitution of (27) in (13) leads to

$$f\left[\frac{\Delta d}{\mu a i}\right]\left[1.5 + \frac{7.8}{C}(1-\beta)\right] + \frac{\Delta d}{\mu a i} f'\left[\frac{\Delta d}{\mu a i}\right](1 - \tfrac{1}{4}\beta) = 0 \quad \ldots\ldots\ldots (28)$$

Three factors remain in Equation (28), namely β, C and $\frac{\Delta d}{\mu a i}$, of which the factor β is assumed here to be constant. The coefficient of de Chezy appears in the term $\frac{7.8}{C}(1-\beta)$, a term which is probably less than 0.2. The variations in this term owing to variations in C are in the order of 0.05, and thus the entire term

$$1.5 + \frac{7.8}{C}(1-\beta)$$

may be considered approximately constant.

(1 see 6.3.4

Now Equation (28) has become a function of the variable $\frac{\Delta d}{\mu ai}$ only, which implies that

$$\frac{\Delta d}{\mu ai} = \delta \qquad \ldots\ldots\ldots (29)$$

in which δ is a coefficient, being approximately constant.

However, as $\mu = f(\frac{\Delta d}{ai})$, as discussed in 6.3.4, Equation (29) can be transformed into

$$\frac{\Delta d}{ai} = \alpha \qquad \ldots\ldots\ldots (30)$$

in which α is a coefficient, being approximately constant. The ripple factor μ, which is a function of $\frac{\Delta d}{ai}$, is then also reduced to a non-varying value.

Summarising, the four conditions (i) to (iv) lead to a relationship between the equilibrium slope i and the depth a in a straight alluvial river with erodible banks and bed (absence of rock or heavy clay), with a rectangular cross-section and with a uniform flow, namely

$$\frac{\Delta d}{ai} = \alpha$$

where α is a coefficient being approximately constant.

Some *consequences of this result* are remarkable.

(i) The most conspicuous characteristic of $\frac{\Delta d}{ai} = \alpha$ is that the depth is independent of the discharge. Although a strange result, it is likely to be correct, because it has been corroborated by model experiments by FRIEDKIN (1, who writes: "It should also be added that doubling the discharges did not cause deepening of the channels".

(ii) Regarding the slope, the depth would be inversely proportional to the equilibrium slope. It is, indeed, generally observed in Nature that deep and narrow channels develop in the lower reaches where slopes are gentle, in contrary to wide and usually braided channels where slopes are steep. Even when the bed is non-alluvial, the phenomenon still seems to occur, as follows from a description of the Shoshone River, of which MACKIN (2 writes: "The stream is only mildly cutting down into the underlying soft sandstones and shales, much less than could be expected from its discharge and channel characteristics, as demonstrated by other streams with milder slopes which are vigorously cutting down in harder rocks".

The gully-erosion in contrast to sheet-erosion results from the fact that minor slopes cause deep gullies and steep slopes shallow and wide channels.

(iii) Substitution of Equation (30) into Equation (7) gives:

$$b = \frac{1}{C}\left[\frac{\alpha}{\Delta}\right]^{\frac{3}{2}} \frac{1}{d^{\frac{3}{2}}} Qi \qquad \ldots\ldots\ldots (31)$$

an equation which is considerably different from that of LACEY:

$$b = 4.8\, Q^{\frac{1}{2}} \qquad \ldots\ldots\ldots (32)$$

(iv) Substitution of Equation (30) into the velocity formula of de Chezy, $v = C\sqrt{ai}$, gives

$$v = C\sqrt{\frac{\Delta}{\alpha} d} \qquad \ldots\ldots\ldots (33)$$

(1 FRIEDKIN, 1945. MOR. 9
(2 MACKIN, 1948. MOR. 21

from which follows that the velocity is proportional to the square root of the grain-size d, and proportional to the coefficient of de Chezy C. The latter varies only slightly with the depth and possibly (because of k_r) with the slope.

(v) Substitution of Equation (29) into Equation (11) leads to

$$S :: b\, d^{\frac{3}{2}}\, \Delta^{\frac{1}{2}} \qquad \ldots\ldots\ldots (34)$$

which indicates that the bed-load per unit width is proportional to the grain-size raised to the power 1.5.

(vi) Substitution of the Equations (29), (30) and (7) all into Equation (11) gives

$$S :: \frac{1}{\Delta C}\, Qi \qquad \ldots\ldots\ldots (35)$$

which states that the quantity of bed-load is proportional to the energy of the flow.

(vii) In 6.3.4 the relationship between the ripple factor μ and the term $\frac{\Delta d}{ai}$ will be discussed, but the resulting functions cannot be applied directly on the formulae of this paragraph, as they are not derived for similar circumstances. Firstly, the results of Zürich and Delft (Diagram 6.3.4-6) have been obtained in laboratory flumes, in which the width is restricted by the walls of the flumes. Secondly, the curve, relating the terms

$$\mu \frac{i_d}{i} \text{ and } \frac{\Delta d}{ai}$$

for various Niger and Benue stations, has been derived from several specific sites not necessarily representing the average circumstances on the appropriate river-section. The one at Makurdi, for instance, is known to be bounded by rocks.

However, the curve representing the relationship between μ and $\frac{\Delta d}{ai}$ for various circumstances (widths) must also include the case in which the width and depth are adapted to the equilibrium profile. The curves of 6.3.4 are, in fact, generally valid because the width is still arbitrary, whereas in the determination of the formula (30) the width is restricted to that particular value for which the cross-section is fully adapted to the minimum slope condition. When Equation (30) is used on a river, it should be used to describe the average situation on a river-stretch and should not be used for a single cross-section.

For a *quantitative determination* of α and δ, the experimental curves of Paragraph 6.3.4 have to be used in conjunction with the theories of the present paragraph.

For various values of $\frac{a}{k_r}\frac{dk_r}{da} = \beta$, the appropriate figure for ψ has been computed, and plotted in Diagram 6.1.1-3. When the assumption is made that k_r is roughly proportional to the depth a (see also 6.3.4), involving $\beta = 1$ ([1], then is

$$\delta = 5.5 \qquad \ldots\ldots\ldots (36)$$

which gives, according to Diagram 6.3.4-6, roughly

$$\mu = 0.4 \qquad \ldots\ldots\ldots (37)$$

Substitution of (37) in (36) gives the approximate figure

$$\frac{\Delta d}{ai} = \alpha = 2 \qquad \ldots\ldots\ldots (38)$$

In 6.1.6, when comparing the calculated width of the Niger and Benue with the measured width, α appears to be smaller than this; a figure of about 1.4 is more likely.

([1] However, α will not be a constant if k_r should happen to be non-proportional to a^{β}.

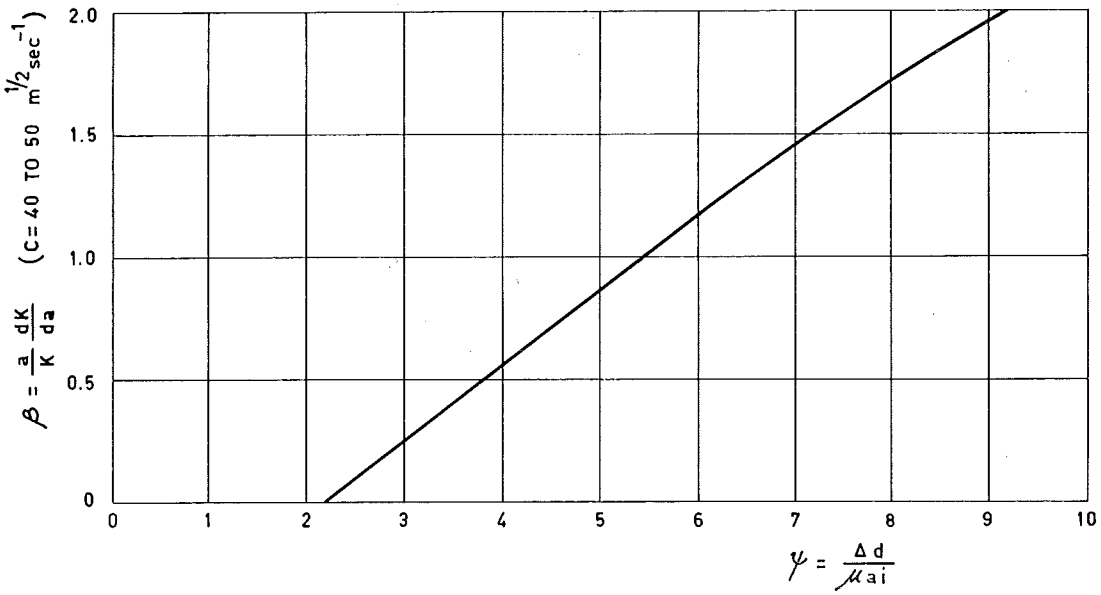


DIAGRAM 6.1.1-3

ψ as a function of β

It should be understood firstly that the grains are represented by the diameter d_{50} only, and that the distribution of the grain-sizes of the bed material will certainly influence the formulae. A coefficient $\alpha = 1.4$, which follows from observations on the Niger and the Benue (see 6.1.6), may have another value when the distribution of the grain-sizes differs from those of the Niger and Benue Rivers. Secondly, the formulae are derived for rivers in equilibrium, rivers in which the transport of material equals the incoming load.

b *With a non-steady flow*

When a river-stretch A is bordered by similar stretches above and below, the sediment transport is equal to the transporting capacity which will be governed only by the discharge Q and the characteristics of the river-stretch A. In other words, S is not an independent variable on that river-stretch as in the case of a steady discharge, but it is directly linked to the variable discharge Q and the characteristics of the river-stretch. The effect of the independent S (erosion to deposition) on the similar stretches above the regarded river-stretch A is taken to have ceased on A.

The slope i is the equilibrium slope for the sediment load S and discharge Q. When, for argument's sake, this slope is considered constant for alternating discharges Q, the width b consequently tends to alternate (Equation (31)), whilst also the sediment load varies accordingly (Equation (34)). The depth, however, tends to remain constant (Equation (30)), involving an alternating bottom height corresponding with the alternating water-level. As the width and the bottom elevation of a channel are much more easily changed (by means of lateral exchange of material over short distances) than the slope (for which enormous quantities of material have to be transported down-river), the conception of varying widths owing to varying discharges seems reasonable. Also model experiments ([1 approve of this hypothesis.

([1 FRIEDKIN, 1945. MOR. 9

Consequently, a river-stretch forming part of a longer section in which similar circumstances occur (no lateral inflow, constant slope and grain-size) tends to shape its width according to the varying discharges and tends to keep its depth constant.

Quick sequences of high water and low water cause little variation in width of the river because the banks then hardly start eroding at high water, while the next low water would cause accretion again. But with long intervals between high water and low water, considerable differences in cross-sections can be expected because erosion and accretion get their chance to develop.

A fairly quick sequence is the period of one year in which, as on the Nigerian Rivers, one high water and one low water occurs. But after a series of wet years the cross-section at bankfull stages will be adapted to the higher discharges and will consequently be wider than after a series of dry years. It will be clear that the worst shipping conditions occur in a dry year that is preceded by a series of wet years (wide and shallow cross-sections).

Any characteristics of the river-bed, such as its width, depth, transversal bed-slope or bank-height, are subject to deformation by each separate group of discharges. The magnitude of this influence is determined by its duration and force, and the complete range and sequence of discharges determines the characteristic.

No single steady discharge can be envisaged that would shape a river-bed with all characteristics similar to those that result from a superposition of the influences of the varying discharges. But for each single characteristic it will be possible to define a characteristic discharge that is dominant for the origin and nature of that quality. For instance, the width of the bed between the shores is determined by the bankfull discharge, as lower discharges will only affect that part of the bed which is wetted by such lower discharges, which does not include the high banks. Local attacks on the high bank by the low-water channel have less significance than the influence of the high bankfull discharge.

Each characteristic has its own appertaining dominant discharge, and a general "bed-shaping" discharge that would shape all characteristic features does not occur.

Taking the bed-level of the river as the selected characteristic, then the definition of the appertaining dominant discharge is based on the phenomenon of scour (see 5.4.1). If it is assumed that the absolute bed-level resulting from the dominant discharge flowing continuously and constantly should be equal to the mean of the varying bed-levels during a cycle of changing discharges, then it follows that the sum total of scour and deposition of the bed during this cycle (for instance, a year) should be zero.

The dominant discharge thus defined can now be computed for a rectangular profile of the river, i.e., with steep banks, or

$$\frac{db}{da} = 0$$

but the banks should not be parallel, which means a non-prismatic channel, or

$$\frac{db}{dx} \neq 0$$

It should be noted that the above-defined dominant discharge has no physical significance in a prismatic channel. In such a channel with a constant width, the stability condition as mentioned in 5.4.1 (ba^{α} = constant) is always satisfied, and the bed will be in a permanent equilibrium: no scour would be possible, unless caused by sideward exchange of material, which is not considered here. It is assumed that the equation for a dominant discharge, as derived for a non-prismatic channel, may be generalised to be valid also for prismatic channels, but no proof for this assumption will be given here.

With DE CHEZY's discharge formula and the condition of stability ba^{α} = constant, it follows that for a constant Chezy-coefficient C

$$a^{\frac{3}{2}-\alpha}\, i^{\frac{1}{2}} = \text{constant},$$

which implies that the water-level gradient shows small discontinuities at places where the width changes. These discontinuities will become negligible when α approaches the value $\frac{3}{2}$, which occurs when the dominant discharge is large (see 4.2.6).

In accordance with the stability condition (5.4.1), the scour per unit of time will be

$$\frac{dz_b}{dt} = -\frac{E}{b}\frac{d\,(ba^{\alpha})}{dx}$$

and therefore

$$\Delta z_b = -\frac{1}{b}\int E\frac{d\,(ba^{\alpha})}{dx}\,dt \qquad \ldots\ldots\ldots (39)$$

where z_b is the elevation of the river-bed to any arbitrary datum.

If the phenomena are considered during the period in which the discharge Q varies from Q_1 to $Q_1 + dQ$, or in which the water-level h varies from h_1 to $h_1 + dh$ (see Diagram 6.1.1-4), then the rate of scour will be constant during the period under consideration, which has a length in time of (n). In this, the scour of the bed is neglected with respect to the total depth of water, which implies that the gradual scour will not affect the value of ba^{α}.

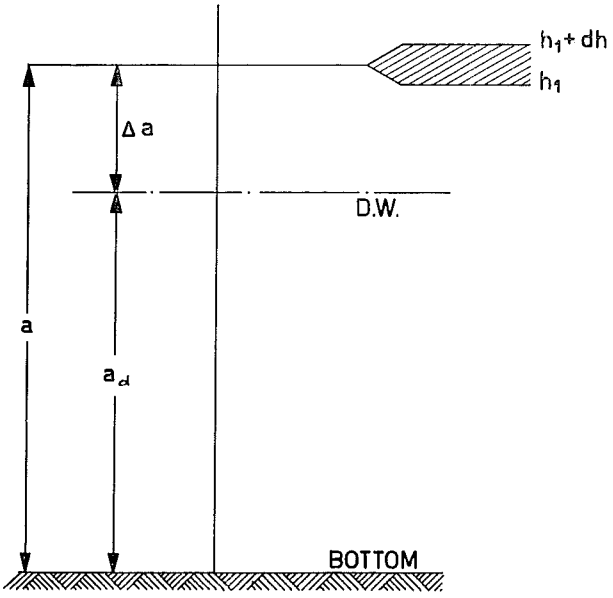


DIAGRAM 6.1.1-4

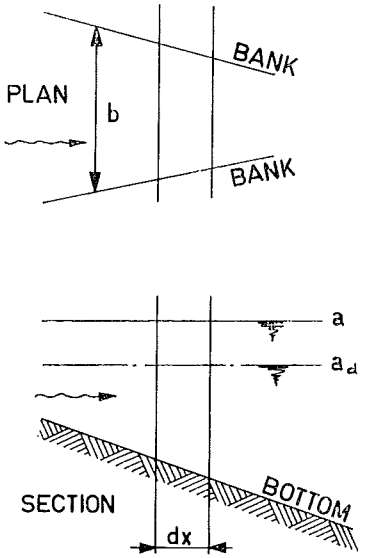


DIAGRAM 6.1.1-5

Definition of symbols on dominant water-level

When the bed-level is taken as datum for all water-levels, the magnitude "water-level" equals "depth". To this respect can the "Dominant Water-level" be symbolised by a_d, while the deviation of the occurring water-level (= depth) from this dominant water-level is written as Δa.

In the group of water-levels between h_1 and $h_1 + dh$, or between a_1 and $a_1 + da$, the scour of the river-bed will then be:

$$\frac{dz_b}{dt} = -\frac{E}{b}(a_d + \Delta a)^{\alpha}\frac{db}{dx} + b\alpha\,(a_d + \Delta a)^{\alpha-1}\frac{da}{dx}$$

or

$$\Delta z_b = \frac{dz_b}{dt}n = -\frac{E}{b}n\,(a_d + \Delta a)^{\alpha}\left[\frac{db}{dx} + b\alpha\frac{1}{a_d + \Delta a}\frac{da}{dx}\right] \quad \ldots\ldots (40)$$

Diagram 6.1.1-5 shows:

$$\frac{da}{dx} = \frac{da_d}{dx} \quad \text{(the water-levels are parallel).}$$

Given and fixed is

$$b = f(x)$$

and further is given that

$$b\,a_d^{\alpha} = \text{constant.}$$

It then follows that

$$a_d^{\alpha}\frac{db}{dx} + b\alpha\,a_d^{\alpha-1}\frac{da_d}{dx} = 0$$

or

$$\frac{da}{dx} = \frac{da_d}{dx} = -\frac{1}{b\alpha}a_d\frac{db}{dx} \quad \ldots\ldots (41)$$

Equation (41) substituted in (40) yields

$$\Delta z_b = -\frac{E}{b}n\,(a_d + \Delta a)^{\alpha}\frac{db}{dx}\left[1 - \frac{a_d}{a_d + \Delta a}\right] \quad \ldots\ldots (42)$$

Equation (17) of 5.4.1 gives the formula for the factor E; if this is introduced, Equation (42) above can be transformed into

$$\Delta z_b = -\frac{2}{b^2}\frac{db}{dx}n\frac{\Delta a}{a_d + \Delta a}\,(S + \tfrac{3}{2}\,b^{\frac{2}{3}}B\,S^{\frac{1}{3}}) \quad \ldots\ldots (43)$$

The last part of this Equation can be transformed by using Equation (16) of 5.4.1:

$$\Delta z_b = -\frac{2}{b^2}\frac{db}{dx}n\frac{\Delta a}{a_d + \Delta a}S\left[1 + \frac{\frac{3}{2} - \alpha}{\alpha - 1}\right] \quad \ldots\ldots (44)$$

which can still be further simplified by introducing

$$S' = S\left[1 + \frac{\frac{3}{2} - \alpha}{\alpha - 1}\right]$$

The total scour of the river-bed over the entire year is then

$$\sum_{\text{year}}\Delta z_b = -\frac{2}{b^2}\frac{db}{dx}\sum_{\text{year}}S'n\frac{\Delta a}{a_d + \Delta a} = 0 \quad \ldots\ldots (45)$$

which can be transformed (see Diagram 6.1.1-6) into

$$\frac{\Sigma nS'}{a_d} = \sum\frac{nS'}{a}$$

This yields the Equation for the Dominant Water-level (D.W.) a_d

$$a_d = \frac{\Sigma nS'}{\sum\frac{nS'}{a}}$$

The above equation is valid only for a rectangular cross-section. If the actual section is different, then the calculations are not exact, and the profile should be sub-divided into separate rectangular sections. Each section then has its own dominant water-level. Another method would be to assume a certain bed-level and perform the above general calculation. Then the mean bed-level can be calculated from

$$\int_0^b a^\alpha \, db = b \, a^\alpha_{\text{average}}$$

which bed-level will not, normally, correspond with the assumed level. The problem can be solved by re-iteration.

From a purely theoretical point of view, it is not permitted to base the calculations of sand-transport and D.W. on an average rectangular cross-section; most sections will show a pronounced channel and one or more shallow areas. The error introduced by the approximation may be considered the local deviation from the average profile, which results from meandering and other causes. The dominant water-levels and discharges may still be looked upon as the general measure for the equilibrium bed-level.

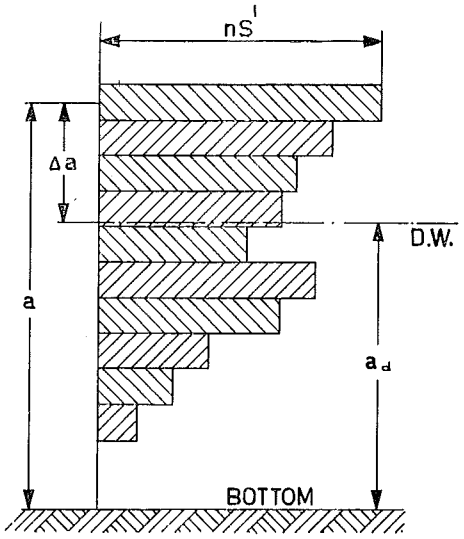


DIAGRAM 6.1.1-6

Determination of dominant water-level

It follows from Equation (46) that the lower groups of water-levels, with consequently a low value of a, have relatively greater influence on the position of the dominant water-level a_d than the higher stages of the river. This is only natural, as small variations in bed-level have a greater effect during the low stages of the river. The sand-transporting capacity of these low stages is less than at high water, which is expressed by the factor nS'.

The actual sand-transport S is always less than the corrected term S' which was introduced above for the sake of simplification. S is multiplied by a factor p:

$$S' = p\,S$$

a factor which approaches unity for high stages (or discharges) of the river; for low water the factor p is greater than unity, as can be seen on Diagram 6.1.1-7, in which p and α have been plotted against the dimensionless term for sand-transport σ:

$$\sigma = \frac{s}{d^{\frac{3}{2}}\, g^{\frac{1}{2}}}$$

With this Diagram the dominant water-level can easily be calculated.

For a better understanding of the construction of the D.W. it is attractive to plot a diagram in which a certain quantity *K* is plotted horizontally against the groups of water-levels on the

vertical axis in such a way that the centre of gravity of the diagram yields the Dominant Water-level. The quantity K should then satisfy the condition

$$\Sigma K \, a \, da = a_d \, \Sigma K \, da$$

or

$$\frac{\Sigma K \, a \, da}{a_d} = \Sigma K \, da \qquad \ldots\ldots\ldots (47)$$

where da (= dh) is the range of each group of water-levels, varying between a_n and $a_n + da$, or between h_n and $h_n + dh$.

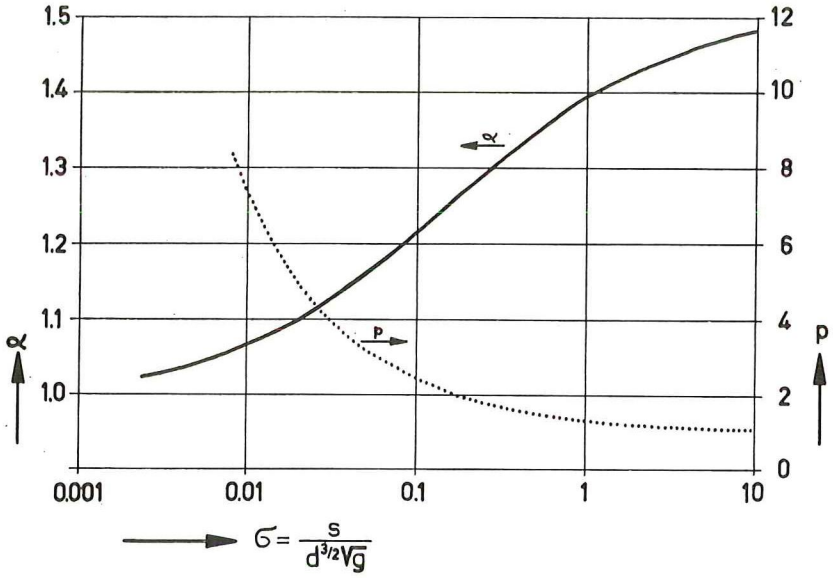


DIAGRAM 6.1.1-7

Coefficients α and p *as a function of the sand-transport*

This equation should be identical to Equation (46), which leads to

$$K = \frac{nS'}{a \, da} \qquad \ldots\ldots\ldots (48)$$

This quantity K, plotted in a horizontal direction against the groups of water-levels, yields a diagram of which the centre of gravity has a level a_d which is the Dominant Water-level. Such diagrams have been constructed in 5.2.4 for five stations along the Niger and Benue of which fairly long records of water-levels are available. For an easy reference, the resulting graphs are repeated in Diagram 6.1.1-8.

By using the stage-discharge relations as shown in 4.3.2, the Dominant water-levels can be transformed into Dominant Discharges.

A change in the Dominant Water-level or in the Dominant Discharge has great effect upon the shape of the river-bed. Such changes could result from human intervention in the regime of the river, for instance, by discharge regulation (see 6.6.9), but also from natural causes such as changes in climate. A series of relatively dry years in succession effects a lowering of the Dominant Discharge, while after a series of wet years the Dominant Discharge will be relatively high. As discussed under a of this Paragraph, a lower D.D. would correspond with a smaller width and not with a smaller depth. During such a series of consecutive dry years therefore the width of the river is decreasing and consequently the bed-level is being lowered.

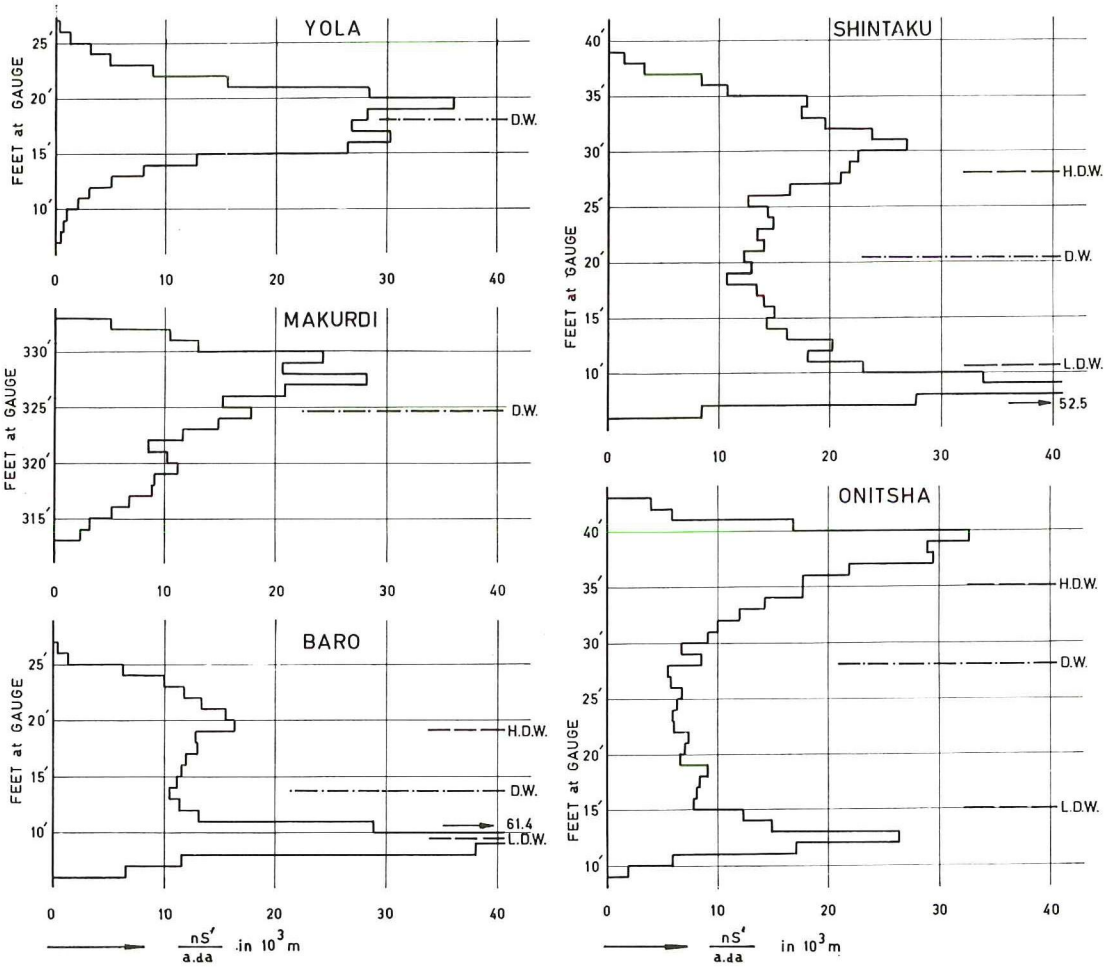


DIAGRAM 6.1.1-8

Dominant water-levels along Niger and Benue

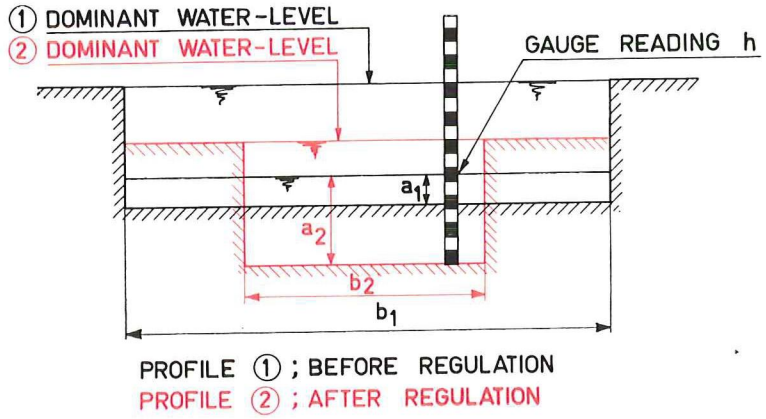


DIAGRAM 6.1.1-9

Change of cross-section by decrease in D.D.

In Diagram 6.1.1-9 let the gauge reading be h for the original cross-section, corresponding to a depth a_1. When the width decreases because of decrease of D.D., the cross-section becomes number two in the diagram, and a gauge reading h corresponds to a depth a_2. It will be clear that for the lower stages, when for the same gauge reading h the depth a_1 is almost zero whilst in situation 2 the depth a_2 is considerably greater, the discharge Q_2 (corresponding to the gauge reading h) exceeds the discharge Q_1, notwithstanding the difference in width. The ratio of discharges is then

$$\frac{Q_2}{Q_1} = \frac{b_2 a_2^{\frac{3}{2}}}{b_1 a_1^{\frac{3}{2}}}$$

which leads to a higher discharge for situation 2 for similar gauge readings.

This numerical example illustrates that extrapolation of discharge measurements, executed in wet, years, results in calculated discharges smaller than the actual ones if the calculation has been made for a series of dry years.

6.1.2. Cross-sections of a river in a continuous bend

The above considerations about cross-sections in a straight sand-transporting river give a first approximation of the actual river. In fact, a straight river rarely occurs and then only over a small distance. Therefore also the cross-section of a river in a bend should be studied and, analogous to the preceding paragraph, the problem is discussed for a steady discharge and for a non-steady discharge.

a *With a steady discharge*

The phenomena in bends have been subject to consideration and discussion for a long time. As early as 1876 a theory was developed by THOMPSON (1 concerning the physical background of the observed behaviour. Literature on the subject is abundant, although the views expressed are by no means in concordance with each other. But generally speaking it is fully agreed by all the different authors that the initial cause of the phenomena is the centrifugal force upon the water particles in the bend, originating in the tendency of a moving particle to flow straight ahead. This centrifugal force, directed at right angles to the flow (into the direction of the

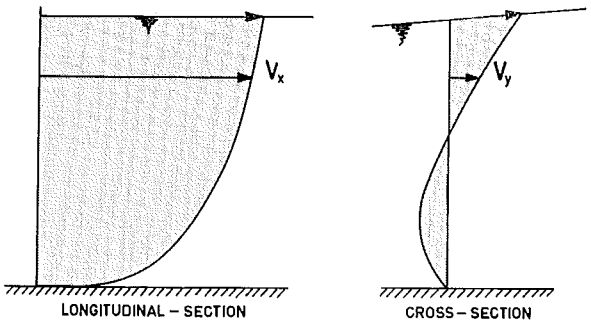


DIAGRAM 6.1.2-1
Vertical velocity distribution in a bend

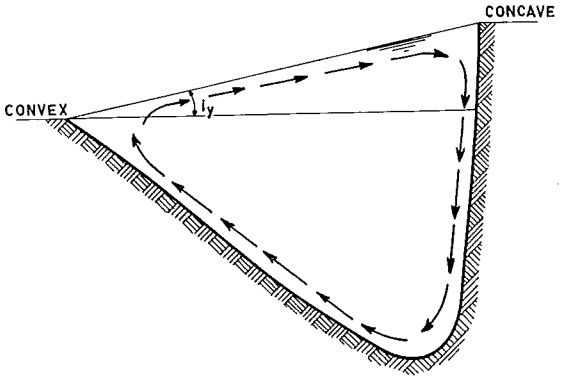


DIAGRAM 6.1.2-2
Scheme of helicoidal current in a cross-section of a bend

(1 THOMSON, 1876, MOR. 30

y-axis) would disturb the transversal equilibrium and is therefore compensated by an adverse force, being a transversal gradient i_y of the water surface. This transversal force is equal for all particles in the vertical and is proportional to the average of the squared velocities in that vertical. However, due to the velocity distribution in the vertical, the centrifugal force of a water particle near the surface (flowing with greater velocity than the average velocity in the vertical) is larger than the centripetal force caused by the transversal gradient; so that as a result this particle is describing a bend with a larger radius than the average one, or, to use a sporting term, is thrown out at the bend. On the other hand, a particle near the bottom, with a smaller velocity than the average, is moving toward the centre of the bend (Diagram 6.1.2-1). The result is a helicoidal secondary current superimposed upon the normal movement into the x-axis; a spiral flow exists outward on the surface and inward along the bottom; at the concave bank the motion is directed downward, along the convex bank upward (Diagrams 6.1.2-2 and -3).

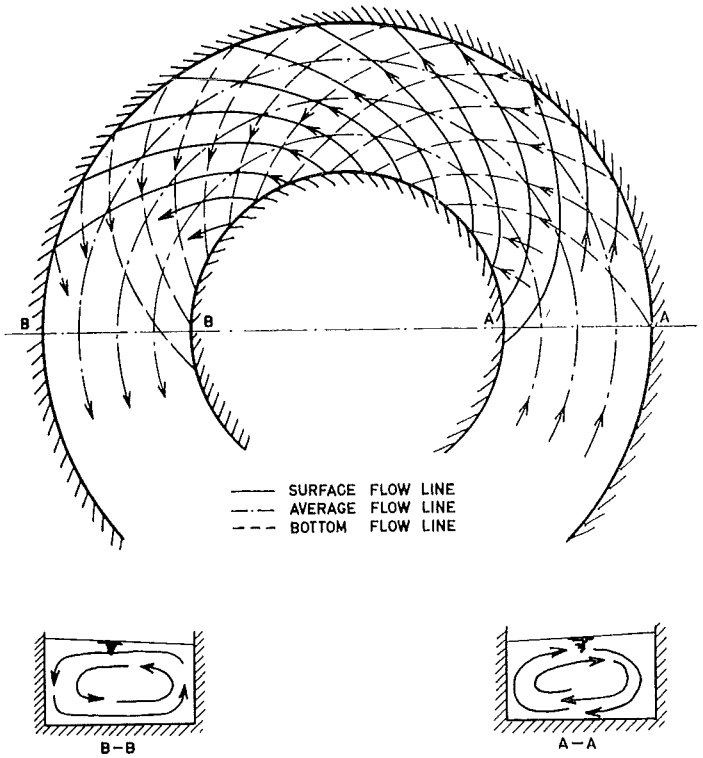


DIAGRAM 6.1.2-3

Spiral flow in a continuous bend

Mathematically the problem of the spiral flow can be solved after some simplifications of the differential equation of this flow, as is described by VAN BENDEGOM ([1]. From this it is concluded that

(i) the transversal gradient of the water surface at a certain point in the cross-section is

$$i_y = 1.06 \frac{v^2}{gr} \qquad \ldots\ldots\ldots \quad (1)$$

(ii) the deviation of the surface velocity from the average direction of flow appears to be

$$\frac{u_y}{u_x} = 0.025 \frac{v^2}{gr\, i_x} \qquad \ldots\ldots\ldots \quad (2)$$

([1] VAN BENDEGOM, 1947. MOR. 1

(iii) the deviation of the tractive force on the bottom, caused by the spiral flow, is

$$\frac{F_y}{F_x} = \tan\lambda = 0.04\,\frac{v^2}{gr\,i_x} \qquad \ldots\ldots\ldots (3)$$

in which formulae v = average velocity in the vertical under consideration;
r = radius of the average stream-line in this vertical; and
i_x = longitudinal slope of the water surface in this vertical.

When using the formula of DE CHEZY

$$v = C\sqrt{a i_x}$$

and assuming a value for $C^2 = 2{,}000$, ref. (ii) and (iii) respectively change into:

$$\frac{u_y}{u_x} = 5\,\frac{a}{r} \quad \text{and} \quad \tan\lambda = 8\,\frac{a}{r} \qquad \ldots\ldots\ldots (4)$$

Although these deviations are relatively small in the case of a normal bend, they prove to be of dominant importance for the formation of the river-bed in bends.

To calculate the ultimate shape of a cross-section in a bend of the river, in the first instance all other factors have to be eliminated, and therefore it is assumed that
(i) the outer bank is non-erodible and has a continuous uniform radius;
(ii) the river-bed and the inner bank consist of homogeneous and erodible material; and
(iii) the water-flow is steady and uniform.

From these assumptions it follows that in the equilibrium state of the cross-section all movement of sand is parallel to the outer bend, i.e., only in x-direction.

As the deviation of the tractive force on the bottom, due to the spiral flow, gives the sand movement a component in y-direction, some force must act to counterbalance it. This will be done by the transversal slope of the river-bed, resulting in a gravity force opposite to the force due to the spiral flow.

In Diagram 6.1.2-4 a sketch is given of the forces working on a sand particle in a bend of a river:

$$F_x = \rho_w g a\, i_x\, \tfrac{1}{4}\pi d^2$$

$$F_y = F_x \tan\lambda = \frac{\delta\,\rho_w g a^2\, i_x\, \tfrac{1}{4}\pi d^2}{r}$$

$$G_x = (\rho_s - \rho_w)\, g \sin\beta_x\, \tfrac{1}{6}\pi d^3$$

$$G_y = (\rho_s - \rho_w)\, g \sin\beta_y\, \tfrac{1}{6}\pi d^3$$

in which $\sin\beta_x$ can be substituted by i_x as in this theoretical case all consecutive cross-sections have the same size and shape.

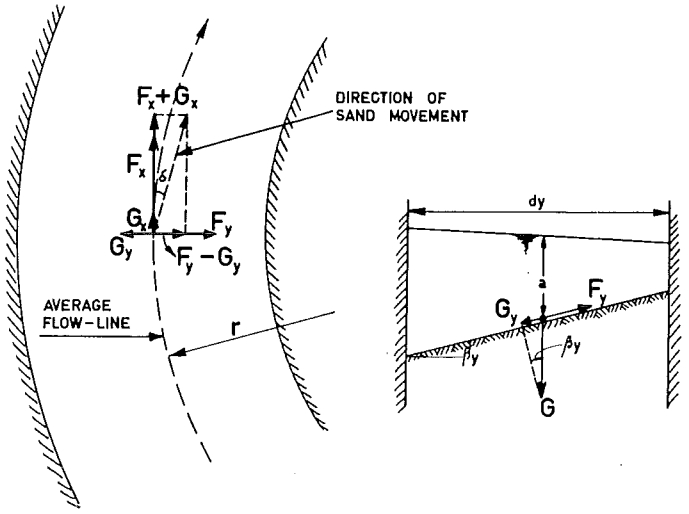


DIAGRAM 6.1.2-4

Forces working on a sand particle

So the equation

$$\tan \delta = \frac{F_y - G_y}{F_x - G_x}$$

becomes

$$\tan \delta \, (3a + 2\Delta d) = 24 \frac{a^2}{r} - 2 \frac{\Delta d}{i_x} \sin \beta_y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w}.$$

Now $\Delta = 1.68$ and $d = 0.5 \times 10^{-3}$ m. As a result $2\,\Delta\,d = 1.68 \times 10^{-3}$ m, which is small in comparison to three times the depth (3a) of the river. As this factor can therefore be neglected in the left part of Equation (5), the equation is then modified into

$$\tan \delta = 8 \frac{a}{r} - \frac{2\Delta d}{3a i_x} \sin \beta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In the equilibrium state of the cross-section $\delta = 0$; thus

$$\sin \beta = \frac{12\, a^2\, i_x}{\Delta\, r d} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

As i_x varies in y-direction, i_x can be substituted by

$$i_x = i_o \frac{r_o}{r}$$

in which i_o and r_o are the slope of the water surface in the outer bend and the radius of the outer bend respectively. Then

$$\sin \beta = \frac{12\, i_o r_o}{\Delta\, d} \frac{a^2}{r^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

As $\sin \beta$ is about $\frac{da}{dr}$, Equation (8) can be written as

$$\frac{da}{a^2} = \frac{12\, i_o r_o}{\Delta\, d} \frac{dr}{r^2}$$

from which follows, when substitutively $a = a_o$ for $r = r_o$

$$\left[\frac{1}{a} - \frac{1}{a_o}\right] = \left[\frac{1}{r} - \frac{1}{r_o}\right] \frac{12\, i_o r_o}{\Delta\, d} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

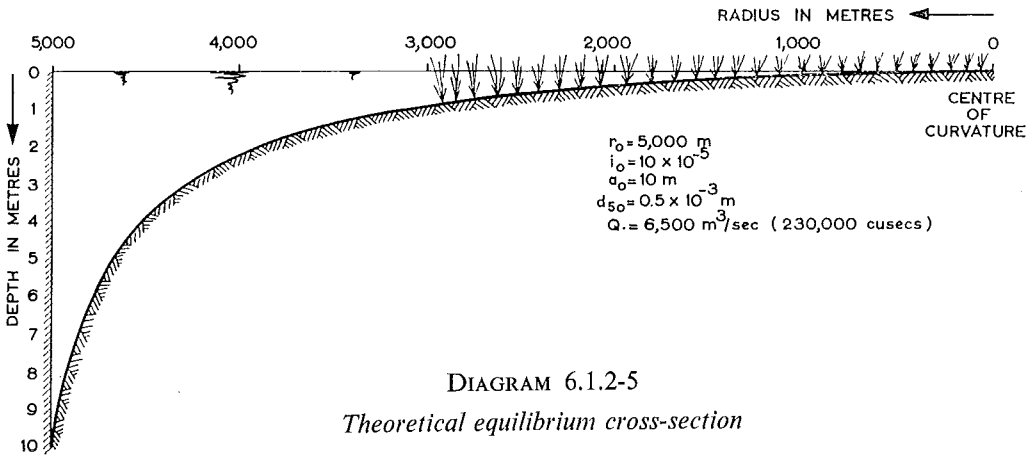


DIAGRAM 6.1.2-5

Theoretical equilibrium cross-section

In Diagram 6.1.2-5 the theoretical equilibrium cross-section in a bend is drawn for a river with $r_o = 5{,}000$ m; $i_o = 10 \times 10^{-5}$; $a_o = 10$ m and $d_{50} = 0.5 \times 10^{-3}$ m. From this diagram it can be seen that the depth decreases rapidly towards the inner bend and as at a depth of about three feet vegetation will probably be able to grow, a river with a width of about 2,000 m will result. The discharge capacity of this bend will be about 6,500 m^3/sec (230,000 cusecs).

The question arises whether the cross-section in a bend will always be a curved one, and if so, whether the curve will be always similar to the one drawn in Diagram 6.1.2-5. To answer this question, Equation (8) is differentiated again:

$$\frac{d^2a}{dr^2} = \frac{24\, i_o r_o a^2}{\Delta\, dr^4}\left[\frac{12\, i_o r_o}{\Delta d}\, a - r\right] \qquad \ldots\ldots\ldots (10)$$

If the cross-section in a bend is a straight line, $\frac{d^2a}{dr^2}$ should be zero, from which follows

$$\frac{r}{a} = \frac{12\, i_o r_o}{\Delta d} \qquad \ldots\ldots\ldots (11)$$

which implies that the centre of curvature is situated on the river-bank. In that case the slope in any vertical is

$$i_x = \frac{H}{r}$$

in which H has a constant value. These equations are now substituted in the formula of De Chezy

$$v = C\sqrt{a i_x} = C\sqrt{\frac{Hd}{12\, i_o r_o}} = \text{constant.}$$

The outcome of this proposition is a bend with an inner bank with a radius of zero, while the velocity is evenly distributed over the cross-section. As these circumstances are not likely to be met in natural rivers (especially a finite velocity in a water depth of zero), it is concluded that the equilibrium shape of a cross-section in a river bend is a curved one.

Concerning the curvature of the bottom figuration two possibilities exist, namely convex or concave. The first possibility occurs when

$$\frac{d^2a}{dr^2} > 0$$

which leads to

$$\frac{12\, i_o r_o}{\Delta d} > \frac{r}{a}$$

or

$$\sin\beta = \frac{12\, i_o r_o}{\Delta d}\,\frac{a^2}{r^2} > \frac{a}{r} \qquad \ldots\ldots\ldots (12)$$

involving a profile as indicated with a full line in Diagram 6.1.2-6, while the second possibility inversely would lead to

$$\sin\beta < \frac{a}{r}$$

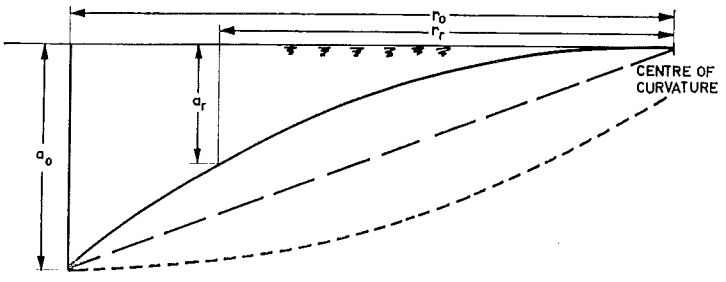


Diagram 6.1.2-6

Possibilities of transversal bottom figuration

which gives a profile as drawn with a dotted line in the said diagram. It will be clear that the latter cross-section cannot exist, as it follows from Diagram 6.3.4-4 that normally for a sand-transporting river

$$\frac{\Delta d}{ai} < 12$$

or

$$\frac{12ai}{\Delta d} > 1$$

which means that

$$\frac{d^2a}{dr^2} > 0$$

It is therefore concluded that the bottom profile in a river bend is always a convex curve.

If, contrary to the above-mentioned assumption (ii) the bed-material is considered to be heterogeneous, and the observed demixing of sand in bends (i.e., the coarser sand in the deeper outer bend and the finer sand in the inner bend) is taken into consideration, the ultimate curvature of the bottom might be somewhat less pronounced. Also a part of the bed-load will occasionally transfer into suspended load by severe turbulence, thus making the equilibrium profile less defined. Another very important factor, which cannot be introduced into the formulae, is the occurrence of rather large bed-ripples. The vortices downstream from these ripples (see 5.4.3 and 5.4.4) may bring about a considerable amount of transversal sand movement which might have a large influence upon the configuration of the entire river-bed.

If the first assumption (i) is abandoned and changed into the more general assumption that the outer bank is also erodible, the calculation of the configuration of the river bend becomes more complicated. To simplify this problem, the critical tractive force is neglected and the sand-transporting capacity per unit width of the river-bed is assumed to be

$$s = A\ (ai)^{\frac{3}{2}} \qquad \ldots\ldots\ldots (13)$$

in which A is constant.

The erodibility of the river-bank is defined as a certain part p of the sand-transporting capacity along this bank into the x-direction. So the erosion E amounts to

$$E = p\ s_{x_o} = p\ A\ (a_o i_o)^{\frac{3}{2}} \qquad \ldots\ldots\ldots (14)$$

in which a_o and i_o are the depth and the slope in the vertical near the outer bank respectively.

As in the supposed continuous bend all cross-sections are equal, s_x cannot vary along the x-axis. So if erosion takes place, the transversal component of the sand movement must be able to transport the amount of eroded sand. Consequently

$$E = s_{y_o} = p\ A\ (a_o i_o)^{\frac{3}{2}}$$

But also

$$s_{y_o} = s_{x_o} \tan \delta_o$$

and therefore

$$p\ A\ (a_o i_o)^{\frac{3}{2}} = A\ (a_o i_o)^{\frac{3}{2}} \left[8 \frac{a_o}{r_o} - \frac{2 \Delta d}{3 a_o i_o} \sin \beta_o \right]$$

or

$$p = 8 \frac{a_o}{r_o} - \frac{2 \Delta d}{3 a_o i_o} \sin \beta_o$$

from which it follows that

$$\sin \beta_o = \frac{12 a_o^2 i_o}{\Delta d r_o} - \frac{3 a_o i_o}{2 \Delta d} p \qquad \ldots\ldots\ldots (15)$$

As discussed before (Equation (12)), it is necessary that

$$\sin \beta_o > \frac{a_o}{r_o}$$

to arrive at a defined shape of the cross-section. Substituting this in Equation (15), the erosion factor p must be

$$p < 8 \frac{a_o}{r_o} - \frac{2 \Delta d}{3 i_o r_o} \qquad \ldots\ldots\ldots (16)$$

When substituting, for example,

$a_o = 10$ m (about 30 feet);
$r_o = 5{,}000$ m (about 3 miles);
$i_o = 10 \times 10^{-5}$; and
$d = 0.5 \times 10^{-3}$ m,

the critical value of the erosion becomes $p_{cr} = 1.5\%$. If the erosion becomes greater than this value, the channel would probably not be stable and consecutive cross-sections along the x-axis would no longer be equal. The conception of a continuous bend is then erroneous, unless a new equilibrium would be established with either less erosion or smaller radius of curvature.

For any given vertical in a bend with an erodible outer bank, situated at a distance r from the centre of curvature, the transversal sand-transport by the spiral flow is

$$S_{y_r} = \frac{E}{a_o} a_r = \frac{a_r}{a_o} p A (a_o i_o)^{\frac{3}{2}}$$

as can be seen from Diagram 6.1.2-7. However, S_{y_r} is also equal to

$$S_{y_r} = S_{x_r} \tan \delta_r$$

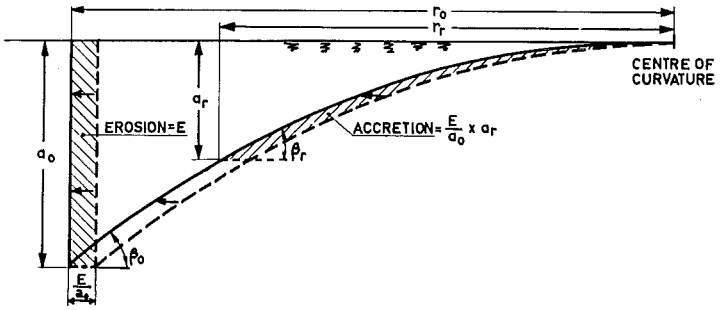


DIAGRAM 6.1.2-7

Erosion and accretion in the cross-section

and therefore is

$$\frac{a_r}{a_o} p A (a_o i_o)^{\frac{3}{2}} = A (a_r i_r)^{\frac{3}{2}} \left[8 \frac{a_r}{r_r} - \frac{2 \Delta d}{3 a_r i_r} \sin \beta_r \right]$$

or

$$p = \frac{a_o}{a_r} \left[\frac{a_r r_o}{a_o r_r} \right]^{\frac{3}{2}} \left[8 \frac{a_r}{r_r} - \frac{2 \Delta d r_r}{3 a_r i_o r_o} \sin \beta_r \right]$$

from which it follows

$$\sin \beta_r = \frac{12 a_o^2 i_o}{\Delta d r_o} \left[\frac{r_o a_r}{r_r a_o}\right]^2 - \frac{3 a_o i_o}{2 \Delta d} p \left[\frac{a_r}{a_o}\right]^{\frac{1}{2}} \left[\frac{r_r}{r_o}\right]^{\frac{1}{2}}$$

Since $\sin \beta_r$ must be larger than $\frac{a_r}{r_r}$, it follows that

$$p < \left[8 \frac{a_o}{r_o} \frac{r_o a_r}{r_r a_o} - \frac{2 \Delta d}{3 i_o r_o}\right] \left[\frac{r_o a_r}{r_r a_o}\right]^{\frac{1}{2}} \frac{r_o}{r_r} \qquad \ldots\ldots\ldots (17)$$

Obviously, as

$$\frac{a_r}{r_r} < \frac{a_o}{r_o}$$

it follows that

$$\frac{r_o a_r}{r_r a_o} < 1$$

So the product of the first and second factors of Equation (17) is smaller than the critical value for p for the vertical near the outer bank. The third factor, however,

$$\frac{r_o}{r_r} > 1,$$

and it is not directly clear from this formula whether the critical value for p in any vertical of the cross-section will be limiting or not; only an extensive calculation with the given values of the particular river bend can give an answer to this question.

b *With varying discharges*

In a natural river the water-level changes throughout the year and this will undoubtedly have an influence on the figuration of the river-bed in a bend. When considering a bend with a non-erodible outer bank, the slope of the river-bed in a transversal direction as described in Equation (7) is no longer constant, since apparently

$$a = f(t),$$

and the average frequency curve of the water-levels has to be used as a basis for calculations like this one.

Analogous to the conception of the Dominant Water-level for a straight river (6.1.1-b), in a bend, too, the magnitude D.W. can be introduced. If it is assumed that the sand movement in a given vertical is directed parallel to the outer bank when the stage in that vertical is the dominant stage, corresponding to a depth a_d, then

$$\tan \delta_d = 8 \frac{a_d}{r} - \frac{2 \Delta d}{3 a_d i_x} \sin \beta_d = 0$$

or

$$\sin \beta_d = \frac{12 i_x}{\Delta r d} a_d^2 \qquad \ldots\ldots\ldots (18)$$

In general, the transversal sand movement in this vertical becomes

$$S_y = S_x \tan \delta = S_x \left[8 \frac{a}{r} - \frac{2 \Delta d}{3 a i_x} \sin \beta_d\right]$$

or

$$S_y = 8 \frac{a}{r} \left[1 - \frac{a_d^2}{a^2}\right] S_x \qquad \ldots\ldots\ldots (19)$$

The condition of equilibrium based on a cycle of one year is

$$\sum_{\text{year}} S_y = 0 \qquad \ldots\ldots\ldots (20)$$

so

$$\sum 8 \frac{a}{r}\left[1 - \frac{a_d^2}{a^2}\right] A\ (ai)^{\frac{3}{2}}\ \Delta t = 0$$

wherein $a = f(t)$ has to be known in order to determine the value for Δt for any interval between a and $(a + \Delta a)$.

From this summation the dominant stage and therefore also the equilibrium transversal slope of the bed, $\sin \beta_d$, can be determined. It has to be kept in mind that in a natural river r and i might prove to be functions of time as well, which makes the problem even more complicated, whilst the possibility of an eroding outer bank should also be put in. In that case, the equilibrium condition as described in Equation (20) is transformed into

$$\Sigma S_{y_r} = \frac{a_r}{a_o} p A\ (a_o i_o)^{\frac{3}{2}} \qquad \ldots\ldots\ldots (21)$$

an equation which is hardly solvable.

6.1.3. Cross-sections of a river under natural conditions

In the foregoing paragraphs, theories of the cross-section of straight channels and channels in continuous bends have been discussed. In reality these phenomena do not appear in natural sand-transporting rivers with erodible banks. Every bend must be limited in length, although in strongly meandering rivers the bends are often more than semi-circular. On the other hand, a straight channel does not occur, because of the instability of such straight channels. Every occasional disturbance of a straight flow will cause curved streamlines, spiral flow and meandering, not only at the site of the disturbance but also upstream and downstream where the streamlines form a counter-curvature. Only where the river is flowing in a bend with such a radius that the influence of the spiral flow is by far larger than the influence of the secondary spiral caused by the disturbance, is the river stable and capable of removing the influence of the disturbance.

So a natural channel consists of a number of curves in different directions and with different radii, linked by a transition zone consisting of a more or less straight alignment. In bends the capacity to discharge water is mainly concentrated in the deep outer bend. In the calculation of the shape of the cross-section the spiral flow dominates; other morphological factors such as the conception of minimum slope do not play a major rôle. In the crossings the curvature is decreasing and with it the influence of spiral flow. Theoretically the channel will become wider and shallower until downstream the equilibrium depth of a straight channel is reached. However, before that a counter-curve has made itself felt, concentrating again the width of the channel. So the depth in the crossing will generally be smaller than the average depth of the channel, but possibly still larger than the theoretical equilibrium depth of a straight river.

It is not possible to give a purely theoretical calculation of the cross-section of such a crossing in freely forming channels. Moreover, in Nature the problem is still more complicated. Variability of discharge causes the so-called "breathing" of the crossing as discussed in 6.4.2, whilst island formation gives normally such a variety of channels and crossings that a theoretical approach is impossible. However, the simple forked river without large flats is to a certain extent comparable with a single-channelled river.

In the lower reaches of the Niger, near and in the Delta Area, several purely meandering channels occur, consisting of alternating bends and counter-bends with only a few small islands. These bends are fairly stable and the erosion of the strongly-curved river-shores is moderate in view of the cohesive clayey bank-material; which by itself may be one of the reasons why the river meanders. The very sharp bend in the Niger near Utu (Mile 168) is a fine example, and

has been drawn in Diagram 6.1.3-1. The length of the bend is such that it might to a certain extent be regarded as a continuous bend.

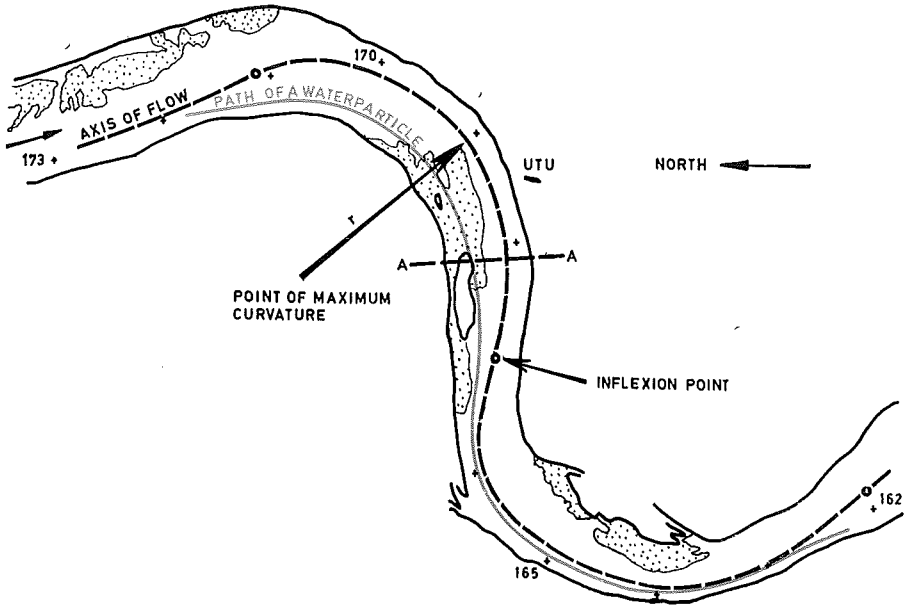


DIAGRAM 6.1.3-1

Meander bend in the Niger near Utu

For the bankfull stage the following data are valid:
$r_o = 3.5$ km (1.9 miles),
$i_o = 5 \times 10^{-5}$,
$d = 0.6 \times 10^{-3}$ m (0.02 inch), and
$v = 1.16$ m/sec (3.8 ft/sec),
whilst the length measured along the hydraulic axis between two inflexion points is
$L = 6$ km (3.8 miles).

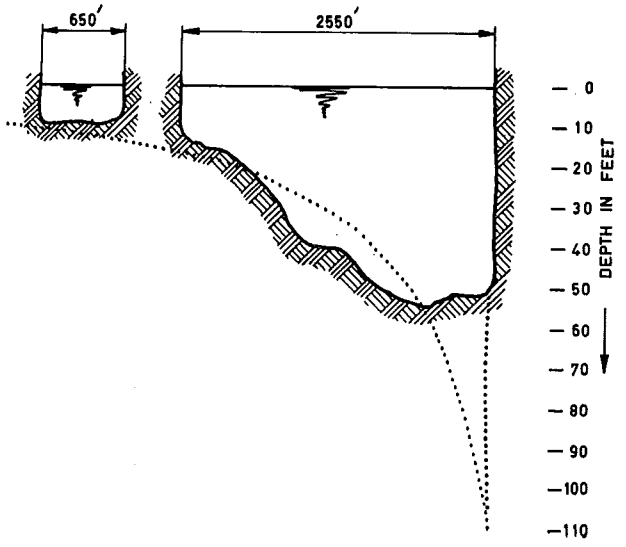


DIAGRAM 6.1.3-2

Sounded cross-section A-A near Utu

In the bend, a little below the point of greatest curvature, the cross-section A-A as indicated in Diagram 6.1.3-1 has been sounded and drawn in Diagram 6.1.3-2. Using Equation (9) of 6.1.2 and the above data, a theoretical cross-section could be calculated; it has been drawn in the diagram with a dotted line. The coincidence between the measured and computed profiles is reasonable, bearing in mind that the bend is actually not a continuous one, that the erodibility of the outer bank is not included in the calculations, and that the location of the measured cross-section does certainly not coincide with the point of maximum curvature of the bend.

The latter argument, however, gives reason for consideration. Observations on various rivers in different parts of the world have shown that the position of maximum transversal bottom gradient does not coincide with the point of maximum curvature. The influence of the curved flowlines upon the bottom configuration lags behind. FARGUE (1 gives for this lag a distance of about one-quarter of the total length of the bend (Diagram 6.1.3-3), based upon observations in the River Seine in France.

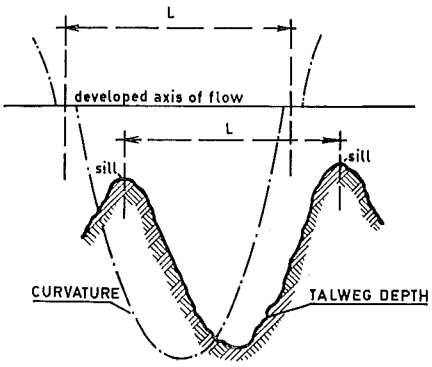


DIAGRAM 6.1.3-3

Fargue's graph on lag of sills

Consequently, according to Fargue also a lag exists in the location of the sill behind the inflexion point of the stream. Fargue's graph (Diagram 6.1.3-3) would give for the case of Utu, mentioned above as an example, a lag of $\frac{1}{4} \times 6{,}000 = 1{,}500$ m (0.93 mile). On the Rhine an experimental formula of LELY (2 gives for the lag a magnitude of $1\frac{1}{2}$ times the width, which means for Utu about 1,600 m (one mile). Both the Seine and the Rhine are relatively narrow rivers.

The physical explanation is obvious. The influence of water upon the river-bed is, of course, effected by variation in sand-transport. Since sand-transport in an alluvial river equals the sand-transporting capacity, these variations can be considered by discussing the changes in the drag (= tractive force) ρgai (see 5.2.1). Let in Diagram 6.1.3-4 the point of maximum curvature exist in the middle B of a curved section AC. At the points A and C the streamlines run parallel and the water-level in transversal direction is horizontal: $i_y = 0$. But in B the sharp curvature of the streamlines brings about a steep transversal slope with the water-level at the left bank higher than at the right bank. The outer streamline therefore has at first a gentle slope and small velocity, which increase after passing B, whilst the inner streamline shows the reverse.

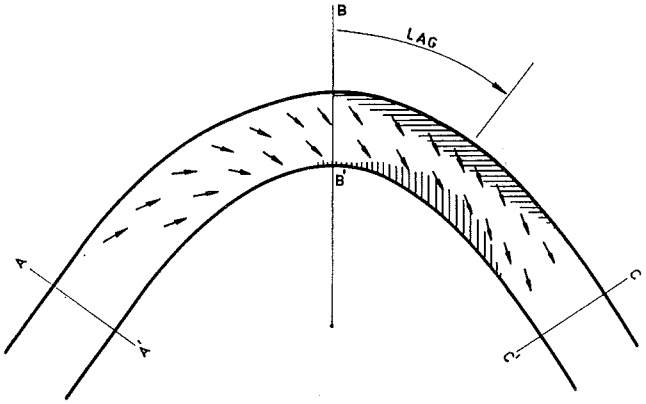
In the first part of the bend between A and B, consequently, at the left side of the river, the drag ρgai gradually decreases, but the resulting deposition of sand is compensated by the transversal sand movement by the spiral flow (6.1.2). The result is that no sand deposits. At the other side of the river the inner streamline shows a continuous increase of sand-transporting capacity, which is fed by the sand supply from the left. The section is in dynamic equilibrium.

In the second part of the bend, however, conditions are quite different. A continuous growth of drag in the outer streamline finds no compensation at all by supply of sand sideward. On the contrary: the circular movement of water still turns anti-clockwise with a component along the bottom directed inward. Severe erosion is the result,

(1 FARGUE, 1908. MOR. 7
(2 LELY, 1922. HYD. 4

partly from the bottom, partly from the bank. At the right side of the river a continuous decrease of sand-transporting capacity, intensified by the extra supply from the left by the spiral flow, effects deposition of sand and the building up of a sand-bank along the inner bank.

Erosion at the outer bank and accretion at the inner bank are therefore strongest between B and C in the second part of the bend, below the point of maximum curvature.



ACCRÉTION

EROSION

DIRECTION OF SAND-TRANSPORT

\+ = INCREASING
− = DECREASING

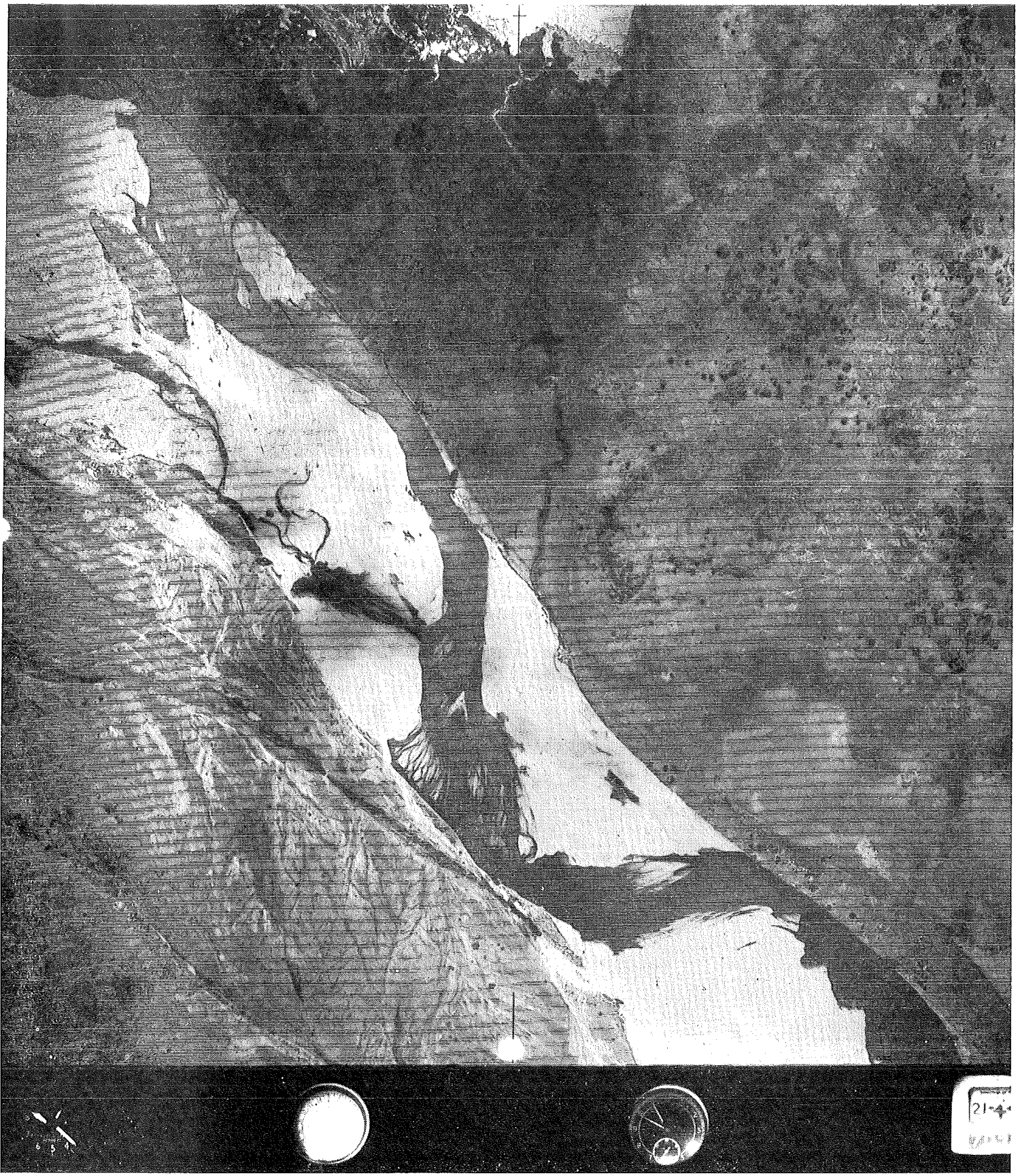
	SUPPLY	− DRAG	= RESULT
LEFT			
AB	−	−	0
BC	−	+	−
RIGHT			
A'B'	+	+	0
B'C'	+	−	+

DIAGRAM 6.1.3-4

Movement of sand in a bend

The actual spiral flow of the water itself is mathematically very complicated, but its value is small. It has been computed that the transversal movement of a water particle in the very sharp bend at Utu, calculated over the full length from crossing to crossing, amounts to only 1,000 feet. The path of such a water particle is shown in red on Diagram 6.1.3-1. But, however small this transversal surface velocity may be, it could hinder downward navigation considerably.

The river-type called "reach" (see Photograph 6.1.3-5), with limited width of the bankfull bed and steep parallel banks planed and straightened by the moving low-water channels, offers still more difficulties for theoretical approach due to the fact that the banks and transitions are moving downstream. Because of this downward propagation a bend may be located at the same position where a few years before a straight channel formed the transition between two opposite bends. These bends and their straight transitions (or crossings) are therefore related in width, as they both are situated between the same parallel banks of the H.W. river-bed. At high water, the flow will be guided to a greater extent by these parallel banks and the curvature of the flowlines resulting from the meandering channel pattern will be less pronounced: the river approaches the straight type as discussed in Paragraph 6.1.1. When the Dominant Discharge is higher than average, as on the Benue (see Diagram 6.1.1-8), then the characteristics of the bed, and in particular its width, may answer Equation (31) of 6.1.1, as will appear from the comparison in 6.1.6. Naturally, when the river shows a lower than average Dominant Discharge or, as on



PHOTOGRAPH 6.1.3-5
River Benue near Ribadu (Mile 907)

the Niger, a low and a high D.D., the resulting characteristics will depend on the features of both curvilinear and rectilinear channel formation.

The braided river, where the channels are moving fast in a shallow bed and where there is no question of real crossings at the transition zone between different channels, gives no opportunity at all to tackle the problems in a theoretical way.

6.1.4. Influence of the rotation of the earth upon the bed

According to CORIOLIS the direction of a moving particle will be deflected under the influence of a force, perpendicular to the direction of velocity, which is caused by the rotation of the earth. In the northern hemisphere this deflection is to the right, irrespective of the direction of velocity.

Also a river as a whole undergoes this deflection, and its magnitude expressed in the dimension of acceleration is

$$Cor = 2\,\omega\,u\,\sin f$$

in which f = geographic latitude,
ω = angular velocity of the earth's rotation,
u = velocity of the water particle.

The result is a tendency of the flow toward the right. The bank resists this tendency and causes a transversal slope of the water surface to the left. Thus a straight path of the average water particle is secured.

Diagram 6.1.4-1 shows the accelerations effected upon the water particle by the various causes. In the x-direction the normal slope of the river with magnitude i_x effects an acceleration gi_x; perpendicular to this the transversal acceleration is gi_y. The direction of velocity is determined by the various accelerations and deflects from the x-direction by an angle α, called positive when the deflection is to the right. The mutual resistance between the different

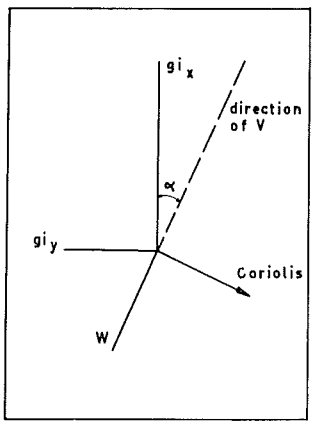


DIAGRAM 6.1.4-1

Accelerations effected upon a water particle

layers of water (as a result of the differences in velocity at variable height) is another acceleration W with opposite direction to the velocity. And finally there is the acceleration of CORIOLIS, directed perpendicular to the velocity and to the right.

In a straight river-section every particle must be in equilibrium, the total acceleration of the particle being zero. This condition results in two equations:

$$gi_x - Cor \sin\alpha - W \cos\alpha = 0$$

and

$$gi_y - Cor \cos\alpha + W \sin\alpha = 0$$

When the acceleration of Coriolis is simplified as

$$Cor = 2\,\omega\,u\,\sin f = p\,u$$

and thus substituted, the above equations are reduced to

$$gi_y - \frac{p\,u}{\cos\alpha} + gi_x \sin\alpha = 0 \qquad \ldots\ldots\ldots (1)$$

With a reasonable accuracy it may be put that

$$\cos\alpha = 1$$

since the angle α is always very small. From this approximation it is derived that

$$u = u_x$$

and

$$gi_y - pu_x + gi_x \sin\alpha = 0 \qquad \ldots\ldots\ldots (2)$$

or integrated over the full height a of the vertical

$$gi_y a - p \int_0^a u_x dz + gi_x \int_0^a \sin\alpha\, dz = 0 \qquad \ldots\ldots\ldots (3)$$

The third term in this equation represents the influence of the resistance W which is dependent on the gradient of velocity

$$\frac{du}{dz}$$

and consequently in the upper layers (where α is positive) its magnitude is smaller than in the lower layers (where α is negative). Evidently the resultant of W integrated over the full height a of the vertical is negative (directed to the right). As the solution of the integral gives difficulties, for the present it is expressed as

$$gi_x \int_0^a \sin\alpha\, dz = (1 - \delta)\, pav \qquad \ldots\ldots\ldots (4)$$

where δ is to be determined later (where it appears to be 1.024).

Solution of the integrated Equation (3) is now possible and leads to

$$i_y = \delta \frac{pv}{g} \qquad \ldots\ldots\ldots (5)$$

in which v = mean velocity over the full height a.

Static equilibrium, however, does not occur, as the velocity of the water particles in the lower layers is smaller than that in the upper layers of the vertical. Also the deflection, being a linear function of the velocity, is greater on the surface that at the bottom. In analogy to the phenomena in a bend, here too a helicoidal current exists. The cross-current is directed on the surface to the right and along the bottom to the left.

The value for i_y from Equation (5) is substituted in Equation (2) while further is stated that

$$u_x = \lambda v$$

in which $\lambda = f(z)$. It then follows that

$$\lambda pv = \delta\, pv + gi_x \sin\alpha \qquad \ldots\ldots\ldots (6)$$

which is a function between λ and v at one side and the angle α at the other side. When the function $\lambda = f(z)$ is known, the angle α can be computed at any height above the bottom. And also the transversal component of the current

$$u_y = u \sin\alpha = \lambda v \sin\alpha \qquad \ldots\ldots\ldots (7)$$

The transversal component of the current along the bottom will be capable of affecting the bottom. It pushes the moving sand particles aside until it is balanced by gravity forces. Equilibrium will be established at a specific transversal bottom gradient: the river is deeper on the right than on the left.

Upon the bottom the following tensions are exerted:

(i) caused by the transversal slope, to the left, positive; and
(ii) caused by Coriolis, to the right, negative.

Ref. (i). The tension caused by the transversal slope is

$$\tau_1 = \rho g a i_y$$

or after substituting Equation (5)

$$\tau_1 = 1.024\,\rho apv \qquad \ldots\ldots\ldots (8)$$

Ref. (ii). The force of Coriolis upon a water particle with a height dz and an area = 1 is

$$\rho pu\,dz$$

and its component into the direction of the y-axis

$$\rho pu\cos\alpha\,dz$$

Thus the total tension from the full height upon the bottom amounts to

$$\tau_2 = \rho p \int u\cos\alpha\,dz = \rho pav \qquad \ldots\ldots\ldots (9)$$

It is concluded that

$$\tau = \tau_1 + \tau_2 = 0.024\,\rho pav \qquad \ldots\ldots\ldots (10)$$

The transversal force exerted upon a single sand grain by the water is now

$$\tau C_w A$$

where C_w = form-resistance coefficient of the grain which is about 0.8, and
A = exposed area of the grain perpendicular to the direction of the current = $\frac{1}{4}\pi d^2$,
while gravity pulls the grain downward along the transversal gradient of the bottom with a force

$$G\sin\beta = g\,\tfrac{1}{6}\pi d^3\,\Delta\rho\sin\beta$$

where β = transversal bottom gradient,
G = weight of sand particle,
d = diameter of the grain,
Δ = relative density of sand = 1.68.

Equilibrium is established when both forces are equal (but conversely directed), from which it can be derived that

$$\sin\beta = 3\,\frac{apv}{d\Delta g}\,10^{-2} \qquad \ldots\ldots\ldots (11)$$

It is now possible to compute the value for δ. From the law of continuity in transversal direction it follows that

$$\int_0^a u_y\,dz = 0.$$

Since

$$u_y = u_x\tan\alpha = \lambda v\tan\alpha$$

this equation can be reduced to

$$v\int_0^a \lambda\tan\alpha\,dz = 0 \qquad \ldots\ldots\ldots (12)$$

From the formula of STRICKLER (1 and from the assumption of a velocity distribution along the vertical according to a parabola of the sixth order, it follows that

$$\lambda = \tfrac{7}{6}\left[\frac{z}{a}\right]^{\frac{1}{6}} \qquad \ldots\ldots\ldots (13)$$

where a = total height of water in the vertical, and
z = height of particle above the bottom.

It can be derived that

$$dz = 2.32\,a\,\lambda^5\,d\lambda$$

or, substituted into Equation (12)

$$2.32\,va\int_0^{\lambda_1}\lambda^6\tan\alpha\,d\lambda = 0$$

where λ_1 = the value for λ at the surface, which is $\frac{7}{6}$. With the approximation that

$$\cos\alpha = 1$$

(1 see 4.3.1

the condition becomes

$$\int_0^{\lambda_1} \lambda^6 \sin \alpha \, d\lambda = 0$$

which equation, together with Equation (6), gives

$$\frac{pv}{g\, i_x} \int \lambda^6 (\lambda - \delta)\, d\lambda = 0$$

or

$$\int_0^{\lambda_1} \lambda^7 \, d\lambda = \int_0^{\lambda_1} \lambda^6 \delta \, d\lambda$$

from which it can be computed that

$$\delta = 1.021$$

which is slightly low due to the assumption that $\cos \alpha = 1$. Making allowance for this approximation, the estimated correct value for δ should be

$$\delta = 1.024$$

The STRICKLER formula and a parabolic velocity-distribution have been used here for the sake of simplicity. Similar results will be achieved by using the formula of DE CHEZY and the logarithmic velocity-distribution.

The helicoidal current, in the northern hemisphere descending along the right bank and ascending on the left, has (although it is weak itself) a gradual and gentle but continuous and constant undermining effect upon the right bank whilst building up the left bank at the same rate. A tendency of the river to propagate sidewards to the right would be the result, but is of course greatly surpassed by the effects of local phenomena such as meandering, composition of the banks, vegetation, formation of islands, etc.

Therefore in short periods of observation it is not possible to recognise the effect of terrestrial rotation, although it certainly can be stated that in the long run the influence must be felt by the course of the river and the building up of its valley.

The influence of Coriolis is noticeable in many places of the world. The Volga, Kira and Amu-Darja are mentioned in Soviet sources as examples of rivers with a very heavy washout due to the helicoidal current. CHEBOTAREV (1 gives some measured values for this helicoidal current in a large river; they are plotted in Diagram 6.1.4-2. KABELAC (2 states that in the Rivers Rhine and Danube the deepening of the bed on the right side is more than on the left, the difference being respectively 1.3′ and 1.0′.

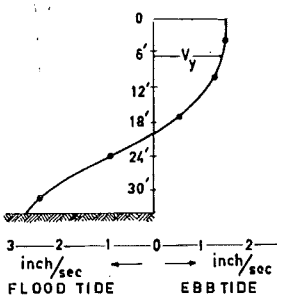


DIAGRAM 6.1.4-2

Transversal component of current as observed in a large river

(1 CHEBOTAREV, 1955. MOR. 3
(2 KABELAC, 1957. MOR. 14

TABLE 6.1.4-3.

THE INFLUENCE OF EARTH ROTATION UPON THE NIGER AND BENUE.

	Niger							Benue						Dimension
	Aboh	Onitsha	Illushi	Idah	Itobe	Shintaku	Baro	Umaisha	Makurdi	Ibi	Lau	Numan	Yola	
mileage	177	232	272	310	332	356	430	401	510	614	778	846	888	miles
geographic latitude	5°31′	6°11′	6°35′	6°59′	7°23′	7°46′	8°28′	8°00′	7°44′	8°12′	9°12′	9°30′	9°23′	north
p Coriolis	14.0	15.5	16.5	17.5	18.5	19.6	21.2	20.0	19.6	20.7	23.2	23.9	23.6	$\times 10^{-6}$
v mean velocity	1.38	1.43	1.50	1.64	1.30	1.75	1.15	1.30	1.87	1.25	1.07	1.20	1.24	m/sec
a mean depth	9.50	8.12	7.80	8.12	7.00	12.50	6.60	5.70	10.40	6.70	5.30	4.10	4.30	m
$\lambda = \frac{u}{v}$ (surface)	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	
α angle of deviation (surface)	10′	9′	11′	13′	10′	16′	9′	13′	6′	8′	6′	8′	7′	sexagesimal minutes
$\lambda = \frac{u}{v}$ (bottom)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	
α angle of deviation (bottom)	–38′	–39′	–41′	–44′	–37′	–57′	–30′	–37′	–22′	–28′	–24′	–28′	–27′	sexagesimal minutes
u_y (surface)	4.49	4.07	5.58	7.05	4.20	9.00	3.37	3.50	3.70	3.10	2.30	3.10	3.00	$\times 10^{-3}$m/sec
u_y (bottom)	– 9.20	– 9.80	–10.70	–12.40	– 8.50	–17.30	– 6.00	– 6.70	– 7.10	– 6.00	– 4.40	– 6.00	– 5.90	$\times 10^{-3}$m/sec
i_y transversal surface slope	0.20	0.23	0.26	0.30	0.25	0.36	0.25	0.27	0.38	0.27	0.25	0.30	0.30	$\times 10^{-5}$
tan β_y transversal bottom gradient	54	53	57	69	50	78	57	38	69	32	23	21	23	$\times 10^{-5}$
b width of river	1,210	1,795	1,855	1,545	2,000	1,170	700	1,625	675	1,500	780	960	760	m
	(3,770)	(5,890)	(6,080)	(5,070)	(6,560)	(3,840)	(2,300)	(5,330)	(2,210)	(4,920)	(2,560)	(3,150)	(2,490)	(feet)
$b\beta_y$ difference in depth right – left	0.65	0.95	1.05	1.05	1.00	0.90	0.40	0.60	0.45	0.45	0.20	0.20	0.15	m
	(2.2)	(3.1)	(3.5)	(3.5)	(3.3)	(3.0)	(1.3)	(2.0)	(1.5)	(1.5)	(0.6)	(0.7)	(0.6)	(feet)

The Rivers Niger and Benue are also influenced by the acceleration of Coriolis. The low geographic latitude would involve only a minor influence, but the very large capacity of the rivers makes the result of reasonable magnitude. Table 6.1.4-3 shows the computed values for the various factors.

The Benue takes its course through about the centre of its valley; the right-pressing Coriolis force seems to be more or less compensated by the supply of silt, most of which is conveyed by the northern tributaries.

Along the Niger, however, both the silt supply from the eastern tributaries and the Coriolis force tend to build up the left bank and to erode the right bank, and here the effect is rather striking.

6.1.5. Composition of the banks; effect on cross-section

Natural river-banks may consist of different materials ranging from easily erodible sand to practically non-erodible igneous rocks, with a number of varieties in between. The rate of erodibility has a great influence upon the equilibrium shape of the cross-section. Such effects on cross-sections in bends have already been discussed in 6.1.2, where it is concluded that a more erodible outer bank results in a more horizontally directed transversal bottom profile, although the spiral flow tends to establish a deep channel along this outer bank. In a straight river-section with a regular pattern of parallel flowlines, easily erodible banks lead to the conception of full adaptation of the cross-section to the characteristics of the stream, as discussed in 6.1.1, while non-erodibility of the banks prevents such adaptation, as is the case in a non-alluvial river. In rivers under natural conditions, where bends and straight transition zones alternate, less erodible banks lead to less "local sand-transport" (see 5.4.2) and to a better guidance of the flow, and therefore to a deeper channel, also in the transition zone. Here, erodibility affects the method of propagation of the meander pattern: the question whether the meanders are travelling downward as a whole or whether the meander loops shift outward until they cut short is completely dependent on the composition of the banks (see 6.2.1).

The actual shape of the cross-section in a straight river-section is highly affected by the characteristics of the bank material. For considerations of a general nature, such as those in 6.1.1, a simplification of the shape was necessary and the assumption was made of the cross-section being rectangular. Such shape, however, would never occur, although wide rivers like the Niger and Benue often approach this assumption.

Several theoretical discussions on the subject of cross-sectional shape have been published. When it concerns a river without sand-transport, the consideration does not meet with great difficulties. A static equilibrium of a sand particle on the sloping bank of the river is established as the forces exerted by various causes compensate each other. These forces are:

(i) the gravity force,
(ii) the friction force, and
(iii) the force exercised by the stream.

Let in Diagram 6.1.5-1 the sloping bank have an angle α with the horizon, while the bank material has a natural angle of repose β ([1]. The three forces can then be determined.

Ref. (i), the submerged weight W of the sand particle can be resolved into its normal component W cos α and into its tangential component W sin α.

Ref. (ii), the friction force will act in the plane of the sloping bank, or perpendicular to the normal component of the submerged weight, and will be proportional to this component and

([1] which means that, when this material is subject to gravity forces only, each grain has a stable position when the angle of the sloping bank equals or is less than β.

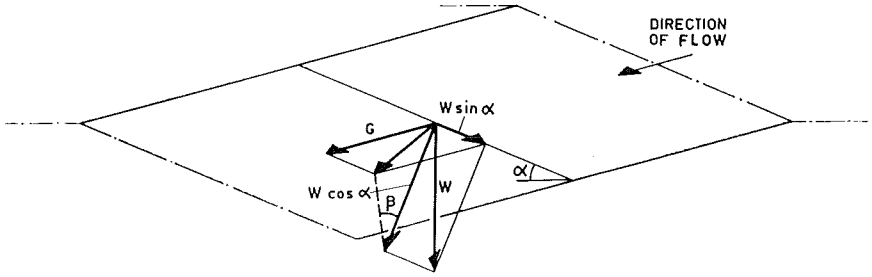


DIAGRAM 6.1.5-1

Static equilibrium of a sand particle in a sloping bank

to the tangent of the angle of repose. In fact, the maximum value this force can reach is $F = W \cos \alpha \tan \beta$.

As for (iii), the force exercised on the particle by the stream is proportional to the depth a and to the hydraulic gradient i, $G = A\,a\,i$ in which A is a constant. This force G is acting in the direction of the stream.

So in the plane of the sloping banks three forces are acting upon the particle, namely W sin α, G and F. Static equilibrium of the sand particle is established when

$$\sqrt{(Aai)^2 + (W \sin \alpha)^2} = W \cos \alpha \tan \beta$$

from which it can be concluded that when the channel is stable the angle α will decrease with increasing depth. Towards the middle of the river, where the depth increases, the transversal bottom slope is directed more horizontally, and the shape of the cross-section is concave.

When the angle of repose of the material β increases, the angle α may increase as well. This explains why banks with a great silt content (β is great) are steeper than banks consisting of sand only (β is small).

In the above circumstances there is no sand-transport in the river. But even if there is such transport, the bank is not necessarily subject to erosion. Let it be supposed that the direction of the stream is parallel to the bank (see Diagram 6.1.5-2). As the depth in vertical 2 exceeds the depth in vertical 1, the velocity of the stream and the sand-transport in this vertical 2 will be greater than in vertical 1. As a result of turbulence there is an exchange of water between

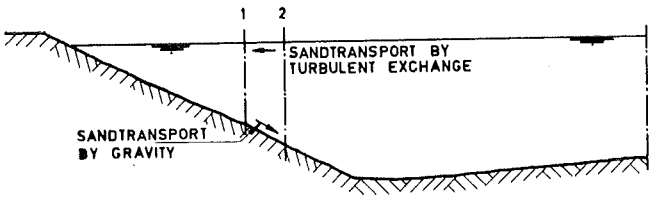


DIAGRAM 6.1.5-2

Dynamic equilibrium of a sloping bank

vertical 1 and vertical 2. As a certain volume of water in vertical 2 contains more sand than an equal volume in vertical 1, the result of the exchange of water will be a certain sand-transport from vertical 2 to vertical 1. On the other hand, although the direction of the stream is parallel

to the bank, the sand-transport will have a component towards the river-bottom, because of the sloping bank.

The ultimate slope of the bank will be such that the component of the sand-transport towards the river-bottom, owing to the gravity force, equals the one resulting from the exchange by turbulence. A quantitative analysis, however, is here not possible, as the exact mechanism of turbulent exchange is not yet fully understood.

Diagram 6.1.5-3 shows a cross-section of a river where one of the banks consists of rock. Because of the long and close contact with the flowing water, some parts of the rock have disappeared by chemical process (chemical erosion). As the flowing water contains hard sand particles, soft parts of the rock have undergone mechanical wearing (mechanical erosion). As a result the rock surface may not be smooth but full of irregularities, which will cause the flow near the bank to be more turbulent than towards the centre of the river. The greater turbulence in

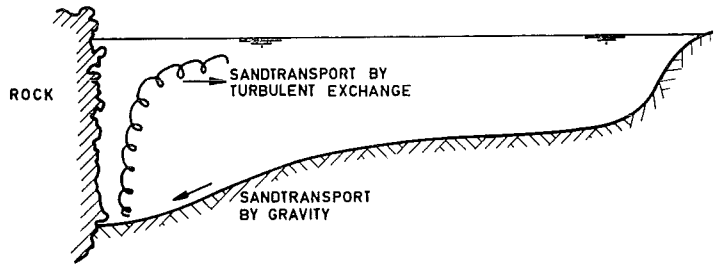


DIAGRAM 6.1.5-3

Effect of rock on dynamic equilibrium

its turn will increase the sand-transporting capacity, and the sand-transport near the bank will exceed the sand-transport more to the right. Consequently there will be sand-transport towards the right by turbulent exchange. But as the sand-transport cannot become less than the sand-transporting capacity, sand particles will be picked up again and the depth near the bank will increase. In this way the river-bed will slope towards the rocky bank, and when the slope exceeds a certain magnitude, particles on the bottom will start to move towards the bank. An equilibrium will be established when the sand-transport by turbulent exchange to the right will equal the amount of sand moving along the bottom to the left.

So along a bank consisting of rock, a deep river-channel will result. As the sand-transporting capacity along such a bank is relatively great, no shoaling will occur and the form of the river-bed along that bank will be rather stable.

The phenomenon described here occurs rather frequently along the Niger and the Benue, not only when the bank consists of rock, but also when the bank is formed of cohesive clay.

Diagram 6.1.5-4 shows the places where rock occurs along the banks of the Niger and the Benue within Nigeria.

6.1.6. Cross-sections of Niger and Benue

Some theories have been discussed in the foregoing paragraphs concerning the shape and size of the cross-section of an alluvial river. In the present paragraph, the last of this Section, some characteristics of the cross-section of the Niger and Benue will be given, such as:

(i) the width of the cross-sections;
(ii) the value for $a^{\frac{2}{3}}b$ of the cross-sections; and
(iii) the frequency of depths of the cross-sections.

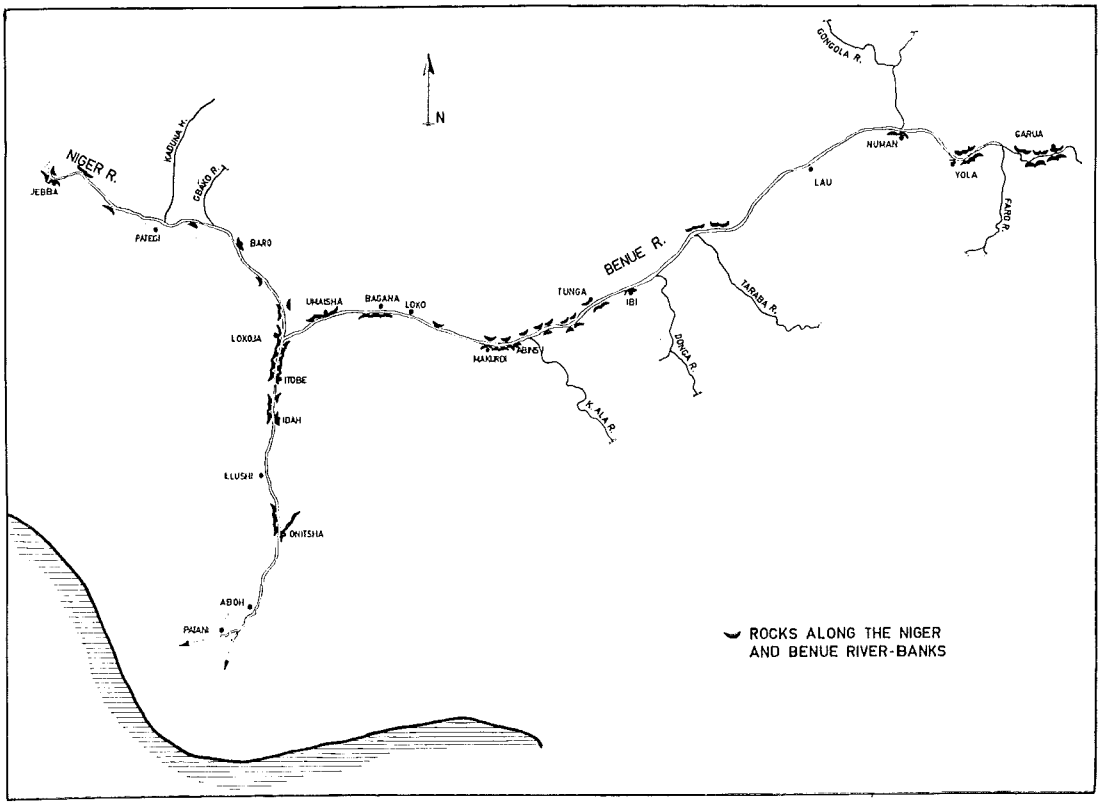


DIAGRAM 6.1.5-4

Rocks along the Niger and Benue

Ref. (i). The widths of a series of cross-sections on the Niger as sounded during the H.W.-period of 1956 have been plotted in Diagram 6.1.6-1. These widths, which can be considered to be those of the cross-sections at bankfull stage, vary considerably, but the general trend is a width of 1,700 to 1,800 m (5,600—5,900 feet) except in the Rocky Section between Lokoja and Itobe where the widths are restricted by the presence of rocks. The marked decrease in width of the river downstream from Aboh finds its origin in the meandering character of this river-stretch between clayish banks. In the same diagram the widths of the river at L.R.L.-stage are also given, as this period is rather important for the navigation on the Niger. It is observed here that when the Niger has a width of between 700 and 1,000 m at L.R.L., the navigability of the river is rather good, but as soon as this width exceeds 1,100 m, a shallow crossing occurs. In Diagram 6.1.6-1 these parts of the river with a width greater than 1,100 m have been shaded, and from this it can be clearly seen that the stretch between Itobe and Idah is unfavourable for shipping purposes. Between Idah and Aboh the river is rather uniform in this respect, but downstream from Aboh, where the river meanders, no bad crossings occur; the L.R.L.-channel here is less than 1,100 m wide.

On the Benue, the width of the river at bankfull stage has been systematically measured from the river-maps and the results put together in Diagram 6.1.6-2. Here a marked increase of the width of the river can be seen every time a tributary has joined the Benue.

In Table 6.1.6-3 a comparison has been made between the actual widths and the width ensuing

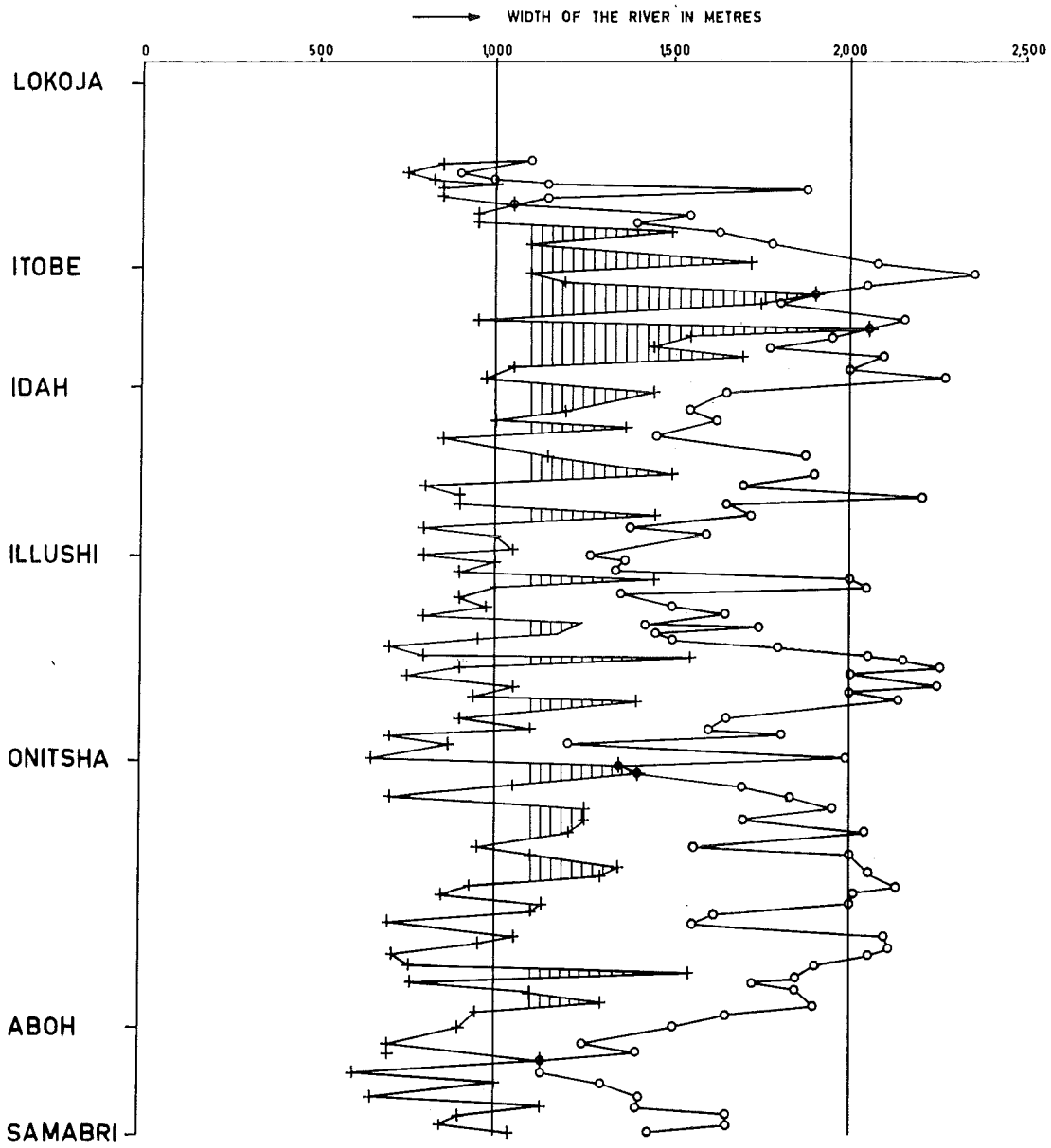


DIAGRAM 6.1.6-1

Widths along the Niger

from the theory as developed in 6.1.1. According to this theory, the width of a straight alluvial river in equilibrium should be

$$b = \frac{1}{C}\left[\frac{\alpha}{\Delta}\right]^{\frac{3}{2}} \frac{1}{d^{\frac{8}{2}}} Qi$$

where α is a coefficient having a constant value. The sequence of the discharges is such that, especially on the Benue, the low flow cannot develop its equilibrium profile because the high floods, which are responsible for large movements of sand, fully destroy the low-water bed. A constant discharge equal to the actual one at bankfull stage has been assumed to mould a

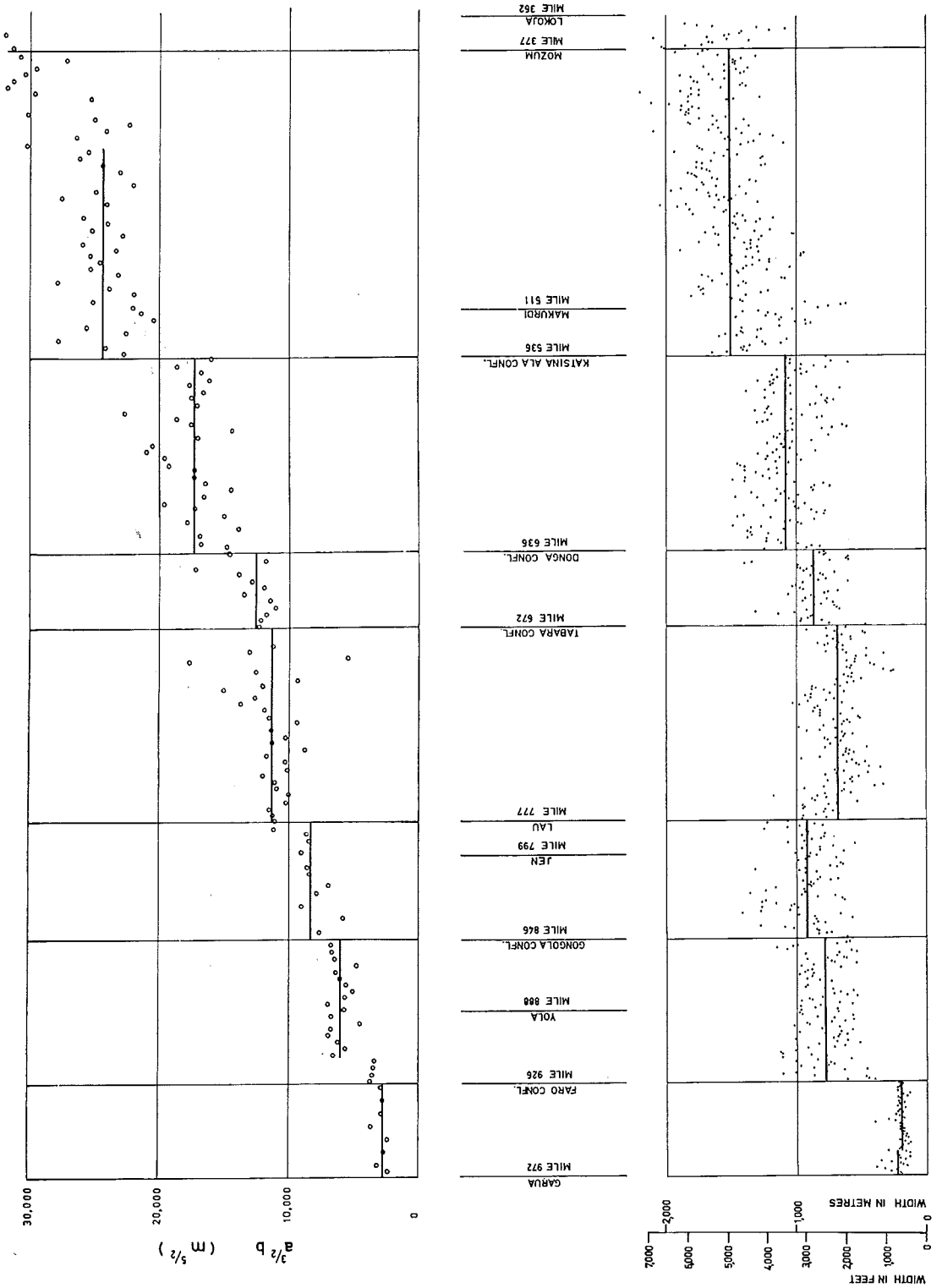


DIAGRAM 6.1.6-2

Widths and values for $a^{\frac{3}{2}}b$ *along the Benue for bankfull stages*

TABLE 6.1.6-3

COMPARISON OF COMPUTED AND MEASURED WIDTHS OF NIGER AND BENUE

River-stretch		Q	i	d_{50}	$a^{3/2} b$	C	Q.i	b calculated			b average measured
								$\alpha = 2$	average $\alpha = 2$	average $\alpha = 1.4$	
		m^3/sec	$\times 10^{-5}$	$\times 10^{-3}$ m	$m^{5/2}$	$m^{1/2}/sec$	$\times 10^{-3} m^3/sec$	m	m	m	m
Baro	— Lokoja	about 6,000	11.0	about 0.5	12,000	48	660	1,560	1,560	900	900— 1,000
Idah	— Onitsha	about 17,000	9.5— 10.0	0.6	37,000	48	1,620— 1,700	2,800— 3,000	2,900	1,690	1,750
Onitsha	— Aboh	18,000— 16,000	9.5— 8.5	0.5	38,500— 36,000	48	1,700— 1,350	3,900— 3,000	3,450	2,000	1,850
Garua	— Faro Confl.	1,500	13— 14	about 0.6	2,850	46— 44	195 210	370— 420	395	230	200
Faro Confl.	— Yola	3,500	25— 22	0.7— 0.9	4,000— 6,000	39	875 770	1,580— 950	1,265	735	780
Yola	— Gongola Confl.	3,500	22		6,100	39	770				
Gongola Confl.	— Lau	4,500	19.5— 18.5	0.6— 0.8	8,300	39— 40	880 830	2,000— 1,190	1,595	930	920
Lau	— Taraba Confl.	5,000— 5,500	15.5— 15.0		11,300	36— 40	750 850	2,090— 1,070	1,580	920	680
Taraba Confl.	— Donga Confl.	6,000— 7,000	about 15.0	0.6— 0.7	12,600	39— 45	900— 1,050	2,380— 1,400	1,890	1,100	865
Donga Confl.	— K'Ala Confl.	about 9,000	13.5— 13.0	0.7	17,400	about 45	1,220— 1,170	1,940— 1,860	1,900	1,105	1,075
K'Ala Confl.	— Mozum	about 11,500	13.0	0.75	24,500	about 41	about 1,500	2,380	2,380	1,385	1,500

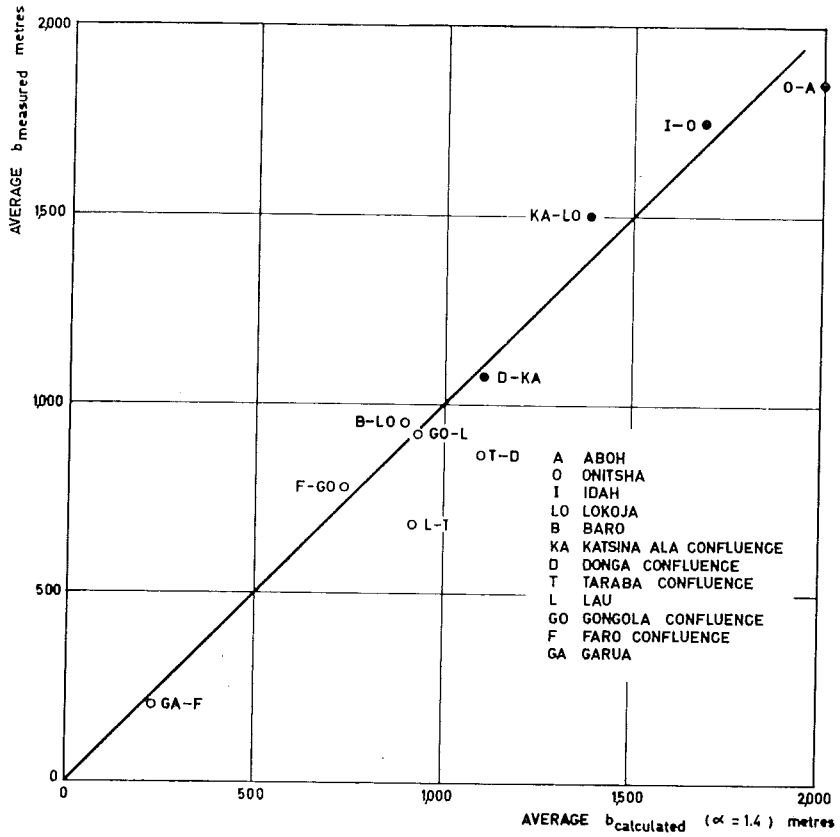


DIAGRAM 6.1.6-4

Comparison of measured and computed widths of Niger and Benue

bed with about the same average width as the present bed. As this present width is easily recognisable and follows directly from the river maps, it can be compared with the width as calculated for a discharge at bankfull stage. Diagram 6.1.6-4 shows that in general a fair concordance between theory and observation exists for $\alpha = 1.4$.

When applied on other rivers, the formula should be used with caution. Nothing is known yet of the influence of the distribution of the grain-sizes and the determination of the correct value for the bankfull discharge is still rather vague.

Ref. (ii). In the discharge formula of DE CHEZY

$$Q = C\sqrt{i}\, a^{\frac{3}{2}}b$$

the factor $a^{\frac{3}{2}}b$ plays a very important rôle, and therefore this factor has been determined for many cross-sections of the Niger and the Benue.

As a function of the distance along the river axis, the dispersion in the values of $a^{\frac{3}{2}}b$, which is also the dispersion in $C\sqrt{i}$ in a river-stretch between two tributaries (Q is constant), gives an idea of the irregularity of the river profile. When the values of $a^{\frac{3}{2}}b$ vary considerably on a short stretch of river, the deceleration losses form a substantial part of the energy losses, and when $a^{\frac{3}{2}}b$ is constant mainly friction losses contribute to the loss of head.

On the Niger the values of $a^{\frac{3}{2}}b$ for various cross-sections of the river were computed for three significant water-stages, i.e., L.R.L., a mean water-level, and the bankfull stage. The

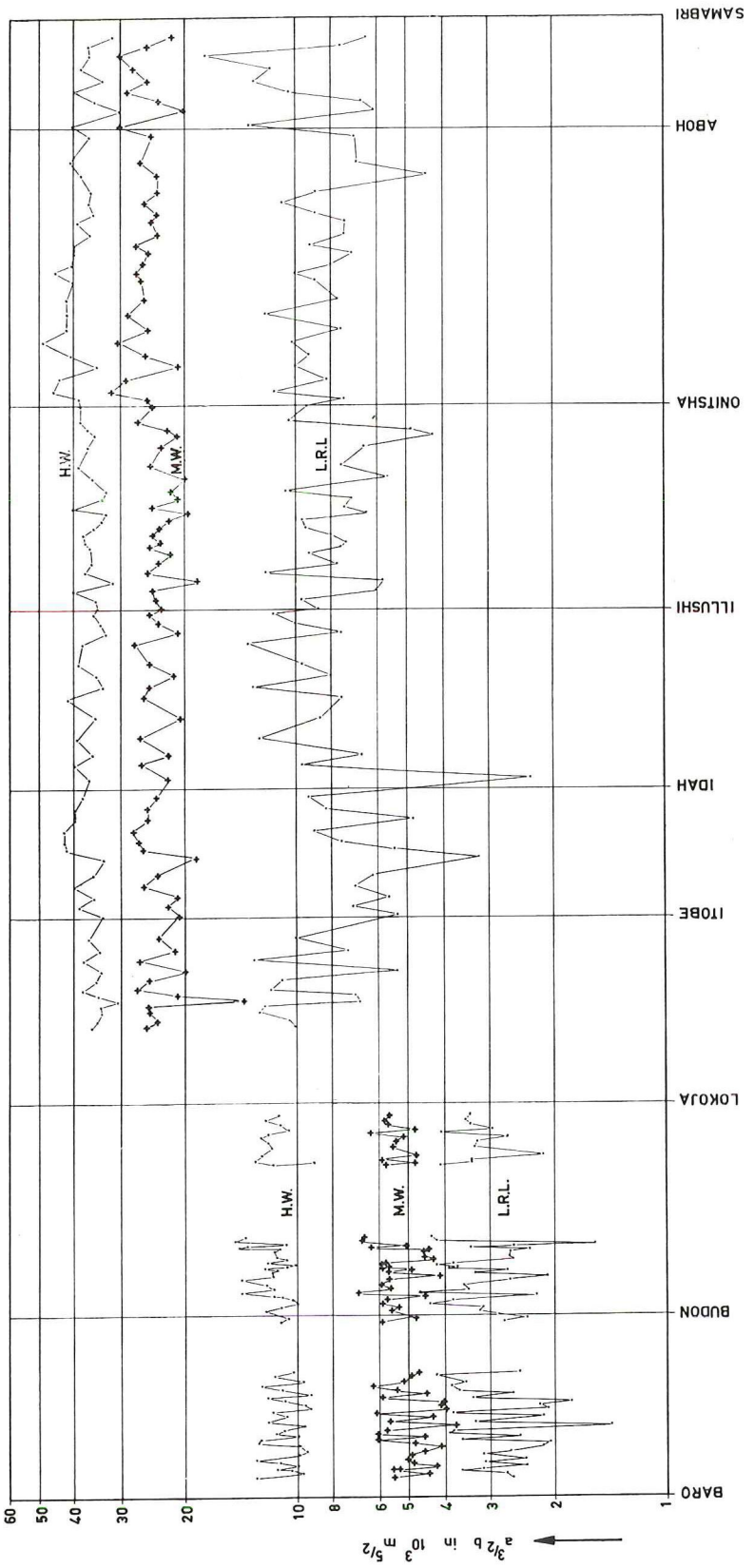


DIAGRAM 6.1.6-5

Values for $a^{\frac{3}{2}}b$ *along the Niger*

results of these calculations are plotted on a logarithmic scale in Diagram 6.1.6-5 to show the relative divergence of $a^{\frac{3}{2}}b$ for these three water-stages, which is found to be the smallest for the H.W.-stage. This seems to be in accordance with the theories set out in the preceding paragraphs, namely, that the High Dominant Discharge, which is about the bankfull discharge of the river, plays a dominant rôle in moulding the shape of the river (see 5.2.4).

The bed of the Benue, because of the very pronounced high waters (absence of the Black Flood), is largely shaped according to the characteristics of the high waters. Here the values of $a^{\frac{3}{2}}b$ have been computed for the bankfull stage, which are plotted on linear division (Diagram

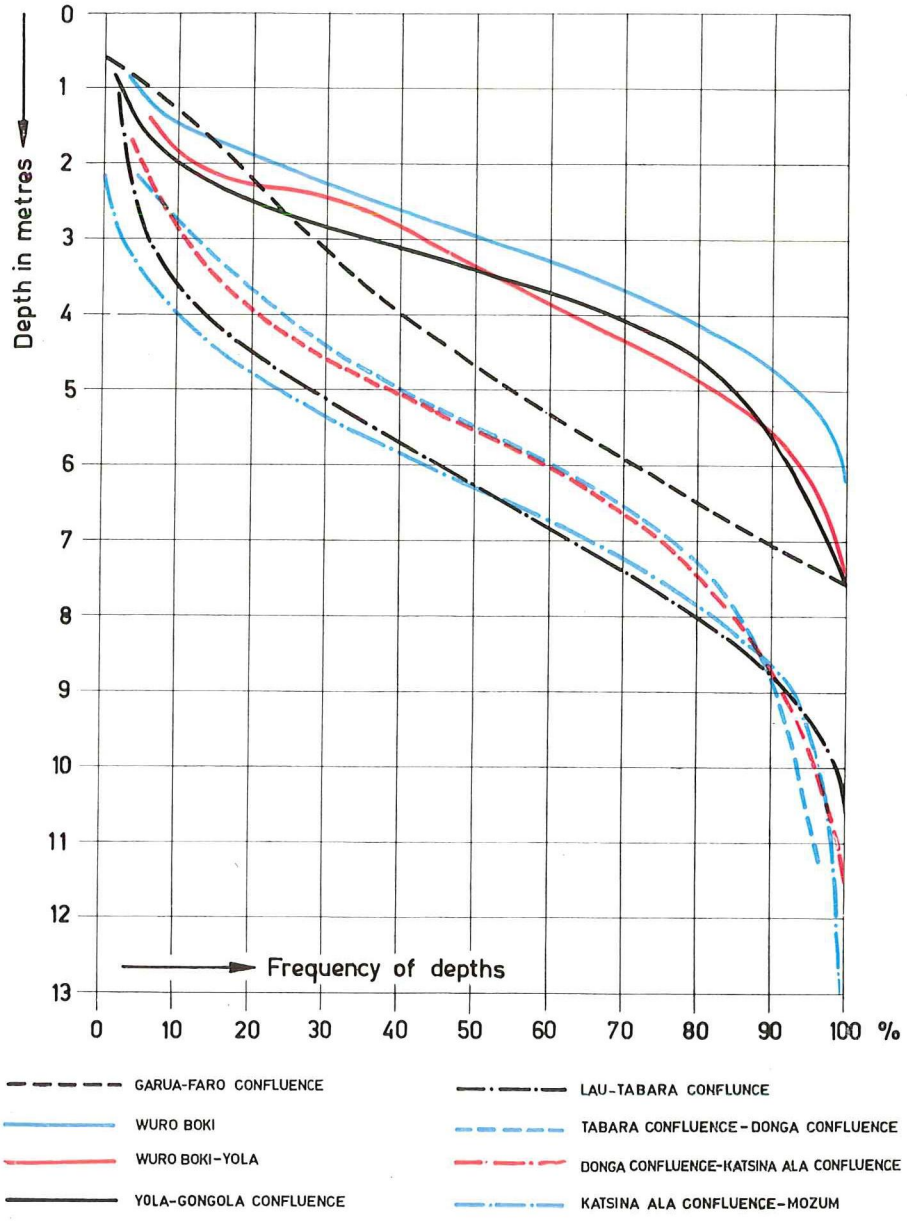
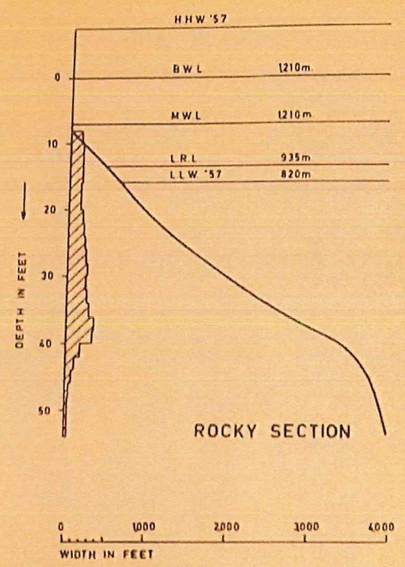
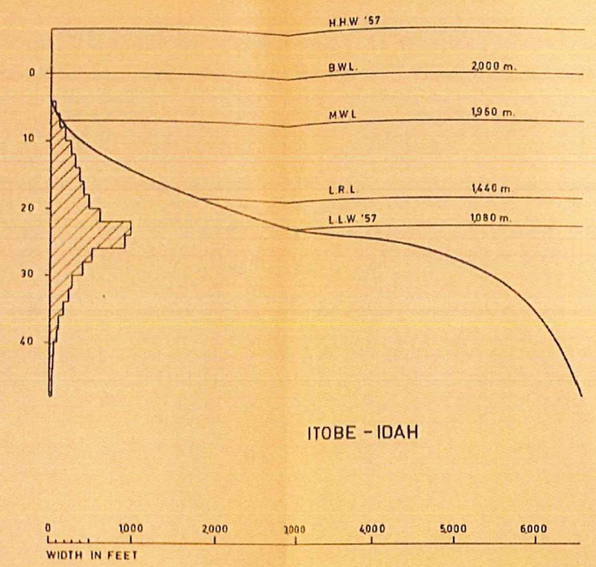


DIAGRAM 6.1.6-7

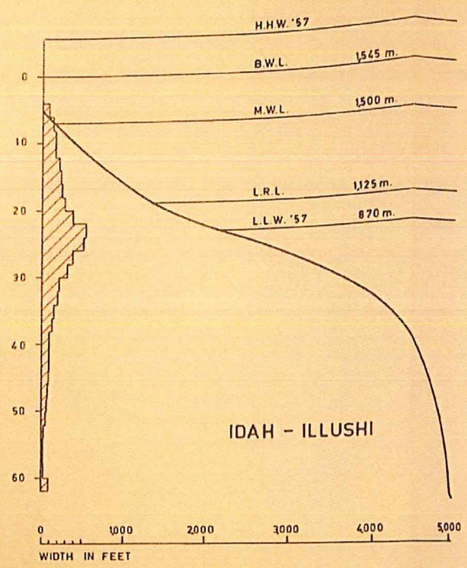
Frequency of depths as a function of the width, Benue



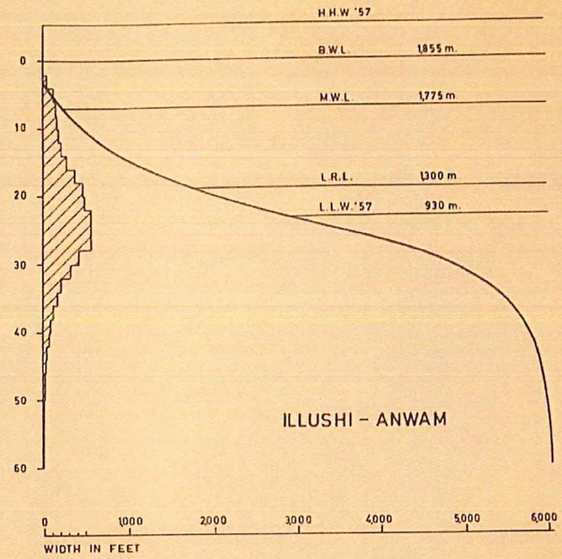
ROCKY SECTION



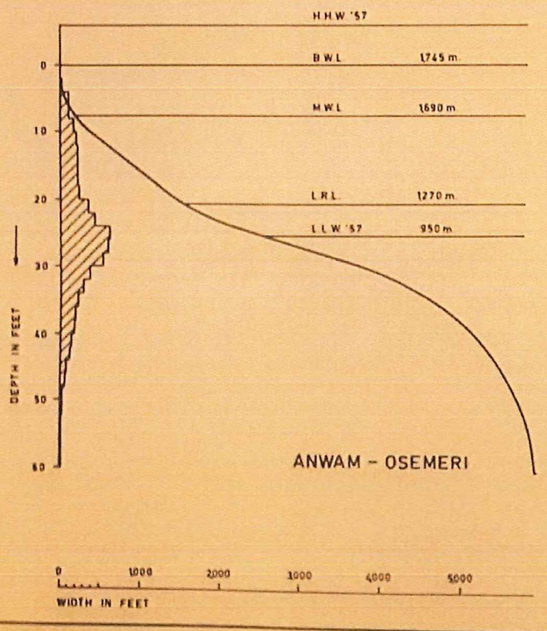
ITOBE - IDAH



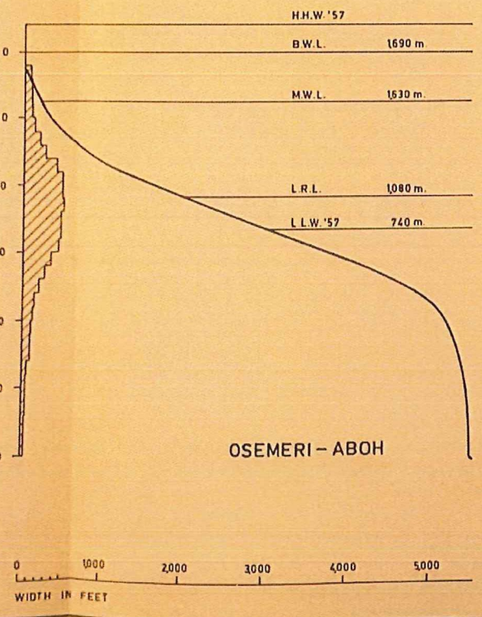
IDAH - ILLUSHI



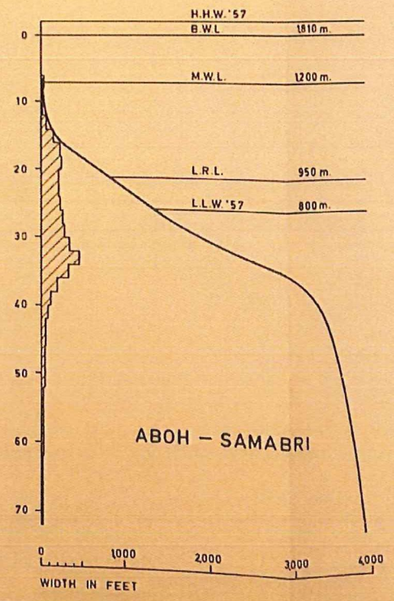
ILLUSHI - ANWAM



ANWAM - OSEMERI



OSEMERI - ABOH



ABOH - SAMABRI

H.H.W. '57 = HIGHEST WATER-LEVEL 1957
B.W.L. = BANK-FULL STAGE
M.W.L. = MEAN WATER-LEVEL
L.R.L. = LOW RIVER LEVEL
L.L.W. = LOWEST WATER-LEVEL 1957

$= \frac{\Delta b}{\Delta a}$

NEDECO NIGER / BENUE	DIAGRAM: III, 6.1.6-6
FREQUENCY OF DEPTHS AS A FUNCTION OF THE WIDTH	

6.1.6-2) and show the same marked increase as was seen at the width. The average of $a^{\frac{3}{2}}b$ over a certain river-stretch was used in conjunction with the corresponding discharge to evaluate the constant C of de Chezy for the computations in Table 6.1.6-3.

Ref. (iii). The distribution of the depths of the river-bed have been computed from the series of cross-sections on various river-stretches. The percentages of the area of the river-bed over a certain depth have been computed and plotted in Diagrams 6.1.6-6 and -7. For a constant length of river-stretch (slightly meandering at L.W. whilst straight at H.W.) the area is proportional to the average width of the channel. Although the channel does meander at lower stages, the average width has been introduced in the diagram of the Niger. This diagram shows the true distribution of the depths, but for the lower stages the average width of the channel should be divided by the meander coefficient. The diagram for the Benue shows the percentages. The average width at bankfull stage (proportional to 100% in Diagram 6.1.6-7) can be read from Diagram 6.1.6-2.

The depths, which are plotted for banfkull stages, show marked differences between the various river-stretches. In the Rocky Section of the Niger (where the width of the river is restricted by rocks on both banks) and in the gentle-sloped meandering river-stretch below Aboh, the 50% depth is about 30 feet. But on the Wuro Boki Flats, where the slope is steep and the sandy banks are easily erodible, it amounts to only 10 feet.

6.2. ALIGNMENT OF THE CHANNELS

6.2.1. Meanders

In the Oxford Dictionary "to meander" is described as: "wander at random, (of stream), wind about; appellative use of the name of a river in Phrygia noted for its windings".

A meander pattern consists of a succession of clockwise and anti-clockwise bends. This winding course of the river is often simplified as a sinusoidal or circular curve, but the appearance in Nature is generally more complex (Diagram 6.2.1-1).

Meandering is an essential part of alluvial river behaviour. At first sight, there are rivers that do not appear to meander, although a closer investigation always reveals the oscillating nature. GRANT ([1] gives a clear definition of a seemingly non-meandering type: "By a braided river is meant the typically wide, steep and shallow course of an alluvial river consisting of a number of stream channels, with islands in between, meeting and dividing again, and presenting from the air the intertwining effect of braid" (Photograph 6.2.1-2). This description itself is an acknowledgement of the non-linear, non-parallel way in which the water flows down the valley. At high water these rivers seem to have a fairly straight bed, but in the tortuous channels the oscillating effect is still present.

Not only is it the typical braided type of river that has oscillating channels, but also the channel in a quiet, straightened river sometimes oscillates. For example, the River Rhine between Strasbourg and Mannheim originally was of a meandering type. Cut-offs straightened the high-water channel and protective works prevented erosion of the banks. But instead of having a troughlike, U-shaped cross-section, shoals of gravel form an oscillating channel in the straightened bed. In the middle course of the Niger and Benue the channel also winds between fairly straight banks (Photograph 6.2.1-3).

It will be clear that meandering is a facet of the more general oscillating nature of stream channels.

([1] GRANT, 1948. MOR. 11

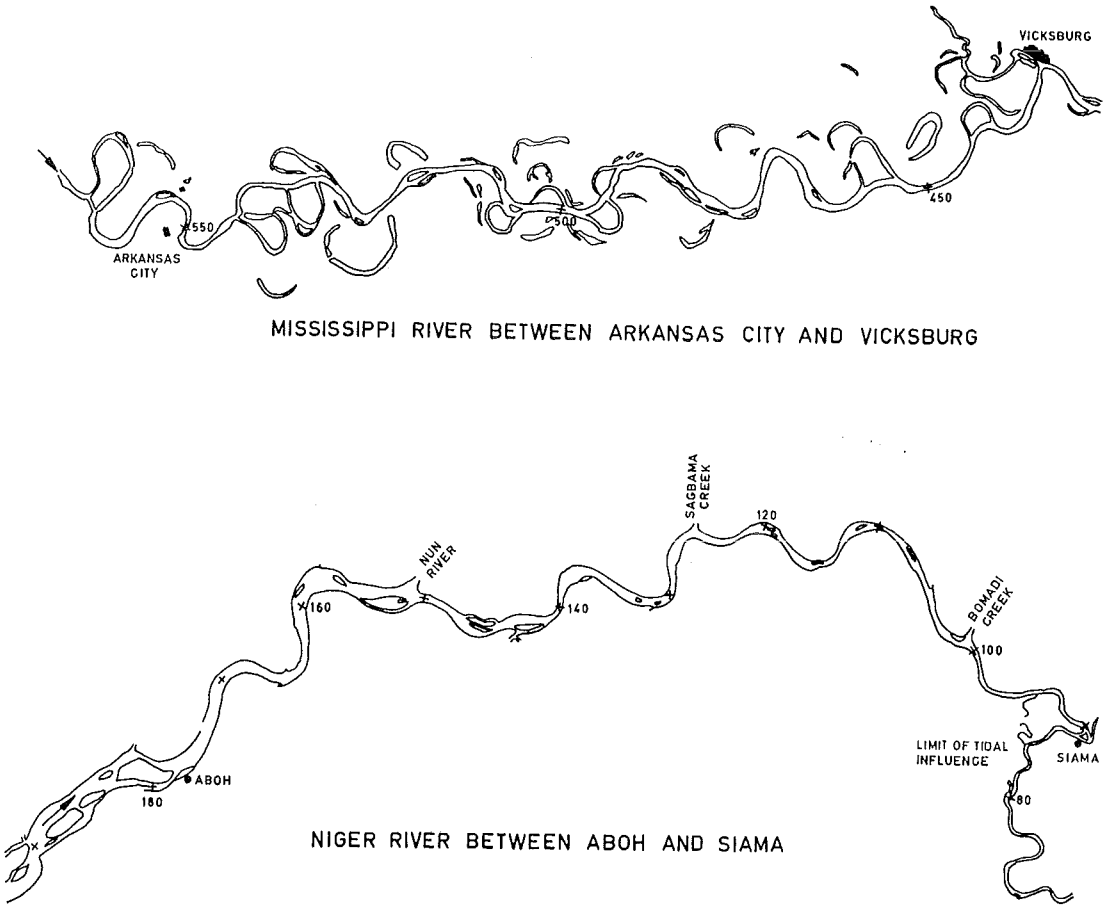


DIAGRAM 6.2.1-1

Meandering rivers

To avoid confusion, the word "meander" will be used in cases of rivers as in Diagram 6.2.1-1. In describing the tortuous channels of "braided" rivers (Photograph 6.2.1-2) or in dealing with winding, sinuous channels in a straight high-water bed, often called a "reach" (Photograph 6.2.1-3), the more general expression "oscillation" will be used.

"The *cause of meandering* springs from the natural oscillation of particles moving downstream under the action of gravity. Under perfect conditions, with a perfectly symmetrical channel, uniform in material and with the flow into the channel perfectly in line and with symmetrical flow pattern, the discharge would be expected to flow in a straight course down the line of the steepest slope and to continue to do so no matter how the discharge or bed-load varied. However, the slightest departure from symmetry or variation in erodibility of the banks will cause an increased flow on one side of the channel and a departure from straight flow". (1

FRIEDKIN (2 found that meandering results primarily from local bank erosion and consequent local overloading and deposition by the river of the heavier sediments which move along the

(1 GRANT, 1948. MOR. 11
(2 FRIEDKIN, 1945. MOR. 9

PHOTOGRAPH 6.2.1-2

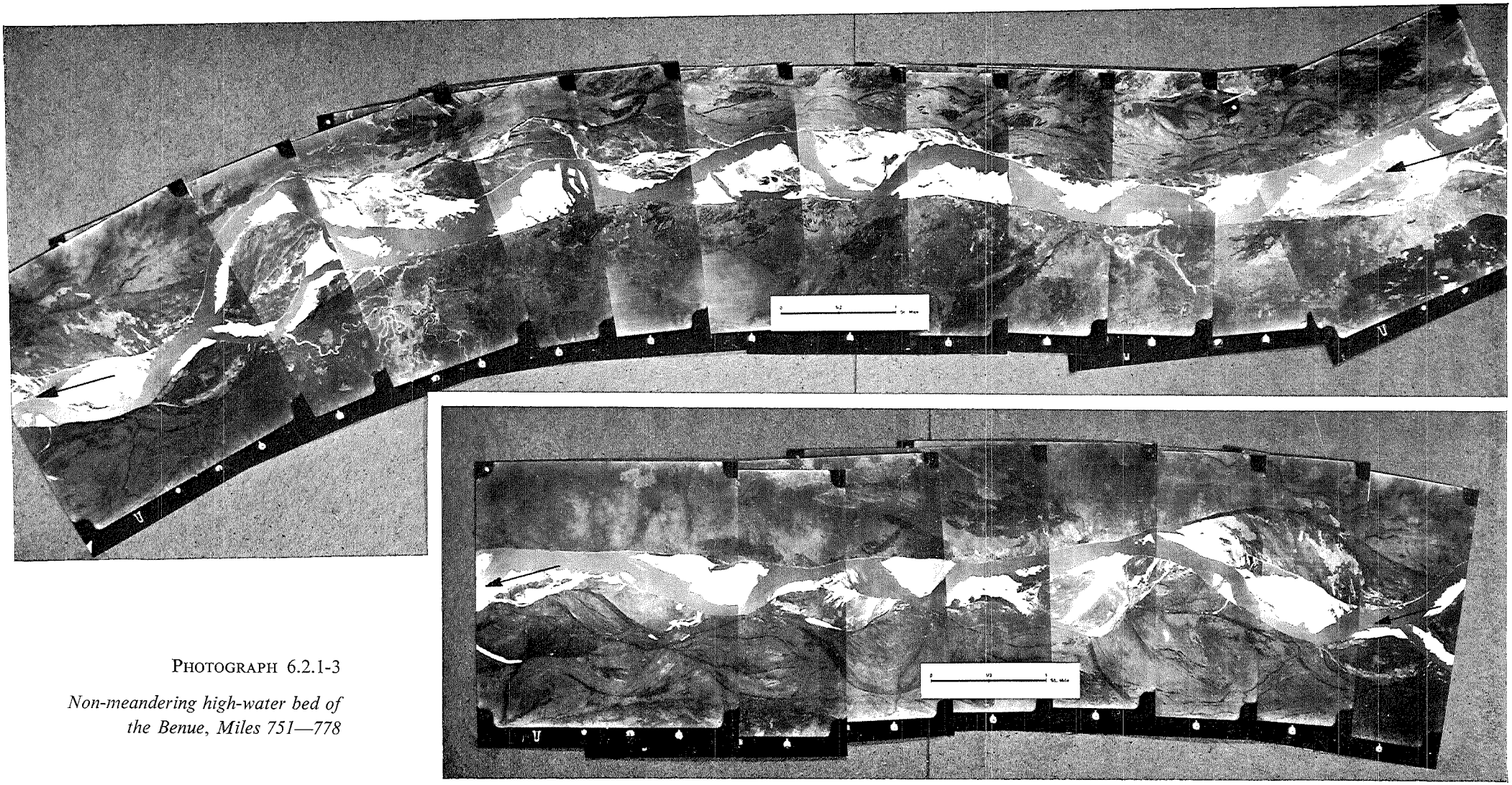
A braided river

Faro, Mile 930

bed. Friedkin arrived at this conclusion after a series of valuable systematic tests on river behaviour in general, and with special application to the Mississippi River in particular.

It has not yet been explained why one river meanders and another does not. Friedkin stated that the only requirement for meandering is bank-erosion. This, however, does not seem to conform with the reaches in the middle courses of the Niger and the Benue Rivers. These rivers are certainly of a non-meandering type at bankfull stages (Photograph 6.2.1-3), but the banks are definitely eroded. The reason for this behaviour may be the very rapid downward propagation of sand-banks and shoals (up to a thousand feet per year), so that the shore-line, the banks which are made up of clayey material, has hardly started eroding when the next oncoming sand-bank deviates the current again. Although this is an explanation of this type of oscillation between fairly straight banks, a further analysis of the various factors affecting the choice between meandering and oscillating between straight banks is likely to increase insight in river behaviour.

Amongst the factors determining the *choice between meandering and merely oscillating between fairly straight banks* are: slope, discharge, bed-load and grain-sizes of bed and bank material. In the following the various factors will be discussed, and although the problem will not be



PHOTOGRAPH 6.2.1-3

Non-meandering high-water bed of the Benue, Miles 751—778

solved some observations and speculations will be made which might be useful when contemplating the regulation of the river.

(i) *Slope*

It is a well-known fact that rivers with gentle slopes sooner have a well-developed meander pattern than rivers with steeper slopes that are often of a braided type. As in the lower reaches of a river the bottom and the bank material usually becomes finer, it has been thought that fine material could be one of the causes of meandering. Although indeed clay-plugs are one of the causes of horse-shoe bends and although the erodibility of the banks, which has its influence on the development of the meander pattern, is determined to some extent by the grain-size, the effect of the slope is generally dominant. This is not only found in New Zealand ([1 but also in Nigeria. For instance, the Taraba River, more or less braided upto 20 miles of its confluence with the Benue, suddenly develops meanders when it reaches the fluviatile delta where the slopes are smaller. Here the cause can only be the decreasing slope, possibly in combination with more erosion-resistant banks. Another example is the Garua Creek, which also develops a meander pattern as soon as its slope decreases towards the Faro Confluence.

It should also be understood that a river which was originally braided, and which by some outside reason starts meandering, decreases its slope because of its increasing length, with the result that the meanders become even more pronounced.

In general, the meandering types of rivers offer better navigable channels than the braided river. The reach-type of river in Photograph 6.2.1-3 is about in between the pure braided and the meandering forms. A very sudden decrease of slope, and consequently of sand-transporting capacity, however, may result in a deterioration instead of an improvement of the channel. Two examples will be given to illustrate this.

First, the Logone, flowing north-east close along the headwaters of the Mayo Kebbi towards Lake Chad, enters in its lower reaches a very flat region, and instead of becoming a neatly meandering single river, the channel divides into many branches and loses itself in a vast plain with swamps and creeks ([2.

Secondly, a similar phenomenon occurred below the Hoover Dam, at the upper limit of the backstage of Parker Dam (U.S.A.). The great quantities of sand eroded below the Hoover Dam and transported downstream were deposited in the upper end of the next reservoir. Although at first a delta developed, soon the channels deteriorated and deposition took place in a random way, with the result that the water flowed through swamps, the channels having vanished ([3.

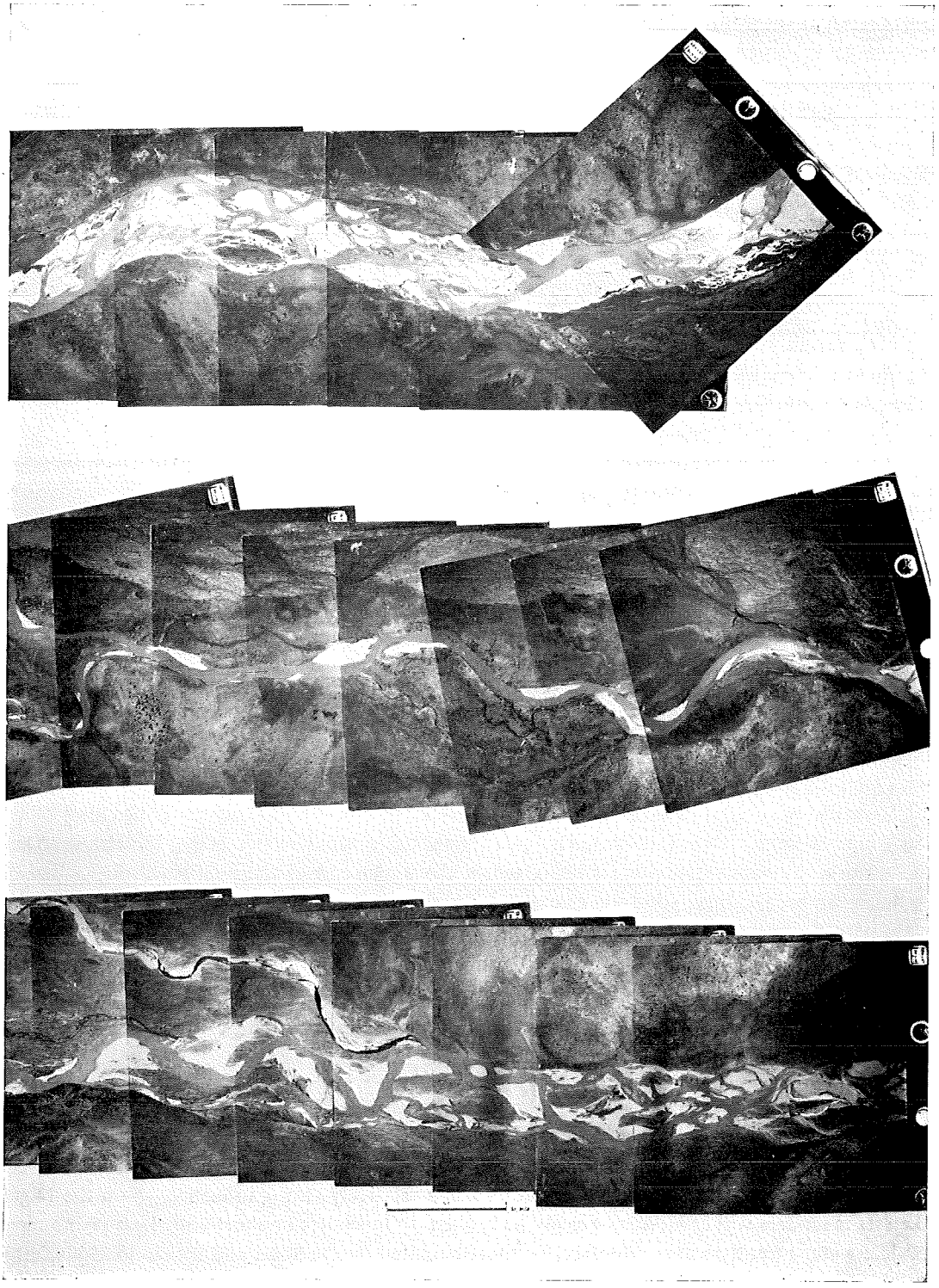
These two examples may prove that a sudden decrease in transporting capacity along the flow axis, and consequently sudden excessive depositions, may deteriorate the channel by changing a meandering river into a braided, even when the discharges and the slopes would not suggest a braided pattern (see alse V, 2.4).

(ii) *Discharge*

With seasonally varying discharges the meander problem becomes even more complicated. Each significant group of stages, or each dominant water-level (if there is more than one), may provoke its own meander pattern, but in reality there is of course a mutual influence between these patterns. When the middle-water group has a relatively strong influence, as on the Niger, then its meanders will at H.W. not easily be broken up by chutes or short-cuts. Less pronounced middle-water meanders may, however, be short-circuited by the flood and if this flood-discharge is large enough and if the slope is not too gentle, a braided channel may result.

In the upper reaches where the discharges are relatively small, a river often is braided, whilst

([1 GRANT, 1948. MOR. 11
([2 ORSTOM, 1954. HYD. 8
([3 VETTER, 1952. MOR. 32



PHOTOGRAPH 6.2.1-4

Effect of change in discharge

From above downwards: braided Faro above Mile 956; one of the meandering channels between Miles 956 and 932; braided Faro below Mile 932

in the lower reaches, when the river has grown to its fullest size, if often meanders. However, whether or not this change from braided to meandering is caused by the increase of discharge cannot be judged, because also the shape of the hydrograph, the slope and the bed and bank material have changed.

Now small tributaries and branches of a braided river sometimes meander, notwithstanding their steeper slope. The conclusion would be that a smaller discharge more quickly develops a meander pattern. A proof of this hypothesis might be found with model experiments, but already some phenomena in Nature indicate this influence of the discharge.

The Faro between Miles 956 and 932 changes from braided to meandering and then again to braided. Above Mile 956 it is a braided river, as can be seen in the upper part of Photograph 6.2.1-4. Between Miles 956 and 954 the river splits up into three meandering channels, of which each channel naturally has a smaller discharge than the Faro above Mile 956. When the three channels are united again below Mile 932, the Faro becomes braided again. Why the river divides at Mile 956 and unites again at Mile 932 is not clear, but Photograph 6.2.1-4 shows indeed that a meander pattern develops with the smaller discharges.

But perhaps the best illustration of the influence of the discharges is to be found in the various parallel rivers of the Parana River Valley between Santa Fé and Corrientes in Argentine (Diagram 6.2.1-5). Here the main Parana River does not meander, but flows in a fairly straight course down the alluvial valley in much the same way as the Benue. Parallel rivers such as the Parana Mini, however, develop a meander pattern. In both rivers the valley slope and the grain-sizes of the bed and the bank materials are necessarily similar; the only variable is the difference in discharge.

Hence the larger the discharge, the more tendency towards a braided character. It should be noted that, with all other factors remaining constant, a larger discharge implies a wider but not a deeper bed (6.1.1).

When regulating the discharges of a river, a change in meander pattern can be expected. Regulation will decrease the highest and increase the lower discharges. As a result, the magnitude of Dominant Discharge (see 6.1.1-b) will be affected. Regulation of the discharges has, therefore, an effect on the shape of the river similar to that of decreasing the discharge. The Upper Benue, at present flowing in a fairly straight course almost in a braided way down its valley, may become a meandering river below a Yola Reservoir. The influence of a Jebba Reservoir on the Upper Niger may also result in a meandering river above Lokoja. Downstream of Lokoja the large discharge peaks of the Lower Benue will most probably maintain the Lower Niger as it is.

(iii) *Bed-load*

As the sand-transporting capacity of a river is a function of the slope, discharge and grain-sizes of the material, bed-load does not need to be mentioned as a special factor influencing meandering, as these three variables are already discussed separately; provided, of course, that the bed-load equals the transporting capacity. There remains, however, the circumstance when the quoted variables are such that the transporting capacity is greater or smaller than the incoming load. This has been discussed for the case of a sudden decrease in slope with subsequent depositions and resulting in a degraded river.

Another point is the conclusion of Friedkin that meandering results primarily from local bank erosion and consequent local overloading and deposition by the river of the heavier sediments which move along the bed. In other words, the non-equality of transporting capacity and actual load caused by the erosion of the banks would be an indispensable condition for river meandering. However, as already pointed out, the non-meandering Niger and Benue Rivers do erode their banks and certainly have successive erosion and deposition also along their banks.

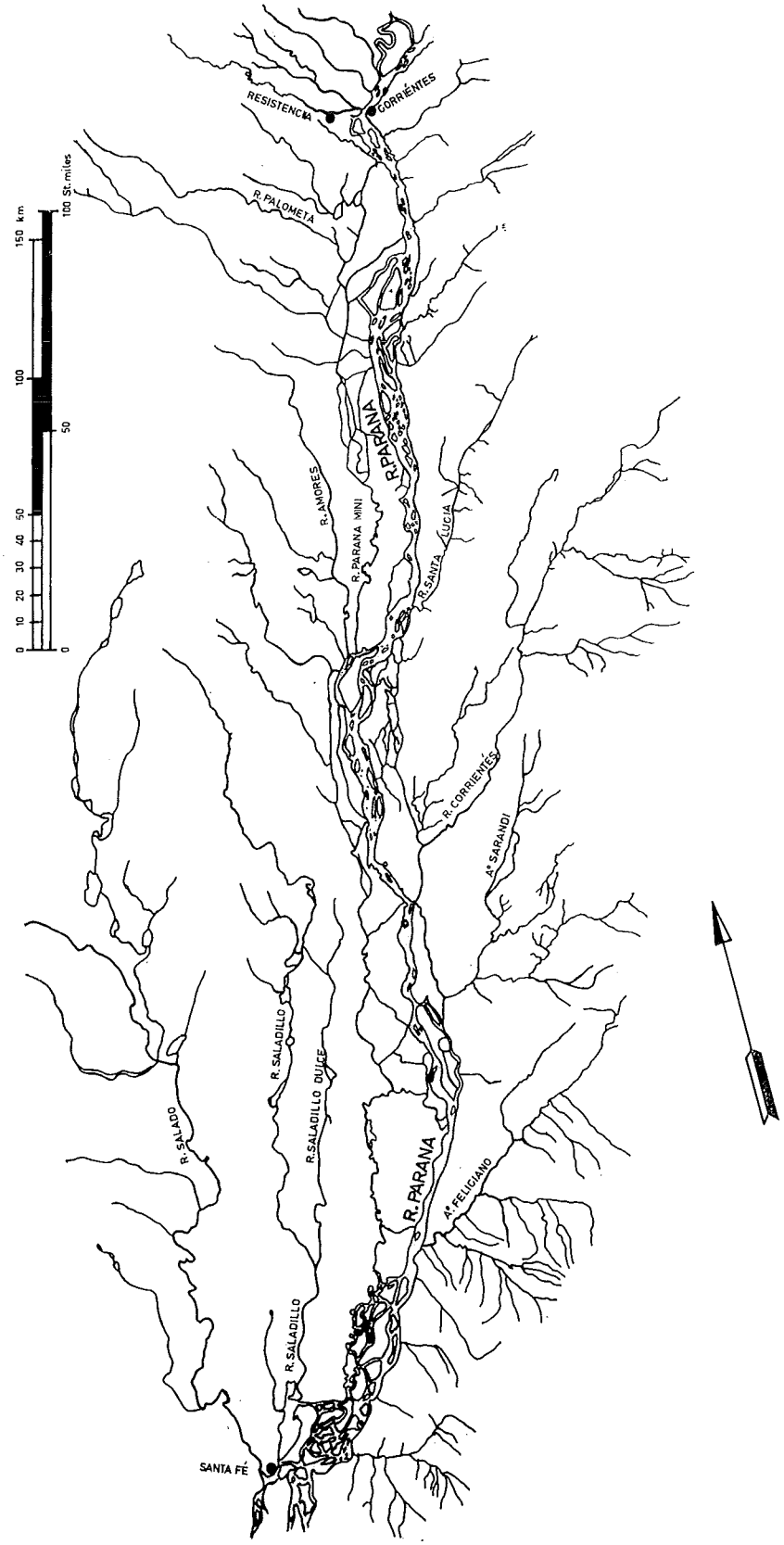


DIAGRAM 6.2.1-5

Parana River valley between Corrientes and Santa Fe (Argentine)

Therefore, although bank erosion together with the transporting capacity is undoubtedly of great importance to the formation of meanders, other factors also influence the choice between braided and meandering.

(iv) *Grain-size*

The grain-size of the bed and bank material will definitely influence the shape of the bed and meanders as well as the choice between braided and meandering. But the absence of sufficient systematically grouped data or of a theoretical basis makes any opinion about this influence too speculative.

In this connection, MATTHES ([1] may be quoted: "Bed-resistance is controlled by the character of the materials composing the alluvium, more particularly by its resistance to erosion. Grain-sizes, specific gravity, cohesion, and the roughness of the channel are important factors. Grain-sizes may range all the way from cobblestones in headwater alluvium to fine sands and silts in the lower reaches of large rivers, but a cobblestone alluvium produces as definite a meander-pattern as does one composed of sand".

Summarising, the following can be stated:

1. A decrease in slope may change a river from braided into meandering.
2. A very sudden decrease in slope and consequently excessive depositions can be the cause of deterioration of the channels and of a degraded river.
3. A decrease in discharge may change a river from braided into meandering. The lowering of the dominant discharges below a reservoir, therefore, may result in a more pronounced meandering and, although it cannot be proved mathematically, the Benue between the Yola Dam and Amar may after a long time well become a meandering river in the sense of Diagram 6.2.1-1, when the Dominant Discharge is lowered because of a Yola Reservoir. Also on the Niger above Lokoja there is a good chance for a more meandering river after a large Jebba Reservoir is put into operation.

Once meanders have been formed, erosion of the banks and in other places accretion of the shores *transform the meander pattern* constantly. If the river should flow without a valley slope, as is more or less the case with tidal creeks, and if the erosion and accretion should be distributed symmetrically over the meander pattern whilst the bed and the banks are of homogeneous material, the meanders would only grow sideways and ultimately cut-offs would occur (Diagram 6.2.1-6). It will be clear that the presence of rocks, clay or other erosion-resistant material is then not a necessity to explain cut-offs.

A valley slope may be the cause of the propagation down the valley of the meander pattern. The body of water flowing from bend to bend has to be forced round, because a change in velocity either in size or in direction results in an acceleration force. The bed-resistance, deceleration and inertia of the body of water causes the erosion and accretion to take place some distance downstream from the arrows in Diagram 6.2.1-6. The centre and the sill of the crossing are also situated downstream from the point of inflexion of the two bends (see also 6.1.3).

These tentative ideas could not be put into mathematical formulae, but the following conclusions may be drawn:

(i) When the valley-slope is small, relative to the erodibility of the river banks, natural cut-offs are likely to occur when the inertia, i.e., the discharge, is not too large. The examples of Diagram 6.2.1-1 might suggest a wide interpretation of "discharge not too large". It should be remembered, however, that the slopes of both rivers (under 10×10^{-5}) are very gentle, which apparently outweighs the effect of the discharges.

(ii) A steep valley (steep relative to the erodibility of the river-banks) in conjunction with relatively large discharges is likely to develop a river flowing down the valley between fairly straight banks, either in the way of the Benue (Photograph 6.2.1-3) or in a more braided way (Photograph 6.2.1-2).

(iii) A river with slopes and discharges in between (i) and (ii) may have a meander pattern without cut-offs when the erodibility of the banks is uniform.

([1] MATTHES, 1941. MOR. 22

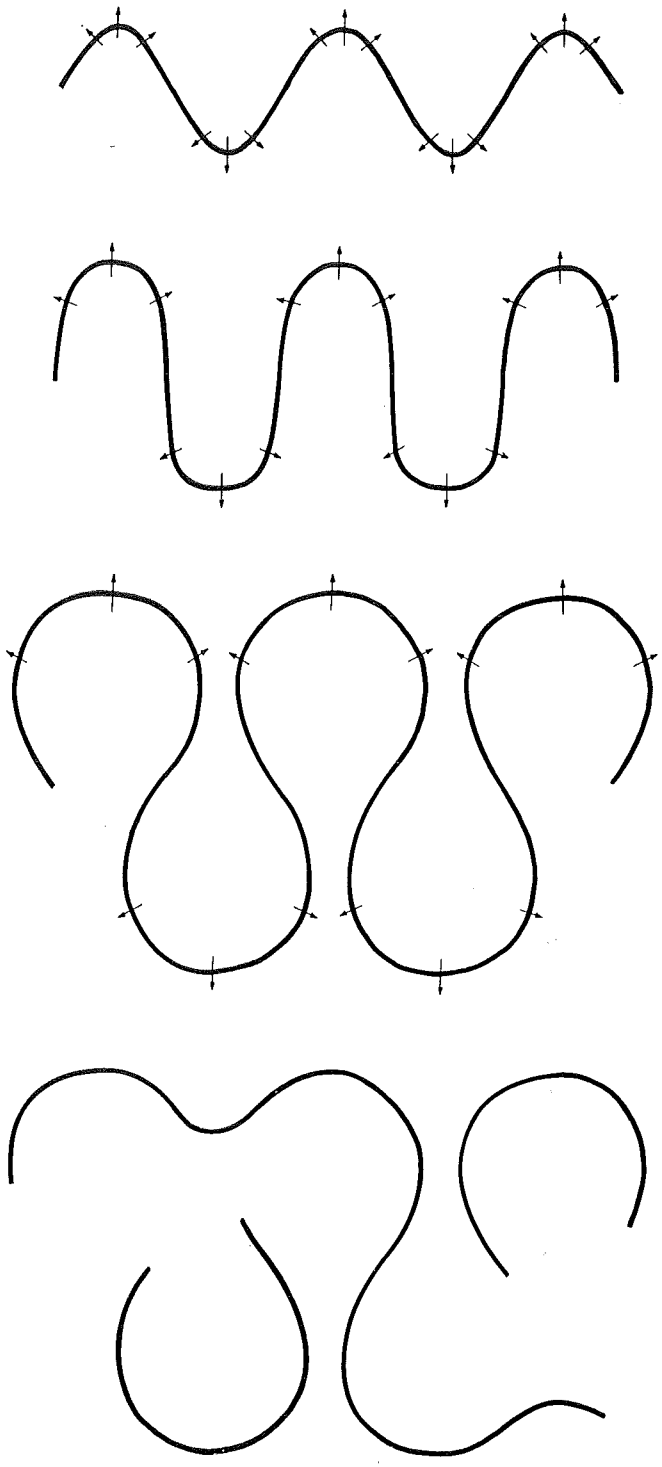


DIAGRAM 6.2.1-6

Development of natural cut-offs

Having regard to the complexity of the phenomenon, it is not surprising that no practicable *theoretical formulae* have as yet been derived that describe the characteristics of a meander pattern.

Empirical relations have been formulated, such as when irrigation and hydraulic engineers investigated rivers in India. In a compilation of data obtained on rivers with moderate to gentle slopes (10×10^{-5} to 20×10^{-5}) INGLIS ([1] relates the meander characteristics to the discharge. These formulae are for rivers in flood-plains

in feet and cusecs

$$M_l = 30\ Q^{\frac{1}{2}}$$
$$M_b = 85\ Q^{\frac{1}{2}}$$

or in metric units

$$M_l = 55\ Q^{\frac{1}{2}}$$
$$M_b = 155\ Q^{\frac{1}{2}}$$

where M_l = the meander length, i.e., twice the distance between two consecutive bends or crossings

M_b = the meander belt, i.e., the width at right angles to the axis of the river between the tangents on either side to the bends and counter-bends

Q = the Dominant Discharge.

In Nature it very seldom happens that a meander can develop without being disturbed by considerable differences in erodibility of the banks. As also the Dominant Discharge is still rather vague, it will be clear that these formulae, or rather any simple formulae, must be used carefully and that in each case the local situation has to be studied.

In comparing these formulae with the characteristics of the Delta Rivers (Diagram 6.2.1-1), it appeared that the constants would have nearly twice the value derived by Inglis.

6.2.2. Bifurcations

Islands may be considered as disturbances in a natural unbraided river. Little has been published about the origin, shape and life of islands in alluvial rivers in their natural state. FRIEDKIN ([2] mentions islands as typical for reaches and although he stopped investigations as soon as islands developed in his test model, his experiments are of use to this subject too. An attempt will be made here to explain the origin and behaviour of islands in rivers like the Niger and Benue.

Several circumstances may stimulate the *formation* of islands. These circumstances, however, may only act as stimulating forces, speeding up and assisting in the eventual realisation of the process caused by the basic sources. Extensive surveys and studies on the Niger and Benue have led to the conclusion that the basic sources, essential to and eventually leading to the formation of islands, may possibly be simplified into the two following conditions:

(i) local variations in bank resistance against erosion; or

(ii) a varying water-level (discharge).

One condition of the two may be sufficient. The presence of both may lead to abundant formation of islands.

These two conditions eventually cause two different types of islands. A varying bank resistance will lead to the stronger erosion of the weaker parts of the river-banks, disturbing the alignment of the banks. In front of the projecting stronger parts the intensified turbulence will scour a

([1] INGLIS, 1947. MOR. 13

([2] FRIEDKIN, 1945. MOR. 9

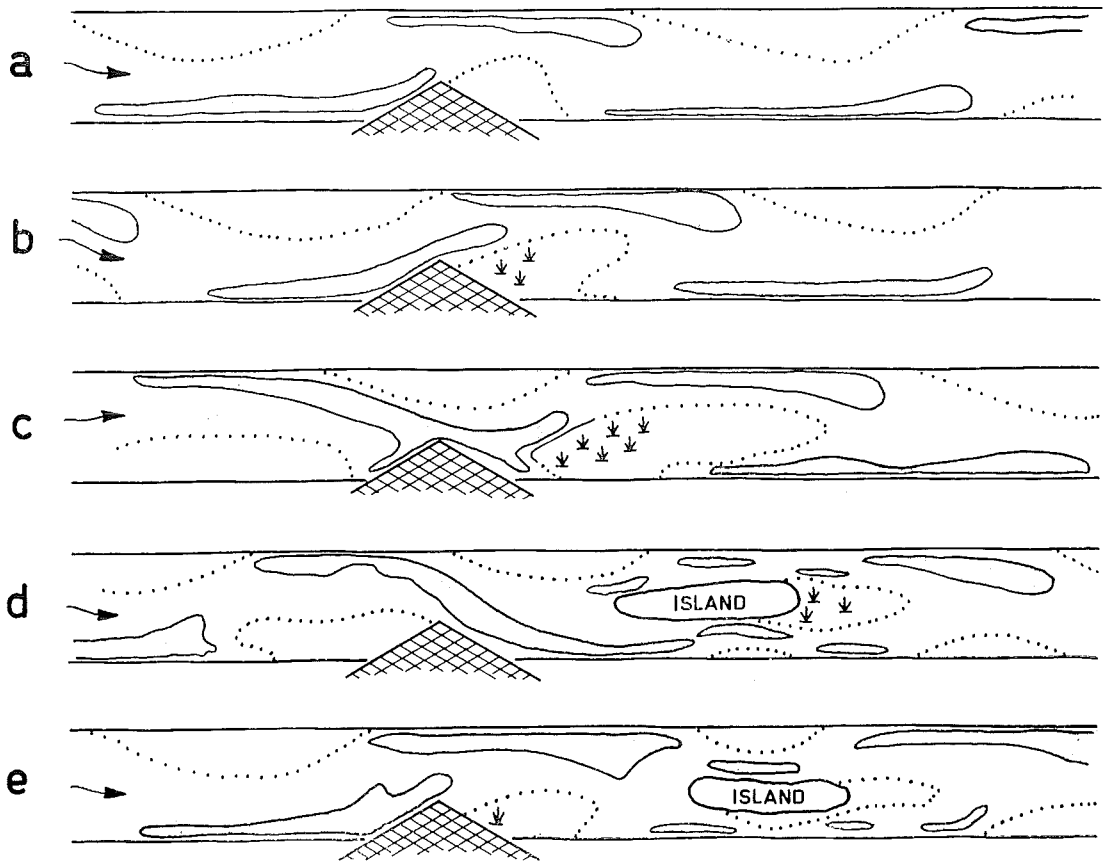


Diagram 6.2.2.-1

Island formation due to differences in erodibility of the river-banks

channel (see 6.1.5). Downstream from the stronghold and protected by it against scour, a high sand-bank will be created (see Diagrams 6.2.2-1a and 1b) which will grow longer and higher. In the course of time the sand-bank may reach a height where vegetation is possible and which will steadily sieve out the sediment, thus increasing the accretion.

While the bottom configuration of the river moves downstream, the channel will remain in the upstream side of the projecting shore, but ultimately velocities will so decrease that even the intensified turbulence here will no longer prevent the accretion. When the channel configuration propagates downstream, the flow, formerly bent off-shore by the projecting part, is able to attack the root of the shoal and may separate it from the main river-bank. If vegetation has developed an island has been born (Diagram 6.2.2-1c and 1d).

Scour on the upstream end of the island by frontal flow attack will threaten the island immediately after its birth. But at the downstream end of the island slackening currents will cause deposition of sand. The island will grow here and thus propagate downstream. As the meander pattern moves further downstream, a new channel in front of the projecting part will develop again, and the cycle will be iterated and re-iterated. As a result, islands will regularly "drip off" the projecting parts of a river-bank (Diagram 6.2.2-1e).

Where there is a varying water-level and a uniform resistance of the banks against erosion, it may be presumed that in general the resistance against scour of the banks is greater than the

resistance of the bed. When the river is in spate, it tends to enlarge its cross-section, initially by deepening but finally by widening. During this process the general cross-section of the bed will show a channel along each shore (Diagram 6.2.2-2a). In a subsequent period of lower water-levels the river will decrease its now too wide cross-section first by accretion and then by narrowing of the bed. This accretion, combined with the fall of the water-level, may cause the mid-river sand-bank to dry up, possibly assisted or followed up by vegetation. The intensified turbulence along the original river-banks will try to maintain the two channels (Diagram 6.2.2-2b). During the following period of high water the river will enlarge its cross-section again, initially by deepening its bed and depositing the scoured material on the banks and on top of the eventually newly-born island. Finally, however, erosion of the river-banks and of the sides of the newly-born island will widen the bed again.

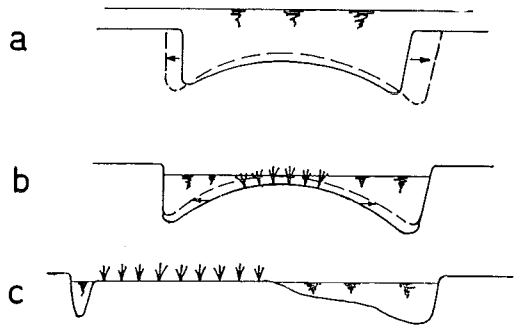


DIAGRAM 6.2.2-2

Island formation due to variation in the water-level

Frontal flow attack as well as flank attack will threaten the island but may be compensated by accretion at the downstream end of the island. Moderately resistant river-bank material (clay or silt) will result in fairly long and narrow islands, but too long a period of high water will annihilate this type of island by flank attack. Too long a period of low water will also demolish such an island by filling up one of the two channels, most likely the channel along the river-bank with the lesser resistance against erosion.

In the majority of cases both sources go together. Formation of bifurcations and closing up of branches will in themselves lead to differences in erodibility of the valley.

Islands are rarely found in meandering rivers, because of the more stable channel configuration ([1]. They could be temporarily formed under the influence of a varying water-level by chute (see 6.2.1). The bed configuration during a very high water-level no longer fits the high discharge in the bend, so a widening of the bed will take place which may be successful in digging a channel along the softer convex bank where the slope is steepest. During the subsequent lower water-level the mid-river shoal in the bend may become overgrown, thus forming a temporary island. But at the same time the chute will start to silt up, tying the island again to the convex bank.

Although variations in erodibility and water-level may lead to the formation of islands, these variations will have to be of a certain magnitude before they can do so, unless certain

([1] Islands formed as a result of cut-offs are not considered here.

favourable conditions for the creation of islands are present. These favourable circumstances, having an influence too on the *durability* of islands, are rather self-explanatory and could include:

a well-developed vegetation (climate);
a variety of bed-load material (clay, silt, sand);
a slope of the river that is neither too steep nor too small;
a non-incising river;
a moderate but not too great difference between highest and lowest water-levels, with intervals of sufficient duration to ensure either that the vegetation will not dry out or be submerged too long; and
the presence of former branches either silted up or not.

The lifetime of islands depends to a great extent on local situations. The frontal attack (and flank attack) and the accretion at the downstream end will cause the island to move downstream. In general, the former will surpass the latter in the long run, gradually curtailing the island, as otherwise the river would be choked with an almost continuous chain of islands. Flank attack may cut one island into two. Large quantities of clay and silt give strong and steady islands, whereas a mainly coarse sediment may lead to a river having short-living and fast-moving islands.

By moving downstream the island will leave the area of influence of its generating sources and may meet a narrow section where destructive forces prevail, annihilating the island.

In the case of an island generated by variations in erodibility, the branch on the side of the projecting river-bank will more often be closed (by an entrance bar) than the other branch (by a bar on the downstream end of the channel). However, if the projecting part of the river-bank and the connected river-banks consist of solid rock, the intensified turbulence may be so strong that the talweg will remain with the channel along this bank nearly permanently and attendant conditions will have to be favourable to complete the origin of an island. Although this statement seems contradictory to the previous reasoning, it should be kept in mind that, in this case, variations in erodibility of the river-bank no longer exist, and that the assumption of an alluvial river is hardly applicable. If a projecting part is followed by a wider and narrower section of river in sucession, an island once generated in the wider section may be practically stationary; the location of the upstream end of the island will change only under the influence of variations in water-level or by the situation of the propagating meander pattern.

In the case of islands generated by variations in water-level in between clayish river-banks, the slow but continuous erosion of these banks will cause a continuous widening of the H.W.-bed. If these banks are of a fairly uniform resistance against erosion, a smooth parallel alignment may be the result with wide and very long stable islands (Diagram 6.2.2-2c), and in the end one branch will be favoured by the river and the other will be reduced to a floodland creek. Which one, however, will depend on local conditions and perhaps on the CORIOLIS acceleration (see 6.1.4). A disuniformity in one of the banks may disturb the smooth alignment, increasing the flow resistance of that branch and causing it to silt up.

On the Niger and the Benue in Nigeria (see the Book of River Charts) the basic sources of the generation of islands are both present: variations in erosion-resistance as well as in water-levels are appreciable. River-bank material ranges locally from loose coarse sand to strong old clay, causing a ragged alignment of the river-banks. The seasonal variation in the hydrograph ranges from 15 up to 40 feet, apart from differences of up to 10 feet in the yearly H.W.-levels. Attendant circumstances such as climate, vegetation, wash-load, etc., also collaborate to generate a stream of islands.

This may be illustrated by the following list, in which the number of islands is given for the several river-stretches:

Stretch	River	Miles	Number of islands per 100 miles
Jebba — Raba	Niger	564—545	115
Raba — Budon	Niger	545—395	65
Budon — Lokoja	Niger	395—360	100
Lokoja — Aboh	Niger	360—177	43
Aboh — Patani	Niger	177—130	30
Garua — Faro	Benue	980—925	only appreciable between Miles 955—960
Faro — Lau	Benue	925—775	77
Lau — Tunga	Benue	775—575	60
Tunga — Abinsi	Benue	575—535	40
Abinsi — Lokoja	Benue	535—360	65

The total number of islands, large and small together, is about 650 over 1,050 miles of river. Both on the Niger and Benue in Nigeria down to the Lokoja Confluence (both of the reach type of river) the average is in between 60 and 70 islands per 100 miles, apart from short stretches with local disturbances. From Lokoja downstream to Aboh the average drops to 43 islands per 100 miles. In several places the river here nearly succeeds in developing meanders, diminishing the number of islands. Besides, the range between high and low water is so great that vegetation on the very high sand-banks is hardly possible during low water by lack of a sufficiently high capillary ground-water supply. Downstream from Aboh and also in the Garua Creek the river has a fully-developed meander pattern, reducing the number of islands per 100 miles to 30 or less.

Among the 650 islands some typical species of the several types just mentioned can be detected.

Islands caused mainly by variation in water-level can be seen on the Niger between Mile 250 and Mile 270. Here the right bank consists of uniform strong clay and the left bank of loose sand. During very high waters the long narrow channels behind the islands are opened up (Miles 257, 260 and 270), but the main branch sticks to the strong, clayey bank. Other examples are to be found between Mile 205 and Mile 220, where the mid-river islands regularly join up to form one long island which is equally regularly cut up in parts by flank erosion. A wider high-water bed with its typical islands may be seen at many places on the Benue (Miles 372, 405—420, 520—535, 592, 598, etc.) as well as on the Niger (Miles 315—320, 330, 370, 385, 405—420, etc.), among which the case of Diagram 6.2.2-2c is also represented clearly. Examples of chutes may be found at Miles 116, 120, 137, 157, etc. Small islands in the Garua Creek near Mile 955, however, are ridges of rock peering above the alluvial valley. In general, on the Niger and Benue practically every island exists as a result of the influence of the appreciable variations in water-level.

Examples of islands mainly caused by local differences in erodibility are difficult to detect, but may be found on the Niger at Miles 187, 221, 244 (comparable with Diagram 6.2.2-1e) and 434 and on the Benue at Miles 421 and 647. The situation at Mile 233 between Asaba and Onitsha is worth comparing with Diagram 6.2.2-1c which could be a copy of it. It is known from the NEDECO surveys of 1955 that at that time the situation was still as shown in Diagram 6.2.2-1b. Local people clearly remember the situation of some 15 or 20 years ago. From their descriptions the situation at that time must have been as sketched in principle in Diagram 6.2.2-1d: a huge sand-bank blocking the quay of Asaba at Mile 236 and shoals blocking the quays at Onitsha with the main channel following the west bank behind an island opposite Onitsha. Another

proof is given in a rough sketch by Lt. J. W. Glover R.N. of the Baikie expedition of 1857—1859. Part of this sketch is reproduced in Diagram 6.2.2-3.

Obvious indications of short-cuts in the Niger and Benue are not present, although some creeks and tributaries give examples, such as Ndoni Creek, Mile 181.

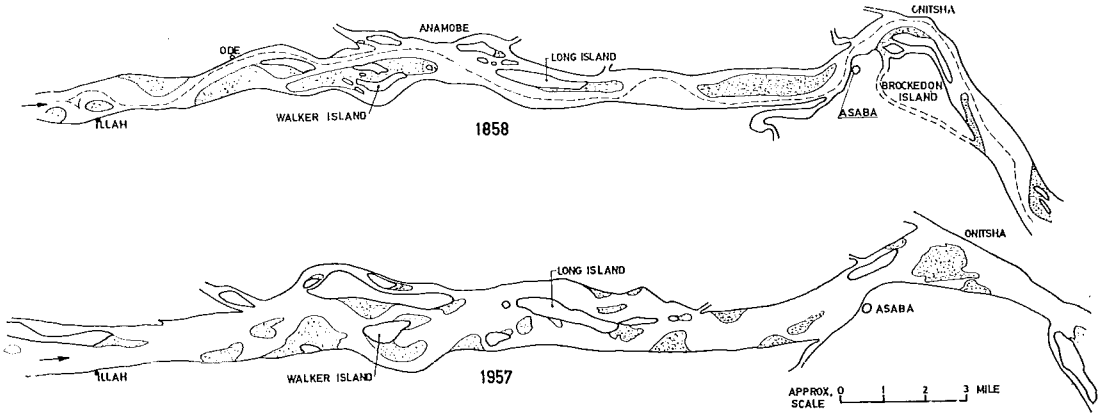


DIAGRAM 6.2.2-3

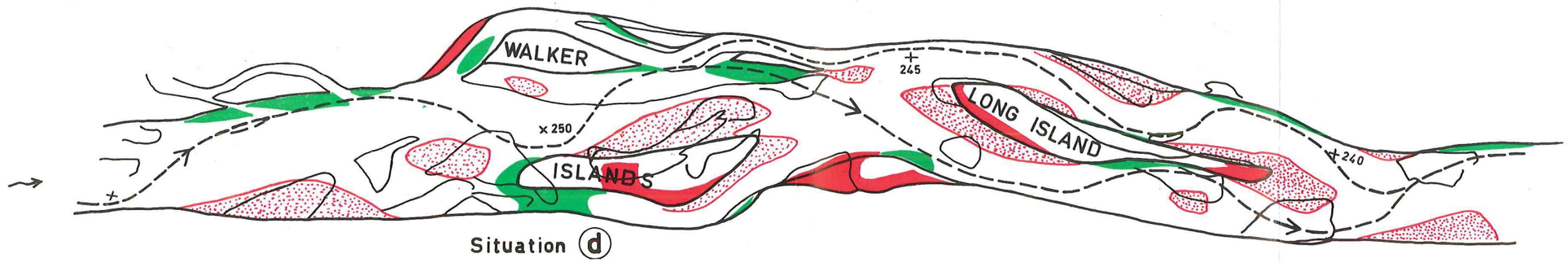
Comparison of the situation of the Niger between Illah and Onitsha in 1858 and 1957

Most islands in the Niger and Benue, however, are a mixture of the two depicted types of islands. Long Islands in the Niger (Mile 245) may serve as an example of such a mixed situation. Here measurements were carried out on local slopes of the river, on distribution of discharges and on direction and magnitude of velocities, while frequent soundings have been taken.

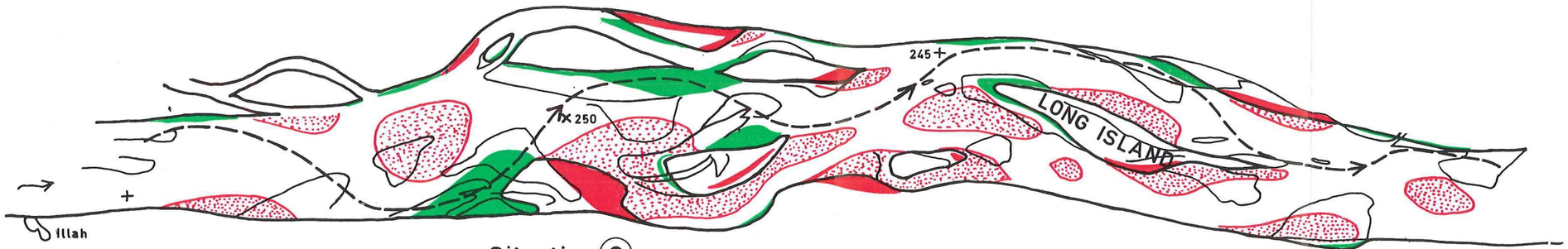
Long Island (Miles 240—245) is situated just downstream of the Walker Islands (Miles 246—250). The origin and presence of these islands is closely linked with the existence of a weak spot (gap) in the right river-bank at Mile 248 (Diagram 6.2.2-4a). This river-bank has a smooth alignment from Mile 265 to Mile 235 (Asaba) and consists of very strong old red-grey clay, with an exception at Mile 248 where the bank has a concave gap of unknown origin. The downstream part of this gap acts as a sort of cape (Mile 247) and although exposed to heavy attack by the current, seems to stand the onslaught very well, leading the current to the opposite river-bank. In front of this cape a channel has been scoured with a depth down to 60′ below L.R.L.

With the above-mentioned considerations on the origin of islands it is simple to explain the presence of this group of islands, arising from the outline of the right river-bank, the pronounced differences in water-levels of over 30′ and the propagation of the meander pattern of the channel down the river. The islands must have been existing in some form or another for a very long period, due to the high resistance against erosion of the right river-bank. A comparison with the old map of the Baikie Expedition of 100 years ago, from a sketch by Lt. J. W. Glover, rough as it may be, shows a remarkable resemblance to the situation of today (Diagram 6.2.2-3). The same gap and cape at the same place are visible as well as the islands, though not in the same shape. It may be safely assumed that as long as the gap exists, which may be very long because of the strong clay, mid-river islands opposite and just downstream of this gap will also be present.

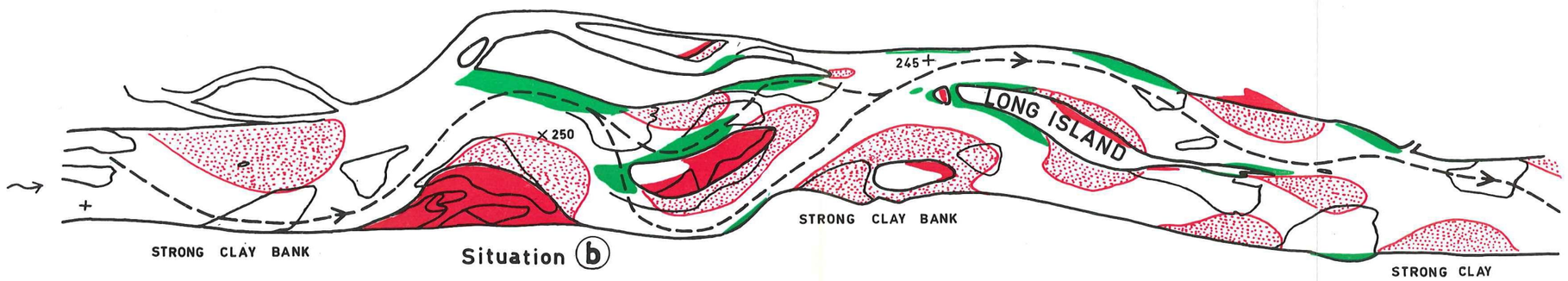
A rough idea of a possible future development of the situation is given in Diagram 6.2.2-4.



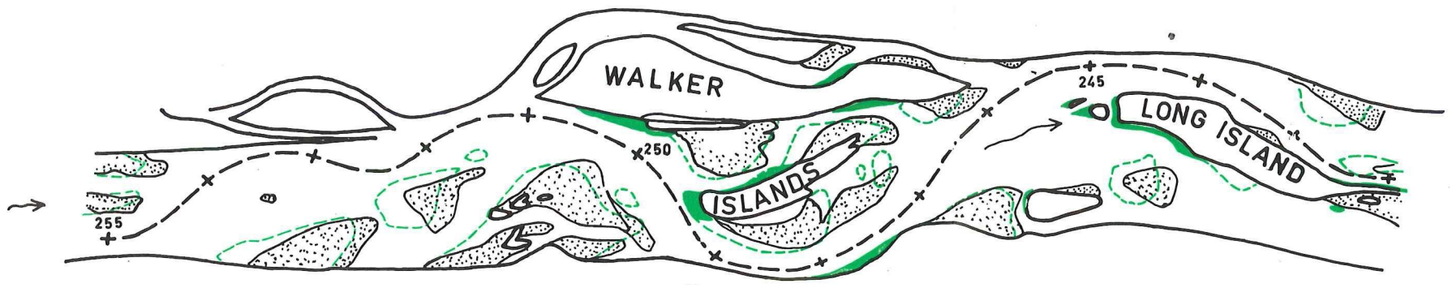
Situation (d)



Situation (c)



Situation (b)



Situation (a) (Dec. 1956)

SCALE

0 1 2 3 MILES

0 1 2 3 4 5 KILOMETRES

RIVERBANK
SANDBANK OUTLINE
NEW RIVERBANK
ERODED RIVERBANK
SANDBANK OUTLINE FEB. 1954
SANDBANK OUTLINE DEC. 1956

NEDECO	DIAGRAM
NIGER / BENUE	III, 6.2.2-4

POSSIBLE FUTURE DEVELOPMENT OF
WALKER ISLANDS AND LONG ISLAND

Depending on the height of the future floods and on the erodibility of the Walker Islands, the future development may vary and differ from the sketch.

An increase in discharge capacity of the middle channel at Mile 248 is likely in the near future. The sand-bank at Mile 251 is nearly overtaken by the sand-bank of Mile 253, causing trouble to shipping by the disturbed meandering pattern at Mile 252½. The propagation of the first is blocked by the deep channel along the gap, attracting the current and fixing the meander pattern on the spot.

In situation (b) the sand-banks at Mile 252 have joined. The erosion of the right Walker Island has continued by the heavy frontal attack on its sandy subsoil, providing space for the upstream sand-bank to shift further downstream. The flow resistance of the right channel in the gap will increase in favour of the middle channel, which will widen by flank erosion of both Walker Islands. The top of Long Island will also be subject to strong erosive forces but may hold out better because it contains ridges of clay on the top left side. The weak upstream right side of Long Island will be eroded, further widening the entrance to the right channel.

In situation (c) the channel in the gap is completely outclassed and may be in use during floods only. On the upstream side its sandy base is attacked by the meandering channel shifting downstream, whilst on the downstream side it is going to reinforce the right-hand Walker Island. The sand-bank at Mile 253 may become a mid-river sand-bank by the presence of the creek debouching at the left river-bank. The left Walker Island is attacked further and may break through, depending on the erodibility of its bank material. The wide entrance to the right channel at Long Island, blocked by masses of deposited sand, is going to be attacked by the current during the floods. Long Island has grown shorter at both ends and wider in the middle.

In situation (d) the shifting meander pattern has developed the middle channel to its fullest size, but the floods have opened up the right channel in the gap. Soon scour will deepen it again to become the main channel as before. Walker left Island is torn to pieces but many grow again with the development of the right channel. The channel configuration, no longer influenced by the cape at Mile 247, has had the opportunity to open up the right channel along Long Island, giving the left channel a chance to silt up.

The situation of Diagram 6.2.2-4d could be compared with the one given in the sketch of Baikie's Expedition. From the progress of the sand-banks it can be concluded that the development just described may take something like 40 to 70 years. However, as already explained, this development is only one of the many possibilities arising from the erodibility of the islands. Series of extreme high or low floods, too, will have an influence on the real process in the future.

To obtain a better insight into the problems around islands, a series of measurements was made at Long Island. One of the detailed soundings is reproduced in Diagram 6.2.2-5. This sounding was taken during H.W. of October 1957, and a direct comparison with a sounding of June 1957 shows a pronounced scouring in the entrance of the left channel and silting-up of the right channel entrance combined with appreciable erosion of the top and right bank of Long Island (Miles 244—245).

Sand-transport measurements were made at three successive stages of the river in 1957. As the wash-load and suspended load are hardly of influence on scouring and silting processes, only the bed-load was measured with BTMA and DF_2 in three cross-sections between Walker Island and Long Island. The results are given in Diagram 6.2.2-6.

The first measurements at a water-level of L.R.L. + 6′ with a total discharge of 5,500 m^3/sec show that the water arrives practically "clean" in the wide ante-room of Mile 246, as some backstage is present. Sand is picked up in the ante-room and carried along in the two channels on each side of Long Island. It may be assumed that a part of this load is dropped again near Mile 244 in the right channel and at some places at the downstream end of the left channel, the latter being no longer drawn down as was the case during the previous lower stage of the river.

The next measurements were made at bankfull stage (L.R.L. + 17′) with a discharge of 13,200 m^3/sec. There is a good correspondence between the alignment of the main channel (talweg) and the meander pattern consistent with this discharge (which is about equal to the Dominant Discharge) leading to well-curved smooth flow-lines. Remarkable is the high sand-transport through the short-cuts of the Walker left and middle channels. The wide stretch between Miles 245 and 247 has a relatively large capacity for discharging water, thus giving the sand an opportunity to deposit. This happens mainly at Mile 245 in front of the entrance of Long Island right channel. Here the bed-load is drawn to the right by the centripetal forces in the bottom layers of the well curved lines of current, to deposit under the lee of the cape. The current pressing against it causes scour off the cape.

The only remarkable feature of the measurements during the flood of 1957 with a discharge

of 21,000 m^3/sec is the relatively heavy scour in front of Long Island right channel. The flattening tendency of the flood with its straighter flow lines carries the newly-deposited sand into the right channel, which has a larger sand-transport with the same discharge as the left channel. More downstream the discharge of the left channel decreases by the loss of water via the flood-land creeks to the Anambra River.

A sand-transport balance of an annual cycle would be very interesting, especially over more stretches in the different channels, but in that case many more sand-transport measurements are needed. As a conclusion it can be said that in the situation such as that of 1957, discharges below 15,000 m^3/sec will cause huge deposits of sand in front of the entrance of Long Island's right channel, blocking it. Discharges above 17,000 m^3/sec, however, will carry this deposit into the right channel and, if time is sufficient, will carry it through the channel, opening it again. In the present-day situation the right channel acts as a kind of chute for the high floods.

Measurements of the water-level at several places along Long Island were made at various stages with the aid of a series of levelled benchmarks. The results are shown in Diagram 6.2.2-7, while the positions of the benchmarks are marked on Diagram 6.2.2-5. Apart from the stages during which sand-transport was measured, a measurement of the slope at a stage of L.R.L. + 0'4" (corresponding to a reading of 13'4" on the gauge of Onitsha) was made in January 1958.

This last measurement shows clearly the blocking of the right channel at its entrance, raising the water-level in the entrance of the left channel by about 2 feet, and causing backstage upstream of R13. The slope at the location of P102 and Sp5 reaches values of 60×10^{-5} ($3\frac{1}{4}$ feet/mile). The water-level in the left channel is drawn down heavily causing high velocities (see float measurement on Diagram 6.2.2-5) which erode the weak banks along the downstream part of the left channel at R7, L2, R2 and L1. This led to a breach in the island in 1955 between R7 and R2, and to deposits of sand in the downstream part of the left channel directly downstream of the eroded parts. The difference in water-level halfway up the island at R3 has not yet led to a breach as the island there, narrow though it is, consists of a ridge of clay.

Apart from the differences in average slope at the different stages of water-level, the most striking fact is that at L.R.L. + 6' the water-level seems hardly affected by the blocking of the right channel. The distribution of the discharge over the two channels is determined by the total resistance of the channels and the increased resistance effected by the blocking sand-bank acts over a short distance. This increase appears to be appreciable at lower water-stages only (see also 4.3.8).

In addition to the water-level measurements, there were also measurements made with surface floats to determine the direction and magnitude of the flow. The results of the measurements at H.W. of October 1957 (L.R.L. + 27'7") and at January 1958 (L.R.L. + 0'4") are depicted in Diagram 6.2.2-5, showing the flow lines as well as the surface velocities.

From these velocities and the data derived from water-levels and soundings, the value of the coefficient of De Chezy C was determined, which varied from 33 $m^{\frac{1}{2}}$/sec in the entrance of the right channel to 55 $m^{\frac{1}{2}}$/sec in the downstream part at L.R.L. In the left channel the coefficient of de Chezy proved to be about 44, which was also the average value of some stretches in both left an right channels at high water. With the value of C roughly known, it was possible to compute the slope in cases where they were not measured, based on de Chezy's discharge formula

$$Q = a^{\frac{3}{2}} b\, C \sqrt{i}$$

The total discharge Q can be known from the discharge rating curves. The relation between the value $a^{\frac{3}{2}}b$ and the water-level can be computed for any section from the soundings and may graphically be represented by a h—$a^{\frac{3}{2}}b$ curve for that section. With these data a rough computation can easily be done graphically with the aid of Diagram 6.2.2-8.

N

LEGEND:

- FLOATERLINES AT L.R.L. } WITH VELOCITIES
- FLOATERLINES AT L.R.L.+27' } IN cm/sec.
- RIVER-BANK
- SAND-BANK (L.R.L.)
- L.R.L. -3'
- L.R.L. -6'
- L.R.L. -9'
- L.R.L. -12'
- L.R.L. -18'
- + 12 HEIGHT OF SANDBANK IN FEET ABOVE L.R.L.
- + 240 MILES FROM ESCRAVOS

WALKER ISLANDS

LONG ISLAND

H.W. CURRENT

LINE OF SANDBANK JAN '58

SOUNDED AT L.R.L. + 27' IN OCT. 1957
SOUNDING REDUCED TO L.R.L.

0 1 MILE

NEDECO NIGER / BENUE	DIAGRAM III,6.2.2-5
SOUNDING AT ANWAM (LONG ISLAND)	
WITH FLOATERLINES AT H.W. AND L.R.L. +6'	

NEDECO
NIGER / BENUE

DIAGRAM
III, 6.2.2-7

WATERLEVELS AND SLOPES OF THE RIVER NEAR LONG ISLAND

HEIGHT IN METRES ABOVE SEALEVEL

HEIGHT IN FEET ABOVE SEALEVEL

LONG ISLAND

NGEGU MILE 248

ASABA

ONITSHA

(1) 21 OCT. 1957 27' 7" ABOVE LRL
(2) 15 AUG. 1957 17' 7" ABOVE LRL
(3) 11 JUL. 1957 6' 1" ABOVE LRL
(4) 17 JAN. 1958 0' 4" ABOVE LRL

- BENCHMARK
- MEASURED } WATERLINE LEFT CHANNEL
- COMPUTED
- BENCHMARK
- MEASURED } WATERLINE RIGHT CHANNEL
- COMPUTED

0.70 m 2'-4"

i IN CM/KM

i IN FEET/MILE

SCALE OF SLOPES OF RIVER

0 1 2 3 4 5 KM
0 1 2 3 4 MILE

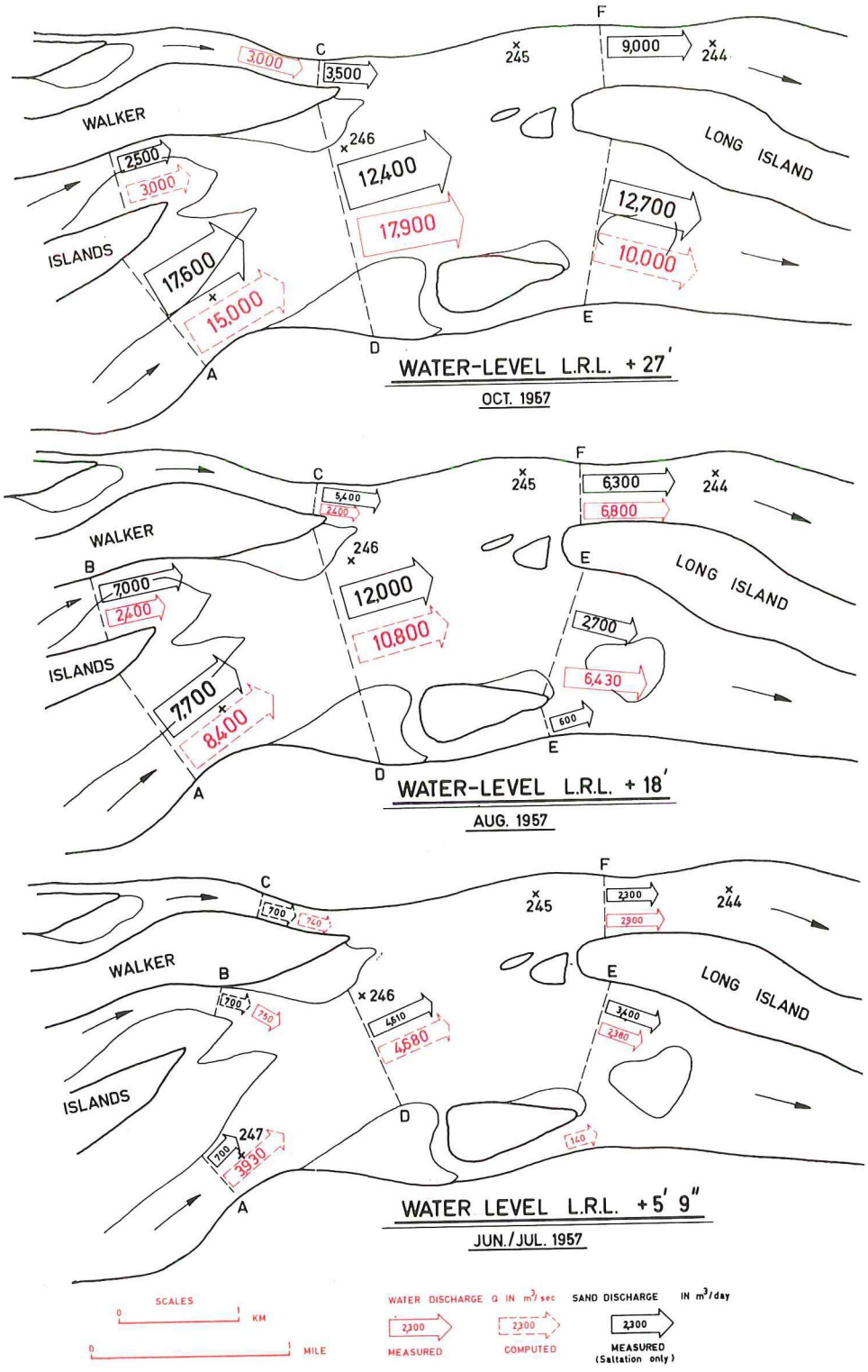


DIAGRAM 6.2.2-6

Sand-transport and water discharge near Long Island

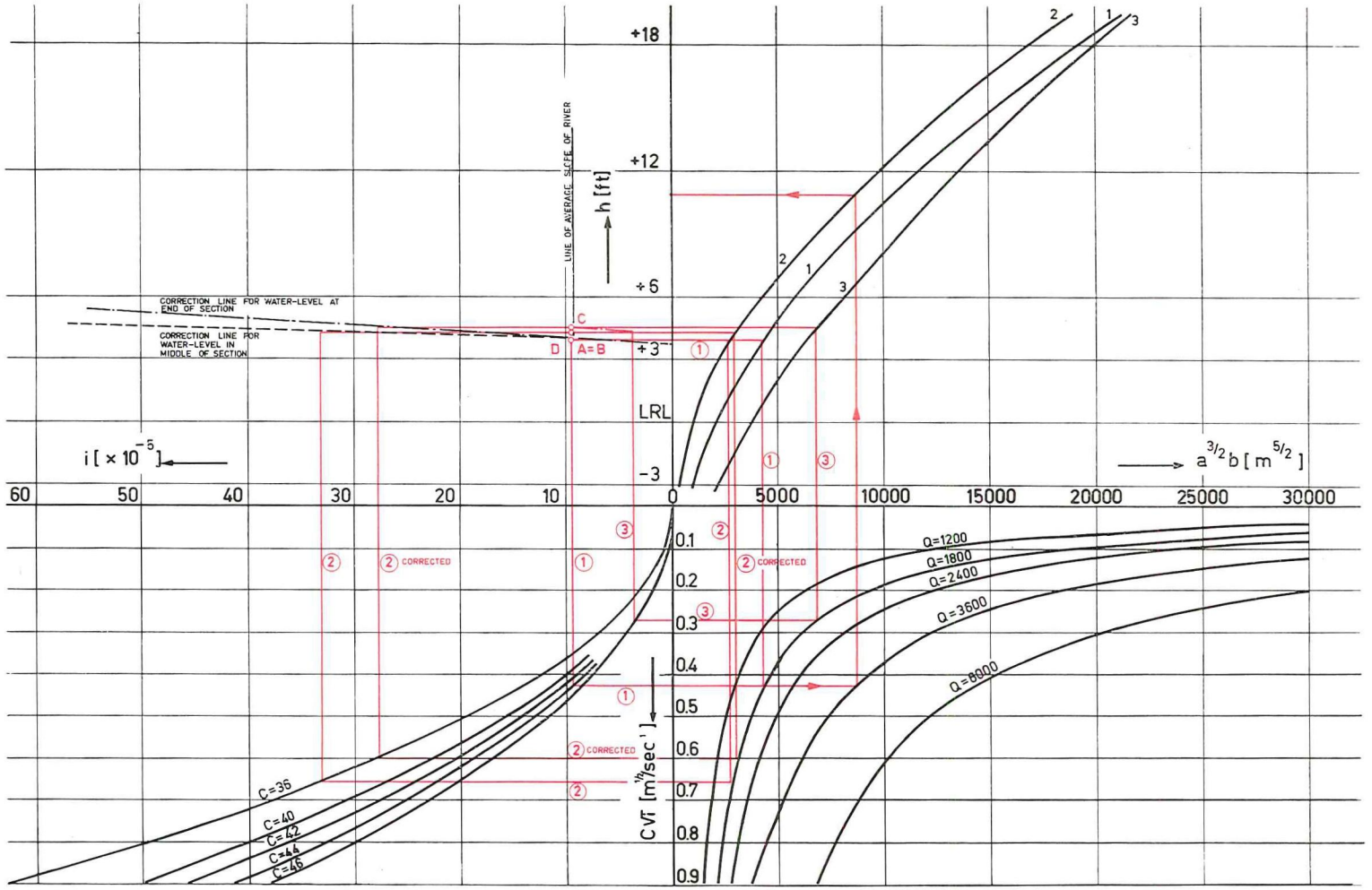


DIAGRAM 6.2.2-8

Graphical method of determining the slope of the water-level from sounding and discharge

In the schematic sketch of a longitudinal section, three stretches (AB, BC and CD) of equal length are taken (Diagram 6.2.2-9). In the middle of each stretch the h—$a^{\frac{3}{2}}b$ curve of each cross-section (1, 2 and 3) is determined and drawn in the upper right quadrant of Diagram 6.2.2-8. If it is supposed that the water-level in A is L.R.L. + 4′ and the average slope of the river is 9.5×10^{-5}, then a horizontal line can be drawn through the upper horizontal axis h at L.R.L. + 4′. Extended to curve 1 the value of $a^{\frac{3}{2}}b$ is found of stretch AB in cross-section 1. Going down to the second quadrant following line 1 to the relevant discharge curve (say Q = 1,800 m³/sec), the value $C\sqrt{i}$ can be directly read on the lower vertical axis ($C\sqrt{i} = 0.42$). Now the value of C must be chosen in the third quadrant, with the aid of the known C-value of a comparable stretch of river. In this case, a value of 44 is chosen, and going up to the fourth quadrant a slope of 9.5×10^{-5} is found on the horizontal left axis. This slope is also the average slope of the river over a long distance. Consequently the water-level in B is also L.R.L. + 4′ (B = A in fourth quadrant). Going round in the same way following line 2 via the h—$a^{\frac{3}{2}}b$ curve marked 2, for the

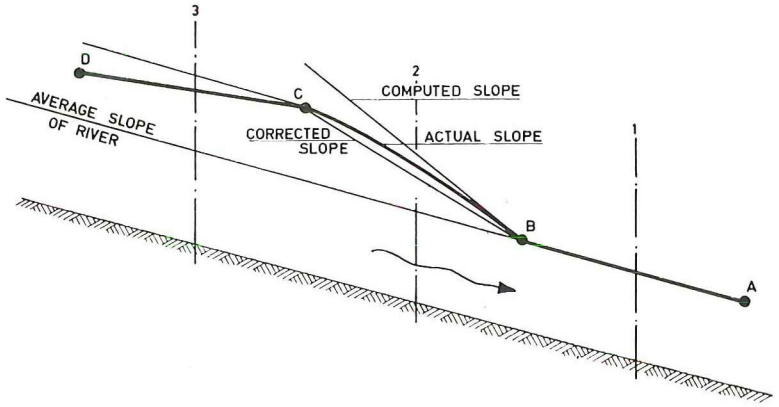


DIAGRAM 6.2.2-9

Schematic longitudinal section

stretch BC a slope of 32×10^{-5} is found via a C-value of 36. This 32×10^{-5} is much higher than the average slope of the river, which means that section BC is drawn down and that the line of the water-level is curved with a maximum slope of 32×10^{-5} at the downstream part of the section at B. The average height of the water-level in section BC, therefore, will be about L.R.L. + 4′ + 0.45 section length × (max. slope − average slope). This height can be graphically found on the "correction line for water-level in the middle of the section" in the fourth quadrant (L.R.L. + 4′4″). From this point on the dashed line the procedure is continued via curve 2 following the lines marked 2 *corrected* to find an average slope for the section BC of 28 cm/km. Going upward in the fourth quadrant to the dash-dot-line, the water-level height in C can be immediately read on the upper axis, being L.R.L. + 4′7″. Going round again via curve 3 the slope in section CD with a C-value of 46 is found to be $3\frac{1}{2}$ cm/km. This section has a curved water-level too by backstage. As the difference from the average slope of the river is only small, this curvature may be neglected and via the dash-dot-line for the correction of the water-level at the end of the section the water-level in D is to be found directly as L.R.L. + 4′4″.

In the case of a bifurcation, the same method may be followed working in an upstream direction. If the discharge in each channel is unknown, first a guess of the division of the discharge is made. The result should then be that the computed water-levels at the upstream ends of the channels are equal. If this is not the case, then the guessed discharge in the channel with the lower water-level at the entrance must be increased.

With the aid of Diagram 6.2.2-8 it is very simple to get a quick idea of the maximum possible raise in the upstream part of one channel if the other channel is completely closed. If the length of the open branch is infinite, the slope in the most upstream part of the other channel will be the average river-slope. In a normal case, this slope will always be steeper. Thus the maximum raise can be found by working anti-clockwise in the diagram, starting with the average line of slope, via the total Q (say 3,600 m³/sec) upto the smallest value of one of the h—$a^{\frac{3}{2}}b$ curves of the upstream part of the open branch (say curve 2) to find the maximum possible water-level in the head (about L.R.L. + 11″ in this example).

Using Diagram 6.2.2-8, the soundings of October 1957 and the computed values of de

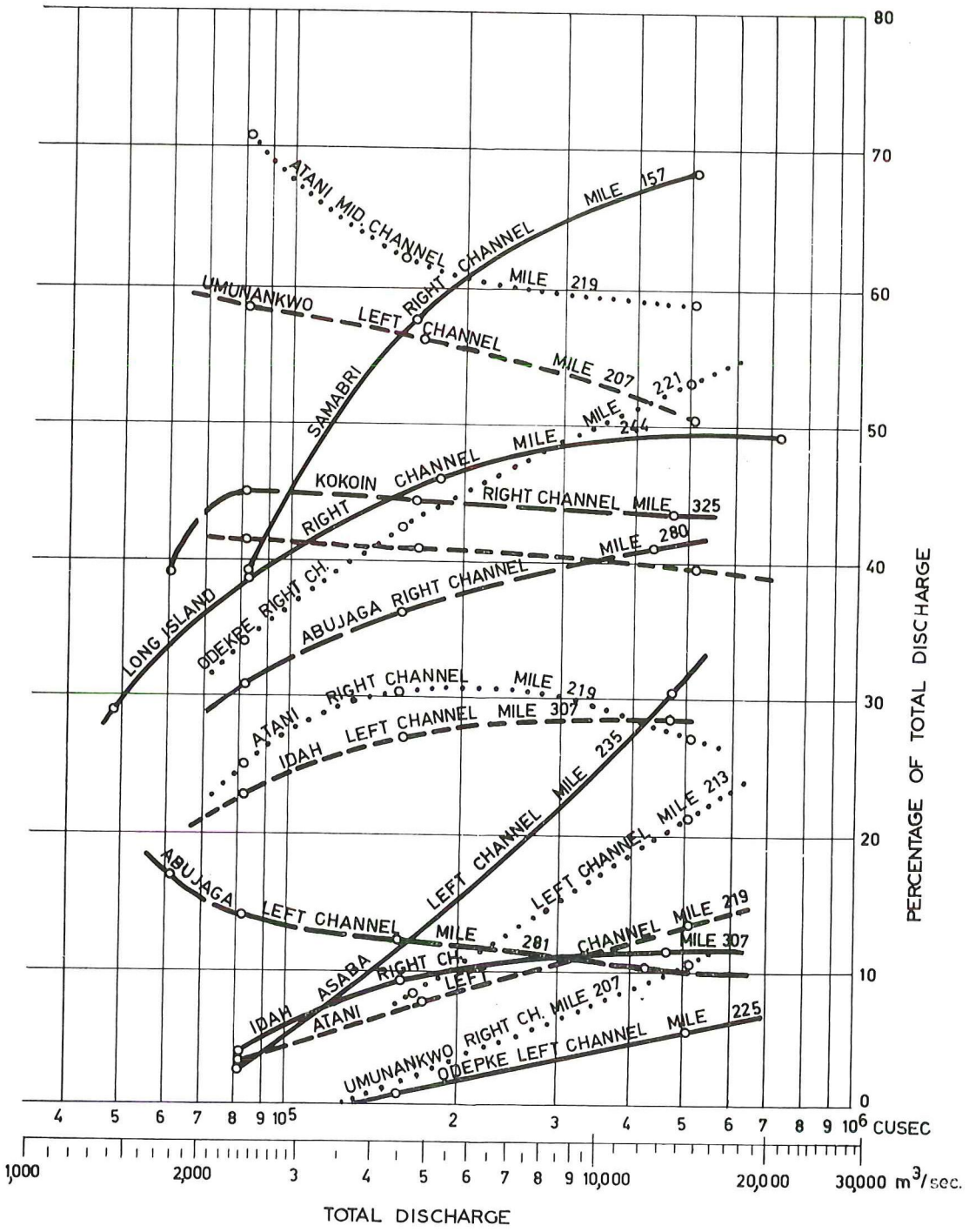


DIAGRAM 6.2.2.10

Distribution of discharges around several islands on the Niger

Chezy's coefficient C the unknown distribution of discharges for January 17, 1958, has been computed, giving at the same time a check on the water-levels in the left channel between R8 and R3. The results of this determination for a discharge distribution of 1,800 m^3/sec in the left channel and 1,200 m^3/sec in the right one is shown by a dashed line in Diagram 6.2.2-7. Taking into account the uncertainties in the determination of the used C-values, the agreement with the measured water-levels is rather good.

Diagram 6.2.2-10 may serve as an illustration that Long Island was not the only island with variability in distribution of discharges. In this diagram the results are given of discharge measurements in 1957 of some branches of the Niger between Idah and Aboh.

It should be noted that all these data about water-levels, distribution of discharges, velocities and current will alter as time goes on, because of the continuously-changing meander pattern of the river.

6.2.3. Confluences

Where two rivers join, a disturbance is imposed upon the main stream depending on the relative size of the tributary and the angle of confluence. The first factor is obvious, because a small tributary exerts a negligible influence upon the main river. The second dependency, however, is more complicated. The main flow is pushed aside by the flow from the tributary, and as a result of curved stream-lines sand deposition takes place at certain locations, interfering with the normal meandering pattern of the river since such depositions are confined to the place of confluence and do not propagate downward. The angle of confluence determines the degree of curvature and hence the rate of deposition. An intersection at right angles will undoubtedly have a much greater effect upon the main flow than an intersection at a small angle of, say, 10°. The latter circumstances would show a tendency for the two rivers to flow alongside each other over a considerable distance without interfering to any great extent.

Because of this tendency not to mix, the "lands-end" between two rivers intersecting at a small angle is comparable to the lower end of an ordinary island; similarly, the lands-end of a confluence may grow as a result of deposition of sand, resulting in a long and narrow sand-spit extending from the confluence downward, which can often be recognised by its young vegetation.

The length of such a spit is limited. If it grows too long, dividing the lower main river channel into two parts, the downward displacement of the confluence would cause the water-level in the tributary to be higher than across the spit in the main river, owing to the normally steeper slope of the first. A short-cut through the sand-spit at the location of original confluence is then likely to occur, especially when at higher water-stages the spit is flooded. The spit then becomes an island which would in general be speedily eroded by front attack. And after that, the process can start again. The slowly downward-propagating meander patterns of both rivers consolidate this phenomenon.

Such a regular cycle of growth of a sand-spit and formation of a short-cut is often disturbed by the water-discharge not being steady but highly variable. In several situations the long spit and the short-cut seem co-existent, where the short-cut then is the main outlet at a period of draw-down of the water-stage of the tributary, while conversely it is the other channel which discharges the greater part of the flow during a period of raise of the tributary's water-level. As normally the rise and fall on the tributary are quicker and more intensive than on the main river, these periods of draw-down and raise can generally be translated into periods of high and low water-stages on the tributary respectively, although exceptions to this general statement might occur.

6.2.4. Effect of vegetation

Barely one drop of rain out of a thousand will fall in fresh water; they nearly all will fall on land and seek their way to a draining river, unless they evaporate beforehand. It depends completely on run-off conditions how long this drainage process will take, i.e., to what degree the irregularity of rainfall will be evened out before the fallen rain reaches the tributaries and the main rivers.

In Section 1.4 it has been shown how the soil and the vegetation largely determine the run-off conditions. As far as vegetation is concerned, the effects may be summarized by saying that dense vegetation has a retarding and, therefore, regulating effect on the run-off. Contrariwise, no vegetation means no retardation, but it also means erosion of the soil as a consequence of surface run-off.

For the tributaries of the Niger and Benue this results in sudden peak discharges loaded with eroded materials whose composition may become coarser as erosion intensifies.

For the main rivers the same is true, but the shots of water and sand from the tributaries are now causing inconvenience to shipping. The river-bed is becoming adapted to high Dominant Discharges and is becoming wider and shallower. The yearly run-off is concentrated in one or several short periods and thus there is a short navigable or a series of unpredictable short navigable periods dependent on rainfall. Also, where tributaries join the main river, peak run-offs result in a large inflow of sediment into the river. In the river-bed this results in local aggradation of the channel and steepening of the slope. Finally, the peak run-off will carry sediments of large particle size, which entails a steeper slope to move them down the river-bed. These circumstances are typical for braided rivers and they tend to a smaller water depth at a certain rate of discharge, when compared with a river-bed situated in an overgrown catchment area.

The run-off from overgrown areas is more uniform and sediment inflow and particle size are smaller, resulting in a relatively lower Dominant Discharge, smaller slopes and velocities and longer navigable periods with greater depths at a certain rate of discharge.

Artificial encroachment upon the existing vegetation can affect the run-off and have either a good or an adverse influence on the river-bed. Bush-fires (Photograph 6.2.4-1) which are

PHOTOGRAPH 6.2.4-1

Bush-fire

common in large parts of Nigeria, destroy the top-soil layers and must finally have an adverse effect, whilst forestry will have a beneficial result. Agriculture may affect the run-off for good or for ill when it replaces vegetation (see Section 1.4).

In the river valley, and in particular on top of and along the banks of the river, vegetation has the effect of increasing the resistance against erosion by the river (Photograph 6.2.4-2). When water-levels rise above bankfull stage, the flooded vegetation resists the flow very strongly

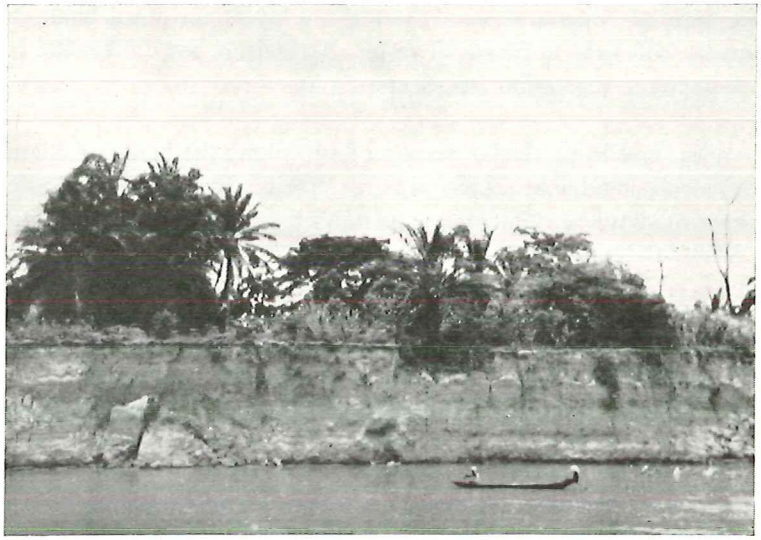
PHOTOGRAPH 6.2.4-2

Flooded bank

and suspended sediment entering the valley from the bed will partly deposit. The deposited particles will be smaller when the banks are higher and the velocities are smaller, thus accounting for the natural decrease in size of grains from the bottom to the top of a river-bank. When the banks become high enough for vegetation, silt will deposit, which is vital to the existence of a strong vegetation; and once it is strong enough, the top of the bank will be protected against erosion.

Erosion at the sides of the bank, however, remains possible, as the slopes are too steep for vegetation; but it will be slower when the vegetation is heavier, with deeper roots (Photograph 6.2.4-3).

When the banks have a very light vegetation, or when they are bare, erosion of top and sides will tend to increase the channel width and at the same time increase bottom heights and decrease channel depths. This can also be thus formulated: the ratio of resistance against bank and bed erosion is higher in rivers with overgrown banks than in rivers with bare banks. The result will then be that the depth/width ratio of the former is higher than that of the latter, and that at a certain rate of discharge a river with more bank resistance under otherwise identical circumstances will be better navigable. This increase in depth of the channels, due to the increased resistance against erosion, has also been proved in Paragraph 6.1.2.



PHOTOGRAPH 6.2.4-3

Vegetation on a Niger bank

Also important from a viewpoint of the population and utilisation of the valley is the height of the water at maximum flow. FRIEDKIN ([1] tested these stages in models with eroding and with stabilised banks. Bare and overgrown banks can in a way be considered as analogous to eroding and stabilised banks respectively. The results of the tests showed that stabilisation of eroding banks (Photograph 6.2.4-4) had a decreasing effect on the maximum flow stages when moderate bends of the channel existed. When the bends had a high or a low degree of curvature, the maximum flow stages after the stabilisation remained equal to the stages before stabilisation. From this it may be expected that no increase in high-water stages will occur when bank erosion is checked by vegetation. On the other hand, an increasing vegetation on top of the banks in the river valley will retard the flow above bankfull stage and higher water-levels can then be expected. The obtaining conditions will determine which of these controversial tendencies will ultimately prevail. This depends on the rate of erosion which is still possible. The extreme case of a completely fixed river (f.i. when bed-regulation is applied) will have the disadvantage that on the long term, silt deposits and overgrowth in the valley along the river will continuously grow higher and will no longer be cleared by the meandering river, so that ultimately the maximum flood levels will increase.

It has been pointed out that vegetation in the river-bed on sand-banks will tend to cause increased deposits on these banks and hardly any sand will be picked up from such overgrown sand-banks. They become stationary and gradually build up to bankfull height when the vegetation is strong enough to survive the high floods (Photograph 6.2.4-5). The circumstances under which a vegetation has a chance to survive are discussed in 6.2.2.

Artificial stimulation of vegetation on sand-banks in the river-bed will thus tend to an increase of the total resistance against bank erosion and the ratio of bank/bed resistance against erosion will increase. Also it will slow down the move of sand-banks, or bring this to a complete standstill. As a compensation, more sand will be scoured from the bed, and part of this sand will be worked

([1] FRIEDKIN, 1945. MOR. 9

PHOTOGRAPH 6.2.4-4

Bankslide on the Benue

along the banks, thus causing a deepening of the channel. The channel capacity will then increase until a new equilibrium is establsished.

In conclusion, it appears that the vegetation is of prime importance to the channel formation of a river and that good vegetation in the whole catchment area, and specially on the borders of a river, leads to a better navigable river.

PHOTOGRAPH 6.2.4-5

Erosion and vegetation of a sand-bank

6.2.5. Bank erosion; changes in the alignment of the rivers

Two types of bank erosion can be distinguished, viz., the direct bank erosion caused by the tractive force of the skimming flow, and the indirect bank erosion caused by excessive internal shear stresses. Without going into mathematical details, a little should be said to describe the respective phenomena.

Direct erosion acts on land surfaces exposed to running water. Even coherent soil particles are loosened by reduction of pore pressures, by chemical action or by dissolution, and at the same time carried away by the tractive force of the water. The process is intensified in swift currents, on steep-sloping banks (where gravity forces act in favour), on coarse cohesionless material or on easily soluble clays. It is obvious that the most serious erosion occurs with a turbulent flow along vertical sandy banks.

Indirect erosion can be apparent in the shape of a landslide, or of a collapsing undermined soil mass. A land-slide may be provoked in clayey banks where a rapid fall of the river causes in-

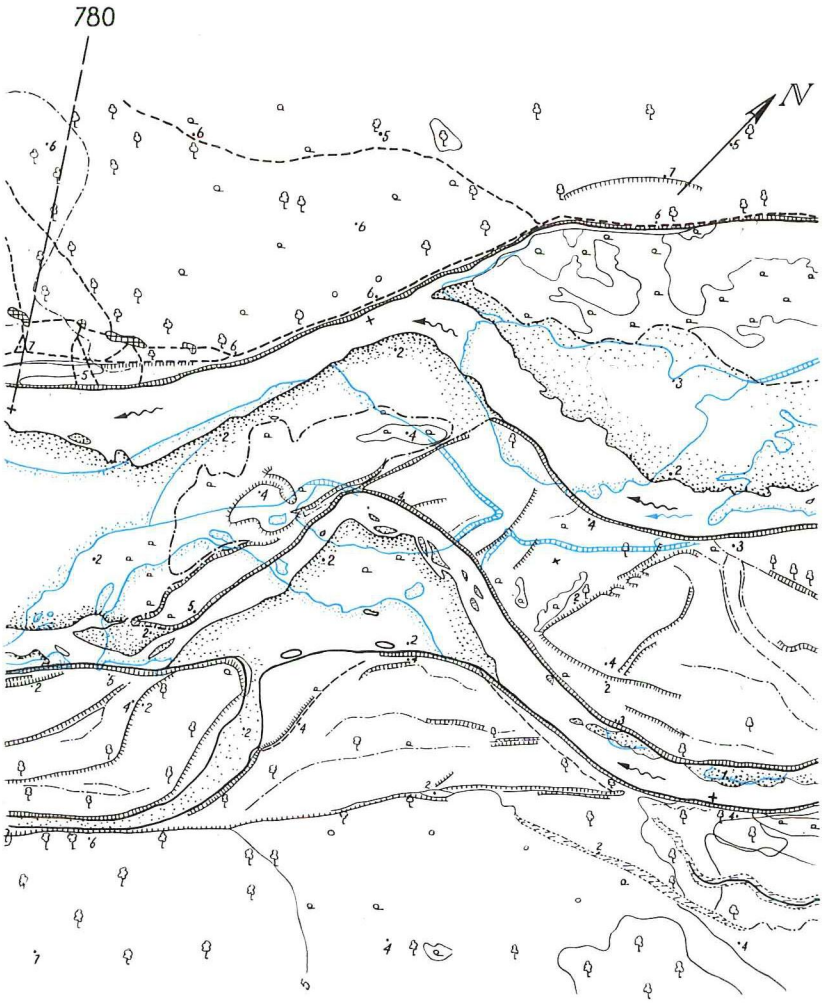


DIAGRAM 6.2.5-1

The Benue at Mile 810 on May 1954 and December 1956

ternal water pressure excessive to the existing stresses. A collapse may occur in clay layers on top of eroding sand layers.

Both forms of indirect erosion are often encountered along the rivers, but it is thought that most of the load of the rivers is supplied by direct erosion. Measurements to determine the scope of either type of erosion have not been carried out during the present investigation, but a few principles can, however, be stated:

(i) the amount of erosion is not related to the transporting capacity S of the river;

(ii) excessive local erosion causes local aggradation of the river with contingent deterioration of the channel; and

(iii) resistance to bank erosion, on the contrary, has a deepening effect on the adjacent channel.

These principles have already been discussed in 6.1.5, and the ensuing wholesome effect of stabilisation of river banks will further be discussed in 6.6.5.

Though the really eroded quantities have not been determined, the rate of erosion can be derived from a comparison of aerial photographs taken at certain intervals, a few examples of which are given here in which the situation of May 1954 is compared with that of December 1956. As practically no erosion is apparent during the low-water periods, the difference may be considered as caused during three high-water periods.

Diagram 6.2.5-1 refers to the Benue at Mile 810, between Gamadio and Tungaladan. Two

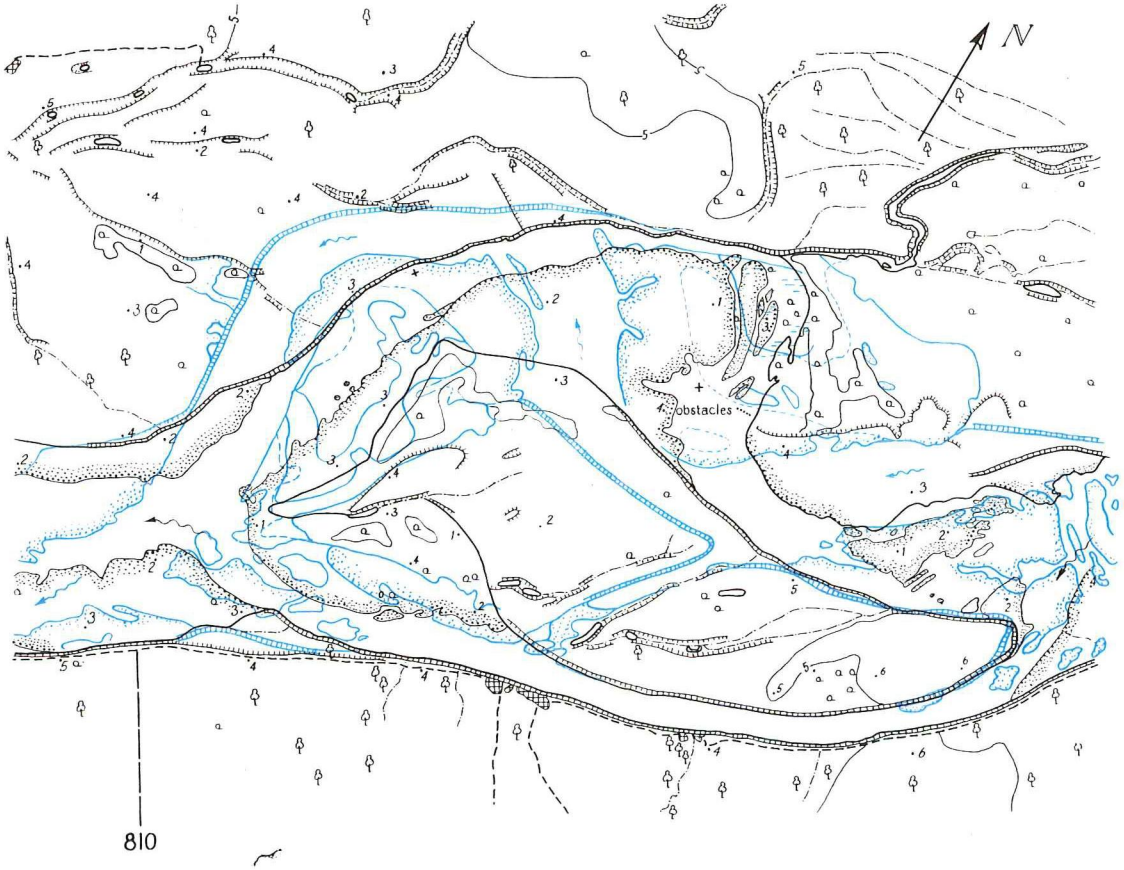


DIAGRAM 6.2.5-2

The Benue at Mile 781 on May 1954 and December 1956

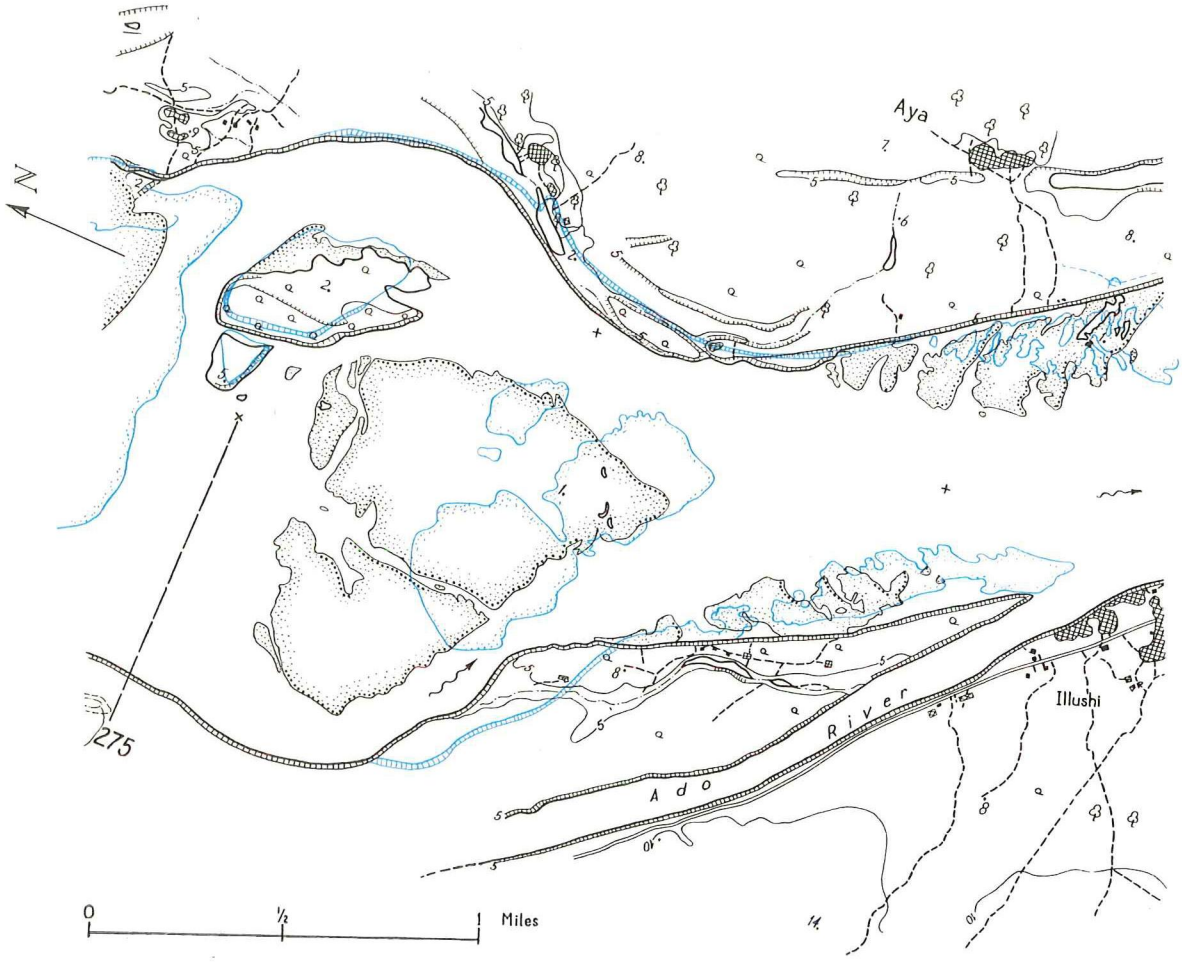


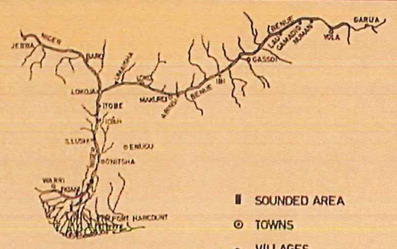
DIAGRAM 6.2.5-3

The Niger at Mile 274 on May 1954 and December 1956

changes are remarkable, i.e., the opening of a former channel through the island, and the shifting bend around the NW end of the island. Both cases of erosion occurred in sandy banks, and hardly any erosion is noticeable along the firm clay banks which form the northern and southern boundaries.

Diagram 6.2.5-2 concerns the Benue at Mile 781, just upstream of Lau. This represents the case of two channels, one on each side of an elongated island. As the northern channel became choked at the upstream end and the southern channel at the downstream end, conditions became favourable for a short-cut through the island. At the weakest point a former channel was opened up in the reverse (northerly) direction and this gap widened rapidly, both by scour and lateral erosion.

Diagram 6.2.5-3 shows the Niger at Mile 274, just upstream of Illushi, where the small Ado Creek debouches. In this part of the river the bed widens abruptly below an enormous sand-bank, and the flow is split by a number of bars and shoals which, in turn, entail a further widening of the bed, notably along the sandy western bank. Once this narrow spit will be broken through it is expected that the main flow of the river will take a westerly course through the mouth of the Ado River and the eastern part will be left to siltation. In that way the present difficult situation might be brought to an end.



NDONI

ISARA

GAUGE

ABOH

176

178

179

180

181

182

184

185

BANKS AND ISLANDS
0 ft
6 ft
9 ft
12 ft
18 ft
24 ft
30 ft
36 ft
42 ft

0 0.5 1 MILE

DIRECTION OF CURRENT

NEDECO NIGER / BENUE	DIAGRAM III. 6.3.1-1
SOUNDING ABOH / NDONI	
MILE 176-185	

UMUNANKWO

OSEMERI

+211

+210

+209

+207

+206

+205

JERBA
BARO
LOKOJA
MAKURDI
GASSOL
GAMADIO
NUMAN
GARUA
DOMA
ILLUSHI
ENUGU
ONITSHA
WARRI
ABOH
PATANI
PORT HARCOURT

SOUNDED AREA
TOWNS
VILLAGES

0 0.5 1 MILE

BANKS AND ISLAND
0 ft
6 ft
9 ft
12 ft
18 ft
24 ft

NEDECO NIGER / BENUE	DIAGRAM III, 6.3.1-2
SOUNDING OSEMERI / UMUNANKWO	
MILE 205 – 213	

These few examples may suffice to show how the alignment of river channels can be changed by erosion. In each case the changes were brought about by the erosion of exposed sandy banks. The erosion of clayey banks is less spectacular, the more so as the point of attack moves downstream together with the moving sand-banks. But in the long run even clay banks are forced to recede.

The rate of erosion along deep channels is subject to a number of conditions, such as direction, duration and force of the attacking current, and resistance of the soil. A few average yearly figures are given here, with the proviso that there are many exceptions known:

erosion by parallel current:	sandy banks 20—50 metres
	clayish banks 2—5 metres
erosion in river bends:	sandy banks 40—100 metres
	clayish banks 4—10 metres
	(1 metre = 1.1 yard)

For reference it may be quoted that erosion of bends along the Mississippi River in many cases has been recorded as 300 metres (or yards) per year.

From the above, it is clear how bank erosion may influence the alignment and the flow pattern locally. The effect is more marked still in river-stretches where, over long distances, the banks consist of very erodible material. There the profile will become shallow and wide, and full of bars and banks which are equally easily erodible. Under these circumstances the channels will become highly unstable and, quite another effect, in the wide bed the range between high and low water may be less. This system again may give rise to a more easy vegetation in the banks. These aspects, however, have already been discussed in more detail in the previous paragraphs, and particularly in 6.1.5, dealing with the effects on the cross-section.

6.3. COMPOSITE CHANNELS

6.3.1. Sounding charts

A sounding chart gives a complete view of the river aspects. In contrast to the simplifications made for the discussion of channels in the preceding Sections, the sounding charts show the complexity of the bed formation. But in spite of this, it remains clearly visible that deep channels are attracted by resistant banks, that the channels show a meander pattern, and that the navigation conditions are worst on the crossings.

Bends, and consequently curved flow-lines as a result of bed and bank formation and also straight sections in a river, have been discussed in 6.1 in their relation to the cross-section (depth and width). In these theoretical considerations simplifications were necessary and the results thereof should be adapted and modified when they are applied to the natural river, which is a complex system of straight and curved flow.

Sounding charts are essential for the design of river-training works, as the bed formation, hidden below the water-surface, is a determinant factor in the lay-out of river works. Diagrams 6.3.1-1 and -2 give examples of such sounding charts, whilst other examples can be found, for instance, in 6.5. Many parts of the rivers have been charted in this way, as shown on Diagram VI, 3.1.3-1.

Detailed measurements necessary to construct these charts are not given here; it is considered sufficient to give contour-lines at three or six-feet intervals. Many of such sounding charts surveyed during the Investigation remain with the Inland Waterways Department at Lokoja and contain detailed figures of sounded cross-sections every 100 to 500 feet on a much larger scale. The sounding procedure applied has been discussed in II, 3.6.3.

From repeated soundings the channel deformation and shifting as well as sand-bank movement can also be studied. Whenever river-works are contemplated, it is of importance to construct sounding charts and to extend them upstream and downstream of the proposed area of construction, so that also a clear insight is gained into the approach and outlet of the flow. It should be mentioned, however, that any proposal for the lay-out and construction of works should be modified with the change of bed formation in the course of time. Sometimes, therefore, it will be important either to start the execution immediately or to wait some years to be able to force the river into the most suitable channels with the least construction costs. Examples of bed-regulation near Kelebe and near Onitsha have been given in VI, 6.4 based upon sounding charts. These examples have also been used for the rough calculation of the costs of river-training works on which some recommendations in this Report have been based.

6.3.2. Talweg and hydraulic axis

The conception of talweg and hydraulic axis is used in various parts of this Report to describe phenomena related to the mechanism of the river. Each of these conceptions is in itself a simplification and a précis of the intricate system of river flow, both of water and sand, but in many instances they fail to define exactly what is meant or are susceptible to several interpretations. Therefore a further discussion of such conceptions may give a better insight into their purport.

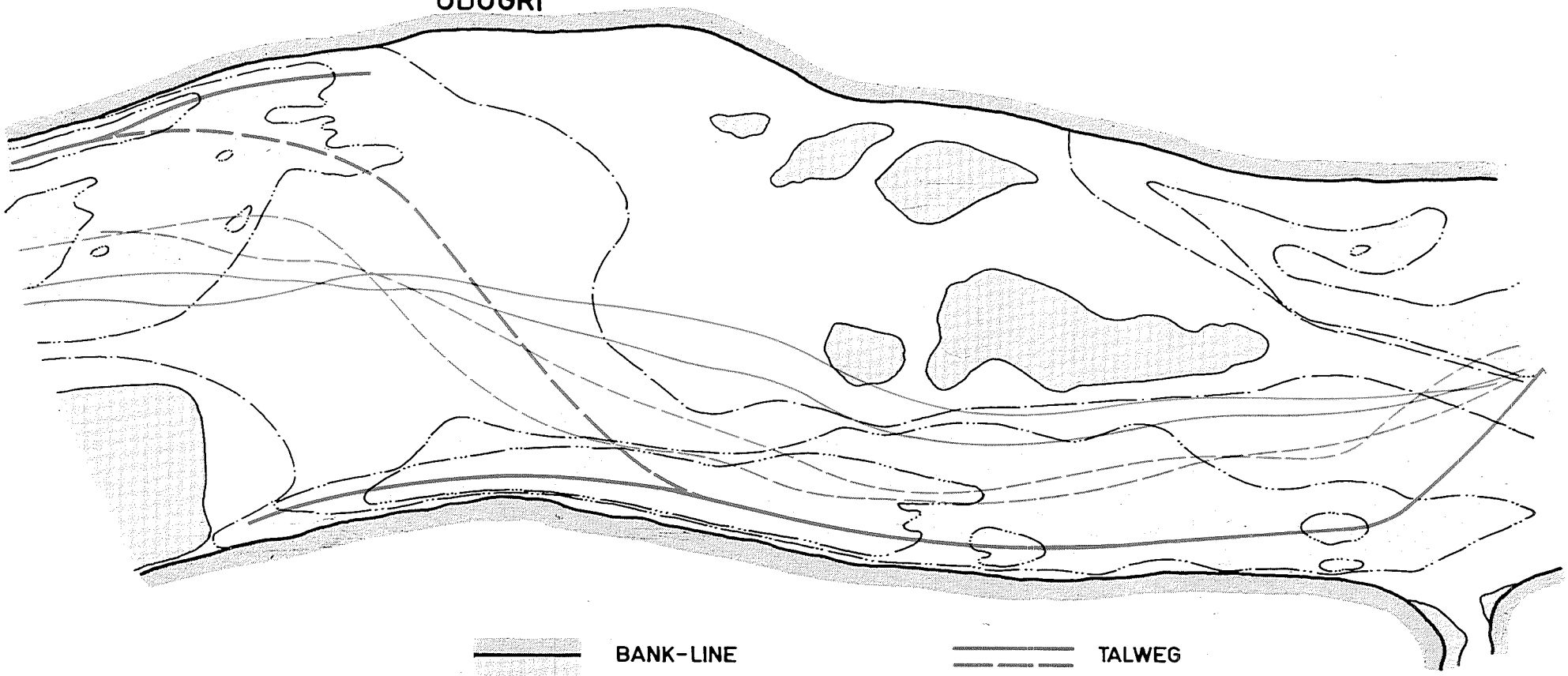
The talweg in a river is the line which connects the deepest points in consecutive cross-sections at a certain stage of water-level. This definition fails to show a continuous line when the cross-section shows several maxima; the talweg line is then discontinuous, which will especially be the case in a braided river and to a less extent near a crossing. Originally the talweg has probably been a further description of the course of the river, which in some instances was not well enough defined by the course of the bank-lines, while it also gave an indication of the best sailing route for ships, although it failed to do so between two well-developed channels where a discontinuity in the talweg exists.

Therefore the definition of talweg would need an amplification to show a continuous line between two independent channels, and should then read: the talweg between two independent channels is the continuous line through the deepest possible points, so chosen that the minimum depth in that line is the maximum possible. This definition of the talweg between two channels may still show a very crooked course which is not navigable for ships. However, for the determination of the least available depths (L.A.D.) it has been normal practice to follow a course which is navigable for ships and which then in some instances may considerably diverge from the talweg. In this Report these two conceptions of talweg and best navigable sailing route have been used more or less interchangeably (Diagram 6.3.2-1).

Although the talweg long ago might also have had a hydraulic meaning, a better conception in this respect has been found in the hydraulic axis. McMATH (1 has described the hydraulic axis as the line formed by connecting points which were established by dropping verticals through the centres of gravity of consecutive cross-sections, each vertical cutting its cross-section into equal areas passing roughly equal volumes of flow.

This definition is not considered completely correct. If equality of volume of flow on either side of the hydraulic axis is indeed the criterion, it is essential to describe the centre of gravity of the mass of flow, which includes velocity and not solely the size of the cross-section. This involves the determination of the hydraulic axis to be based on the term $\Sigma\, ba^{\frac{3}{2}}$, which should be equal on either side of the vertical of gravity, by which it is assumed that the slope each in cross-section is equal over the full width. McMath used in fact Σ ba as the criterion. In Diagram

(1 in a Report of the Mississippi Commision, 1881



BANK-LINE

L.R.L.

L.R.L. - 6'

L.R.L. - 12'

L.R.L. - 18'

TALWEG

HYDRAULIC AXIS

BANKFULL
L.R.L.
Σ ba$^{3/2}$

BANKFULL
L.R.L.
Σ ba

NEDECO NIGER / BENUE	DIAGRAM III, 6.3.2-1
TALWEG AND HYDRAULIC AXIS (ODUGRI MILE 188)	

6.3.2-1 the hydraulic axes derived from both methods are indicated for water-levels at Low River Level (L.R.L.) and at bankfull stage. In most instances the location of the lines do not differ much, although the developed length along the hydraulic axis according to $\Sigma\, ba^{\frac{3}{2}}$ will be slightly longer than according to Σ ba.

It is the pronounced difference between the H.W. and the L.W. hydraulic axes which is considered the basic cause of the difficulties encountered by navigation on shallow rivers. The H.W. and L.W. hydraulic axes show on the crossings a marked intersection. This means that the H.W. and L.W. flow-patterns attempt to shape the river-bed on crossings in a different way. The hydraulic axis at high water lies somewhere near the centre of the river parallel to the banks while the line of gravity of the low flow crosses the river at several locations, generally between sand-banks. These two deteriorate each other's bed formation, resulting in an area on the crossing without well-defined channels.

It should be noted that the H.W. and L.W. hydraulic axis change into one another gradually with the changing water-levels and that a certain difference in time is present between the occurrence of the one and the other. During this time the bed-shape has changed and sand-banks have moved forward so that, to indicate the intersection of the two hydraulic axes, it would have been better to use two sounding charts of the same area, one during H.W. and one during L.W. However, as the H.W. hydraulic axis will always be somewhere near the middle of the river parallel to the banks, there is no doubt about this intersection. The further consequences for the talweg of such crossing hydraulic axes at different water-levels have been discussed in Section 6.4.

A better navigable river would result if both L.W. and H.W. hydraulic axes would coincide to a greater extent, a condition which should be aimed at when designing bed-regulation works. The conflicting tendencies of low and high water are then minimised.

A normal river changes the length of its hydraulic axis in the course of time, but, averagely seen over a longer period, these changes are limited. A strongly meandering river will lengthen its course by the development of wide meanders, but shorten it again by short-cuts.

6.3.3. Meander-coefficients; radius of curvature

Both the Niger and the Benue are flowing between H.W.-banks which are essentially straight (in contrast, for instance, to the Mississippi which is by nature a meandering river). Exceptions to this straightness are usually caused by fixed points in the banks such as autochtone protrusions. Only on the lower part of the Niger, below Aboh, has a natural meandering developed; this section can, however, be considered as part of the Delta (see Section 2.4) and both slope and sediment are of a different character. The winding Faro—Garua section is a special case, and will be discussed in 6.5.1.

In between these straight banks during the H.W.-period a bed formation is moulded, showing to a certain extent a meandering pattern, which becomes exposed during the subsequent L.W.-period. The ratio of the length of the sinuous talweg and the rather straight centre-line of the bankfull river is termed here the meander-coefficient. The talweg is determinant for the L.W. characteristics of the channel, whereas the H.W. characteristics are more or less linked with the centre-line parallel to the banks. For shipping the talweg is significant; only during high water can it be ignored and may a straight course be taken.

In Table 6.3.3-1 meander-coefficients are given for the various (arbitrarily chosen) river-sections. The lowest figure is found for the upper part of the Benue between Garua and the Faro Confluence, where the meandering river is so narrow that centre-line and talweg practically coincide. A more or less similar case is met on the lower part of the Niger between Aboh and Onnya, where also the obtaining conditions are favourable for meandering and where high and low-water bed fairly coincide. The meander-coefficient as used here does not, therefore, indicate the degree of meandering of the high-water bed with respect to an imaginary straight line.

TABLE 6.3.3-1

CHANNEL SINUOSITY

section		MILES		meander coefficient L.W./H.W.	number of crossings	number of H.W. miles per crossing
		L.W. talweg	H.W. centreline			
	NIGER					
Patani	— Onnya	22	20.2	1.09	14	1.4
Onnya	— Aboh	24	22.8	1.05	11	2.0
Aboh	— Umunankwo	32	28.5	1.12	15	1.9
Umunankwo	— Onitsha	22	19.5	1.13	10	1.9
Onitsha	— Illah	25	22.5	1.11	13	1.7
Illah	— Illushi	16	14.7	1.09	10	1.5
Illushi	— Idah	38	31.8	1.19	15	2.1
Idah	— Itobe	22	20.3	1.08	14	1.9
Itobe	— Lokoja	30	28.4	1.06	14	2.0
Lokoja	— Baro	72	64.2	1.12	41	1.6
	totals	303	273		157	
	average			1.11		1,75
	BENUE					
Lokoja	— Umaisha	39	34.8	1.12	14	2.5
Umaisha	— Bagana	33	27.8	1.19	15	1.8
Bagana	— Loko	20	17.7	1.13	7	2.5
Loko	— Makurdi	57	51.0	1.12	27	1.9
Makurdi	— Abinsi	17	15.8	1.08	9	1.8
Abinsi	— K'Ala Confl.	9	8.0	1.12	5	1.2
K'Ala Confl.	— Tunga	41	37.5	1.09	31	1.2
Tunga	— Ibi	36	35.4	1.02	21	1.7
Ibi	— Donga Confl.	20	17.2	1.16	8	2.1
Donga Confl.	— Taraba Confl.	38	34.2	1.11	21	1.6
Taraba Confl.	— Angwan Taru	10	9.2	1.09	5	1.8
Angwan Taru	— Kamberi	14	13.0	1.08	5	2.6
Kamberi	— Kw. M. Biu	23	21.0	1.09	17	1.2
Kw. M. Biu	— Kw. Muri	38	33.4	1.14	25	1.3
Kw. Muri	— Lau	20	18.5	1.08	16	1.2
Lau	— Jen	22	17.6	1.25	17	1.0
Jen	— Gamadio	16	14.4	1.11	12	1.2
Gamadio	— Numan	31	28.0	1.11	22	1.3
Numan	— Geren	22	19.4	1.13	18	1.1
Geren	— Yola	20	17.8	1.12	16	1.1
Yola	— Faro Confl.	38	36.6	1.04	29	1.3
Faro Confl.	— Garua	46	45.0	1.02	23	2.0
	totals	610	524		340	
	average			1.14		1.55

Low values are found also in the Rocky Section Itobe—Lokoja, where the valley width does noth generally permit a sinuous talweg to develop. Figures of about 1.12 are most commonly found, and averages are near this value. Exceptionally high figures are found in the sections Umaisha—Bagana, where the talweg curves around many islands, and Lau—Jen, which is a very tortuous channel indeed.

The same Table shows the number of crossings counted in each section, the total for the Niger and Benue amounting to 500, most of which have some peculiarity or other, and all together form a burden to the pilot's hand. It is noticed that the number of crossings is practically invariable. Even if the meandering system moves downstream and some crossings, thereby, will be crushed or dissolved, other crossings will develop more upstream and make up the number.

The number of crossings per mile differs considerably, however, in different parts of the rivers.

But it must be observed that most crossings are connected with meandering and that more meanders per mile will develop in a small-size river-section or in a bifurcated river along an island than in a one-channel section of a lower river. This is clearly seen from the figures shown. Remarkably few crossings appear on the sections Itobe—Lokoja (narrowed rocky section), Ibi—Donga Mouth (wide loops and straight clay banks), Angwan Taru—Kamberi (no obvious explanation) and Faro Mouth—Garua (large-scale meandering). A large number of crossings occur on the sections Illah—Illushi (continuous meandering within the H.W.-bed), Idah—Itobe (the same), Katsina Ala Mouth—Tunga (the same) and Kamberi—Faro Mouth (small-size river).

From a point of navigation preference is given to a channel which is either straight or regularly meandering, which means mathematically a channel with a low meander-coefficient or a high number of miles per crossing (this figure to be seen with regard to the size of the river).

"Meander-coefficient" is a term used in the case of channels which are not straight, although it is not imperative that such channels should be regular meandering channels: they may be winding or tortuous in an irregular way, and still the term meander-coefficient would apply.

The curvatures of bends (i.e., the curvature of the talweg) — whether meandering or not — are found to vary a great deal both in shape and size. It is namely a matter of the angle and the force of attack and the resistance of the bank against such attack which determine the resulting curvature.

Possibly the shortest bend on the Lower Niger is found at present near Kokoin (Mile 322) where at L.W. a radius of 800 or 1,000 feet has to be negotiated by the ships. Still more difficult is the bend near Garua in the Benue (Mile 962) with a radius of not more than 700 feet. In both cases rocks are preventing a full development of the curvature. Near Gbekebo (Mile 60) an equally difficult point is found with a radius of 800 feet.

On the other hand, there is no minimum curvature. Some bends, according to the alignment of the channel, practically coincide with straight banks.

Attempts have been made to determine mathematical relations between the curvature of meandering banks and the amount of flow, but this succeeded only in special cases, i.e., where there was a uniform flow and a specific size of the particles which constitute the bed and the banks. In the cases of the Niger and Benue these conditions are not satisfied. The flow, far from being uniform, is variable to a considerable degree, and each size of flow tends to mould a corresponding size of curvature. Also the size of the particles which constitute the banks varies over a considerable range. It is not surprising, therefore, that only widely-scattered results could be obtained; the more so as other irregularities in the alignment of the rivers have influenced the processes.

It was observed, however, that curvatures whose development was frustrated by the composition of the banks often gave rise to "bad" crossings. After discarding the composite river-sections, observations led to the conclusion that wherever the radii of curvature exceeded certain values, the depth of the ensuing crossing was favourable.

It appeared then that for a 10′ channel at L.R.L. the critical radius amounted for the Upper Niger (Baro—Lokoja) to 1,000 m (3,300 feet) and for the Lower Niger (Lokoja—Samabri) to 1,800 m (6,000 feet). In the case of the Benue no suitable data for a similar evaluation were available, nor were they required as a base for the design of river-works, as these are not contemplated for this river. It must be observed in this connection that training-works could allow for smaller radii and similar results if thereby erosion in the bend would be reduced.

A further elaboration of the above minimum radii showed that these observations are not contradictory to the suggestion made, for instance, by INGLIS ([1] that the dimensions of meanders

([1] INGLIS, 1947. MOR. 13

are generally proportional to the square root of the discharge. If in the case of the Niger the bankfull discharge was taken at 6,000 m^3/sec for the Upper Niger and at 18,000 m^3/sec for the Lower Niger, the said relation is found to follow the formula

$$r = 14 \sqrt{Q} \text{ (for the metric system)}$$

or

$$r = 7.3 \sqrt{Q} \text{ (expressed in feet and cusecs).}$$

It must be observed that a clear-cut scientific approach in natural rivers is extremely difficult due to the large number of coexisting influences.

6.3.4. Channel roughness

The bed of the river, as any surface, is not completely smooth. Water particles flowing closely along the bed will feel resistance against their motion. By the viscosity of the water this resistance is transferred onto the water particles in higher layers (internal friction). Thus two forces exert their influence upon the moving mass of water, viz., the gravity force in downstream and the resistance in upstream direction, the latter being dependent on the velocity e. Equilibrium will be established at a specific value for v. The smoother the bed is, the higher the velocity can be. Consequently a river with a smooth bed will have a relatively small depth.

Roughness orginates from two causes, namely:

(i) The granular composition of the sediment. If the bed material were spread quite evenly, the roughness would have a specific value, dependent on the size of the grains. It is often accepted that for a mixture of various sizes the average roughness can be expressed as the diameter d_{90} (see 5.1.2). The roughness expressed in this way has a dimension of a length, for instance, mm; it is symbolised by k_s, and is called the grain roughness.

(ii) The shape of the bed as a whole. A sudden widening of the bed, the existence of a deep channel and a shallow sand-bank, the horizontal curvature of the flow and the composition of the banks all have influence upon the resistance of the bed against movement of water. But most of all, and also most frequently occurring, the existence of ripples, dunes or ridges on the river-bottom determines the total roughness. The exact value cannot be derived theoretically, but must be measured or estimated. This total bed roughness k_r includes, of course, the grain roughness k_s.

Generally speaking, resistance causes transfer of energy into heat generated by the friction of water particles along each other and along solids of the bed. It is well known that, especially at places where the velocity is suddenly decelerated, the turbulence involves mutual friction between the water particles at such a rate that loss of energy here is considerable. Sudden deceleration of velocity occurs in many circumstances, in the first place mostly where man has intervened in the natural course of a river. But also a ripple on the river-bottom (which is a completely natural occurrence) decelerates the velocity. Even the huge sand-banks, dry at low water but flooded at the high stages, cause resistance of this kind. It has been observed on the Niger that the streamlines over the sand-bank and downstream therefrom are nearly straight, from which it can be concluded that the velocity immediately below the sand-bank must decelerate considerably (see 6.4.2).

Obviously the grain roughness k_s has a fixed value for a specific river-section where the sediment does not vary, but the magnitude of the bed roughness k_r may change from place to place and from time to time. This is shown in Diagram 6.3.4-1, where for a cross-section near Ibi on the Benue (Mile 614) the value for k_r has been plotted against the discharge Q. It is concluded that the roughness tends to lag behind upon the varying Q. During the rise k_r is too small and during the fall it is too great. The stroke line in the graph indicates the value for k_r which would

occur with the river-bed in instantaneous equilibrium as computed from an assumed unique and smooth relationship between Q and the basic data of the cross-section. The influence of this lagging behind upon the discharge Q is only about 2%, which is less than the measuring accuracy.

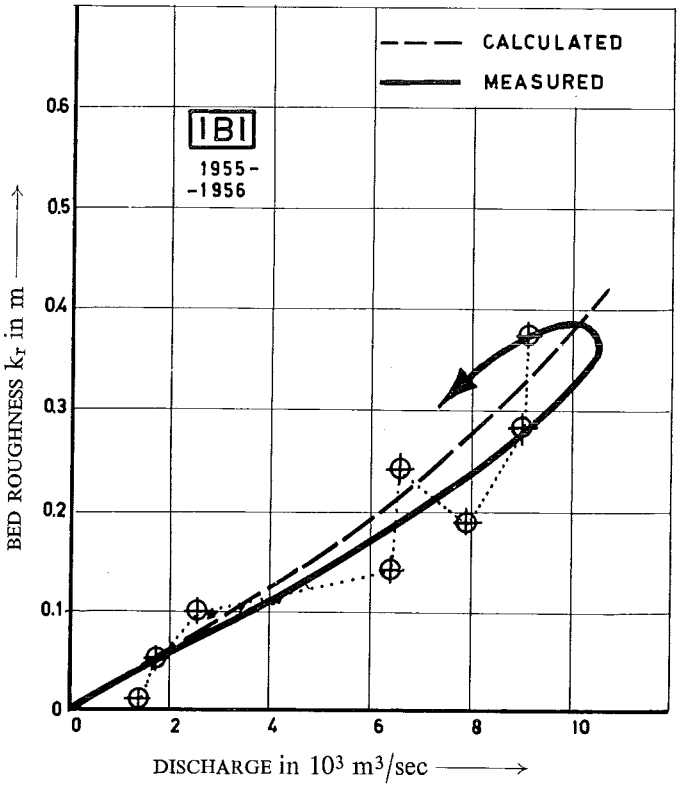


DIAGRAM 6.3.4-1

Relation between channel roughness and discharge as computed for Ibi (Benue, Mile 614)

In 4.3.1 the discharge formula of STRICKLER

$$v = \frac{\varepsilon}{k^{\frac{1}{6}}} R^{\frac{2}{3}} i^{\frac{1}{2}} \qquad \ldots\ldots\ldots (1)$$

has been mentioned. Here k stands for k_r as the formula should be applicable for measurements on the river. It is, however, hypothetically possible to change k_r into the grain roughness k_s provided also that the hydraulic radius R is adjusted to keep the velocity v at the same value. The formula is then

$$v = \frac{\varepsilon}{k_s^{\frac{1}{6}}} R'^{\frac{2}{3}} i^{\frac{1}{2}} \qquad \ldots\ldots\ldots (2)$$

where R′ is the so-called reduced hydraulic radius, being the hypothetical value if the bed roughness is composed of the grain roughness only.

An evaluation of the influence of the roughness upon the water depth is obtained by introduction ([1] of the ripple factor μ, where

$$\mu = \frac{R'}{R} \qquad \ldots\ldots\ldots \quad (3)$$

From the foregoing it can be derived that

$$\mu = \left[\frac{k_s}{k_r}\right]^{\frac{1}{4}} \qquad \ldots\ldots\ldots \quad (4)$$

A greater bed roughness means a lower value for the ripple factor μ and consequently a greater hydraulic radius R (= depth a).

Apart from the roughness the inverse is in use, namely, the discharge coefficient as proposed by DE CHEZY in his formula (see 4.3.1)

$$v = C\sqrt{Ri} \qquad \ldots\ldots\ldots \quad (5)$$

where

$$C = 5.75\sqrt{g}\,\log\frac{12\,R}{k_r} \qquad \ldots\ldots\ldots \quad (6)$$

Here also two different values for C are possible, one being the actual discharge coefficient in the river as determined from measurements, and the other a theoretically derived value for a hypothetical river-bed without ripples. The latter value can be found with

$$C' = 5.75\sqrt{g}\,\log\frac{12\,R}{k_s} \qquad \ldots\ldots\ldots \quad (7)$$

Based on this difference, the ripple factor μ' can also be derived from the discharge coefficient. It is then

$$\mu' = \left[\frac{C}{C'}\right]^{\frac{3}{2}} = \left[\frac{C}{5.75\ \sqrt{g}\ \log 12\,R/k_s}\right]^{\frac{3}{2}} \qquad \ldots\ldots\ldots \quad (8)$$

It appears that the ripple factor derived with this formula, μ', is not exactly equal to the former one, μ, due to the difference between the formulae of DE CHEZY and STRICKLER (see 4.3.1). The ripple factor μ', derived from De Chezy, seems to be preferable. To make an easy computation of μ' possible, Diagram 6.3.4-2 has been constructed, giving the value for μ' (henceforth denoted by μ) as a function of C and R/k_s.

The results of computations on observations in Niger and Benue have been collected in Table 6.3.4-3. It gives an idea about the magnitude of C, μ and k_r on these rivers.

The ripple factor exerts its influence not only upon the depth of the river, as stated above, but also upon the sand-transporting capacity S (see 5.2.1). In the formula for S the μ has an important position within the term $\frac{\mu ai}{\Delta d}$

It is generally accepted that sand-transport takes place in the form of dunes and ripples (see 5.4.3). The greater the sand-gransport, the larger are the ripples. These ripples cause turbulence and give resistance against the water flow and the bed roughness k_r is for a great part determined by the size and shape of these ripples. A quantitative relationship between k_r and the bed-ripples has not been analysed, but it would follow that k_r could only increase with increasing discharge Q, or at least remain constant, but would not decrease. This assumption is not proved; on the contrary, some authors ([2] arrived at the conclusion that k_r would be inversely proportional to

([1] FRIJLINK, 1952. MOR. 10
([2] BRETTING, 1958. MOR. 2

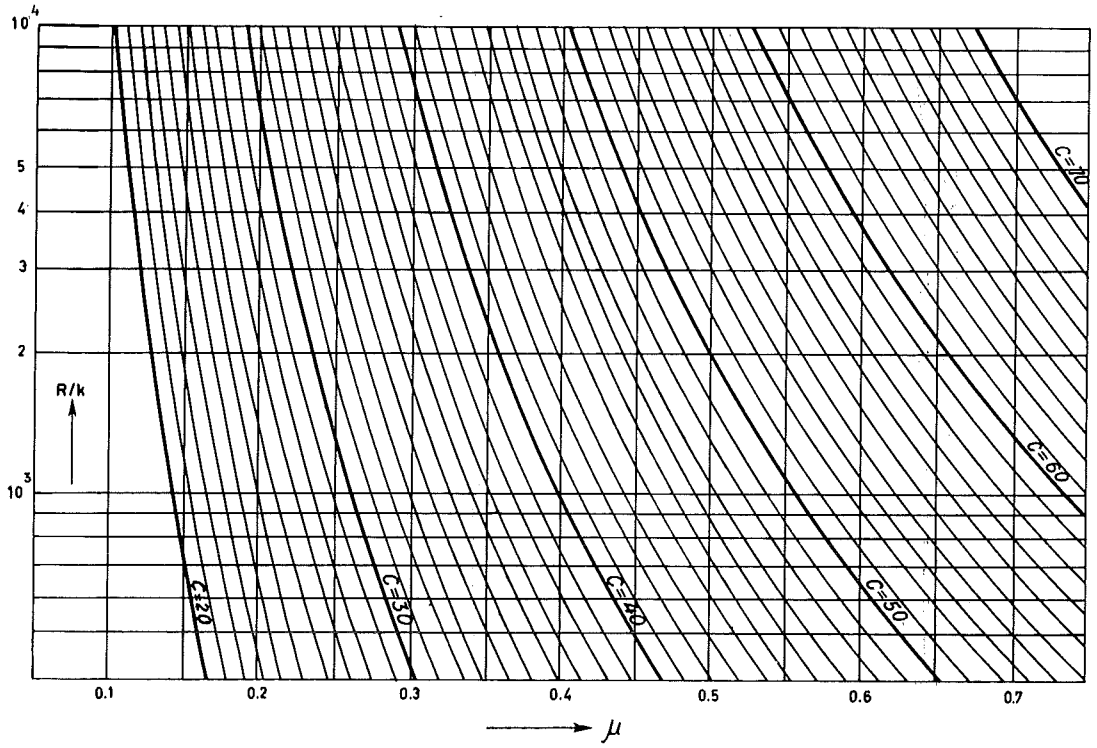


DIAGRAM 6.3.4-2

Ripple factor μ *as a function of* $\frac{R}{k}$ *and* C

TABLE 6.3.4-3

VALUES FOR C, μ AND k_r IN THE VARIOUS STATIONS

station	mileage	C ($m^{\frac{1}{2}}$ sec^{-1})			μ			k_r (m)		
		max.	L.R.L.	min.	max.	L.R.L.	min.	max.	L.R.L.	min.
NIGER										
Baro	428	45	40	39	0.37	0.34	0.33	0.5	0.3	0.2
Shintaku	357	50	44	42	0.46	0.44	0.42	0.4	0.2	0.1
Idah	311	60	48	46	0.56	0.49	0.47	0.2	0.07	0.02
BENUE										
Garua	972	48		38	0.47		0.35	0.3		0.1
Wuro Boki	923	35		30	0.32		0.26	1.5		0.4
Yola	887	39		35	0.35		0.30	0.5		0.2
Numan	843	34		27	0.27		0.24	0.9		0.4
Ibi	612	58		43	0.78		0.46	0.3		0.01
Makurdi	510	31		25	0.24		0.20	2.4		2.4
FARO										
Kossel	932	44		32	0.64		0.31	0.5		0.01
GONGOLA										
Bilachi	851	40		33	0.42		0.36	0.3		0.1

1 $m^{\frac{1}{2}}$ sec^{-1} = 1.81 $ft^{\frac{1}{2}}$ sec^{-1}
1 m = 3.28 feet

the depth a. However, the impression is obtained that such is impossible, and the above-mentioned assumption is maintained.

As the ripple factor μ is a measure for the existence of ripples, which depend largely on the magnitude of sand-transport, it is obvious that a certain interaction exists between μ and the sand-transport. Such an interaction, expressed by

$$\mu = f\left[\frac{\Delta d}{ai}\right] \qquad \ldots\ldots\ldots \quad (9)$$

has been given already by MEYER-PETER AND MUELLER (1 and by FRIJLINK (2 as the results of investigations in laboratories. These functions, denoted as "Zürich" and "Delft" respectively, have been drawn on the left-hand side of Diagram 6.3.4-6.

For stations along the Niger and Benue μ has been calculated from the basic data as given in Diagram 5.2.2-3, and has been plotted against the term $\Delta d/ai$ which is the independently variable parameter in the formulae for sand-transport (see 5.2.2). Every cross-section appears to have a separate line in this graph, given in Diagram 6.3.4-4 and in the first instance no general tendency follows from the result. However, the measurements on the Niger and Benue have been made under the influence of a largely varying discharge Q.

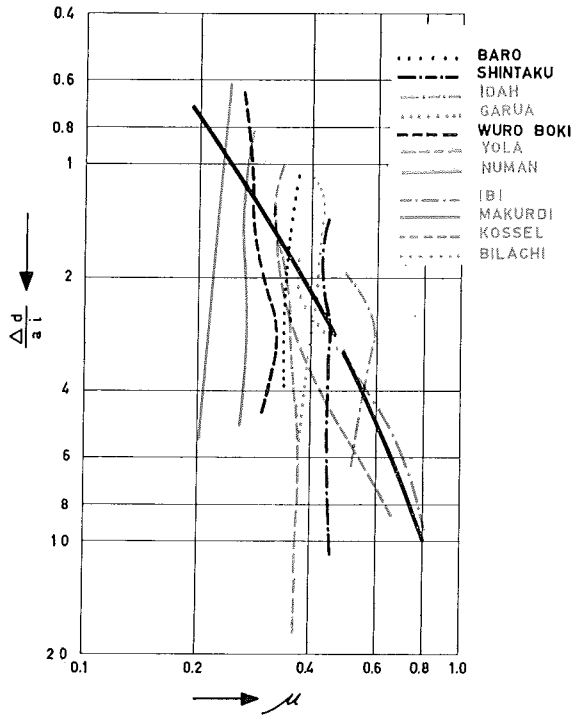


DIAGRAM 6.3.4-4

Relations between μ and $\frac{\Delta d}{ai}$ from observations at various stations

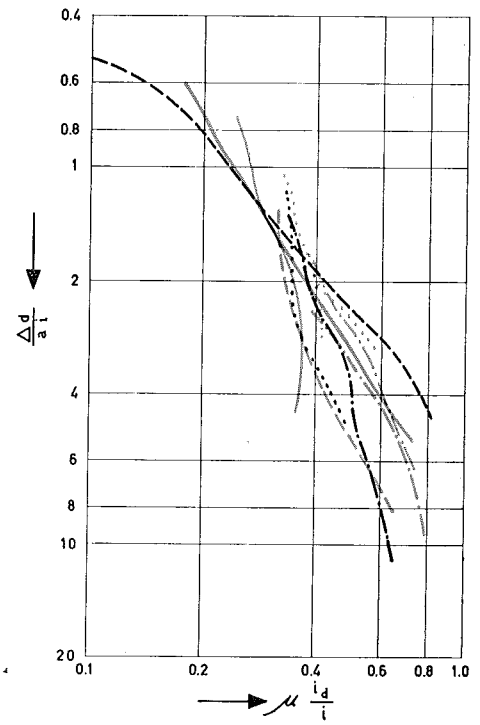


DIAGRAM 6.3.4-5

The function $\mu \frac{i_d}{i} = f\left[\frac{\Delta d}{ai}\right]$ as found on the Niger and Benue

(1 MEYER-PETER AND MUELLER, 1948. MOR. 23
(2 FRIJLINK, 1952. MOR. 10.

A steady stage, as in the laboratories, would possibly give better results in the search for a universal relationship between μ and $\Delta d/ai$. Therefore, in the first instance, on each line (for one cross-section only) the point has been fixed where the discharge Q equals the Dominant Discharge Q_b as defined under 6.1.1. The connection of these points for both the Niger and Benue forms one smoothly curved line, running more or less in the same direction as the lines of Zürich and Delft (Diagram 6.3.4-6).

Now, for those cross-sections where the slope i does not show large variation with Q ranging from very high to very low — as, for instance, in Garua, Ibi, and Faro River — the whole of the line coincides fairly well with the general curve; whilst for cross-sections with a highly variable slope the line deviates considerably. This fact has led to the conception that in the graph the ripple factor μ must be multiplied by the factor

$$\frac{i_d}{i}$$

where i_d is the slope occurring at Dominant Discharge, and i is the local and temporary slope in the measured cross-section. Local, because it is only valid in the cross-section being measured; and temporary, because it is variable with variation of water-level. The slope i has to be measured by levelling over a short distance of not more than some hundred feet only, which is very difficult with respect to the relative accuracy, while variation in the energy height $\frac{v^2}{2g}$ should be taken into account. However, i_d is very well measurable, as from the definition of Dominant Discharge it follows that the water-line is straight and the slope constant over the concerning river-section.

In Diagram 6.3.4-5 the function

$$\mu \frac{i_d}{i} = f\left[\frac{\Delta d}{ai}\right] \qquad \ldots\ldots\ldots (10)$$

has been constructed for the various cross-sections. The lines appear to follow the general trend of that formed in Diagram 6.3.4-4. Deviations could be caused by erroneous basic data (v, b, Q, a, d), by acceptance of an incorrect local slope i, or by the fact that the conception about a universal relation between μ and $\frac{\Delta d}{ai}$ as given by Equation (10) might be wrong. The function (10) is fully experimental and follows from observations on Niger and Benue only and even there it has not yet been proved to be valid universally for all places under all circumstances.

Further investigations on basic data and application onto this conception might lead to very interesting results in bed roughness and its influence upon river behaviour. Two examples of such, behaviour may be mentioned here.

Where a cross-section is situated in a river-section with constant width b, the water-level varies in a parallel way up and down with variation of discharge Q. In that case $i = i_d$ and the ripple factor follows the formula

$$\mu = f\left[\frac{\Delta d}{ai}\right]$$

giving a greater roughness with higher water. When, however, the cross-section is situated in a narrowing, the slope at high water will be steeper, and consequently the ripple factor μ greater, which means a smoother river-bed. Such a phenomenon occurs very frequently in Nature: where boundary conditions are changed, two opposite forces are raised as a result, together establishing a new equilibrium. In this case, the narrowing acts as a resistance to water flow, while the smoother bed is the opposite force permitting the water to flow more casily. In a wide cross-section the reverse occurs: the river-bed has a greater roughness during high-water to act as a resisting force against the easily-flowing water.

The above relation between μ and $\frac{\Delta d}{ai}$ has been drawn again on the left-hand side of Diagram 6.3.4-6, where it is compared with the analogous functions found in Zürich and Delft, both from laboratory experiments under steady circumstances and with a constant slope $i = i_d$.

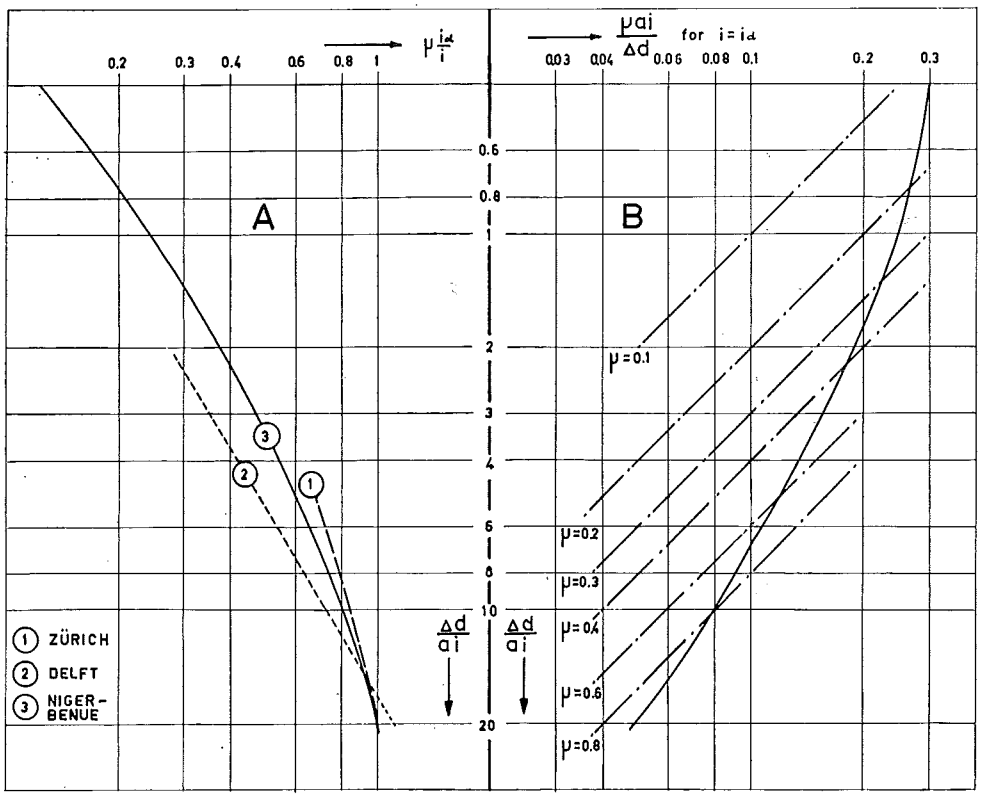


DIAGRAM 6.3.4-6

The experimental function $\mu \frac{i_d}{i} = f\left(\frac{\Delta d}{ai}\right)$ *as found on the Niger and Benue*

For such a steady circumstance or for a river-section with constant width, where $i = i_d$, the relation found between μ and $\frac{\Delta d}{ai}$ can be applied to considerations on sand-transporting capacity, the parameter of which is $\frac{\mu ai}{\Delta d}$. To this aspect, the function

$$\frac{\mu ai}{\Delta d} = f\left[\frac{\Delta d}{ai}\right]$$

has been computed on the right-hand side of Diagram 6.3.4-6, from which the important influence of μ upon the sand-transport can be concluded. With a constant μ one of the straight lines would have been followed, but now it is the curved line giving the relation between sand-transport (expressed by the term $\frac{\mu ai}{\Delta d}$) and the tractive force (expressed by $\frac{\Delta d}{ai}$).

Lastly, it now appears possible to predict DE CHEZY's discharge coefficient of a given section of an alluvial river as a function of i, i_d, d, k_s and a.

6.4. LONGITUDINAL SECTION OF THE RIVER-BED

6.4.1. Talweg profiles

A talweg section is a longitudinal section of the river, showing the bottom line and the available depth of the deepest possible channel at a certain stage of the water-level. The talweg, deep in the bends and shallow on the crossings, is an undulating line on which the smaller wave-lines of the sand ripples are superimposed. The talweg section will be used when determining:
(i) the maximum depth in any cross-section;
(ii) the distribution of the maximum depths over a certain stretch of river and the quality and quantity of the shallow places; and
(iii) the least available depth (L.A.D.) of a river-stretch.

When the talweg has been constructed from a line sounding or from a rough channel sounding, conclusions from the talweg sections should be made with caution, as it is quite possible that the very deepest line has been overlooked so that the talweg section might be too shallow and a discrepancy of half a foot on the shoals and of over a foot in the deeper parts can be expected. If a chart of the river were available showing the depth in every place, it would be possible to determine an accurate talweg section. However, to save time, the talweg sections have often been measured with the use of local knowledge of pilot and surveyor.

If the exact talweg section follows a crooked course, ships cannot possibly sail along this curved route; however, in order to have the least available depth (for shipping purposes) read from the talweg profile, a more straight course is followed in the survey, deliberately deviating from the exact talweg.

As the river bottom is subject to scouring and silting (see 6.4.2), the talweg profile continuously varies in the course of the year, while considerations about the Niger differ from those concerning the Benue.

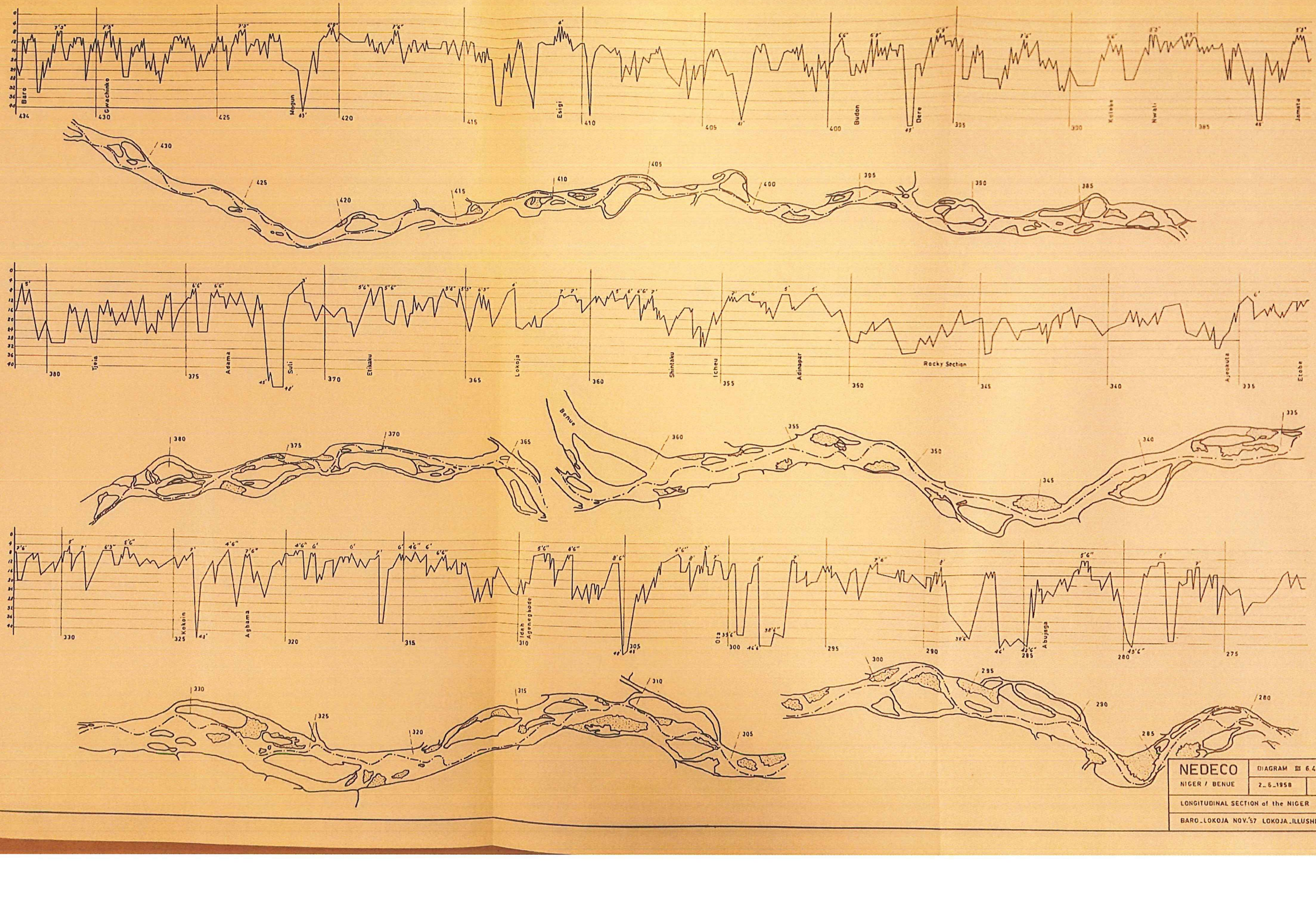
a *The Niger*

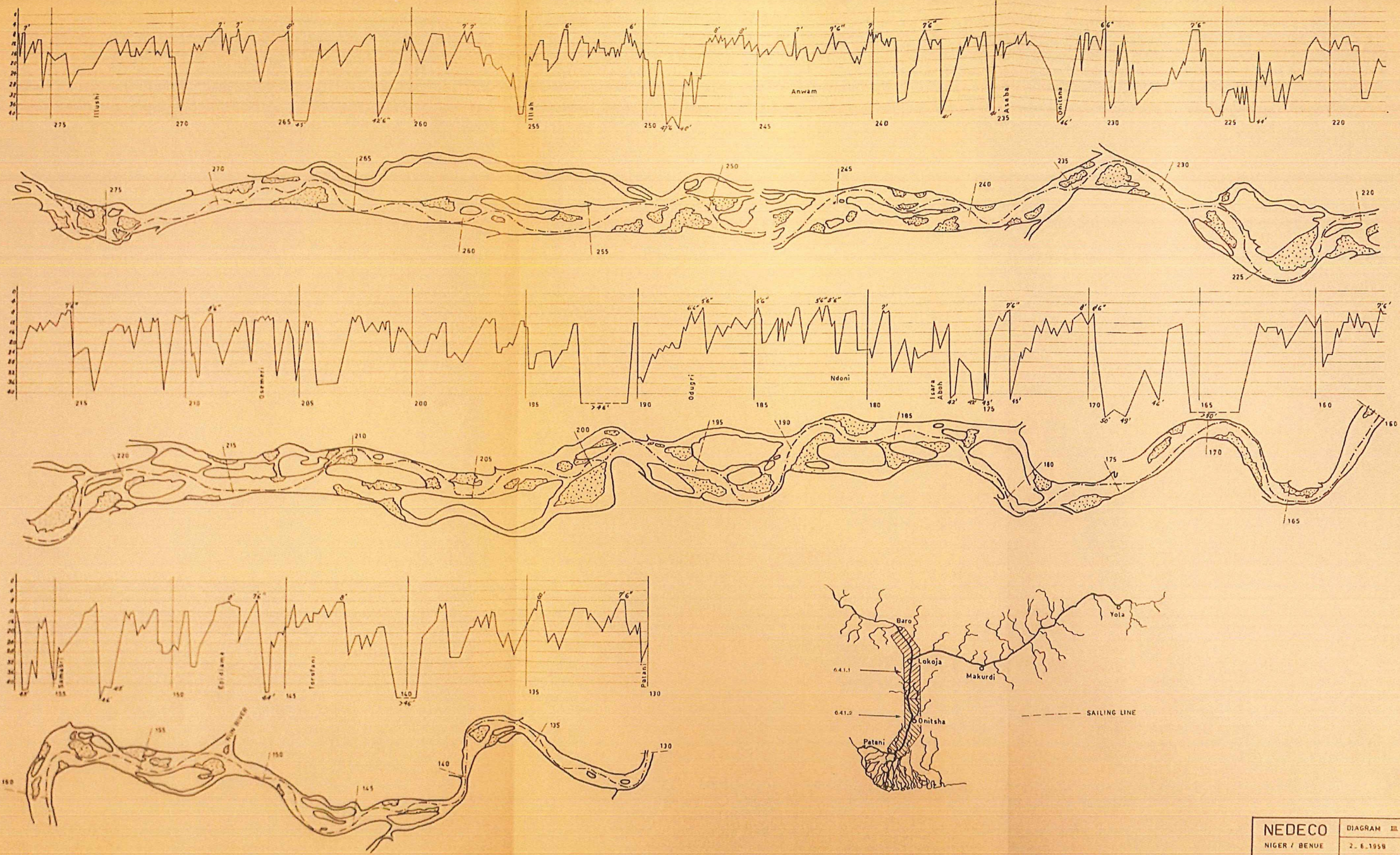
The Niger talweg profile from Baro (Mile 434) to Patani (Mile 130), as reproduced in Diagrams 6.4.1-1 and -2, was surveyed above Lokoja on November 1, 1957 and downstream of Lokoja in July, 1957. Several places of ill-repute, like the flats at Nwali, Adama, Lokoja, Shintaku, Icheu and Kokoin-Agbama, show clearly in the profile. More downstream the L.W. meander length and width increase, as can be seen from the longer deep stretches and the longer crossings.

To compare the talweg profiles the depths are reduced to L.R.L., the reductions varying from place to place owing to the difference in range between H.W. and L.W. To some extent this is taken into account via the data derived from gauges and benchmarks. For intermediate stretches the reductions are interpolated. Though this may be sufficiently accurate at higher river-stages, at the lower stages a relatively steeper slope develops on the crossings and sills, causing incalculable divergencies in the reduction of up to 6 or 9 inches. In the case of a river bifurcated around an island with one branch temporarily blocked by a sand-bank, the water-level can be even more disturbed by backstage, causing differences of up to 2 or 3 feet (see 6.2.2).

Two remarkable stretches are the Rocky Section and the meandering section downstream of Aboh. In the first, the width is restricted by the rocky hills on each side; the width of the river at high and low-water stages is practically the same. The shipping channel hardly crosses from one bank to the other but is determined by the local rocks in the river-bed. This part is characterised by the absence of shallow crossings whilst the depth does not exceed 28 feet.

In the meandering section downstream of Aboh, the deep stretches in the outer bends are clearly visible (see 6.1.2). On account of the normal coincidence of H.W. and L.W. meandering,


Baro
Gwachinko
Mogun
Esigi
Budon
Dere
Kolobe
Nwali
Jamata
Tjeia
Adama
Suli
Etikaku
Lokoja
Shintaku
Icheu
Adinapar
Rocky Section
Ajaokuta
Etobe
Benue
Kokoin
Agbama
Idah
Agenegbode
Abujga
NEDECO
NIGER / BENUE
DIAGRAM III 6.4.1 – 1
2_6_1958
N
LONGITUDINAL SECTION of the NIGER
BARO_LOKOJA NOV.'57 LOKOJA_ILLUSHI JULY'57



NEDECO NIGER / BENUE	DIAGRAM III 6.6.1 - 2	
	2-6-1958	A1
LONGITUDINAL SECTION of the NIGER		
ILLUSHI-PATANI SURVEYED JULY 1957		

835 830 825 820 815 810 805 800

KABAWA FLATS

KABAWA

GINNO

GAMADIO

TUNGALADAN

470′ 465′ 460′ 455′ 450′ 445′ 440′ 435′ 430′ 425′ 420′ 415′ 410′ 405′

H.W

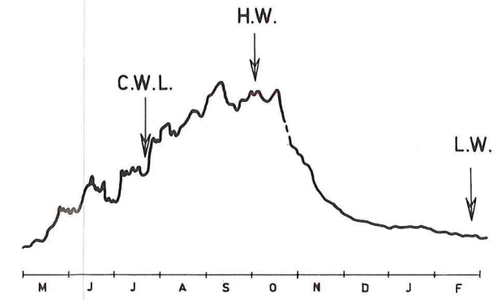
C.W.L.

L.W.

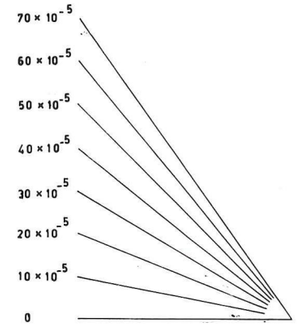
FEET ABOVE M.S.L.

36′ 43′ 32′

TALWEG SOUNDING 20-7-1956



WATERLEVEL NUMAN 1957



SLOPES

LEGEND

H.W. = High Water

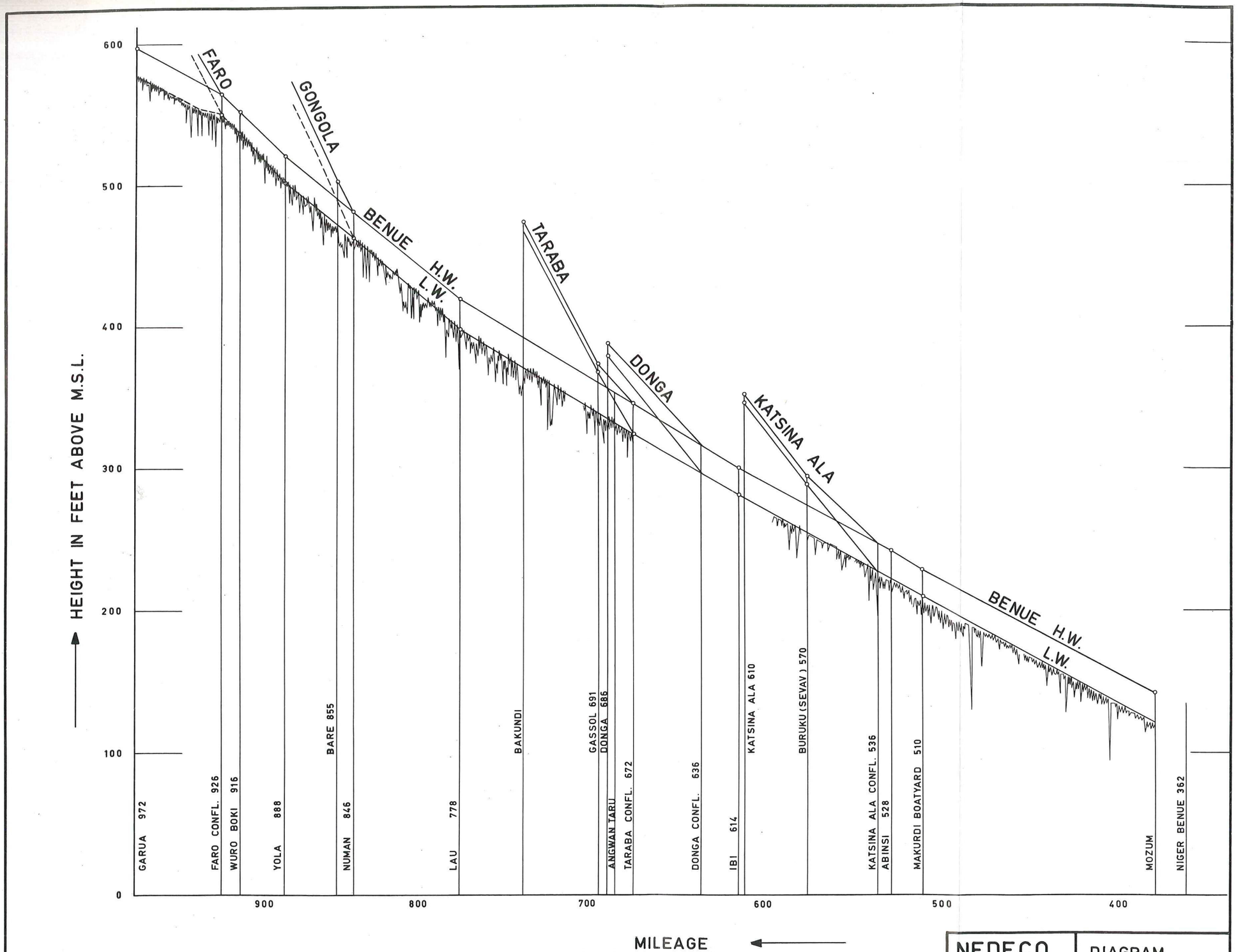
C.W.L.= Corresponding Waterlevel 1957 of Talweg Sounding 1956

L.W. = Low Water

0 ——— 5 MILES

Distances along L.W. Channel

NEDECO NIGER/BENUE	DIAGRAM III 6.4.1-3	
	29-7-1958	A/
LONGITUDINAL SECTION OF BENUE MILE 800-835		



NEDECO NIGER/BENUE	DIAGRAM III, 6.4.1-4
BENUE RIVER	
LONGITUDINAL PROFILE	

and because of the restricted width by the clayey banks, the crossings are relatively deep and long. Downstream of Patani, to Burutu, navigation encounters hardly any trouble. If there is any, it is not due to lack of water-depth but to the narrowness and crookedness of the creeks as well as to cross-currents at bifurcations.

Frequencies of talweg depths for various sections of the Niger are shown in Diagram VI, 4.2.1-1.

b *The Benue*

Of the 610 miles between Garua and Lokoja, 530 miles have been surveyed, some of them more than once.

Diagram 6.4.1-4 gives an impression of the talweg depths compared with the average slope. Between Garua and the Taraba Confluence the shallow parts are generally above the average low-water line. This effect is caused by the heightening of the sills between the time of low water and the date of sounding. The other part, from the Katsina Ala Confluence to Mozum, which has been sounded earlier in the season, does not yet show this effect.

Of the soundings, the stretch between Mile 800 and 835 is drawn in Diagram 6.4.1-3. Gamadio and environment has been chosen because here the water-lines, measured on several occasions, together with the talweg clearly show some peculiarities of the talweg section in general, as well as the situation around the well-known Gamadio Flats in particular. The talweg was sounded on July 20, 1956, and has been plotted against a water-line of 1957. In the date of the water-line (slope) measurement, the Numan gauge reading was the same as in the preceding year when the talweg was sounded.

The deepest parts are always found where the current hugs the clayey bank. The shallow parts are less obviously placed. In general, the crossings are shallow, but also along a straight shore-line a submerged sand-bank may decrease the depth considerably.

The slope on the shallows increases from about 25×10^{-5} at H.W. to around 50×10^{-5} at L.W. Even at the beginning of the shipping season, the slope over the Gamadio Flats is still about 45×10^{-5}. The talweg over the flats is then about 2 feet higher than in February, indicating a silting since L.W.

The range between H.W. and L.W. at the beginning of the Flats is $2\frac{1}{2}$ feet less than just downstream of them. When the height of the crossing at Mile 818 is plotted against the Gamadio gauge, which is placed just below the Flats, the apparent heightening of the sill is then for an amount of $2\frac{1}{2}$ feet due to changes in slope, and the difference in absolute bottom height is $2\frac{1}{2}$ feet less than that derived from the graph.

Very clearly the part between Mile 816 and Mile 821 rises above the general trend of the talweg. The rather even slope at H.W., combined with this elevation of talweg, indicates wide cross-sections, and the discharge needed to obtain the same least available depth is greater than in a stretch with normal cross-sections. The restrictive crossing, that is the crossing determining the limit discharge and the least available depth, is therefore mostly to be found between Mile 816 and Mile 821.

The Benue has been divided into nine stretches, each of them with more or less uniform conditions regarding discharge, slope, and sediment. The talweg depths have been plotted against the local water-level. Contrary to the Niger, they have not been reduced to another water-level (L.R.L.) as for this purpose some hundred gauges or benchmarks would have been needed on the 610-mile stretch instead of the existing ten river-gauges.

To get an idea of the prevailing water-depths in a certain river-stretch, the gauge determinant for that river-stretch has been plotted alongside the frequency curves of the talweg depths

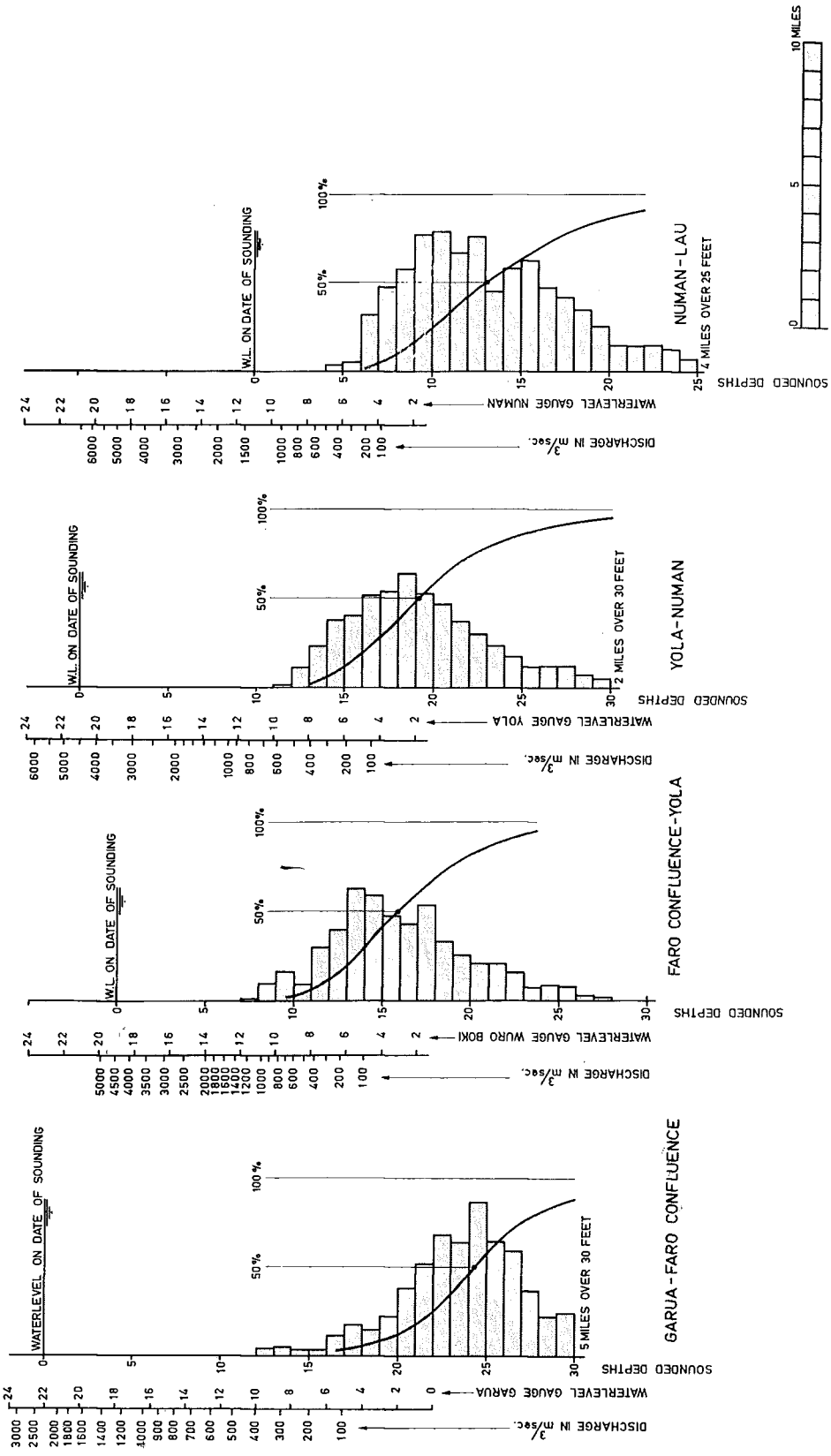


DIAGRAM 6.4.1-5

Frequencies of talweg depths, Upper Benue

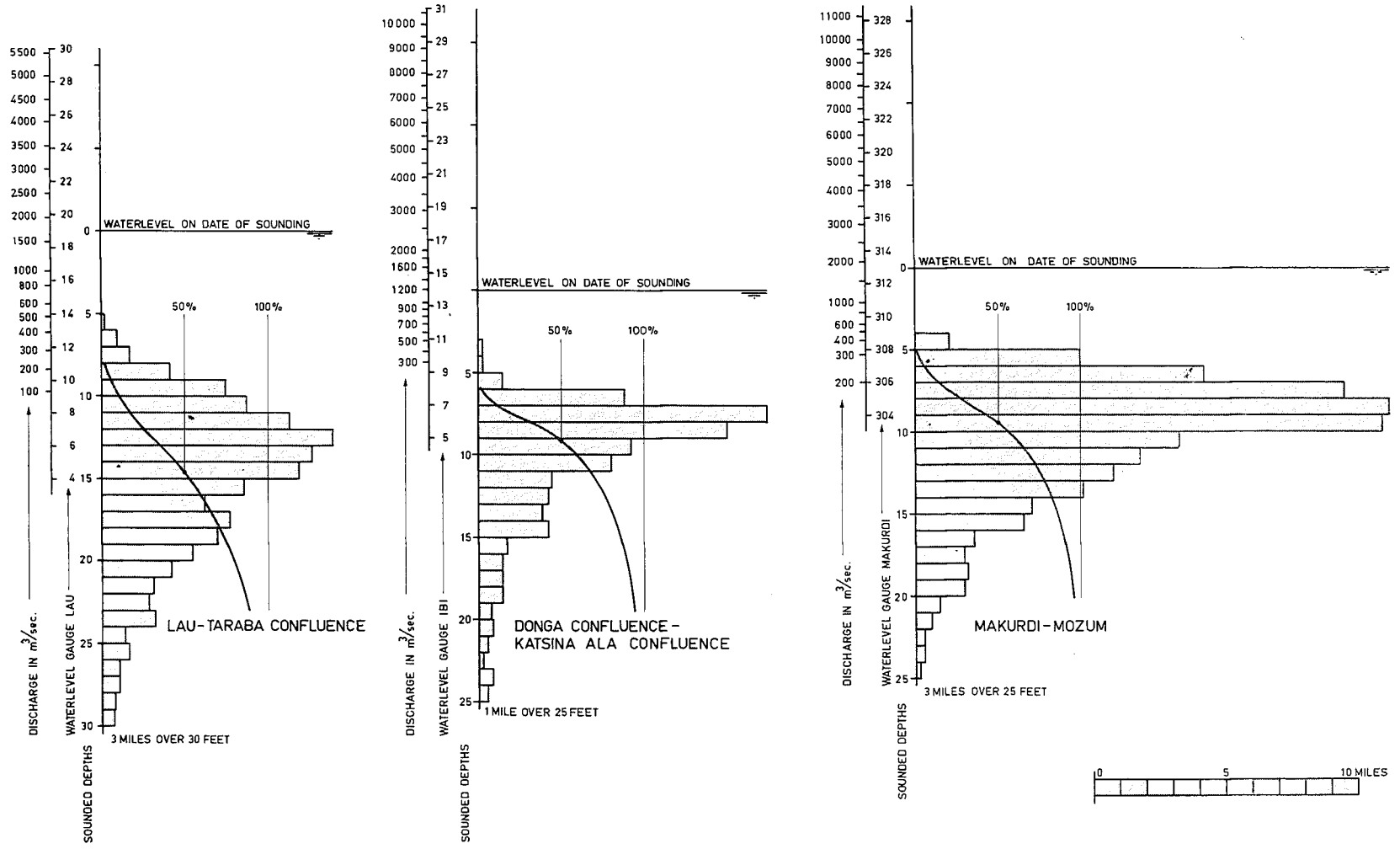


DIAGRAM 6.4.1-6

Frequencies of talweg depths, Lower Benue

(Diagrams 6.4.1-5 and -6). At stages above and below the water-level of the sounding, however, the depths will be subject to changes due to the differences in slopes, and to silting or scouring of the river-bed.

For every section a comparison is made between the sounded minimum talweg depth and the water-level on the day of sounding minus the water-level at a discharge zero, both measured at the gauge determinant for the section. Of these two values, the former is always the smaller. This is caused by

(i) the breathing of the sills (see next paragraph);

(ii) the forming of a very narrow, crooked channel at very small discharge, a channel which often disappears as soon as the rising water smoothes out the bottom and which in any case cannot be considered a shipping route;

(iii) change in size of bottom-ripples. A bottom-ripple, of which the height (from crest to trough) increases from 2 feet to 6 feet, and of which the shape (height-length ratio) remains about the same, decreases the talweg depth by $\frac{6-2}{2} = 2$ feet; and

(iv) changes in slope between low and high water.

On the stretch *Garua—Faro Confluence* (Miles 972—926), the influence of the Confluence is noticeable some ten miles upstream; the depths on this river-stretch depend on the discharges both of the Benue and the Faro. On the remainder of the 46 miles only the Benue discharge determines the height of the water-level. The talweg has been sounded on September 23, 1956, when the Garua gauge read 22′ and the discharge was 2,300 m³/sec (80,000 cusecs). The zero discharge corresponds to about 2′ reading Garua gauge. The minimum talweg depth since low water apparently has heightened some 8 feet when compared with the readings on the Garua gauge. This elevation is a combination of the factors mentioned above, divided, to make a guess, into 6 feet bottom-movement and 2 feet change in slope.

The river-stretch *between the Faro Confluence and the Gongola Confluence* has been divided into two parts, because of the Wuro Boki Flats determining the navigation above Yola.

The talweg between the Faro Confluence and Yola (Miles 926—888) has been sounded on September 23, 1956, when the Wuro Boki gauge read 19′ and the discharge was 4,500 m³/sec (160,000 cusecs). The zero discharge is at around 3′ reading Wuro Boki gauge. The crossings heighten about 5 feet between the beginning of the shipping season and high water. Before that period, changes in slope and in sand-ripples may be responsible for another two to three feet. These two factors together give 7 to 8 feet, whereas the difference between the height at zero discharge and the measured maximum talweg height is between 8 and 9 feet. A deviation from the actual talweg route may be responsible for the remaining discrepancy.

Below Yola and upstream of the Gongola Confluence (Miles 888—846), the talweg has been sounded on September 25, 1956, when the Yola gauge read 21′ and the discharge was 4,500 m³/sec (160,000 cusecs). The zero discharge is at about 2½′ reading Yola gauge. The difference between the measured maximum talweg height and the bottom-height at zero discharge is 6½—7½ feet, for which the silting of the crossings and heightening of the bottom-ripples, together with changes in slope, are responsible.

The river-stretch *between the Gongola Confluence (Numan) and the Taraba Confluence* has been divided into two parts, of which the one above Lau has a steeper slope and contains the Gamadio Flats.

The talweg between Numan and Lau (Miles 846—777) has been sounded on July 28 and 29, 1956, when the Numan gauge read 11′ and the discharge was 1,400 m³/sec (50,000 cusecs). The zero discharge is at 2—3′ reading Numan. The range in water-levels on Numan gauge between the date of sounding and that of zero discharge exceeds the measured minimum talweg depths by about 4 feet, which is largely due to differences in range (slope).

Of the talweg on the stretch Lau—Taraba Confluence (Miles 777—672) the miles 777—711 and 699—672 have been sounded on July 26 and 27, 1956, when the gauge at Lau read between 17′9″ and 19′0″. The talweg soundings have been reduced to a gauge reading of 19′0″, corresponding to a discharge of 1,700 m³/sec (60,000 cusecs). The zero discharge is at about 8′ reading Lau gauge. The range between the water-levels on Lau gauge on the date of sounding and that of zero discharge is about 6 feet more than the sounded minimum talweg depth, of which possible deviations from the actual talweg route may be responsible for, say, a foot. The remaining 5 feet can be explained by the factors (ii)—(iv) inclusive.

Between *Donga Confluence* and *Katsina Ala Confluence* (Miles 636—536), the stretch from Mile 596 to Mile 536 has been used to determine the distribution of the depth. The talweg has been sounded on June 17 and 21, 1956, when the Ibi gauge read 14′10″—14′5″. The talweg sounding has been reduced to 14′0″, corresponding to a discharge of 1,200 m³/sec (42,500 cusecs). The zero discharge is at 6—7′ reading Ibi gauge. The difference between the water-level on the day of sounding and that of zero discharge, both read on the Ibi gauge, exceeds the sounded minimum talweg depth by about 4 feet, which is likey to be caused by the factors (ii)—(iv) inclusive.

The talweg between Katsina Ala Confluence and Mozum (Mile 536 — Mile 377) has been sounded on June 10—14, 1956, when the gauge at Makurdi read between 311′6″ and 313′0″. The depths have been reduced to 313′0″ corresponding with a discharge of 1,900 m³/sec (67,000 cusecs). The zero discharge is at 303—305′ on Makurdi gauge. The difference between the water-level on the day of sounding and that of zero discharge, read on the Makurdi gauge, exceeds the sounded talweg depth by 4 to 5 feet, of which the factors (ii)—(iv) inclusive are the cause.

6.4.2. Crossings and sills

The talweg in a non-braided river will alternately follow the right and the left banks. This phenomenon can be observed in practically all rivers which flow through their own sediments, either with straight or with meandering banks, either with permanent or with varying discharges. Where the talweg switches from one bank to the opposite bank the flow crosses the river-bed. Flow-lines curve in the bends and are approximately straight over the crossings. The flow meanders in the bed (Diagram 6.4.2-1).

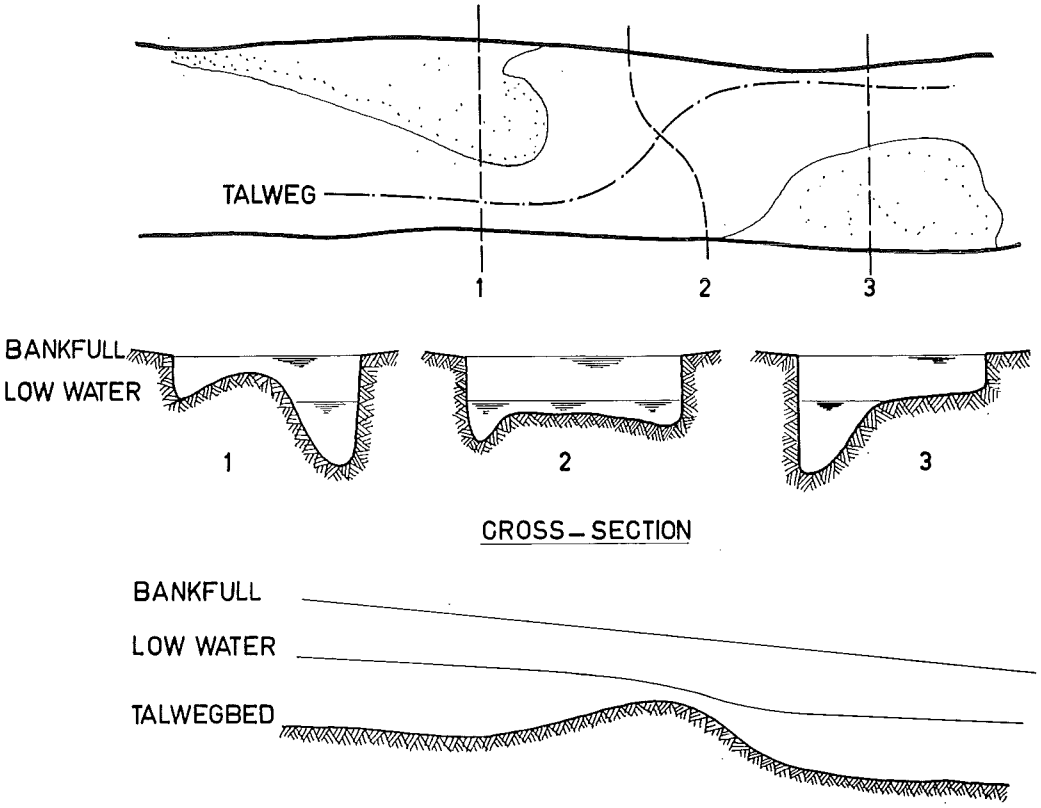


DIAGRAM 6.4.2-1

Talweg, cross-sections and slopes near a crossing

The cross-sections differ considerably in shape along the river. In the bends they are deep along the concave bank while they have a shallow bar along the convex bank. In the crossings, the depth is more uniformly distributed, the general picture being that of a saddle, sloping gently downwards along the talweg and upwards at right angles to the talweg.

The slope of the water surface during high water is approximately straight over bends and crossings. At low-water stages, the slope is less than the average in the deep pools of the bends and considerably steeper than the average over the crossings (Diagram 6.4.2-1).

The bed along the talweg rises in the crossing between the depressions of the pools in the bends above and below the crossing. The sill is related to the inflexion of the opposite windings and FARGUE ([1] states that the crest of the sill is found 1/8 of the meander-length below the inflexion (see 6.1.3). This may be true for perfect meanders, but is not clear in the Niger and Benue where

([1] FARGUE, 1908. MOR. 7

sand-banks between two practically straight banks do not indicate perfect meanders. The shallowest spots in the talweg are thus found on the crossings; they have the special attention of navigation and the talweg research.

It has been observed that the talweg bed on the crossing varies in elevation in the course of the seasons. At low water the talweg bed may scour, and at very low water it certainly scours as long as the flow has a carrying capacity for sediments. The hydraulic laws governing this phenomenon have not yet been fully discovered. It is known that the resistance of banks against erosion, the slope, depth, width, shape of cross-section and the roughness of the bed are related to discharge and sediment-transport. These relations, however, are very intricate and only partially known. There may even be more factors which should be brought in to understand fully the flow of sand and water over the complexity of a crossing.

However, it is possible to give a descriptive explanation of the scour at low or very low water-stages. When the slope of a river-stretch as it is with a certain discharge (Diagram 6.4.2-1) would not alter in each cross-section when the discharge or stage decreases, the result at a certain water-level would be a dry crossing and a discharge of water in the deep pools. This is, of course, in contrast to the law of continuity. Therefore, when there is a discharge smaller than a preceding discharge, the slope will decrease in the deep pools and increase over the crossings (stepped-up water-line); and at zero discharge the water in the deep pools will come to a standstill with a zero slope.

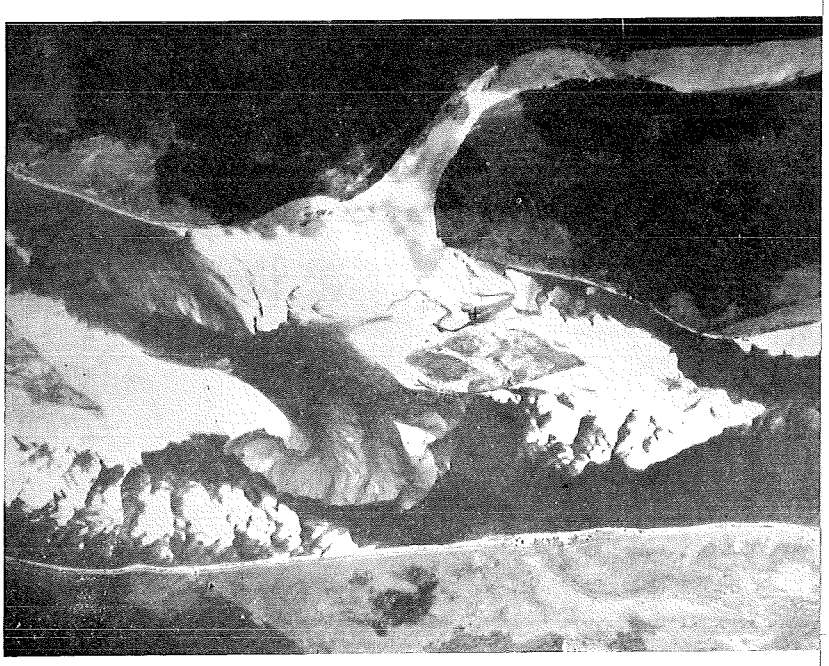
When the discharge is raised from zero to a small discharge there will still be hardly any velocity in the relatively large cross-sections in the deep pools, while on the crossing the profile changes from zero to a certain, still relatively small, value. The velocity and therefore the transporting capacity per unit width will be higher on the crossing than in the pools. As the width of the crossing is of the same order as the width in the deep pools, the total transporting capacity on the crossing will exceed that in the deep pools, thus resulting in scour of the crossing. For a more exact approach, secondary influences have to be taken into account, but the overall picture remains the same.

During low water, the difference in sand-transporting capacity between the deep pools and the crossing often results in the building of a kind of fluviatile delta just below the crossing. The sand, scoured on the crossing, deposits again as soon as it enters the deep pool downstream. The deposition, in the shape of a trumpet, is shallowest on the rim because the divergence of the flow reduces the depth. This peculiar feature of the river may repeat itself when the flow breaches through the rim at one or more points and deposits another trumpet more downstream. Often it is then possible to navigate at shallow draught just downstream successive rims, thus finding a channel which permits the passing of the crossing with more draught then when a straight course over the rims would have been taken (see Photograph 6.4.2-2). Such navigation, often in very crooked channels, can also be sucessfully used on the crossings where shell-shaped bed-ripples range side by side (see 5.4.3).

Scour will deepen the talweg. This will normally become perceptible when the flow recedes between the sand-bank and the bank along the deep pool; at the same time the flow directions over the crossing show sharper angles with the banks.

It is only possible to speak of a horizontal movement of the river-bed when the position of marked bed formations is compared with the fixed river-bank. Such bed formations may be the steep downstream side of a sand-bank or the highest point in the talweg, i.e., the crest of the shoal in a crossing (Diagram 6.4.2-3). The horizontal movement of the shallowest spot on the crossing reflects the flow directions at various water-stages.

The whole system of sand-banks and shoals moves parallel to the banks at high water (Photo-



PHOTOGRAPH 6.4.2-2

Flow over a crossing delivering a trumpet of sand into the deep channel downstream

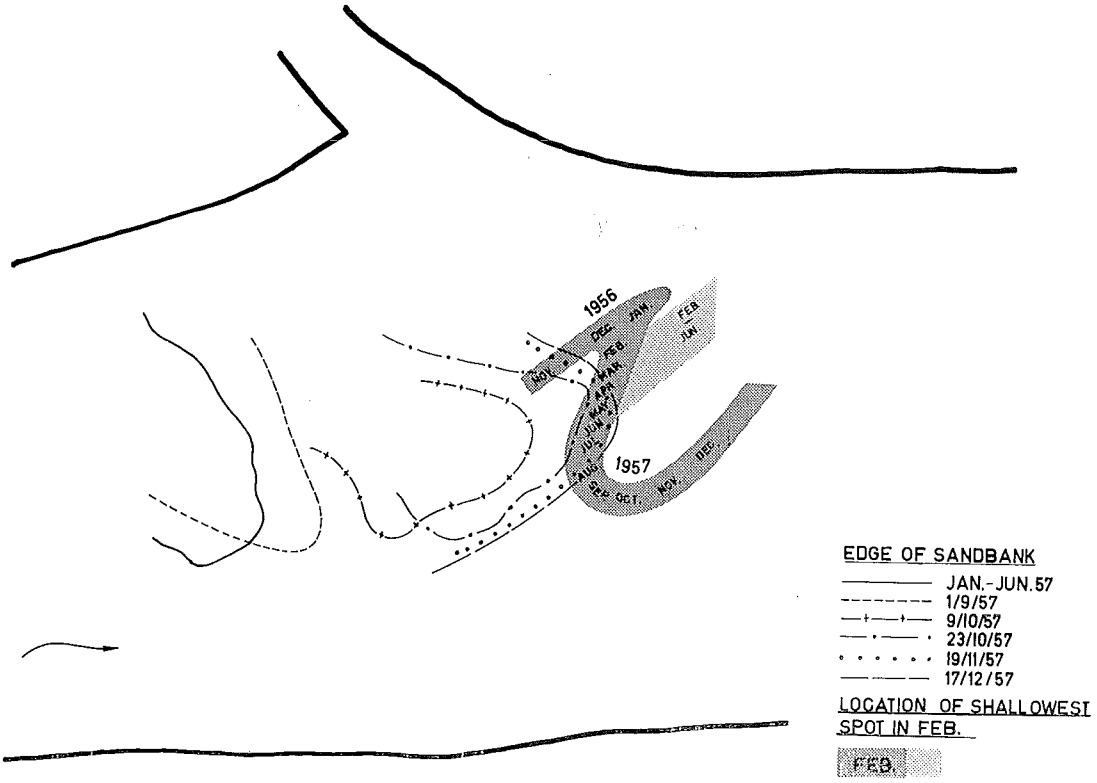
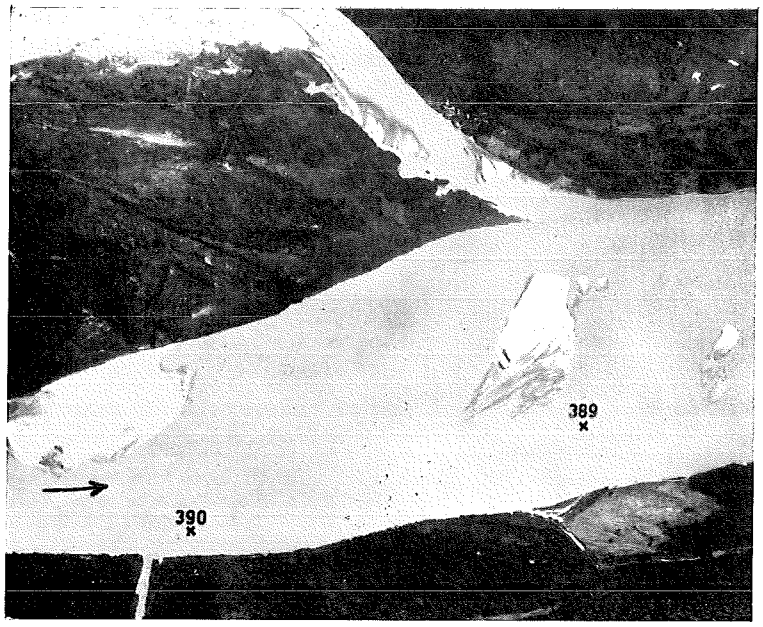


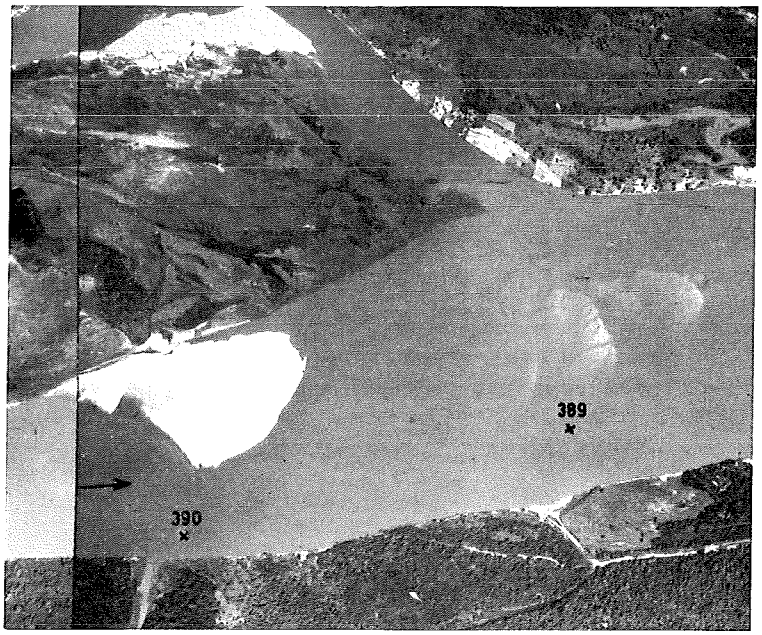
DIAGRAM 6.4.2-3

Horizontal movement of marked bed formation on Kelebe crossing (Mile 389)

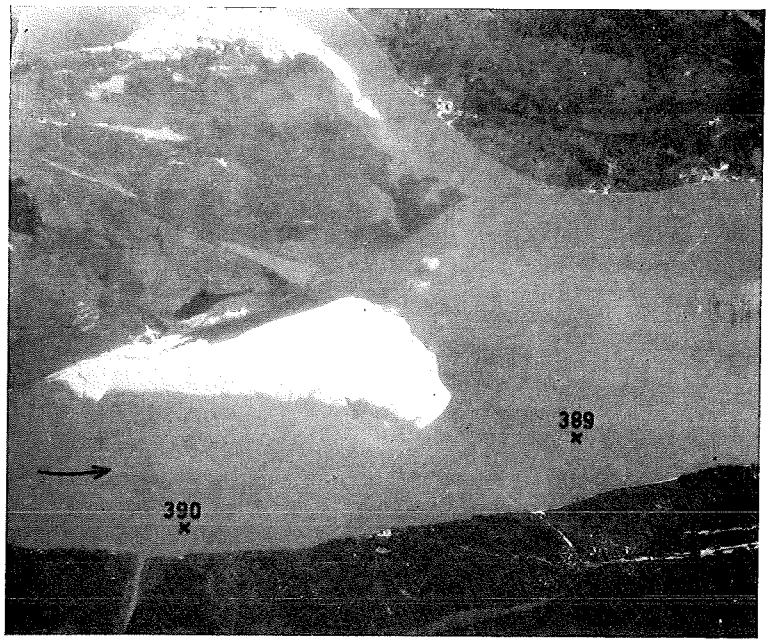
May 1954



December 1954



December 1956



PHOTOGRAPH 6.4.2-4

Propagation of the sand-bank on the Niger near Kelebe, Mile 389

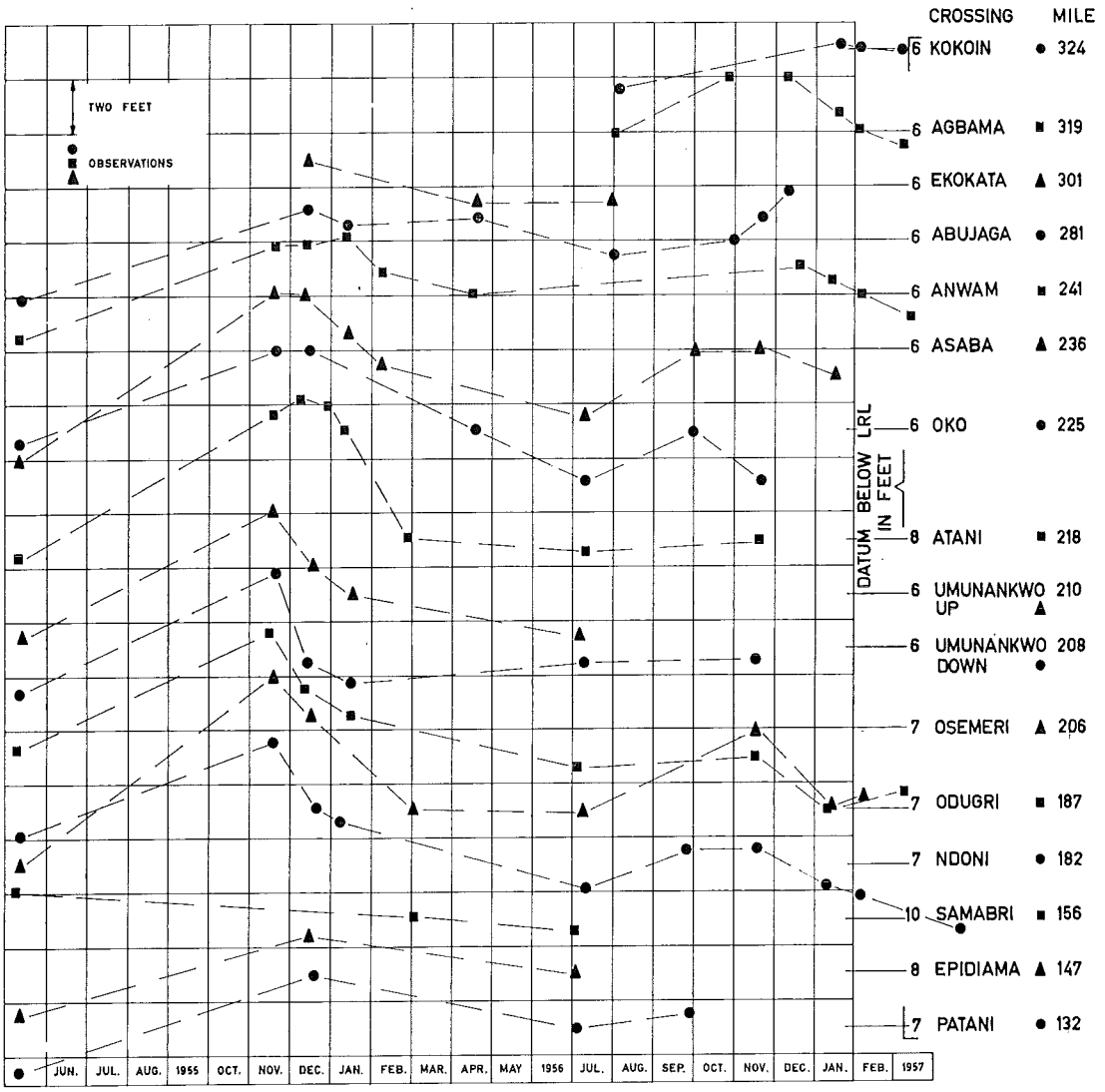


DIAGRAM 6.4.2-5

Minimum talweg depths on crossings in the Niger

graph 6.4.2-4). At low-water stages, the flow-lines (see Diagram 6.4.2-8) cross the river in a sharp angle with the banks and the horizontal movement must necessarily be more in that direction.

The horizontal movement is interwoven with the vertical movement of the bed as it is also the result of differences in transporting capacity along flow-lines. During low stages, this transporting capacity is largely concentrated on the crossings owing to the increase in slope over the crossing. Scour of the crossing can be expected, as has been explained above, but there is only little movement of the bed as a whole, although the crest of the crossing moves downward as well as the edge between shoal and deep channel, which moreover becomes more sharply defined. The shoal is pushed into the deep pool below. When the water has risen to bankfull and higher

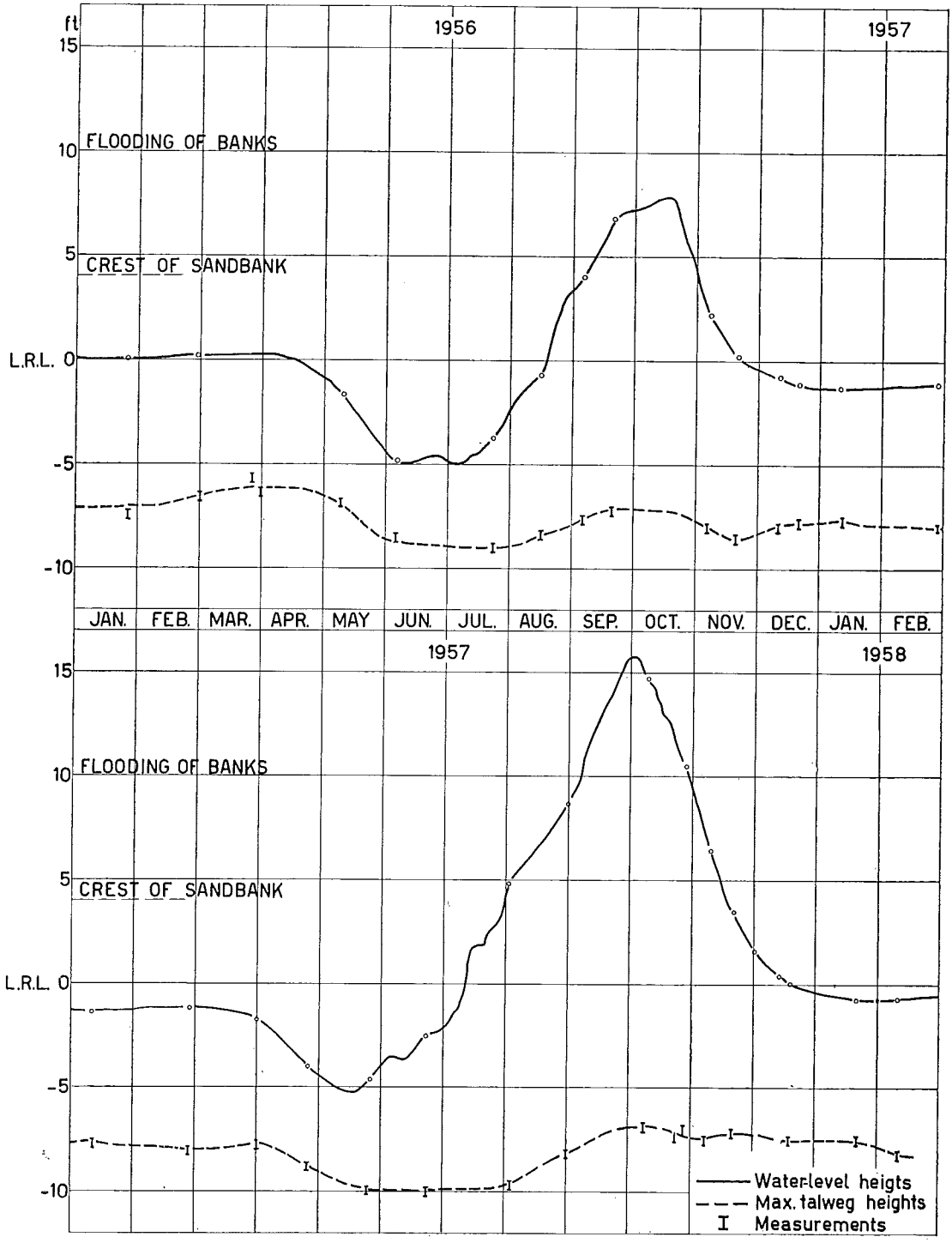


DIAGRAM 6.4.2-6

Talweg depths and water-levels on the Kelebe crossing (Mile 389)

the picture changes completely. Sand-banks move and with them the channels as well as the crossings. On the Niger and Benue this movement can be so fast that the position of the talweg over a shoal in one year can become the position of a sand-bank in the following year.

The move-up of the talweg is related to deposition of sediment. During high-water stages there is doubtless a great deposit just below the edge of the sand-bank, by sand which moves over the bank as well as by sand which is brought in front of the bank by horizontal eddies (see 5.4.4). The main direction of the sand movement over the shoal between two sand-banks during high-water is approximately parallel to the banks which may deviate up to 40 degrees from the talweg direction on the shoal. The flow of sand across the talweg will level out the crossing which has been scoured during low-water stages.

Observations on crossings and sills were taken mainly on the Niger where the occurrence of the Black Flood means that a slight change in crossing height involves a considerable influence upon navigation conditions. A special study of the behaviour of the crossing near Kelebe (Mile 389) has been made during the Investigation. On the Benue, with its rapid rise and fall of water-level, such a special study on a separate crossing was not necessary. There, the determination of least available depths on river-stretches was more important.

a. *Observations on the Niger*

Bottom scour on the crossings in the talweg has first been observed during very low water in 1955, and systematic observations started in 1956 when the shallowest spots on many crossings in the talweg were measured. The small differences in bottom height, the occurrence of ripples and the large areas on which the shallowest spot had to be sought for, as well as the great depths during high water, all required very careful measurements and judgment.

Diagram 6.4.2-5 gives the measured minimum talweg depth at several crossings of the Niger below Lokoja. Generally the bottom is higher during high water and scours during low water.

The same tendency is seen in Diagram 6.4.2-6 of the Kelebe crossing (Mile 389) in the Upper Niger, which has been watched closely over 1956 and 1957. When for the same crossing the least available depth is plotted against the water-level, a hysteresus curve appears (Diagram 6.4.2-7), indicating that water-levels and bottom height on the crossing are not in phase with each other. With rising water-levels the bottom does not follow directly, nor will scour follow directly from falling water-levels; there is a time-lag between them. This is the general pattern on a crossing, although many crossings will behave differently.

Much depends on the situation, the sand-bank height, the distance between sand-banks, the curvature of the flow-lines, etc. As has been explained above, the current on a crossing deviates during low water from its high-water direction. A cross-section over the crossing increases then in width and it is possible that the crossing becomes too "wide" for the discharge so that shoaling may result (see also next paragraph).

The current deviation has been measured on the Kelebe crossing in the Upper Niger (Diagram 6.4.2-8). The general direction of the main flow over that crossing varied between 10° and 50° from the general direction of the banks. The width of a cross-section over this crossing at right angles to the flow-lines varied from 1,100 m (3,600 feet) at high water to 1,550 m (5,100 feet) during low-water stages.

Important are the available depths on the shallowest crossings during the navigation season. In 1956/1957 these restrictive crossings appeared to be:

(i) on the Niger above Lokoja

Nwali	Mile 387
Adama	Mile 373

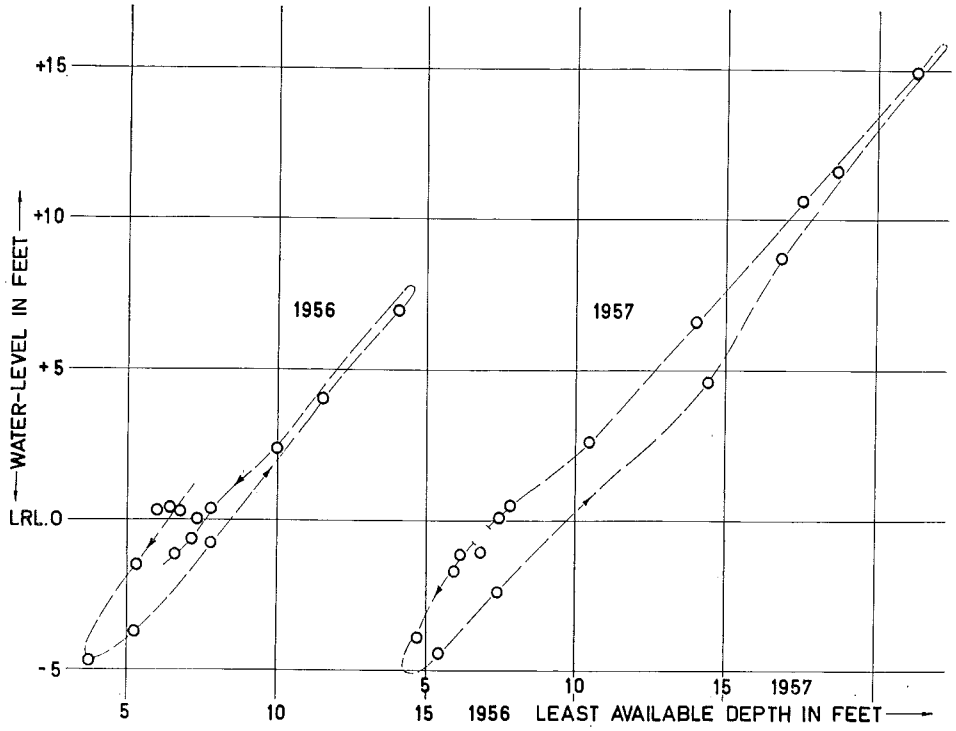


DIAGRAM 6.4.2-7

Hysteresus curve of available depth versus water-level of the Kelebe crossing (Mile 389)

(ii) on the Niger between Lokoja and Onitsha

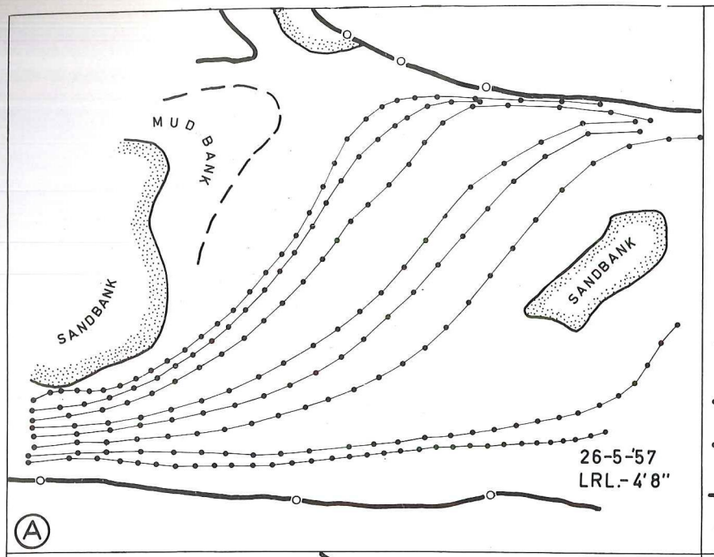
Lokoja Flats	Mile 359
Kokoin	Mile 324
Agbama	Mile 319
Abujaga	Mile 281
Nzam	Mile 253
Annam	Mile 241

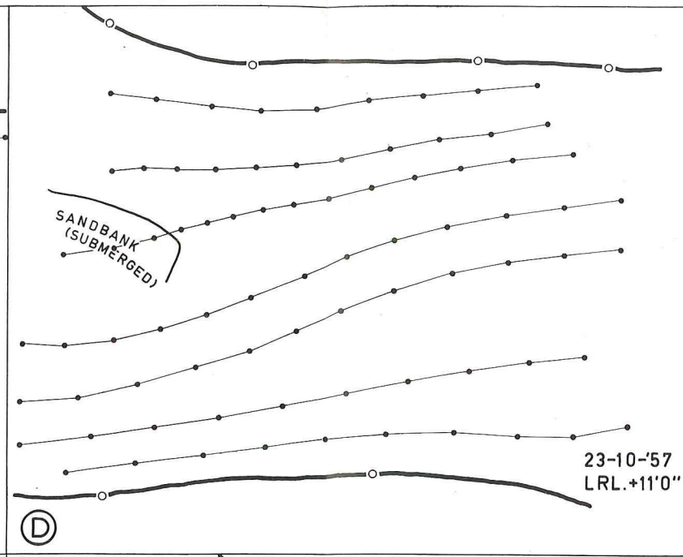
(iii) on the Niger below Onitsha

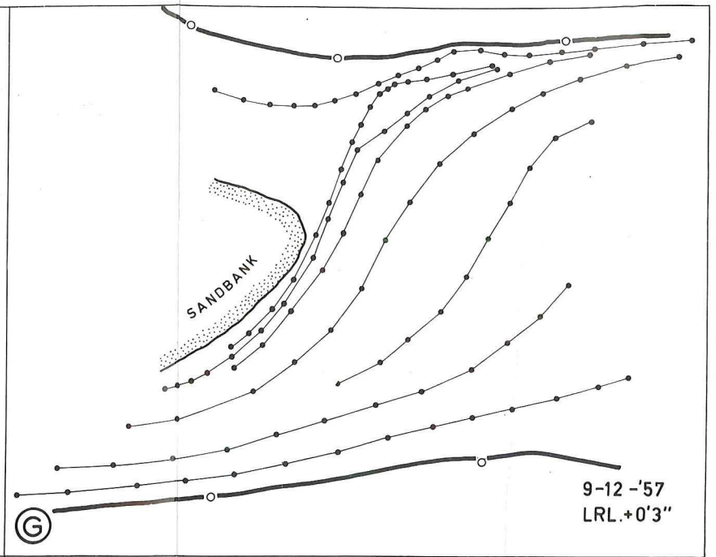
Patani	Mile 132.

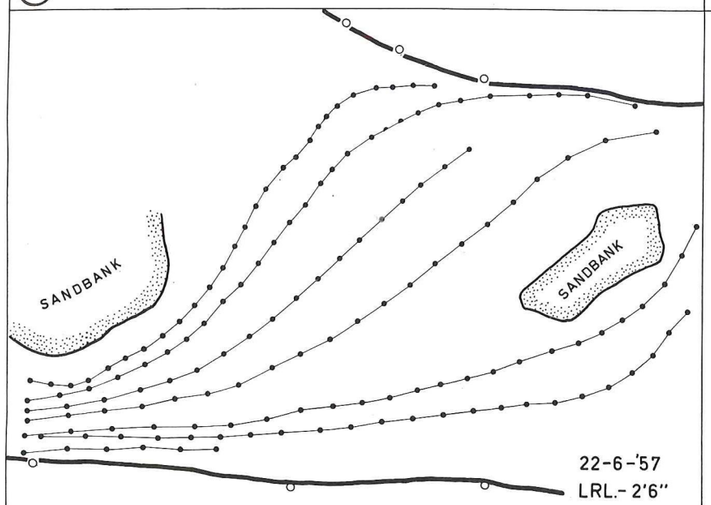
The horizontal movements of marked bed formations have been watched closely in the crossing of Kelebe (Mile 389). Diagram 6.4.2-3 showed the movement of a sand-bank edge as well as the movement of the shallowest spot of the talweg on the shoal. During low-water levels, when the sand-banks are above water, the shallowest spot in the talweg moves downward in the direction of the current over the shoal, a movement which practically stops at a certain distance from the shore. The rim between the crossing and the deep channel downstream becomes more sharply defined, as can be seen in Diagram 6.4.2-9 and on Photographs 6.4.2-10 and -11.

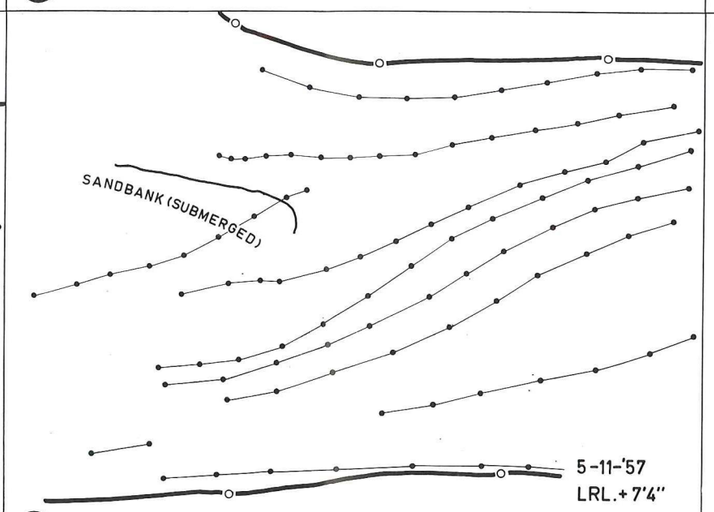
The shoal has been carried forward and squeezes the deep channel between the bank and the shoal. Because all the water to the left of the talweg has to pass between the rim and the shore, velocities will increase and carry the sand further downstream in the deep pool.

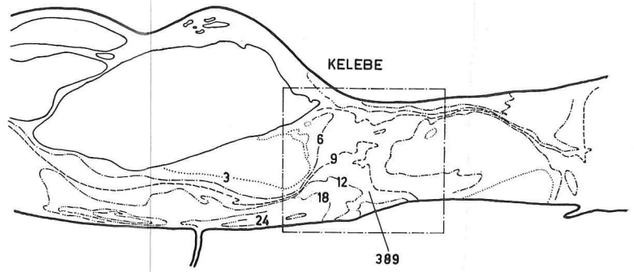




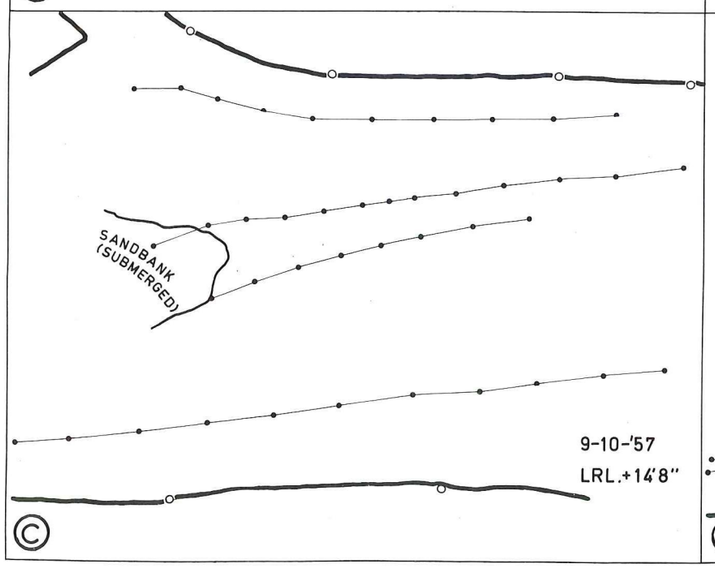


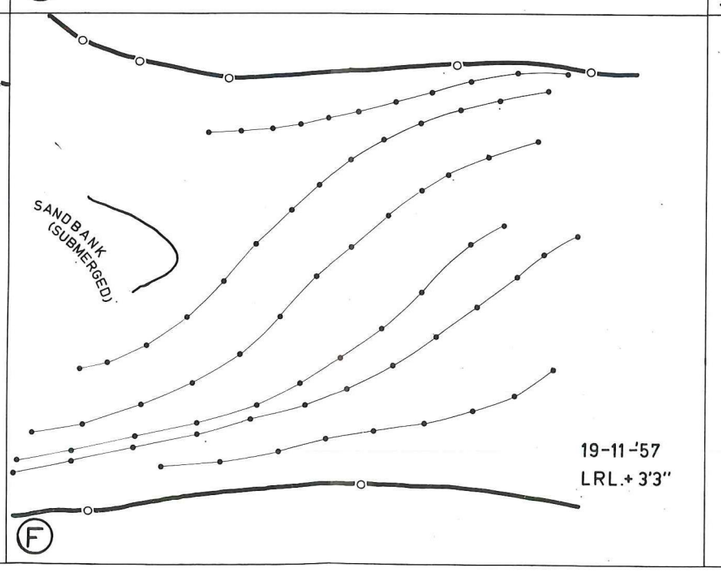






SITUATION 30-3-'57





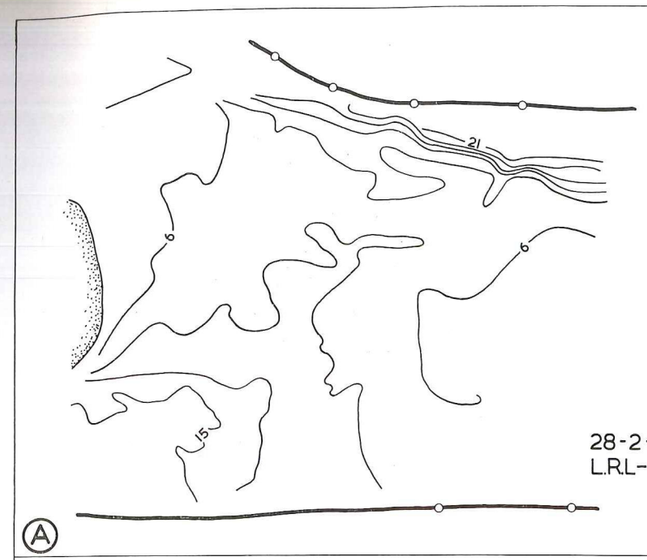
BANKLINE

VELOCITIES 50 cm/sec.(1 kn.)
100 cm / sec.(2 kn.)

DATE OF MEASUREMENT 19-11-'57

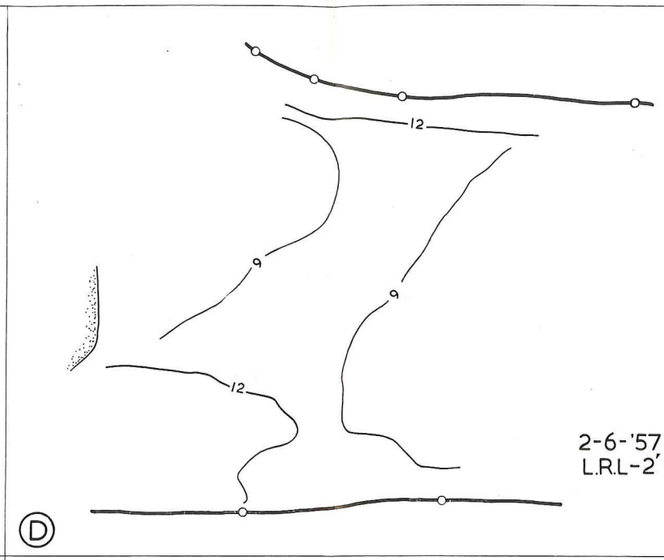
WATER-LEVEL DURING SOUNDING LRL.+3' 3"

NEDECO NIGER/BENUE	DIAGRAM III,6.4.2.8
FLOW DIRECTIONS AND VELOCITIES	
ON THE KELEBE CROSSING (MILE 389)	



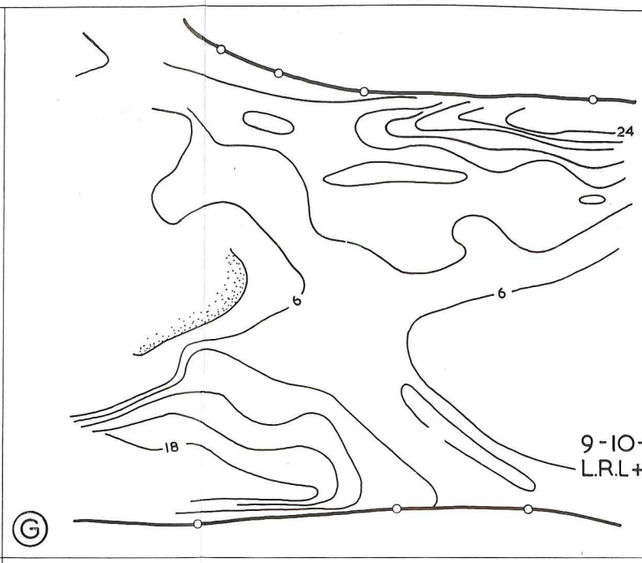
28-2-'57
L.R.L-1'2"

Ⓐ



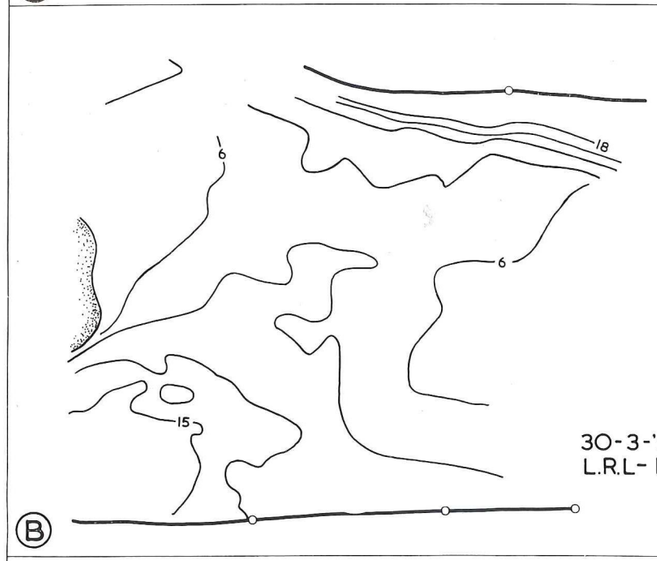
2-6-'57
L.R.L-2'6"

Ⓓ



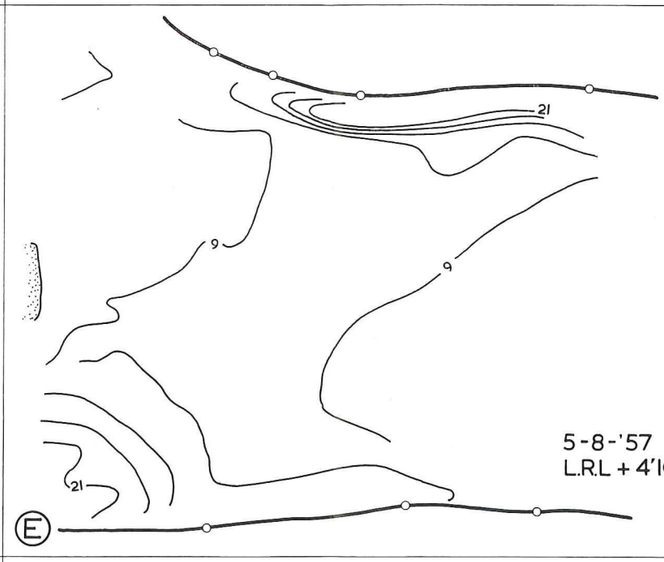
9-10-'57
L.R.L+14'8"

Ⓖ



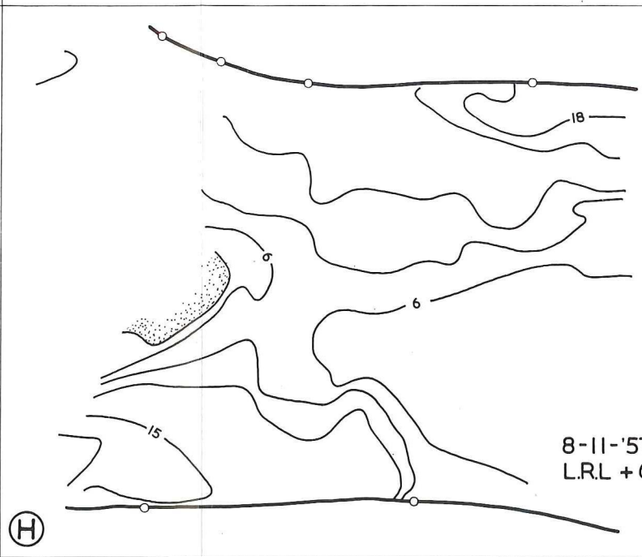
30-3-'57
L.R.L-1'9"

Ⓑ



5-8-'57
L.R.L+4'10"

Ⓔ

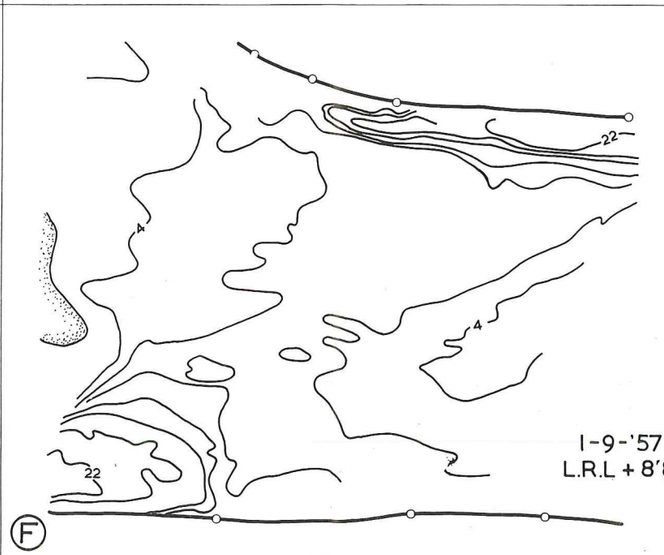


8-11-'57
L.R.L+6'6"

Ⓗ

25-5-'57
L.R.L-4'8"

Ⓒ



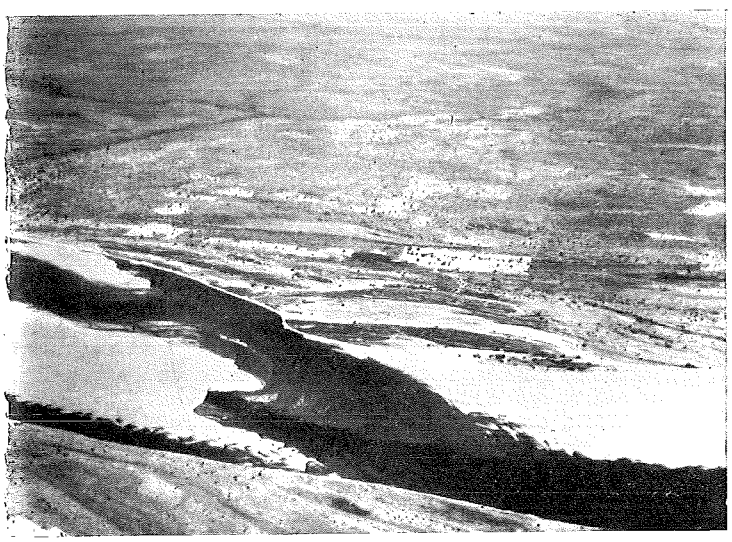
1-9-'57
L.R.L+8'8"

Ⓕ

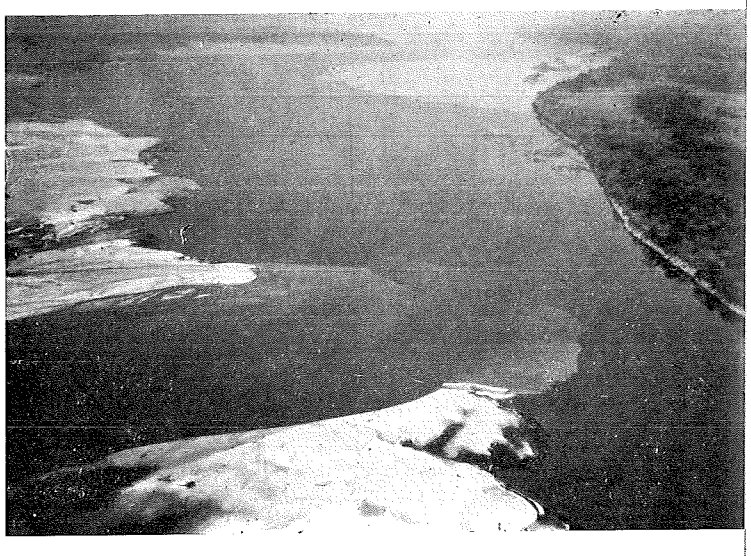
BANKLINE
SANDBANK
CONTOUR 9 Feet below L.R.L — 9 —
DATE OF SOUNDING 30-3-'57
WATERLEVEL DURING SOUNDING L.R.L-1'2"

NOTE THE SHARP DEFINED RIM BETWEEN SHOAL AND CHANNEL DOWNSTREAM Ⓒ

NEDECO NIGER-BENUE	DIAGRAM III,6.4.2_9
KELEBE CROSSING (MILE 389)	
CONTOURLINES AT 3 FEET INTERVALS	



PHOTOGRAPH 6.4.2-10



PHOTOGRAPH 6.4.2-11

Marked partitions between shoal and deep channel

During high water a strong movement of the crossing and the talweg parallel to the direction of the banks is visible (September—November). The talweg of the previous year is overrun by the sand-bank, and the new talweg is often found only a few hundred yards downstream of the edge of the sand-banks.

From the limited number of observations which could be made, there are several indications which allow preliminary conclusions for the crossings in the Niger:

(i) The average crossing is over 6 feet deep at Low River Level (L.R.L.) and some tend to scour during low-water stages. Pronounced scour occurs on practically all crossings when water-levels fall below L.R.L. during April, May and June. Scour will normally not start before the river flows in its low-water bed, i.e., when the main sand-banks are exposed. The water-level at which appreciable scour of the bed may start is generally not above L.R.L. + 1 foot on the Niger above Lokoja and L.R.L. + 3′ on the Niger below Lokoja.

(ii) The crossings with less than 6 feet of water at L.R.L., thus restricting present navigation, are small in number and generally found below a bifurcation of the river-bed or where the river-bed is very wide, perhaps as a result of easily erodible banks.

(iii) The restrictive crossings hamper navigation after the rapid drop of water-levels in November and December when rain has stopped. The Black Flood (see 2.3.1) arrives in December and stabilises river-levels at about L.R.L. Just after the drop in water-level and before scour has developed a deeper channel, the worst shipping conditions occur. On the worst crossings the least available depth in the talweg may then decrease to 4′0″—4′6″. Where, however, such a situation occurred, scour took place until the least available depth increased 3—6 inches in from 3 to 14 days. This has been noticed several times.

Usually the least available depth in the talweg from Patani—Baro is determined by a crossing above Lokoja in December, when below Lokoja the discharge is still sufficient because of inflow from the emptying Benue. When in January this Benue water falls to a negligible amount, the restrictive crossing can be expected on the Niger below Lokoja.

A small rise of 3—6 inches in water-level during the Black Flood in January and February and a combined scour of 3—6 inches on the worst crossing in these months may gradually improve the talweg to a minimum depth of 4'9"—5'3". This has been the case in 1956 and 1957, years with high Black Flood discharges.

(iv) On crossings with a depth of 5'6" or more at the beginning of the Black Flood, scour may hold off, and in exceptional cases shoaling may occur. The chance of shoaling is greater when more depth is available on the crossing, but it will always remain rare and, when silting continues, finally result in a sudden switch of the talweg into a new one across the shoal.

(v) When in March or in April the Black Flood ends, water-levels again drop rapidly and scour will occur on an increasing number of crossings. As this drop may be 4 feet or more, least available depths may fall to 2'—2'6" on the restrictive crossing, even while a scour of 2—3 feet of the bed is not unusual. Navigation has to stop or will be restricted to the section of the Niger below Onitsha.

(vi) During the observation period 1956—1958 the Black Flood discharges on the Niger have always been above the average, in height as well as in duration. An average discharge of the Black Flood will bring water-levels during January and February approximately 1'6" below L.R.L. A restrictive depth of 4 feet in December improving to not over 4'6" during January and February may well be expected in an average year, and the end of the Black Flood will then be at the end of March or early in April.

(vii) The number of crossings that must be dredged to gain 1 foot more depth available during the steady Black Flood is limited to some 8 or 10. The fall in discharge and water-level at the end of the Black Flood is so large that no further results can then be expected from continued dredging.

(viii) With the rise of water-levels — when the new rains start — there is little chance of deposition in the talweg on the shoal before the sand-banks are covered. When the water rises above the sand-banks, water and sand move across the talweg in large enough quantities to give sufficient deposit to change or even level out the old talweg of the previous low-water season. At such water-levels, however, the available depth will be more than adequate for unhampered navigation.

b. *Observations on the Benue*

Contrary to the system on the Niger, where many crossings were held under observation, the measurements on the Benue have been restricted to the determination of the least available depth on a river-stretch. Only the behaviour of one particular part of the river, the Gamadio Flats, has been studied closely, where many soundings and other relevant measurements were taken (see 6.5.3).

The Benue River between Garua (Mile 972) and the Lokoja-Confluence (Mile 362) has been divided into 8 stretches. In each of the river-sections, bounded by the confluences of the main tributaries Faro, Gongola, Taraba, Donga and Katsina Ala, the characteristics of the river are more or less steady; only the stretches Faro to Gongola and Gongola to Taraba, containing respectively the Wuro Boki Flats and the Gamadio Flats, had to be divided into extra sections.

The least available depths on these river-stretches, discussed in the next paragraph, are correlated with the main gauges. Whilst the range between low water and high water on the main gauges is about 20 feet, the range in least available depth appears to be only 13—15 feet. This phenomenon is caused by the breathing of the sills, the amplitude of which is somewhat larger than on the Niger, probably as the high-water/low-water ratio on the Benue is larger than on the Niger.

There is siltation at the crossings during rising water; scour begins somewhere during the

fall. The sharp fall of the Benue causes a considerable time-lag in the process of scouring.

For instance, a crossing just above Umaisha restricted the least available depth from Makurdi to Lokoja to $7\frac{1}{2}$ feet on November 16, 1957 (corresponding Makurdi gauge 319'6"). The fall set in on October 21 (Makurdi 330'8"), but only after October 28 (Makurdi 329'5") did the river fall sharply. The least available depth for the same discharge before high water was over 10 feet.

Because of the sharp fall and the retarded scour it is safer to assume no scour during this fall for operations with ships drawing 5 feet and more.

The silting of the crossings can be read from the diagrams in the next paragraph.

6.4.3. Least available depth and limit discharge

The two preceding paragraphs describe the basic data necessary to determine the least available depth (L.A.D.), which is the least sounded talweg depth on a given river-stretch. Generally, the L.A.D. on a certain stretch of river is a function of the height of water-level and of the time of the year. On a certain crossing the depth may be increasing to a less extent than the water-level is rising, due to shoaling; whilst on another the reverse may occur, indicating a scouring. In general, shoaling during the rising stage may be expected, followed by scouring after high-water stage (see preceding paragraph), although in certain circumstances the reverse may be the case. An island, a bend in the H.W.-bed, a tributary, or a sudden cut-off across a sand-bank are all possible causes of such abnormal behaviour.

The discharge required to maintain a certain L.A.D. on a river-stretch is named the "limit discharge" (for that L.A.D.) of the river-stretch. A combination of the discharge hydrographs with the observed minimum talweg depths of a certain stretch results in the determination of these limit discharges. It will be clear that they will be lower before H.W. than after, due to the shoaling of the crossings.

The measurements resulted in the curves of Diagram VI, 8.5.3-2. But as the river conditions vary from year to year, these curves should be considered as provisional.

a. *Niger*

As the Niger during the H.W.-stages offers no difficulties for shipping, no soundings were made for the purpose of determining the L.A.D. for this period. Only when the water-levels drop to the Black Flood level in November/December does navigation become restricted and is the L.A.D. of great interest for shipping.

The crossings have been shoaling during the preceding H.W.-period and it takes some time before the crossings are scoured. The effect of this so-called "retarded scour" has been discussed in 6.4.2, and is shown again in Diagram 6.4.3-1, where the L.A.D.'s of the Niger are given as a function of the discharge in m^3/sec. A few soundings during the rather fast rise of the Niger are also plotted in this diagram, and show clearly that no difficulties will be met with as soon as the Niger rises.

On the Upper Niger between Baro and Lokoja (Miles 434—362), the retarded scour is rather noticeable and is an uncertain factor in the prediction of L.A.D.'s. If this graph is used for the calculation of limit discharges in case of a reservoir in the upper reaches of the Niger, the effect of the retarded scour will be less, because of the reduced H.W.-flow due to the reservoir, and in that case the drawn line can probably be used.

On the Lower Niger downstream from Lokoja (Mile 362), the effect of the retarded scour is even more pronounced than on the Upper Niger, as the ratio between the H.W.-discharge and Black Flood discharge has a more adverse influence on the situation of the crossings. Especially do the crossings down-stream of the Rocky Section exercise limitations, and, as a whole,

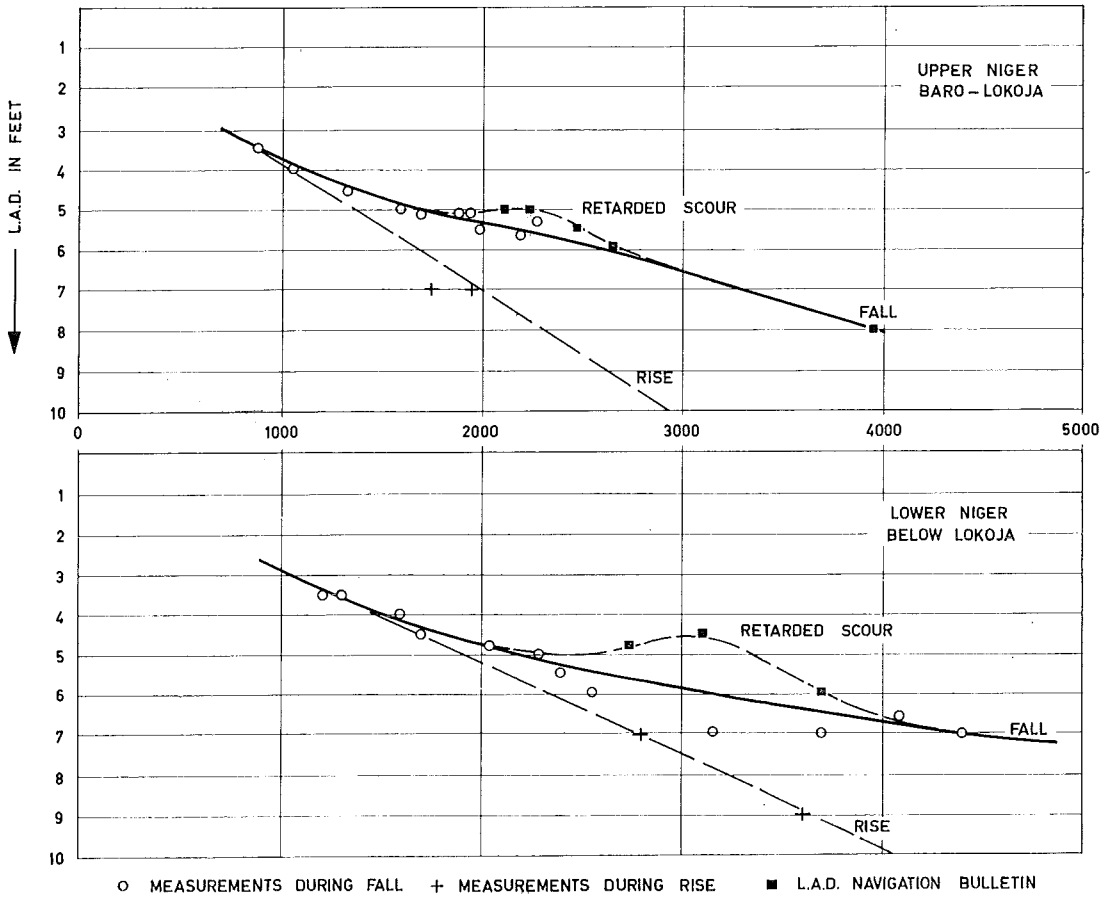


DIAGRAM 6.4.3-1

Least available depth on the Niger

the Lower Niger will limit the navigation to Baro as soon as the discharges of the Benue fall below 400—600 m^3/sec (15,000—20,000 cusecs).

b. *Benue*

The discharge hydrographs of the Benue are different from those of the Niger because of the absence of the Black Flood. There is an abundance of water in September and October, whereas from January to May there is hardly any run-off. This purely tropical type of river can only be effectively improved by discharge regulation. Buoyage may considerably improve navigation in the flood season, but the only way to extend the shipping season is by means of reservoirs. Therefore the L.A.D.'s on the Benue are measured particularly with a view to regulating the discharge by means of a reservoir.

Most of the measurements were made at rising water. At present, the water rises hesitatingly, causing difficulties to navigation sometimes for weeks; a close study of the depths at this period can lead to useful material for buoyage schemes. The fall, however, is very sharp; the accurate determination of the L.A.D. after the flood is not very interesting as the ships would at most gain a few days by a good knowledge of the L.A.D. With a fall of a foot a day, an uncertainty in L.A.D. of 3 feet would mean a departure possibly 3 days too early. Naturally the buoyage

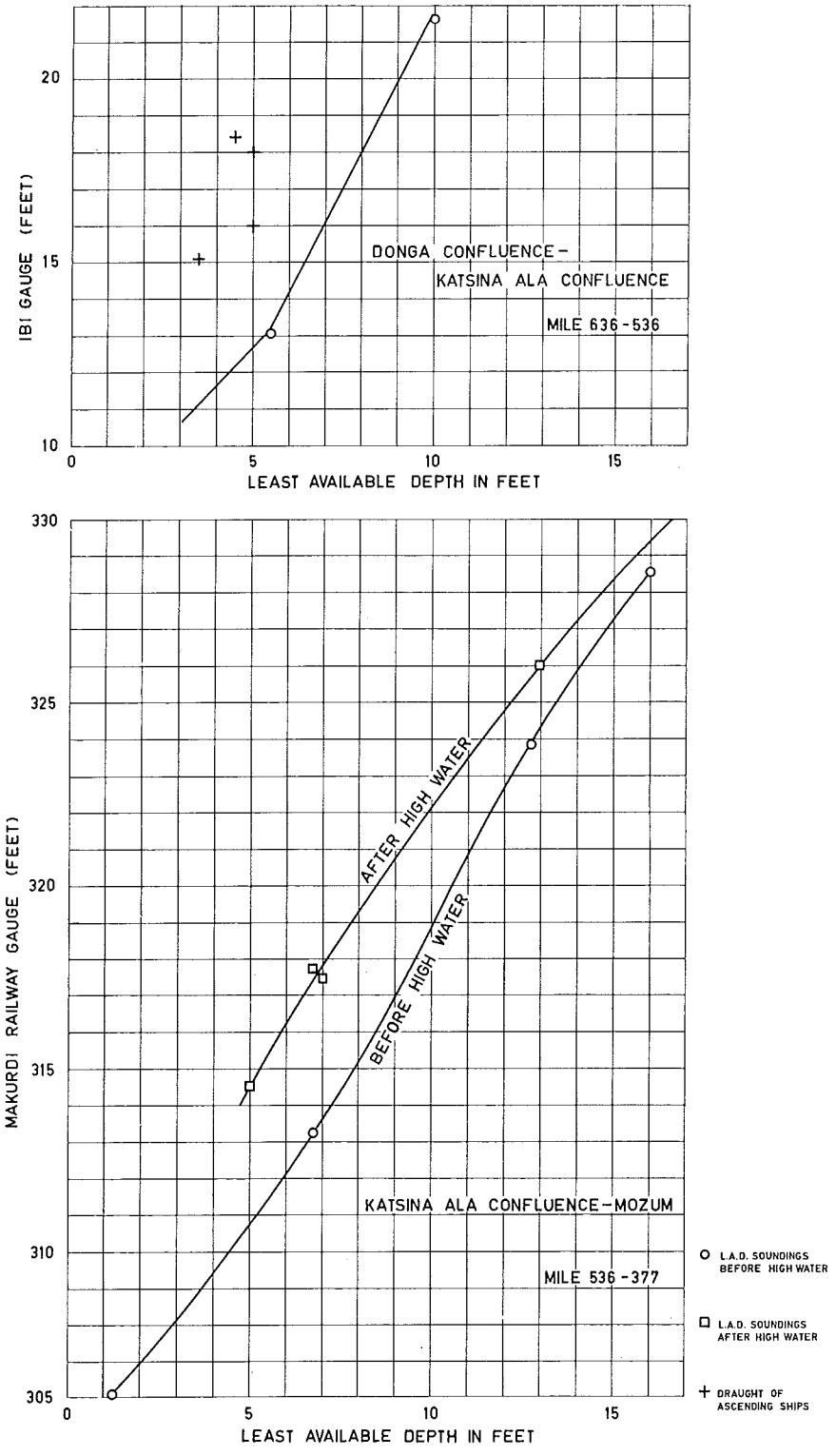


DIAGRAM 6.4.3-2

Least available depth on the Benue below the Donga

teams should pay close attention to the least available depth when the water is falling in order to prevent groundings at falling water.

As mentioned before, the main purpose of the L.A.D. measurements on the Benue has been to obtain data for reservoir operating schemes. When regulating the discharges by means of a large reservoir, the peak flow will be captured, thereby preventing the crossings from shoaling. The limit discharges will then not exceed the present pre-H.W. ones (i.e., measured before high water). Only on the Lower Benue, downstream of the main tributaries Taraba, Donga and Katsina Ala, have the measurements been continued throughout the whole hydrological cycle. Here the influence of a discharge regulation of the Upper Benue will be considerably lessened by the inflow from the tributaries between Angwan Taru and Makurdi.

In Diagrams 6.4.3-2 and -3 the least available depths for the various river-stretches of the Benue have been plotted against the gauge reading corresponding to the water-level on the date of observation.

The various peculiarities of the graphs will be discussed for each river-section separately.

(i) *Mozum—Katsina Ala Confluence* (Miles 377—536).

This part of the Benue ends fifteen miles above the confluence with the Niger. For the depths on the Confluence, see V, 3.1.2.

The least available talweg depths from the Katsina Ala Confluence to Mozum are given against the water-level at Makurdi. If a rise of 10′ on Makurdi gauge would correspond to an increase of 10′ in talweg depth, the relationship in Diagram 6.4.3-2 would have been a line under 45°. But due to breathing of the sills and the difference in range (change in slope) on the stretch, the rise on the gauge at Makurdi exceeds the increase in talweg depth. Further, the effect of retarded scour is clearly illustrated by the two lines, one giving the relationship before and the other after high water.

A comparison with the draught of ships could not be made, as the ships always passed with many feet of water under their keel. They either entered the Benue when the water had already risen to a comfortable depth (1955) or they had to wait at Lokoja because the Benue Bar determined the time of ascent (1956, 1957).

The least available depth is often determined by the Akpanaja Flats (Miles 501—505). Six miles above the flats, in the valley narrowing at Makurdi, the river-bed is scoured at high water and the excessive quantity of sand thereof, deteriorating the river-bed downstream, then forms the Akpanaja Flats. In 1957 a peculiar crossing at Miles 405—407, three miles above Umaisha, determined the least available depth when the river fell. From the River Charts it follows that the width of the crossing just before the sand-banks are exposed is 2½ times the width of the river at bankfull stage.

(ii) *Katsina Ala Confluence—Donga Confluence* (Miles 536—636)

Only three talweg soundings have been made, all before high water. This hundred-mile stretch of river is not regarded as difficult in any way.

(iii) *Donga Confluence—Taraba Confluence* (Miles 636—672)

Two talweg soundings at rising water and the draught of six ascending ships give a rough idea of the least available depth versus discharges. As no gauge exists on this river-stretch, an imaginary gauge has been computed with the help of the stations Ibi (Mile 614) and Angwan Taru (Mile 683). The addition of the discharges at Amar and at Gassol then determines the points in Diagram 6.4.3-3. The restrictive crossing is often near Dampar (Mile 654) in the S-shaped high-water bed.

(iv) *Taraba Confluence—Lau* (Miles 672—777)

Compared to the river parts more upstream, the river downstream of Lau is rather easy to navigate. Five talweg soundings and the draught of six axcending ships determine the L.A.D. at rising water (see Diagram 6.4.3-3).

The crossing just above Gidan Usuman Creek, at Mile 764, determined the L.A.D. early in 1957.

(v) *Lau—Gongola Confluence* (Miles 777—846)

The difference in depth between the river parts above and downstream of Lau cannot be explained by a difference in discharges, as the contributions of the Kunini and Lamurde Rivers (Miles 788 and 763) are too small to have that effect. But the steeper slope above Lau is probably the cause of the shallower river.

The Tungaladan area (Miles 806—808), the Gamadio Flats (Miles 816—821) and the Kabawa Flats (Miles 827—835) are notorious in shipping circles. The restrictive crossing is generally around Mile 818, but otherc rossings (i.e., Miles 807, 820, 821, 842, 843) now and again take over that dubious privilege.

Three talweg soundings and a selection from ascending ships and navigation bulletins of 1957 give a fair idea of the L.A.D. at rising water (see Diagram 6.4.3-3).

(vi) *Gongola Confluence—Yola* (Miles 846—888)

Once past the flats below Numan, ships generally proceed to Yola without delay. Only with an early rise of the Gongola do the depths over the flats exceed the navigation depths between Numan and Yola. Waiting, due to a temporary fall of the Benue, as happened in 1958, may of course occur on any part of the river.

(vii) *Yola—Faro Confluence* (Miles 888—926)

The majority of the ships calling at Yola proceed further to Garua. They have to pass the Wuro Boki Flats

of which the region around Mile 922 usually determines the L.A.D. The slope here is steeper than at Gamadio, and the depths are generally less. The least available depths have not been studied intensively by NEDECO for two reasons: first because this region will be submerged when creating a reservoir by building a dam at Dasin Hausa, and secondly, because the French research team of Electricité de France concentrated on these flats. From their studies there resulted a least available depth of 5 feet for a limit discharge of 1,200 m³/sec (42,000 cusecs) at rising water.

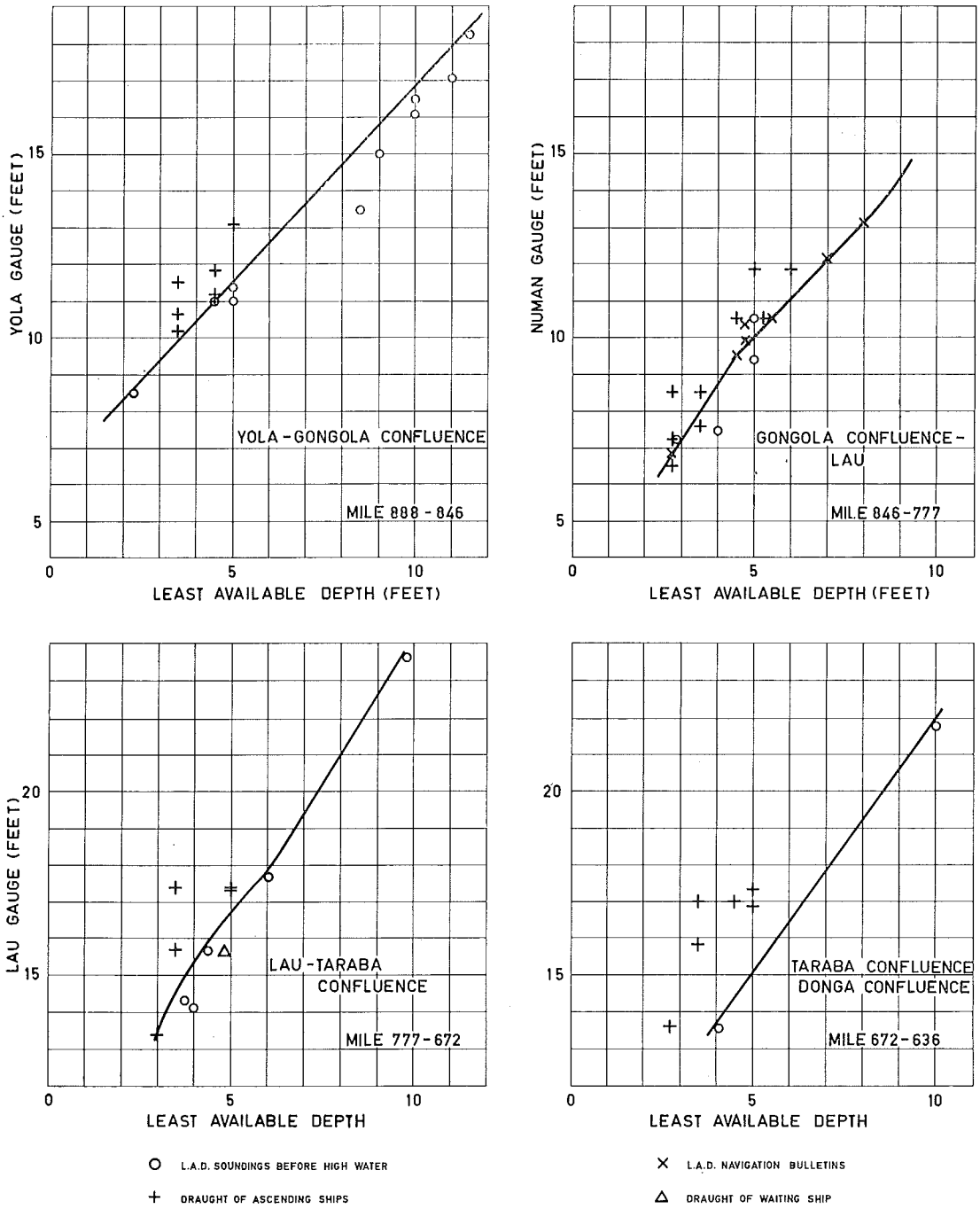


DIAGRAM 6.4.3-3

Least available depth on the Benue above the Donga

(viii) *Faro Confluence—Garua* (Miles 926—972)

The limit discharge above the Faro Confluence is always smaller than on the Wuro Boki Flats. Neither in existing river conditions nor in case of a Yola reservoir regulating the discharges does this part of the river impose restrictions on navigation.

Only when changing the discharges by means of a reservoir at Lagdo (Mile 1,010) are the L.A.D.'s here of interest. The L.A.D.'s have been measured by Electricité de France, which concluded that a limit discharge of 400—500 m^3/sec (14,000—17,700 cusecs) is required for an L.A.D. of 5 feet.

6.5. EXAMPLES OF CHANNELS AND THEIR NATURAL DEVELOPMENT

6.5.1. Garua Creek

The Benue above the Faro Confluence is named the Garua Creek. This indication by pilots and masters suggests an outlook of the river different from the rest of the Benue. And indeed the Benue here appears to be a meandering river, narrow and fairly deep, forming a good shipping route as far as its depth is concerned (Diagram 6.5.1-1). The sharp bends, however, put a limit

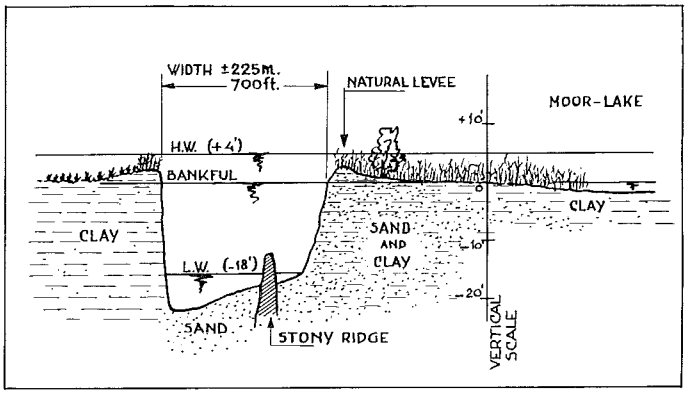


DIAGRAM 6.5.1-1

Garua Creek cross-section

to the length of the tows on Garua. At Kinada, Mile 930, the radius of the bend is 1,000 feet and the width of the channel 400 feet. Fairly straight reaches connect the bends. In general the banks consist of clay and the bed of sand, but in places rock can be observed in the river-bed in the form of ridges, often parallel to the stream flow, which gives the impression that some of the meanders are not fully natural (Diagram 6.5.1-2).

The genesis of the Garua Creek and the Faro round the Benue-Faro Confluence have been discussed in 3.4.7-c. At present a static equilibrium has not yet been reached and the Confluence is still in the process of heightening, in which a part of the material carried by the Benue above Garua is deposited on the large flood-plains above the Confluence. This raise of the Confluence causes the gentle slope of the Garua Creek and subsequently a deep and narrow channel. The banks of the channel, in comparison with the sandy shores downstream of the Confluence, are erosion-resistant because of the clay and silt content, and it is these banks, in combination with the gentle slope, that have caused the Garua Creek to meander (see 6.1.1 and 6.2.1).

The Garua Creek and the Faro have about the same annual run-off, but due to the difference in slope (Garua Creek between 10 and 15 $\times$ 10^{-5} when in spate and the Faro over 50 $\times$ 10^{-5})

and to the difference in discharge hydrograph (a high peak carries relatively more sand than the same amount of water spread over a longer period by smaller discharge) the sediment-transport of the Faro is three to five times greater than that of the Garua Creek.

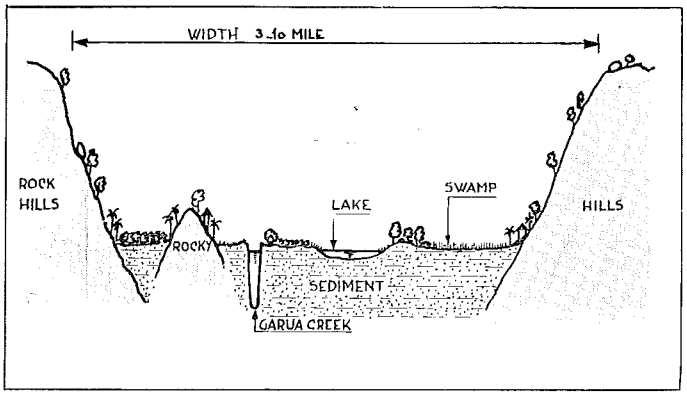


DIAGRAM 6.5.1-2

Garua Creek Valley

It looks as if the slope of the Garua Creek has been so greatly decreased that a moderate sand-transporting capacity remains only in the bends. The straight reaches that connect two opposite bends probably show a very small transport of sand; the pattern of reaches and bends seems hardly to propagate downstream and the one-time meanders appear to be dead. This may explain the peculiar sharp beds and long reaches of the Garua Creek.

6.5.2. Faro

The Faro River is the only tributary discussed in a separate paragraph in this Chapter, mainly to emphasise its morphological importance. The Faro is so similar in appearance to the Benue inside Nigeria, and the Garua Creek so different from the river below the Confluence, that the Faro might be considered the proper Benue and the Garua Creek its tributary. The process of formation of the river system connects the Faro directly with the Benue. According to the geological investigation (3.4.7-c) the original system was a Faro-Benue system, which at some time has captured a river of the Chad Basin group. The old course of the Faro was south-west along Beka and the depression near Beka is still evident (see also Diagram VI, 8.5.1-1). Here the Faro, when in spate, covers large areas of land and the watershed is indistinct.

The Confluence (Mile 926) and the meandering Garua Creek have been mentioned in the preceding paragraph, but it should be noted that this type of confluence is not very rare. The confluence of the Faro and Deo (Photograph 6.5.2-1) is almost a duplicate of the Benue-Faro Confluence. Here the Deo descends from the Alantika Mountains, carrying large amounts of sand down into the Faro and apparently raising the Confluence and thereby causing the Faro above the Confluence to meander.

Between the Deo Confluence and its mouth the Faro is of a braided type, but between Miles 956 and 932 the river is meandering. There the Faro is divided into three branches (see Photograph 6.2.1-4). As also noticed on the Upper Niger, meanders develop sooner in a branch of the river

PHOTOGRAPH 6.5.2-1
Faro-Deo Confluence

than in the main river. This effect of the discharge on the formation of meanders has been dealt with in 6.2.1.

The Faro cannot be called a navigable river. The rapid rise and fall and very shallow crossings render navigation unattractive for commercial vessels and only canoes and launches of the river investigators use it. Even when the river is in spate the water still flows over very shallow and very rapidly shifting sand areas (the average grain-size is less than one millimetre and the slope exceeds 50×10^{-5}). The crooked channels, connected and cross-connected by shallow junctions and crossings, are only around 100 feet wide against a total bankfull width of 1,000 to 2,000 feet. In short, the Faro is a braided river.

The sand discharges of the Faro could not be measured accurately because the type of instrument as used on the Niger and Benue was not specially adapted to the high transports of this tributary. Some tentative figures, however, may be given. During peaks of about 2,000 m^3/sec water discharge the bed-load movement will be roughly 15,000 m^3/day and during very high peaks this transport may rise to 20,000—30,000 m^3/day.

The discharge is intermittent as the drainage area of the Faro is not large and because much of the water enters the river as surface run-off. Consequently, the Faro occasionally pours large quantities of sand into the Benue (possibly 50,000 to 100,000 m^3 in one week). As these amounts of sand cannot be transported instantly by the Benue, subsequently large sand-banks, fast growing when the Faro is in spate and gradually decreasing when the Faro discharge has lessened, can be noticed at the Confluence (V, 3.2.2).

The effect of the intermittent discharge on the Wuro Boki Flats some miles downstream of the Confluence is not yet clear, but it is fairly certain that the Faro sand has built the Wuro Boki Flats (V, 2.4).

6.5.3. Wuro Boki and Gamadio Flats

River navigators have given the term flats to certain regions of the river. On these flats the talweg depth in general has a minimum. At bankfull stage the river is much wider than the average width and at high water the value for the scour criterion $a^{\alpha}b$ is larger on the flats than upstream, whilst at low water it is smaller (see 5.4.1). In this last respect a flat behaves like a normal crossing: heightening at high water and scouring at low water. However, a flat is characterised not only by a shallowness and by the raising of the bed during high water, but also by undistinguished channels, often more than one across the flats, the depths of which may differ only some inches. When the deepest channel has silted only a few inches whilst another channel has scoured only some inches, the (deepest) shipping route can change suddenly. In this respect a flat differs from a normal crossing over which one shipping route exists, changing only gradually (see also V, 2.4).

A flat may be formed when the sediment-transporting capacity along the river axis suddenly decreases, resulting in a deposition of material and a wider river-bed. This change in transporting capacity can be found, for instance, near changes in slope (Gamadio Flats), especially occurring below confluences (Wuro Boki Flats, Lokoja Flats). The river may also form flats after flowing through a narrow passage (Makurdi, Rocky Section on the Niger) and widening into the alluvial plain downstream of those narrowings (Akpanaja Flats, Agbama Flats, Etobe Flats).

Excessive decrease of transporting capacity and subsequent excessive deposition may even lead to a complete deterioration of the river-bed, as has been demonstrated by the examples of the Logone and the Hoover Dam (see 6.2.1).

The Wuro Boki Flats extend from Mile 923 to about Mile 920, but also at other places between Yola and the Faro Confluences very shallow areas with ill-defined channels develop at times

(for instance, Parkumo area). However, the worst area is generally around Mile 922. The origin of these Flats can be understood when studying the genesis of the river. In 3.4.7-c the development of the Faro-Benue system into a Faro-Garua Creek-Benue system has been described and apparently an equilibrium at the Confluence has not yet been reached.

The annual sediment supply from the Garua Creek plus the Faro River exceeds the annual sediment discharge of the Benue downstream of the Confluence, so that subsequently deposition of material occurs which causes the deterioration of the river into flats. The Confluence and adjacent river stretches will be raised by this deposition till the slope downstream of the Confluence will have increased so much that the average annual sediment transporting-capacity there equals the average annual sediment supply of the Garua Creek plus the Faro. The zone of deposition is then downstream of the adapted section, and the whole process propagates downward, with a continued raising of the Confluence. The question as to when this will end is somewhat academic as it will take at least centuries to arrive at an equilibrium. The major part of the sand at the Confluence is contributed by the Faro, as the slope of this tributary exceeds that of the Garua Creek four to five times; consequently, the Faro is considered the cause of the Wuro Boki Flats.

Engineers of Electricité de France have frequently sounded the Wuro Boki Flats, and some soundings of the worst area have been compiled in Diagram 6.5.3-1. The charts reveal changes in the channel depths, leading to a switching of the shipping route from the north channel in 1955 to the south channel in 1957. The situation in 1957 has been rather stable but in 1956 and in 1955 the undistinguished shallow channels are clearly illustrated by the charts.

It should be understood that from these sounding-charts, on which the depths have been reduced to a water-level corresponding with a reading of 350 cm on the gauge at Wuro Boki, no absolute quantities of material in sand-banks or from channels can be computed, because changes in slope (differences in range) cause differences in water depth, which are not eliminated by the applied method of reducing. Important, however, is the fact that with the above-mentioned method the actual depth at any point is the depth as shown on the chart plus the difference between the actual gauge reading at Wuro Boki and the reference level of 350 cm.

For detailed information reference is made to the French consolidated report ([1.

The Gamadio Flats, comprising in fact part of the whole stretch between Mile 805 and Mile 825, are situated in an area of decreasing slope: about 20×10^{-5} near Numan and only 15×10^{-5} near Lau. The origin of the Flats has to be sought in this decrease of slope, as it entails a decrease in sediment-transporting capacity and subsequently a deposition of material.

The reason for the decrease of river-slope could only be found in a previous abrupt change in the regime of the Benue, a change which may have occured many thousands of years ago and can have had several causes (see V, 2.4).

The location of the Flats is not so strictly confined to one area as, for instance, the Wuro Boki Flats because the stretch over which the slope decreases is many miles long. In the course of time different places may have become the worst area and occasionally the Tungaladan Area (Miles 806—809) determines the least available depth between Numan and Lau instead of the notorious Gamadio Crossing (Mile 818).

The nature of the Flats is such that a slow progression in a downstream direction is likely. This downward progression and the possible evening out of the present zone of flats, however, is so slow that the impediments to navigation will certainly remain for the foreseeable future.

The Gamadio Flats have been sounded frequently, and on four occasions also the adjacent area upstream has been sounded (Diagrams 6.5.3-2 and -3). The actual Gamadio Crossing is

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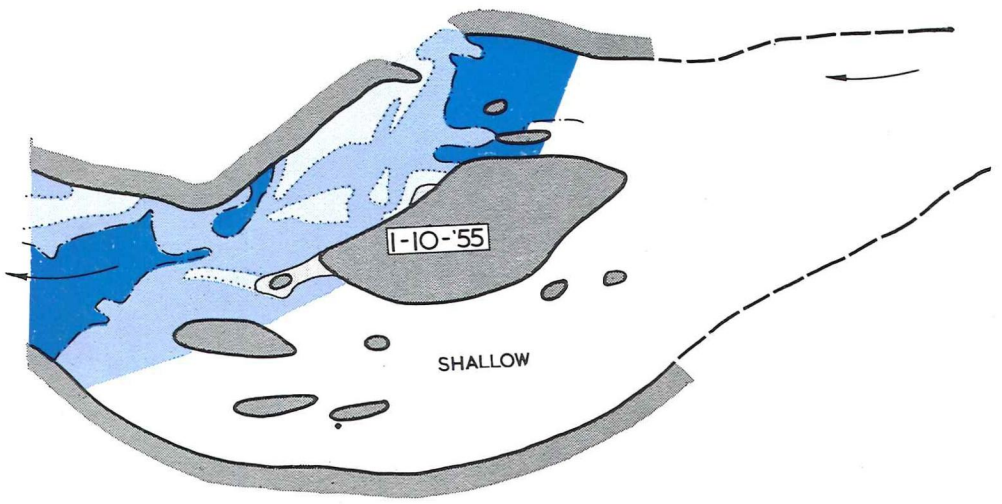
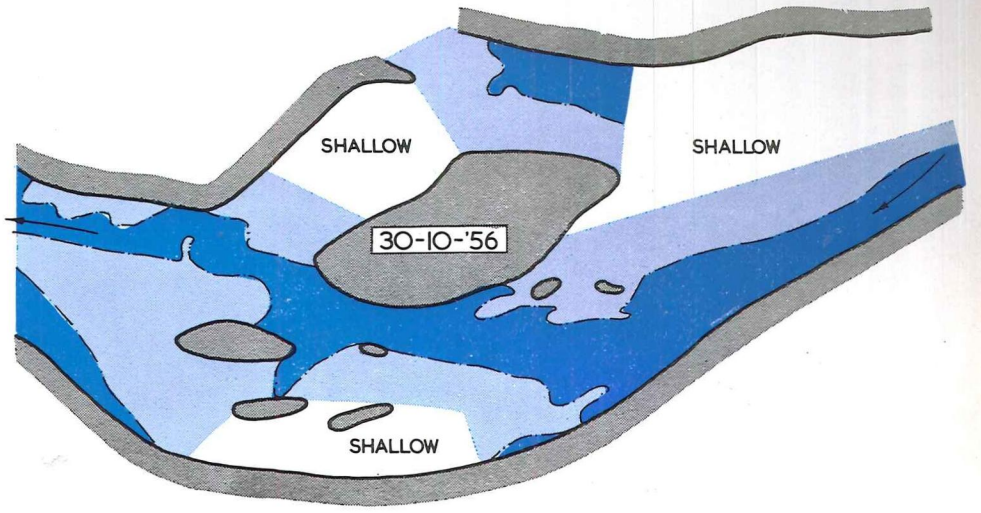
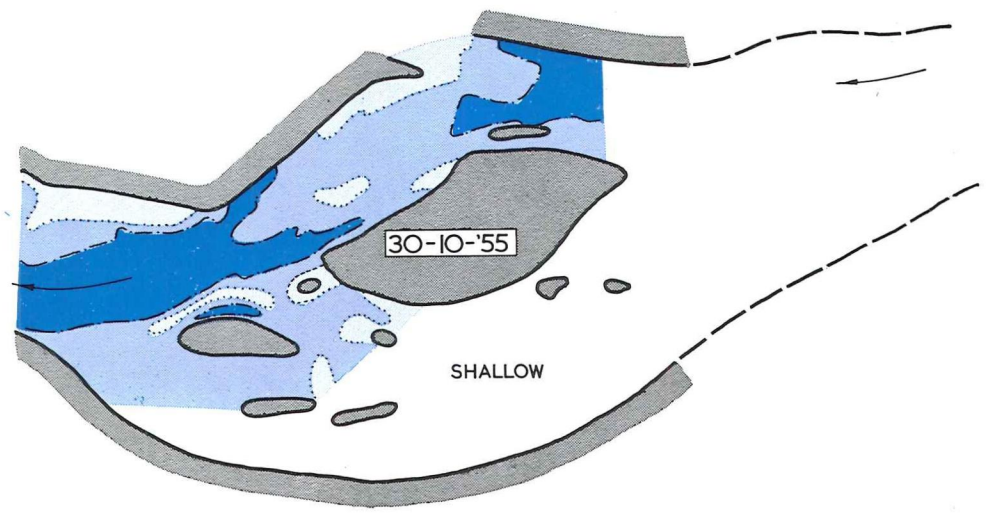
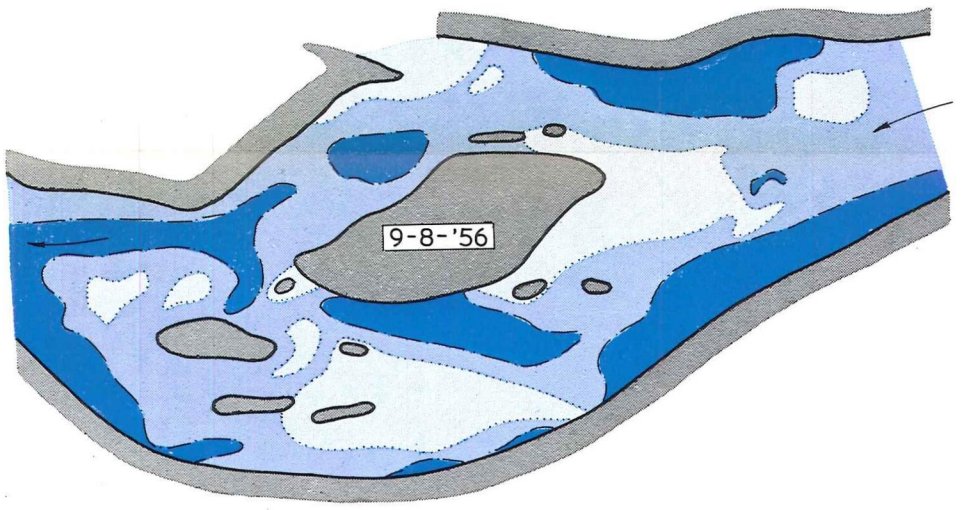
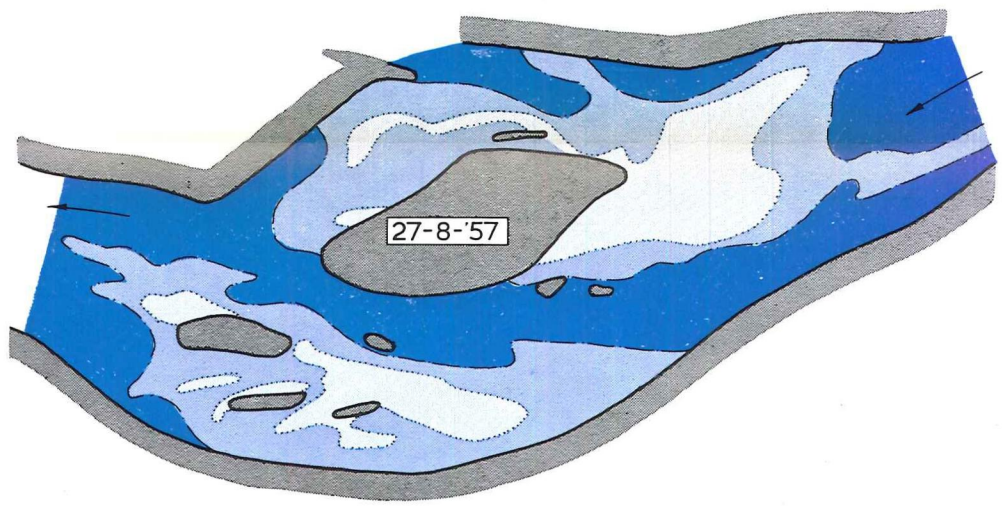
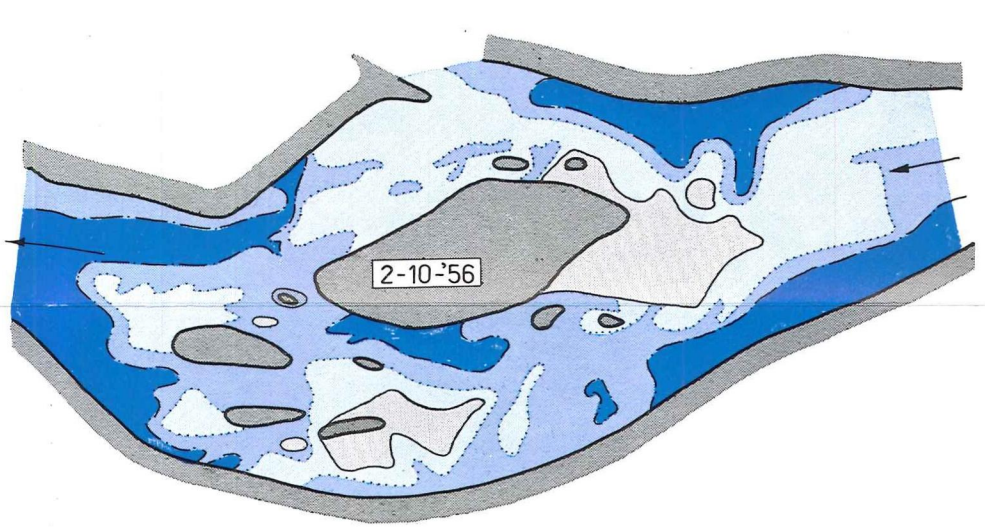


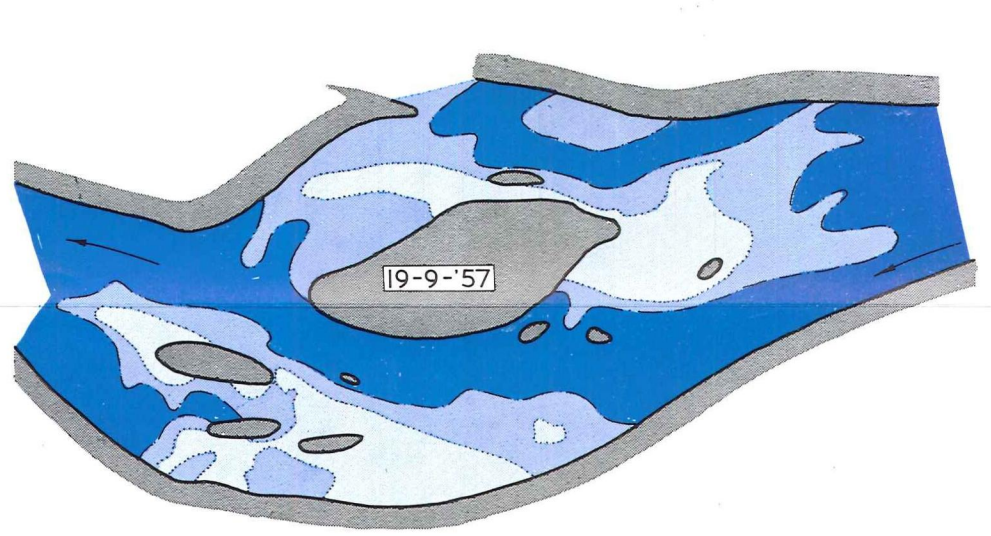












0 0,5 1,0 1,5 km

0 0,5 1,0 St.miles

SOUNDINGS REDUCED TO WURO BOKI GAUGE 350 cm

BANKS AND ISLANDS

0

– 3 ft.

– 6 ft.

OVER 6 FEET

NEDECO NIGER/BENUE	MAP III , 6.5.3-1
SOUNDINGS WURO BOKI FLATS	
SOUNDED EN PLOTTED BY ELECTRICITE DE FRANCE FOR THE GOVERNMENT OF THE FRENCH CAMEROUN	

mile 817
mile 816
mile 818
mile 819
mile 820
mile 821
mile 822
GINNO (GIDAN BUBA)
I
GAMADIO GAUGE
B
II
III
IV
DATUM OF SOUNDINGS
I.R.L. GAMADIO
WATERLEVEL GAMADIO 1957
M J J A S O N D J F
+6 ft
+3 ft
0
-3 ft
-6 ft
OVER 6 ft
BANKS AND ISLANDS
SOUNDINGS REDUCED TO 15 FEET GAMADIO GAUGE
15 st mile

NEDECO NIGER/BENUE | SOUNDINGS GAMADIO FLATS | MAP III,6.5.3-2

mile 818

mile 819

mile 820

mile 821

mile 822

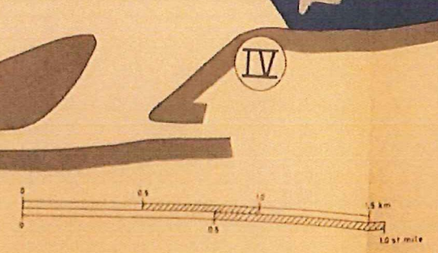
GINNO
(GIDAN BUBA)

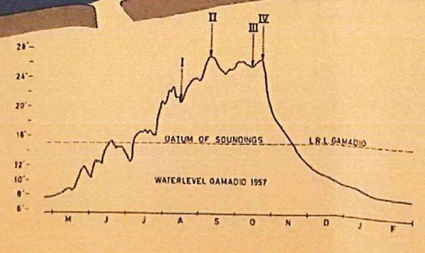
III

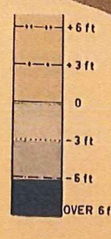
GAMADIO
GAUGE

D

IV







BANKS
AND
ISLANDS

SOUNDINGS REDUCED TO 15 FEET GAMADIO GAUGE

NEDECO NIGER/BENUE | SOUNDINGS GAMADIO FLATS | MAP III,6.5.3-3

situated between Miles 817 and 818, and in the diagrams the various channels are clearly visible.

From 1955 to 1958 two major routes existed, one in a westerly direction along the two small islands in the middle of the river, and the other in a winding way keeping more or less to the southern bank. Especially when the first one was the best shipping route, small channels a few hundred yards apart often altered their depth, thereby changing the shipping route frequently from one channel to the other. In 1956, at high water, the southern channel was buoyed and used by the tows, but early 1957 the westerly route was again the deeper.

Upstream of Mile 818.5 a deeper channel exists, bifurcating at Mile 820 into a North Channel and a South Channel. Of these two channels the southern was the shipping route in 1955, while a solid sand-bank blocked the North Channel round Mile 822. During high water of that season the sand-bank cut through between the shore and the bank, and ever since the North Channel has been used by the tows. When the sand-bank was cutting through, great quantities of sand moved along the north bank, part of which deposited again, forming a shallow area at Mile 821. This shallow area still existed during the 1957 survey (Diagram 6.5.3-2).

It should be noted that, when comparing soundings II, III, and IV with sounding I, no conclusions may be drawn as to the absolute heightening of the sand-banks or the deepening of the channels, as the soundings have been reduced to a gauge reading of 15 feet at Gamadio, changes in slope not taken into account. The range in water-level below the Flats is larger than on the Flats, and as the gauge is situated below the Flats, the shallowness of high water is exaggerated when compared to a sounding at lower stages. As the water-levels during soundings II, III and IV were about equal, the depths on these charts may be directly compared.

The situation at rising water in 1957 was as follows (see Sounding I). Above Mile 821.3 a straight deep channel runs along the north bank, a shallower channel along the south bank and large sand-banks lie in between. At Mile 821 is a shallow area in the North Channel while the South Channel is fairly deep; this channel, however, could not be used because it is blocked higher up. At Mile 820.5 the North Channel is deflected by two islands and at Mile 820 the two channels are joined. From Mile 820 to Mile 818.5 a peculiar situation arises as instead of a normal crossing, a fairly deep channel finds its way along the sand-banks. This channel changes into the troublesome Gamadio Crossing at Mile 818 where even with the guidance of buoys the shipping route may be difficult.

Downstream of Mile 816 a deep channel exists, but between Miles 816 and 817 difficulties may be encountered at the start of the season. Here sand is deposited during L.W. because of a local widening of the bed. The shoals will be scoured again at the high water-stages.

Less than a month later, the area has been sounded again (Sounding II), when the river was in spate. Obstructions were noticed in the North Channel between Miles 822 and 821. Had this concentration of sand been a bit more, the South Channel would possibly have become the principal route, resuming its position of 1955.

Much sand has moved between Miles 821 and 818 and the channel has become tortuous indeed. For navigation, however, the depths are comfortable because of the high water-level, and the tows can sail straight across most of the banks. Between Miles 819 and 818 a second northerly channel develops, but that is blocked again a month later. Between Miles 818 and 817 the situation is still somewhat undefined but from Mile 817 downwards a good deep channel has developed.

In Sounding III, the channels are straightened but the highest talweg elevation has been raised to about L.R.L. This, however, corresponds with a least available depth of over 11 feet as the water-level is L.R.L. + 11 feet. The blocking of the Northern Channel by the sand-bank at Mile 821.5 has not succeeded and the northerly channel at Mile 818.5 has not developed. Two weeks later, at Sounding IV, it is noticed that the situation just before the fall of the water has settled into a good channel in which the talweg elevation has been lowered to over L.R.L. — 3 feet.

To study the behaviour of the actual Gamadio Crossing at Mile 818, a number of detailed soundings and flow measurements have been made (Diagram 6.5.3-4); the "breathing-effect", as discussed in 6.4.2, is clearly illustrated by these measurements. At the lower stages (July 23) the sediment-transport on the crossing is about twice the transport in the cross-section above the crossing, whilst at high stages (September and October) the transport on the crossing is exceeded by the transport in the cross-section upstream. But the crossing is wider than a normal one, and at lower stages, when on a normal crossing the flow lines distinctly form a certain pattern, the floats here follow ill-defined and rather tortuous paths. Better than words, however, is a visual comparison of the Diagram 6.5.3-4 with the photographs and diagrams of 6.4.2.

The Tungaladan area (Miles 806 to 809), the second worst area between Numan and Jen, has been sounded on four occasions (Diagram 6.5.3-5). Even more than on the Gamadio Flats, the changes are noticeable here. In 1955 the ships followed the Northern Channel, but in 1956 a large sand-bank obstructed the channel at Mile 808 and the deepest route went through the third (counted from the north) channel.

In 1956 the huge sand-bank blocked the area upstream of the first and second channels effectively and a strong flow scoured the fourth (southern) channel, which widened and became the main channel in 1957. The large amount of material eroded in this channel partly deposited where the channel debouches into the wide area at Mile 806, and consequently the tows had difficulty in entering the south creek from the downstream side. During 1957 the situation stabilised and the south creek remained the main channel.

At Mile 809, however, it is interesting to notice the blocking of the crossing by a sand-bank that made contact with the huge sand masses at Mile 808. A southerly channel developed and towards the end of 1957 the shipping route was along the south bank all the way along, apart from small deflections at Miles 808.5 and 807.2.

6.5.4. The Benue below Lau

The Benue below Lau (Diagram 6.5.4-1) can be named the Lower Benue. Above Lau the river has the characteristics of upper reaches, distinguished by sudden rises and falls, whilst below Lau the effect of the intermittent rainfall is evened out by the storage capacity of the river and flood-plains and by the increasing number of tributaries from various drainage (and rainfall) areas contributing to the much larger discharge of the main river. The storage capacity of the river and subsequent evening out of the flood-peaks is large between Numan and Amar, where the flood-plain is several miles wide. Between Miles 672 and 536 the river is fed by three of its largest tributaries, and below the Katsina Ala Confluence the Benue enters its true lower reaches.

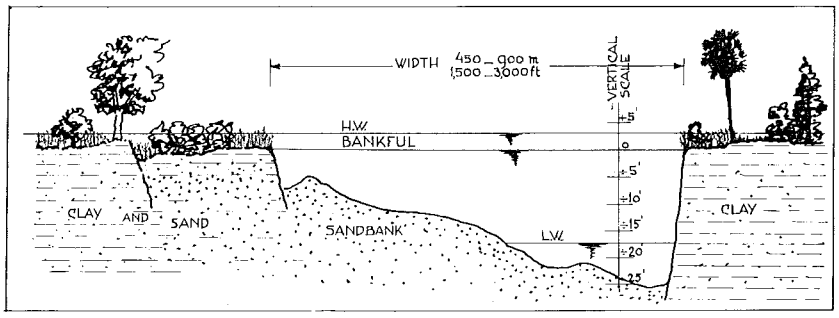
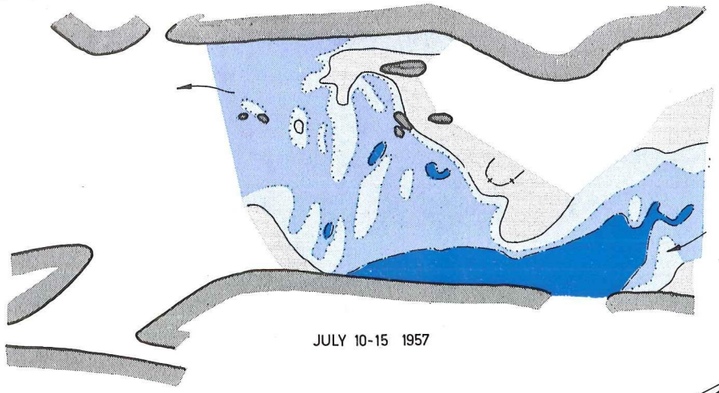


DIAGRAM 6.5.4-1

The Benue between Lau and Amar

But although the current is not so swift as on the upper reaches and the transport of material per unit width is not so large, the changes in the river in the course of time can be enormous. Huge sand-banks move at a rate of a few hundred yards per year, and the banks are subject to erosion and accretion. Although the general appearance of the high-water bed changes rather slowly, there are places where an erosion of 300 yards after one high water has been observed.

As illustrations of such alterations over one century, two cases are selected where the former courses could be traced with the aid of differences in vegetation and in soil structure as could



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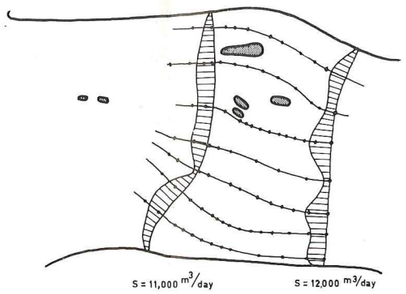

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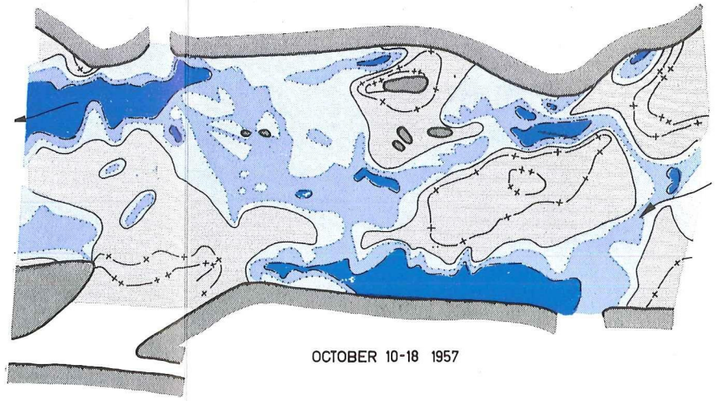

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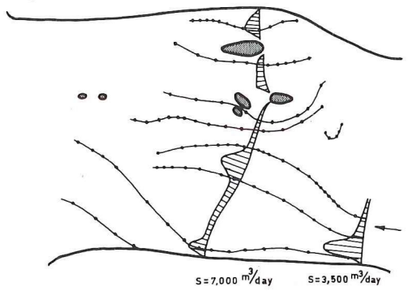

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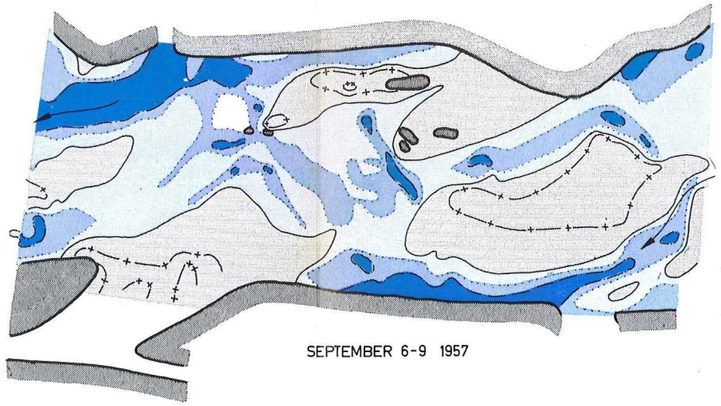

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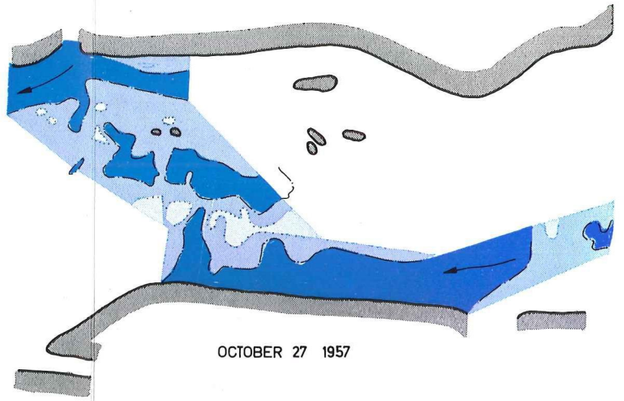

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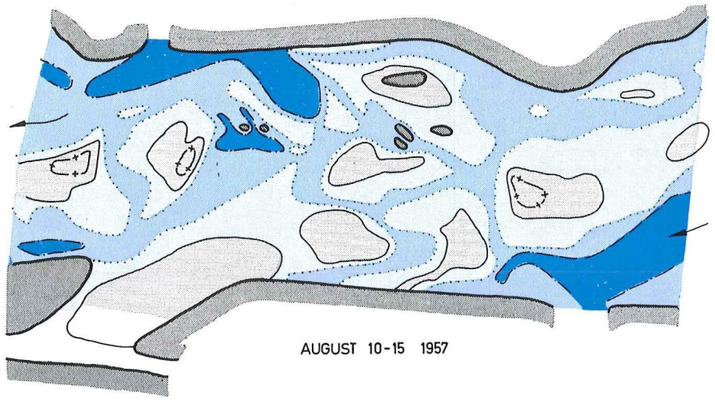

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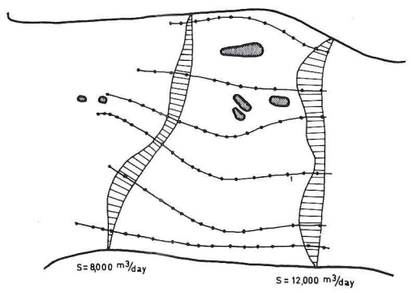
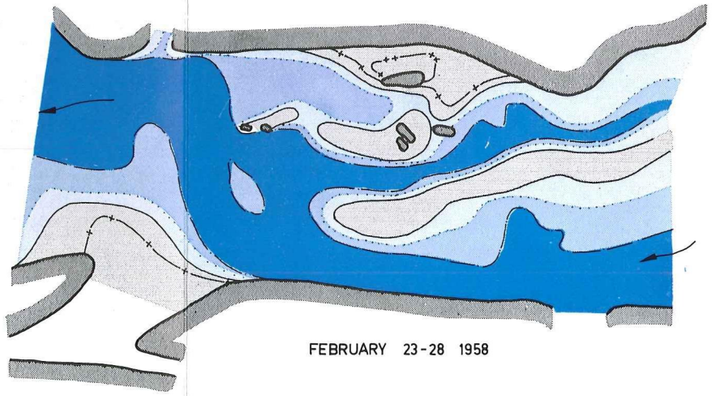


OCTOBER 8-9 1957



FEBRUARY 23-28 1958

BANKS AND ISLANDS

+ 6 ft
+ 3 ft
0
- 3 ft
- 6 ft
OVER 6 ft

20 m3/day PER METRE
BED LOAD AND SALTATION LOAD
10 m3/day PER METRE

FLOWLINE AND POSITION OF FLOATER ; ONE MINUTE INTERVALS

VELOCITIES

m/sec	(ft/sec)
2.5	(8.2)
2.0	(6.5)
1.5	(4.9)
1.0	(3.3)
0.5	(1.6)

0 0.5 1.0 1.5 km.
0 0.5 1.0 st.mile

NEDECO NIGER / BENUE	DIAGRAM III, 6.5.3- 4
GAMADIO CROSSING mile 817-819	
SOUNDINGS AND FLOWLINES	

1956
AUGUST 14-16, 1956

mile 807

TUNGALADAN

B

A

1957 I
AUGUST 18-20

mile 807

mile 808

TUNGALADAN

D

C

1957 II
SEPTEMBER 10-14

mile 806

mile 807

mile 808

TUNGALADAN

F

E

1957 III
OCTOBER 10-18

mile 806

mile 807

mile 808

TUNGALADAN

BANKS AND ISLANDS

+ 6 ft
+ 3 ft
0
- 3 ft
- 6 ft
OVER 6ft

1957 I
1957 II
1957 III
(1956)

28'
24'
20'
16'
12'
8'
4'

DATUM OF SOUNDINGS
L.R.L. GAMADIO
WATERLEVEL GAMADIO 1957

M J J A S O N D J F

0 0.5 1.0 1.5 km
0 0.5 1.0 st mile

SOUNDINGS REDUCED TO 15 FEET GAMADIO GAUGE

NEDECO NIGER/BENUE	MAP III,6.5.3-5
SOUNDING TUNGALADAN	

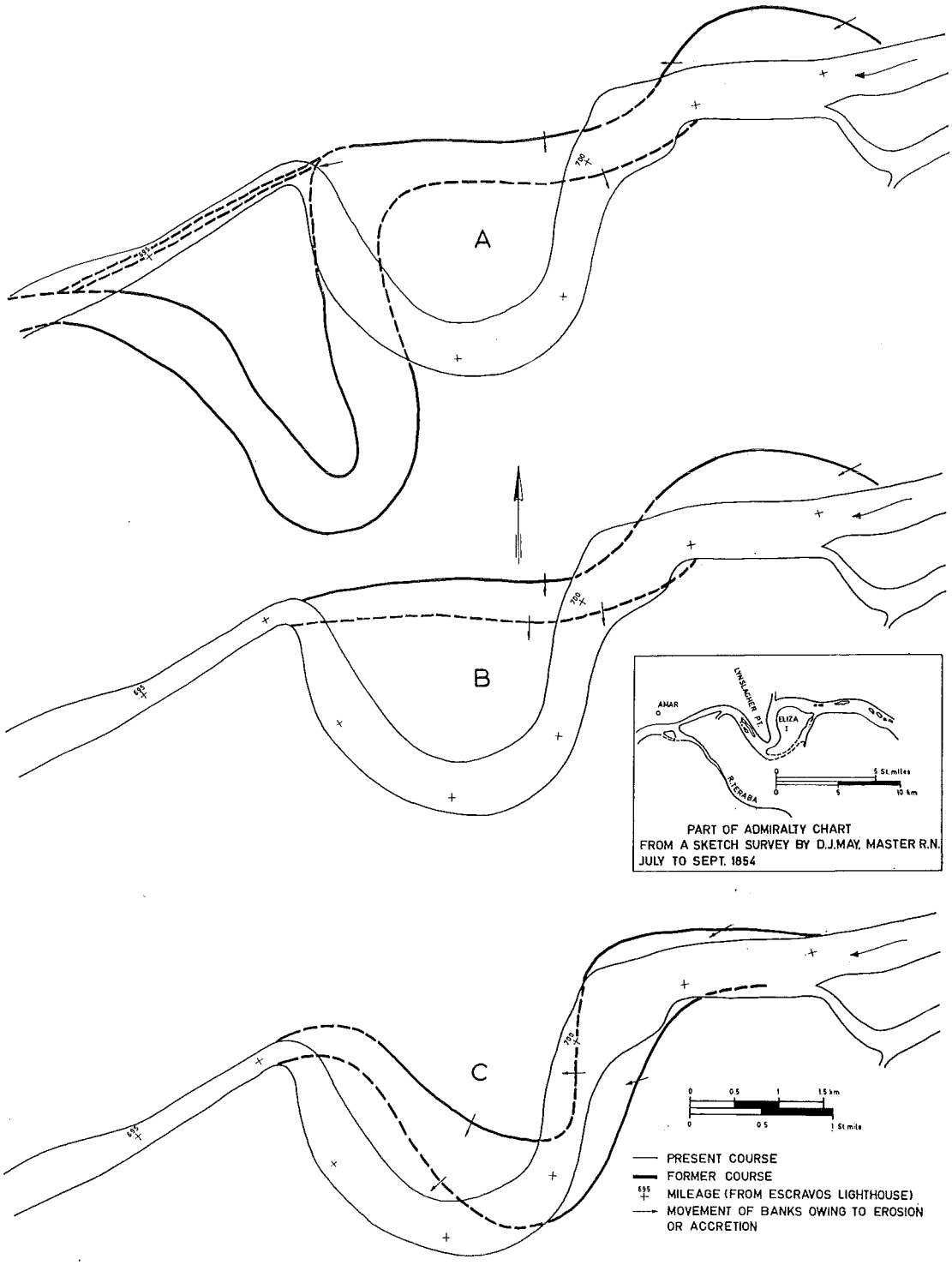


DIAGRAM 6.5.4-2

Development of Lynslagher Point (Benue, Mile 700)

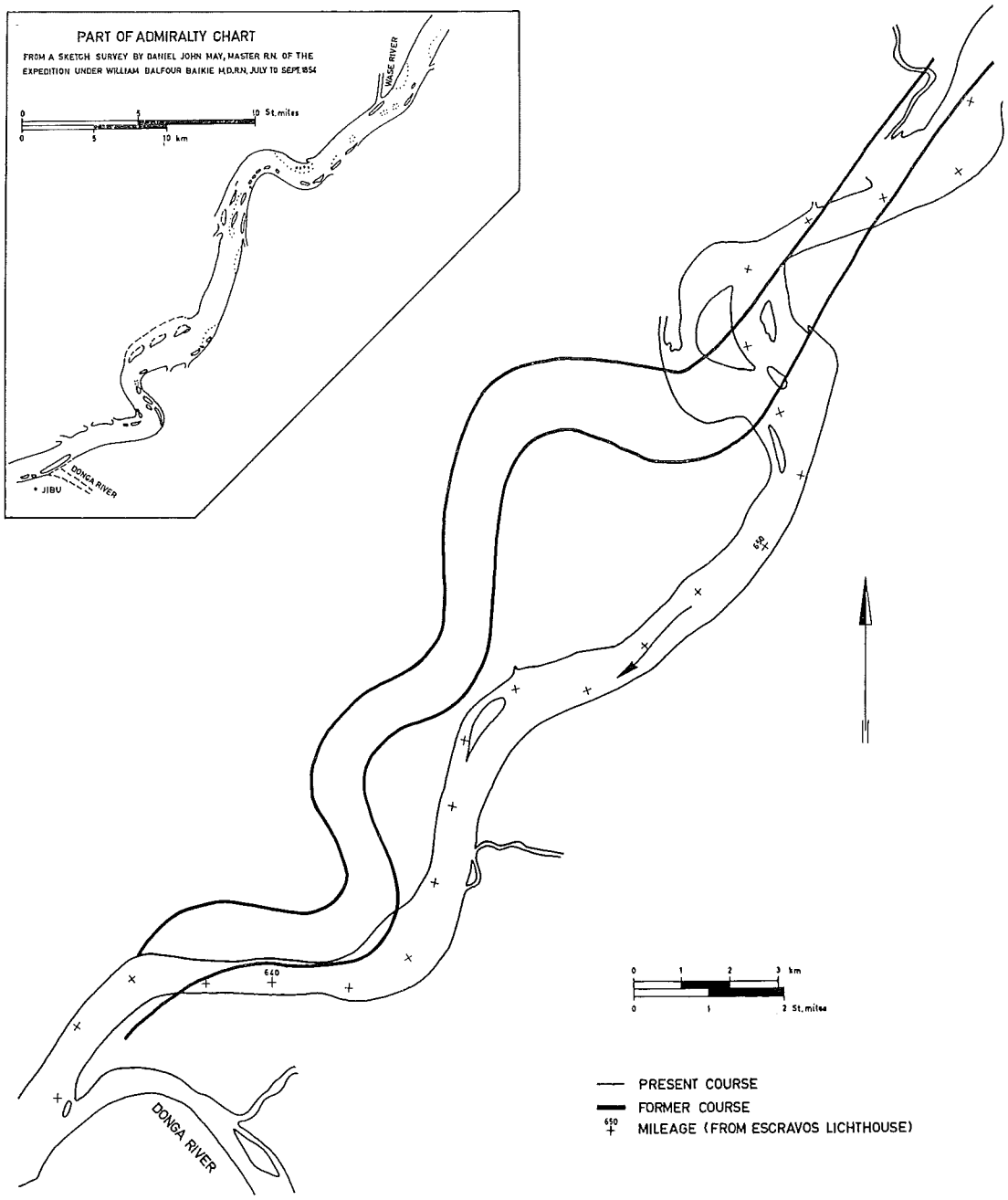


DIAGRAM 6.5.4-3

Benue, Miles 636—658; Reconstruction of course in approixmately 1850 with the aid of aerial photographs

be deduced from aerial photographs. In both cases the reconstructed courses bear a good resemblance to the respective river-stretches of a map made in 1854 by Daniel John May ([1].

In Diagram 6.5.4-2 an old loop has been reconstructed resembling the present loop near Kamberi (Miles 696—700). The origin of these loops could not be traced with certainty, but

([1] His sketch has been used in Admiralty Charts until recently

it is likely that they are effected by the presence of rocks and possibly of two rock facies, one downstream and the other upstream of Kamberi, at slight angles to each other. The earliest form of the loop corresponds with the shape of Lynslagher Point in the 1854 survey.

But Lynslagher Point is only 4 to 5 miles upstream of the Taraba Confluence, whereas the present and reconstructed situations are over 20 miles east of the present Confluence. To explain this discrepancy, Baikie may be quoted in his own account of the voyage:

"On the 12th (September 1854) we passed the first affluent which we had observed since we left the little Okwa, below Panda (1. It is of inconsiderable size, and flows from the southward, but forms a small fluviatile delta at its confluence. We made enquiries afterwards, but could never accurately learn the name. Some told us that it was called Bankundi, and that a few miles up it was a small village called Akam, while others again reversed this (2. Immediately above this the main river suddenly contracted, until not more than 200 to 250 yards across, along which the current ran like a sluice, being 5 to 6 knots. Although this rapid was not more than half a mile in length, it took us fully three-quarters of an hour to get beyond it. Further up, the river again widened into a large stream. No good wooding spot could be seen from the masthead; so we anchored about noon opposite a place where were some small trees, and hauling along the bank, sent all hands on shore.

"Our anchorage was at a very peculiar spot, as just ahead a double stream poured upon us; one, the smaller of the two, came directly from the east, while the other ran from the northward, doubling a long projecting cape, which we named Point Lynslagher (3. We subsequently ascertained that some miles further up the river diverged into two branches, enclosing a wide, irregular island."

As is already mentioned in the general description of the Benue in 2.3.2, the tributaries enter the Benue unobtrusively, so that it need not be wondered that Baikie sailed past the Katsina Ala and the Donga without noticing them. Probably the tributary referred to by Baikie (Akam or Bankundi) is the creek entering the Benue at Mile 687 (Taraba Confluence at Mile 672), possibly in Baikie's time one of the mouths of the Taraba. The narrow point could have been at Mile 685 or 687, where rocks on the north side force the river back, but other places where rocks or clayish banks occur could answer the question as well. The distance from the present junction of the creek to the beginning of the loop round Lynslagher Point would have been 694 – 683 = 11 miles; 6 miles more than follows from May's map. In Baikie's time, however, the creek might easily have debouched at any place between Mile 683 and Mile 690, which accounts for the discrepancy.

Another example of such changes in the course of the river is illustrated by Diagram 6.5.4-3 concerning a section of the Benue just upstream from the Donga River. Intermediate stages were too much concealed or faded out, and only one former course could be reconstructed.

The river below Makurdi (Diagram 6.3.4-4), where it has grown to its fullest size, is not as restless as in the regions described above, but the lakes that can be seen from the air between Makurdi and Lokoja certainly formed part of the Benue once upon a time. The changes in the river channels, very frequent above Lau, take place on another time-scale in these lower reaches.

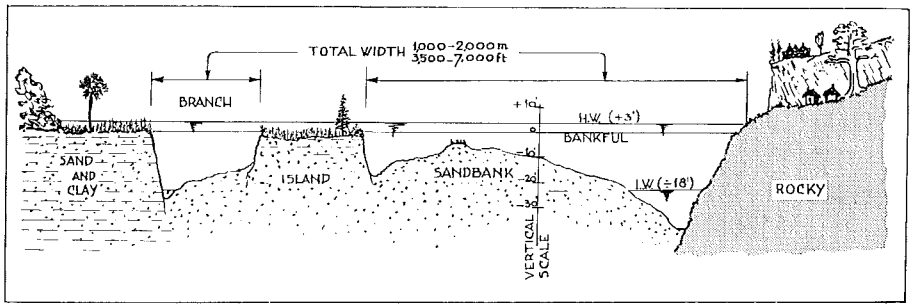


DIAGRAM 6.5.4-4

The Benue between Makurdi and Lokoja

Only in some specific unstable areas, as the Akpanaja Flats, can considerable changes be expected almost every year. The origin of these Akpanaja Flats is not a sand-discharging tributary nor a considerable decrease in slope but the existence of the narrowing at Makurdi. The Flats are

(1 That was probably the Ahini River just upstream from Umaisha
(2 The Kam is a tributary of the Taraba and the present Bakundi is a village at its confluence with the Taraba.
(3 After the Governor of Fernando Po.

formed by the sand masses passing through the gorge at high water and depositing in the wide area downstream.

6.5.5. Upper Niger

The Niger between Jebba (Mile 564) and Lokoja (Mile 362) can be classified neither as a meandering nor as a braided river, but as an intermediate type of river (named reach) flowing in its own alluvial sediment. The talweg is winding in between essentially straight river-banks (see 6.2.1).

The river-bed consists of a main channel with a sandy bottom and wide alluvial flood-land (fadama) with small creeks taking part in the discharge of high floods (Diagram 6.5.5-1). The wide main river-bed is sometimes slightly curved or follows an irregular zigzag pattern. Islands, either solitary or in groups, are a regular feature. In several places the main river-bed lies against

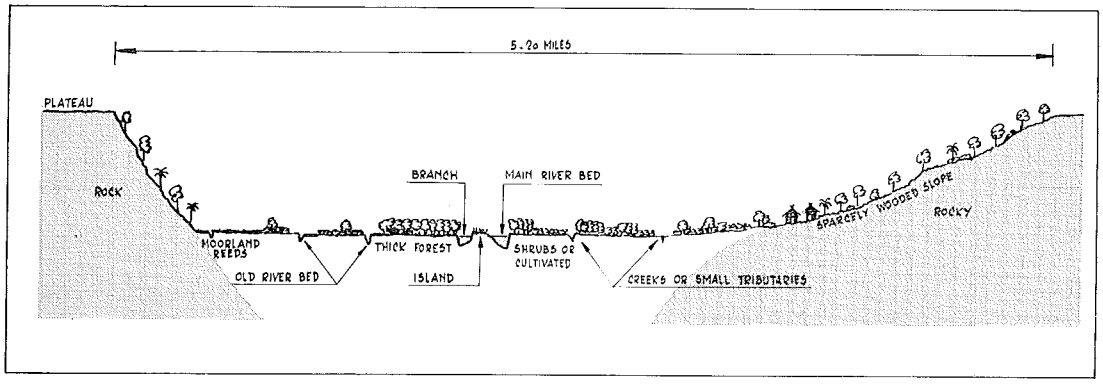


DIAGRAM 6.5.5-1

Upper Niger Valley

a projecting part of the plateau. Here, generally speaking, concentrations of islands can be observed (see 6.2.2). The subsoil of the flood-land is a mixture of sand, silt and clay, varying from pure sand (sand-bank built up in the former river-bed) to heavy clay (silted-up and blocked former branches). Very often eroded banks show a building-up pattern in layers containing more or less quantities of sand or clay. In several places strong red-grey clay, apparently of very old origin, is to be found in the banks of the main river or the flood-land creeks. Land at and above H.W.-level has the usual savana vegetation of dry grass and solitary trees. If, however, the flood-lands at H.W.-level contain sufficient clay to guarantee capillary water supply, heavy bush and forest occur. On land situated between H.W. and L.W.-levels the vegetation may consist of dry reeds and grasses on sandy subsoil or of heavy grass, shrubs and low forest on clay-containing soil. This land appears very suitable for cultivation, as the river guarantees sufficient ground-water in the dry season and supplies natural fertiliser during the floods. Land below L.R.L. is usually overgrown with high reeds. Trees and grasses would be submerged too long to survive the floods.

This L.R.L.-stage, which coincides with the occurrence of the Black Flood (see 4.5.4), is a striking feature on the Niger and especially on the Upper Niger. This second flood on the Niger, lasting two to four months from January onwards, is apt to have some influence on the formation of the channel, as is illustrated by the conception of the Dominant Water-level (D.W.)

which is described and analysed in 6.1.1-b. In Diagram 6.1.1-8 the D.W. at Baro, which is assumed to be representative for the whole Upper Niger between the Kaduna Confluence and Lokoja, has been calculated for an average year. The graph shows two peaks, one at the H.W.-stage of the river and one at the Black Flood stage. The centre of gravity of each of these parts represents a D.W., each with its own influence on the configuration of the river-bed. It will be clear that the successive occurrence of those two (different) D.W.'s will result in two bed-building forces which at some places will counteract each other annually. The changes in the river-bed will depend on the magnitude of the influence of each D.W. and thus on the ratio between the areas of the parts of the graph in Diagram 6.1.1-8, which respectively belong to the H.D.W. and L.W.D.

For an average year the said ratio at Baro is 0.84, the H.W. influence being smaller than the one of the Black Flood period. From this it can be seen that the Black Flood plays a very important rôle in the build-up of the channels of the Upper Niger. For the stretch upstream from the Kaduna Confluence, the Black Flood is even more dominant as the Kaduna River contributes more than half of the local flood of the Niger at Baro.

Apart from this conclusion for an average year in Baro, the D.W.'s for H.W. and for the Black Flood can be drawn for every year separately. The channel, which is adapted in the long run to the average D.W.'s, will not change within half a year according to the annual D.W., but the annual D.W. may give an idea of the trend of the bed deformation during that particular year, whilst the deviation from the average can also be interesting.

Especially where a certain correlation is found between high local floods and high Black Floods, and conversely, it may follow from a series of observations that when an extremely high local flood is followed by a high Black Flood, these changes within one year become noticeable. During the investigations of NEDECO such trends were believed to be found, but the period of observation was considered too short to express a definite opinion about this phenomenon.

a *Jebba—Pategi* ([1]

From Jebba to Pategi (Miles 556—480) the width of the main river-bed varies from 500 to 1,000 m (1,500—3,000 feet) as shown in Diagram 6.5.5-2.

In the first twenty miles downstream from Jebba the river is characterised by surrounding nearby hills. The river-banks contain rock and stiff old clay, and here an average of 11 islands per 10 miles may be counted, whilst further downstream this average is about 6 or 7 islands per 10 miles (see also 6.2.2). The height of the islands is about L.R.L. + 3′. Shore-heights vary from L.R.L. + 3′ to L.R.L. + 6′, although the H.W.-level is about L.R.L. + 10′.

Sand-bank heights are up to L.R.L. while Black Flood and L.W. normally are at a level of L.R.L. — 1′ and L.R.L. — 6′ respectively. In comparison with the river downstream from the Kaduna Confluence, the sand-banks are low, short and irregularly shaped and situated.

The main river-bed at L.R.L.-stage has a rather clean-cut outlook. This will be partly due to the relatively small variation in discharge (and sand-transporting capacity) between H.W. and L.R.L. as compared to downstream from Pategi. But this cannot be the sole reason.

The shape of the flood-lands leads to the assumption of another reason. In the flood-lands former river-beds can be clearly observed in between former islands which are overgrown with solid bush and forest. These old river-beds are silted-up to about L.R.L. — 1′ and are overgrown with reeds and grass, although some parts are in use for the cultivation of rice. The presence of natural levees along these former river-beds (which also exist along the present bed) explains

([1] Although the stretch of river from Jebba (Mile 556) to Baro (Mile 434) was not officially included in the investigation some measurements and surveys were carried out here. These were needed for the explanation and solution of several features and problems of the river-stretch downstream from Baro. During the measuring tours some morphological data, though not as intensive and accurate as below Baro, were collected as well.

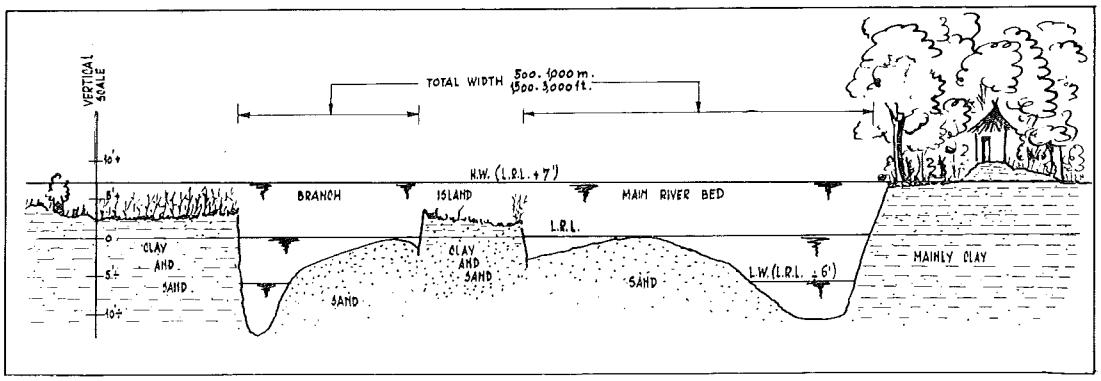


DIAGRAM 6.5.5-2

The Niger between Jebba and Pategi

the presence of these clearly visible former river branches. A new course of channel is not formed by the river shifting sideways but by suddenly breaking through the natural levee, abandoning the former bed and leaving it to a gradual process of siltation at higher stages of the water. This procedure, however, is only possible if the percentage of coarse material in the transported sediment is low, causing a valley build-up by finer erosion-resistant material, and producing a dense vegetation. The suspended material is sieved out in this vegetation along the channel, thus building up a natural levee. More surveys and measurements at different stages of the river are needed, however, to obtain a deeper insight into the processes taking place in this part of the river and to see if the above-mentioned assumptions are correct.

Especially the wide flood-lands in the 30 miles upstream from Pategi show the marks of a gradual process of silting-up as the deposition of suspended material during H.W.-stages is intensified by backstage from the Kaduna River.

b *Pategi—Lokoja*

At Pategi the Kaduna River joins the Niger, changing the channel of the river by adding huge quantities of its coarse bed-load material during H.W. The width of the river here varies from 750 m (2,500') to 1,500 m (5,000').

The sand-banks with a height of up to L.R.L. + 5' and the river-banks with a height of up

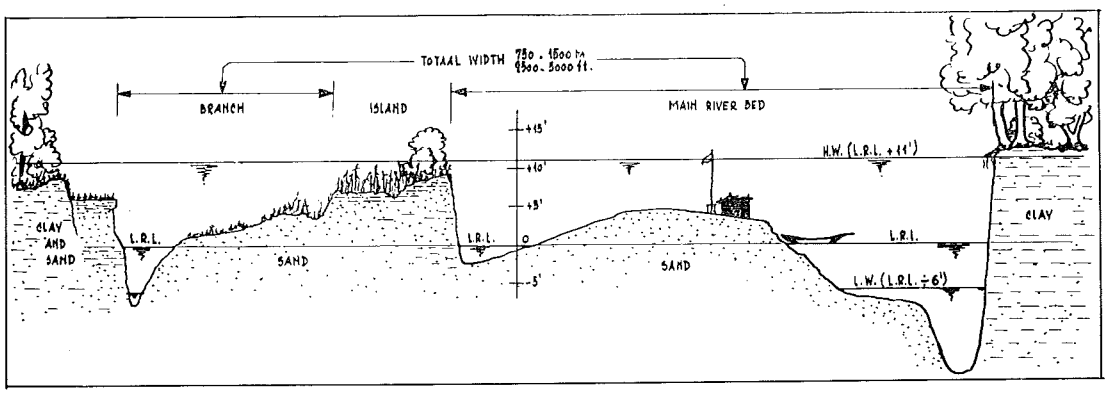


DIAGRAM 6.5.5-3

The Niger between Pategi and Lokoja

to L.R.L. + 7′ to L.R.L. + 12′ or more often merge into each other. This transition can also be seen with the islands, which have a height normally between L.R.L. + 5′ and L.R.L. + 9′ (see Diagram 6.5.5-3). Both banks and islands contain more sand than upstream from Patégi. Although H.W.-level is about L.R.L. + 11′ here, it still seems that at comparable high water-stages the river has a relatively larger sand-transport here than upstream from Patégi. But, again, more measurements in the stretch Jebba-Patégi would be needed to prove this. Striking is the sideways shifting of the channel by eroding one bank and building up the opposite one, though this process is rather slow here in comparison with the Niger downstream from Idah. Remarkable are the many creeks parallel to the main river, especially between Baro and Lokoja. These creeks are fairly deep and stable, most often following a bank of hard clay. Sometimes they are temporarily blocked by a sand-bank at the entrance or by trees eroded from the high clay bank.

At Mile 385 the river enters the 2-miles wide "gorge" at Koton Karifi, flowing close against the right-hand plateau slopes, as illustrated in Diagram 6.5.5-4. In the surrounding area strong

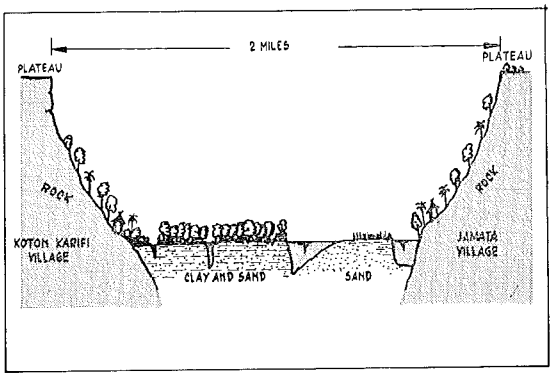


DIAGRAM 6.5.5-4

"Gorge" at Koton Karifi

banks of presumably very old clay may be observed, and the number of islands is raised from 6 or 7 per 10 miles to 9 per 10 miles in the stretch from Budon (Mile 399) to Lokoja. This latter section is subject to backstage by the Benue (see 4.2.6). During the H.W. of 1956 a clay layer of 20 cm (8″) was deposited here at several places. The banks near Lokoja show a high percentage of recent clay in the top layers, apart from the very old clay banks.

6.5.6. Lower Niger

On the Lower Niger, i.e., the Niger below Lokoja, the influence of the Black Flood is less dominant than on the Upper Niger above Lokoja. But it is still such that it probably causes the river to meander in its lower section where other factors stimulate this meandering (such as, for instance, the cohesive river-banks).

The difference between mean H.W. and mean L.W. is about 30 feet, the former being about L.R.L. + 25′. The river-banks have a height of 20 to 25 feet above L.R.L., while the islands average a height of L.R.L. + 20′. In the lower section, where meanders gradually come to a better development, the islands decrease in number.

In the *Rocky Section* from Lokoja to Etobe (Miles 362—332) Basement Rocks appear at the surface. The river flows in a relatively narrow valley through these Basement Rocks; but nevertheless the bed-level is nowhere more than 30 feet below L.R.L., probably due to lack of curvature in stream-lines. Sand-banks are practically absent and the cross-sections show a trough-like profile with slight variation in depth over the width (Diagram 6.5.6-1).

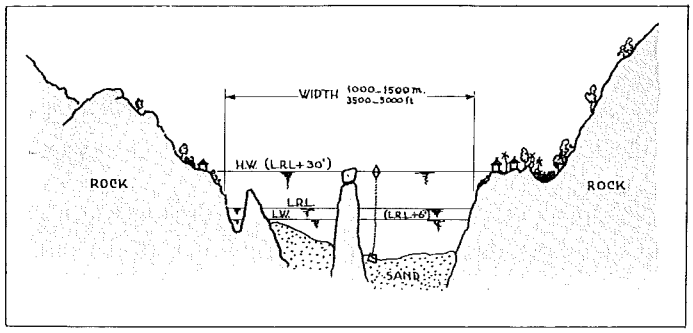


DIAGRAM 6.5.6-1

The Rocky Section of the Niger

During H.W. the bed is very narrow compared to the river-sections more upstream and downstream. As a result raise by backstage occurs upstream from the Rocky Section (see 4.2.6) where huge masses of sand are deposited. At the same time the bed in the Rocky Section is deepened by erosion (comparable to the phenomena occurring at the elimination of a secondary branch as discussed in 6.6.4), while the scoured material deposits again immediately downstream of the Rocky Section where rocks no longer restrict the width.

Consequently at L.W. the Rocky Section is too deep; draw-down occurs in the upstream end and raise in the downstream end of the Section, with sand deposits in the Section and a maximum range between H.W. and L.W.-stage at the upstream end.

The Rocky Section could be seen as a natural bed-regulation by channel contraction (see VI, 6.2.5) with only the absence of the regularity of gently-curved meanders. Although deep navigation channels exist, it also shows the dangers of a regulation over a short distance: sand deposits during H.W. at its downstream end deteriorate the navigation channel. A bed-regulation, therefore, should be carefully planned in its downstream end, and should be gradually adapted to the natural river conditions of those sections where no major difficulties to navigation exist.

In the Etobe-Idah stretch (Mile 332—310), which is of the *reach type* of river, sand deposits from the Rocky Section have caused a badly developed channel pattern. The sand-banks are low, ranging from L.R.L. to L.R.L. + 5'; islands and the river-banks show a sandy build-up and erode easily; and irregular rocky spurs may be observed on each side of the river. Unfortunately the outline of these rocks along the banks presents hardly any guidance to the flow. On the contrary, their outline is so ragged — and if the rocks are present on both sides the width in between is just a little more than the establishment of a good navigation channel would need — that the result is often two half-developed channels with underdeveloped islands and wide sand-banks in the middle of the river.

Below Idah (Mile 310) the reach type of river gradually changes into a slightly *meandering type*. Many well-developed bends occur but too often the rhythm is disturbed by chutes, where

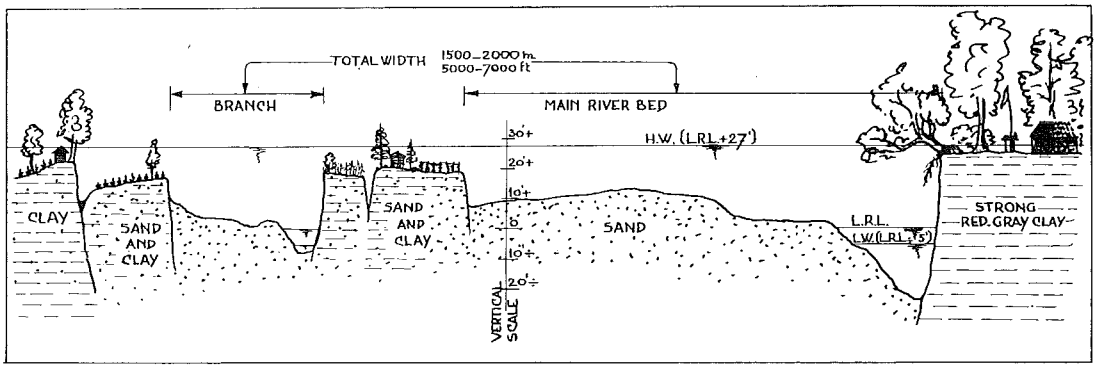


DIAGRAM 6.5.6-2

The Niger between Illushi and Onitsha

the floods no longer follow the meandering talweg but cut through the sandy convex bank. Islands may be formed in that way and can also disappear by the silting up of one branch. Old channels may re-open again later, when conditions become favourable in the channel configuration which in the meantime propagates downstream. This is probably the reason why on certain islands old vegetation is present (mature trees).

To the south the flood-lands and banks gradually become more erosion-resistant, due partly to the smaller particles which in the lower regions of the river are brought on top of the banks and partly to the climatic conditions which together allow a denser and stronger vegetation.

From Illushi to Onitsha (Miles 272—231) the right bank is practically straight and is composed of cohesive red-gray clay, while not far from the river-banks hills are present; the left bank contains mostly sand and the flood-lands are wide (Diagram 6.5.6-2). So the right bank does not move so easily and is 3 to 5 feet higher than the left bank (possibly consolidated by the Coriolis acceleration, see 6.1.4). Sand-banks are moderate between L.R.L. + 10′ and + 15′ and merge on the left side into the river-banks; while on the right side only a few sand-banks exist as the flow leans predominantly against the hard bank.

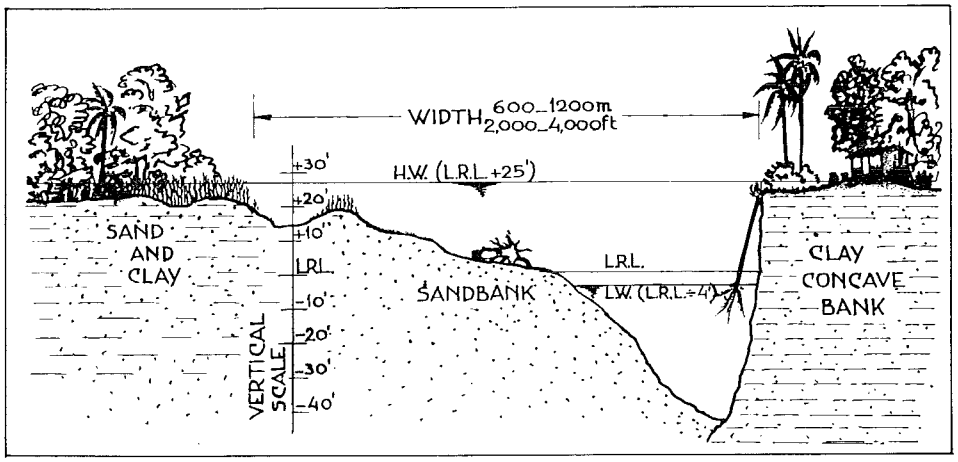


DIAGRAM 6.5.6-3

The Niger below Aboh

Below Aboh (Mile 173) the meandering character of the river arrives at its fullest scale Fine long bends with regular sand-banks rising on the convex side and deep channels along the outer bank are normal in this section (Diagram 6.5.6-3), and navigation is only hampered at those places where a separate L.W.-meandering deviates from these high-water bends and the respective hydraulic axes (6.3.2) cross under rather large angles.

6.5.7. Delta Creeks

Below the division of the River Niger into the Nun and the Forcados Rivers at Mile 152 near the village of Onnya, the river flows through its Delta and bifurcates more and more into distributaries, each of which carries only a part of the flow. This decrease in discharge, combined with a gradually decreasing slope (see Section 2.5), causes the velocities to decrease and fine sand and later even silt particles to be deposited on the banks which in consequence are made up of clayey material. Under these conditions the river-branches develop a meander pattern, firstly with sand-banks in their inner bends but further downstream without such sand-banks because of the absence of sand. In the actual Delta Creeks, indeed, hardly any sand is found, and in the bends even the concave sides are rather deep.

As these Delta Creeks are situated not far away from the sea, the tidal currents have their influence, too, which finally greatly surpasses the influence from the river-discharge. Sand-discharge originating from the River Niger is taking place mainly by those distributaries which have the steepest slope, i.e., which follow the shortest route to the sea. Of the Western Delta area ([1 it is the Nikorogbo Creek and the Ramos River which carry nearly all the sand from the Forcados River, the other distributaries and intersecting creeks having banks consisting of pure mud and clay, bound by the strongly-interwoven roots of mangrove trees (Diagram 6.5.7-1). Most creeks have a depth of between 20 and 30 feet; in sharp bends this depth is sometimes even greater.

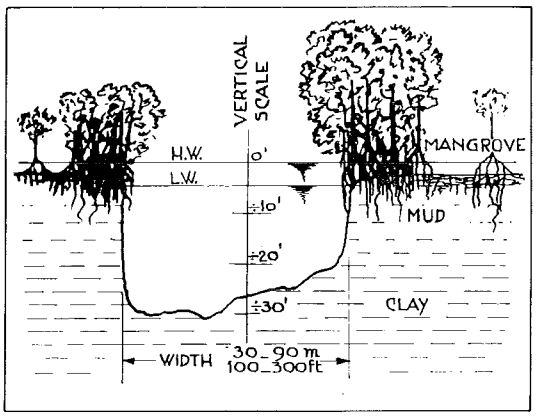


DIAGRAM 6.5.7-1

A Delta Creek

As the Eastern Niger Delta is still under investigation, no further comments on this area are given here. The impression has been obtained, however, that the Nun River, formerly a good navigable river, has had its shipping conditions decreased by a disproportionately large sand supply from the Niger, while as the Forcados River receives relatively more water, it is

([1 NEDECO, 1954. GEN. 23

this river which now offers the best navigation conditions. An explanation, however, has not been sought for in this Investigation, and more observations would be necessary for any further consideration.

6.5.8. Lokoja Confluence

The confluence of the two large rivers Niger and Benue at Lokoja (Mile 362) has been a subject of particular interest during the three years' investigation of NEDECO.

From a scientific standpoint it is interesting because of the special problems concerning backstage of each others' water-levels, and concerning deposits of sand in the lower sections of both upper rivers as well as immediately downstream from the Confluence. Although problems like these occur on every confluence, no exhaustive research is known to have been published on these subjects, mainly because they normally exist on a very small scale. The great difference of the hydrographs of both the Niger and Benue Rivers, however, results in phenomena clearly observable, analysis of which is made easily possible by their extreme sizes.

From the standpoint of navigation the Lokoja Confluence has always been notorious for hampering shipping to a great extent.

When looking at the map of the Lokoja Confluence given in Diagram 6.5.8-1, the dominating aspect is the division of the Benue into two channels: North Channel and South Channel. The first is the normal shipping route, but there might be circumstances when the South Channel temporarily provides a better way. The distribution of discharge over the two channels has been dealt with in Paragraph 4.3.8, where it has been shown that the South Channel normally draws 60% of the Benue discharge except at the low-water period, when the South Channel has a higher percentage. It can then even happen that a part of the Niger discharge flows through the North Channel "upwards", and back via the South Channel.

The decrease of the relative discharge through the North Channel at low water is caused partly by the phenomenon of backstage and partly by the existence of a huge sand-bank above the Benue Island, more or less forcing the flow into the South Channel by effecting an extra resistance in the upstream end of the North Channel. Since older charts or photographs of this area are lacking, it is impossible to say whether this sand-bank has always been there, but it is, of course, travelling gradually downward together with the entire meandering picture. In the course of the three years' investigation, this propagation extended so far that the blocking of the North Channel was almost effected, and a breach through the Benue Island finally occurred securing again the original discharge distribution of 60% and 40% through North and South Channels respectively. It seems probable that the said sand-bank will in the near future be split up into a number of smaller sand-banks travelling downward via the North Channel, whilst a new sand-bank above the Benue Island may be formed again.

The existence of the Benue Island must be rather recent. From the description of the explorations by RICHARD and JOHN LANDER ([1], the impression is obtained that when they passed the Confluence on October 25, 1830, the Benue Island either did not exist or was so low that the occurring flood-level inundated the entire island including vegetation. Nowadays even the highest flood-level leaves parts of the island almost uncovered, and at least shows great areas with vegetation extending above the water. The next information about the Lokoja Confluence is a chart made by CAPTAIN WILLIAM ALLEN, R.N., in September 1841. Although this chart, which is given in Diagram 6.5.8-2, is drawn on a very small scale, it seems that there are a number of small islands at the Confluence. A large island extending upward into the Benue (River Chadda), however, is not shown, nor is it to be seen on the Admiralty Chart No. 2446, based

([1] LANDER, 1832. GEN. 19

on MAY's survey made in August 1854 ([1]. However, a situation sketch of 1910 could be reconstructed and here a large island appeared, as shown on the first chart of Diagram 6.5.8-3. The "North Channel" at that time was very narrow, and it may be possible that it originated by a short-cut through the long and narrow sand-spit between the two rivers. The development can

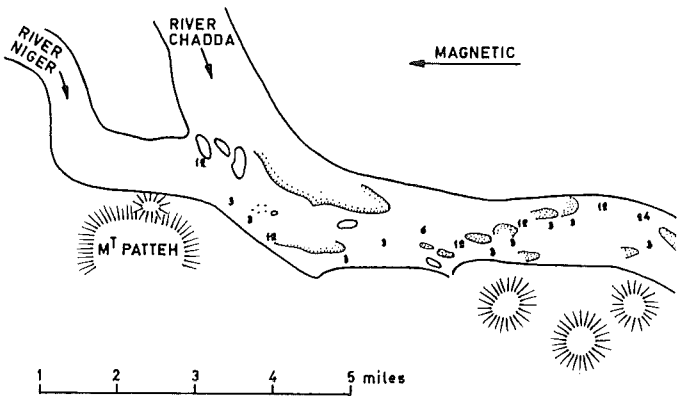


DIAGRAM 6.5.8-2

Sketch of Lokoja Confluence made by Captain William Allan, 1841

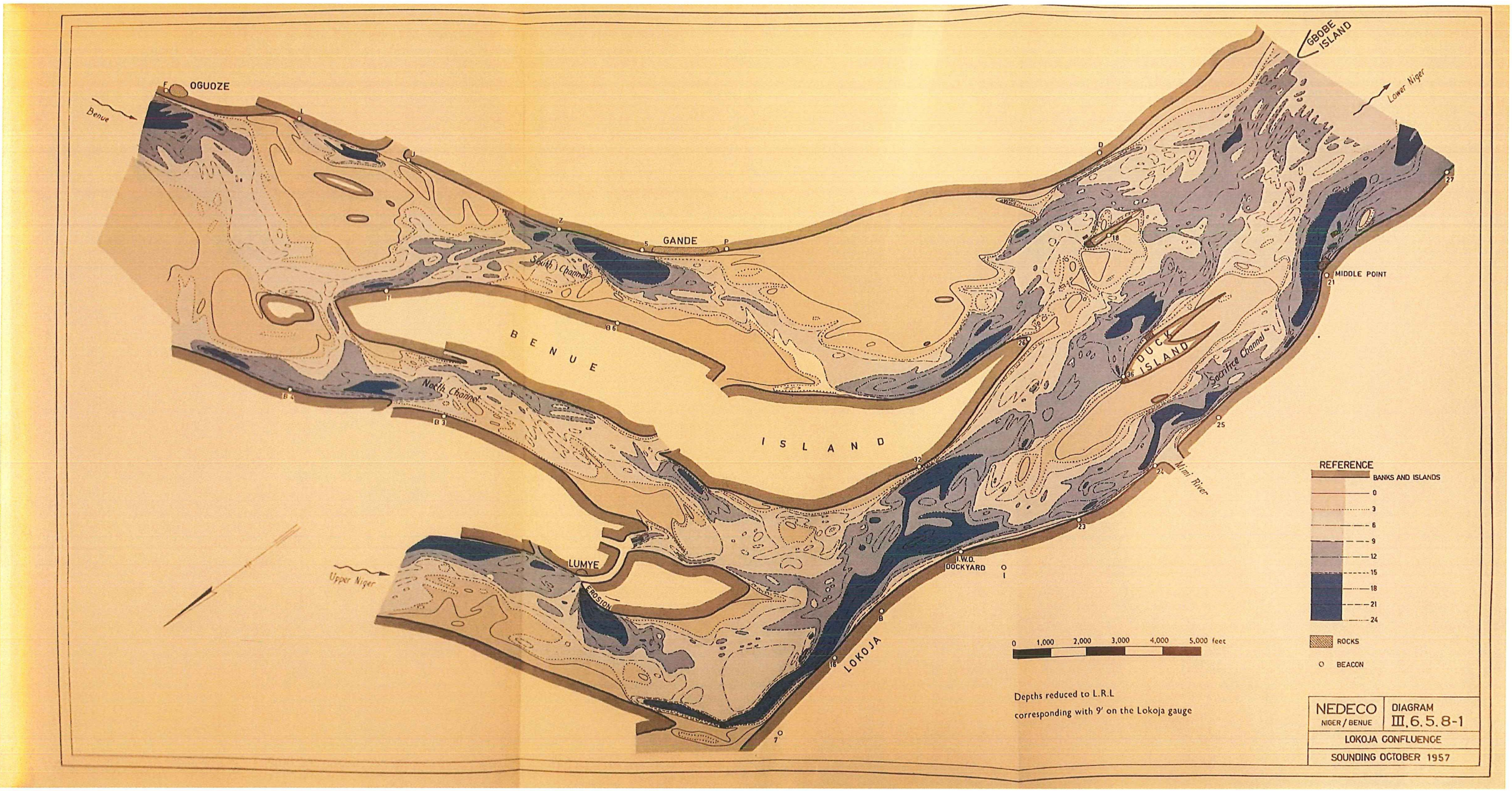
be followed but not very well analysed by the scarce data available. The chart prepared by A. L. E. DENNIS in 1933 provides the next situation, given in the second section of Diagram 6.5.8-3, while the recent alignment as surveyed by NEDECO is expressed in the third section of the diagram.

In this period of over 100 years no changes occurred in the right bank of the Niger, as this bank consists entirely of rock and stone, and prevents the location of the Confluence shifting westward. Individual rocks scattered over the Niger below Lokoja have little influence upon the flow, although they may stimulate the origin of an island on its leeside, if conditions are favourable. For example, Duck Island and Valiant Ridge both have rocks in its upstream end, defending the island against erosion.

Led by the occurrence of an unusually great number of rocks in the river immediately downstream from the Mimi River, right across Duck Island and Valient Ridge, observations have been made in that particular section to find indications about a possible rocky sill in the river-bottom determinant for the morphological behaviour of the river. By means of a water-jet a pipe was pushed into the bottom untill it struck rock. Diagram 6.5.8-4 shows the results, giving no indication about the existence of such a sill. Although the pipe was only 26 feet long and borings could not be extended beyond that depth, it has been proved that in the greater part of the cross-section the bed consists of sediment with rocks buried sufficiently deep to have no influence upon the river morphology. This would correspond with the findings of boring observations at Onitsha, Makurdi and Yola, where the rocks appear to be over 30 m (100 feet), 90 m (300 feet) and 30 m (100 feet) respectively below the actual sandy river-bottom (see Chapter 3).

From the charts of Diagram 6.5.8-3 it would be concluded that changes of the lay-out in general are only very gentle. However, local changes may be very fast. The south bank of the Benue Island near its upstream end has been severely eroded, where in a single year at least 200 m (700 feet) land has been washed away into the river. Another example of such a speedy

([1] BAIKIE, 1855, GEN. 1


OGUOZE
Benue
GBOBE ISLAND
Lower Niger
GANDE
South Channel
BENUE
ISLAND
North Channel
MIDDLE POINT
DUCK ISLAND
Sacrifice Channel
Mimi River
LUMYE
EROSION
Upper Niger
I.W.D. DOCKYARD
LOKOJA
REFERENCE
BANKS AND ISLANDS
0
3
6
9
12
15
18
21
24
ROCKS
BEACON
0 1,000 2,000 3,000 4,000 5,000 feet
Depths reduced to L.R.L
corresponding with 9' on the Lokoja gauge
NEDECO
NIGER / BENUE
DIAGRAM
III.6.5.8-1
LOKOJA CONFLUENCE
SOUNDING OCTOBER 1957

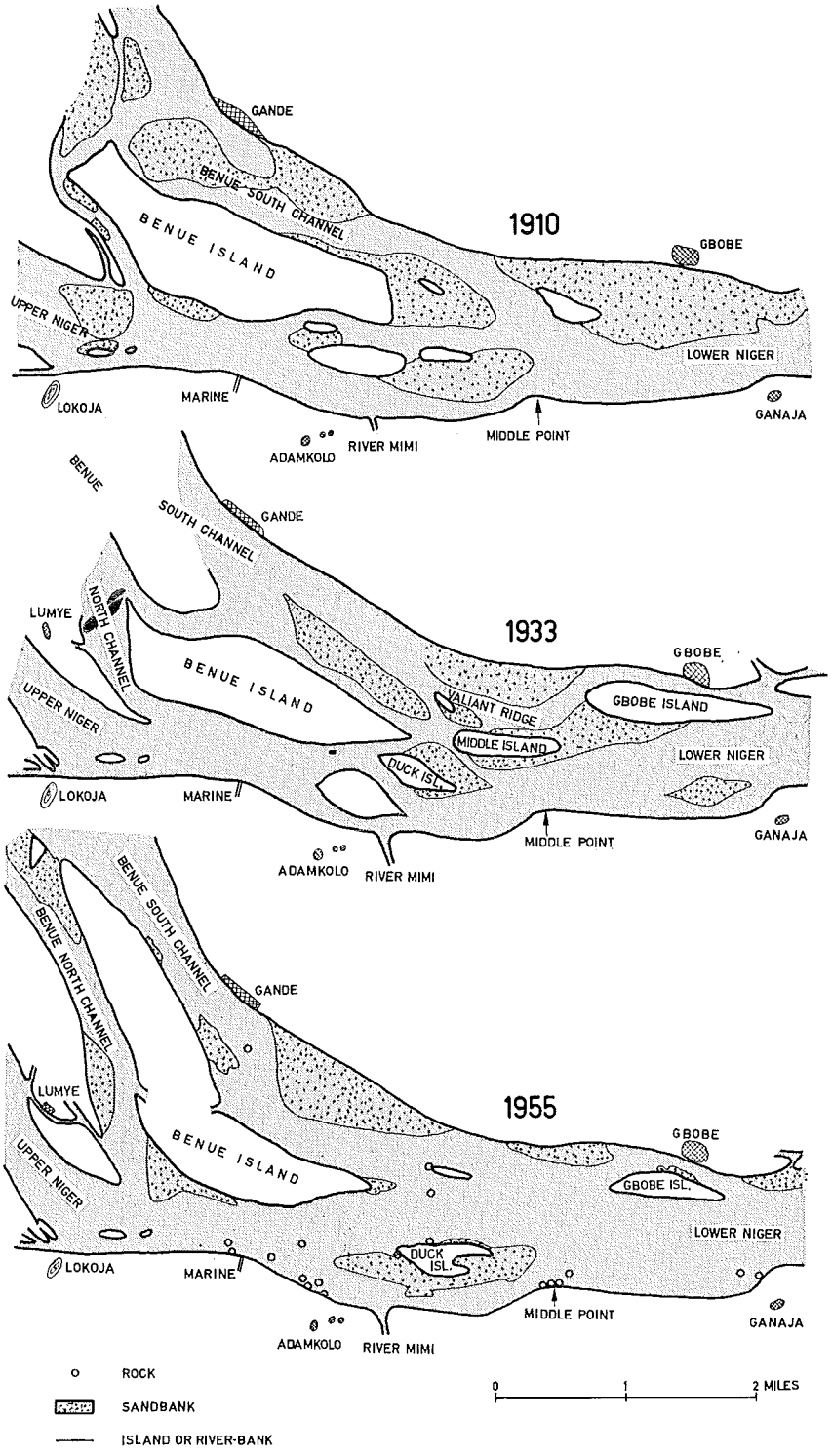


DIAGRAM 6.5.8-3

Recent development of Lokoja Confluence

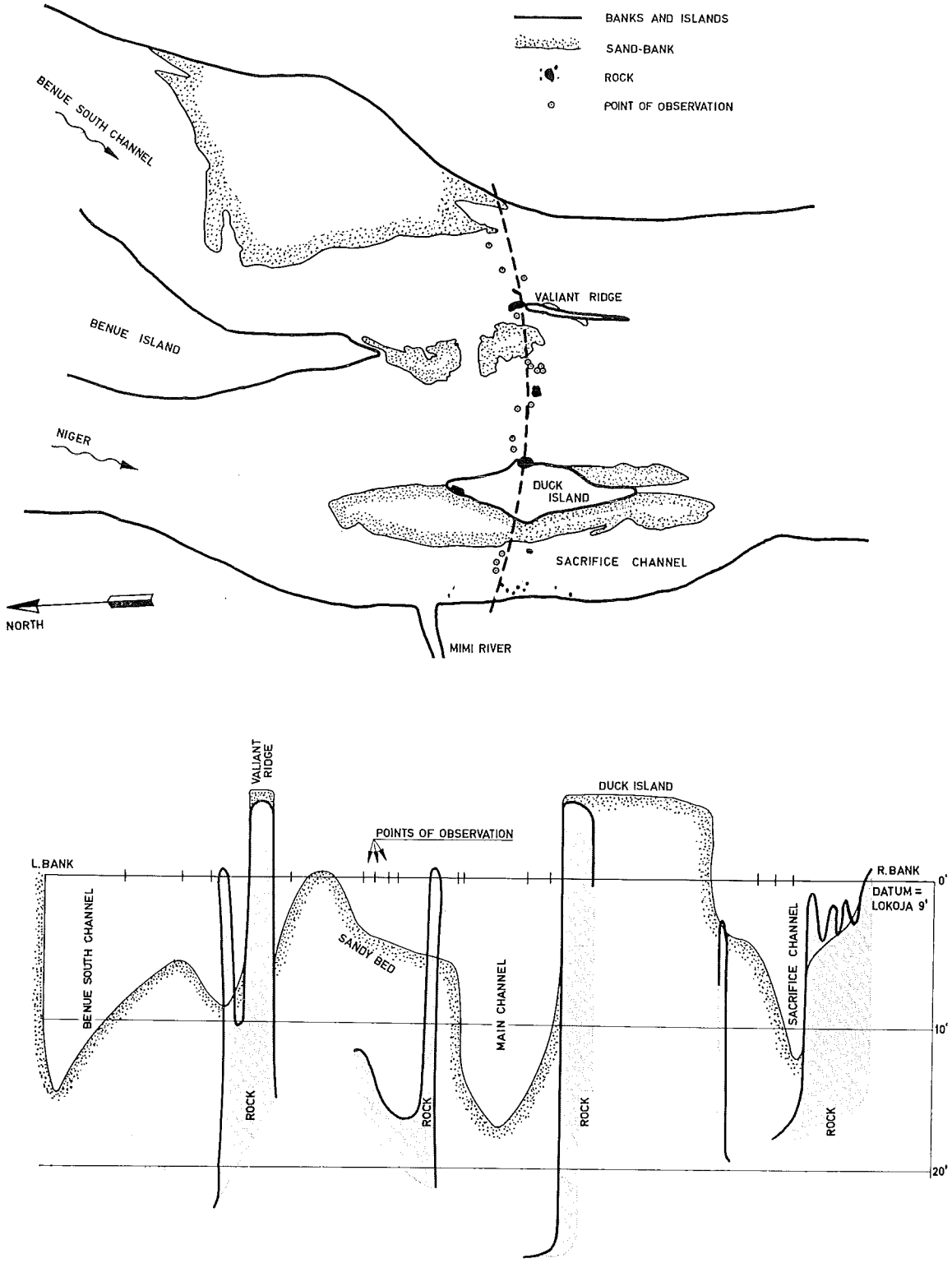
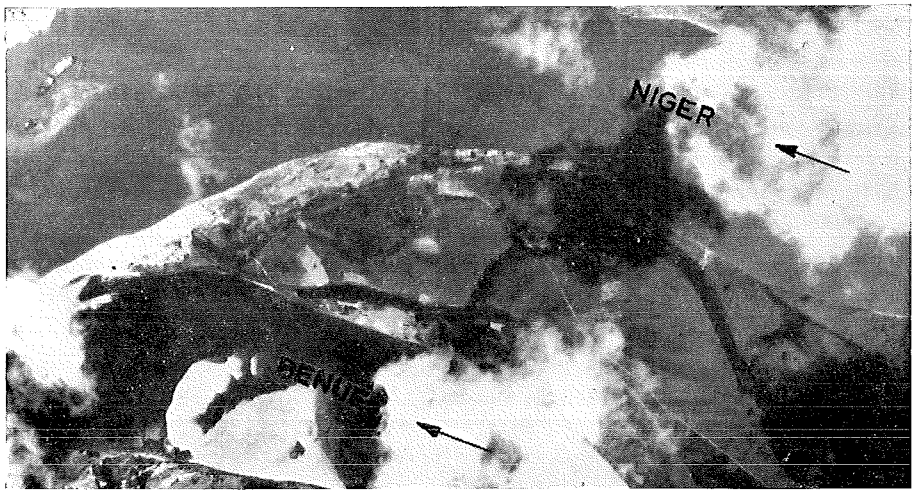


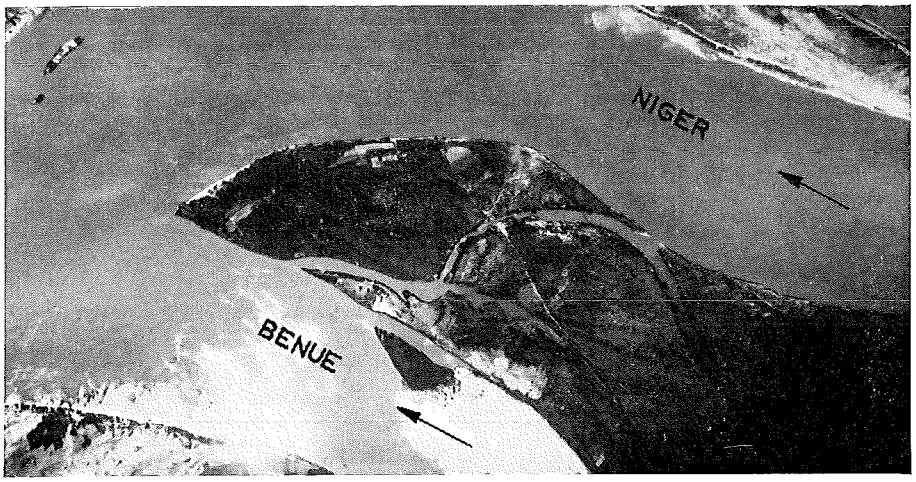
DIAGRAM 6.5.8-4

Exploration of rocks in the river-bottom of the Niger below Lokoja

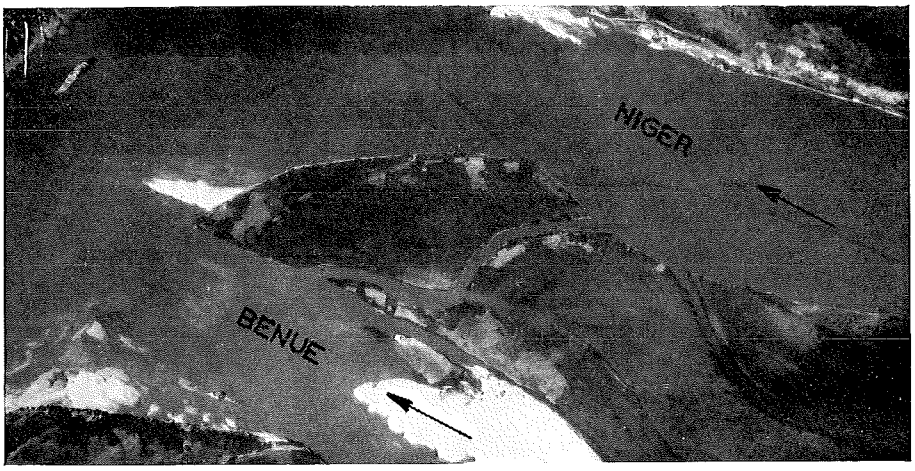
1949



May 1954



December 1956



PHOTOGRAPH 6.5.8-5

Origin of Lumye short-cut

erosion can be found opposite Lumye. The Lumye short-cut formerly was only a narrow creek belonging to the Benue system. By sideward shifting, the Niger captured this creek (see Photograph 6.5.8-5) increasing its width and depth, and at present the short-cut draws a large discharge from the Niger, especially because the diversion near Lumye is situated in an outer bend of the Niger. The result is a very heavy attack on the newly-formed island in front of Lumye, an island which is fast eroding at an annual rate of at least 300 m (1,000 feet).

It has been already stated that the North Channel is the normal shipping route, and local information suggests that this was also the case in former times, although occasionally in certain years navigation used the South Channel, as, for instance, in 1957. Comparison of the two channels did not lead to a reason for a preference for one of them. The confluence of the North Channel with the Niger is blocked by a shallow place, the notorious Benue Bar, whilst the South Channel debouches into the Niger at a reasonable depth, although it is not certain that this will always be so. On the other hand, a very shallow place is situated immediately below the confluence, called the Lokoja Flats. These flats must be crossed by ships bound for the South Channel, but could be avoided in the route through the North Channel by using "Sacrifice Channel", a more or less narrow branch west of Duck Island (see Diagram 6.5.8-1). Sacrifice Channel actually was followed by navigation in 1957, and would provide an excellent shipping route if some dangerous rocks did not prevent full-scale use. It must be noted here that the depths as drawn in Diagram 6.5.8-1 have been measured at high water in 1957. At that time of the year there is no Benue Bar and the Lokoja Flats are not shallow. The difficulties for navigation occur at lower stages. The Lokoja Flats hamper shipping during and after the Black Flood period up to July (see V, 3.2.2), while the Benue Bar prevents navigation from entering at a time when the Benue itself is already navigable as far as Makurdi, which normally happens in May or June (see V, 3.1.2).

The formation and deformation of the Benue Bar can be clearly followed from a series of soundings given in Diagram 6.5.8-6. All charts of this diagram have their respective depths reduced to the same datum, being L.R.L. with a reading on the Lokoja gauge of 9′.

The first chart shows the situation in April 1956. The Benue at that time had a discharge of approximately 600 m³/sec (20,000 cusecs) while the Niger discharged some 2,200 m³/sec (80,000 cusecs). The Benue Entrance was closed with a depth of only 3½ feet below datum. But shortly afterwards the Niger fell to a discharge of about 900 m³/sec (30,000 cusecs) whilst the Benue showed a considerable rise of water-level. In July, when the second chart has been sounded, the Benue reached a discharge of 4,000 m³/sec. Scouring on the Benue Bar started and a new channel was being formed which was completed before the third sounding was made in September. At that time a depth in the channel of over 9′ below datum was available. The discharges of the Niger and Benue were 5,500 m³/sec (200,000 cusecs) and 10,000 m³/sec (350,000 cusecs) respectively. Apparently the flow from the Benue was easily capable of maintaining a good channel at the Confluence, pushing aside the sand-spit which exists between the two rivers (see 6.2.3). The alignment of the channel was directed towards SW×S, making an angle of about 40° with the main direction of the Niger flow.

However, during the highest stage in October the increased Niger discharge caused the sand-spit between the two rivers to turn toward the Benue, and consequently the direction of the Benue Channel turned more south. The angle of confluence decreased to some 10°, effecting an easy transport of sand from the downstream end of the sand-spit. This sand travelled downward and settled in the lower end of the Benue Channel, forming small shallow patches. It was these patches which were in the first instance the cause of the closing of the channel in December, when after high water the Benue discharge had abruptly dropped to some 800 m³/sec (30,000 cusecs) while the Niger maintained its discharge at about 2,000 m³/sec (70,000 cusecs) due to the Black Flood. In January 1957 the closing of the Channel had been nearly completed. Sand from the Niger deposited in the Benue Entrance due to lack of flow, and the entire area was silting up. A short-cut between the two rivers, the Lumye short-cut, brought an extra amount of sand into the Benue (see 5.4.5) and effected an accelerated deposition of sand, with the result that in March 1957 a depth of not more than 3½ feet below datum was available, while the sand-spit between the two rivers was directed almost in front of the Benue Entrance.

It is worth to mention the propagation of the sand-bank in the Benue on its left bank during the cycle of one whole year: it moved downstream over a distance of some 200 m (650 feet).

Also the stream-pattern of the Benue flow is interesting. In the North Channel during low water it is, of course, concentrated along the right bank, the remaining part of the width being

APR. 17, 1956

JULY 18, 1956

SEPT. 24, 1956

OCT. 24, 1956

DEC. 8, 1956

JAN. 7, 1957

MAR. 13, 1957

APR. 11, 1957

REFERENCE

BANKLINE

0'

3'

6'

9'

12'

15'

NEDECO NIGER / BENUE	DIAGRAM III, 6.5.8-6
LOKOJA CONFLUENCE	
FORMATION AND DEFORMATION OF THE BENUE BAR	

dried up. At high water, however, although the deepest channel is located near the right bank, the main current has been found a little over the middle of the river on its left-hand side, probably brought there by the pushing power of the Niger current.

The alignment and the depth of the Benue Channel and the direction and extension of the sand-spit between the two rivers depend on the composition of both hydrographs of the Niger and Benue. In the year of observation, 1956/1957, the Benue appeared to have a rather high flood, whilst the Niger remained fairly low. Variation in the difference between the discharges of the Niger and Benue causes variation in the shape of the Benue Channel, but the main moving forces on the sand, scouring and depositing as described above, will always exist. And it is not only the discharge itself, but also the phenomenon of backstage (see 4.2.6) which influences the sand-movements. During the Black Flood of the Niger, the Benue discharge is small and therefore the current slow, but the backstage of Benue's water-level will still further reduce this velocity of current and thus accelerate deposition of sand. The causes and consequences of the Benue Bar will be considered further in V, 3.1.2.

Apart from the seasonal variations in the bottom configuration caused by the yearly cycle of raise and draw-down by backstage, a general influence of this backstage upon the average equilibrium state of the river-bottom is most important. The deposition taking place when the river is raised during a part of the year is compensated by the scour due to draw-down during another season. Whether the ultimate equilibrium involves a deep or a shallow channel depends on the rate and duration of the raise and draw-down. The latter has a larger influence upon the river-bed than the former, but on the other hand it is the former which extends its influence much farther upward.

Under some approximations and assumptions the phenomenon can be calculated, based upon the sand-transport formula of MEYER-PETER and MUELLER as mentioned under 5.2.1.

In its most simple form, consecutive cross-sections of the river are thought to be equal in shape and size (prismatic channel) with a constant bottom-gradient along the river-axis.

The scour criterion, as derived in 5.4.1,

$$b a^{\alpha} = \text{constant}$$

can be modified with the help of the discharge formula of DE CHEZY into

$$b a^{\frac{3}{2}} a^{\alpha-\frac{3}{2}} = \frac{Q}{C\sqrt{i}} a^{\alpha-\frac{3}{2}} = \text{constant}.$$

With the assumption of Q and C being constant, the criterion becomes

$$CR = \frac{a^{2\alpha-3}}{i} = \text{constant}.$$

Here, the coefficient α varies between 1 (zero sand-transport) and 1.5 (very large sand-transport). The criterion is then

with zero sand-transport

$$CR_0 = \frac{1}{a i} = \text{constant},$$

and with large sand-transport

$$CR_\infty = \frac{1}{i} = \text{constant}.$$

A raise by backstage will — under the said assumptions — decrease the slope i and therefore increase the term $1/i$. With large sand-transport, which in general takes place in the deep parts of the cross-section, this means deposition of sand, since the criterion $CR \neq$ constant but increases (see 5.4.1). However, in the shallow parts of the cross-section, where sand-transport is negligible, the depth a plays an additional rôle: while the slope i decreases the depth a increases, and it is the increase of the depth which in shallow areas outweighs the decrease of the slope. The result is a decrease of the criterion CR involving an erosion.

Conversely, at a period of draw-down the deep parts of the cross-section will undergo an erosion, while on shallow places deposition will take place. Sand-banks therefore behave conversely from channels.

For the Upper Niger, immediately above the Lokoja Confluence, the magnitude of deposition and erosion

could be computed as based upon the rate and duration of the periods of raise and draw-down as found in 4.2.6.

It appears that in the lowest part of this river-section the total year-influence of the period of draw-down exceeds the one of the raise: the channel is eroded involving a low equilibrium of bottom-height, while the sand-banks heighten. Here, however, a complication must be taken into account: during the period of draw-down the very high sand-banks are dry, and consequently no deposition there can take place. During the period of raise, when the high sand-banks are flooded, scour occurs. The ultimate result is continuous erosion on the very high sand-banks without compensation by deposition. From computations it follows that the transition zone between the lowering high sand-banks and heightening low sand-banks is about the level of L.R.L. (Low River Level), corresponding with a reading on the Baro gauge of 11 feet.

More upstream, the effect of draw-down decreases relatively more than the effect of raise, since the latter extends its influence farther upward. Computations show that the yearly resulting erosion of the channel gradually diminishes, going upward from Lokoja, until it reverses into a deposition involving a heightening of river-bottom.

These phenomena have indeed been observed on the Upper Niger. High sand-banks with a level of over L.R.L. + 6′ as occurring frequently above Jamata (Mile 382) gradually disappear between Jamata and Etikaku (Mile 368) and are not found below Etikaku. As for the

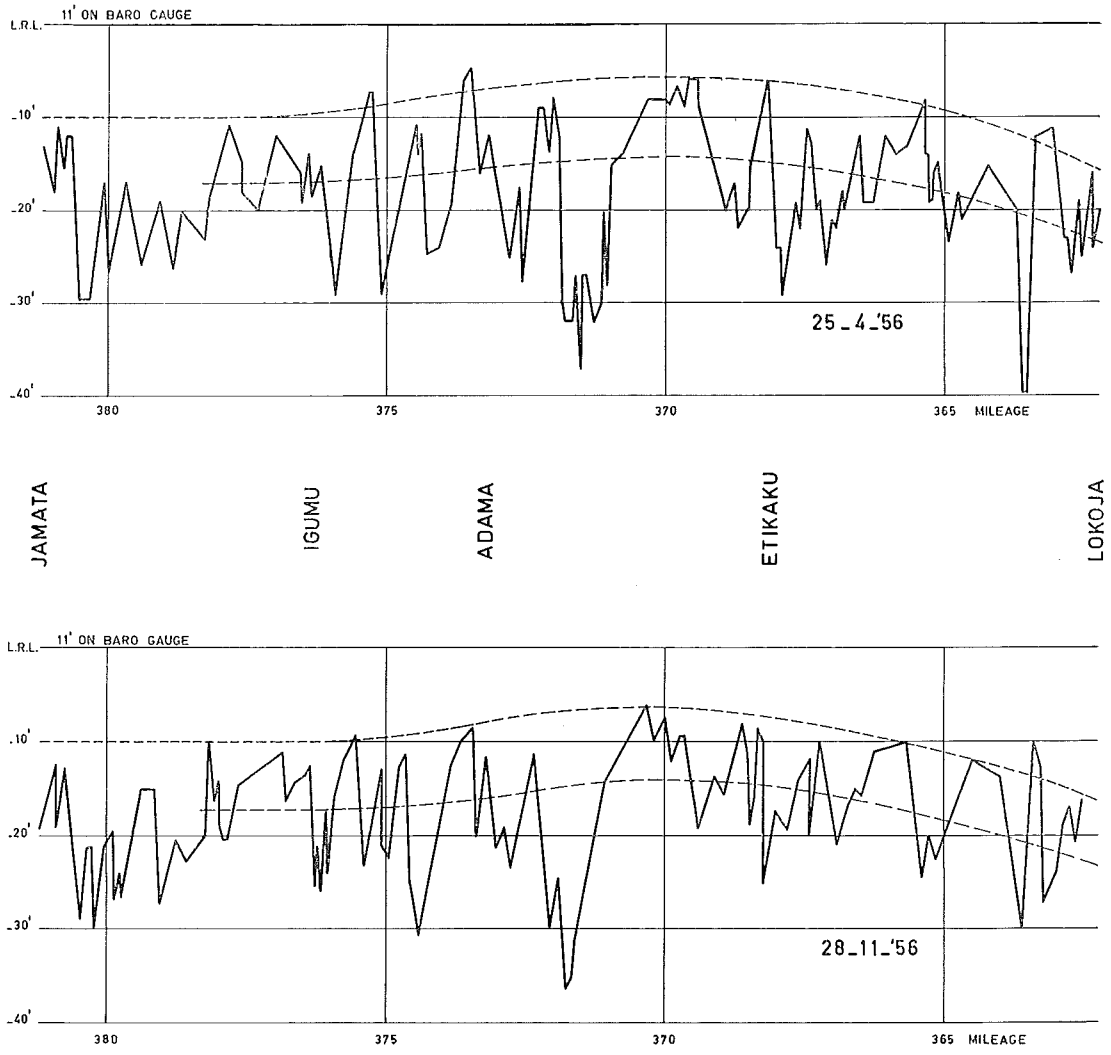


DIAGRAM 6.5.8-7

Talweg of lowest river-section of Upper Niger

sounded on April 25, 1956 and on November 28, 1956

channel, corresponding with the computations, a shallow section exists a few miles upstream from Etikaku and causes difficulties to navigation (Suli Bank), while below Etikaku a gradual deepening has been observed, as shown on Diagram 6.5.8-7.

Quantitatively the observed channel deformations do not correspond exactly with the computations, which probably is caused by erroneous assumptions. There are, for example, the prismatic shape of the channel and the constant bottom-gradient along the river-axis, and their influence is very complex and hard to trace. If the mathematical model of the river were not simplified with these assumptions, computation of the phenomena would appear entirely impossible. Qualitatively, however, the results of the computations correspond satisfactorily with the observations, as schematically shown in Diagram 6.5.8-8.

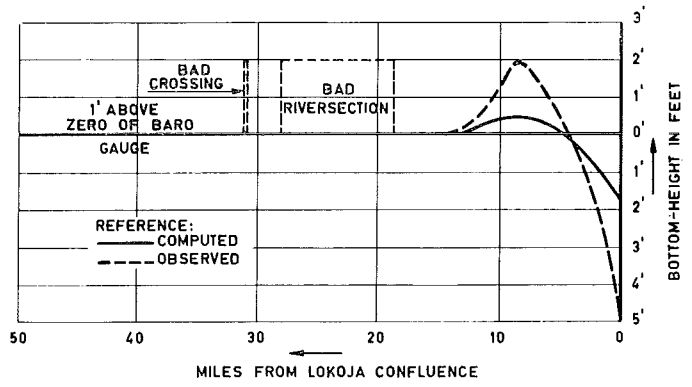


DIAGRAM 6.5.8-8

Comparison of computed and observed bottom-height in the lowest river-section of the Upper Niger

6.6. EFFECTS OF HUMAN INTERVENTION ON THE DEVELOPMENT OF CHANNELS

6.6.1. Effect of dredging a deeper channel

Before a decision can be taken as to the practicability of dredging channels through the shallow parts of the crossings in order to increase the least available depth (L.A.D.) for shipping purposes, it will be of great importance to study the theoretical outcome of such an undertaking and to determine the factors which have their influence on the alignment of such a channel.

A dredged channel through a shoal on a crossing should as closely as possible meet the following three requirements:

(i) be as short as possible;

(ii) not re-shoal within the season when the deeper channel is needed; and

(iii) not lead to a channel which is too crooked to be navigated by ships, nor have cross-currents which hamper such navigation.

Ref. (i) will directly have its influence on the amount and the costs of the initial dredging, while ref. (ii) will ensure a regular improvement of the shipping possibilities without the need of recurrent dredging within the season.

During the H.W.-period the flow pattern of the river is rather uniform and follows roughly the trend of the river-banks, while at lower water-stages the flow meanders through the river-bed and on the crossings strongly deviates from the H.W. flow-pattern. To fulfil the second requirement it seems obvious that the direction of a dredged channel will be best chosen when it follows the current during the river-stage when the ships will require it, i.e., on the Niger at Low River Level (L.R.L.).

Under the present hydrological conditions dredging on the Benue is considered not practicable, as described in VI, 4.3, and therefore only dredging on the Niger is discussed here. If in the future by discharge-regulation on the Benue, similar conditions occur as on the Niger, with its rather steady Black Flood discharge, the theories discussed hereafter will also be applicable on the Benue.

The consideration that the dredged channel has to coincide with the flow at L.R.L. leads directly to a restriction of the date of commencement of dredging, as during the high flood cross-currents would flow over this channel and the rather large sand-transport may level out the dredged channel before it becomes useful to navigation. From a study of the flow-pattern over the crossings (Diagram 6.4.2-8) it follows that the commencement does not seem practicable before the water-level has dropped below 6 feet above L.R.L. on the Upper Niger (17′ on the Baro gauge) and 8 feet above L.R.L. on the Niger below Lokoja (21′ on the Onitsha gauge), i.e., late October or early November.

To illustrate the effect of a dredged channel on the water-levels an example is given of a representative crossing in the Niger (Kelebe, Mile 389, Diagram 6.6.1-1). The situation is given at a water-level of 3′3″ above L.R.L., a moment when dredging is feasible. The channel which whould be dredged is indicated; its direction is according to the flow-lines at L.R.L., which prevail for some months from December onward. As to the depth of the channel to be cut, a minimum of 3—4 feet seems necessary in relation with the dredging plant. The cross-section A-A in Diagram 6.6.1-1 has been drawn at right angles to the flow-lines and over the crest of the sill. From this it can be clearly seen that such a channel has only little effect on the distribution of the flow, which follows also from a rough calculation when using the formula of DE CHEZY

$$Q = C\sqrt{i}\ \Sigma b a^{\frac{3}{2}}$$

At a water-level of L.R.L. + 3′3″ the value of $\Sigma\, b a^{\frac{3}{2}}$ increases, due to the dredged cut, from 7,250 to 7,600 $m^{\frac{5}{2}}$, which brings about a decrease of the slope of approximately 10%, when C is assumed to remain constant. The cross-section drawn is that where the cut has the greatest effect on the slope, as from the other cross-sections over the crossing less sand will be removed. When the sand from the dredged channel is dumped in the cross-section itself, $\Sigma\, b a^{\frac{3}{2}}$ will alter less and the decrease in slope will be less.

As a consequence of this decrease in slope, a drop of water-level upstream of the dredged crossing occurs, but its magnitude is very small.

A rough idea of this effect can be obtained when a plausible value for C (= 40 $m^{\frac{1}{2}}$/sec) is taken. At a water-level of L.R.L. + 3′3″, the discharge amounts to 3,600 m^3/sec and as $\Sigma\, b a^{\frac{3}{2}} = 7{,}250\ m^{\frac{5}{2}}$ the slope over the shallowest part of the crossing is 15×10^{-5}. When the total length of the cut is 2,000 feet, and the slopes of the river-sections up and downstream from the cut are taken as constant, the total drop in water-level just upstream from the dredged channel will be

$$\tfrac{1}{2} \cdot \frac{10}{100} \times 15 \times 10^{-5} \times 2{,}000 \text{ feet} = 0.015 \text{ feet.}$$

Such a drop in water-level is negligible compared with the depth of the cut.

Another effect of the cut is the concentration of the flow-lines in the upstream part of the cut. These flow lines diverge in the downstream part of the channel when the new situation is compared with the original situation. This is clear from the fact that the deepened channel must draw more water. Also this effect is small. Calculations show that an extra 100 m^3/sec may be drawn through

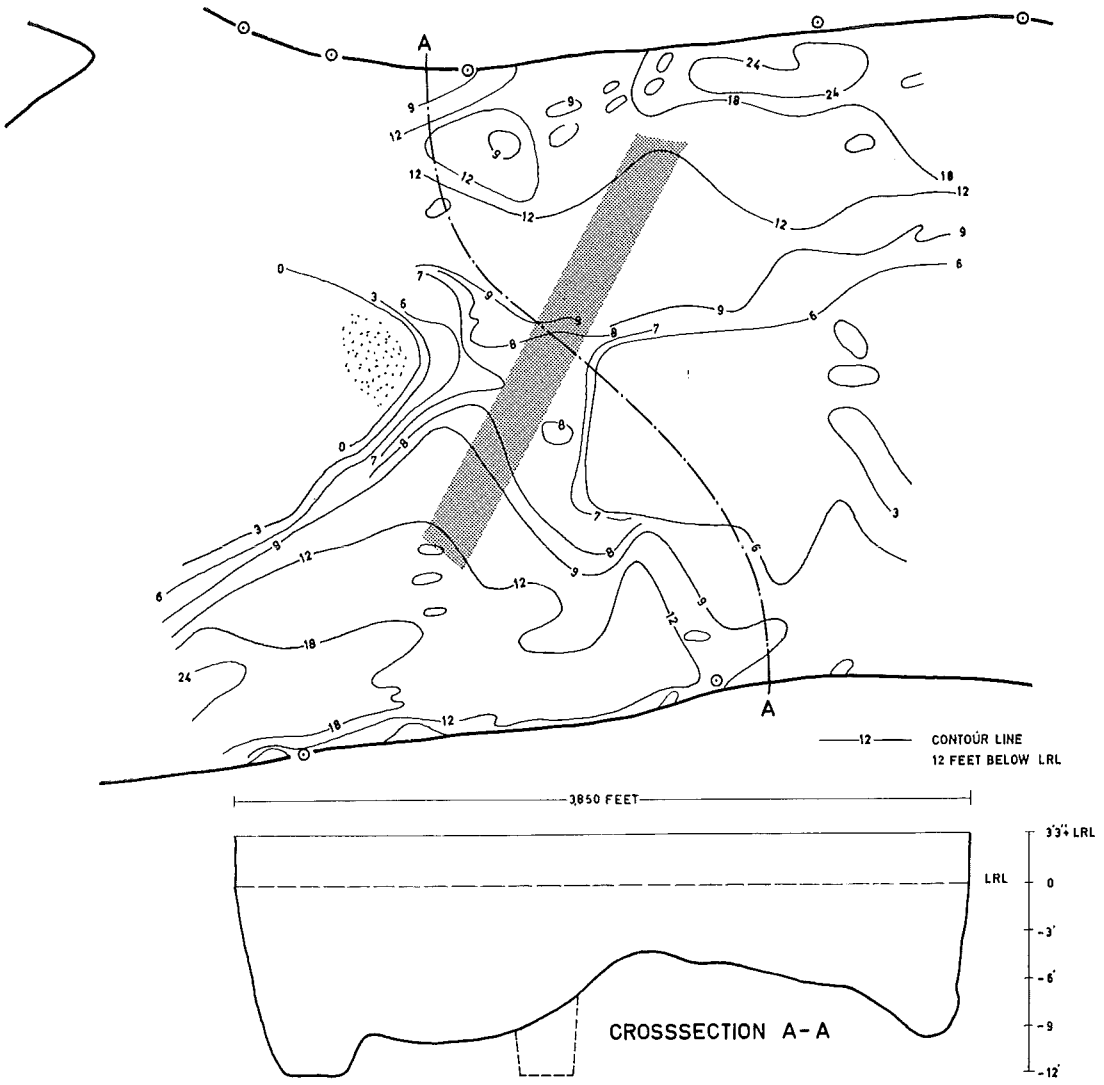


DIAGRAM 6.6.1-1

A dredged channel on Kelebe crossing

the channel, where the influence of the cut has the largest effect. This is less than 3% of the total discharge.

The conclusion is that the entire flow pattern hardly alters, as the cross-section of the cut has a very small size compared with the total cross-section over the river.

The question whether or not such a dredged channel will untimely silt can only be approached from the experimental side, as the complex pattern of sand-transporting capacity, scour, deposit and length of particle jumps is not predictable. Only trials with a dredger can give a definite conclusion. However, there are several considerations which need discussion in order to weigh the chances of success.

The fact that the sand-movement concentrates at the crossings during low river-stages as a result of the increased slope over the crossing leads to the conclusion that the river naturally

is inclined to even out the slope over crossings and deep pools (see 6.1.1). The final consequence would be, if this assumption is correct, that the slope on the crossing discussed above would become 11×10^{-5}, as is the present valley slope of the Niger near Kelebe. The width would certainly not be wider than the width between the banks, i.e., 1,050 m (3,400 feet) and a plausible value of the coefficient of De Chezy would be 44 $m^{\frac{1}{2}}$/sec (80 $ft^{\frac{1}{2}}$/sec). The hydraulic depth on the crossing at L.R.L. with a discharge of 2,250 m^3/sec (80,000 cusecs) will then follow from the discharge formula of De Chezy and is 2.85 m (9′3″), i.e., a bottom-height at L.R.L. — 9′3″. In an average year, the rather steady discharge of the Black Flood on the Niger above Lokoja is 1,700 m^3/sec (60,000 cusecs) and the water-level 1′6″ below L.R.L. The hydraulic depth on the crossing under similar assumption will then be 2.40 m (7′10″) and the bottom-height at L.R.L. — 9′4″.

This is a reason to believe that when this crossing on the Upper Niger strives to an equilibrium depth of 9′ to 9′6″ below L.R.L., a channel dredged up to that depth will not tend to re-shoal, which for this crossing is more or less proved by the bottom-height it maintained during 1956 and 1957 (see Diagram 6.4.2-6).

However, the width between the banks at L.R.L. can vary strongly; on the Niger below Onitsha between 1,400 m (4,600 feet) and 600 m (1,950 feet); in the stretch Onitsha—Lokoja between 1,900 m (6,200 feet) and 700 m (2,300 feet), and in the stretch Lokoja—Baro between 1,300 m (4,250 feet) and 700 (2,300 feet). The stretch Onitsha—Lokoja has undoubtedly the worst conditions. The place where the width is 1,900 m between the banks at L.R.L. is Agbama (Mile 324), known as one of the worst crossings in the Niger, situated below an island. When after long flow of the L.R.L.-discharge, i.e., for an average year 2,000 m^3/sec (71,000 cusecs), the slope on the river-section where this crossing is situated would be evened to 9×10^{-5}, being the valley slope, the hydraulic depth would be 1.95 m (6′4″) when the coefficient of De Chezy is taken as 40 $m^{\frac{1}{2}}$/sec (72.5 $ft^{\frac{1}{2}}$/sec).

Some considerations make it probable that even greater depths than the hydraulic depth maintain themselves after dredging. As has been seen above, slope alterations as a result of a dredged channel will remain small. In the dredged channel along the flow-lines, a higher slope and a higher sand-transporting capacity can still be expected than in the deep pool above the crossing. As a consequence the scour of the sill will also continue in the dredged channel. Secondly, the dredged channel draws extra water compared with the original situation, and with this increased discharge capacity of the channel goes an increased sand-transporting capacity.

In the upper half of the dredged channel flow will contract, in the lower half diverge, compared with the original situation. It has been observed in 6.4.2 that in a natural channel shoaling never took place on the limiting crossings during low water-stages, except when a new position of the talweg developed. There is only a tendency of the shoal to shift downward into the deep pool below. It can be expected that the sediments transported through a dredged channel will also deposit in the deep pool below the shoal. The only indication about the amount of sediment deposit in the pool below can be obtained from the sand measurements which were taken on the crossing at Kelebe.

The results of these measurements on the crest of the shoal along the flow-lines are given in Diagram 6.6.1-2. Each measurement is the result of 10 B.T.M.A. captures and 2 or 3 DF_2 captures. Suspended transport will pass the crossing, and the suspended load can only be expected to deposit far downstream in the deep pool. Noticeable is the fact that there is no significant difference in transporting capacity over the crossing at high and low water-stages, which strengthens the theory that the sand-transport concentrates on the crossing (the measurements of 19-11-'57 are suspect and it is possible that the B.T.M.A. has not worked properly). Further it can be noted that the sand-transporting capacity at high water-stages is more uniform over

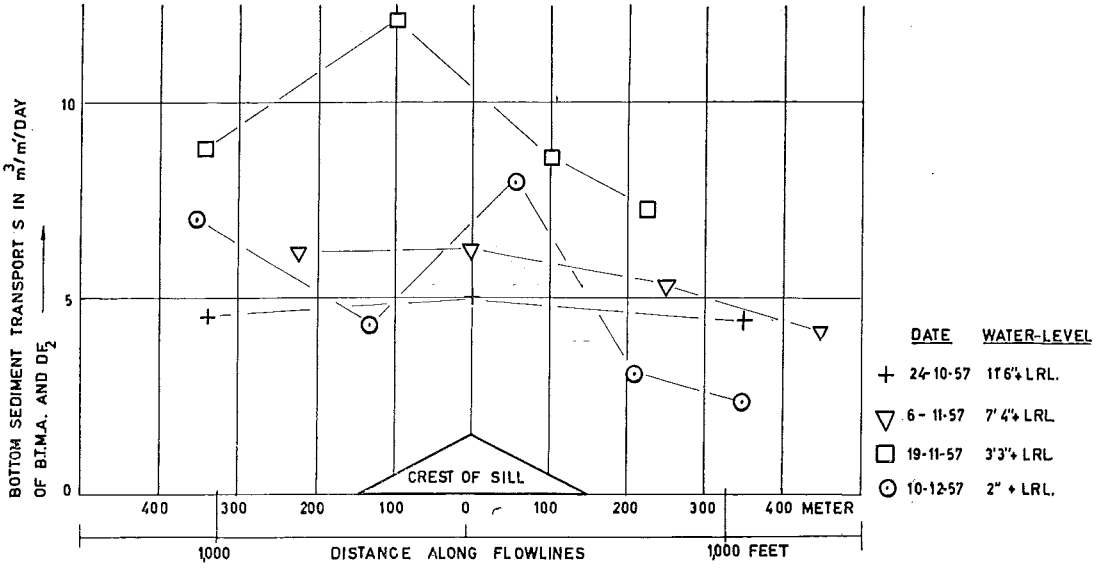


DIAGRAM 6.6.1-2

Sand-transport measurements on Kelebe crossing

the crossing than at low water-stages, when sand is transported in irregular blasts. This is very likely, as the irregular bottom formation at low water-stages has more effect on the transport of sand and the water discharge than at high water. The water-surface also shows these irregularities, pronounced in slope as well as in weak boils which can be characterised as macroturbulence. Finally, it can be observed from this diagram that sand deposits in the deep pool below the shoal, thus being a part of the complex movement downstream of shoals, pools and sand-banks.

Diagram 6.6.1-3 shows the talweg bed and the measured sand-transport along the proposed axis for a channel to be dredged. The measured sand-transport is a momentary record, which has the disadvantages of the irregularities of the macroturbulence. An average sand-transport is indicated which shows a maximum decrease at the point where the flow enters the deep pool below the shoal. When the sand deposit following from this decrease in sand-transport is calculated from the assumed average sand-transport (dash line in Diagram 6.6.1-3), scour and silting might be as indicated after one month's time.

This, however, shows only trend, because it is likely that the building-up of such a rim of sand at the end of the dredged channel will be counteracted by increased sand-transport at the shallowest spot of the rim and that the sand is pushed further downstream in the deep pool. The building-up of a trumpet of sand is likely (see 6.4.2). At the same time, the sand-transport in each point (dash line) will change.

All this will retard and decrease shoaling and the outcome of the above gives good hopes that dredging will be effective as long as the position of the channel is well chosen. Furthermore, it is of importance that the required depth is not over 6 feet, a depth which is less than the hydraulic depth of the river in equilibrium at an average low-water discharge. On the Niger there can thus be expected what has already been proved on the Mississippi, namely, that only on a few crossings is maintenance dredging necessary and that on most crossings the dredged channel during the navigable period will remain.

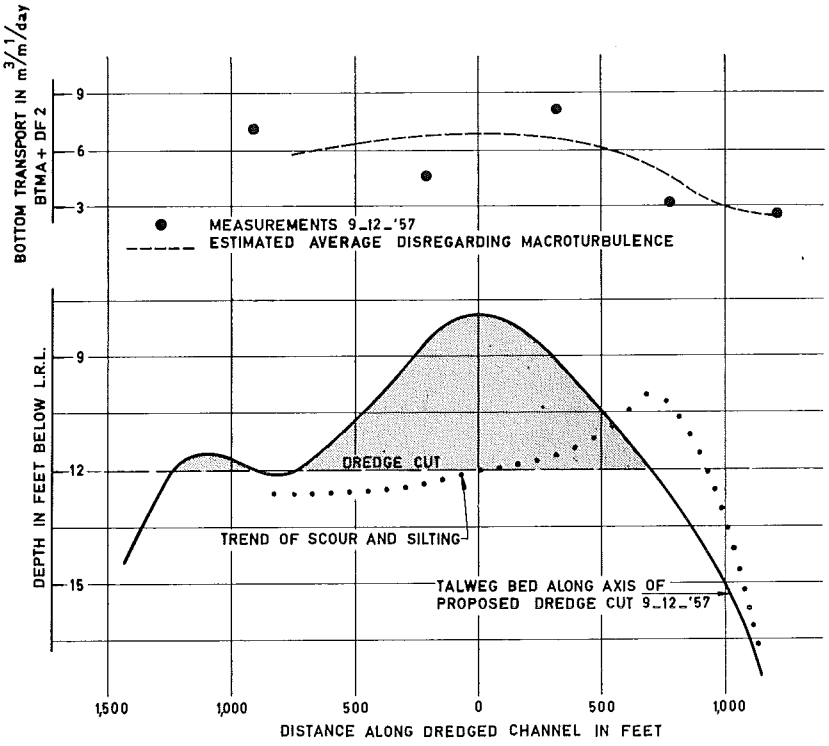


DIAGRAM 6.6.1-3

Movement of sand along a dredged channel

Summarizing it can be said:

(i) Water-levels are hardly affected by dredging a channel through a shoal and the differences are of no importance to shipping, so that the available depth on a crossing will improve by the depth of the dredged cut.

(ii) The hydraulic depth to which the river strives when the average low-water discharge would become dominant is on crossings in the Niger above Lokoja at least 9 feet and below Lokoja at least 6 feet 3 inches. Re-shoaling after dredging, leaving a smaller depth, does not seem likely.

(iii) The strongest deposit of sand can be expected at the downstream end of the dredged channel and in the deep pool. The former may lead to small quantities of maintenance dredging on the rim of the sand trumpet which will be built out at the downstream end of the dredged channel. The deposits in the deep pool do not affect shipping.

(iv) Natural re-positioning of channels over the crossing may cause re-shoaling of a dredged channel and call for maintenance dredging. Experience in choosing the right alignment for a channel will greatly reduce the chances of this happening.

6.6.2. Effect of removal of rocky sills

In the case of a rocky section in a river, where the bedrock forms a sill across the river which is high with regard to the sandy river-bed up and downstream, it seems attractive to remove the whole sill by blasting it. However, the consequence of this would be in many cases an increase in velocity and sand-transport upstream, and a deposition of sand downstream. This might

not only hamper the shipping downstream, but also result in a lowering of the entire river-bed upstream, giving perhaps new troubles for shipping if other rocks were exposed in the navigation channel upstream.

It would, therefore, be better to blast only a narrow channel through the rapid, reducing the lowering of the water-level upstream and the sand deposition downstream to negligible quantities. But even then, it is sometimes necessary to make special arrangements for ships to pass, as strong currents in the new channel make navigation in downstream direction hazardous and in upstream direction difficult or, in case of small engine-power, even impossible. The solution in that case can be found in spreading the local drop of water on the rapid over a greater length by the construction of a separation dike, forming a lateral canal with reduced current velocity.

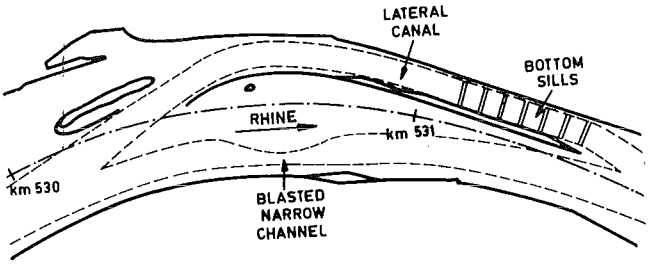


DIAGRAM 6.6.2-1

The rocky sill in the Rhine near Bingen

Diagram 6.6.2-1 shows how this solution has been applied on the Rhine near Bingen. The length and the height of the separation dam have to be calculated with regard to the velocity and the head of water at different water-levels. Also a sand-transport calculation has to be carried out to investigate the necessity of the construction of bottom-sills in the sandy bed of the lateral canal.

6.6.3. Effect of cutting bends

The construction of short-cuts in the curves of strongly meandering rivers is sometimes applied as a means of eliminating bad crossings and also shortening the shipping-route.

After dredging the new channel a situation with two branches is present. It will be clear that the slope in the short-cut will be steeper than the initial slope along the meander bend, and the newly-dredged channel will rapidly scour while the old one will gradually silt up. The scouring effect in the short-cut will be extended upward by draw-down of the water-level in the river upstream, and the whole upper river will gradually be affected till a new equilibrium is reached in which the slope of the water-level will attain about the same value as in the original situation. A comprehensive lowering of the river-bed upstream from the short-cut is the result.

The (temporary) increase in sand-transport in the upstream part of the river and in the short-cut will cause deposition of sand downstream from the short-cut, which will gradually decrease in intensity when the upstream part approaches its new equilibrium state.

When the method of short-cutting the bends is applied, it must be borne in mind that the natural inclination of the river to form new bends is not eliminated. Therefore bend-cutting will nearly always have to go hand-in-hand with bed-regulation in order to give it a more permanent character.

6.6.4. Effect of eliminating secondary branches

Islands in a river exert a large influence upon available depth, as generally the shipping channel along an island shows less depth than a single channel pattern. Such a situation might be improved by closing one of the two channels, thus attaching an island to a main river-bank.

For this purpose two systems can be followed: a high dam, with its crest above high water, or a low dam, only affecting the river conditions at a lower water-stage.

As will be discussed hereafter, in each case the closure of one branch effects a deeper shipping channel in the second branch; but in the unbranched river, both upstream as well as downstream from the island, initial formation of bars takes place. With a high dam the upstream bar gives difficulties to navigation during lower water-stages, while the low dam causes especially the downstream bar to grow.

In 4.2.6 it has been stated that with a discharge either steady or dominant, the water-line can be approximated to be a straight line. The river-bed adjusts itself to this steady discharge; nowhere along the river does a large variation of resistance exist, not even along an island where the river branches into two channels.

Closure of one of these channels results in an immediate increase of resistance; the remaining river-bed is too small for the total discharge, and the water-level inside the open branch rises involving a raise by backstage upstream from the island. Equilibrium is restored when the rise is sufficient to arrive at a discharging capacity of the cross-section (now composed of only one branch) equal to the original capacity of both branches together before closure (see Diagram 6.6.4-1c).

Downstream from the island the water-level remains unchanged and the rise in the open branch is compensated by a draw-down, affecting only the lowest part of the branch when it concerns a long island but extending its influence over the total length when it concerns a short one. In the latter circumstance the full rise of water-level in the open branch is not attained; discharge is secured by increase of slope compensating the decrease of the rise (see also 4.2.6).

The aim of the closure is to affect the available depth in the open branch. Its depth is increased because of the rise, while also above the island improvement is acquired due to the raise by backstage. In the downstream part of the open branch, however, the level is drawn down to the original height.

Such is the immediate situation after closure of the channel. Now the factor "time" starts its influence. Variation of water-level, slope and width all affect the sand-transporting capacity S and when the river-banks are assumed to be non-erodible, consequently the river-bottom itself is affected. Increase of S in a downward direction results in erosion of the river-bed, and conversely.

According to 5.2.1, sand-transport capacity S depends on drag (ai) and width (b) of the river-bed; simplified is

$$S = b\, A\, (ai - D)^{\frac{3}{2}}$$

where A and D are constants. The raise above the island involves an increase of depth but at the same time a decrease of slope. Now, for any cross-section DE CHEZY's formula gives

$$Q = b a^{\frac{3}{2}} i^{\frac{1}{2}} C = \text{constant},$$

or with the assumption of b and C being invariable,

$$a^{\frac{3}{2}} i^{\frac{1}{2}} = (ai)^{\frac{1}{2}} a = \text{constant}.$$

Thus the increased depth upstream of the island involves a decrease of drag, and consequently decrease of sand-transport S, so $S_1 < S_0$ (Diagram 6.6.4-1d), which means that sand deposition above the island takes place.

a. *Original situation*

b. *Branch 2a closed*

c. *Water depth after closure*

d. *Sand-transport after closure*

e. *Water depth after a long period*

f. *Water depth at subsequent L.W.*

g. *Sand-transport at L.W.*

h. *Water depth after a long L.W.*

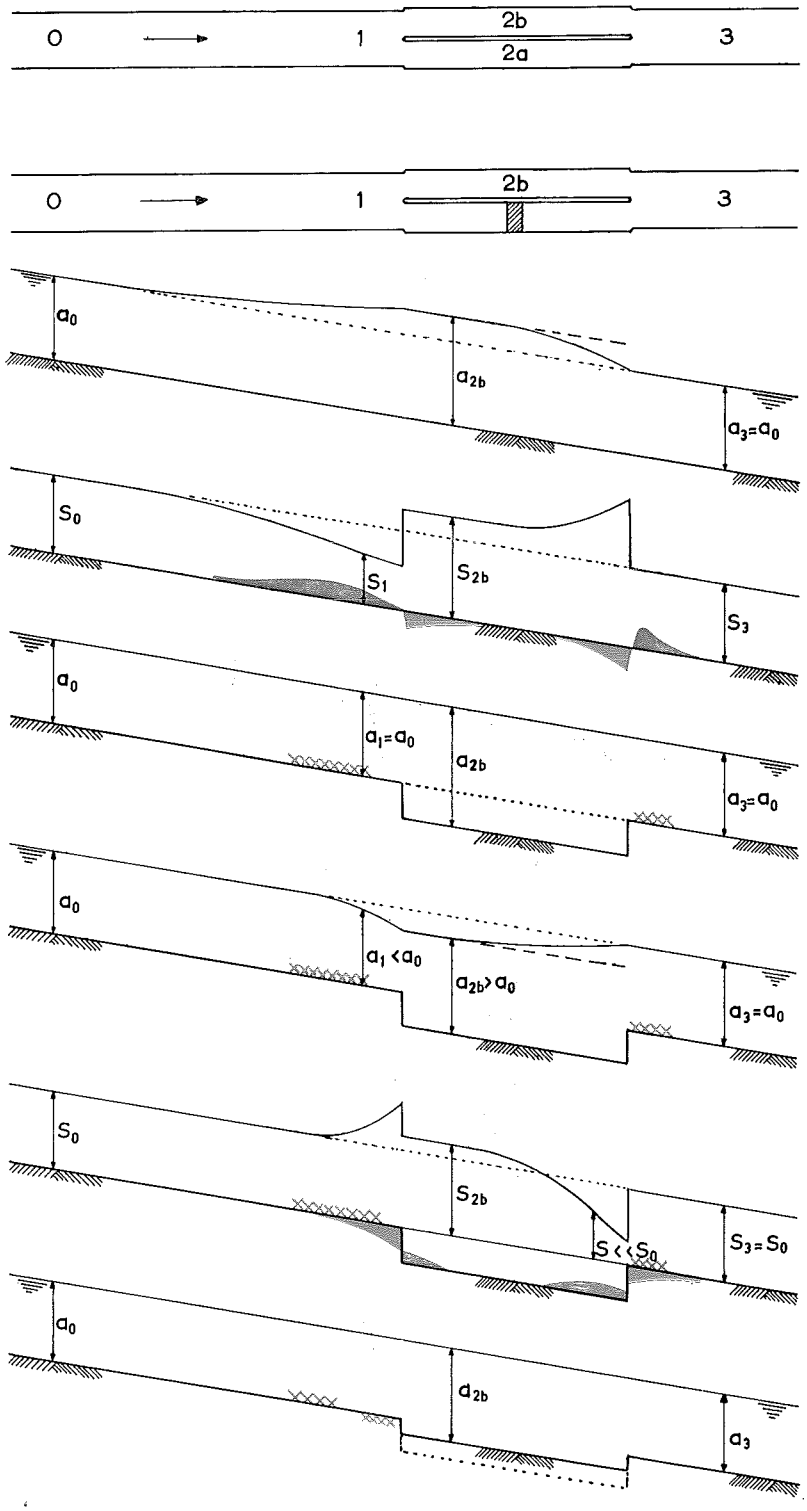


DIAGRAM 6.6.4-1

Schematic changes in a river-bed with non-erodible banks, as a result of closure of a branch

Using the scour criterion as defined under 5.4.1, it follows directly that deposition above the island takes place as, going downstream, the value for ba^{α} increases.

Inside the open branch along the island (section 2b in Diagram 6.6.4-1a) the width b_{2b} is smaller than in the original unbranched river b_o. When the island is assumed to be very long, the slope in section 2b should be equal to the original slope

$$i_{2b} = i_o$$

while here, too, De Chezy's formula is valid; it follows that

$$b_2 a_2^{\frac{3}{2}} = b_o a_o^{\frac{3}{2}}$$

Substituting these equations in the above-mentioned formula for sand-transport, the increase of drag (ai) appears to be partly compensated by the decrease of width, but still

$$S_{2b} > S_o > S_1$$

Hence it is concluded that in the upstream part of the open branch 2b strong erosion occurs.

Here, too, application of the scour criterion facilitates the conclusion. It can be derived that

$$\frac{b_2 a_2^{\alpha}}{b_o a_o^{\alpha}} = \left[\frac{a_o}{a_2}\right]^{\frac{3}{2}-\alpha}$$

which is always smaller than unity as $a_2 > a_o$ and $\frac{3}{2} > \alpha > 1$. Scour evidently takes place at the upstream end of the island.

Also in the downstream part of this branch erosion takes place. For, similar to the calculation above where raise appeared to result in accretion of the river-bed, it can be proved that conversely draw-down generally involves increase of S and consequently erosion takes place.

Finally, in the unbranched river downstream from the island, conditions are not changed by any closure, and

$$S_3 = S_o$$

Diagram 6.6.4-1d shows how the sand-transport S varies according to the above considerations, and how, as a result, the river-bed builds up and erodes. Upstream from the island a bar is built by deposition of sand. In the upstream part of section 2b erosion occurs since the sand supply is less than the transporting capacity. Down in this same section much sand is eroded by draw-down and ultimately deposited on a second bar just below the island. When in the course of time the erosion in section 2b propagates along the full length of the branch, the total masses of eroded sand are brought down and deposited on or closely near this downstream bar, which is concentrated over a small area.

For the upstream bar the circumstances are different; the accretion is spread over a considerable length, as it results from raise by backstage only. Moreover, the water-level over this upstream bar is higher than originally (and the navigation depth is not less than the initial one before closure), whereas the water-level over the downstream bar has a retarded tendency to rise with the accumulation of sand. Obviously the downstream bar, which is built up gradually after the closure of branch 2a, involves a serious reduction of the available depth.

This reduction, however, is a temporary one. Formation of a bar involves a higher resistance, a small rise of water-level and a steeper slope over the bar. Hence the drag over the bar grows, and the sand-transport increases. By this effect the bar has the tendency to be removed, the mass of sand being gradually spread downward over a longer riversection. However, due to the well-known phenomenon of time-lag, firstly some time elapses after the closure of the section 2a before the bar is felt, and secondly the formation is always far ahead of scour.

As time goes on, the erosion in section 2b affects the situation more and more. The bottom in section 2b is gradually lowered, and consequently the rise of water-level is nullified. Also the raise in the unbranched section 1 gradually decreases to zero. In this stage the bar upstream from the island effects a small reduction of available depth, and consequently undergoes the influence of removal forces. Here, too, the time-lag is important and the bar may give some difficulties to shipping. This situation has been drawn in Diagram 6.6.4-1e.

It is concluded that after closure of one of the parallel branches, temporary bars are formed in the unbranched river, upstream as well as downstream from the island. The downstream one reduces the available depth seriously; the upstream one is less important, but may give some reduction after considerable time has elapsed since the closure. Both bars are temporary, and will have been removed when an ultimate equilibrium is reached. On the other hand, the section 2b, probably shallow before closure, shows considerable improvement, first by rise of water-level, and later by erosion of its bed.

The above considerations are based upon the assumption that the discharge Q is constant. In fact, however, the yearly variation of discharge affects these phenomena strongly. But before these influences are discussed, distinction must be made between three fundamentally different methods of closure, viz., a high dam, a low dam and a gradual closure by means of an open row of piles (pile-dike). The top of a high dam should be either above high-water level or equal to the top-level of the island; a low dam has the restricted purpose of closure at lower water-stages only. A pile-dike is not discussed in the present paragraph, but some comments are made in VI, 6.3.1.

The question arises whether a *high dam* would achieve the desired results. During the high-water period the available depth is generally sufficient for shipping purposes, and a closure in that stage is not necessary. Nevertheless the high dam gives a maximum rise and a considerable extra depth just during that high-water period. On the other hand, the very high sand-transporting capacity brings about quick adjustment of the bed to the new situation and rapid formation of the bars. Because of the high water no difficulties for navigation arise here. But during the subsequent fall, the section 2b is too deep (as it is adjusted to high-water conditions), involving a drawn-down instead of a raise above the island in section 1, a lower water-level inside section 2b, and a raise in the downstream part of this section (Diagram 6.6.4-1f). Analogous to Diagram 6.6.4-1d, the variation of S is plotted in Diagram 6.6.4-1g, which shows erosion in sections 1 and 3 and accretion in section 2b.

Now, upstream from the island the available depth is reduced seriously since a lower (drawn down) water-level covers a higher bottom (being remainders of the old bar). Although erosion starts to remove the sand, the sand-transporting capacity during low water is small and much time will elapse before this erosion has scoured a shipping channel. This means that during the L.W.-period the upstream bar restricts the available depth. The downstream bar does not give problems: demolition of the bar has already started during the high-water period and is only accelerated during the fall. The accretion in channel 2b could give some troubles when it happens irregularly, but the water-level rises together with the bottom and finds its ultimate equilibrium as drawn in Diagram 6.6.4-1h: the channel is always deeper than originally before the construction of the high dam.

A *low dam* causes completely different conditions. During high water the closure exerts its influence as a relatively small increase of resistance in section 2a. The water-level and sand-transport will be only slightly affected, and the lay-out of the river-bottom will not differ much from the one without any closure. During the fall the dam starts to work. Raise above and rise along the island take effect and the above discussed phenomena of erosion, accretion and bar formation gradually start.

Formation of bars does not give difficulties yet; at this fairly low water-stage the sand-transporting capacity is small and the formation of the downstream bar slow. It is only after considerable time that a reduction of the available depth by this downstream bar will be worth mentioning.

However, with a continuous fall to very low water-levels the raise and rise will diminish, or even reverse into draw-down and fall. In this circumstance the situation becomes worse, the upstream bar reducing the shipping depth considerably (analogous to the existence of a shallow channel in the L.W.-period due to construction of a high dam). Section 2 itself, however, will always remain deeper than it was originally before construction of the dam.

In the foregoing discussion, the river-banks were assumed to be non-erodible: increase of sand-transporting capacity resulted in erosion of the bottom only. This assumption, of course, cannot hold true except where the banks are composed of clay or rock. Where this is not the case, it could be the width instead of the depth adjusting itself to the eroding powers of the water.

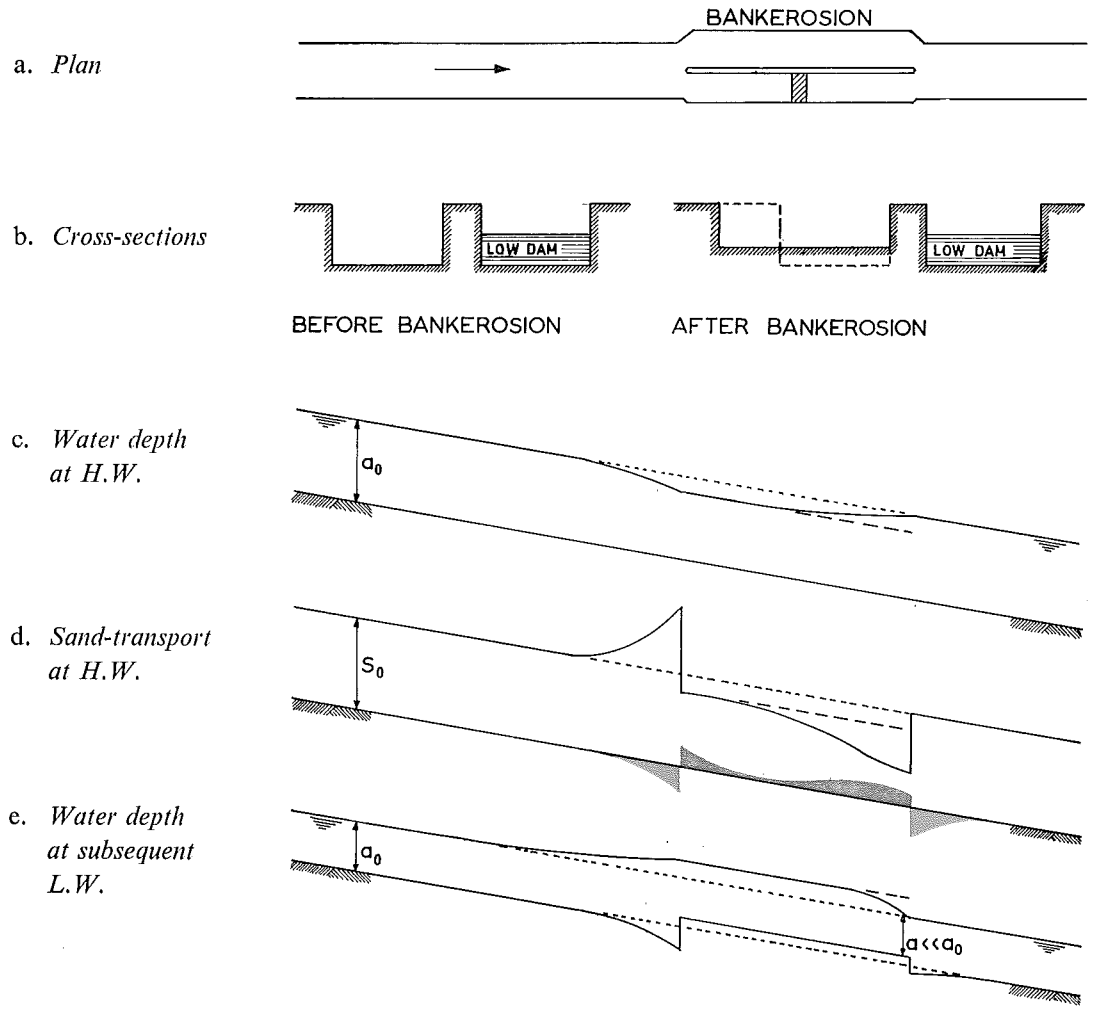
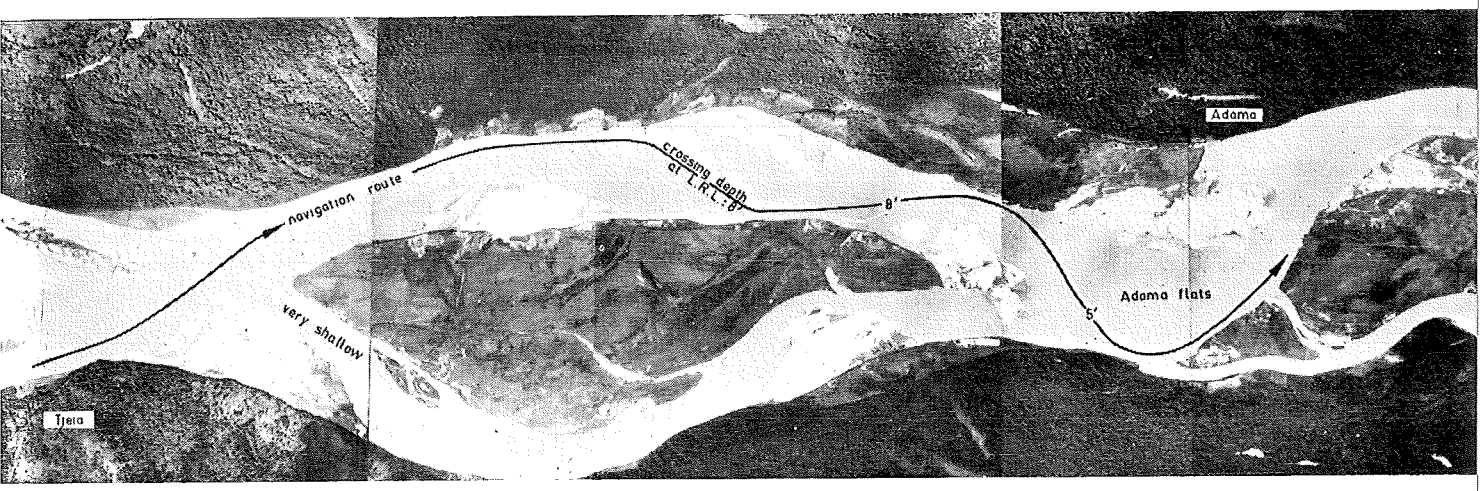


DIAGRAM 6.6.4-2

Schematic changes in a river-bed with erodible banks, as a result of closure of a branch



PHOTOGRAPH 6.6.4-3

Natural closure in the Niger near Tjeia, Mile 377

With a steady discharge, the bank erosion would continue till the width is equal to the original value of the two branches together. The specific improvements are by then lost, but the situation would have been transferred from a bifurcation into a single-channel pattern. This already would be a considerable improvement.

However, the discharge is not steady; after construction of a low dam in branch 2a, the section 2b erodes its banks (Diagram 6.6.4-2b). The increased width is too large for high water (as during high water channel 2a is in use again), and this results in a lower water-level in the section with consequently an accumulation of sediment (Diagram 6.6.4-2c and d). Obviously, deposition of sand cannot narrow a river within a short time, and the accretion takes place mainly on the bottom. In the next low-water period, the cross-section of channel 2b is not wide, but relatively shallow, due to this deposition during high water. A rise of water-level is the result, and thus the sand-transporting capacity increases, involving erosion, partly occurring from the banks. So every year high water will deposit sand on the river-bottom and low water will erode sand partly from the banks. The result is a very wide, very shallow channel. Moreover, at the downstream end of the section 2b the raised water-level is drawn down again to the original height, while the river-bed is extra high by the extra accretion due to the raise in this part during high water.

Thus a very bad place for shipping has been born (Diagram 6.6.4-2e), located inside the channel 2b. Its origin and nature are different from those of the downstream bar described earlier, but it is much more serious; the situation is probably worse than it was before closure of the branch 2a. In general, however, the period necessary to arrive at such a bad condition is very long, since the bank erosion takes place at low water only, when the sand-transporting capacity is relatively low.

The closure of the branch 2a is not necessarily an artificial one. A natural sand-bank, travelling downward by the normal meandering process of a river, can temporarily block a branching channel and act as a low dam. This phenomenon is seen, for example, just below Tjeia along the Upper Niger (Mile 377) where a branch on the right side of the river is almost totally blocked by a low sand-bank positioned there already for several years. The main river-bank in the open

channel between Tjeia and Adama (Photograph 6.6.4-3) consists of clay and clayish sand with a high resistance against erosion. This branch, therefore, is a fine shipping channel. The two crossings in the section are deep and do not cause any trouble. However, in harmony with the above-discussed theories, below the island a very shallow place exists, called "Adama Flats"; the shallow and narrow shipping channel changes and silts up frequently and causes many difficulties, mainly in the second half of the Black Flood period, a process which is entirely in agreement with the above.

Another example of natural closure exists near Anwam in the Lower Niger (Mile 244). Here, however, the bank of the open branch mainly consists of pure sand and is highly erodible. Consequently the most shallow place in this system is not the downstream bar below the island but the lowest part of the shipping branch along the island (Diagram 6.6.4-4). This matter is discussed in more detail in 6.2.2.

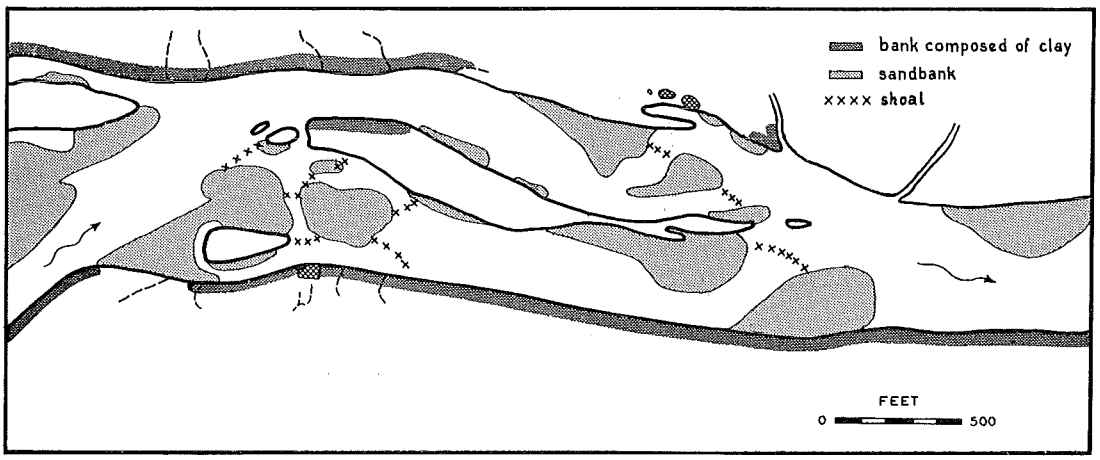


DIAGRAM 6.6.4-4

Natural closure in the Niger near Anwam, Mile 244

6.6.5. Effect of stabilising the banks

The first and most important effect of a stabilised bank is that the land behind it is protected against further erosion, which is a contribution to the well-being of the people living along the banks of the river. But in the long run, as the river valley is no longer eroded from time to time by the river, the valley will gradually silt up, and the vegetation will become denser. Finally the capacity of the flood-plain to discharge the high floods will decrease, resulting in higher flood-levels and bringing about an increased silting-up of the river-banks. So by stabilising the banks, and in general by fixing the river into a definite course, the natural balance between erosion and deposition is disturbed. When planning a radical change of the river from its natural state to a complete guidance, this problem has to be kept in mind.

The other effects of bank-stabilisation, if it is carried out without further overall planning but only coinciding with the present alignment of the banks, are rather small. The river will not shift sidewards any more, but along the axis of the river the formation of sand-banks and islands still goes on and an improvement of shipping conditions by mere bank-stabilisation is hardly to be expected.

Only if the river-flow is artifically concentrated into one channel along the stabilised banks will deeper channels be formed. In this system of channel concentration (VI, 6.2.), bank-stabilisation is applied as a part of the possible construction methods.

6.6.6. Effect of channel concentration

When a river with shifting and branching channels and with wide and shallow crossings has to be improved for shipping purposes, the method of channel concentration can be applied. By this the flow is forced into one (or perhaps two) channel(s) by guiding works and bank revetments. But as channel concentration is based upon the original natural circumstances of the river, after the construction of these works the slope at Dominant Water-level will still be determined by the same conditions. Consequently, the new channel(s) will have a cross-section, of a value for $a^{\frac{3}{2}}b$ equal to that in the old situation, while the total width will be smaller. As a result, the depth of the improved river is greater.

This involves that the new cross-section is larger in comparison with the original situation where it concerns stages below the Dominant Water-level, and that during these low stages the water-level is lowered. On the other hand, the high-water discharges will find the new cross-section smaller than before, from which higher H.W.-stages will ensue. So as a result of channel concentration the range between H.W. and L.W.-stages will increase (see also 4.2.6).

Due to the increased depths, a small overall increase in surface-velocities of the flow has to be anticipated.

This subject is treated in more detail in VI, 6.2.4.

6.6.7. Effect of channel contraction

Contrary to channel concentration, where the width of the river is still defined by natural rules and only the course of the flow is fixed, channel contraction aims at the fixation of the width of the channel as well.

This width is related to the depth that is aimed at, which in its turn is determined by navigation requirements. As soon the depths brought about by channel concentration are no longer sufficient, the channel must be contracted, mostly at the crossings, thus causing a local scour which results in a deepening of the navigation channel over the crossings. When planning channel contraction, caution is needed not to bring about too large a difference between the width in the contracted sections and the width in the remaining part of the river, as this would effect large differences in the sand-movement from one cross-section to another, resulting perhaps in worse navigation conditions. The increased sand-transporting capacity of the contracted cross-section would entail deposition of sand downstream, where the sand movement is supposed to be equal to the average of the river, while raise by backstage upstream from the narrow section might also result in sand-deposition (see also 6.6.4).

If the navigation requires a rather deep channel, contraction of the river in the bends, too, has to be taken into consideration, as in the first place the cross-slope of the river-bed in the bends (see 6.1.2) might hamper shipping by too small depths in the inner bend, whilst secondly the irregularities in sand-transporting capacity, as discussed before, are evened out by continuous contraction. A regular depth of the navigation route is then the result.

It will be clear that channel contraction will have the same effect on the range between H.W. and L.W. as discussed in 6.6.6. This range will even increase more than in case of channel concentration because the natural shape of the river is more interfered with.

6.6.8. Effect of canalisation

This method of river improvement aims at raising the water-levels by the construction of weirs or dams in the river. The depths are increased by this method without in the first instance affecting the bed of the channel itself. However, the changes in velocity and sand-transport caused by the raised water-levels will result in a gradual modification of the bed. Because of the lack of sand supply a heavy scour will occur directly below the weir, while on the other hand sand will be deposited over a certain stretch upstream from the weir (Diagram 6.6.8-1). These changes of the bed will extend downward and upward respectively until a new equilibrium is established.

When only one weir is constructed, the upper river will undergo a complete heightening of its bed, and in the final stage the Dominant Water-level and the river-bed will be parallel to the original slope, both raised over the same height (Diagram 6.6.8-1). So in the long run the result is that nothing has been improved, while deep scouring has occurred downstream from the weir. In many cases, however, this process develops very slowly and can even be neglected.

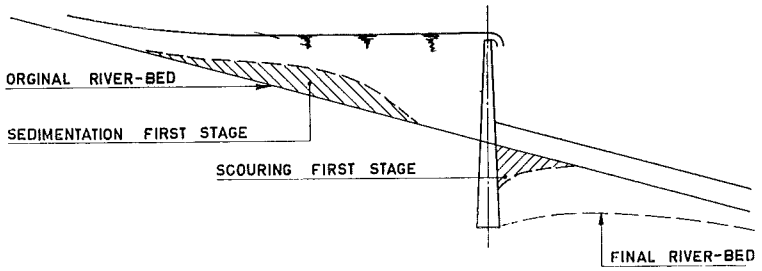


DIAGRAM 6.6.8-1

Scour and deposition near a fixed weir

When canalisation is executed with a series of weirs the changes in the river-bed are more profitable. Through the above-mentioned scouring and deposition, the slope of the bed in a section between two weirs will flatten, resulting in a greater depth immediately downstream of the weir just where the limiting depth for shipping is found (Diagram 6.6.8-2). The depositions in the more downstream part of the section will cause no difficulties to navigation as the depth there remains always larger than in the upstream part.

Thus, a series of fixed weirs improves the navigability considerably. However, difficulties might arise under special circumstances, such as the existence of a tributary joining the main river in a canalised section. During periods of high water the tributary will bring large quantities of sand into the main river, which already has a strongly decreased sand-transporting capacity due to the canalisation. The result will be the formation of large sand-banks near the confluence, by which navigation might be hampered. This is the reason why application of fixed weirs in the main river is often undesirable when the river has large, sand-transporting and not-regulated tributaries.

In such a case, the application of movable or adjustable weirs gives a better solution, as it will then be possible to open the gates of the weirs during high water (when the depths in the river are sufficient for navigation purposes) and to restore the original sand-transporting capacity. There will then be a canalised period with a small water-discharge and a small sand-transport

influencing the river-bed to a small degree, followed up by an open-river period with a large water-discharge and a large sand-transport influencing the river-bed to a large degree. The resulting river-bed will depend on the ratio between the sand-transports in the two periods, but will probably not differ very much from the original situation.

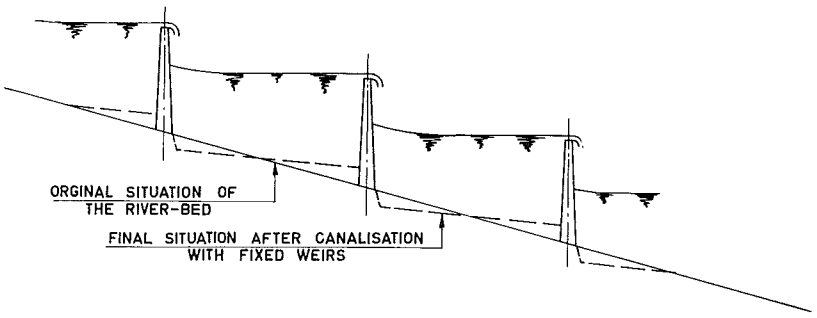


DIAGRAM 6.6.8-2

Modification of the river-bed with a series of fixed weirs

The seasonal deviation of the bed from its state of equilibrium depends on the duration of each period. After a long high-water period some deposition directly downstream from a weir might occur, but in general it can be stated that the depth at that location, which is the limiting depth for navigation, will increase in the years after the canalisation has been started. An exact calculation of this improvement, however, is not possible, but the trend of the new state of equilibrium has been drawn in Diagram 6.6.8-3.

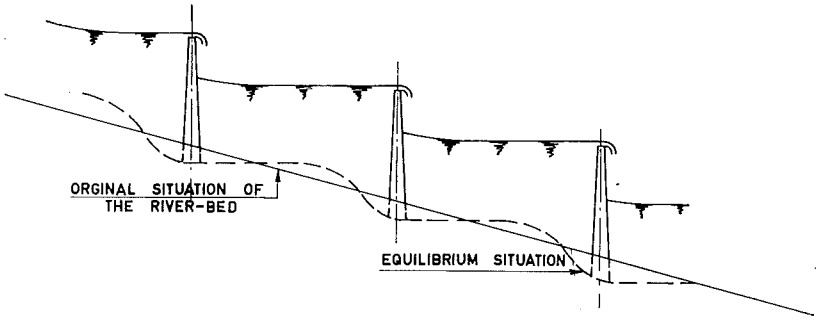


DIAGRAM 6.6.8-3

Modification of the river-bed with a series of movable weirs

6.6.9. Effect of discharge regulation

Construction of reservoirs is the only practical way to effect changes in the discharges. The reservoir is used to store an excess of water and to release this surplus when needed. The effect on the morphology of the river-bed will be discussed hereafter.

a *In the reservoir area*

Sediment load continues to come down the river and into the reservoir. In the reservoir area

the velocity drops because of the enlarged cross-section and consequently the transporting capacity decreases and material is deposited. This deposition of material is most pronounced at the upper limit of the reservoir. Density currents are responsible for a further transport of the finer parts of the incoming load, filling the reservoir gradually also near the dam. When calculating the rate of silting of a reservoir, it is advisable to assume that the total incoming load is deposited and that only clear water leaves the reservoir. Before building a reservoir, measurements and calculations have to be carried out on the amount of bed-load, suspended load and possibly wash-load of the rivers debouching into the planned reservoir area.

When the reservoir has to be used for navigation purposes, it is of importance where the material will be deposited. When a port has to be served at the upper limit of the backstage, provisions as to the maintenance of the access route will have to be taken. Dredging, possibly in combination with other works such as groynes and dikes, may be necessary.

When the incoming load is considerable, large amounts of material are deposited in relatively short periods, thereby deteriorating the channels. Silting may then occur at random all over the place and the channels may vanish completely (see 6.2.1). In that case a dredger will be needed to guarantee access to the area.

When the incoming material is deposited more gradually, formation of a delta can be expected. Although guidance of the channels will still be needed, this delta development is regarded more favourable for shipping purposes, but when the water-levels in the reservoir vary largely, still great difficulties for navigation will be met with.

b *Downstream of the reservoir*

(i) *Scour below the dam*

The clear water leaving the reservoir will scour the river below the dam. The flow will carry the amount of sand according to its transporting capacity, and as no sand is fed from the sluices of the reservoir, the river will be scoured. This scour can be considerable: for instance, a scour of more than 20 feet occurred below the Hoover Dam in U.S.A. Immediately below the dam structure special constructional details can modify the scour so that the stability of the dam will not be unfavourably affected by the erosion. Generally, model experiments to shape the best form of the outlets are advisable when large discharges have to be released into a sandy river.

Calculations of the erosion of the river-bed are difficult, particularly when the width (of the alluvial river) is variable; and predictions of erosion should be used with caution.

(ii) *At confluences with tributaries*

The tributaries continue to discharge their water and sediments into the main river. The modified discharges, however, decrease the variable transporting capacity of the main river because the sediment-transporting capacity is more than proportional to the discharge. This inevitably causes deposits near and below confluences, acting unfavourably on shipping conditions (see V, 3.2.2). The extent of the deterioration, which also depends on the ratios of the discharges of water and sediment of main river to tributary, cannot be predicted, except perhaps by model experiments. Apart from this silting process, the yearly cycles of raise and draw-down near confluences (4.2.6) are altered, which in its turn has effect upon the state of equilibrium of the river-bottom immediately upstream from such a confluence. The latter effect has been considered with respect to the Lokoja Confluence in 6.5.8.

Discharge regulation on the tributaries, however, would have a beneficial effect on the main river at the confluence, whilst even further downstream the regulated discharge would also act favourably on the shape of the main river.

So the tributaries are likely to deteriorate their confluences with the main river when the

discharge of the main river is regulated. As these effects are local and occur gradually, measures can always be taken when the situation needs to be improved.

(iii) *Changes in the cross-section*

The river-bed is largely moulded by the discharges around bankfull which are capable of transporting much more sediment than the smaller ones. Reducing those large discharges has the effect of decreasing the Dominant Discharge (see 6.1.1b). The cross-section will eventually have a smaller width whilst the average depth at the reduced Dominant Discharge will be about equal to the former depth occurring at the higher Dominant Discharge before the regulation (see 6.1.1a). Taken into the extreme, an infinitely small discharge would still create a considerable depth. Naturally, the phenomenon does not appear as far as that, and the formulae and approximations (for instance R = a) apparently call a stop somewhere in this procedure. Anyway, the relation between least available depth and discharge is then favourably modified and a more efficient use of the reservoir water will be the result of the changes in cross-section.

CHAPTER 7

TOPICS FOR CONTINUED REGIME STUDIES

7.1. INTRODUCTION

The river data collected in the three-years' NEDECO survey and explained in this Part will serve as a basis for the execution of the improvements recommended in Part VI. Continued studies, however, will be necessary.

This in the first place is caused by the character of the river itself. The bed of the river is continuously changing: shoals propagate downstream, banks are eroding, new banks are being built and islands may be deformed. At one place the river may be aggrading, at another place scouring. If the development of the form and the position of the river-bed is already a topic for future studies by itself (buoyage, dredging, floating training-works and regulation), it may have also its effect on hydrological relations as, for example, the discharge rating curves.

In the second place, for some methods of river improvement more data are necessary than could be obtained up to now. To establish, for example, more water-level prediction schemes for some river-stretches, more must be known about channel and valley storage and more gauges should be read. To enable also the prediction of the available depths, intensive survey and study of the channels will be indispensable. In general, it should be stated that a thorough and continuous research is always essential for a development of the rivers.

In the following paragraphs some studies required for the improvement of the navigability of the rivers will be considered in more detail.

7.2. REQUIRED STUDIES

7.2.1. Hydrology

A further study of the *hydrological cycle* (see 4. and in particular 4.5) will be necessary for establishing water-level prediction schemes along the Niger and the Benue.

Water-level prediction will already now be of assistance to navigation, but it will be indispensable when reservoirs are being operated (VI, 3.6.4). As it will take several years to establish the required schemes, it seems advisable to start already now with preparing these schemes. This will require the collection of more data. Some of these data, although collected for the purpose of improving the navigability, will also serve other purposes such as agriculture (irrigation) and road-building (computation of the design-flood for bridges), etc.

In the first place, *water-level hydrographs* of more places along the tributaries will have to be known. This will require the construction of more river-gauges, and at some places the installation of recording gauges may be necessary.

But besides water-level records, more information will be needed. The procedure of predicting water-levels can be defined as the extrapolation of the hydrograph at a certain station along

the river with the help of hydrographs of the stations situated more upstream in the river basin. To make this extrapolation possible, the analysis of the hydrographs is necessary. The most important elements which determine the form of the hydrograph are:

(i) rainfall (see 4.1),
(ii) the rainfall—run-off relation (4.3.3 and 4.5.4), and
(iii) the channel and valley storage (4.2.7 and 4.5.2).

Regarding (i): To avoid the necessity of gauging every small river of a basin use has to be made of *rainfall data*. The existing density of rainfall stations (see Table 4.1.2-3) has therefore to be increased and an efficient regular inspection of these gauges has to be carried out.

Regarding (ii): Some "*pilot basins*" with a limited drainage area must be selected for an intensive study to establish rainfall—run-off relations, making use of small units of time. These relations can be used for other basins which possess analogous physical properties.

As for (iii): To establish stage-storage relations (see 4.3.7 and 4.5.2) use must be made of recession curves (see 4.3.7). These curves can be made by some series of *discharge measurements* during the lower river-stages.

Also necessary are *discharge-rating curves*. The form of these curves may vary slowly (see 4.3.2 and 4.3.4), so this will have to be checked by making discharge measurements regularly.

Combination of rainfall data and the rainfall—run-off relations for smaller basins with the recession curves of stations along the main rivers will enable a detailed analysis of the hydrographs, which in its turn will make it possible to establish the water-level prediction schemes for the navigation.

For a reservoir on the Benue at Yola, an estimate of the *evaporation* which can be expected has been made (4.4.2). As it is expected that the use of a more modern formula (which would require special climate data) may only slightly change the obtained figure, the economic feasibility of this reservoir will not depend on the result of advanced evaporation studies. But the exact knowledge of the monthly evaporation on such a reservoir will assist in the reservoir operation.

For smaller reservoirs, however, the evaporation to be expected may determine their economic feasibility. Hence, with a view to future construction of reservoirs, it seems advisable to start already now with a study of the evaporation that can be expected. The collection of the proper climate data can then be taken in hand.

7.2.2. Morphology

An insight into the mechanism of the behaviour of the river-bed seems only possible on the basis of knowledge about the principal characteristics of the river. Many morphological magnitudes have been measured by NEDECO during the three years' investigation, but still more, and more detailed, data are necessary to gain sufficiently accurate information.

For determination of *sizes of sand grains* about 3,000 samples have been taken by NEDECO (see Table 5.1.1-2) which is an average of less than 3 per mile of river-length. It is necessary to continue the collection of samples, bottom samples with the grab as well as samples from the yields of sand-transport instruments, and including the tributaries at least as far upstream until the backstage influence from the main river is negligible. Interpretation of the results and analysis of its variations are very useful for an understanding of, for instance, the immeasurably slow and gradual movement of the river-bed, such as degradation or accretion of an entire river-section as a whole (see 2.5). Also future tendencies of possible human intervention in the natural condition can be derived from such an analysis.

The *slopes* of the water surface have been determined mainly from the results of the levelling executed by the Survey Department, connecting the main stations along the rivers with Mean Sea-Level datum. The general aspect of the river-system has, indeed, been concluded from these results; but a detailed study of local phenomena could not be based upon such average figures. Slopes, therefore, should be submitted to further study, as it is most interesting to know the variation of slopes along the river-axis under a steady flow as well as with variable discharge. Particularly at the location of the measuring sites is the local slope important for computations from the measured magnitudes, for example, as has been discussed in connection with the calculations of sand-transport in 5.2.2.

Although from the standpoint of navigation silt in the Niger and Benue does not form a direct problem, it might be interesting to collect more data on *silt and silt concentration.* The mineralogical composition of the silt as a natural fertiliser of the flood-plains is important for the agricultural development of the country, whilst the silt concentration affects the quality of the river-water for purposes of human and industrial consumption. High silt concentrations also mean severe erosion in parts of the drainage area, and loss of great quantities of soil might give rise to activities on local soil conservation. Since in future the river authorities will be expected to have adequate information on every aspect of the river, the silt should be a subject of further detailed study.

Although resistance of the river-bed against flow affects the water-depth and the sand-transport, little is known about *roughness of the river-bed.* In 6.3.4 an attempt has been made to describe the complex problems around this subject, and it may be understood that much research is needed before practical conclusions can be drawn.

Apart from measuring the basic characteristics of the rivers — necessary for the application of hydraulic theories onto the river morphology — it is highly advisable to follow closely the actual *behaviour of the river-bed,* its formation and deformation, and to analyse the causes and consequences.

Observation of *the least available depth (L.A.D.)* for all sections of the Niger and Benue which are or will be suitable for navigation is required not only for guidance of the present shipping but also for determination of the actual navigability as a statistic phenomenon. Means of improving the navigability, such as dredging, training-works or the most efficient use of a possible reservoir planned at any place along the river, also require continued observations. L.A.D.'s for the Benue have already been measured rather satisfactorily by NEDECO, but to attain a higher accuracy it will be good to continue observations over a long period of many years. The Niger, however, has given difficulties through the Black Flood giving deviations of the normal shape of the hysteresis curve in the graph of the L.A.D. against water-stage. This problem has not yet been solved. Observations on L.A.D.'s for the sections Baro—Jamata, Jamata—Lokoja and Lokoja—Delta form therefore a good subject for further study.

The L.A.D. for a river-section is determined by the depth at the most shallow crossing. When in future a reliable prediction of water-levels can be made, the value of such a prediction will rise highly with a possibility of additional prediction on the L.A.D. Study of *the behaviour of a crossing* in general has been started by NEDECO (see 6.4.2) and should be continued, also for the benefit of the choice of the correct alignment of a dredged cut over a crossing.

Next to such study it seems to be very useful to carry out *experiments on a crossing*, for example, with floating training-works or other temporary measures as described in VI, 5. Execution of such improvements on a large scale would only be efficient after reasonable knowledge has been obtained about the expected results.

Lastly, the rate of *bank-erosion* along the rivers should be further studied.

PART IV

TRANSPORT AND NAVIGATION

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CHAPTER 1

TRAFFIC AND GOODS

1.1. PRODUCTION

1.1.1. General

The economy of Nigeria is based on agriculture. Over 80 % of the working population derives an income directly from agriculture and nearly all exports are from agricultural origin. Stock-breeding in the North and forestry in the South complete the general picture, together with transport, industry and mining.

Transport originates from production of one or more crops above the consumption level of these crops in a certain area, the excess being disposed of by internal exchange of crops or by export.

Production of local food crops greatly exceeds production of export crops in tonnage by an estimated ratio of 15 : 1, whilst in value it is estimated at 5 : 1.

Transport of export products can easily be evaluated through statistics of Marketing Boards, ports and produce-buying stations, but internal transport is far more difficult to estimate owing to lack of data. Traffic censuses on the number of vehicles are available for the major roads, but no data exist about tonnages, origin and destination of the loads. It can only be assumed that internal transport of goods is of the same, or even higher, magnitude as transport directly connected with imports and exports.

1.1.2. Production areas

R. M. BUCHANAN and J. C. PUGH ([1] distinguish three main elements in the agricultural economy of Nigeria: (a) production for local consumption, (b) production for internal trade and (c) production for exports.

a *The basic subsistence economy* Diagram 1.1.2-1

This economy is everywhere present, but practically no traffic or only traffic over short distance originates from it. Production in this economy is equal to local consumption.

b *The internal exchange economy*

Improved transport facilities and urbanisation have stimulated the production in this economy. Basic foodstuffs such as guinea corn and cattle in the North, yams in the Middle Belt, palmoil in the South and specialised production of rice, fruit, sugar, kola and also coal are the main commodities in the transport resulting from this economy.

([1] BUCHANAN and PUGH, 1955. GEN. 3

c. *The export production economy* (Diagram 1.1.2-2).

This economy aims at the external exchange of goods as a result of which transport is directed to coastal harbours and finally leads to import and distribution from coastal harbours. Products

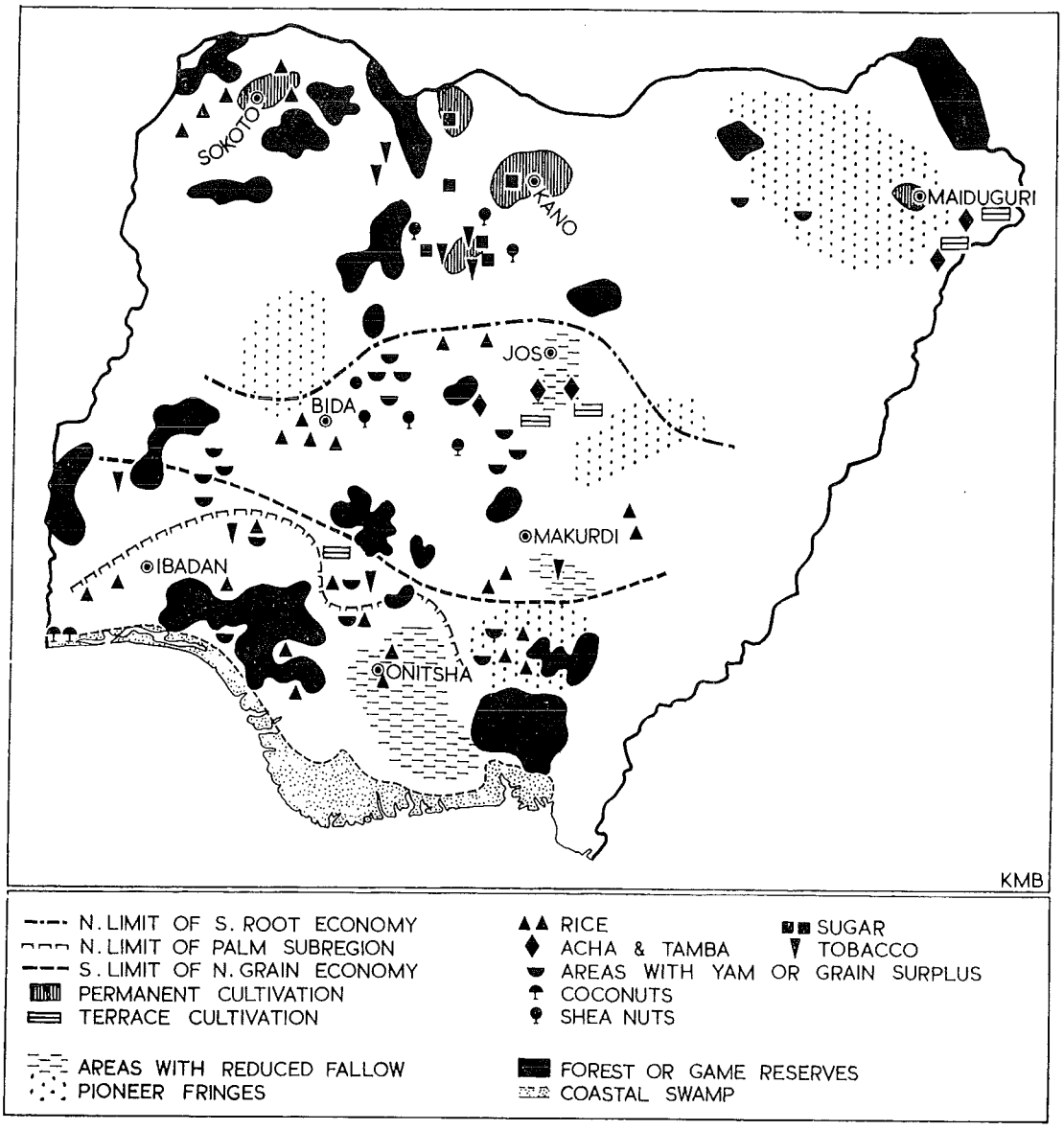


DIAGRAM 1.1.2-1 (1

Some features of the subsistence crop economy

in this economy are groundnuts, cotton and a small quantity of benniseed from areas in the North and East; cocoa, palm produce, timber and rubber from the rain-forest zone in the South and mining products as tin, columbite from the Jos area and coal from the Enugu coalfields.

(1 from: BUCHANAN and PUGH, 1955. GEN. 3

Along these lines a clear traffic pattern could be visualized, but this would necessitate an extensive survey of the locations and magnitude of the three kinds of economy. This is, however, beyond the scope of this Report. In general, the picture is that in the North and in the South internal exchange and export production are found, whilst in the Middle Belt little export production and only locally internal exchange occurs. It seems that the absence of well-developed transport routes has a very distinct effect on production.

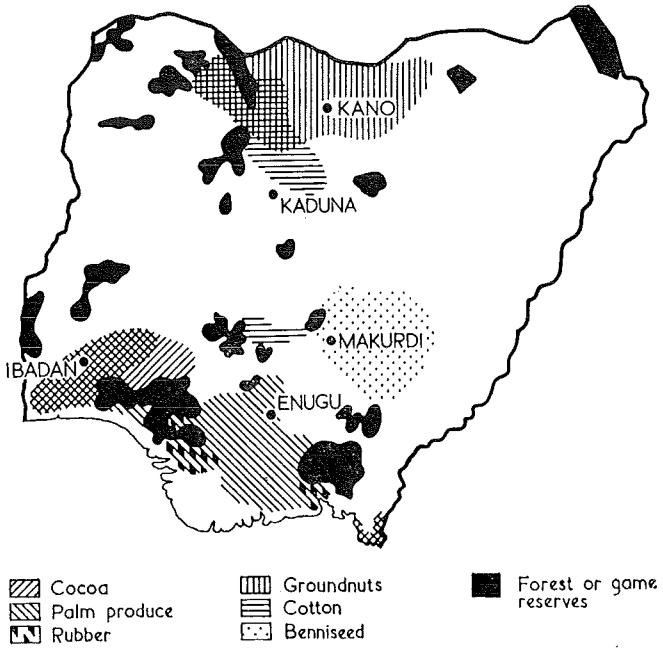


DIAGRAM 1.1.2-2 (1

Export crops

1.1.3. Period of harvesting, quantities, estimated increase

The time of harvesting of the agricultural products is of great importance to the traffic pattern. Most of the yields come available for transport after the rains, between October and February, i.e., just at the time when the river-levels are low. Although many of these crops are well-suited for river transport, the result is that alternative but more expensive evacuation routes are often used. This is an unfortunate though natural situation.

Basic food production and consumption are at a satisfactory level in Nigeria. Only a small proportion of available land is under cultivation and the production of these foodstuffs will probably increase at a rate proportional to the increase in population and income per head. But above this basic consumption there will arise, with increasing development, a need for improved diet and food, better living conditions and a certain degree of luxury. This will cause a much faster increase in transport in the internal and external exchange economy. The more production rises above the locally-fulfilled basic needs, the higher will be the percentage of income which will be used for services, of which transport forms an important part (at present 15% of Nigeria's income) in the country's economy. Extra production for internal exchange and export, the main factors in development, is therefore strongly related to transported tonnages and ton-mileage, while improved transport results in greater production and increasing development.

(1 from: BUCHANAN and PUGH, 1955. GEN. 3

In the summary of the important and traffic-producing transport products which is given below, the Report of the World Bank ([1, an issue in a series of Overseas Economic Surveys ([2 and the Digest of Statistics ([3 have been used as a guide:

Product	Period of harvesting	Estimated yearly production (millions of tons)
a. Basic foodstuffs		
(i) Yams	early crop: Jul.—Sep. main crop: Oct.—Jan.	11
(ii) Cassava	as required 12—24 months after planting	12
(iii) Guinea corn	Dec.—Jan.	2.5
(iv) Millets	Aug.—Sep. and Dec.—Jan.	1.25
(v) Maize	early crop: Jun.—Aug. late crop: Dec.—Jan.	0.6
b. Palm produce	throughout the year, with peak in Apr.—May	1.1
c. Groundnuts	Aug. in Southern Nigeria Oct.—Nov. in Northern Nigeria	0.75
d. Rice	Aug. and Nov.—Jan.	0.3
e. Kola	Aug.—Dec.	0.15
f. Cocoa	main crop: Oct.—Jan. light crop: May—Aug.	0.10—0.12
g. Seed cotton	Dec.—Feb. in Southern Nigeria Dec.—Jan. in Northern Nigeria	0.10—0.12
h. Livestock	——	—
i. Minerals	——	1.0

Diagram 1.1.3-1 shows changes and expansion in the agricultural pattern during the last decades in the internal exchange and export economy.

a. *Basic foodstuffs* (Yams, cassava, guinea corn and millets).

A considerable quantity of foodstuffs travels internally. The pattern is not clear, but the main movements will be in a southern direction towards the densely-populated areas or the areas where agriculture aims principally at export crops as, e.g., the Cocoa Belt in the West. The exception to this forms the Plateau minesfield, which imports considerable quantities of foodstuffs from the Niger and Benue Basins; and the North which imports large quantities of palm-oil from the South. The largest part moves by road transport, but the quantities by rail and water cannot be ignored. Yams, for instance, are railed from the Ilorin and Minna areas into the south-west and from the Middle Belt between Kafanchan and Makurdi into the south-east. Over the past years movements of foodstuffs accounted for 20—30% of the railway ton-mileage.

([1 WORLD BANK, 1954. GEN. 41
([2 OLIVER, 1957. TRP. 4
([3 FEDERAL STATISTICS, 1958. TRP. 3

The transport by the inhabitants in canoes on the rivers and creeks consists mainly of agricultural products. Ten million ton-miles on the Niger-Benue system is an estimate, taking into account only hauls over longer distances. This transport is mainly in the hands of Northerners and is at present 7—10% of total transport on this river system.

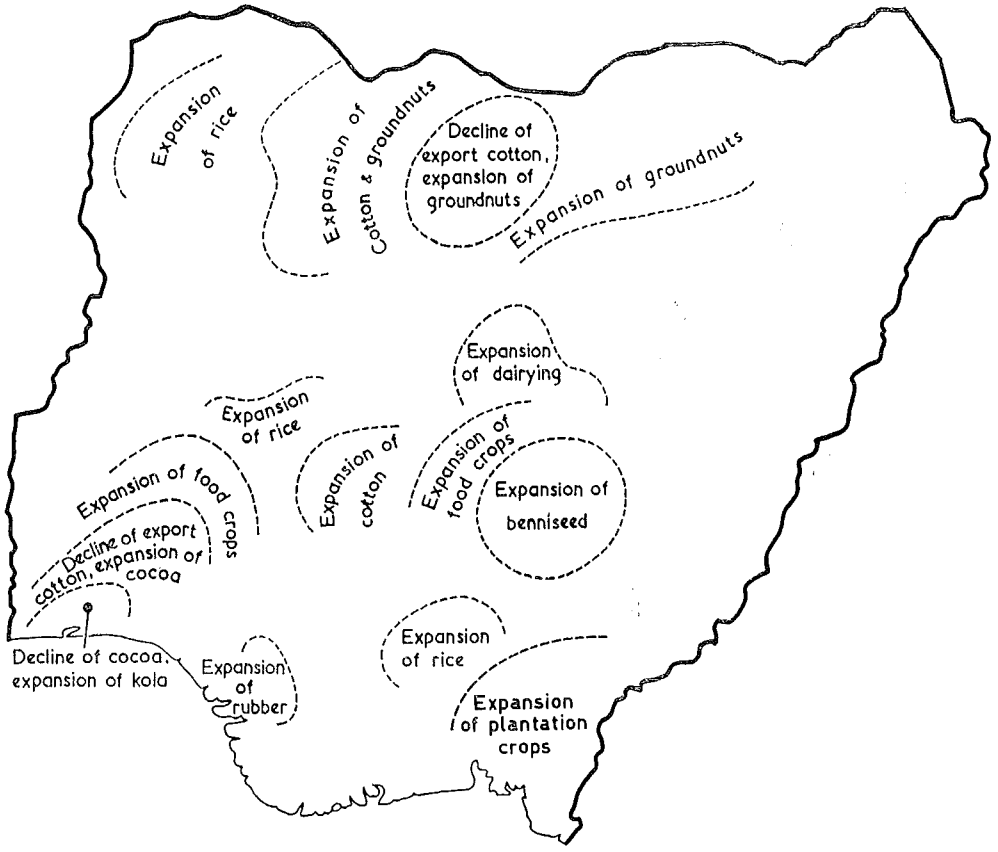


DIAGRAM 1.1.3-1 ([1]

Changes in the agricultural pattern

b. *Palm produce*

Oil-palms are found in the two Southern Regions and to the north as far as the high-forest zone. From the production about one-half of the quantity of palm-oil from the fruit and all the palmkernels are exported (Diagram 1.1.3-2). On the basis of seven parts of kernels to ten parts of oil in the fruit by weight, a total yield of 650,000 tons of oil could be estimated from the export of 450,000 tons of kernels. However, most of the oil is still extracted by the local population and the average extraction rate is only 60%, while mechanised extraction can reach 95%. The export of oil is, therefore, only in the neighbourhood of 200,000 tons. Under steady world market conditions a yearly production increase of 3% may be expected; a yearly increase of 3—5% for exports could be obtained if the rate of extraction were raised.

([1] from: BUCHANAN and PUGH, 1955, GEN. 3

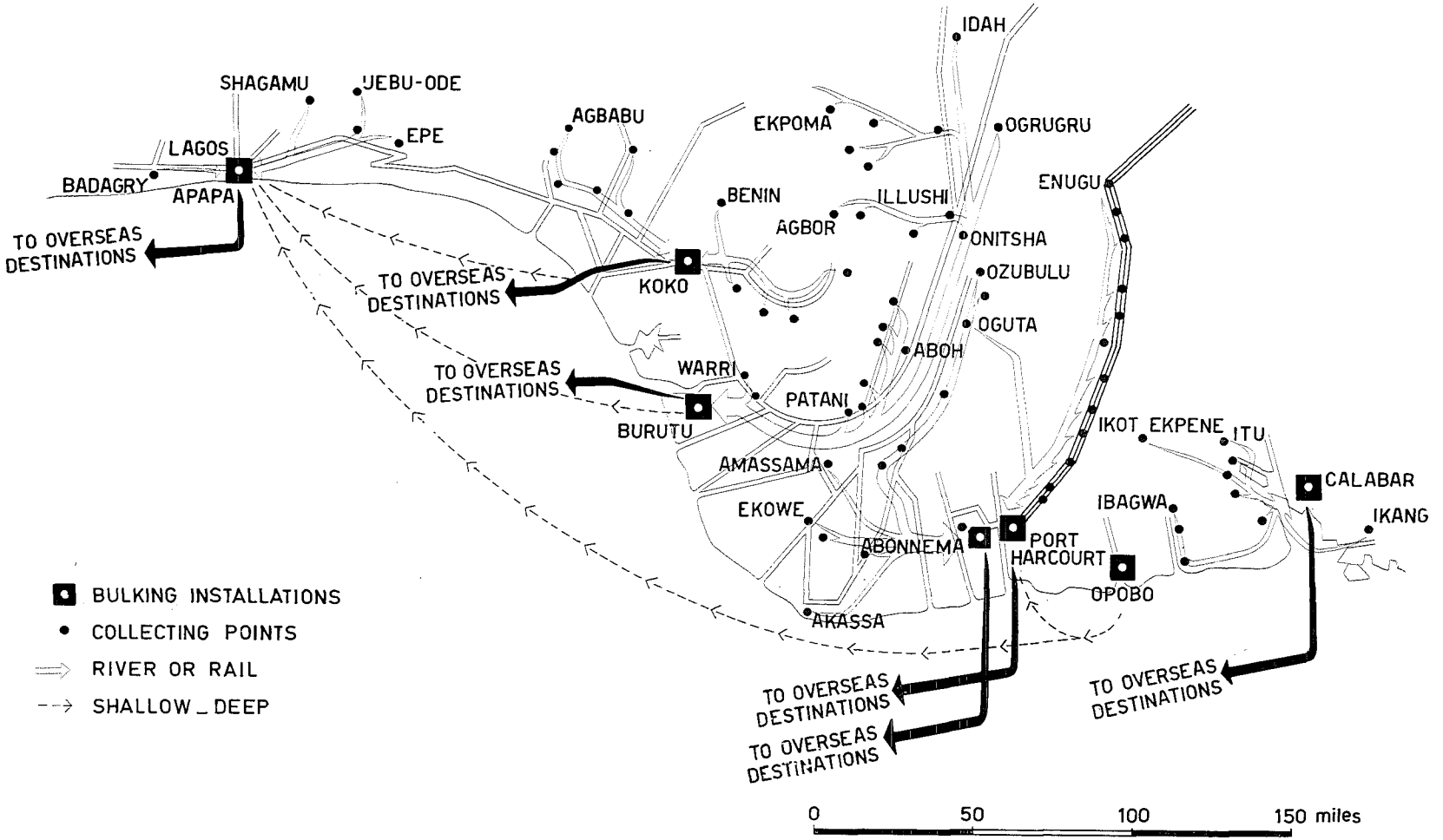


DIAGRAM 1.1.3-2

Palm-oil evacuation route

(from: U.A.C. GEN. 36)

c. *Groundnuts*

Export is roughly 80% of the total production, the remainder being consumed locally or used for planting. About 90% of all exports comes from the Kano, Sokoto, Katsina and Bornu Provinces, and the rest from Adamawa Province and from the neighbourhood of Minna, Jos and Makurdi. The influence of existing railways is evident. Although suitable soils for groundnuts are found in all 12 Northern provinces, only the five provinces mentioned with rail or river connections produce for export, while the other provinces produce only in the basic subsistence economy (Diagram 1.1.3-3).

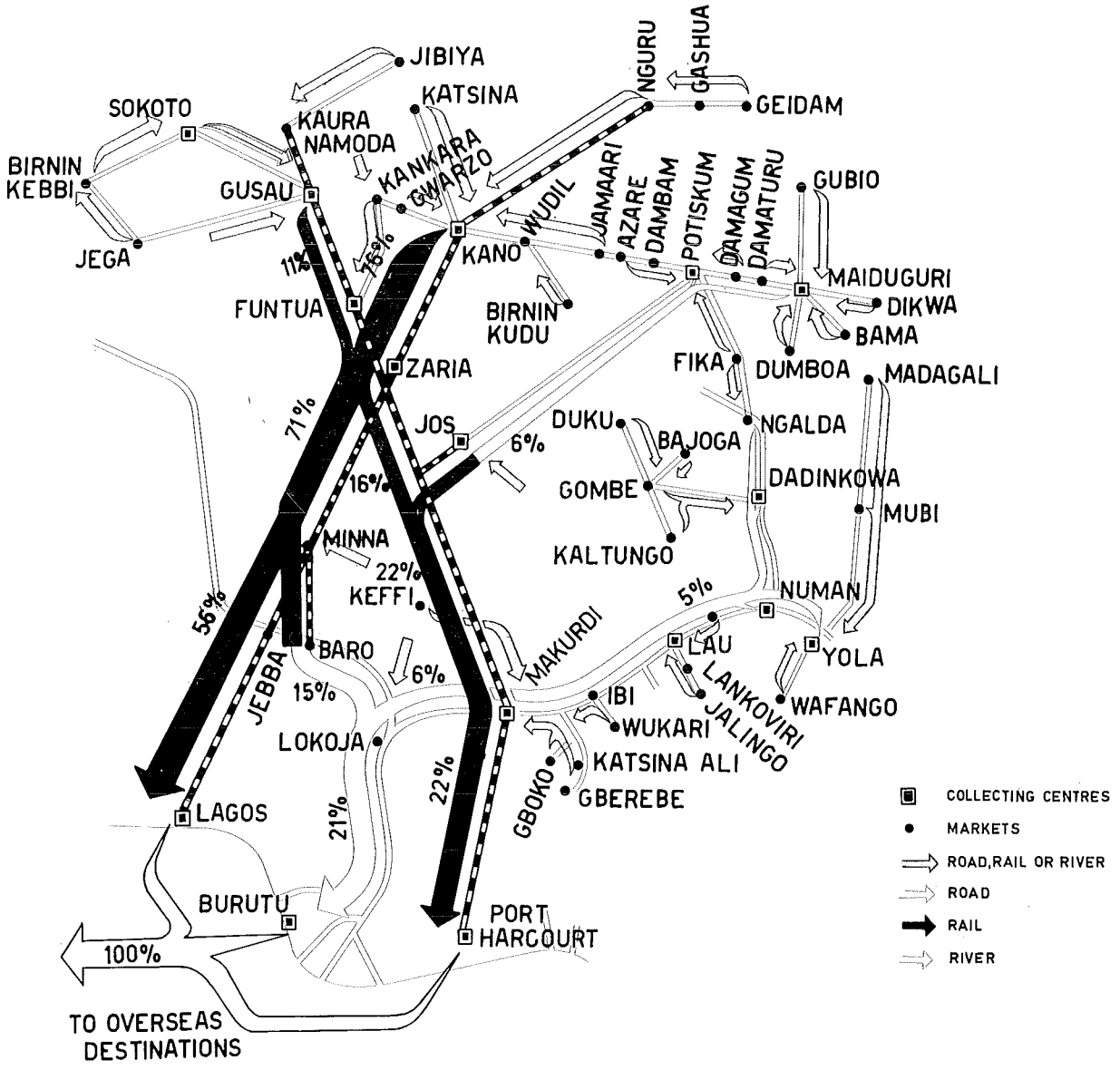


DIAGRAM 1.1.3-3

Groundnut evacuation routes

(from U.A.C. GEN. 36)

Greater production for export is no doubt possible and could be reached by an increase of the acreage under crop and by the use of phosphates. Both of these, however, will depend on the prices paid to the farmer and thus on world market prices, on the stabilising effect of Marketing Boards, and on extension and efficiency of the transport facilities. For example, it may be mentioned that in an area around Kano with good railway connections practically all the land is under cultivation at present, while west of Sokoto groundnuts can only be profitably grown when exceptionally high prices can be paid. Freight rates from Sokoto to railhead are in the order of £ 10 per ton, or 17d per ton-mile, while the average freightrate on the Nigerian Railways is 2.8d per ton-mile.

The Mission of the International Bank for Reconstruction and Development ([1] foresees an annual increase of 5% in the groundnut production for export over the period 1955—1960. Annual fluctuation in yield and world market prices can be large, but such an increase does not seem overestimated. Under stable world market conditions and an active policy of the Nigerian Government in developing transport, a continuing increase by at least 5% a year over the period 1960—1970 may be expected, when it is realised that in the Northern Region the ratio of cultivated to uncultivated land is 1 : 6 not counting bushfallow and forests.

d. *Rice*

Rice is grown along the rivers scattered throughout the southern provinces, but 80% of it comes from the Northern Region where rice cultivation is concentrated in the Niger and Sokoto Provinces. The rising demand and the relative ease of cultivation under Nigerian conditions give good prospects for expansion of the production.

Fadamas (the fertile river banks), irrigated fields and even mangrove swamps could produce many times the present production. An increase in outturn of 50% over a ten-year period may be expected. Rice is considered a higher quality of food and extra production goes to the richer inhabitants in the West and East.

e. *Kola*

The main commercial kola area is found between Ibadan and Lagos. From 50 to 60% of the production goes in internal exchange; about 50,000 tons travel northward and another 15,000 tons go to the east. Expansion has been rapid over the past decades and is estimated at present as 3—5% yearly.

f. *Cocoa*

Roughly 95% of Nigeria's cocoa is produced in the Western Region in an area around Ibadan. Expansion possibilities seem to be restricted and production fluctuates between 100,000 and 120,000 tons. Nigerian Railways have lost nearly all cocoa transport to road transport, which is directed almost entirely towards Lagos.

g. *Seed cotton*

Cotton production is almost entirely limited to Northern Nigeria, due to soil conditions and the quantity of rainfall; only 2% is grown in the north of the Western Region.

Seed cotton produces in weight $\frac{1}{3}$ cotton lint and $\frac{2}{3}$ cotton seed. Respectively, 30,000 tons and 45,000 tons are exported, i.e., 60—70% of the total production.

([1] WORLD BANK, 1954. GEN. 41

Most of the export comes from areas bordering the railway, specially the Kaura Namoda—Kafanchan—Jos line. Further, a considerable quantity of cotton is transported over the Benue River, a large part coming from Garua in French Cameroun. This again stresses the importance of existing transport routes and gives good hopes for expansion of the crop in still uncultivated areas following the extension of such routes. At present cotton production expands in the Gombe area and downward to the Benue River. A yearly increase of 5—10 % in future under circumstances as mentioned for groundnuts (see under c) seems possible.

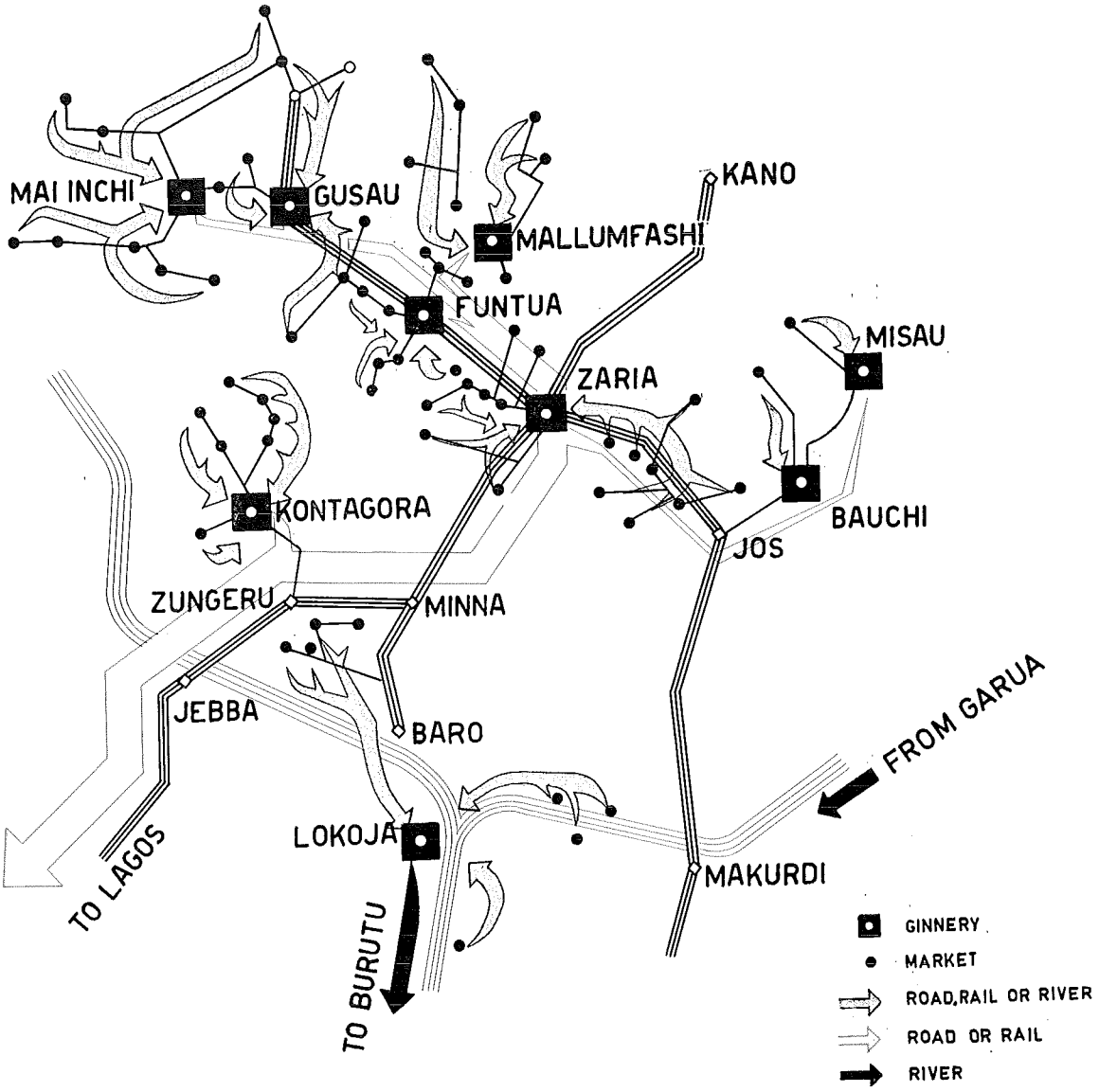


DIAGRAM 1.1.3-4

Cotton evacuation routes

(from U.A.C. GEN. 36)

h. *Livestock*

Livestock products play an important part in the internal economy. From different sources it can be computed that the total cattle population (Diagram 1.1.3-5) is in the neighbourhood of 10 million, and exported hides number one million with a weight of 6,000 tons. The numbers of goats and sheep are estimated at 15 million and 5 million respectively. Export of goat and sheep skins are roughly 4,500 tons.

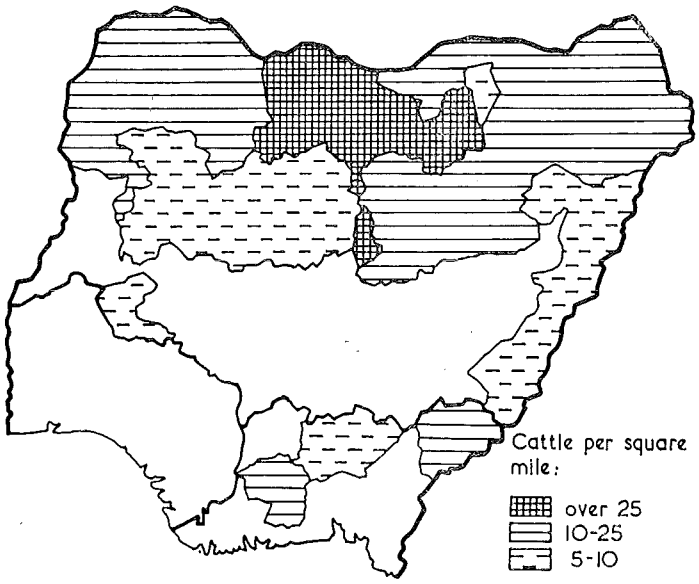


DIAGRAM 1.1.3-5

Cattle density

(after BUCHANAN and PUGH)

Goats and sheep as well as dwarf cattle have resistance against the tsetse fly disease which occurs throughout Nigeria except in the extreme north, where the Zebu cattle herds are reared. In the Middle Belt a crossbreed of the Zebu and dwarf cattle is common. Meat is the first importance and goats, sheep and most of the dwarf cattle in the south come under the basic subsistence economy. Surpluses of cattle in the north move to the densely-populated and richer areas in the south, $\frac{3}{5}$ on the hoof (Photograph 1.1.3-6) and $\frac{2}{5}$ (or approximately 150,000 head of cattle) by rail. Rising living standards will go with an improved diet of the population through more animal protein. Meat consumption, and thus exports of hides and skins, will probally rise by 3—5% yearly.

i. *Minerals* (see also III, 3.3.1)

The main quantities of minerals produced are 800,000 tons of coal, 13,500 tons of tin ore and 2,500 tons of columbite. Coal, all from the Enugu fields, is consumed mainly in Nigeria by railways, thermal power stations, river craft and a cement plant near Enugu; about 100,000 tons are exported. Over the past decade there was an average yearly production increase of

2—3 %. Increase of tin and columbite production from the Jos Plateau depends largely on world market prices and no estimates can be given. In the past the high value of these minerals has accounted for a considerable quantity of imports.

Oil has been found in the south-east near Port Harcourt. It is presumed that transport will be along a pipe-line and that unrefined oil will be exported. Estimates of future production of these fields, however, would be speculative.

PHOTOGRAPH 1.1.3-6

Cattle crossing the Niger on their way south

Lignites near Asaba, lead and zinc in a belt between Abakaliki in the Eastern Region to Zurak in Plateau Province, and iron ores in Kabba Province along the Niger are minerals of potential economic significance and may in future give a considerable transport, specially on the rivers.

1.2. CONSUMPTION

1.2.1. General

The interaction between production and consumption causes transport. The production in the basic subsistence economy is locally consumed and the resulting transport is negligible. Further consumption requires transport. All three forms of transport, by road, rail and river, take part in the internal and external exchange, but road transport probably mainly accounts for internal transport, while rail transport consists for about 60 % of import and export movements. River transport in the internal exchange is by canoe; river-fleets carry the imports and exports. Because internal transport cannot be studied without proper statistics, which do not yet exist, the following comments and figures must be restricted to the consumption of imports.

1.2.2. Consumption of imported goods

Consumptive and capital goods will normally move from coastal harbours directly or indirectly to areas with excess production. Transport and distribution services account for 15—20 % of the national income, and it can be imagined that 15—20 % of the imports are consumed "en route".

Of the imports, 55 % are consumptive goods and 35—40 % capital goods. Distribution will be proportional to production (services included). In 1956 the average value of the export was £ 64 per ton, while the average value of the imports was £ 67. For 1955 and 1954 these figures were £ 67 against £ 68 and £ 76 against £ 69. That the average value of the export is so high is due to cocoa, tin and columbite exports, which considerably raise the value of the average exported ton. The total import tonnage is not much less than the total export tonnage and even surpassed export tonnage recently without causing a serious deficit on the external trade balance.

The main imports with their respective tonnage and estimated yearly increase are:

Mineral oils	500,000 tons	15 %
Salt	105,000 „	3 %
Cement	500,000 „	7 %
Cotton and rayon piece goods	320,000 thousand sq.yards	5 %
Constructional steel and iron sheets	105,000 tons	7 %
Sugar	55,000 „	6 %
Flour	40,000 „	6 %
Stockfish	35,000 „	7 %

1.3. TRANSPORT

1.3.1. Road transport

Very little is known about the road transport in Nigeria. Some official information on it is given in the Digest of Statistics, but this is practically the only government source. Only recently have two studies been made in this wide and unexplored field.

Roads in Nigeria (see Map B in back cover) are classified for administrative purposes as Trunk roads A, Trunk roads B and Local roads.

Trunk roads A, financed by the Federal Government, constitute the basic framework of the road system. Three main south-north arteries, of which the Bamenda—Yola road is not yet completed, four main east-west arteries, and several links between them connect the large centres in the Regions.

Trunk roads B, financed by the Regions and local authorities, supplement the Trunk road A system, linking large towns, ports and trunk roads A in the region.

Local authorities finance provincial, district and township roads.

The quality of roads in Nigeria is not very high. The major part is not bitumen-faced, and many miles are impassable in the wet season, necessitating long detours. The capacity is limited by small widths and by deterioration. Holes and corrugation are very common and the uneven road surfaces shorten the life of motor vehicles considerably. Maintenance costs are high and exceedingly difficult to provide. When the life of a vehicle is estimated at three-fifths of its life in European countries, it means that in comparison with Europe £ 4—5 million are lost yearly by the fast depreciation on the value of all Nigerian vehicles, a sum near the annual capital expenditure on roads.

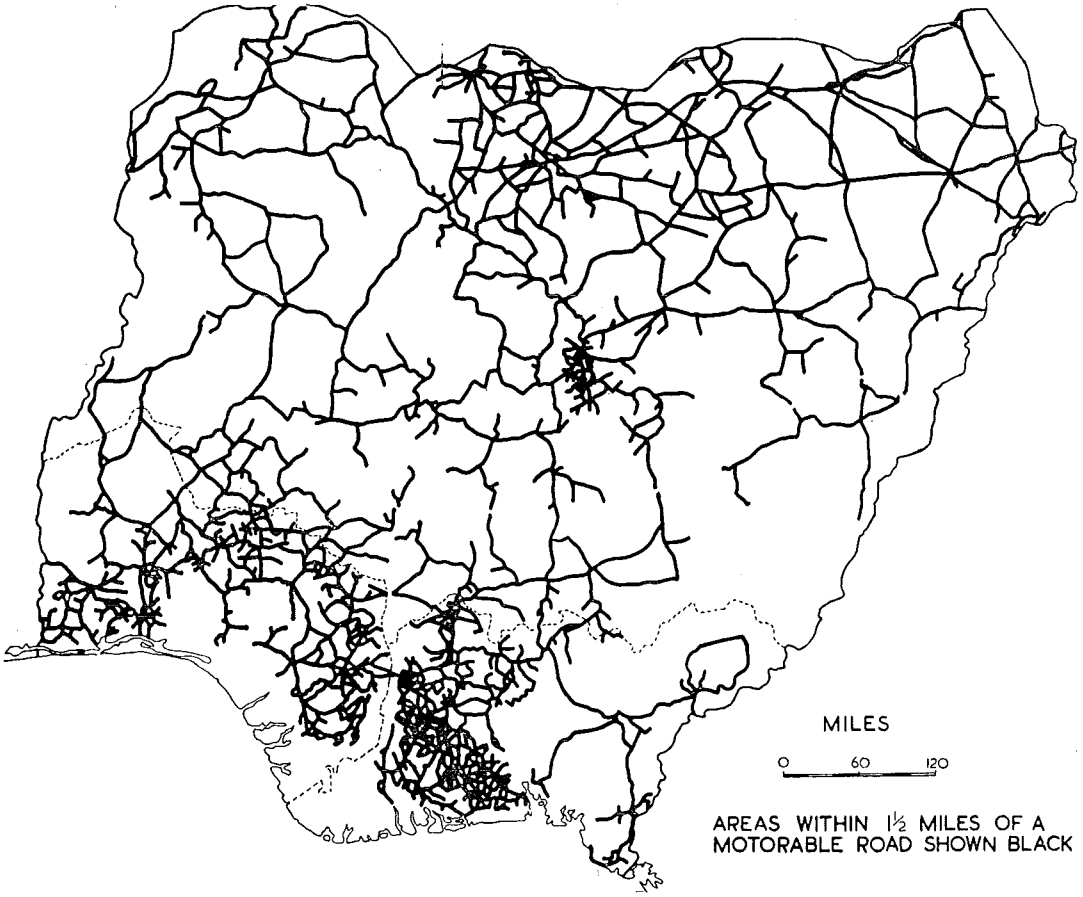


DIAGRAM 1.3.1-1

Road density

(after BUCHANAN and PUGH)

So far, little has been done to improve the inter-territorial road system for West Africa, facilitating trade and growth of the respective economies.

The first main trunk road was constructed in 1905 from the railhead at Ibadan northward to Oyo. Since then the road network has extended rapidly. The total mileage of roads rose from approximately 25,000 miles in 1947 to 36,500 miles in 1957, with an average annual increase of 3.8 % over the past decade. At present roughly 10 % is tarred, but the average annual increase of tarred roads over the past decade has been 16½ %.

The importance of better roads is well understood in Nigeria but the task is very heavy. Many areas are still a long way from a motor road and very little of the country is within 1½ mile of a road (Diagram 1.3.1-1).

The road system is still divided by the Niger and Benue Rivers. Crossings are only possible over the rail-road bridges at Jebba and Makurdi and on the ferries at Onitsha, Lokoja, Yola, Numan and recently Idah. The very high cost of permanent bridges, not only across the large rivers but also over the numerous smaller waters, hampers the development of the road system. The roads serve as feeders to the railway lines and the rivers, but over shorter distances, especially in the south-west and south-east, the roads compete directly with the railways.

The density of roads varies widely: a high density in the Palm Belt and a very low density in Bornu Province and the Middle Belt (Diagram 1.3.1-1). Only a special study could determine whether the road system in certain areas is over- or under-developed in relation to the economic significance of that area and the ability of the country to bear the investments for development.

Traffic development has been rapid since the Second World War. In recent years, the number of commercial vehicles has increased by almost 17.5 % annually. Where the Mission of the World Bank estimated 400 million ton-miles road transport over 1952-1953, the present ton-mileage can be estimated at 900 million in view of the 125 % increase in the number of commercial vehicles (Diagram 1.3.4-1).

The heaviest traffic radiates from:

(i) ports (distribution and collection of goods or passengers within competitive reach of road transport);

(ii) large towns (concentration of car parks for local traffic); and

(iii) railheads in the north (feeder and distribution roads).

The cost of road transport varies widely. Actual costs are estimated between 5d and 10d per ton-mile, depending on the state of the roads, fuel and repair costs and type of goods. Charged costs may be considerably below and above these levels, due to competition and the availability of return loads.

1.3.2. Rail transport

In contrast to roads, railway tracks ([1] — all single-line — have not been extended for a long time. Over the first period of exploitation the construction of the tracks between 1910 and 1940 has necessarily offered an expensive means of transport. Recently, the light-railway line Zaria—Jos has been abandoned but the work on the railway extension from Kuru via Bauchi, Gombe to Maiduguri has already started; the World Bank granted a loan of £ 10 million for the development of the railways in May, 1958.

The capital investment had to be borne in 1938 by 0.9 million tons paying freight, while at present this figure is in the neighbourhood of 2¼ million tons. Moreover, the average length of haul has increased from 380 to 450 miles. Passenger miles have more than doubled since 1937. In the past 10 years traffic receipts have risen from £ 2,800,000 to £ 12,800,000 (over 1957).

([1] See Map B in back cover

The railways are now self-supporting, and extensive surveys indicated the economic feasibility of the extension of the routes by about 400 miles into Bauchi and Bornu Provinces, reaching Maiduguri (1 (2.

Rolling-stock and maintenance of equipment are now adequate after the difficulties in the period 1948—1953 had been overcome. The single-track capacity can substantially be increased by improving upon the average number of cars per goods train, the number of crossing loops and the speed. The turn-round of trains can also be accelerated. Nowhere along the line is traffic so heavy that doubling of tracks must be considered, as was concluded by the Mission of the World Bank (3.

Total railway ton-mileage is at present approximately 1,200 $\times$ 10^6 ton-miles and has increased by an average annual percentage of 10.5 over the past decade (Diagram 1.3.4-1). The tonmileage can be divided in percentages as:

Groundnuts	30%
Petroleum products	8%
Internal traffic, foodstuffs	30%
Internal traffic, coal	15%
All others	17%

In interpreting these figures it must be taken into consideration that the traffic is essentially agricultural and subject to fluctuations. Weather condition and crop diseases can have a marked effect on the percentages.

The cost of rail freight depends on the type of goods, which are classified, each class having its own rate, which decreases with increasing haul. For some goods special rates are in use. The costs per ton-mile vary between 0.7d for yams and 6.4d for tin. A better basis for comparison is that the average receipt of the railways is 2.9d per ton-mile.

1.3.3. River transport

Rivers and creeks form a network of waters in Nigeria, and in the Delta they are often the only means of transport. Extension of this system by constructing canals is at present not opportune, but much can be done for the improvement of the existing river system.

The difficulties lie in the navigable periods, the available depths and sometimes the width of the channels. Traffic on the rivers can be severely hampered by this, and must adapt itself as far as possible to these factors. On the other hand, water routes provide an even surface and resistance is small, so that energy consumption per ton-mile is low. The capacity for transport of most water routes is practically unlimited.

Canoes can navigate nearly all waters, but tugs and barges are confined to the larger water routes, such as the creeks and the Niger, Benue, and Cross Rivers.

The river-fleets (see also Chapter 4) on the Niger and Benue seem to be adequate for the transport they attract at the present freight rates. If these rates could be reduced because of an improved navigability and efficiency, extension of the fleets will certainly be necessary to cope with offered freight.

Total river transport fluctuates strongly with good and bad river seasons and good and bad years in the agricultural production.

(1 CRAWFORD, 1955. TRP. 1
(2 CRAWFORD, 1956. TRP. 2
(3 WORLD BANK, 1954. GEN. 41

Diagram 1.3.4-1 shows the increase of river tonnage of the largest shipping company, the Niger River Transport (N.R.T.). Holt's Transport and the smaller shipping lines together produce about one-third of the total, so that at present the total figure of water transport moves around 250,000 tons and 120×10^6 ton-miles.

Diagram 5.1.5-1 shows the distribution of transport over the Niger-Benue system in 1955-1956. The prolonged Baro season of 1958 and the heavy yield of groundnuts in that year, together with improved coordination between rail and water transport, have made it possible to treble the transport over the river from Baro and brought it up to 74,000 tons (see Diagram 2.1.2-1).

On the Benue, in spite of adverse river conditions, record tonnages were transported here as well, resulting in an overall increase of over 25 million ton-miles, or 20%, in one year.

Transported tonnages of the largest shipping company are given in Table 1.3.3-1 (1.

TABLE 1.3.3-1

TONNAGES SHIPPED BY NIGER RIVER TRANSPORT LTD.

year	upward				downward			
	Garua	Benue (1	Niger	total	Garua	Benue (1	Niger	total
1945/46	9,200	6,200	19,800	35,200	12,500	11,200	60,600	84,300
1946/47	9,500	6,300	24,700	40,500	12,000	14,400	62,900	89,300
1947/48	13,000	5,200	28,100	46,300	10,300	17,400	69,000	97,700
1948/49	9,900	8,000	25,600	43,500	13,100	15,700	76,400	105,200
1949/50	10,200	5,700	23,300	39,200	10,400	11,200	77,300	98,900
1950/51	15,900	4,600	22,900	43,400	15,300	12,300	74,900	102,500
1951/52	8,500	11,200	27,100	46,800	11,700	12,100	79,700	103,500
1952/53	17,900	5,500	29,200	52,600	16,700	13,100	78,300	108,100
1953/54	17,700	4,500	32,400	54,600	13,900	13,700	91,600	119,200
1954/55	14,700	5,900	42,400	63,000	17,200	20,200	80,900	118,300
1955/56	16,200	6,300	41,700	64,200	11,200	17,200	74,800	103,200
1956/57	11,900	6,700	47,400	66,000	19,700	19,400	80,100	119,200

(1 excluding Garua.

The charges per ton-mile for river transport are — like those of rail transport — classified for type of goods. Also special rates are in use for the main export products such as groundnuts and cotton, whilst rates are adjusted to length of haul and the risks of a journey. On the Benue, freight rates per ton-mile are considerably above the average because of the short period of navigation there and the unpredictability of the water-levels. Where there is competition between rail and combined rail-water transport, water transport is at a disadvantage. In the north, the rivers do not reach into the main production centres and so river transport remains to a certain extent dependent on the railways for its freight. On the other hand, the rivers provide access to areas which have not hitherto been served by railways and where modern communications are required if those areas are not to fall behind other parts of the country in economic development. At the same time, water transport charges are restricted to what is left by the railways, i.e., the difference between the charge for rail transport only and the part of rail transport in the combined transport.

Freight rates per ton-mile vary between 1d and 6d. The average freight rate is between 2.7d and 2.9d per ton-mile.

(1 by courtesy of Niger River Transport (N.R.T.); subsequent data are given later in this Report.

1.3.4. Comparison of the different transport methods

Road, rail and river transport are essential in the development of a country's economy. The three must co-exist to lead to the country's most economic development and use of resources. They fulfil this in two different ways, the competitive and the complementary way.

Competition tends to the most effective employment of man and capital to serve the production and consumption with the highest quality of transport against the lowest cost for each different type of goods. The mutual complementary function of the three different kinds of transport tends to the most effective ratio between the capital outlay and the quantity of a certain kind of transport.

It is the Government's duty to see that these two basic principles work to the full advantage of the whole country. It is possible that in private economics one of the transport methods is preferred, even though it is not in the interests of the country as a whole.

Road transport is more suitable for small quantities because road routes and vehicles can be best adjusted to the quantity of transport. The fixed costs can be kept small when the quantities are small. This is not the case with rail and river transport, which need larger quantities. Variable costs of road transport are highest and of river transport lowest among the three different transport methods. Therefore road transport is more suitable for short hauls and rail and river transport for longer hauls.

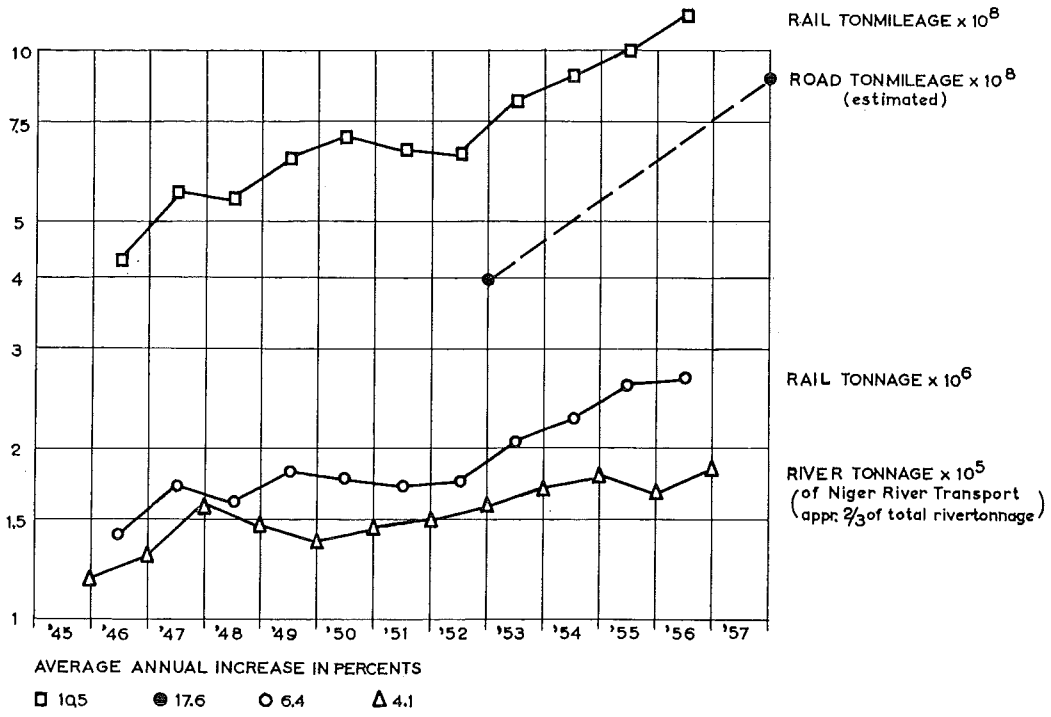


DIAGRAM 1.3.4-1

Development of transport

In the past, without employment of capital, the rivers were at first the only transport routes used to penetrate into the country. The area that could be reached was limited and restricted by natural circumstances. Rail routes were then constructed to overcome this. The choice for rail transport in the first decades of this century was strongly influenced by the fact that at the time

rail transport was ahead of road transport development. Road transport has now gained in Nigeria with the steady improvement of motor vehicles and the expansion of road network and takes its place where fast and versatile transport of limited capacity is of prime importance.

In Diagram 1.3.4-1 a comparison of the development of the three different forms of transport is given.

Striking is the fast increase of motor transport, made possible by the small capital investment needed for a lorry, the few restricting regulations and the relatively simple organisation of small-scale traffic which brought motor transport within reach of the local population. The danger of such development is that because of the low initial costs the most expensive transport gains a position contrary to the interests of the country as a whole. On a long term the basic rule holds that water transport is the cheapest mode of transport with increasing quantities and hauls.

From the diagram it can also be seen that the average annual increase in river transport remains 50% below that of rail transport. If river transport in Nigeria were overdeveloped this would do no harm, but up to now hardly any investments have been made to develop river transport, so at present the situation is probably the reverse. The underdevelopment of the rivers as a proper water route causes the river to lose its share of the expanding traffic.

At first sight it seems that in Nigeria river transport has gradually fallen behind as a result of lack of capital expenditure on river routes in the past decades. In Nigeria the ratio of cost per ton-mile rail and river transport is approximately 1 while this ratio in more developed countries varies between 2 and 4. This could certainly be improved, and with the present quantity of river transport, the future prospects and the practically unlimited capacity of the Niger-Benue system, capital investment certainly seems justified.

These remarks do not, of course, cover the whole complex pattern which rules the quantity, quality and distribution of transport over road, rail and river routes; but a complete study of the traffic is outside the scope of this Report. Study and continuous planning will be needed to bring and keep the three transport methods in balance.

Anxiety has been expressed at different times about the possibility of rail and river competition, especially if the 400 miles extension of the railway is built out to Bornu. This particular issue was considered by the Honourable Abubakar Tafawa Balewa, the Minister of Transport, now the Prime Minister of the Federation, in his Report on the Mississippi:

"The branch line from Baro to Minna was constructed to carry a tonnage of 120,000 tons gradually in each direction. In fact, it has never carried even a quarter of this amount, one of the difficulties being that the river-fleets have been unable to supply import cargoes to fill empty waggons for the return journey to the North. Any improvement in the Niger channels to Baro will therefore help to convert an uneconomic section of line into a paying asset, a prospect which the General Manager welcomes. It can perhaps be argued that, in developing Baro, freight will merely be diverted from the Western line. This particular reasoning, with which the General Manager does not agree, can be discounted, first, because the Railway is only now free to resume its freight services in the Western Region and, secondly, because of the increasing volume of traffic being offered. The International Bank Mission estimated the traffic increase for the whole country (in million ton-miles) as follows:

Northbound: 384 in 1952-53, 615 in 1959-60; and
Southbound: 443 in 1952-53, 854 in 1959-60.

"Even if these figures should prove over-optimistic, a steady increase in traffic appears certain which should more than balance any diversion of traffic to the Baro branch line.

"Subject to whatever the consulting engineers may say, it must be many decades and only at heavy capital cost — if the lessons of the Upper Mississippi are any guide — before the Benue

within Nigeria can be trained to the extent that it will provide a navigable shipping channel throughout the year. Apart, however, from this consideration, there are geographical factors which should militate against any cut-throat competition between the two forms of transport.

"In general, the key to this question of possible competition between rail and river in North-Eastern Nigeria lies with the lorry-owner. Serious competition will only arise if he can undertake the journey from Bornu to Yola at a cost which will make it worthwhile to take advantage of the cheaper river freights; but in view of the long distances and high cost of vehicle maintenance this appears to be unlikely."

CHAPTER 2

SHIPMENT

2.1. PORTS AND SUPPLY ROUTES

2.1.1. River-ports

Within the scope of this Report, a description of the main river ports along the Niger and Benue Rivers must necessarily remain rough and incomplete, but Diagram 2.1.1-1 gives a survey of some of the aspects of the principal river ports.

In most ports, provisions for the quick handling of goods are inadequate. Landing stages are absent, quays are uneven, sheds have often a bad lay-out, handling is not mechanised, and among a number of other imperfections which delay a quick turn-round of ships must be mentioned the irregularity in arrival of goods trains (Baro), the silting and erosion of berths (Ibi and Idah) and the badly-organised cooperation of customs and health services (Yola). This is only natural, as the total tonnage handled in the river ports is very low and it does not pay to have expensive provisions which are only of limited use. Nevertheless, real savings can sometimes be effected with very little effort. For example, along the Benue it is common to store a large part of the groundnut crop on a stone base and the stocks are covered with a tarpaulin. Owing to the short navigation season on the Benue, storage capacity there has to be of the same magnitude as the total tonnage handled.

All improvements to river ports in Nigeria have until now been carried out by private companies, of which the United Africa Company and John Holt are the largest. These improvements consisted of the building of sheds, quays and berths, the installation of a radio-telephone communication system and improved organisation of the running of river ports. Especially in the last decade have the ports of Warri, Burutu and Onitsha been improved considerably and plans have been made for the building of quays and berths in Baro. In French Cameroun, the Government has strongly stimulated the extension and improvement of the port of Garua.

No remarks need be made regarding the situation of the ports as most of them are well-sited along high banks and sufficiently accessible from the river and from the hinterland.

Although much remains to be done to river ports, it can be stated here that the conditions of the ports are not at present adversely influencing the river transport in a major way. Admittedly, ships spend long periods in port, as can be seen in Chapter 5 of this Part; but apart from the slow handling of goods this is due to a great many other causes such as fuelling, marketing, waiting for freight, river conditions, etc. Improved traffic management, abolishing coal as fuel, better navigability and also barge-shuttling will greatly reduce the times spent in port and some of these influences are already noticeable.

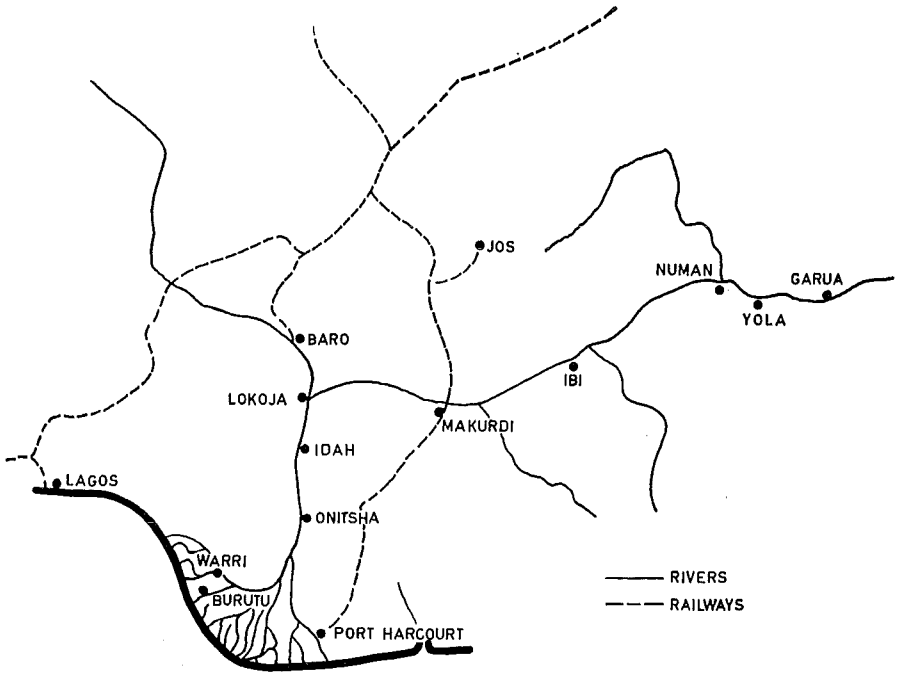
Man-handling of goods is probably the cheapest method at present. But it can be safely assumed that an improved navigability and an increasing trade on the river will result in further improvements to the port facilities.

2.1.2. Feeder and distribution routes

The production and consumption areas have been discussed in the previous Chapter. River transport to and from these areas goes via the river port, using the road, rail and water routes radiating from the river ports.

On the Niger, a small quantity of goods is carried to and from Jebba by canoe where the river is not navigable for tugs.

Baro is a port where almost exclusive rail transshipment exists. This port serves, in combination with rail and road transport, the North and North-West of Nigeria. Diagram 2.1.2-1 shows the rapid rise in tonnage transshipped via Baro. The downward shipped tonnage



	approx. annual tonnage handled	covered storage near waterside	facilities	remarks
Warri	100,000	12,000	Q B L M	Q = quay
Burutu	350,000	40,000	Q T M	B = berth
Onitsha (1	80,000	25,000	Q T L M	T = tanks for petroleum products
Idah (2	20,000	6,000	L	L = man-handling
Lokoja	10,000	8,000	T L	M = mechanised handling
Baro	75,000	10,000	L R	R = railway connection
Makurdi	12,000	10,000	L R	(1 including Asaba opposite Onitsha
Ibi	3,000	4,000	L	(2 including Agenebode opposite Idah
Numan	7,000	8,000	L	(3 including Dalmare opposite Yola
Yola (3	8,000	9,000	L	(4 large covered storage away from waterside
Garua	35,000	17,000 (4	Q T L M	

DIAGRAM 2.1.1-1

Principal ports along the Niger and Benue

consists almost entirely of groundnuts. The upward shipped tonnage is negligible compared with the downward tonnage, causing a very inefficient transport to and from an important production centre in the North around Kano for both river-fleet and railway.

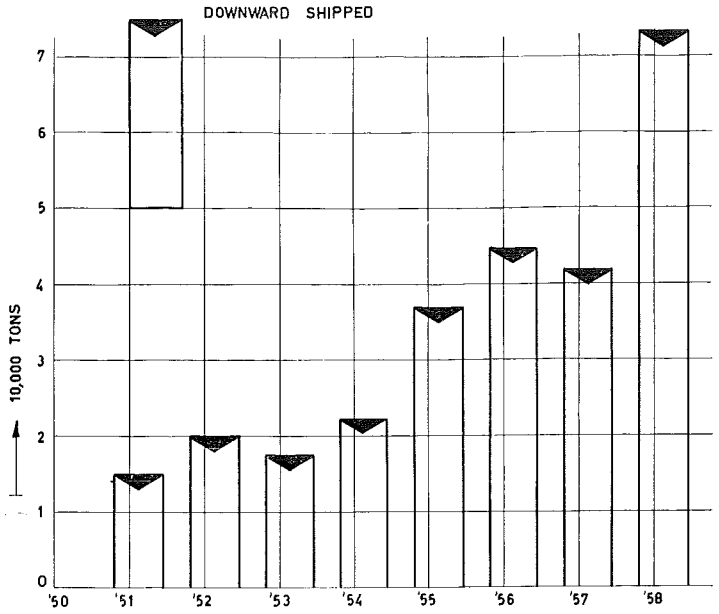


DIAGRAM 2.1.2-1

Baro tonnages in the past decade

On the Benue, Makurdi has rail transshipment, but it is limited because in most cases it is more economic to lead goods transport directly to and from Port Harcourt by rail, thus avoiding transshipment in Makurdi.

Makurdi and Numan are used as transshipment ports of the Benue tributaries, the Katsina Ala, the Donga and the Gongola Rivers (Photograph 2.1.2-2). Feeder-tows, small units of the shipping companies and canoes provide the transport. Makurdi and Lokoja can to a certain extent also be used as transshipment ports of the upper reaches of the Benue, because the navigation season of the Upper Benue is much shorter than that to the ports of Makurdi and Lokoja. In this way it is possible to clear a larger quantity of cargo to and from the upper reaches of the Benue with a smaller fleet tonnage.

The hinterland of all other ports is served by roads.

Warri and Burutu, the ports in the Niger Delta, receive the cargo from up-river from where it is shipped to overseas destinations and to Lagos. Transshipment to Lagos is necessary because of the shoals in front of the sea entrances of the Delta, which permit only the passage of sea-going vessels with limited draft. The normal freight carriers of about 6,000 tons which sail to the West African ports can therefore only load up to 1,500 tons in Warri and Burutu. Transport in the reverse direction is, of course, also subject to these restrictions.

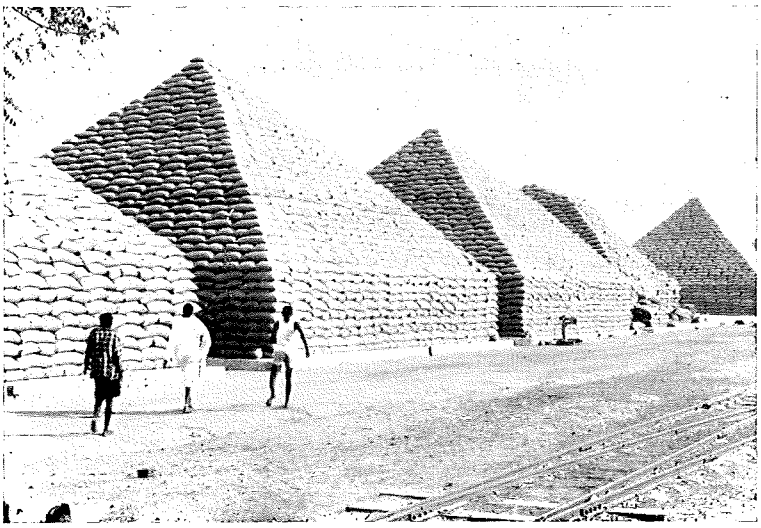
The extent of the hinterland and the transport tonnage of each river port is determined by the type of goods, the quality of transport wanted for these goods, the destination and the costs of transport. Some ports have a very large hinterland, such as when water transport has no competition (Garua) or when water transport can be linked to the hinterland of the railways as in

PHOTOGRAPH 2.1.2-2

Groundnut buying station Dadin Kowa on the Gongola River

Baro (Photograph 2.1.2-3) or when ports such as Burutu and Warri are favourably situated at the mouth of the Niger-Benue system.

A broad outline of the hinterland of the main river ports has been given in Diagrams 1.1.3-2 to -4, whilst the areas of economic influence (Diagram VI, 9.1.1.-1) give an indication of the feeder and distribution routes of the Niger and Benue Rivers.



PHOTOGRAPH 2.1.2-3

Groundnut stacks in Kano, partly transhipped via Baro

2.2. HANDLING

2.2.1. Practised methods

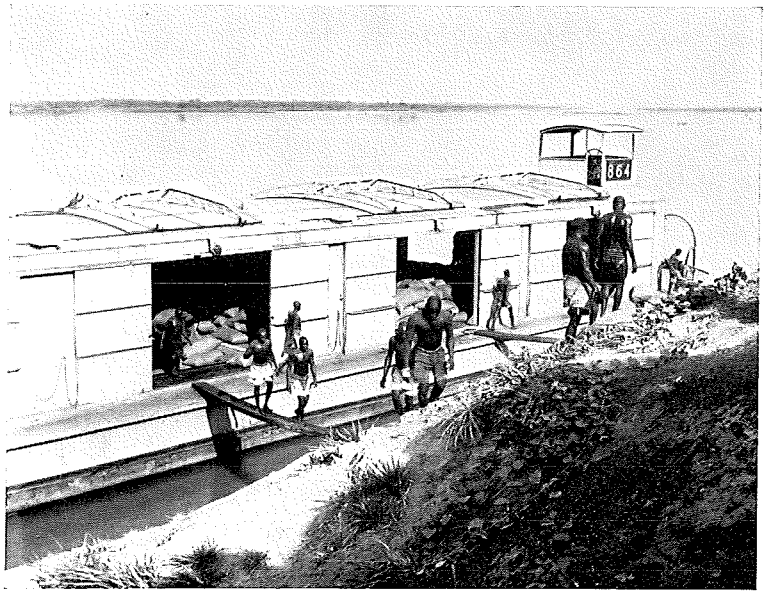
Handling of goods in ports is manual, mechanised or a combination of the two.

Man-handling can be very efficient in Nigeria. Loads of up to 200 lbs. can be carried by one man provided the load (bag) is placed on his head or shoulders and the transport is in a downward direction. Distances of several hundreds of feet are thus covered by one man. The rhythm of a drum-band greatly stimulates the regular and speedy performance of the labour gangs. Wages vary from 2 to 3d per load. Gangs of about 150 men are known to have loaded 1,200 tons of groundnuts in a single day (Photograph 2.2.1-1).

Mechanised handling involves stationary or mobile cranes. Fork-trucks may be applied with palletising, i.e., the loads are stacked on pallets in the sheds and sometimes in the barges.

The main factors in the choice of one of these practices is influenced by:

(i) the handling costs per ton;
(ii) the quality of handling (speed and breakage); and
(iii) the capacity wanted and the labour available.



PHOTOGRAPH 2.2.1-1

Man-handling of groundnuts into several holds of a barge

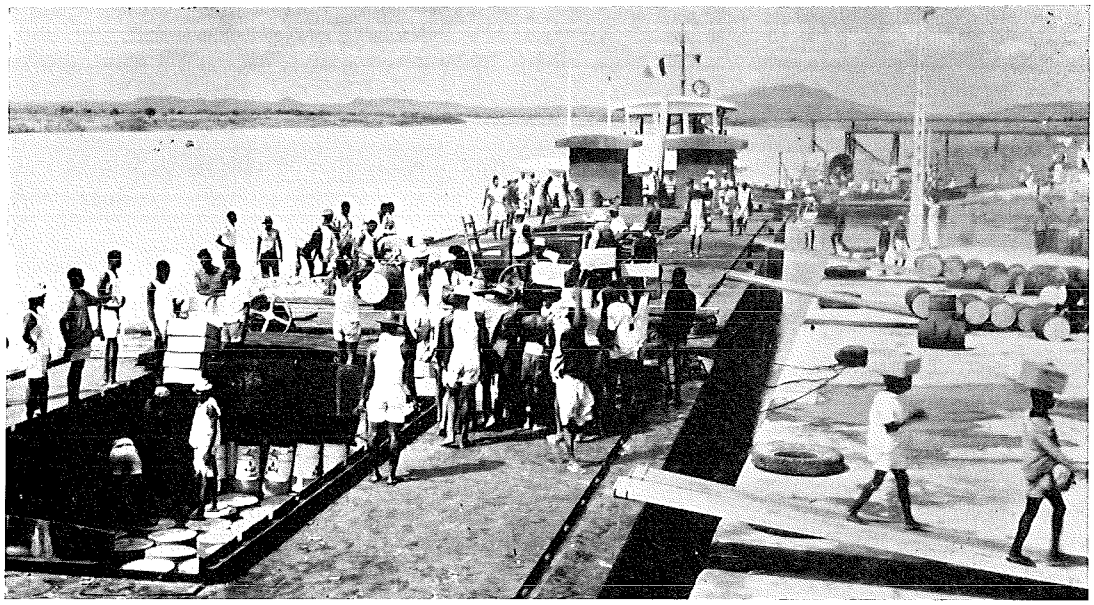
note the deck up-building

The distance between shed and ship and the difference in level between river and quay are important factors in the handling costs by labour, which vary in general from 2 to 3 shillings per ton. Labour in most ports is sufficiently available and the yearly tonnages handled in these ports and the daypeaks of handled tonnage are so low that the capital investment which the mechanisation entails is not warranted.

The experience in Nigeria is that a regular daily handling of 800—1,000 tons is about the minimum for mechanisation to become advantageous. The port of Burutu is fully mechanised;

Warri, Onitsha, and Garua are partly mechanised. Garua is in an exceptional position because the navigation season is so short.

Although the handling costs may be reduced when the quantity is large enough, it sometimes occurs that the speed of loading and discharging is reduced. This can be caused by the way in which barges are built up (see Photograph 2.2.1-1), for cranes cannot always easily reach into the hold of the barges. When open decks are used, mechanised handling becomes much easier (see Photograph 2.2.1-2), and speed of handling is not reduced but often increased.



PHOTOGRAPH 2.2.1-2

Open decks simplify handling

A great advantage of mechanised handling is that the human occupation of decks, quays and sheds is greatly reduced, which benefits the loading and discharging and makes all port operations much clearer. In the special case of Burutu, the reduction of the labour force means an important saving on the labour-housing estate and the other social arrangements which are necessary to attract labour to the island of Burutu in the swampy Niger Delta.

Finally, it must be mentioned that dependency on casual labour has disadvantages compared to dependency on mechanical equipment and trained labour, specially where workshop facilities are available. This is a point to the advantage of mechanised handling, whilst in view of development, it is also to the advantage of the employee, who often receives a free training to a higher level of skill.

2.2.2. Capacities

Transshipment capacity in the different harbours is in general adequate. Annual tonnages handled are in general not very high (see Diagram 2.1.1-1) and the distribution over the year of incoming and outgoing ships in the different ports is good, so that daily handled tonnages are also low.

This can be best understood when it is mentioned that altogether only about 50 units sail on the Niger-Benue system. On an average, they are 1 in every 4 or 5 days in port, loading and discharging, and there are about 25 ports which are regularly called at. Most of the ports have 2 beaches, so that it is obvious that congestion is rare. Exceptions to this rule are the basic ports of Warri and Burutu where all river transport concentrates, and Garua where the shipping season is only $1\frac{1}{2}$ months. Yola, Makurdi and Baro must also handle a rather large tonnage in a restricted period.

One man handles an average of 1 to $1\frac{1}{2}$ tons/hour, depending on the type of goods and the distance between shed and ship. Work by these bearers is done in gangs, sometimes consisting of up to 60 men. A temporary rise in their output can be reached by using more labour, but this of course has its limits. The second step will be to make longer quays. Baro is a good example of long quays, and loading or discharging of ships can reach over 1,200 tons a day without causing difficulties.

Mechanised handling is the next step. Cranes can take many tons in one swing into or out of a ship and the use of pallets and fork-lift trucks speeds up handling in sheds, on quays and of cranes. This is already practised in Warri, Burutu, Onitsha and Garua.

Improvement of the beaches can sometimes be obtained by simple means. The eroding banks of the river are often a problem, but this can be overcome with pontoons, thus facilitating landing and tieing up of ships and handling by labour (Idah and Numan). Instead of pontoons a barge can be used, which is often the practice when coasters sail on the Niger and Benue during high-stages. These ships which draw upto 12 feet cannot come close alongside because of the sloping banks and the risk of damaging their screws.

The ultimate goal is of course permanent jetties and quays, with sloping or vertical walls and an even surface. Vertical walls will be preferred in case of complete mechanical handling, but, as has already been said, in most river ports the quantity of handled goods does not warrant the capital outlay. Sloping walls have a large advantage when man-handling is used, as the difference between high and low water can be great.

CHAPTER 3

THE RIVERS AS NAVIGABLE WATERWAYS

3.1. WATERWAY CHARACTERISTICS WITH RESPECT TO SHIPS

3.1.1. Slope and water velocity

The slope (i) and water velocity (v) are related according to the formula of DE CHEZY (see III, 4.3.1):

$$v = C\sqrt{Ri}$$

The slope will not vary much over longer stretches as it is dependent on the valley slope. From the formula it follows that water velocities can increase considerably with rising water (R increases), the more so as C tends to increase also with higher water.

A ship has to overcome a difference in height when sailing upstream. When a tow of a 1,000 tons displacement equipped with a 400 h.p. engine and a speed of 9 miles per hour sails at 6 miles an hour against a current of 3 miles an hour in a river with a slope of 15×10^{-5} and the efficiency of the screw is 0.5, only slightly less than 3% of the engine output is used to conquer this difference in height.

The water velocity is of much more importance, which can be understood when a comparison is made between the performance of such a ship in still water and in running water. In still water the ship would cover 9 miles in a round trip of one hour, while in water running at 3 miles an hour the distance covered would be 8 miles in one hour (4 miles upstream and 4 miles downstream). When the same distance has to be covered as in still water, i.e., when the speed of the tow in running water has to be $\frac{9}{8}$ times of the speed of the tow in still water, the engine should have 40% more output (if it is assumed that the engine h.p. is related with the third power of the speed). With a smaller difference between the speed in still water and the water velocities this percentage would be considerably higher.

Slopes over longer distances are given in III, 4.2.5. During low water slopes are between 4 and 7×10^{-5} in the lower reaches of the Niger, increasing to between 10 and 12×10^{-5} in the Baro—Lokoja stretch. During high-water stages these slopes may increase by 2 to 3×10^{-5}. On the Benue during the shipping season slopes vary between 11 and 13×10^{-5} in the lower sections and increase to between 20 and 25×10^{-5} in the upper reaches. Above the Faro Confluence, in the Garua Creek the gradient is between 12 and 14×10^{-5}.

The slope varies widely from point to point along the talweg, especially during low water. Just above crossings in the deeper sections of the river, the slope may be even less than 4×10^{-5}, while over and just below crossings slopes may occur of over 40×10^{-5}.

Water velocities on the Niger during low water vary between 1 and 4 m.p.h., with an average of 2—3 m.p.h. During high water these velocities are between $2\frac{1}{2}$ and 5 m.p.h. with an average of 3—4 m.p.h. in the talweg. The high velocities occur in the deeper stretches of the river.

Velocities have been computed from upward and downward sailings on the Niger and part of the Benue with the same speed in the same vessel over the same stretches. They will, therefore, represent the average water velocities that are of interest to navigation (Table 3.1.1-1).

The relations between the increase in water velocities and the water stages for a few stations are given in Diagram 3.1.1-2. These velocities are the maximum surface velocities observed in

TABLE 3.1.1-1

WATER VELOCITIES IN THE NIGER AND BENUE RIVERS

location	Mile	High Water Sep./Oct.		Middle Water Nov.		Black Flood December		Black Flood March	
		m/sec	m.p.h.	m/sec	m.p.h.	m/sec	m.p.h.	m/sec	m.p.h.
Jebba	556	0.8	1.8	—	—	—	—	—	—
Pategi	483	1.0	2.2	—	—	—	—	—	—
Baro	434	1.3	2.9	—	—	0.7	1.6	—	—
Budon	399	1.6	3.6	—	—	1.45	3.25	—	—
Lokoja	361	2.0	4.5	1.35	3.0	—	—	1.3	2.9
Itobe	332	1.85	4.2	1.1	2.5	—	—	1.0	2.3
Idah	310	1.5	3.3	1.2	2.75	—	—	0.9	2.0
Illushi	272	1.5	3.3	1.1	2.5	—	—	0.9	2.0
Illah	256	1.95	4.4	1.1	2.5	—	—	0.9	2.0
Onitsha	232	1.65	3.7	0.9	2.0	—	—	0.9	2.0
Umunankwo	209	1.2	2.7	0.9	2.0	—	—	—	—
Aboh	177								
Taraba Confl.(1	672	—	—	1.2(2	2.7(2	—	—	—	—
Lokoja Confl.(1	362								

(1 Water velocities showed very slight variations over this river stretch, the velocities between the piers of the Makurdi bridge being the only exception.
(2 Measured in July.

the cross-sections that were used for discharge measurements. These cross-sections were usually narrow and between high banks, so that the current speeds here are larger than the averages of Table 3.1.1-1. The water velocities in the narrow stretch near Numan and between the piers of the Makurdi bridge can be considered as the largest water velocities encountered by ships on the Niger and Benue (Diagram 3.1.1-2).

3.1.2. Width and depth

The width of the navigable stretches does not restrict shipping in general. The passage of crossings and flats may sometimes be difficult but the available width is normally well over 500 feet. Exceptions are the Wuro Boki and Gamadio Flats on the Benue and a few crossings

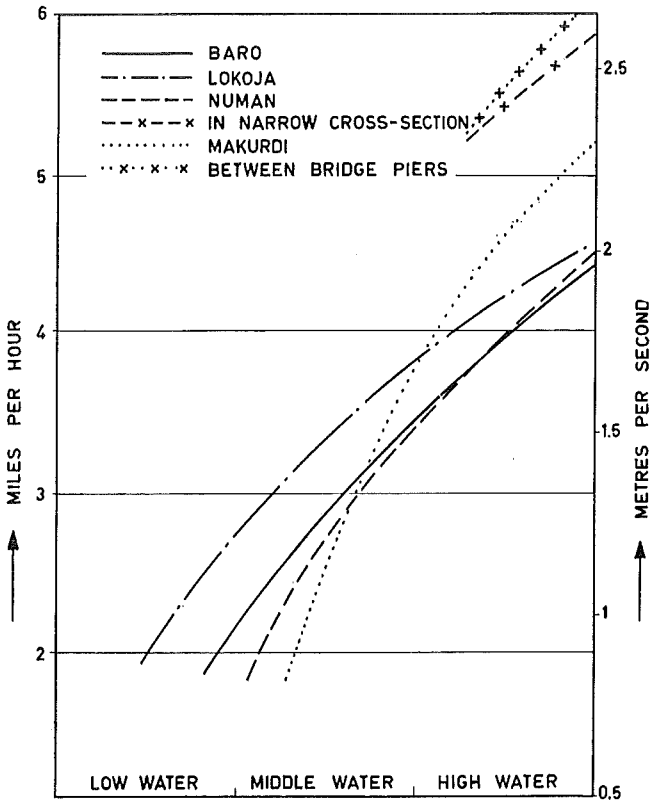


DIAGRAM 3.1.1-2

Water velocities

on the Niger during low-water stages where, under exceptional conditions, the width of the required channel (depending on the draught) can be restricted to 150 feet.

From the viewpoint of resistance to ships, the Niger and Benue and their tributaries can be compared with a channel of infinite width.

The least available depth (L.A.D.), however, is important. It varies during high-water stages between 15′—20′ near Baro and 25′—35′ near Onitsha on the Niger and between 6′—9′ on the Gamadio and Wuro Boki Flats and 20′—30′ on the Lower Benue. During high water it is possible for coasters with 12′—14′ draught to navigate as far as Makurdi without taking undue risks. During middle-water stages shipping on the Niger and Lower Benue is very well possible with 8′—10′ draught but on the flats near Gamadio and Wuro Boki navigation is then restricted to 3′6″—5′. During low-water stages this picture changes considerably. The Benue is not navigable with more than 1′—2½′ draught after November and before June, whilst the Niger remains to a certain extent navigable during the dry season as a result of the Black Flood; 4—5 feet can be expected to be the L.A.D. until the Black Flood recedes and then no more than 2—3 feet will be available above Onitsha during two to three months.

The duration and frequency curves for the water-levels and the depth along the talweg for each river-stage and river-section give the graphical précis of the navigation restrictions by available depth (see Diagram 3.2.2-1).

Too much emphasis is in general laid on the shallowness of the Niger and Benue Rivers. This may be correct insofar as it is a restriction to the draught and a warning of groundings,

but it is incorrect with regard to the drag from the bottom encountered by a ship. From that viewpoint the Niger and Benue are deep rivers.

To illustrate this, a frequency curve of water-levels on a gauge (III, 4.2.3) can be combined with a talweg profile (III, 6.4.1) near that gauge. This is done in Diagram 3.1.2-1 for the Baro gauge and the Baro—Lokoja river-stretch, where the time frequency of the depth/draught ratio encountered by a ship is given. In this it is assumed that the ship continuously sails the stretch with a fixed draught during the time when the least available depth in the stretch is greater than the fixed draught. This time, for ships with $3\frac{1}{2}$, 4, 5 and 6 feet draught respectively, is 300, 280, 145 and 105 days during an average year. The diagram shows clearly that a ship sails most of the time in deep water.

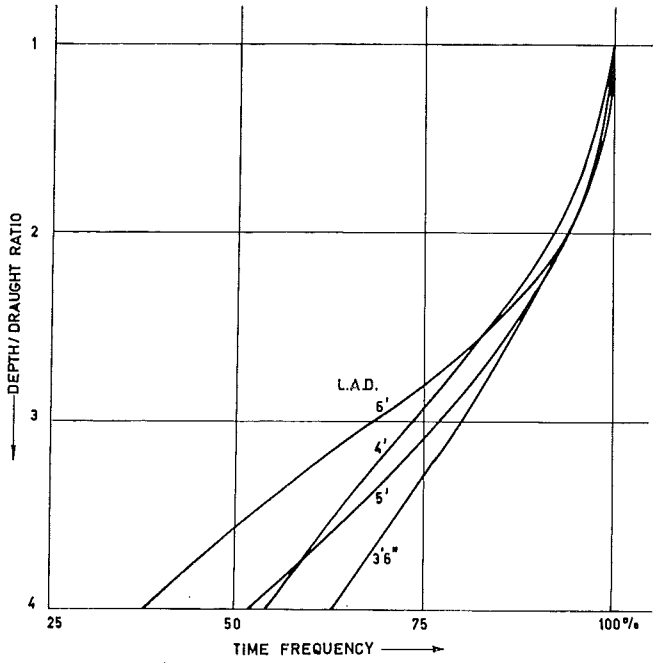


DIAGRAM 3.1.2-1

Depth during the navigable period in the Baro—Lokoja river-section

Diagram 3.1.2-2, which shows the resistance increase in percents over the deep water resistance at varying depth/draught ratio, is based on experiments for river flotillas as carried out in the U.S.A. ([1].

When the data from Diagram 3.1.2-1 are combined with the drag which a ship encounters, it is possible to calculate the depth of a hypothetical prismatic canal which would give a comparable drag as in the Baro—Lokoja stretch. The result of two such calculations showed that with an L.A.D. of $3\frac{1}{2}'$ and 6′ or more during 300 and 105 days respectively in an average year and a river flotilla sailing during these times with $3\frac{1}{2}'$ and 6′ respectively, the resistance met by this flotilla would be of the same order as in a canal of 12′ and 21′ depth respectively and infinite width.

In conclusion it can be said that on the Niger between Baro and Lokoja a ship designed for this stretch encounters an average drag comparable with the drag of a ship in a canal with a depth 3—$3\frac{1}{2}$ times deeper than the draught of the ship.

([1] UNITED NATIONS, 1954, page 47. TRP. 5

Among the navigable stretches of the Niger and the Benue, the Baro—Lokoja stretch has relatively the least variations in discharge, and the other river-stretches will have an even deeper equivalent constant canal depth with respect to the resistance encountered by a ship sailing during the navigable periods.

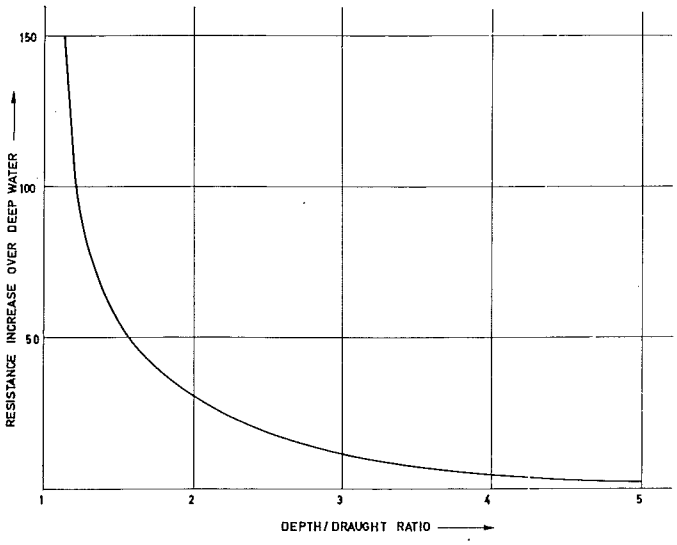


DIAGRAM 3.1.2-2

Drag encountered by a river flottilla in shallow waters

3.1.3. Curvature of the channels

The curvature of the talweg is such that ships with 5—7 feet draught and up to 700′ in length can navigate the Niger and Benue up to Jebba and Gamadio during high-water stages. Reduction of this length over the Gamadio and Wuro Boki Flats and in the Garua Creek can become necessary to prevent unjustified risks. It is possible to sail with even greater length on the Lower Niger, but a few bends in the Delta, notably the bends near Gbekebo (Mile 60) and Siama (Mile 89), are only safe for smaller length. These bends have a radius of only 800′ and a channel width of 250 feet, with hazardous cross-currents. On the Benue a radius of 800—1,000 feet with 200—300 feet channel width must be expected on the Wuro Boki and Gamadio Flats. In the Garua Creek near Kinada (Mile 930) a radius of only 1,000 feet is available and a width of 200—300 feet, while near Mile 962 only 700 feet radius is available with a channel width of 200′. In the Garua Creek groundings are not likely, but damage from a collision with the banks is not uncommon. The flats are most dangerous for groundings because of the small radii and narrow channels, combined with the strong cross-currents.

During low water, when navigation on the Niger with 4 to 5 feet is still possible, the Gbekebo and Siama bends remain restrictive, with a radius of 700 to 800 feet and a width of 250′. Under very rare conditions a channel over flats in the Niger may show such a radius; nearly always, however, the channels have a radius of well over 1,500 feet and the width is normally at least 300 feet.

3.1.4. Causes of groundings

The main causes of running aground can be classified as:

(i) being unacquainted with the situation;
(ii) insufficient available depth;
(iii) lack of manoeuvrability; and
(iv) inattention of bridge personnel.

Ref. (i) is the result of the frequent and fast shifting of the talweg, especially of the channels over the crossing during high water. On the Niger, available depths are large and do not give serious difficulties, and missing the channel does not directly result in a grounding. On the Benue, however, available depths, especially on the flats in the upper stretches of the river, are still restricted during high water, and groundings may occur. It must also be noted that the lower stretches of the river are more frequently passed than the upper stretches, and so it is only logical that river pilots are more acquainted with the lower stretches. To anticipate this, it is the good custom of river pilots to make an orientation trip on the Benue by canoe during low water. Moreover, there are special pilots for the Benue who board the ships at Lokoja, whilst at particularly bad stretches there are local pilots. This has the advantage of more frequent trips and better knowledge of the river stretches.

During low water, when ships ply on Baro, the number of groundings on the Niger due to lack of acquaintance with the situation remains small. Sand movement is not fast and shifting of the channels on the crossings is not very frequent. Running aground on the large sand-banks is impossible, as they show above water. A great advantage is the short distance, so that the time interval between passing the same difficult crossings is short. Pilots exchange information if necessary when passing each other.

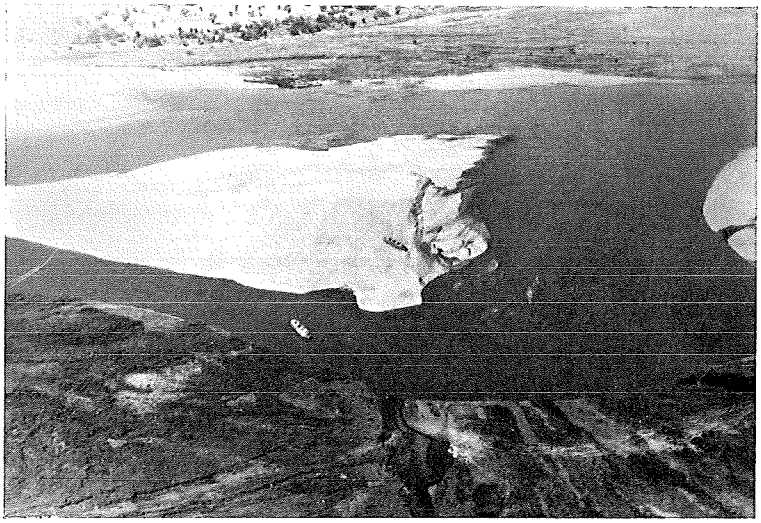
Although groundings as a result of lack of acquaintance with the situation do occur, the knowledge of the pilot is as a rule very wide and his memory and ability to read the water are often amazing. But a system of channel demarcation (VI, 3.3) will be of great help.

Ref. (ii) can only be discussed in relation with the loaded draught of the vessels. It is extremely difficult for river operators to foresee a drop in water-levels and to forecast the time of rising water-levels. River operators can only rely on their experience, but the conditions are from year to year different. As a rule, ships are at the beginning of the Benue season loaded at the Delta Ports to draughts between 4 and 5 feet. When reaching the entrance of the Benue, some time must often be waited before the bar at the Lokoja Confluence can be passed. When sailing into the upper reaches of the Benue time may again be lost at restricting crossings, and a sometimes occuring August fall (see III, 4.1.3) may hamper ships in the upper sections of the river. River operators have to take these risks in order to make full use of the season. At the end of the Benue season, however, they cannot take the risk of having ships locked up in a river section until the next high water 8 or 9 months later. In general, ships leave the Benue too early or are not loaded to full capacity at the end of the season, so that a case as shown in Photograph 3.1.4-1 is rare.

During low-water stages, when ships ply on the Niger and especially on the port of Baro, sudden drops in water-level do not occur. However, available depths are only 4 to 5 feet, and only small drops in water-level or a slight shoaling may result in groundings, as ships will be loaded practically to the available depth. Experience has taught that when the Baro gauge drops below 8 or 9 feet, the end of the Black Flood has come, and ships must withdraw below Onitsha. Navigation on the Niger and Benue under these circumstances is risky and is often something of a gamble. A system of water-level prediction can greatly reduce these risks.

Ref. (iii) speaks for itself. When the channel is sufficiently deep, but is sinuous and restricted in width, and when cross-currents make the situation even more difficult, a high manoeuvrability of ships is of prime importance.

In this connection it should be realised that greater power and speed increase manoeuvrability as they increase the rudder action. The rudder arrangement as well as the whole design of the ship should always aim at the highest degree of manoeuvrability.



PHOTOGRAPH 3.1.4-1

Barges of a rivertow in the Upper Benue caught by the rapid drop in water-levels

Ref. (iv) is a human factor, which can only be reduced by raising responsibility among the crew members and rewarding good performances. The training and the working conditions of pilots and captains could also be improved.

3.2. THE NIGER AND BENUE

3.2.1. Navigable stretches on the Niger and Benue River System within Nigeria and a description of the bottle-necks

The navigable stretch of the Niger within Nigeria, as already mentioned in III, 1.2.4, is situated downstream from Jebba and covers about 550 miles. Above Jebba navigation with the usually powered ships is hardly possible because of the rapids. At H.W.-stages, however, light stern-wheelers have managed to pass these rapids down the river. Transport with large native canoes takes place in both directions over the rapids, although now and then some capsize.

On the Benue, Garua, 972 miles from Escravos Lighthouse and 610 miles from the confluence with the Niger, is the last potential port on the river, but there have been commercial ships as far as Rei Bouba (Mile 1,046).

On the tributaries of the Niger, navigation is only possible during the rainy season, sometimes for a distance of 50 miles from their confluences with the Niger, i.e., the Kaduna, Gbako, Gurara

and Anambra Rivers. Navigation may be tricky by sudden unpredictable drops in the water-level, rapidly changing sand-banks and sharp bends. Only the Anambra River is regularly used by river craft to evacuate some produce from Aguleri, 15 miles from Onitsha.

The tributaries of the Benue in French Cameroun are unimportant as shipping routes, being swift-running, shallow rivers with sudden peaks and falls in water-levels.

The main tributaries of the Benue in Nigeria are the Gongola on the north side and the Taraba, Donga and Katsina Ala on the south side.

The Gongola, flowing into the Benue at Numan (Mile 846), has been sailed by powered vessels as far as Nafada, about 150 miles upstream from the confluence with the Benue. Nowadays most of the produce is evacuated by other means to the railways and to the main ports on the Benue. A fleet of poling-barges is still in operation on the lower reaches of the Gongola, evacuating produce from riverain areas to Numan.

At Mile 672 the Taraba flows into the Benue. Commercial ships call at Gassol, 20 miles from the confluence. For shallow draught vessels the river is navigable upto the border of the Cameroon Trusteeship, 70 miles above Gassol.

The confluence of the Donga River is at Mile 636, and river steamers sail the river to Donga Town, 50 miles from the confluence. The navigability ends 20 miles above Donga Town at the Zambana rapids.

The Katsina Ala, main tributary of the Benue, has its confluence at Mile 536, which is 26 miles above Makurdi. Stern-wheelers evacuate produce from Katsina Ala Town, the last large village on the river, 70 miles from the confluence. Fifteen miles above Katsina Ala Town the navigability ends in rapids.

On the Niger, navigability at the H.W. and M.W.-stages is quite good and enables ships with a draught of 12—15 feet to reach Baro and sometimes even Jebba. Therefore the regular river-fleet with its normal maximum draught of 7 feet can sail the Niger unrestrictedly up to Jebba during the H.W.-period and some coasters and other small ocean-going vessels are then to be seen on the river down from Baro.

Around Low River Level (L.R.L.) coinciding with the so-called Black Flood, the navigability on the Niger is restricted to river craft with a draught of between 6 and 4 feet.

During the L.W.-season the water-level may fall so low that navigation between Baro and Onitsha is limited to craft drawing less than 3 feet. Downstream of Onitsha the conditions provide better possibilities of navigating the lower part of the Niger even during the L.W.-period (Diagram 3.2.2-1).

For the commercial fleets navigation on the Benue is impossible in the dry season, good in the wet season, and difficult at the beginning and at the end of the wet season. Lack of water is the main source of shipping troubles. Rock outcrops, at some places peering through the alluvial river-bed, do not really have an unfavourable effect on the navigability.

During the shipping season the barges are usually loaded with an average draught of about 5 feet, but coasters, loaded to about 10 feet, operate on Makurdi. A limit to the operation of sea-going vessels is put not only by the shallowness of the river above Makurdi, but also by the railway bridge with a clearance of 40 feet at high water.

The defects of the navigability in general are dealt with at length in Part V; in this paragraph only an enumeration of the most difficult spots on the river will be given with a short description of the defects and their importance.

On the Niger the difficulties for the present navigation start when the water-level of the river falls below the 13 feet mark on the Baro gauge, 11 to 12 feet on the Lokoja gauge and 14 feet on the Onitsha gauge, levels which are just a little above the L.R.L.-stage of the river.

As can be seen from III, 4.2.3 these river-levels are consecutively reached during the fall, first at Baro and finally at Onitsha. The explanation is that while the discharge of the Niger above Lokoja is already inadequate to ensure a sufficient depth for unrestricted navigation, the Niger below Lokoja still receives some discharge from the Benue. Only when the flow of the Benue drops below 1,000 m^3/sec (35,000 cusecs) does the Niger below Lokoja, with a much larger river-bed than up the river, become the bottle-neck for the shipping between Baro and the Delta ports.

This period of the fall and of the following Black Flood is of major importance in connection with the navigation of the regular river fleet as discussed in detail in 5.1.1. Therefore the main attention will be given to the problems just before and during the Black Flood period when water-levels around L.R.L. occur which may last for a period of upto 5 months.

During the rise the sequence is reversed, as the rains in the south start earlier than in the northern parts of the drainage basin (III, 4.1.3), and it may take a month or more before the Niger upstream from Lokoja has the same navigability as the Niger downstream from it (see Diagram 3.2.2-1).

On the Baro—Lokoja stretch the first difficulties at the start of the Black Flood period will be the large sand ripples left by the preceding H.W., blocking the L.W.-channel. These barriers will most often be reduced by erosion in a short time (for instance, Esigi, Mile 411, Dec. 1957). When they are removed, however, some other badly navigable places will remain where circumstances to create a bar are favourable. As these circumstances (see Chapter V, 2) are not likely to change in one or two years, places of ill-repute are the results, such as Dere (Mile 396), Nwali-Awarra (Miles 387—385) and Adama (Mile 373), of which at least one is likely to be the dominant sill.

Downstream from Lokoja, however, trouble starts in the second part of the Black Flood period. The flats between Lokoja and Shintaku (Mile 357) caused by a too wide river-bed and sand deposits from the Benue, and the Icheu-Adinapa Flats (Miles 352—354) caused by backwater and draw-down from the Rocky Section, are an annually recurrent headache to shipping. Downstream from the Rocky Section the river is too wide, and spoiled by sand deposits from the narrow Rocky Section; the results are the notorious flats at Ajeokuta (Mile 335), Itobe (Mile 333), Kokoin (Mile 324) and Agbama (Mile 320), of which at least one is top-ranking among the most troublesome spots every year on the Niger.

At the end of the Black Flood period, the Niger between Idah and Aboh may give trouble as well, mainly by bars formed right downstream or sideways from an island, for instance, Abujaga (Mile 282), Anwam (Mile 241), Odekpe-Atani (Mile 217), Umunankwo-Osemeri (Miles 206—210), Ndoni (Mile 182) and Samabri (Mile 157), as already explained in III, 6.2.2 and III, 6.6.4. Downstream of Aboh in the meandering section the depth of water is seldom a bottle-neck to navigation unless the L.W.-channel does not coincide with the H.W. one as, for instance, is the case at Epidiama (Mile 148) and Patani (Mile 132). The remaining bad spots are of a more or less temporary character and are mainly initiated by sand-banks dwelling in an odd location.

Of the above-mentioned places of ill-repute only a very few determine the available depth for shipping on the Niger at a certain moment. Moreover, the available depth does not depend on the depth on the bar only but also on the crookedness of the channel on the spot and the length of the shallowness. In the case of a short sill blocking the fairly straight L.W.-channel, it is possible to push ships across this spot with hardly any clearance at all. In a flat or a crooked narrow channel, however, ships will need some clearance to prevent running seriously aground while manoeuvring.

However, the troubles in navigating the Niger are not necessarily confined to the above-

mentioned places, as can be seen from the many groundings all over the river during the course of the years.

On the Benue, as already stated, the difficulties are mostly met at the beginning and at the end of the wet season.

Sailing upstream, the first bottle-neck on the Benue is the Bar at the confluence with the Niger (Mile 362). The effect of this bar is a delay of about one or two weeks, as is explained in Section V, 3.1. Once this bar is passed, river steamers sail without difficulties up to Makurdi (Mile 510) and the Katsina Ala Confluence (Mile 536). Only in years with an exceptionally early rise of the Niger by which the Benue Bar is drowned, ships might have difficulties above Umaisha (Mile 404), above Bagana (Miles 435—445) or at Akpanaja (Miles 500—506).

Between Miles 536 and 673 the Benue is fed by its tributaries Katsina Ala, Donga and Taraba. The Benue above the Taraba Confluence provides only 40% of the annual run-off of the Benue downstream of the Katsina Ala Confluence. Furthermore, the rainy season starts earlier in the drainage areas of the three tributaries than in the drainage area of the Benue above the Taraba Confluence. It happens, therefore, that ships sailing without difficulties from Lokoja to Makurdi get into trouble above the Katsina Ala Confluence. A slight mistake of the pilot, a misjudging of cross-currents at sharp bends or on crossings, then often results in grounding. Frequently the ships just cannot pass because of insufficient navigable depth, so that waiting for a rise of the river is the only answer.

Although the character of the shallow places between the Katsina Ala Confluence (Mile 536) and Lau (Mile 777) varies from year to year and from place to place, some names are worth mentioning. There are the Gunga Bakari Flats (Miles 604—610) downstream of Ibi, Dampar (Miles 651—656) between the Donga and the Taraba Confluences, some crossings in the neighbourhood of Kwatta Nanido and Kwatta Mutum Biu (in 1956 Mile 717), the Mayo Fan Confluence (Mile 732) and Mile 764 at Gidan Usumanu Creek.

Above Lau (Mile 777) the notorious Gamadio Flats (Miles 815—822) and Wuro Boki Flats (Miles 920—923) are often seriously delaying river tows. The Gamadio Flats and adjacent bad crossings are dealt with in detail in III, 6.5.3. The talweg sounding in Diagram III, 6.4.1-3 also illustrates the shallowness of the Gamadio crossings (Mile 818).

Between Numan (Mile 846) and Yola (Mile 888) at places around Mile 856 and at Geren (Mile 868), ships will sometimes have to wait, but mostly it can be said that passing the Gamadio Flats means arrival at Yola a few days later. Only during the beginning of the shipping season of 1958 were many ships in this area caught by an unexpected drop of the water-level.

The Wuro Boki Flats, situated between Yola and the Faro Confluence, have been studied by the French engineers of Electricité de France (see also III, 6.5.3).

The Benue above the Faro Confluence is a rather narrow meandering creek, 500—800 feet wide, carrying enough water to allow ships to proceed to Garua (Mile 972) once they passed the Wuro Boki Flats. This part of the Benue, often called the Garua Creek, is the only river-stretch where H.W.-meandering might necessitate tows to negotiate bends with "backing and flanking".

Snags, i.e., uprooted trees in the channels, do not normally create a hindrance to shipping on the Niger and Benue. Only a single area between the Taraba and Donga River Confluences, especially around Mile 661, is notorious for the presence of such snags in the navigation channel.

3.2.2. Theoretical navigable periods for various draughts

With the relations between least available depth and the stage or discharge it is possible to calculate from the frequency of the discharges the theoretical navigable periods for each river-stretch. These relations have been produced in III, 6.4.3.

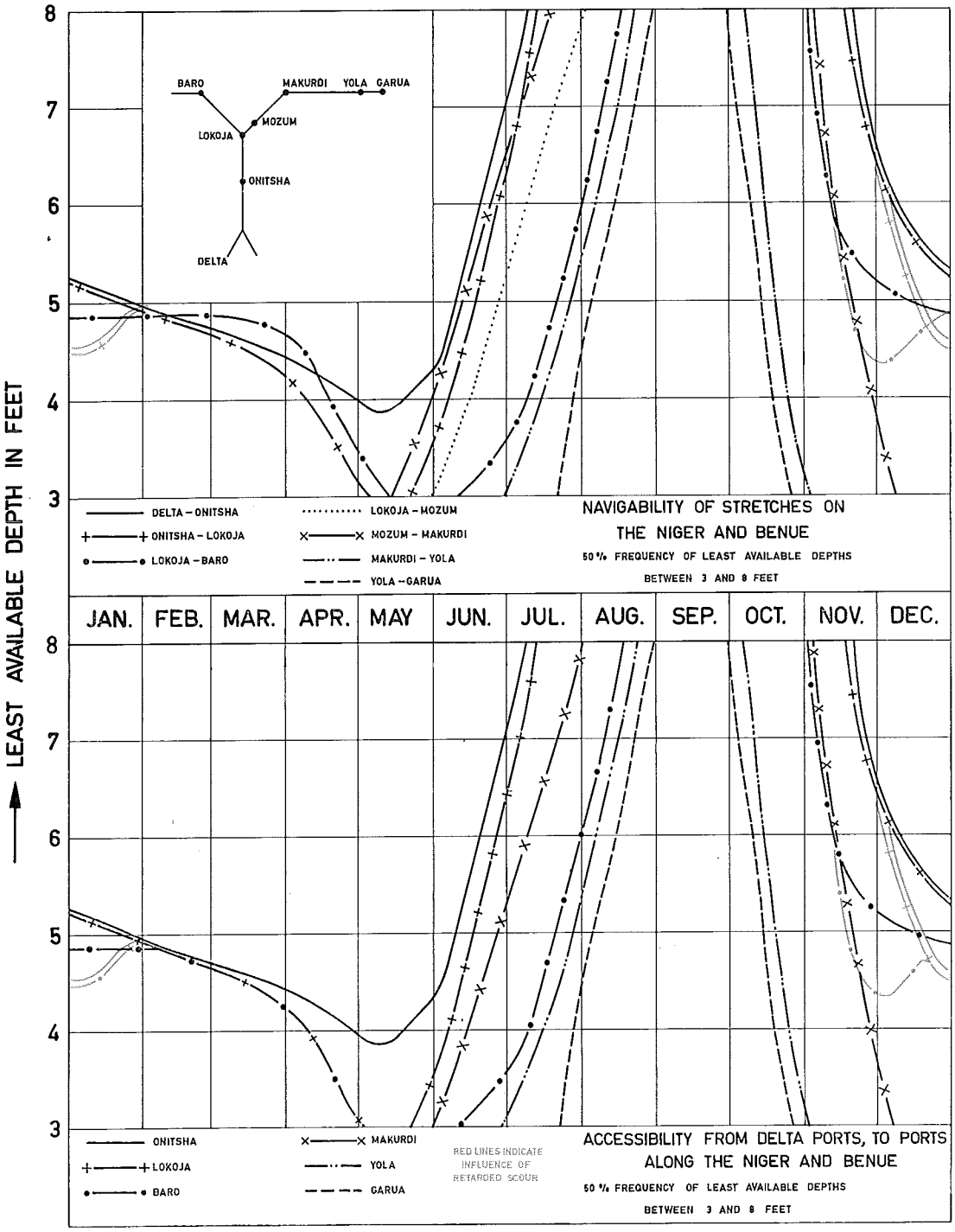


DIAGRAM 3.2.2-1

Navigability of the Niger and Benue

The discharge at a certain date has been translated into a least available depth on the river-section for which this discharge is representative. When using the 50% frequencies of the discharges (see III, 4.3.4) a reliable average is obtained. Diagram 3.2.2-1 shows the theoretical navigable periods thus calculated.

The upper half of the diagram gives the periods in which each river-section is navigable for a certain draught and the lower half of the diagram indicates the theoretical period in which river-ports along the Niger and Benue can be reached from the Delta ports. The scour during low water has been taken into account in calculating the available depth during rising water.

A clear and uniform relation between the Niger discharges during the fall and the extent of the retarded scour could not be established. From the observations during the investigation, as described in III, 6.4.2, an approximation of the retarded scour has been derived which is given in red lines in Diagram 3.2.2-1.

3.2.3. Operational periods 1956—1957

In the preceding paragraph was discussed how from all available gauge-readings over the past decades, from the relation between water-levels and discharges, and from the relation between available depths and discharges the theoretical navigable periods have been deduced. In the same way it is possible to obtain afterwards the navigable period and the available depth during each separate year.

For a comparison between the navigable periods and the actual navigation Diagram 3.2.3-1 has been made. It gives the periods during which ports could be reached from the Delta ports with draughts as indicated, while the movements of the first ship and last ship sailing in each river-stretch have also been plotted.

The following general remarks can be made:

(i) In the high-water period between July and October navigation concentrates on the Benue. Practically the total fleet capacity is sailing to and from the Benue to evacuate the produce of the preceding year from the Benue ports and to supply these ports with general merchandise and petroleum products.

(ii) The Baro—Lokoja stretch is practically not navigated during high water as new produce is not yet available and very little merchandise moves to the port of Baro. The Baro season does not start, in fact, before the end of November when the new crops become available. Only a few ships arrive in Baro earlier, often loaded with empty bags for the groundnut crop.

(iii) The indication of the first ship and last ship sailing on a river-stretch gives no impression of the intensity of the traffic on each stretch. In general these first and last ships are of small size or only partly loaded. Therefore, also the first and last sailings of middle-large tows on a river-stretch are indicated.

From Section A of Diagram 3.2.3-1 it follows that the 1956 shipping season has been used nearly to full extent, while Section B shows that in 1957 the advantage of the long Benue season could be drawn on only partially. This was not due to too careful planning or any fear of the river operators but was caused by a lack of available cargo, as the consignors were too careful as a result of experiences in the 1956 season, when not all the cargo could be shipped as had been planned. The shipping companies fulfilled their contracts in 1957 long before the Benue season ended. For both the river operators and the consignors, this 1957 Benue season must have been very unsatisfactory.

To anticipate at least a part of the risks which lie in the Benue navigation, shipping companies have in 1958 gone so far as to guarantee the shipment of contracted cargo, thus taking new risks, but at least partly avoiding that a Benue season is so poorly utilised as in 1957. In the bad

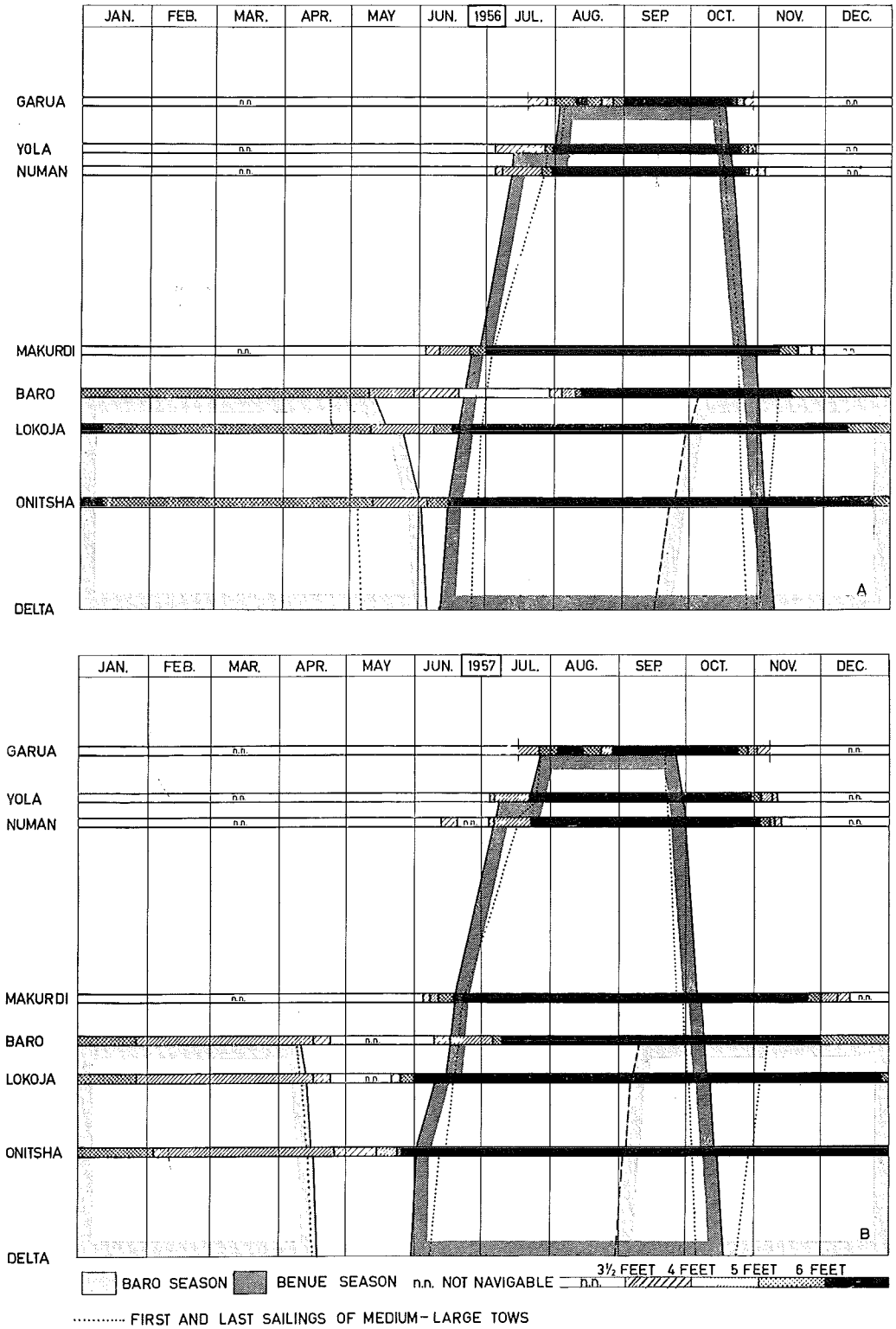


DIAGRAM 3.2.3-1

Baro and Benue shipping seasons in 1956 and 1957

Benue season of 1958, when this guarantee was first operated, the contracts have been fulfilled due to the great efforts by the shipping companies and the successful modifications of their fleets (see Section 4.1.).

Owing to the regularity of the water-levels during the Black Flood and the experience that the Baro season ends when water-levels drop below 9 feet on the Baro gauge, it has always been easier for the river operators to use the Baro season to full extent. Since in 1957 NEDECO was able to predict for the first time several months beforehand at what date the water-level on the Niger would drop below 9 feet on the Baro gauge (VI, 3.6.2), it has become possible for operators to plan, with the estimates of the crops, the evacuation of large quantities of produce from the north of Nigeria.

3.3. THE NIGER PROJECTS OUTSIDE NIGERIA

3.3.1. Description of the various projects

a. *A dam in the Niandan*

A mission of the Electricité de France (E.D.F.) investigated the possibilities of building one or more dams in the upper part of the Niger or in one of the tributaries, with the purpose of (see III, 1.2.4):
(i) the improvement of the shipping possibilities between Koulikoro and Ségou; and
(ii) supplying the "Office du Niger" with sufficient water for a complete irrigation during the dry season.

After a rough investigation two suitable places were found: one in the Tinkisso and one in the Niandan. The last appeared the best and for this E.D.F. has made a draft scheme.

The regime of the Niandan shows an average annual discharge of 7×10^9 m^3 (250×10^9 cuft). The annual discharge during a dry year is 5.3×10^9 m^3 (190×10^9 cuft), whilst in a wet year 9.2×10^9 m^3 (330×10^9 cuft) can be expected.

The maximum contents of the reservoir is 5.2×10^9 m^3 (185×10^9 cuft) of which, after deduction of the evaporation losses, somewhat less than 5×10^9 m^3 (175×10^9 cuft) is available to be discharged in the dry season.

The programme of supply is planned to be as follows: Between June 20 and December 20 the water is stored in the lake, while during the month of September about 10^9 m^3 (35×10^9 cuft) must be discharged for agricultural purposes along the Niger (traditional irrigation). Under this programme of supply with the evaporation losses taken into account, the lake could be filled to capacity in an average year, whilst also the limit discharge — being sufficient for shipping purposes — could be maintained between January 1 and the end of June, as based on those monthly discharges at Koulikoro which are surpassed in three out of four years as an average.

The cost of this work, according to a 1957 estimate, would be 6 milliard francs CFA (£ 12,500,000) and in the opinion of representatives of the Department of Travaux Publics, this dam will certainly be built within the coming 10 or 20 years.

b. *Dams in the Niger between Bamako and Koulikoro*

To make shipping possible over the 40-mile stretch between Bamako and Koulikoro, plans for the construction of small dams and lateral canals with locks have been made in order to overcome the fall of 100 feet over this stretch, which is concentrated in the rapids of Sotuba and those of Kenie.

As the amount of river transport does not yet seem to justify the necessary expenditure, this project will only be considered in a later stage of development of the river.

c. *The irrigation of the Office du Niger*

As already described in detail in III, 1.2.4b, these irrigation works will ultimately cover an extensive area downstream from the weir at Sansanding. For this project of 300,000 ha (750,000 acres), dependent on the cultivation schemes, between 6.6×10^9 and 13.4×10^9 m^3 (230×10^9 and 470×10^9 cuft) of irrigation water will be needed annually. The intensified cultivation schemes using such large amounts of water will only be possible when the dam in the Niandan, as mentioned under (a) of this paragraph, has been built.

d. *The diking of the area on the left bank of the Niger near Mopti*

This concerns the expansion of the area that can be irrigated by means of the dam of Sansanding. A dike would have to be built from Ké-Macina upto 50 km (30 miles) downstream of Mopti along the left of the Niger, but as access to the Marigot de Diaka would remain open, this creek will therefore also have to be diked. Through these works between 800,000 and 1,200,000 ha (2 and 3 million acres) of the flood-plain of the Niger will be diked in, from which about 700,000 ha (1,750,000 acres) of arable land can be irrigated (see Diagram III, 1.2.4-7).

The possibility that this work will be executed is for the time being not very great, as the Office du Niger has sufficient work on hand with the works of Sansanding.

e. *The "amenagement des lacs"*

At present farming in the Central Delta Area, which for the major part is covered by lakes and swamps, is rather hazardous because of the uncontrolled floods. Therefore this area has recently been investigated to see whether it was practicable to regulate the water-levels of these lakes in order to increase the possibilities for the cultivation of essential food-crops in the region. This has resulted in a plan known as the "amenagement des lacs", which has been described in detail under III, 1.2.4b.

As the profits of this plan are said to be much larger than the costs, it seems probable that the scheme will be executed in the near future.

f. *Hydro-electric power station in the "W" between Niamey and Malanville*

The plans for this are still very vague, but the situation in the "W" seems to be asking for a hydro-electric power station and therefore its possibilities are being investigated. The preliminary plans are described in detail in III, 1.2.4c.

3.3.2. Influence of the projects outside Nigeria on the Niger within Nigeria

When the entire complex of the projects on the Niger is considered, the following plans can be distinguished:

(i) The irrigation works at Sansanding, when 300,000 ha (750,000 acres) become available and are irrigated according to the first irrigation plan, or irrigated with one of the more extensive irrigation plans, for which the building of a dam in the Niandan is necessary.

(ii) Expansion of the irrigation works of Sansanding to the maximum size of 900,000 ha (2,250,000 acres), resulting in the dam in the Niandan being already necessary for the first irrigation plan.

(iii) The irrigation works on the left bank near Mopti covering 700,000 ha (1,750,000 acres) in addition to the irrigation works of Sansanding.

(iv) The amenagement des lacs in combination with (i), (ii) or (iii).

For irrigation according to the first irrigation plan the following quantities of water will be needed annually:

(i) 7.8×10^9 m^3 (275×10^9 cuft)
(ii) 23.4×10^9 m^3 (825×10^9 cuft)
(iii) 24.1×10^9 m^3 (850×10^9 cuft)
(iv) 39.6×10^9 m^3 ($1{,}400 \times 10^9$ cuft)

When the more extensive irrigation plans are applied, these quantities will at maximum be doubled.

The minimum annual discharge of the Niger, however, amounting at Koulikoro to about 25×10^9 m^3 (900×10^9 cuft.) puts a limit to the cumulation of all schemes, even if half of the annual discharge of the Bani could be utilised for irrigation of the area near Mopti. Investigations are in progress as to what are the maximum quantities of water which can be withdrawn from the Niger and the Bani for irrigation purposes, considering the minimum annual discharges of both rivers.

Rough calculations show that as a result of the complete irrigation of 750,000 acres at Sansanding according to the maximal culture plan, the water-levels at Baro become between 1 and 6 inches lower. The trebling of the irrigation area at Sansanding only doubles the fall of this water-level, namely, to between 2 inches and 1 foot. In both cases the largest fall occurs at the smallest annual discharge of the Niger.

A complete extension of Sansanding and Mopti cannot be sufficiently irrigated in the dry years, but eventually in the wet years, the lowering on the water-level at Baro will not be more than 1 foot.

To all this, for the "amenagement des lacs" a 2-inch rise should be added in a wet year and a 2-inch lowering during dry years if there is a dam at Timbuctu. If a dam at Tosay is chosen instead of one at Timbuctu, an extra lowering of 5 inches may occur in Baro during dry years.

Next to the aspect of the rise or the lowering of the water-level at Baro, there is the time which is necessarily needed by the H.W.-crest of the Niger at Koulikoro to reach Baro. At present this time-lag amounts to 5 months and will alter little or nothing as a result of the works at Sansanding. But the irrigation works at Mopti will decrease the flooding area of Niger strongly by which the H.W.-wave will pass this swamp more rapidly. As a result, it is anticipated that the H.W.-crest of the French Niger will arrive in Nigeria about half a month earlier, which means that besides the above-mentioned water-level changes, there will also be an advanced fall of the river. Both effects will affect the navigability in an unfavourable way.

3.3.3. Conclusion

With the information the French authorities have made available, it has been possible to get an insight into all plans of all works in and along the Niger in French West Africa.

Although already by REFFAY ([1] consideration has been given to the influence of some of these works on the water-level of the Niger at Baro, very precise calculations will have to be made to come to a definite conclusion about it. The French hoped to have a new report concerning this ready in 1958.

It appears from rough calculations that the present works of Sansanding will have a negligible influence on the water-level at Baro. Only on the entire completion of the 750,000 acres (which even with doubling of the present speed would probably last some 35 years) and the construction of the dam in the Niandan (in order to give a higher output to the irrigation project) can any noticeable influence on the discharge of the Black Flood in Nigeria be spoken of.

The works at Mopti, which will probably only be executed after those of Sansanding, will have an adverse effect on the shipping possibilities on the Niger in Nigeria.

([1] REFFAY, 1948. HYD. 9

CHAPTER 4

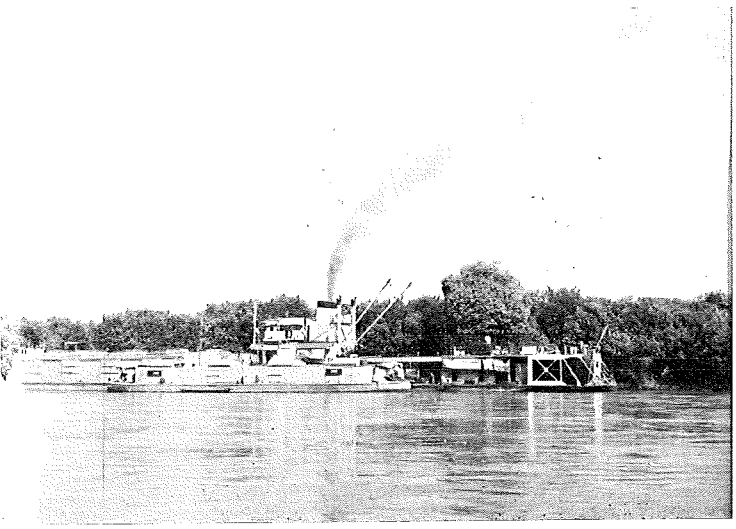
SHIPS

4.1. COMMERCIAL FLEETS

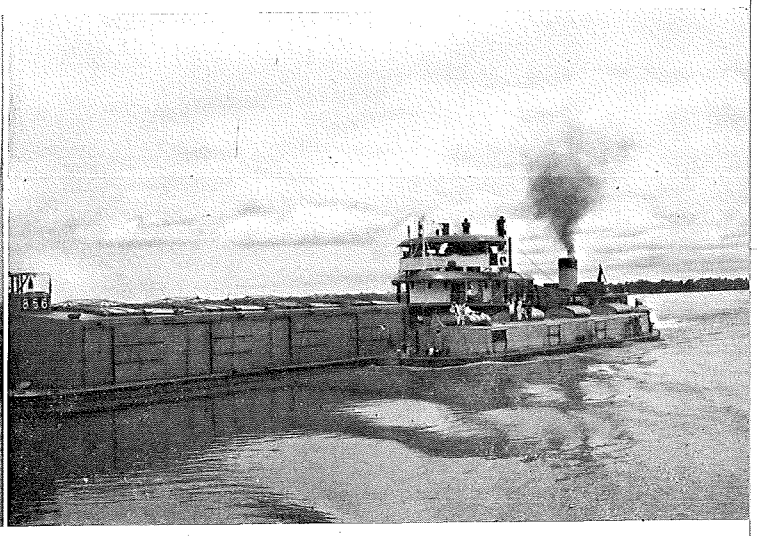
4.1.1. Niger River Transport (N.R.T.)

The Niger River Transport is a self-supporting transport department of the United Africa Company in Nigeria, with its Headquarters at Burutu. Its river-fleet consists of 27 towboats or power units and 92 barges, totalling 119 craft, varying in capacity from 30 tons to 500 tons, with a total carrying capacity of about 22,000 tons.

The power of the towboats varies with the size, the range being from 70 h.p. for the smallest to 1,100 h.p. for the largest. Most of these are steam propelled and the majority still burn coal from the Enugu coal-fields in Eastern Nigeria, for instance, the "Chadda"-type vessels (Photograph 4.1.1-1). But three of these and the "Bauchi" have already been converted into oil burners.

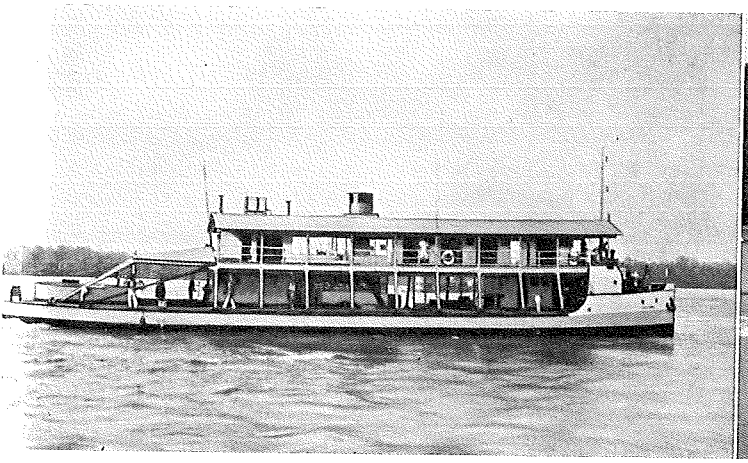


PHOTOGRAPH 4.1.1-1
"Chadda" N.R.T.

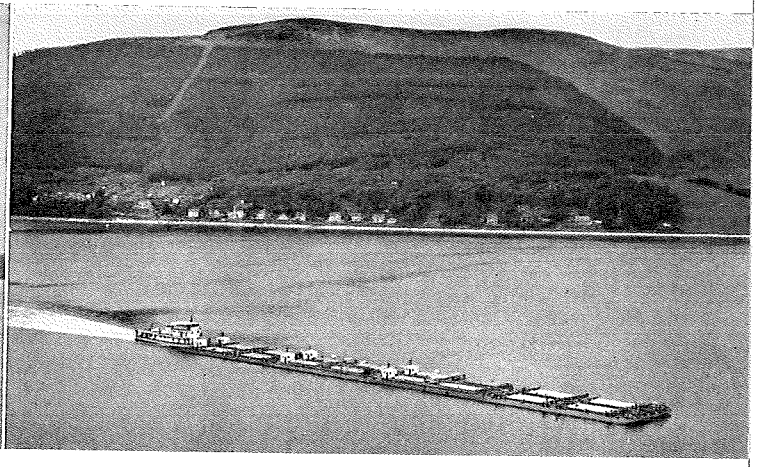


PHOTOGRAPH 4.1.1-2
"Lander" N.R.T.

In 1948 only three of the power units were diesel-propelled, namely, two Quarter-wheelers (the "Lander"-type, Photograph 4.1.1-2), and one Voith Schneider propelled (the "Katsena", Photograph 4.1.1-3). At present there are 9 diesel-propelled units including the recent additions, the "Gongola" and the "Yola" (Photograph 4.1.1-4).



PHOTOGRAPH 4.1.1-3
"Katsena" N.R.T.



PHOTOGRAPH 4.1.1-4
"Gongola" N.R.T.

TABLE 4.1.1-5
POWER BOATS N.R.T., BURUTU

Number	Type	Propulsion	h.p.	Length	Breadth	Depth	Draught	Names
POST-WAR								
2	Pusher tugs	(diesel)	1,100	104′9″	23′0″	7′0″	4′3″	Gongola, Yola
2	Quarter-wheel	(diesel)	400	138′0″	34′0″	6′0″	4′9″	Lander, Leclerc
1	,, ,,	(steam)	830	200′0″	43′0″	8′0″	5′6½″	Trenchard
5	,, ,,	(steam)	415	150′0″	34′0″	6′0″	4′8″	Aberdare, Chadda, Okorodudu, Pinnock, Quorra
1	,, ,,	(diesel)	120	90′0″	19′0″	5′0″	4′0″	Orashi
1	,, ,,	(diesel)	90	68′8″	17′4″	5′6″	2′9″	Thomas Welsh
2	Voith Schneider	(diesel)	90	70′0″	17′4″	5′0″	2′9″	Sultan, Tugwell
PRE-WAR								
1	Voith Schneider	(diesel)	250	130′0″	24′0″	6′6″	3′9″	Katsena
1	Quarter-wheel	(steam)	500	217′0″	38′0″	8′3″	7′0″	Watts (2
1	,, ,,	(steam)	500	200′0″	38′0″	8′3″	7′0″	Kirk (1
1	,, ,,	(steam)	800	172′5″	35′2″	8′0″	5′8″	Col. Ratsey (2
3	,, ,,	(steam)	400	152′0″	26′0″	7′0″	6′0″	Goldie (2, Lenthall Wallace (2
1	,, ,,	(steam)	400	150′0″	26′0″	7′0″	5′8″	Naraguta (2
1	,, ,,	(steam)	450	141′6″	26′0″	6′6″	5′0″	Ribago (2
1	,, ,,	(steam)	350	132′0″	24′0″	6′6″	4′6″	Boussa (1
1	,, ,,	(steam)	90	85′0″	18′0″	5′6″	4′3″	Atta (2
1	,, ,,	(steam)	70	55′0″	18′0″	4′0″	3′0″	Suma (1
1	,, ,,	(steam)	550	196′0″	37′0″	7′6″	7′0″	Bauchi
		9 diesel 18 steam						

(1 Scrapped after Benue season 1958.
(2 Laid up after Benue season 1958.

From U.A.C. Coast Transport Dept. 8/7/'58.

Details of the motive craft and barges of the N.R.T. are given in Table 4.1.1-5 and 4.1.1-6 below (1.

TABLE 4.1.1-6

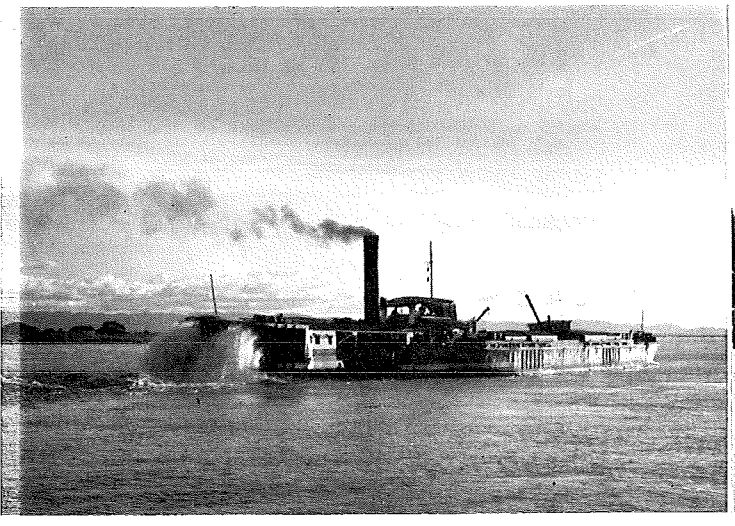
BARGE FLEET, N.R.T., BURUTU

Number of barges	Draught	Capacity	
		per barge	total
8	5′0″	(integrated)	3,500
6	6′0″	400	2,400
34	6′0″	350	11,900
2	6′6″	300	600
4	5′6″	250	1,000
4	—	200	800
3	—	150	450
4	—	100	400
16	various	50	800
11	2′0″	30	330
92			22,180

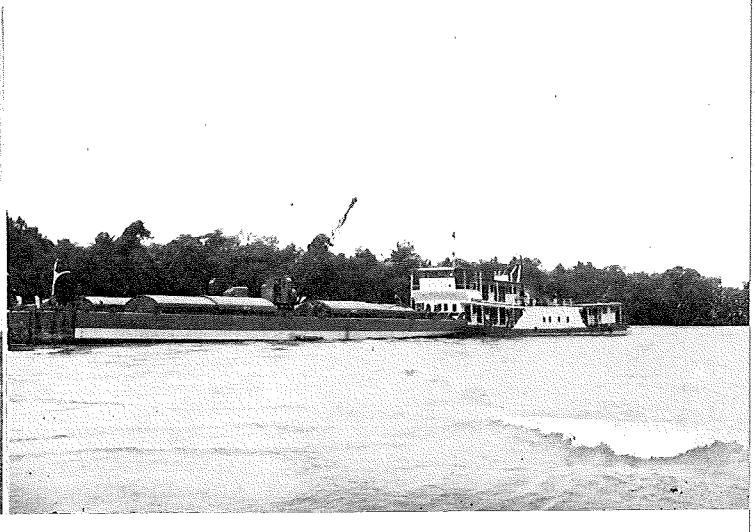
The dimensions of the formation of the "Trenchard" with 6, 4 or 2 barges are respectively 605′, 470′, and 335′ × 59′. The modern "Gongola" and "Yola" with 8, 4 or 2 integrated barges are 630′, 369′ and 239′ × 66′ respectively. Other units, such as the "Ratsey" and the medium steam and medium diesel units, are 130′ × 26′, barges included.

4.1.2. Holt's Transport (H.T.)

Holt's Transport is a river transport department of John Holt and Company Ltd. in Nigeria, with its headquarters at Warri. Its river-fleet consists of 12 power units and 51 barges, altogether 63 craft, varying in capacity from 10 tons to 250 tons with a total carrying capacity of about 5,500 tons; excluding a number of barges originally owned by Elder Dempster, some

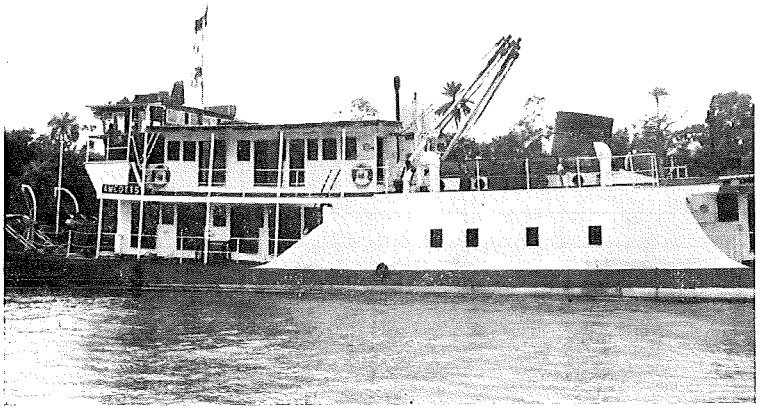


PHOTOGRAPH 4.1.2-1
"Scawby" H.T.



PHOTOGRAPH 4.1.2-2
"Amcotts" H.T.

(1 by kind permission of N.R.T.



PHOTOGRAPH 4.1.2-3
"Amcotts" Tug H.T.

of which are fitted with diesel winches and derricks. These barges are mainly employed in the carriage of palm-oil in drums from Idah to the bulk oil plant.

Most of the power units, such as the "by"-class tugs, are still steam-propelled and burn coal (Photograph 4.1.2-1). One of these stern-wheelers, however, has been converted to diesel propulsion and, subject to the prototype being successful, the Management intends to proceed with the conversion of the complete fleet.

In 1956 Holt's Transport put a new craft into operation, the "Amcotts" (Photograph 4.1.2-2), consisting of a 425 h.p. tug (Photograph 4.1.2-3) 122′ × 23′9″ × 6′4″ with a draught of 3′6″ and four integrated barges each 130′ × 24′ × 6′0″ with a draught of 4′6″".

Before this "Amcotts" was put into service, during the high-water periods of 1955 and 1956, two coasters each on time-charter for one year made several trips to Makurdi and Lokoja.

Details of the motive craft and barges of the Holt's Transport fleet are given below (1.

Motive Craft	*Barges*
Stern-Wheelers	1 barge of 10 tons
1 Scawby	8 barges of 15 tons
2 Appleby	1 barge of 20 tons
3 Laceby	5 barges of 60 tons
4 Roxby	6 barges of 75 tons
5 Normanby	4 barges of 80 tons
6 Spilsby	3 barges of 120 tons
7 Ashby	19 barges of 150 tons
8 Bigby	4 barges of 250 tons
9 Broughton	
10 Luddington	
Screw tugs	
1 Ada	
2 Joyce	
3 Amcotts	

The moulded displacement of the "Scawby"-class stern-wheeler is about 85 tons at 3′3″ draught. The "Broughton" is mainly used in the creeks. The "Luddington" has been modernised with oil burners.

The total tonnage of the 51 barges amounts to 5,430 tons, making altogether with the former Elder Dempster's barges a total tonnage of more than 6,000 tons. The mean light draught of the 150-ton barges is 1′2″, and fully loaded these draw 4′0″.

(1 by kind permission of Holt's Transport

4.1.3. Compagnie de Transport et Commerce (C.T.C.)

In 1956 a new (French) Transport Company named the "Compagnie de Transport et Commerce" has started with a new ship, the "Susie", on the Niger and Benue Rivers. This fast and modern vessel is of the "semi-integrated tow" design, i.e., a powerful towboat of 600 h.p. (Photograph 4.1.3-1) pushes the interlocking barges which together form a streamlined unit.

The "Susie" tow consists of a towboat and two barges, capable of lifting a total of 1,000 tons at 5 feet or 1,400 tons at 7 feet draught. The light draught is only 1 foot. The total length of the formation is 345′. A small house-boat is often taken alongside for the accommodation of the manager (Diagram 5.1.6-3).

It is intended to add more ships of this semi-integrated type to the C.T.C. fleet.

PHOTOGRAPH 4.1.3-1
"Susie" Tug C.T.C.

4.1.4. Socony Vacuum Oil Company (S.V.O.C.)

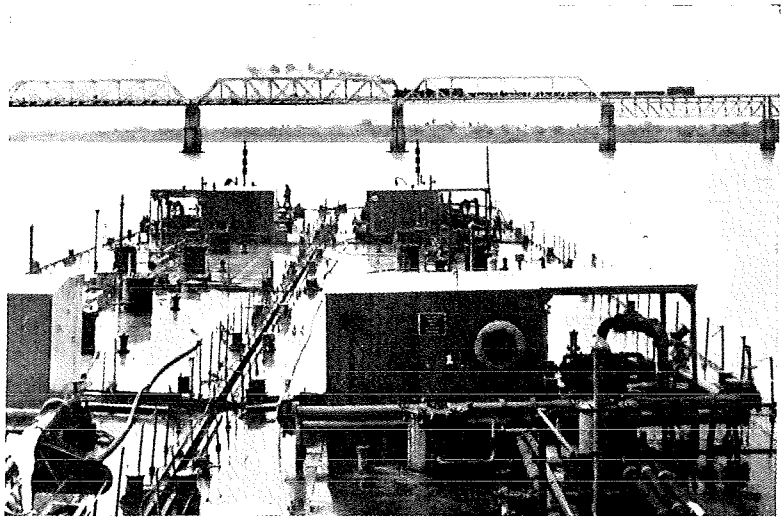
The inland tanker "Adama" of the Socony Vacuum Oil Company which has been on the Niger and Benue since 1952 is also of the "semi-integrated tow" design.

The "Adama" (Photograph 4.1.4-1), carrying oil and petrol in bulk, is a twin-screw towboat (450 h.p.) with propellers in tunnels, drawing 3′10″ and consists further of 8 barges, pushed in rows of four. They are divided in two leading barges, two trailing barges and four box-barges in between. Recently another two box-barges have been added, making a total of ten barges.

With eight barges loaded to 4′10″, the maximum capacity of the "Adama" is 1,410 tons, and the light draught of the barges with water-ballast is 2 feet. The total length of the formation with the 8 barges is 420 feet.

Oil is carried by the "Adama" from the bulk oil storage at Sapele (Warrifi) to Onitsha, Lokoja and Garua. The Lokoja storage tanks are used for shuttling purposes: in June, when the Niger begins to rise, the Lokoja storage is filled up in three voyages from Sapele, and during the Benue season it is then possible to make three voyages from Lokoja to Garua, returning

downstream with empty barges. During the remainder of the season, Onitsha is supplied and time is required for overhauling the unit.



PHOTOGRAPH 4.1.4-1
"Adama" S.V.O.C.

In addition to the "Adama" two vessels of the Monrovia Navigation Company Inc. operate on the Niger and Benue Rivers.

Firstly, the "Paola", which has so far been used to supply mineral oil in bulk to the Onitsha storage tanks. This vessel with a length of 47.25 metres (155 feet) and beam of 8.20 metres (27 feet) has an empty draught of 0.70 metres (2'4"). The maximum carrying capacity is 550 tons with a draught of 8 feet.

Secondly, the latest addition to the fleet is the motortanker "Makurdi", which will also operate on the Niger and Benue Rivers during the high-water stage of 1959 as far as Makurdi. The "Makurdi" has a length of 61.90 metres (200 feet), a beam of 9.40 metres (31 feet) and an empty draught of 0.80 metres (2'8"). The maximum carrying capacity is 850 tons with a draught of 8 feet.

The "Paola" and "Makurdi" motortankers have a twin-screw propulsion with 460 and 470 h.p. respectively, and are both fitted with a R/T equipment.

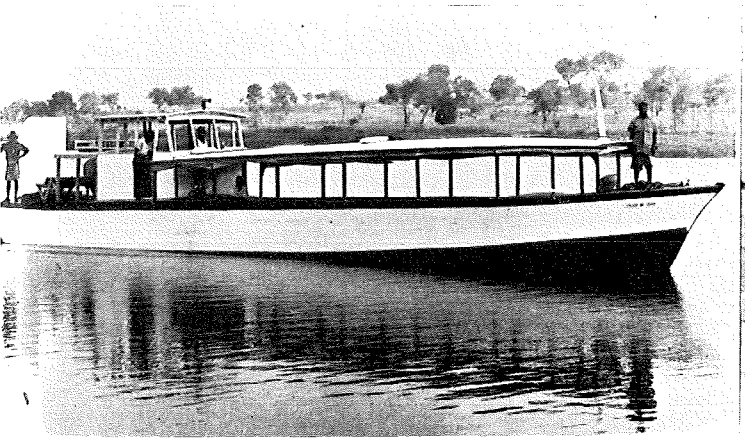
4.1.5. Compagnie Française de l'Afrique Occidentale (C.F.A.O.)

The commercial French firm C.F.A.O. owns in Nigeria some small self-propelled vessels with activities limited to the creeks and Onitsha during the low-water stage of the Niger and in the vicinity of Makurdi during the high-water period.

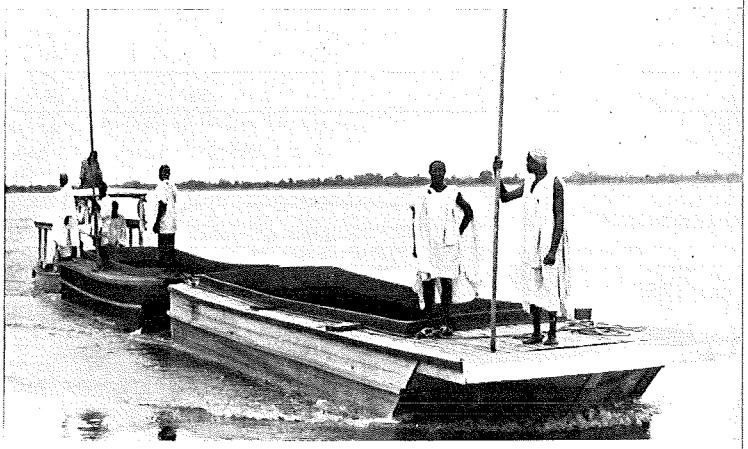
The total tonnage of this fleet will probably not exceed 500 tons.

4.1.6. Makurdi boatyard products and canoes

There is a need for boats of size intermediate between the river companies' barges and the African-owned canoes, generally of two- to three-ton capacity.



PHOTOGRAPH 4.1.6-1
Passenger launch built by the Makurdi boatyard



PHOTOGRAPH 4.1.6-2
"Semi-integrated tow" built by the Makurdi boatyard

PHOTOGRAPH 4.1.6-3
Canoe making

PHOTOGRAPH 4.1.6-4

Sailing canoes

After the war a project was started to introduce shallow-draught motor barges of small capacity at a sufficiently low price to enable the local population to buy them. As a result, in each Region of Nigeria a boatyard exists, sponsored by Government: in the Western Region at Epe, in the Eastern Region at Opobo, and in the Northern Region at Makurdi.

The Opobo and Epe boatyards design and build vessels specially for the creek service, while the Makurdi boatyard designs and makes various types of wooden vessels to be used for service on the Niger and Benue and their tributaries. In the three years 1955—1957, the Makurdi boatyard produced 40 passenger punts, 2 passenger launches (Photograph 4.1.6-1), 3 launches, 1 sand barge of 5 tons, 1 power barge, 1 cattle ferry (30 cattle), 1 motor ferry (5 tons loads + 30 passengers), and 3 tug tenders (Photograph 4.1.6-2).

Recently a fairly large passenger-cum-cargo vessel was launched from the Makurdi boatyard. This ship, owned by an Onitsha merchant, will ply between Onitsha and Yola during the Benue season, and between Onitsha and Baro during the Niger season.

In Nigeria there are also thousands of dug-out canoes in use on the creeks and the rivers (Photograph 4.1.6-3). For centuries they have been the most important means of transport and are still important for local and small-scale transport. Where this type of vessel could be used it was much less laborious, and often quicker, than movement by carrier, besides permitting the movement of loads much too heavy for head carriage.

These canoes with their shallow draught (2—3 feet) not only carry foodstuffs between the small villages and the markets, but also extend the services of the river companies to bush stations. They are, however, slow, probably averaging not more than two knots (Photograph 4.1.6-4).

There are very large canoes carrying a load of over 5 tons. Some of them are 40 feet long, sometimes of a square section, and must have entailed a prodigious amount of man labour to reduce them from a growing tree to a shapely craft.

Although the majority are still moved by man-handled paddles, the number of canoes driven by outboard engines is increasing. The Ministry of Transport supervises the latter, as a certificate for the engine-drivers is prescribed. Seen on the whole, however, canoe transport has declined from a predominant position to one in which it is largely the servant of modern means of transportation. An increasing number of passengers is being carried on the rivers by powered canoes.

4.1.7. Total tonnages and capacity

From the previous paragraphs the total carrying capacity of the fleets of the main transport companies operating on the Niger and Benue Rivers can be summarised as follows:

N.R.T. (Niger River Transport)	22,200 tons
H.T. (Holt's Transport)	6,000 tons
C.T.C. (Compagnie de Transport et Commerce)	1,400 tons
S.V.O.C. (Socony Vacuum Oil Company)	1,400 tons
C.F.A.O. (Compagnie Française de l'Afr. Occ.)	500 tons
Total	31,500 tons

The potential for transport of most water routes is practically unlimited.

As has been mentioned in 1.3.3, and shown in Diagram 1.3.4-1, the river tonnage of the largest shipping company, the N.R.T., is increasing. Together with Holt's Transport and the smaller shipping lines, who contribute about one-third, the total figure of available water transport moves around 250,000 tons and 120 millions ton-miles.

The capacity of the present fleet to transport goods on the Niger and Benue is much more and depends on such factors as location and time of available produce, storage, river conditions, etc.

To make a first approach to a calculation of the possible maximum capacity under the present conditions, but subject to the availability of sufficient cargo, the following assumptions are made:

(i) regarding the present river conditions, i.e., navigating on the Benue during the high-water period and on the Niger during the low-water (Black Flood) period, a total of 10 months (or 300 days) average navigation per year may be reckoned with;

(ii) the average load factor (i.e., the ratio between the actual and the maximum load of the barges) as a result of the river conditions and the dominantly downward river traffic is about 45%;

(iii) the average haul is 450 miles;

(iv) the time of steaming for this haul averages nine days for sailing upstream and five days for the return journey; and

(v) the time of loading and unloading is four days per journey.

The tonnage capacity per year will then be

$$2 \times \frac{300}{18} \times \frac{45}{100} \times 31{,}500 = 475{,}000 \text{ tons}$$

The introduction of night navigation and improved handling of cargo in ports may reduce the round-trips by about 40%, whilst river management, dredging and the development of upward

transport may increase the load factor by 65%. This indicates that the above tonnage capacity, calculated for present conditions, may become

$$475{,}000 \times 1{,}4 \times 1{,}65 = 1{,}100{,}000 \text{ tons}$$

within the near future.

Concluding, under improved conditions the present fleets should be able to transport over half a million tons of cargo per annum, i.e., more than twice the present amount. With further improvements, this amount may even rise to more than a million tons per year.

A comparison of the traffic load of the Niger with the traffic load of the West European rivers is given in Paragraph 5.1.5.

4.2. GOVERNMENTAL FLEET

4.2.1. History

When at the beginning of 1900 the British Government took over the administrative and military assets of the Royal Niger Company (see III, 1.1) on payment of compensation, the only means of communication and transport were the Rivers Niger and Benue. From that time a Governmental fleet has existed. There were no roads through the forest and, because of the tsetse fly, animals could not be used. The only means of transporting loads through the forest

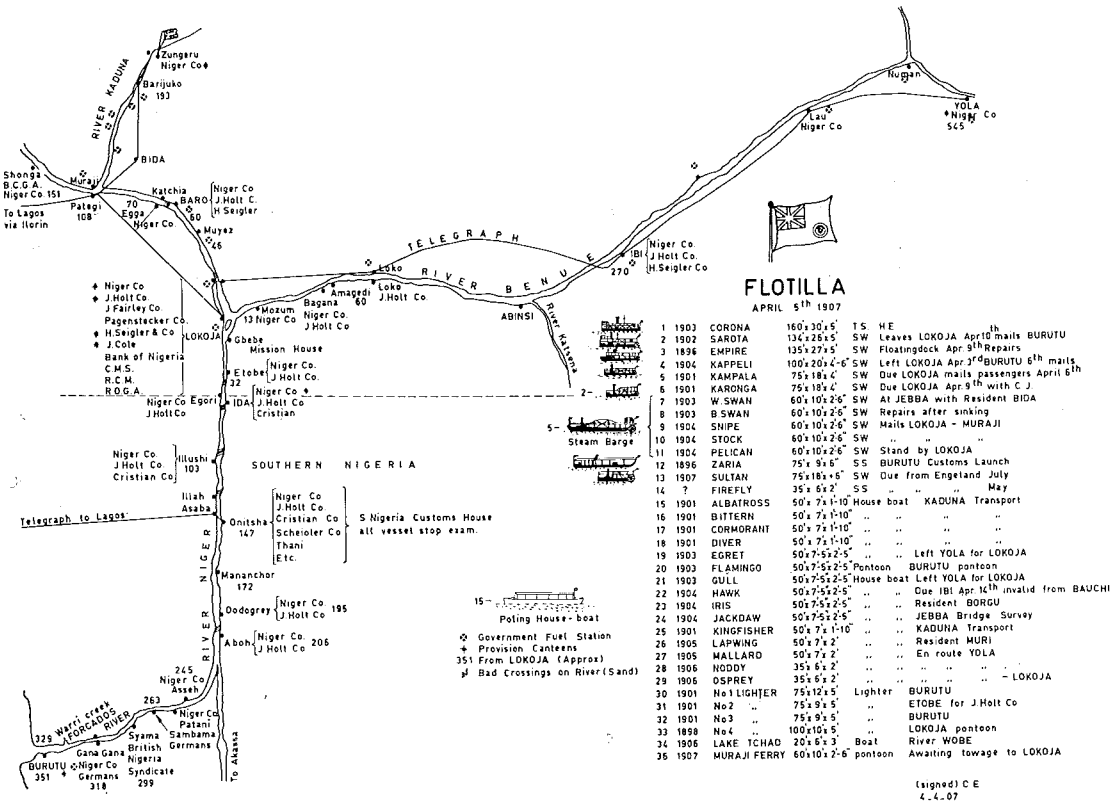


DIAGRAM 4.2.1-1

Governmental fleet in 1907

PHOTOGRAPH 4.2.2-1
Touring launch I.W.D.

PHOTOGRAPH 4.2.2-2
W-Launches I.W.D. at Lokoja

was on the heads of human porters along narrow and winding footpaths. The railway started with Lagos—Ibadan in 1898—1901, reaching Jebba in 1909; the road developed decades later with the introduction of motor vehicles.

According to an old map of 1907 (diagram 4.2.1-1), the shipping flotilla at that time consisted of 14 self-propelled vessels, most of them stern-wheelers, 15 poling house-boats, 4 lighters and 2 pontoons, in total 35 units.

4.2.2. Present fleet

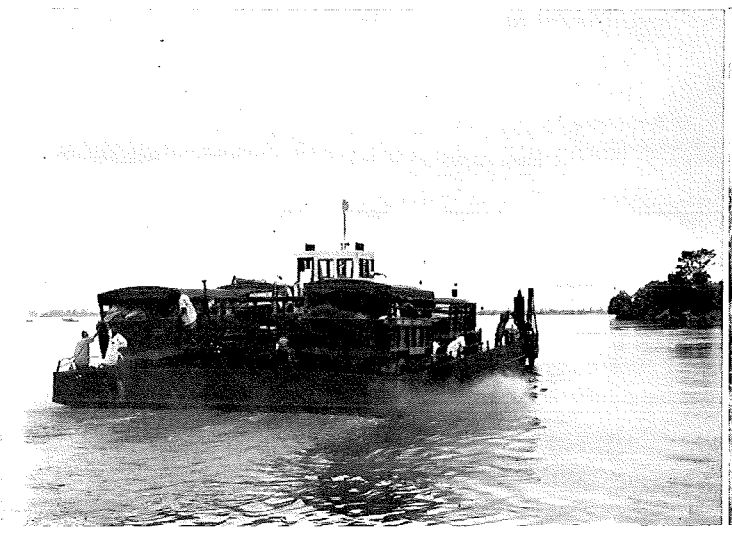
The present Navigation Branch of the Inland Waterways Department supervises and maintains 179 units of various craft, divided into 36, 59 and 84 units serving respectively in the Northern, Eastern and Western Divisions.

Among these vessels are 46 launches of various types: D, H, L, N, S and W-classes (Photographs 4.2.2-1 and -2), 8 ferries (Photograph 4.2.2-3), 5 motor barges, 1 towing craft, 1 dredger, 36 poling barges, 51 dinghies, 4 pontoons, 10 lighters, 14 gigs and 3 Accra canoes.

Of the total of 179 units about 50 units are in use on the Niger and Benue Rivers, while the other units mainly operate in the creeks.

The users of Government transport are all Government Departments, like the Medical Department and the Inland Waterways Department with its Navigation Branch including public ferry and creek mail service (Photograph 4.2.2-4), and its Hydrological Branch including Survey and River Patrol.

PHOTOGRAPH 4.2.2-3
I.W.D. Ferry Onitsha—Asaba



PHOTOGRAPH 4.2.2-4
"Vampire" I.W.D. creek mail

CHAPTER 5

SHIPPING

5.1. COMMERCIAL NAVIGATION

5.1.1. Structure of transport

The structure of transport is determined by the following factors:
(i) the time of the year when the produce is available;
(ii) the place of origin and destination of the goods;
(iii) the river conditions throughout the year on the different river-stretches; and
(iv) the quantities of goods available for transport.

Under the present circumstances, by far the largest quantities of produce in Nigeria are offered for shipment from mid-November to mid-February; benniseed (Makurdi area) is available in July—September. As the Benue is not navigable before the end of June, it is logical that the fleet serves the Niger ports and in particular Baro from the end of the Benue season onwards, i.e., from November until the end of the Black Flood in April. During a part of April, May and a part of June only the river-stretch between the Delta and Onitsha is navigable with a restricted draught (see also Diagram 3.2.2-1). During this time only a part of the fleet can be used and this period is suitable for an annual overhaul of the vessels.

At present the river-fleet handles almost exclusively produce with overseas destinations, so that the destination of ships transporting produce is always one of the Delta ports. Furthermore, all sorts of merchandise and petroleum products are shipped up-river to ports along the rivers, each of which serves a part of the hinterland of the rivers. The predominant agricultural production of this hinterland practically determines the fleet capacity, as the produce shipped downwards to the Delta is about three times that of the merchandise shipped up-river. An exception is the up-river traffic of petroleum products which is a one-way traffic, so that the tanker fleet always travels empty down-river.

The Benue and the Niger below Lokoja become navigable after the new rains have started. As the produce of the latest crop has already been stored in ports along the Benue for some months, and only relatively small quantities of palm products become available in the Niger ports, practically the whole fleet will concentrate on serving the Benue ports, in particular the ports of Garua, Yola and Numan, where the largest quantities are available. The quantities and the long haul over which these quantities have to be shipped, combined with the short navigable period of the Benue, determine in fact the fleet's capacity.

This situation leaves very little room for serving the Niger ports during this period, and specially the Baro port, as they are out of the route. This is not so serious insofar as it concerns produce for shipment down-river, as the large groundnut and cotton crops of the next yield are not yet available. However, the continuation of up-river shipment of merchandise via Baro

Mile	Station
40	BURUTU
46	WARRI
130	PATANI
178	ABOH
231	ONITSHA
256	ILLAH
272	ILLUSHI
310	IDAH
332	ITOBE
362	LOKOJA
434	BARO
401	UMAISHA
434	BAGANA
454	LOKO
510	MAKURDI
528	ABINSI
614	IBI
682	AMAR
712	KWATA NANIDO
778	LAU
799	JEN
846	NUMAN
886	YOLA
916	WURO BOKI
972	GARUA

DECEMBER 1955 JANUARY FEBRUARY MARCH 1956 APRIL MAY

JUNE JULY AUGUST SEPTEMBER 1956 OCTOBER NOVEMBER

Note:
SHIPS MOVEMENTS FROM DEC. 1955 - MAY 1956
BY HOLT'S TRANSPORT.
BIGBY = —·—·— SPILSBY = — — —
APPLEBY = ——·——·—— LACEBY = ————
SCAWBY = - - - - - - -

REFERENCE: N.R.T

JOS. FLINT	———
OKORODUDU	———
WALLACE	———
PINNOCK	—·—·—
QUORRA	—··—··—
NARAGUTA	——·——·—
COL. RATSEY	—··—··—
ABERDARE	—···—··—
CHADDA	·····
TUGWELL	+++++++
R. LANDER	+–+–+–+
TRENCHARD	+·+·+·+·+
BOUSSA	+···+···+
GEN. LECLERC	·····
GOLDIE	—·—·—·—
EKETIAN	o o o o o o
THOM. WELSH	o o o o o o o
RIBAGO	o·o·o·o·o·o
ATTA	o–o–o–o–o–o
JOHN KIRK	oo–oo–oo–oo
SUMA	oxoxoxoxoxo
WALTER WATTS	o+o+o+o+o+o
BAUCHI	o—o—o—o—o
ADAMA (S.V.O.C)	——·——
SUSIE (C.T.C.)	o o o o o o

NEDECO NIGER/BENUE	DIAGRAM IV, 5.1.2-1
MOVEMENTS OF SHIPS	
JUN. 1956 - NOV. 1956	

Mile	Station
40	BURUTU
46	WARRI
130	PATANI
178	ABOH
231	ONITSHA
256	ILLAH
272	ILLUSHI
310	IDAH
332	ITOBE
362	LOKOJA
434	BARO
362	LOKOJA
401	UMAISHA
434	BAGANA
454	LOKO
510	MAKURDI
528	ABINSI
614	IBI
682	AMAR
712	KWATA NANIDO
778	LAU
799	JEN
846	NUMAN
886	YOLA
916	WURO BOKI
972	GARUA

DECEMBER 1956 | JANUARY | FEBRUARY | MARCH | 1957 APRIL | MAY

JUNE | JULY | AUGUST | SEPTEMBER | 1957 OCTOBER | NOVEMBER

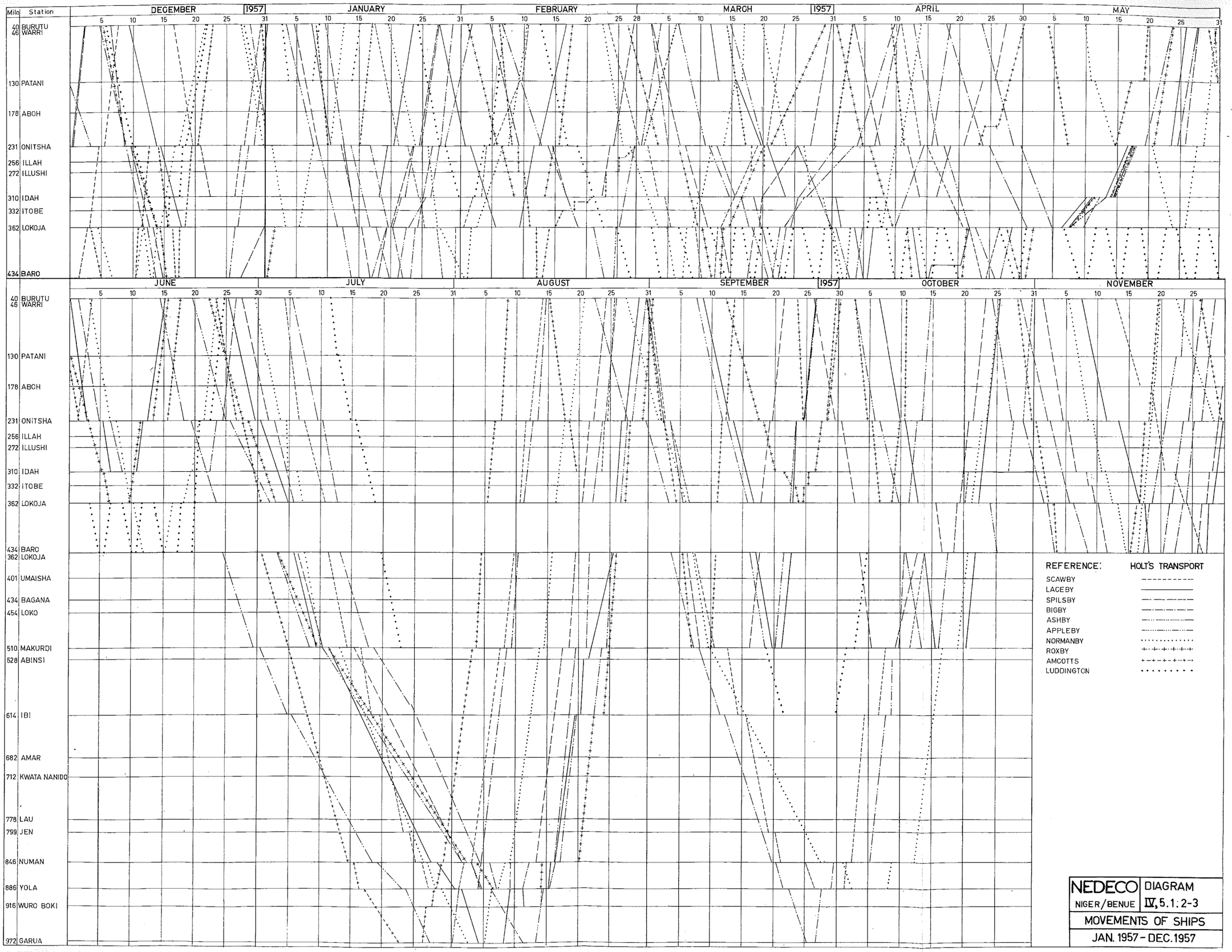
REFERENCE: N.R.T.

- JOS. FLINT
- OKORODUDU
- KATSENA
- WALLACE
- PINNOCK
- QUORRA
- NARAGUTA
- COL. RATSEY
- ABERDARE
- CHADDA
- TUGWELL
- R. LANDER
- TRENCHARD
- BOUSSA
- GEN. LECLERC
- GOLDIE
- SULTAN
- THOM WELSH
- RIBAGO
- ATTA
- JOHN KIRK
- SUMA
- WALTER WATTS
- LENTHALL
- EKETIAN
- BAUCHI
- ORASHI
- ADAMA (S.V.O.C)
- SUSIE (C.T.C.)

NEDECO | DIAGRAM
NIGER/BENUE | IV, 5.1.2-2

MOVEMENTS OF SHIPS

DEC. 1956-NOV. 1957


Mile
Station
DECEMBER
1957
JANUARY
FEBRUARY
MARCH
1957
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
1957
OCTOBER
NOVEMBER
40 BURUTU
46 WARRI
130 PATANI
178 ABOH
231 ONITSHA
256 ILLAH
272 ILLUSHI
310 IDAH
332 ITOBE
362 LOKOJA
434 BARO
362 LOKOJA
401 UMAISHA
434 BAGANA
454 LOKO
510 MAKURDI
528 ABINSI
614 IBI
682 AMAR
712 KWATA NANIDO
778 LAU
799 JEN
846 NUMAN
886 YOLA
916 WURO BOKI
972 GARUA
REFERENCE:
HOLT'S TRANSPORT
SCAWBY
LACEBY
SPILSBY
BIGBY
ASHBY
APPLEBY
NORMANBY
ROXBY
AMCOTTS
LUDDINGTON
NEDECO
NIGER/BENUE
DIAGRAM
IV, 5.1: 2-3
MOVEMENTS OF SHIPS
JAN. 1957 - DEC. 1957

Mile	Station
40	BURUTU
46	WARRI
130	PATANI
178	ABOH
231	ONITSHA
256	ILLAH
272	ILLUSHI
310	IDAH
332	ITOBE
362	LOKOJA
434	BARO
362	LOKOJA
401	UMAISHA
434	BAGANA
454	LOKO
510	MAKURDI
528	ABINSI
614	IBI
682	AMAR
712	KWATA NANIDO
778	LAU
799	JEN
846	NUMAN
886	YOLA
916	WURO BOKI
972	GARUA

DECEMBER 1957 | JANUARY | FEBRUARY | 1958 MARCH | APRIL | MAY

JUNE | JULY | AUGUST | 1958 SEPTEMBER | OCTOBER | NOVEMBER

REFERENCE: N.R.T.

- JOS. FLINT
- OKORODUDU
- KATSENA
- WALLAGE
- PINNOCK
- QUORRA
- NARAGUTA
- COL. RATSEY
- ABERDARE
- CHADDA
- TUGWELL
- R. LANDER
- TRENCHARD
- BOUSSA
- GEN. LECLERC
- GOLDIE
- SULTAN
- THOM. WELSH
- RIBAGO
- ATTA
- JOHN KIRK
- SUMA
- WALTER WATTS
- LENTHALL
- EKETIAN
- BAUCHI
- ORASHI

ADAMA (S.V.O.C)
SUSIE (C.T.C)

NEDECO NIGER/BENUE

DIAGRAM IV, 5.1. 2-4

MOVEMENTS OF SHIPS

DEC. 1957 - OCT. 1958

to destinations in the north of Nigeria is desirable. It can be carried out with up-river traffic throughout 9 or 10 months of the year, when the Benue trade no longer absorbs the entire fleet capacity.

The quantities of goods available for transport by river are, of course, in the first place dependent on a good or a bad harvest, but they are above all limited by the possibilities of evacuation. As the Niger is only navigable as far as Baro and Jebba, ports which are also connected by railway and roads to the south, the actual way of evacuation is a matter of competition. The Benue, however, offers the only way of evacuation for very large production areas, thus forming the exclusive key of development by enlarging the quantities.

Summarising, the operation now practised is as follows: All the year round on the Lower Niger, but the period April to June on restricted draughts; the Upper Niger with full loads during October and part of November, and reduced loads during the period November to April; the Benue River from July to October; and the period April to July in general being used for annual overhaul of the craft.

In the next two paragraphs the movements of ships are dealt with in more detail.

5.1.2. Movements of ships (Niger)

The movements of ships have been recorded by NEDECO ([1] during the investigation from June 1955 to May 1958; the results are given for the Niger in the upper sections, for the Benue in the lower sections of Diagrams 5.1.2-1 to 4 inclusive.

The ships' movements of the N.R.T. were collected daily in full cooperation with the management since 1956 by exchanging information from the radio station NEDECO-Lokoja with the N.R.T. radio shore-stations Burutu (1956), Onitsha (1957), Baro (1957), Makurdi (1956), and Yola (1956) and with the ships equipped with radio transmitters.

The ships' movements of the Holt's Transport have been collected from the ships' logbooks for the years 1955 (Niger season) and 1957 (Niger and Benue season) by kind permission of the H.T.'s management.

In the graphs the vertical axis shows locations with the distances in miles from the Escravos Lighthouse, and from top to bottom Warri/Burutu to Baro and further from Lokoja to Garua. The horizontal axis shows the months. Thus, the movement of the ship along the river is represented by a slanting line, and when the ship is in a port, waiting, or aground the line is horizontal.

The following conclusions may be derived from the diagrams for the Niger. With regard to the Baro navigation from November 1955 to April 1956, it may be seen that nearly every ship has been grounded several times.

A marked contrast is shown in the Baro navigation from November 1956 to April 1957, when practically no groundings have been reported, except for a very few ones early in the season when the buoyage experiment was in its initial stage. From mid-December 1956, this improvement will be partly due to better river conditions, as that year's Baro season was not preceded by an exceptional high flood as in the previous year. But the buoyage of shallow crossings and the announcement of available depths will undoubtedly have had beneficial effects both in limiting the number of groundings and in increasing the tonnage of produce shipped from Baro. However, between Lokoja and Onitsha there have evidently been difficulties in 1957 and throughout the Baro season groundings and delays occurred in this section, though decreasing in number after the Lokoja, Agbama and Kokoin Flats had been buoyed in January, 1957.

([1] I.W.D., when taking over the routine work of NEDECO, continued the records after May 1958.

The Baro navigation from November 1957 to May 1958 shows a continuance of the improvement, as no important groundings have been reported at all, not even on the stretch between Lokoja and Onitsha. That year the buoyage was extended even towards Aboh, covering a total of 38 crossings.

5.1.3. Movements of ships (Benue)

Diagrams 5.1.2-1 to 4 inclusive have already been mentioned as giving the movements of ships on the Benue. Several interesting points are derived from these Diagrams.

By the end of June 1956 the sill at the Benue Entrance near Lokoja caused a considerable delay to many convoys which had to wait in Lokoja before they could cross the Benue Bar, while several groundings occurred there (see V, 3.1). It can be read that the first Benue-bound convoys experienced many difficulties on the Lower Niger between Idah and Lokoja, whilst on the Benue a sufficient depth of water was already available. The delay caused by the Wuro Boki Flats is clearly illustrated: at that place many ships had to wait in August before continuing their trips.

It can be seen from the 1957 Benue graph that the system of shuttling has been introduced by N.R.T. This system is a possible means of improving the navigation by adapting the type of shipping to the characteristics of the river (VI, 2.2). On the lower reaches of the Benue and on the Niger, the big power units were employed, pushing four and sometimes even six barges, while on the Upper Benue above Ibi or Makurdi the more manoeuvrable modern towboats took two or three barges at a time to Yola or Garua and back.

The Benue season 1957 has found an early end, as there was no cargo available at Garua owing to the bad harvest of produce in 1957. The Benue season 1958 shows the normal start with the greater part of the N.R.T. fleet, but due to the exceptionally low stages a total of more than 165 days were lost by waiting downstream of Yola for further rise of the river.

5.1.4. Analyses of movements

The available records, of which the origin has been mentioned in 5.1.2 and which have been represented in the graphs of the previous paragraphs, have been carefully analysed.

Analyses of ships' movements have since June 1956 been made for each navigation season divided into Benue and Niger (Baro) seasons thus resulting in three Benue seasons and two Baro seasons for the N.R.T. fleet and 1 year's navigation (1957) for the Holt's Transport fleet. To avoid confusion by providing all the detailed figures, only a summary per ship of one particular season (Table 5.1.4-1) and the final summaries of all the participating ships per season (Table 5.1.4-2) are given below.

Table 5.1.4-1 shows the summary of the N.R.T. ships' movements during the Baro season from December 1956 to April 1957. In the Column 1 (itinerary) the abbreviations for the river-stations are indicated as follows: Bu = Burutu, On = Onitsha, Id = Idah, Lo = Lokoja and Ba = Baro. Column 2 (sailing) gives the number of days the ships have spent on the river out of the ports. It represents the time of actual steaming and the time of normal night stops on the rivers, without any delay due to bad river conditions. Column 3 (aground) gives the number of days lost by the grounding of one or more barges. Column 4 (waiting) shows the number of days reported to have been spent on delays as stops for soundings (to find a navigable channel in unbuoyed crossings), waiting for the rise of the water, and time lost by assisting other stranded ships for refloating. Column 5 (in port) gives the total number of days in all ports of call with

TABLE 5.1.4-1

SUMMARY OF SHIPS' MOVEMENTS (NRT), DURING THE BARO SEASON DECEMBER, 1956 — APRIL, 1957

Towboat	Date	1 Itinerary	2 SAILING		3 AGROUND		4 WAITING		5 IN PORT		6 TOTAL	
			days	%	days	%	days	%	days	%	days	%
Aberdare	19.12 to 28. 4	Bu — Ba	61½	47	14½	11	13¾	10½	41½	31½	131¼	100
Atta	5. 2 to 16. 4	Bu — Ba	18½	55	—	—	3	9	12	36	33½	100
Bauchi	13.12 to 31. 3	Bu — On	43¾	46	6¾	7	—	—	45	47	95½	100
Chadda	5.12 to 14. 4	Bu — Ba	31¼	47	—	—	16¾	25	19	28	67	100
Goldie	6.12 to 28. 4	Bu — Ba	73½	63	6	5	2½	2	36	30	118	100
Katsena	13.12 to 27. 4	Bu — Ba	45½	35	—	—	8¾	7	73¾	58	128	100
Kirk	19.12 to 12. 3	Bu — On	38	46	3	4	—	—	41½	50	82½	100
Lander	4.12 to 11. 4	Bu — Ba	56½	44	2	1½	16	12½	53¾	42	128¼	100
Leclerc	2.12 to 20. 4	Bu — Ba	62¼	47	2¼	2	—	—	67¼	51	131¾	100
Lenthall	4. 4 to 30. 4	Bu — On	9¼	82	—	—	—	—	2	18	11¼	100
Naraguta	2.12 to 18. 3	Bu — Ba	56½	54	—	—	6¼	6	41½	40	104¼	100
Okorodudu	3.12 to 21. 4	Bu — Ba	59¾	59	4½	4½	—	—	36¾	36½	101	100
Orashi	8.12 to 23.12	Bu — On	10¾	88	—	—	—	—	1½	12	12¼	100
Pinnock	3.12 to 16. 4	Bu — Ba	59½	48	4	3	8¾	7	15¼	42	123½	100
Quorra	15. 1 to 19. 4	Bu — Ba	48¾	52	—	—	8	9	36¼	39	93	100
Ribago	13.12 to 20. 4	Bu — On	58¾	47	—	—	—	—	65½	53	124¼	100
Sultan	19. 1 to 25. 4	Bu — Ba	59½	42	—	—	5	5	32½	33	97	100
Tugwell	9. 4 to 1. 5	Bu — Lo	16¼	75	—	—	—	—	5½	25	21¾	100
Wallace	2.12 to 30. 4	Bu — On	40½	47	—	—	7	9	38¼	44	85¾	100
Watts	9. 3 to 28. 3	Bu — On	8¾	46	—	—	—	—	10¼	54	19	100
Welsh	8. 1 to 3. 4	Bu — Ba	48½	57	—	—	9	11	27¾	32	85¼	100
Total General:			907½	50.6	43	2.4	104¾	5.8	738¾	41.2	1,794	100
Ships & barges for Baro only			636	52.4	33¼	2.7	89	7.3	455½	37.6	1,213¾	100
Others			271½	47	9¾	1.5	15¾	2.5	283¼	49	580¼	100

TABLE 5.1.4-2

FINAL SUMMARIES OF ANALYSES OF SHIPS' MOVEMENTS PER SEASON AND PER YEAR

ANALYSIS Sub	SEASON	NUMBER OF VESSELS	STARTING DATE From	ENDING DATE To (incl.)	(2) SAILING days	%	(3) AGROUND days	%	(4) WAITING days	%	(5) IN PORT days	%	(7) AT BASE days	%	(6) TOTAL days	%
(1)	BENUE	15	Jun. '56—	Oct. '56	993½	63.2	70½	4.5	161	10.2	347½	22.1	—(1	—	1,572½	100
(2)	BENUE	12	Jun. '57—	Oct. '57	680	55.7	10½	0.8	67½	5.6	461¼	37.9(2	—	—	1,219¾	100
(3)	BENUE	15	Jun. '58—	Oct. '58	950	54.5	44¾	2.5	259¼	14.9	490¼	28.1(2	—	—	1,744¼	100
(4)	NIGER (BARO)	21	Dec. '56—	Apr. '57	907½	50.6	43	2.4	104¾	5.8	738¾	41.2(2	—	—	1,794	100
(5)	NIGER (BARO)	14	Nov. '57—	May '58	580½	43.8	12	0.9	30	2.3	702	53.0(2	—	—	1,324½	100
(6)	NIGER (BARO)	21	½Nov. '56—	May '57	907½	22.2	43	1.0	104¾	2.6	738¾	18.0	2,301	56.2	4,095(3	100
(7)	BENUE	12	Jun. '57—	½Nov. '57	680	34.4	10½	0.5	67½	3.4	461¼	23.3	760¾	38.4	1,980(4	100
(8)	N.R.T. (YEAR)	16	Nov. '56—	Oct. '57	1,587½	26.1	53½	0.9	172¼	2.8	1,200	19.8	3,061¾	50.4	6,075	100
(9)	H.T. (YEAR)	9	Jan. '57—	Dec. '57	1,334¾	41.2	89	2.8	46	1.4	1,669¼	51.5	(101)	3.1	3,240	100
(10)	"ADAMA" BENUE	1	Jun. '57—	Oct. '57	78¼	57.9	—	—	—	—	56¾	42.1	—	—	135	100
(11)	"SUSIE" BENUE	1	Jul. '57—	Sept. '57	42¾	46.4	—	—	—	—	18¼	20	31	33.6	92	100
(12)	"AMCOTTS" NIGER/BENUE		Jan. '57—	Dec. '57	132¼	36.0	21¼	6.0	—	—	210½	58	—	—	364	100

(1 Not included.
(2 Loading and unloading at Burutu included.
(3 21 × 195 days.
(4 12 × 165 days.

the exception of the downstream base, i.e., Burutu, while column 6 (total) gives the total of Columns 1 to 5.

Table 5.1.4-2 shows the final summaries of all the participating ships per season. The representation of Columns 2, 3, 4, 5, and 6 is the same as in Table 5.1.4-1 and have been explained above.

Sub 1, 2 and 3 give the analyses for the Benue seasons of 1956, 1957 and 1958, while sub 4 and 5 give the analyses for the Niger seasons of 1956-57 and 1957-58, all being ships' movements of the N.R.T. fleet. Sub 9 gives the analysis of the ships' movements of nine ships of the Holt's Transport fleet for the year 1957 with a total of 9 times 360 days = 3,240 days.

To compare the analyses of the N.R.T. ships during the same period of one year with those of the Holt's Transport, the total days of sub 2 and 4 have been increased to 165 days per ship for the Benue season and to 195 days per ship for the Niger season (sub 6 and 7). For each season one month has been included in the figures for repairs, overhaul, etc.

Thus sub 8, being the total of sub 6 and 7, gives a summary of one year's river operation of an average of 16 ships which have been operating by the N.R.T. during 1957 under the same river conditions as the Holt's Transport (sub 9).

Sub 10, 11 and 12 give some figures of the modern types of ships operating on the Niger and Benue. They are the Adama (S.V.O.C.), Susie (C.T.C.) and Amcotts (H.T.).

5.1.5. Transported tonnages

In the absence of complete statistics of river transport, it is only possible to refer to figures given by the U.A.C. in their periodical Statistical and Economical Review and from verbal information supplied by representatives of the river operators.

To summarise and to recall the figures already mentioned in the previous Chapters 1 and 4 of this Part, Diagram 5.1.5-1 shows the partitions of the total fleet tonnages, ton-miles and

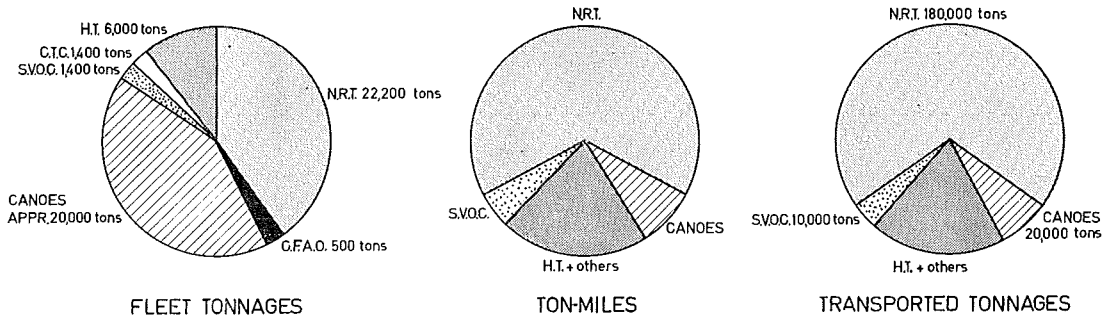


DIAGRAM 5.1.5-1

Niger/Benue transport

transported tonnages on the Niger/Benue. With the exception of the transported tonnage of petroleum products by the S.V.O.C., the total northward flow of merchandise in tons of each commercial firm is far less than the total southward tonnage.

Diagram 5.1.5-2 shows the average annual amount of goods transported on the Niger and Benue Rivers in the middle 1950's; both upstream and downstream tonnages have been indicated.

Table 5.1.5-3 ([1] shows the average annual tonnages transported by the Niger River Transport fleet during the periods 1935—1939, 1945—1947 and 1951—1953, while the river stations are divided into three river-stretches, namely, the Niger below Lokoja, the Niger above Lokoja, and the Benue River.

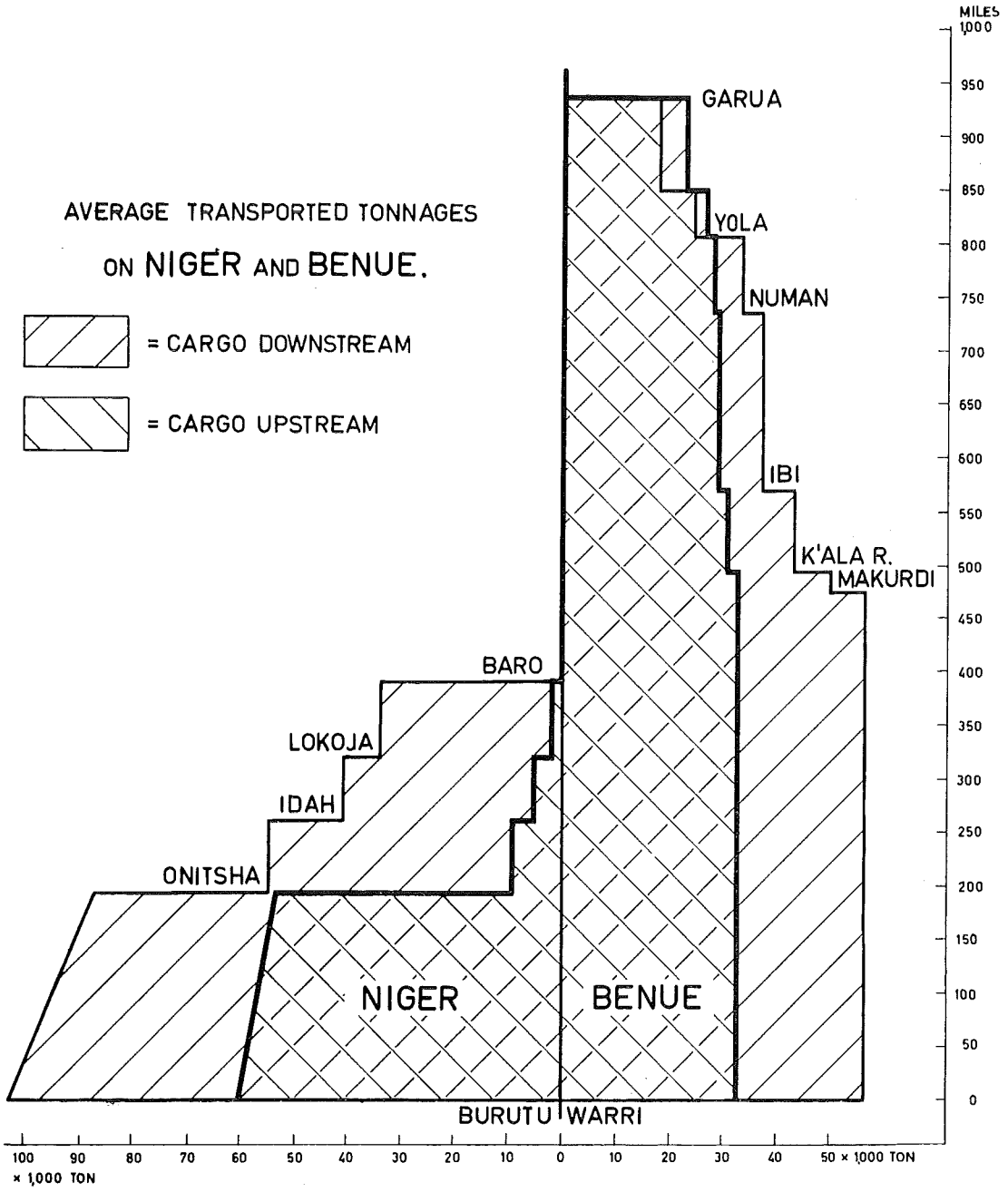


DIAGRAM 5.1.5-2

Average transported tonnages

([1] U.A.C. STAT. & ECON. REVIEW, No. 14, 1954. GEN. 36

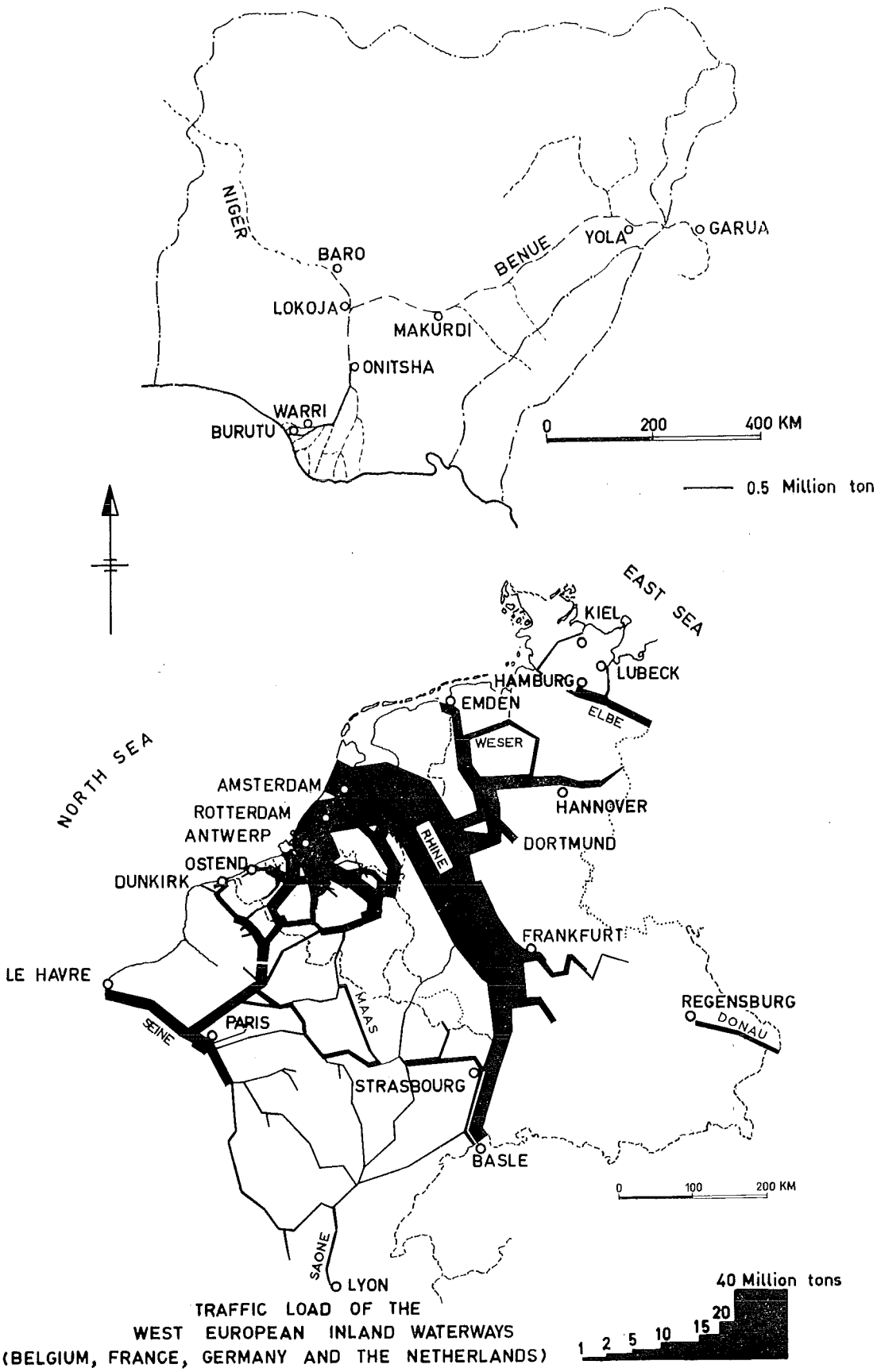


DIAGRAM 5.1.5-4

Comparison of traffic load on the West European rivers and the West African river Niger

TABLE 5.1.5-3
NIGER RIVER FLEET
(Nearest thousand)

Average annual tonnages	1935—1939		1945—1947		1951—1953	
	Merchandise Upward	Produce Downward	Merchandise Upward	Produce Downward	Merchandise Upward	Produce Downward
	Tons	Tons	Tons	Tons	Tons	Tons
Stations between Lokoja & Burutu	26,000	50,000	12,000	44,000	24,000	72,000
Jebba, Baro and Northern Stations *via* Baro	17,000	27,000	9,000	20,000	2,000	30,000
All stations on the Benue River	7,000	25,000	18,000	25,000	23,000	37,000
	50,000	102,000	39,000	89,000	49,000	139,000
Total tonnage carried	152,000		128,000		188,000	

In 4.1.7 an approach has been made to calculate the possible capacity of the present river-fleet under slightly improved river conditions, but subject to the availability of sufficient cargo, leading to a figure well over 500,000 tons. For comparison of this half million tons of traffic load on the lower part of the Niger with the traffic load of the West European rivers, Diagram 5.1.5-4 has been prepared. On the Rhine a total of more than 40 million tons was reached in 1952. This difference is even more remarkable when it is taken into account that the other means of transport (by railway and road) in Western Europe are also highly developed. Of course, this part of Europe is very densely populated and is not directly comparable with Nigeria, but the expectations of a future development in which the river system will take an important part is certainly justified.

Especially is the influence of river improvements very interesting to mention in this connection. Such can be seen on the Mississippi, where in 1950 the total tonnage carried from Minneapolis, Minn., to the mouth of Passes, La., was 67 million tons, which means that since 1935 there has been an increase to 5 times as much in 15 years. This renaissance in Mississippi River navigation may be attributed to maintenance of a dependable year-round navigation channel, to the enlargement of the Gulf Intra-coastal Waterway, and to the construction and use of many modern towboats and barges. These vessels move the bulk commodities of oil, sulphur, and other chemicals from Texas, Louisiana and Mississippi States northward via the Intra-coastal and Mississippi River Systems.

5.1.6. Comparison of performances

For decades it has been the normal practice on the Rivers Niger and Benue to constitute a tow out of one power-craft and two barges towed alongside (Diagram 5.1.6-1; Photograph 5.1.6-2). For long, too long, nothing has been changed in river transport, as the tasks of changing conditions seemed too large, the country was not ripe for change and river transport was looked upon as of minor importance. Old practices remained, old ships remained, and the spirit to find new ways seemed to be lost.

At last, after the second World War, new impulses started to raise the rivers and river transport from the position into which they had sunk. River companies started with the addition of new

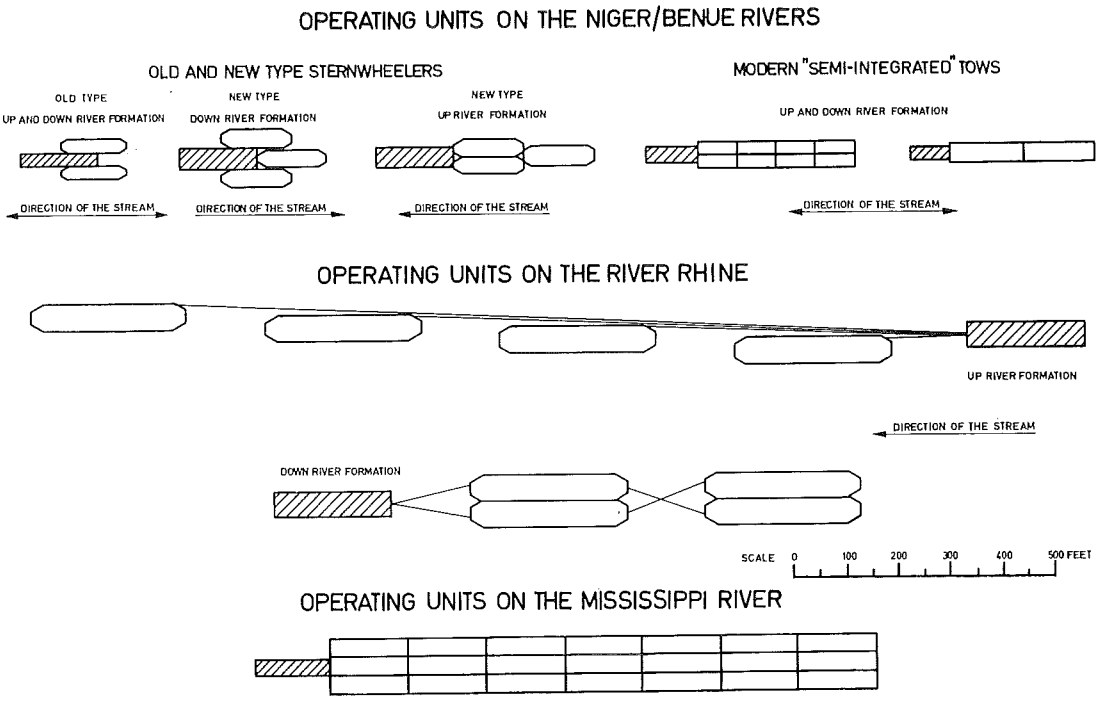
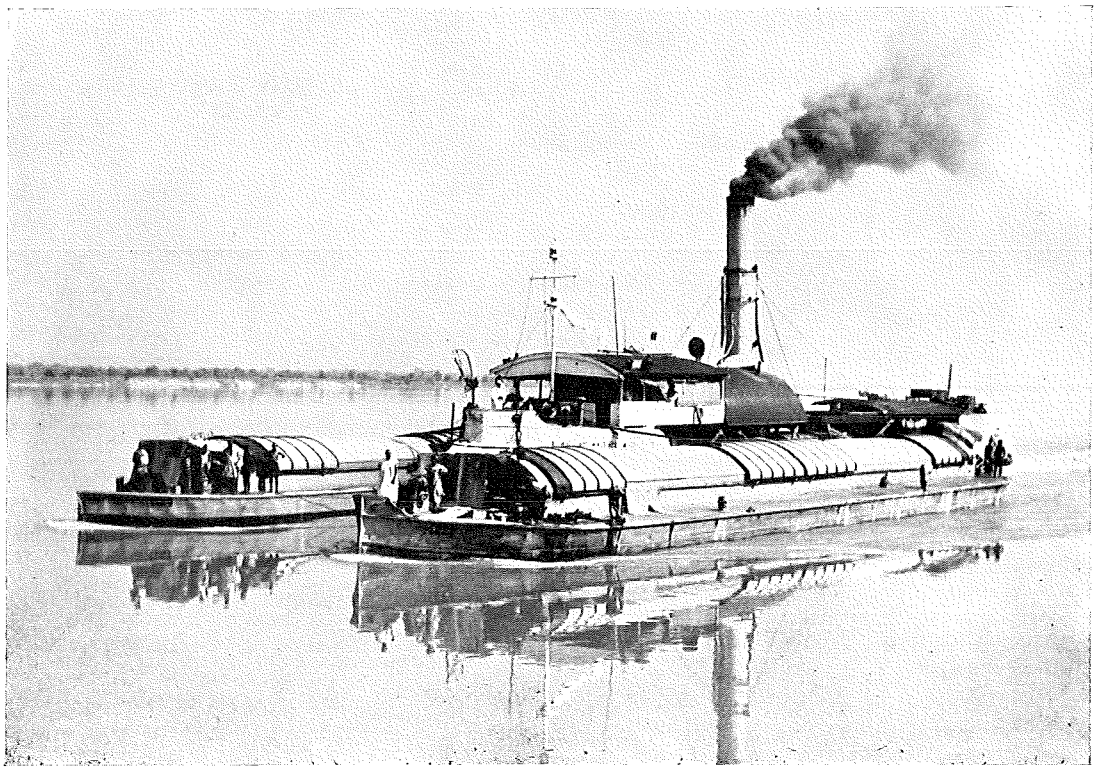


DIAGRAM 5.1.6-1

Different methods of towing



PHOTOGRAPH 5.1.6-2

"*William Wallace*", *N.R.T.*

ships to their fleets and changed their towing methods according to more modern opinions. The first semi-integrated tanker appeared on the river. Then gradually the interest of Government was awakened, and one result was that recently it was considered that the outlet of the Niger and Benue to the sea should be improved and that the improvement of the navigability of the Niger and Benue Rivers should follow. Meanwhile the shipping companies went on with improving their fleets (coal-burning is gradually being abolished) and increasing their fleets' capacity. The modern additions to the fleets are all semi-integrated (Diagram 5.1.6-3), and the latest ones even have a carrying capacity of 3,600 tons, a size which also allows the taking out of service of old and uneconomical craft (see Table 4.1.1-5). However, smaller units (Photograph 5.1.6-4) should continue to be used as feeders to the bigger units.

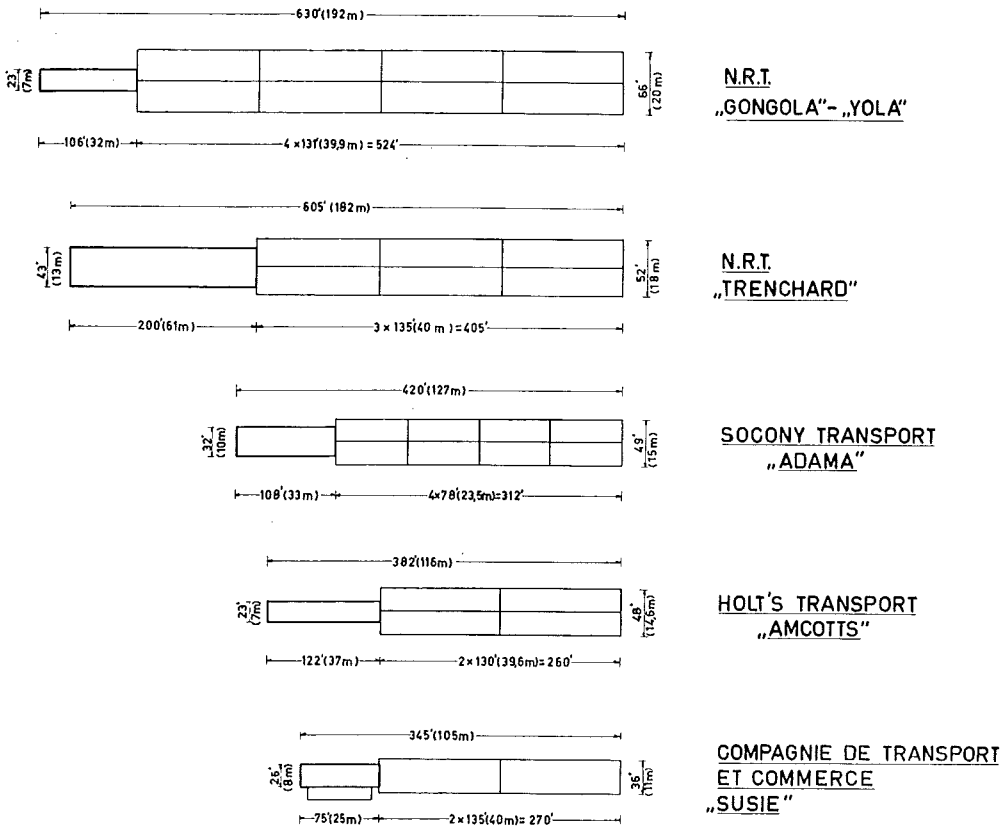


DIAGRAM 5.1.6-3

Comparison of the semi-integrated tows in Nigeria

Nevertheless, the fleets still carried in the middle 1950's to a considerable extent the marks of the pre-war period. Those of N.R.T. and H.T. differ in size of total capacity as well as in size of single craft.

A comparison of performances of these two fleets, together with the performance of tankers of S.V.O.C., will be given below, as this may well throw good light on navigation on the Rivers Niger and Benue.

PHOTOGRAPH 5.1.6-4

"Tugwell" N.R.T.

Figures of 1955 have been compiled in Table 5.1.6-5 from data kindly made available by U.A.C., N.R.T. and Holt's representatives in reports and discussions. It should be emphasised that these figures do not try to give the actual tonnage and ton-mileage transported during a particular complete river-season by all those who use the river, because on the one hand the data are not sufficient and sufficiently specified, and on the other hand the yearly fluctuations in transported tonnage and ton-mileage to and from a river port are of minor importance for the purpose of this comparison. Certain figures have been derived by calculation with the aim at having total figures with an accuracy of about 10%.

The carrying capacities of the fleets estimated in the middle 1950's are:

N.R.T.	
barges	18,750 tons
power units	2,750 tons
H.T.	
barges	4,000 tons
coasters	700 tons
S.V.O.C.	
(motor oil and motor spirits)	2,700 tons

The following freight-carrying units have been brought into account in which the coasters are counted as two-fifths of the Company's fleets, and the oil fleet tonnage only one-third, because they do not operate during a complete river-season.

	Number of units	Total tonnage	Average tonnage/unit
N.R.T.	69	21,500	310
H.T.	33	4,300	130
S.V.O.C.	3	900	300

TABLE 5.1.6-5
TRANSPORT PER YEAR

	TONS			TON-MILES (thousands)		
	total	per unit	per ton-unit	total	per unit	per ton-unit
N.R.T.						
down	115,000	1,665	5.34	52,750	764	2.45
up	63,000	913	2.93	31,300	454	1.46
down + up	178,000	2,578	8.27	84,050	1,218	3.91
H.T.						
down	44,000	1,330	10.22	20,600	624	4.79
up	17,000	530	4.07	7,150	216	1.66
down + up	61,000	1,860	14.29	27,750	840	6.45
S.V.O.C.						
down	—	—	—	—	—	—
up	10,000	3,330	11.11	5,385	1,792	5.98
down + up	10,000	3,330	11.11	5,385	1,792	5.98

Comparing the figures of the three main Companies in Table 5.1.6-5, S.V.O.C. tankers transport far more per ton-unit or ton-barge considering that they have never a return load. The main reasons for this are that

(i) they are modern vessels with more horse-power per ton and they have therefore good speed and manoeuvrability;

(ii) the tankers are plying only in the period when the Niger and Benue are best navigable and the load factor can be at a maximum while during periods of restricted navigability the tankers leave the rivers; and

(iii) the type of commodity implies quick loading and discharging, so that a relatively large percentage of the available time can be used for sailing.

When H.T. and N.R.T. are compared it seems that H.T. uses her fleet nearly twice as intensively as N.R.T. This is, of course, not the case. The chartered coasters for H.T. took a considerable part of the total tonnage and ton-mileage, and their speed and size are responsible for raising the figures, according to sub (i) and (ii) above. In 1955 this worked in favour of John Holt.

Furthermore, it is evident that

(i) small units do not need to reduce their draught as much as large units, and groundings at low water-stages are more likely for big units than for small ones;

(ii) smaller units lose less time per ton-unit during loading and discharging at river ports;

(iii) N.R.T. carries more merchandise upstream, which implies a longer stay in ports; also it is believed that handling of merchandise asks more time; and

(iv) carrying merchandise at high transport tariffs may mean that N.R.T. uses her fleet not so intensively as H.T. but at least as profitably.

The first three arguments work in favour of H.T., and apart from differences in management it may well be that N.R.T. has relatively more barges to meet the problem of large units engaged in river ports when loading and discharging, specially during the Benue season.

In Paragraph 1.3.3 the transported tonnages are given for the year 1945/46 showing a total of 119,500 tons, and for 1955/56 a total of 167,400 tons, which is an increase of about 40%, while in the same 10 years the fleet tonnages have increased gradually by some 30% only.

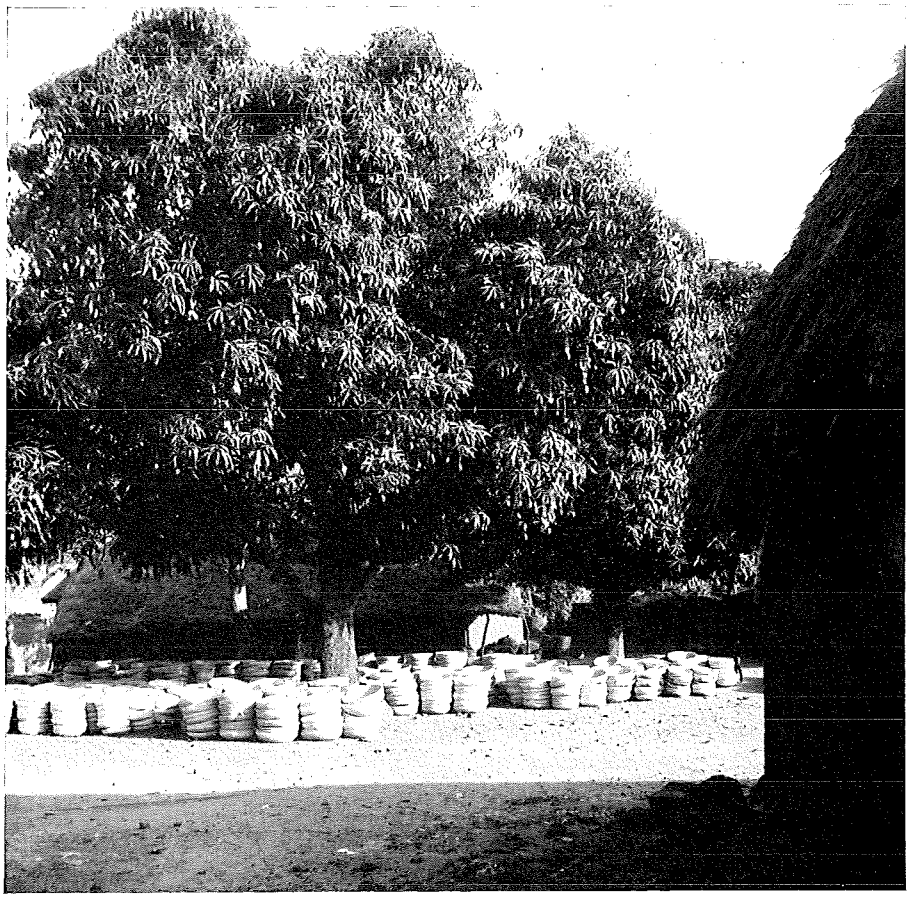
Since 1955 there have been considerable improvements, such as modern new ships, modernised old ships, river buoyage, radio communications, stage prediction on small scale, etc., while

other improvements may be expected in the near future; it will therefore be very interesting to have a similar comparison of performances again in 1960. To realise this with a fair accuracy, it is recommended that there be established a Department of Information and Statistics under the H.Q. of the I.W.D. for the benefit of all parties concerned (VI, 3.8.3).

5.2. LOCAL TRADE

5.2.1. Markets and shipment

The exchange of goods between various parts of Nigeria is of long standing. Practically every family produces something for sale or exchange in the local market and none can live for long without obtaining something he needs from it.



PHOTOGRAPH 5.2.1-1

Calabashes at Baro

The amounts of produce the family has to offer and the goods it requires in exchange are often small in quantity and value. They could not afford to send these small parcels of goods very far, nor could they travel far to sell them or to make their small purchases.

So a considerable number of small traders visit the town markets, selling to and buying from the bigger dealers or foreign merchants. Modern changes in Nigerian conditions have led to an increase in this internal trade. Easier and more speedy means of transport have made the wider spreading of products possible. Thus in addition to imports and exports, large quantities of local produce are now carried by rail, road and water. The small village markets are served from nearby farms by headload, bicycle or canoe, while the larger markets such as Onitsha may receive local produce from many miles away by motor-transport or canoe.

PHOTOGRAPH 5.2.1-2

Transport by head and by canoe

There are well-recognised large-scale movements of local produce in Nigeria, sometimes from one end of the country to the other (Diagram 5.2.1-3). Examples of such are kola nuts, moving from the south to the north, partly even passing over the border into French territory, and cattle and dried meat which travel from the north (partly from French territory) to the markets in the south ([1.

In general, kola nuts, palm-oil, maize, yams, cassava and fruit, all required for consumption in Nigeria, flow northward against a stream of export produce, whilst beans, onions, cattle and dried meat, dried fish, and much of the guinea corn and rice is transported from north to south. In South Nigeria, particularly in the regions known as the Rivers Area and the Niger Delta, the only means of transport is the canoe; but in the other parts of the country motor road transport has been developed far more than water transport.

It is difficult to enumerate all the river-markets that are important to the local trade, as practically every river port mentioned in 2.1.1 has a market which attracts a good deal of canoe shipping. In addition, there are important local markets near centres of food crops. A good example of this is Dere (Mile 394) on the Niger, well-known for its yams.

([1 U.A.C. STAT. & ECON. REVIEW, No 14, 1954. GEN. 36

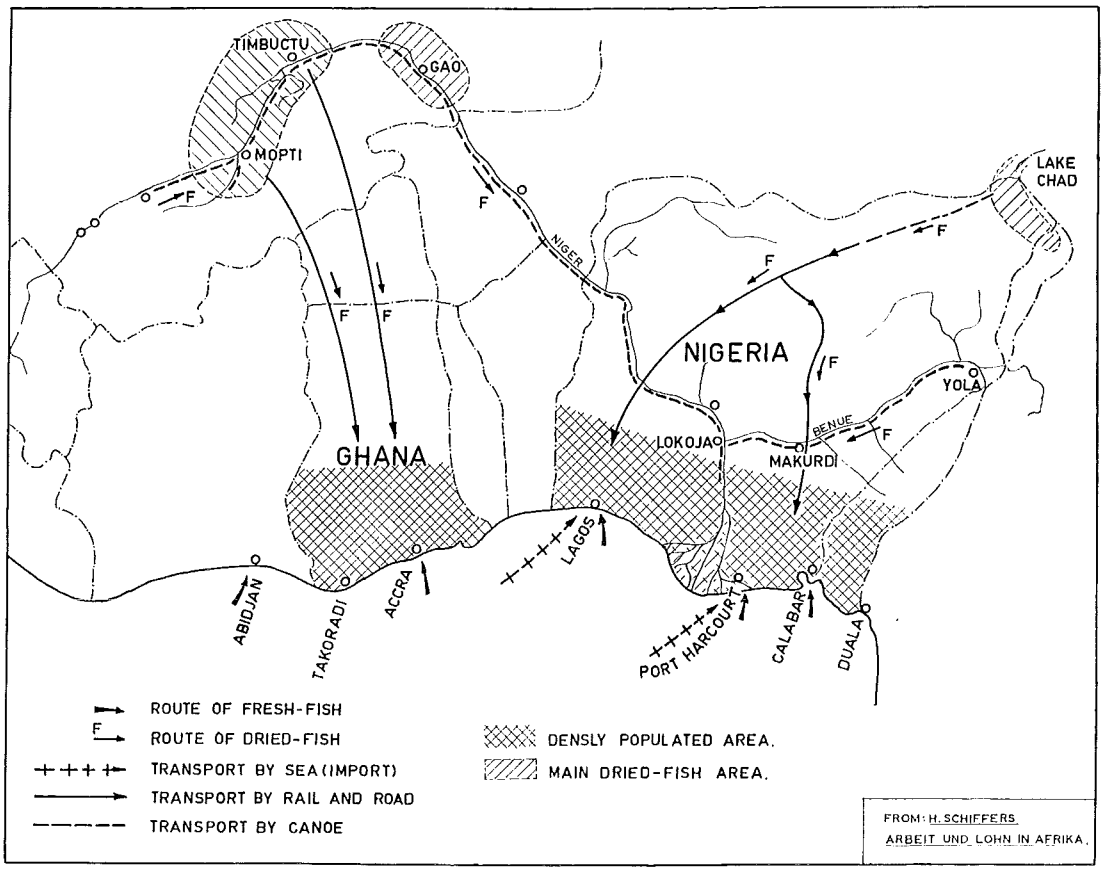


DIAGRAM 5.2.1-3

Dried-fish transport routes

5.2.2. Transport of produce and cattle

As mentioned already in 5.1.1, the river fleets at present handle practically exclusively produce for export and import goods; transport concerning the domestic trade (distribution of the import goods included) is handled mainly by African merchants. On the roads the "Mammy Waggons" — named after their African proprietresses — are the most remarkable means of transport for local trade and passengers. Besides a few road transport departments of larger enterprises — collecting raw materials and produce for their own industries or distributing imports (including fuel to pump-stations) — all the local trade is moved by African transporters.

In 1.1.3 an estimate has been made of the transport by canoe of about ten million ton-miles on the Niger-Benue system, taking into account only hauls over longer distances. This is at present 7—10% of the total transport on this river system.

As there are no other figures available about the amount of transported tonnages of the local trade either by canoes on the rivers or by lorries on the roads, it can only be established that the increase of local transport by canoes (by the introduction of outboard engines and by designs of vessels differing from the conservative canoe-type) has been very small in comparison with the tremendous progress of the road transport (by the introduction of motor vehicles).

Except where there are ample supplies by fish, the southern part of Nigeria is short of animal protein, a deficiency which is partly met by import of cattle from the north. The nomadic Fulani

drive large herds of cattle from the north "on the hoof" towards the south in search of markets, the cattle often travelling great distances, sometimes nearly 1,000 miles. These travelling herds frequently arrive in a pitiable condition and having been decimated by the combined effects of trypanosomiasis (the disease carried by the tsetse fly) and sheer exhaustion ([1].

It is essential to remember that, contrary to common belief, the tsetse fly is not to be found everywhere in Nigeria, but only within the tsetse fly area. In the northern parts of the Middle Belt, the tsetse is confined to the valleys and riverain areas, and large tracts of country are free from the scourge. This has an important bearing on the seasonal movement of the cattle.

The taking of cattle by rail from the north to supply meat to the southern towns is already common, and it is to be wondered therefore why there have been no developments at all of cattle transport by river. By the use of special motorised cattle-barges, this smoother and quicker way to the towns in the south not too far from the river offers economic propositions.

PHOTOGRAPH 5.2.2-1

Cattle being ferried over the river

5.2.3. Feeder-lines of cash crops

The principal cash crops, in the order of the quantities produced for export, are palm kernels and oil, groundnuts, cocoa and benniseed. Groundnuts are grown extensively in the northern provinces, whence they are evacuated by rail for export from Lagos and Apapa, or by rail (via Baro) and by river for export from Burutu and Warri. Palm products are the principal business of the Eastern Region and also the adjacent areas of the Western Region. Palm-oil, which is

([1] U.A.C. STAT. & ECON. REVIEW, No. 8, 1951. GEN. 36

PHOTOGRAPH 5.2.3-1

River-station Idah on the Niger (Mile 310)

produced from the soft fleshy mesocarps of the fruits, is extracted locally and either consumed as an important item of the local dietary, or exported. Palm kernels are generally exported as such, local extraction of oil being undertaken only on a limited scale. The main centre of the benniseed crop is in the country of the Tiv peoples.

Other cash crops include cotton, rubber, bananas, and tobacco, though the latter is grown mainly for the local manufacture of cigarettes and not for export. Another cash crop, which is not exported, is rice.

The feeder-lines of cash crops for export to river-stations along the Niger (Photograph 5.2.3-1) and Benue Rivers are shown on Diagram 5.2.3-2.

To the river-stations Yola and Lau on the Benue the cash crops are mainly supplied by road, while at Baro on the Niger the cash crops arrive by railway.

The feeder-lines of cash crops by river to river-stations for direct shipment as exports are, for instance, on the main river from Yelwa to Jebba or to Baro, and on the tributaries Gongola and Katsina Ala from Dadin Kowa to Numan and from K'Ala Town to Makurdi respectively.

Cotton is transported along the river from Benue stations such as Amageda and Umaisha to the ginnery at Lokoja from which it is shipped for export after it has been ginned.

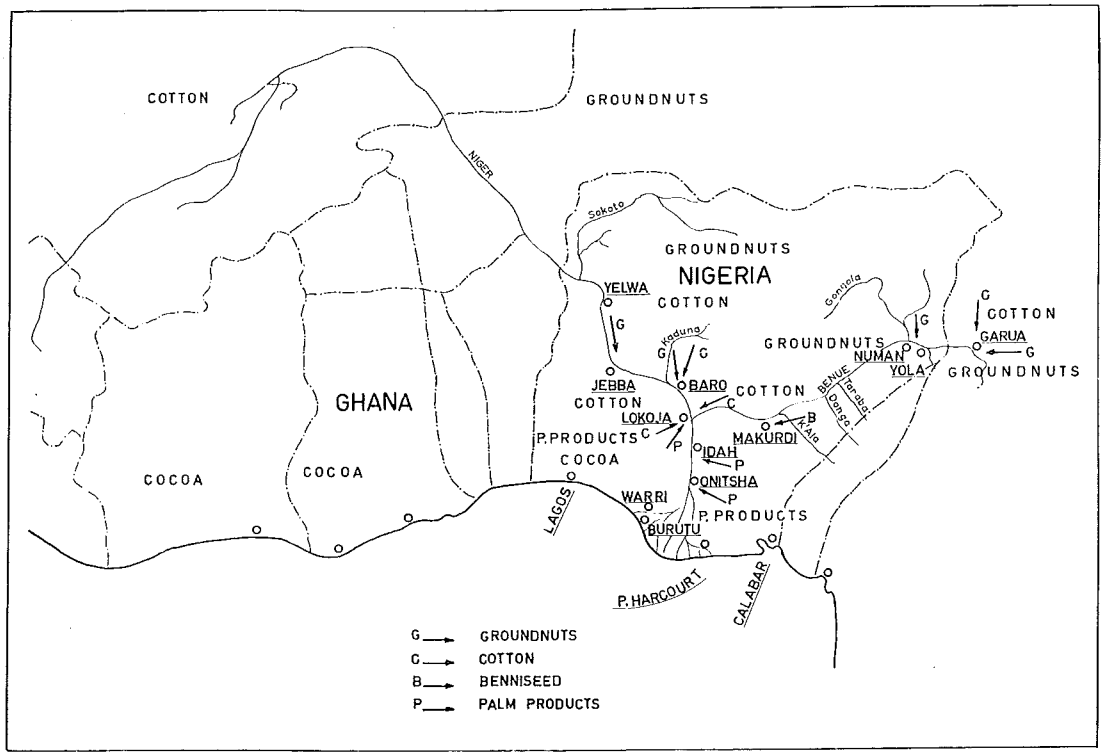


DIAGRAM 5.2.3-2

Main producing areas of cash crops and river-stations of evacuation

5.2.4. Passengers

There is no information available about the number of passengers using the rivers as their travel route, neither of their destinations nor the means of transport they prefer. However, from the Statistical and Economical Review (No. 14, 1954) of the U.A.C. the following figures have been derived:

Numbers of Passengers transported by the N.R.T.

1943-1944	53,000
1944-1945	29,000
1945-1946	23,000
1946-1947	7,000
1947-1948	9,000
1948-1949	8,000
1949-1950	5,000
1950-1951	4.000
1951-1952	6,000
1952-1953	5,000

PHOTOGRAPH 5.2.4-1

Passenger canoe

From this summary the decreasing total from 23,000 passengers in 1945-1946 to 7,000 passengers in 1946-1947 is most remarkable. This seems to be caused by rapid development of other means of transport since the end of the War, due to the extension of roads and the much greater number of lorries compared with before the War, whilst on the river outboard engines on existing canoes came into use (Photograph 5.2.4-1) and new locally-made passenger vessels were launched. During the three years investigation by NEDECO the number of motorised canoes has been steadily increasing. Many of these special passenger vessels now maintain regular services, often daily, between ports and villages along the rivers.

PART V

DEFECTS OF NAVIGABILITY

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CHAPTER 1

DISCHARGES

1.1. INTER-ANNUAL IRREGULARITY

In Section III, 1.3 the climatic conditions in the Niger and Benue drainage basin have been discussed. From year to year, from month to month, even from day to day, variations in precipitation, evaporation and run-off occur. As a result, the actual discharge curves of a river station show for each year wide variations. This is probably best illustrated by the frequency curves of the discharges in Diagrams III, 4.3.4-1 to -7 inclusive, from which can be read:
(i) the large variations of discharge which are possible on a certain date in consecutive years and consequently the large variations in the available depth;
(iii) the large variations in duration from year to year when a certain discharge and available depth prevails.

Both effects hamper navigation by raising uncertainty about available depth, and about the duration of this available depth.

1.2. SEASONAL VARIATIONS

Seasonal variations in discharges are also expressed in Diagrams III, 4.3.4-1 to -7 inclusive. Simplified hydrographs for some main stations along Niger and Benue are given in Diagram 1.2.1-1. These variations depend on the seasonal variations in climate and run-off. A constant run-off would give under natural conditions a channel with a certain minimum depth. Each discharge seeks to establish its own characteristic cross-section for that discharge. According to the theory expressed in III, 6.1.1 under a, the river will have a certain depth independent of the discharge (only of other magnitudes) if a certain discharge would continue long enough to mould the cross-section. However, the variations in discharge are so quick that the cross-sections cannot maintain themselves continuously adapted. At low-water stages the cross-section is too wide and the depth will thus be smaller than could be expected from a constant discharge. The larger and quicker the variations in discharge over the season, the worse are the defects when water-levels fall below the dominant discharge, i.e., the discharge for which the cross-section is built, through the succession of discharges over a long period of years (see III, 6.1.1 under b).

To discuss the defects of navigability a distinction between three river-sections is made.

On the *Niger above Lokoja* (navigable up to Jebba), a clear distinction in high, middle and low-water discharges can be made. The high-water discharges occur from August to November and are caused by the direct run-off of the large precipitation in these months. But for a special circumstance, this high water would directly be followed by low-water discharges, as the climatic

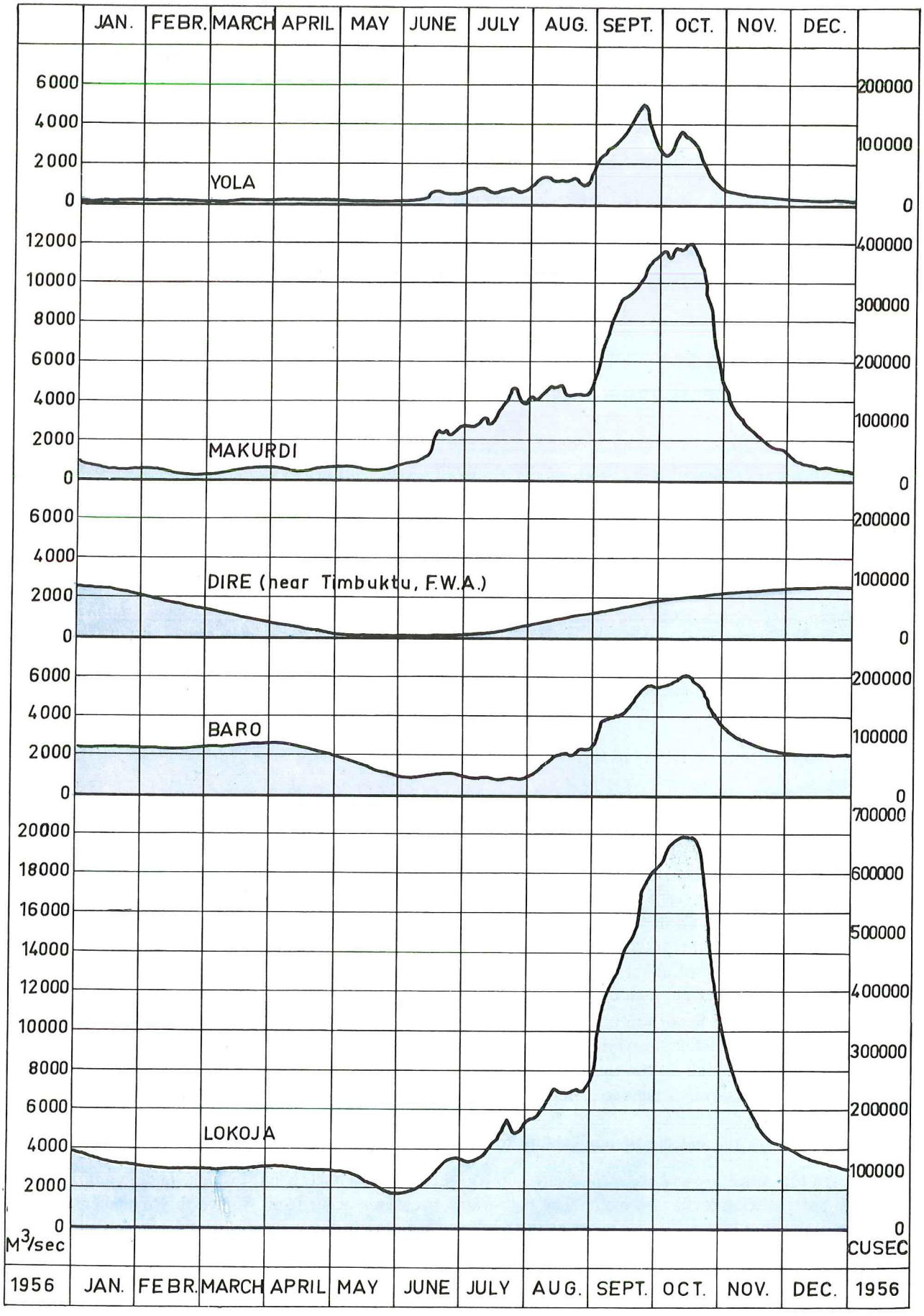


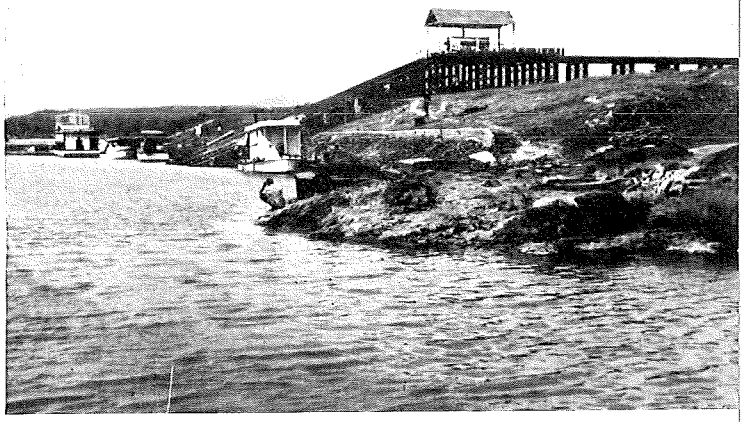
DIAGRAM 1.2.1-1

1956 Discharges of Niger and Benue

conditions are such that after the rainy season precipitation is practically zero for the rest of the hydrological year. However, the run-off from the basins of the upper catchment areas in French West Africa takes 4 to 6 months to reach Baro. The flood in the upper reaches of the Niger is by then flattened to a practically constant discharge, which is for a large part caused by the vast swamps in the Timbuctu area, as well as by the normal evening-out of a high-water wave when it travels over long distances. The fall from high water to the sustained middle water (Black Flood) is rapid, and many shoals formed during the high-water period need some time to be partly adjusted by scour to the middle water. Early in the Black Flood (December) navigation experiences this influence, which has been described as retarded scour (see Diagram IV, 3.2.2-1). In the low-water period (April—July) the discharge decreases to such small quantity that although scour of several feet may occur navigation is impracticable.

The *Benue* has only the distinction between high and low-water discharges. High water (June—November) is normally ahead of high water in the Niger above Lokoja, as the drainage basin of the Benue lies further south and the precipitation is more intense. This is the only period in which navigation is possible with draughts of more than 4 feet. In the upper sections of the Benue this period is even confined to the months of August, September and October. After the rapid drop of water-levels at the end of the rains, which is every year a hazard to ships, discharges are just too small for shipping of any size. Even with the obtaining scour of several feet the available depth then soon falls below two to three feet.

PHOTOGRAPH 1.2.1-2



PHOTOGRAPH 1.2.1-3

High and low water at Lokoja

Moreover, the climatic conditions are such that in July or August, especially in the Benue drainage basin, a temporary reduction of precipitation often occurs. This is known as the "little dry season", and the effect on the river-levels is known as the "August fall". In years when this August fall is pronounced, it is a very unpleasant drawback to navigation, which may lose time for a complete round-trip into the upper reaches of the Benue.

Finally, the very large range of discharges in the Benue — a common feature of tropical rivers — has adverse influences on the channel formation. The sudden and large run-off of precipitation in tributaries causes great movement of sediments. Near or downstream of the confluences such sudden sediment discharge will shoal the channels when the main river cannot

directly carry all these sediments downstream. The high-water discharge causes also a large sediment transport in the main river-bed with fast moving sand-banks and shoals. Navigation therefore calls for great care.

On the *Niger below Lokoja*, all the above-described defects of navigability, — resulting from the distribution of discharges and deficient discharge at low-water, retarded scour after rapid drop in water-levels, shoaling of channels near or downstream of confluences, and the fast shifting of sand-banks and shoals during high-water, — are found back here, but not, however, as pronounced as in the river-stretches which join near Lokoja. This is due to the fact that a part of the low-water period on the Niger above Lokoja is covered in June by the rise in the Benue, and the low-water discharges of the Benue are overlapped by the Black Flood of the Niger. The result is that on the Lower Niger the high-water period starts approximately a month earlier than on the Niger above Lokoja, while the low-water period is at least a month shorter, as the rains in the south also start earlier; the tendencies of the defective navigability are smoothed because the two hydrographs of the Upper Niger and Benue are not in phase. An August fall on the Benue can also be noticed on the Niger below Lokoja, but as discharges are already large, this does not affect the navigability.

CHAPTER 2

RIVER-BED

2.1. CROSS-SECTIONS

2.1.1. Origin

In III, 6.1.1 a formula was derived for the relation between equilibrium slope (i), depth (a) and grain-size (d) of a straight alluvial river with erodible banks and a uniform flow:

$$\frac{\Delta d}{ai} = \text{constant, probably about 2}$$

where Δ is the relative density of the sand grains (i.e., 1.68).

With the small grain-sizes and moderate slopes obtaining on the Niger and Benue, this would lead to an equilibrium depth (at uniform flow) of a few metres (yards). A similar depth may occur at the dominant discharge of a non-steady flow, which implies that at lower discharges (often occurring) the depths will hardly be sufficient for an economic navigation.

The width of the rivers can also be expressed in a formula (III, 6.1.1) from which it follows that the small grain-sizes, moderate slopes and considerable discharges of the Niger and Benue result in widths of the river-bed that are proportional to the discharges, and vary between 500 m (1,650 feet) in the upper reaches to 2,000 m (6,500 feet) in the lower sections of the rivers.

The ratio between width and depth could also be calculated, and it is found that the width of the rivers is several hundred times their depths.

In III, 6.1.2 it was explained that the erodibility of the river-banks tends to flatten the cross-section of the river in a bend. Here, too, the width of the river is more than a hundred times its depth, although the latter is usually ample for navigation.

Summarising, it can be said that the small grain-sizes and moderate gradients of the Niger and Benue river-beds are the origin of a very unfavourable cross-section, in spite of the large discharges of water, which only affect the width and not the depth of the bed.

2.1.2. Effects

The effect of the unfavourable cross-section is a most inefficient use of river-water from the point of view of navigability. The width of the channels is almost everywhere many times larger than necessary, and the depths are generally insufficient.

It is evident that neither the grain-sizes nor the valley-slopes can be altered to improve the depths. But by artificially restricting the width of the rivers, a more efficient use of the considerable discharges of water may be made, a method which is discussed in VI, 6.2.5. Another means of increasing the efficiency of the discharges in maintaining a more favourable cross-section is by a discharge regulation which evens the flow and thus maintains a dominant discharge during a longer time.

2.2. BANK EROSION

2.2.1. Origin

In III, 6.2.5 bank erosion has been discussed. There are two main causes of bank erosion:

(i) Direct erosion, which acts on the banks exposed to running water. Reduction of pore pressure, chemical action and dissolution all cause the loosening of particles from the bank which are then carried off by the tractive force of the water or sink to the bed when this tractive force is not sufficient.

(ii) Indirect erosion, which results from bankslides or collapses of undermined banks. The former are related to ground-water flow out of the banks (mainly after a rapid drop in water-level in the river-bed) and softening of the banks by inflowing ground-water (mainly during a rapid rise), both of which cause a disturbance of the equilibrium in the bank. The latter (often stimulated by the former) find their origin in the strong attack of the running water at the foot of a bank.

The extent of the erosion of the river-banks depends, of course, on the erodibility. Many of the Niger and Benue banks consist of highly erodible sands, with an admixture of clay in the upper layers; some banks, however, are definitely clayey and more resistant to erosion.

Especially important for the effect of erosion is the local erosion, i.e., the difference of erosion in consecutive cross-sections.

2.2.2. Effects

The first effect of bank erosion is that the river will tend to meandering.

The flow between two consecutive loops of a meander has practically straight flow-lines, and there the cross-section of the river has almost equal depths throughout the width. This is the so-called crossing, and at middle and low-water stages the width on the crossings may become larger than the width upstream and downstream (in the channels) as a result of current deviation (see III, 6.4.2). The resulting picture is that of a variation in available depth along the talweg, a depth which each time has a minimum over a crossing. These minima reach extremes in the following cases:

(i) When locally the erodibility of banks is large, so that the cross-section is very wide in its equilibrium and when this cross-section happens to coincide with a crossing. This will occur regularly in the downward movement of the sand-banks.

(ii) When excessive erosion has led to the formation of an island in the river-bed. Then the channel is less efficient than the single undivided river and many shoals may occur in such split channels. Lastly, the large-scale erosion of the banks of the Niger and Benue creates a major instability of the river-bed and contributes substantially to the transportation of sediments.

(iii) When in the cross-section on each side along the banks a deep channel exists, one of which was formed in the past when the flow followed the one side, the other formed more recently when the main flow attacked the other side. Under these conditions, on its way from the deep channel on one side to the deep channel on the other side the talweg passes a point with extreme little available depth, specially during medium and low-water stages.

2.3. MIDSTREAM ISLANDS

Islands in a river cause disturbances in the regularly meandering stream pattern of a single channel with alternating bends and crossings; and such disturbances in the basic system of equilibrium always result in sand deposition at odd locations.

The island divides the cross-section into two parts, each of which has a smaller discharge than the undivided river upstream. Consequently, the meandering characteristics (such as the meander-length) in the two branches differ from the original ones. In the zone of transition the picture of the meandering flow is not clearly distinguishable, in particular below the island where the two separately oscillating branches join and must return to a single system. It is, for instance, very probable that the two meandering channels are at the lower end of the island in antiphase, resulting in the flows crossing each other, as shown in Diagram 2.3.1-1. It then takes a long way before their mutual interference declines into a single pattern again, while often such a single equilibrium is not reached because of the existence of another island, more downstream, the formation of which is consolidated by the crossing flows.

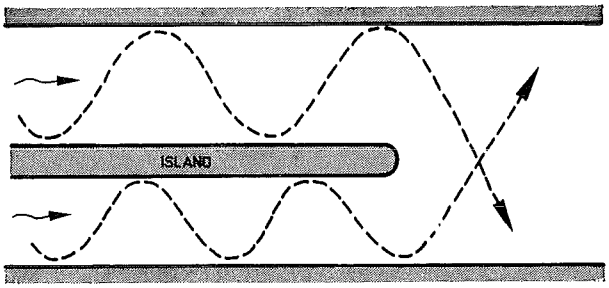


DIAGRAM 2.3.1-1

Crossing currents below an island

The distribution of discharge over the two branches largely influences these phenomena. Where the discharging capacity of each channel is more or less equal, disturbance by crossing flows has a maximum effect. When, on the other hand, one channel discharges only a small fraction of the total flow, the picture downstream from the island is dominated by the stream from the main channel, and a quick adaptation toward a single channel pattern is effected.

On the upstream side of the island, the undivided meandering channel can enter the bifurcated section in various ways. If, in the first instance, the meandering flow enters gently into one of the channels and the second channel branches off on the inner side of the bend (section A of Diagram 2.3.1-2), the result is the existence of a sand-bank in the entrance of the second branch, reducing the flow through that branch by the extra resistance of the sand-bank (see III, 4.3.8). The situation can be described as a natural closure of one branch, as discussed under III, 6.6.4, where it was concluded that the navigation conditions in the main branch are excellent.

The meandering channel, however, gradually moves downward, and the time will come when the main flow attacks the upper end of the island right on its front side (section B of the diagram). The sand-bank in the entrance of the second branch will also be moved downward, or even possibly have disappeared as such, having, for instance, been split up into a number of small sand-banks, the shape, size and mutual distance of which are adapted to the conditions of flow in the branch, and differing from those in the single upper river. The discharging capacity of both channels would be more or less equal.

Neither of the branches can now be described as the main channel and there is no distinctly continuous meander. It is this state of transition which causes irregularities in the stream pattern. Both branches, as well as the upstream approach towards these branches, might be shallow, while, as already stated, below the island the crossing currents do not present good shipping possibilities.

At a later stage of development, the downward motion continues and it will be the turn of the second branch to discharge the major part of the total flow, corresponding with the existence of a sand-bank in the entrance of the first branch (section C of Diagram 2.3.1-2). The result then is a good navigation channel.

Islands, therefore, do not necessarily hamper navigation by their mere existence, but they form the origin of a cycle with the main flow switching over from one branch to the other and back. Such a state of transition gives difficulties for ships to pass.

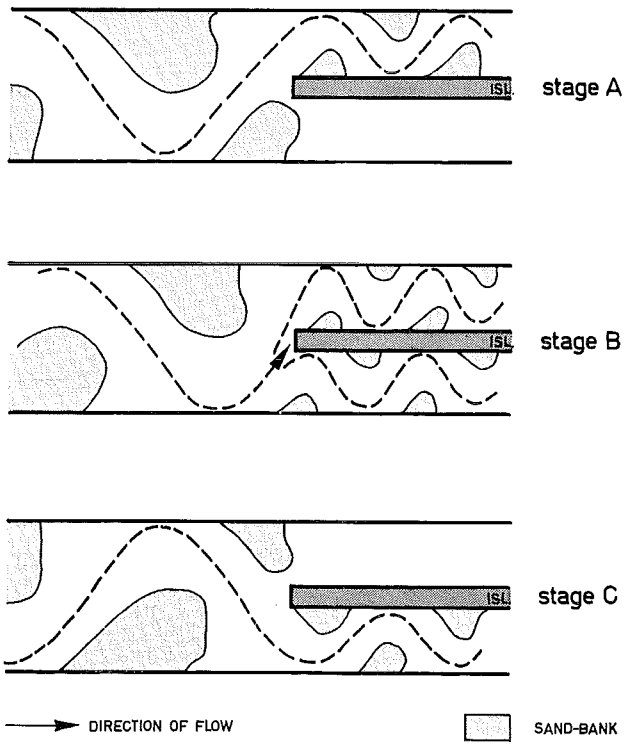


DIAGRAM 2.3.1-2

Meander-cycle passing an island

The above considerations have been outlined without taking into account that the discharge varies seasonally. During high water, a possible existence of a sand-bank in the upper entrance of one branch has little effect upon the discharge distribution (see III, 4.3.8), while a clear meandering of the flow at H.W. does not occur. Crossing below the island of currents from the two branches is, therefore, limited to the medium and low stages of the hydrograph; but any tendency to the formation of a navigation channel below the island as a result of one branch discharging the major part of the flow, will be counteracted by the yearly local depositions of sand during the medium water-stages when the main branch is eroding, due to the influence of the natural closure of the second branch by the sand-bank (see III, 6.6.4). Such a situation is very complex, but has nearly always somewhere some adverse effect on shipping conditions, either upstream or downstream from the island, or inside the branches along the island.

Indirect causes of defects of navigability near islands originate from the total width of the river-bed. As an island exists wherever the conditions for its formation are favourable, this will

in the first instance be in a section with a large width. However, formation of an island may be delayed and it appears from observations on the Niger (Diagram 2.3.1-3) that immediately above the island the river is wider than averagely. On the other hand, the lower end of the island

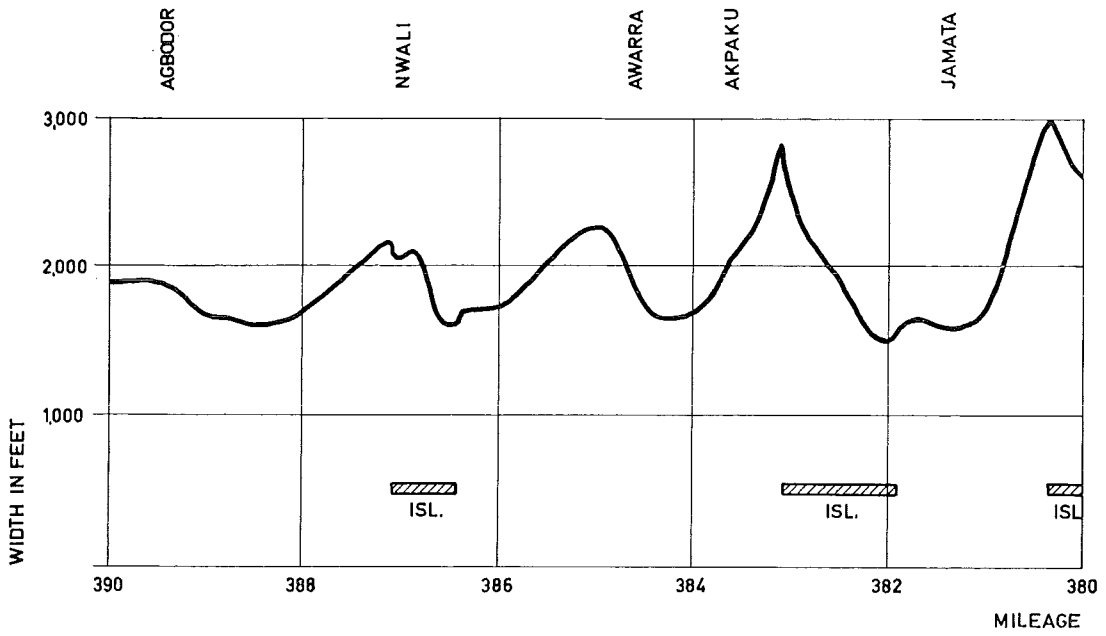


DIAGRAM 2.3.1-3

The width of the Niger as related to the existence of an island

has been in most cases formed by gradual deposition of sand on its leeside, with the probability of the island growing actually too far downward, which is also a type of lagging behind. Generally speaking, a flat-like feature occurs upstream from the island, while the sudden widening at the downstream end also causes sand deposition. These phenomena, however, are believed to be of secondary importance; the first-mentioned direct effects of an island upon the channel configuration prevail over the latter.

2.4. FLATS

2.4.1. Origin

A flat is a section in an alluvial river where the width of the river at bankfull-stage is larger than the average width of the river and where the bed formation is such that channels are hardly distinguishable. Mainly as a result of the great width there will be extreme minima in the talweg depth, where the flow from one badly-defined channel crosses into another. Island formation on flats, like channel formation, is under-developed. The flow hesitates and frequently changes its preference for a channel.

In a wide river-stretch the size of a cross-section, expressed by the value for the scour criterion ba^{α} (see III, 5.4.1), does not correspond with the average size in the river-sections upstream and downstream. At high water the value for ba^{α} is greater, while at low water it is smaller,

than the ba^{α} in the average river (see III, 4.2.6), involving a deposition during high water and a scour during low water in the wide river-stretch.

The great width between the banks on a flat and the unbalanced bed formation are related. Probably the unbalanced bed formation will be due to sand deposition during rising and high water, which is excessive in developing channels, as the ba^{α} in developing channels is inclined to increase most.

Also on crossings the value of ba^{α} is large and sand deposition occurs, but as a crossing is situated between two consecutive well-defined channels, it is more or less stable in its location. The difference with a flat, however, is that a flat has a large value of ba^{α} over a relatively long distance along the axis of the river, which means that on a flat the deposition during high water can and will occur in the channels where ba^{α} is highest. The result is that on a flat a constant process of development of channels and counteraction by deposition takes place during rising and high water, so that the shipping route may change overnight, in contrast to the shipping route over a crossing which is more or less stable.

It is also clear that, as a result of the small value of ba^{α} during low water, strong scour occurs on flats. The differences between the determining talweg elevation at high and low water are, therefore, in general larger on flats than on crossings; in other words, breathing of flats is stronger than of crossings (see III, 6.4.2).

During high water there will, in fact, be no restrictions on the present navigation, since the ships' draught is also determined by navigation in other seasons. However, when, as a result of discharge regulations, these other seasons permit a greater draught, flats will also during high water become restrictive and should be improved by training-works. During middle and low water-stages flats are at present determining the ships' draught.

A flat, as follows from the above, originates from a sudden change in boundary conditions. However, when an alluvial river-bed has been gradually built up and no disturbances in this process have occurred, the characteristic features of the river, such as slope, width, depth, composition of banks and discharges of sand and water, will also gradually change in consecutive cross-sections. No sudden changes resulting in flats can happen, although local disturbances will always remain. Then, only crossings between two consecutive curved channels will determine the navigation depth. The best examples of such gradually built-up river-beds can normally be found in the lower sections of a river, where it reaches its own delta.

Nevertheless, a flat must find its origin in a sudden change of boundary conditions, and such a change is, for example, possible as a result of regime changes in the past, such as:

(i) a lowering or upheaval in the river basin;
(ii) a heightening of the sea;
(iii) a decrease or increase in catchment area; or
(iv) a change in climate.

The change of regime will remain noticeable as a change in slope at a certain point along the river axis. Near this point, in the transition zone between the new and the old regimes, a kind of sediment delta propagates downward, gradually establishing the new equilibrium further downstream in the alluvial river. Flats may then occur in this transition zone.

Purely local circumstances might also lead to the existence of a flat. The composition of banks, for instance, differs from place to place. The alluvial bed is normally many times wider than the actual stream-bed, and the differences in composition are a result of silting under different circumstances. When the river in its course through the alluvial bed happens to flow in a part where both banks are easily erodible, a wide cross-section may result, forming a flat.

Where local spurs of the basement rock resist a free development of an alluvial bed, they often create a well-developed channel of restricted width. Such a circumstance can also be responsible for strong variations in ba^{α} along the river, and then again irregular sand-transport through the year results in consecutive sections. In the river-sections above and below a section with such well-defined channels, the ba^{α} during high water can be relatively greater and the resulting sand deposition can lead to flats when this is excessive.

2.4.2. Examples

Wuro Boki Flats, probably caused by the pulsating sand-movements from the Faro River and possibly accentuated because of a heightening of the river-bed. The latter effect should be caused by the difference in annual transporting capacity of the Benue below the Faro Confluence and the combined annual supply of sand of the Faro and the Garua Creek, the former being the greater. For more details reference is made to III, 6.5.

Gamadio and Tungaladan Flats, probably caused by the change in slope, which is 20×10^{-5} at Numan against 15×10^{-5} at Lau. Gradually the flats will shift downstream and probably they will even out in due course (but not in a lifetime). They may be originated by a change in regime (capture of the Kabia by the Logone?).

Akpanaja Flats, Agbama Flats and Kokoin Flats, caused by the seasonal scour (at high water) of the narrow river-sections upstream (Makurdi Narrows and Rocky Section of the Niger respectively) and subsequent seasonal deposition (at high water) in the wide cross-sections below the narrowings. This effect is something like the breathing of the sills, but on a larger scale.

Lokoja Flats, originating from the non-synchronised hydrographs of the Niger and the Benue (see 3.2.2). Alternating deposition and scour occurs; the Flats are "breathing".

2.5. MEANDERS

2.5.1. Shifting channels

In III, 6.2.1 a description has been given of the meandering of the Niger and Benue channels. The most widespread feature is that of a fairly straight high-water bed, a "reach" with parallel shorelines, between which the channel oscillates from one shore to the other, winding around sand-banks that are alternately attached to the right and left shores. This whole system propagates downward during the flood period, making it difficult to locate the deepest channel for navigation.

Problems are even greater when it is not a single oscillating channel that shifts, but a braided channel. Then there is often a choice between several channels of which one is slightly deeper than the other; but during the flood, one of the other channels may within a few days become the deepest, the former being blocked by a moving sand-bank.

2.5.2. Curvature of channel

Another problem presented by meandering channels is their curvature. The reach-type of river, however, gives this kind of difficulties only occasionally, e.g., when during medium stages a crossing happens to be in an unfavourable position. Local radii of some 800 feet may then occur.

The purely meandering sections (Garua Creek, Forcados River) at several places show sharp bends with radii of less than 800 feet (see IV, 3.1.3) which are difficult to navigate.

2.5.3. Composite meanders

The purely meandering Forcados River presents still another problem. Due to the appreciable medium discharges, a secondary meander-pattern seems to be superimposed on the meanders of the high-water bed; or, in other words, the deepest channel meanders between the meandering shores. Where these two meanders (H.W. and M.W.) coincide, a deep channel results. But where the H.W. and M.W. channels cross each other at an angle, a shallow crossing will occur.

It should be noted that such a divergence also occurs in the reach-type of river where the flow over a crossing at H.W. is different in direction from the one at L.W., resulting in a shallow crossing (III, 6.4.2). But the angle between these two flow-directions is more pronounced with composite meanders, and occasionally shallow crossings may occur (Epidiama, Mile 146; Patani, Mile 130) notwithstanding the generally favourable channels of the purely meandering-type of river.

CHAPTER 3

AFFLUENTS

3.1. BACKWATER

3.1.1. Origin

In the above chapters, the situation on a single river has been discussed. Difficulties occurring there are always due to factors within the river's own regime or its boundary conditions.

As soon as an outside influence upon the river is apparent, a number of complex phenomena produce effects which cannot easily be analysed quantitatively and which cannot be represented by average or mean circumstances, since such circumstances vary from year to year with two dimensions of variation.

Such an outside influence is present where the main river is joined by a tributary. The downstream water-level is determined by the total discharge of the main river and tributary together, while the water-level in the upstream sections of each river undergoes an influence from the other. Such backwater influences have been described under III, 4.2.6.

Not only the water-level, but also the river-bottom is affected. This originates in the excessive erosion due to draw-down of water-level and deposition of sand during a period of raise. In the first case, the motive power for sand-transport (the drag) increases gradually towards the point of maximum draw-down (being the point of intersection), where it reaches a multiple of its original value. The resultant growing sand-transport involves erosion, either from the bottom or from the banks. In the second case, the reverse happens; by decrease of drag, sand is dropped.

The situation is complicated by the fact that raise propagates farther upward than draw-down. During the yearly variation of period and magnitude of backwater, the section of the upper river located further upstream feels the effect of the raise only, while the lowest section immediately above the confluence undergoes both influences equally. Moreover, the eroded masses of sand during a draw-down of, say, 1 foot are larger than the deposition during a raise of 1 foot. As a result, the ultimate equilibrium of the river-stretch above an intersection is such that the yearly raise of its water-level lasts longer or has a greater magnitude than the corresponding yearly draw-down.

It might be possible to approach such an equilibrium by assuming an average picture of backwater, occurring every year equally. This has been done in III, 6.5.8 for the case of the Lokoja Confluence, where the lowest section of the Upper Niger has been severely affected by the influence from the Benue. However, such an average yearly cycle does not exist. Just as a small difference of two large numbers is very inaccurate, the secondary phenomenon as a result of the mutual interaction of two un-correlated hydrographs could not be accurately calculated from the average of each of these hydrographs. The example of III, 6.5.8 should, therefore, be considered only as a general explanation, and it is not astonishing to find a temporary shoal

in the Upper Niger Entrance due to backwater influences, although the general calculation of this river-section would indicate very deep water at this Entrance.

3.1.2. Effects

A notorious example of backwater influence is the existence of a shallow "bar" in the north entrance of the Benue near Lokoja, hampering navigation on a large scale. The north entrance is the normal route for navigation, possibly because it is the shortest way from Lokoja, while rocks in the south entrance frighten the masters of the river vessels. However, although observations in the south entrance have been few, the impression has been obtained that this south entrance provided a deeper channel than the north entrance during the investigation by NEDECO. The probable cause for this is a temporary one: the meandering channel of the Niger intersects the Benue South Channel accidentally in such a way that a sand-spit between the two rivers (see III, 6.2.3) like the one near the north entrance hardly exists. There is, however, another reason which might make the north entrance preferable: the Lokoja Flats immediately below the confluence of the Niger and the Benue South Channel. Especially at the time of the first rise in the Benue, these flats are shallow (see 3.2.2) and a good crossing channel might be hard to find, although this, too, is a matter of changing possibilities from year to year. Anyway, it seems that a constantly navigable channel in this area exists along the so-called "Sacrifice Channel" near the western bank behind Duck Island (see Diagram III, 6.5.8-1). This route was used during the low-water period of 1957 on recommendation by NEDECO. In this way crossing of the Lokoja Flats is not necessary and the use of the South Channel does not come into consideration. This, connected with the possibility of a future deterioration of the south entrance when the accidental temporary meandering condition at the point of confluence comes to an end, makes a consideration of the Lokoja Bar in the north entrance of the Benue interesting in all respects.

When, after the low-water season, a small rise of the Benue already permits navigation on that river, the river fleet has to wait in Lokoja for a chance to enter; in some years more than two weeks have been lost in this way.

The cause of the Lokoja Bar in the entrance of the Benue must be sought in non-synchronised phases of Niger and Benue. As stated in III, 6.5.8, a sand-spit between the two rivers at one time blocks the Upper Niger and at another time the Benue Entrance. The most powerful of the two rivers will scour any blocking sand in its own entrance and cause deposition in the other.

During the long dry season, it is the Niger with its Black Flood that is much more powerful than the Benue, and consequently the entrance of the latter becomes very shallow. This is partly caused by deposition of Benue sand in its lowest section due to raise of water-level by the Niger, but mainly by deposition of Niger sand in the Benue Entrance by eddies and velocity-drop at the very confluence (see III, 5.4.5).

The influence of the Niger upon the Benue reaches some 30 miles upward; in the more upstream sections of the Benue, where no raise from the Niger is felt, no abnormal deposition of sand occurs. There, a sill on a crossing scours during the low-water season, and when the first rains effect a small rise of water-level (rise of discharge), the channel has a reasonable depth. The least available depth between Makurdi and Mozum (16 miles above Lokoja) might then be sufficient for navigation; but the increase in discharge of the Benue has certainly not yet been able to scour in a short time the huge masses of sand from the Benue Entrance.

To make matters worse, the Benue water-level is drawn down by the very low Niger just at the time when ships want to enter the Benue and pass the Lokoja Bar. This, on one hand, will accelerate the scouring of the bar by the Benue discharge, but on the other hand will still further

reduce the available depth. The first influence needs time to take effect; the second is instantaneous. As mentioned under III, 4.2.6, the Benue has been drawn down by the Niger in

1955 from June 10th to July 21st,
1956 from June 3rd to September 20th,
1957 from May 10th to July 12th.

Diagram 3.1.2-1 gives an insight into the occurrence of the phenomenon. Water heights and bottom heights, both expressed in feet above Mean Sea Level, have been plotted against a time-axis. The black line is the hydrograph as it actually occurred at the very point of confluence of both the Niger and Benue. Raise and draw-down of the Benue by the Niger, as calculated under III, 4.2.6, have been used for the construction of the red line which indicates the water-level that would have occurred without any influence by the Upper Niger. The height of the sill, determinant for the L.A.D. of the Benue Entrance, is shown by the grey area. A normal sill in a crossing of the upper river (Benue) would be heightened by high water and scoured during

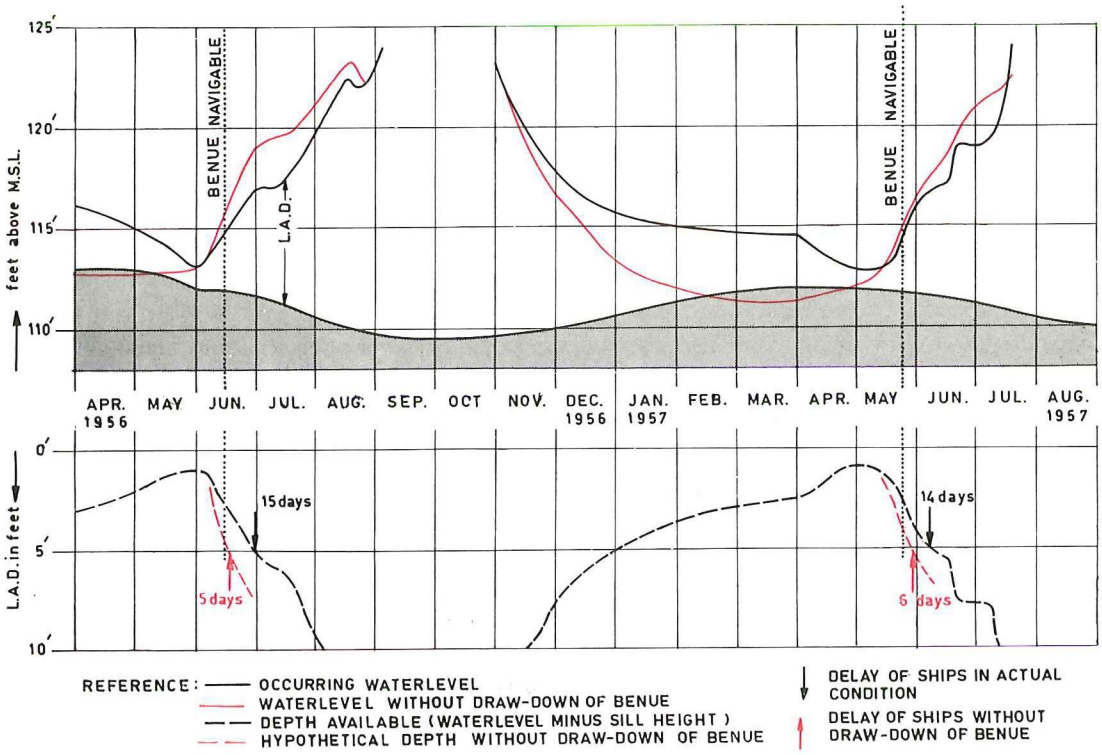


DIAGRAM 3.1.2-1

Origin and effect of the Benue Bar

the fall. Here the adverse is seen, effected by deposition mainly of Niger sand during the raised period (November till May), and scour by the Benue itself mainly during its period of draw-down (June and July). The depth can be derived from the above as the difference in height of water-level (black line) and the bottom (grey area). It has been plotted in the downside of the graph as a black stroke-line.

The day when ships (drawing 5′ when going up the Benue at the beginning of the season in June) can pass the Lokoja Bar has been marked with a black arrow, while navigation on the

Benue itself appeared to be possible from an earlier date, given by a vertical dotted line in the diagram. A delay of 15 days in 1956 and of 14 days in 1957 appeared to occur; this delay is partly caused by the draw-down of Benue water-level and partly by deposition of sand in the entrance during its previous period of raise.

In the depth-graph a red stroke-line has been drawn in addition to the black line, indicating the depth on the Lokoja Bar that would have been available without draw-down of the Benue. In that case the day of passing the bar would have been earlier than actually occurred, viz., 10 days in 1956 and 8 days in 1957 (both marked with a red arrow). The remaining delay of 5 and 6 days respectively is due to the deposition of sand already mentioned.

It can be concluded from the diagram that (apart from other possibilities) an eventual requirement to make the Benue Entrance navigable on the very same day as the Benue River itself is navigable could be obtained by dredging the deposition or by artificial raise of the Benue effected by an increase of discharge from the Upper Niger (see VI, 8.3.5).

Summarising, the backwater effect at the Lokoja Confluence results in the loss of some 2 weeks on the navigable period of the Benue.

3.2. SEDIMENT DEPOSITS FROM TRIBUTARIES

3.2.1. Origin

Deposition of sand in an alluvial river always takes place where the supply is more than the transporting capacity. Such is the case, for example, at raise by backstage, as described above.

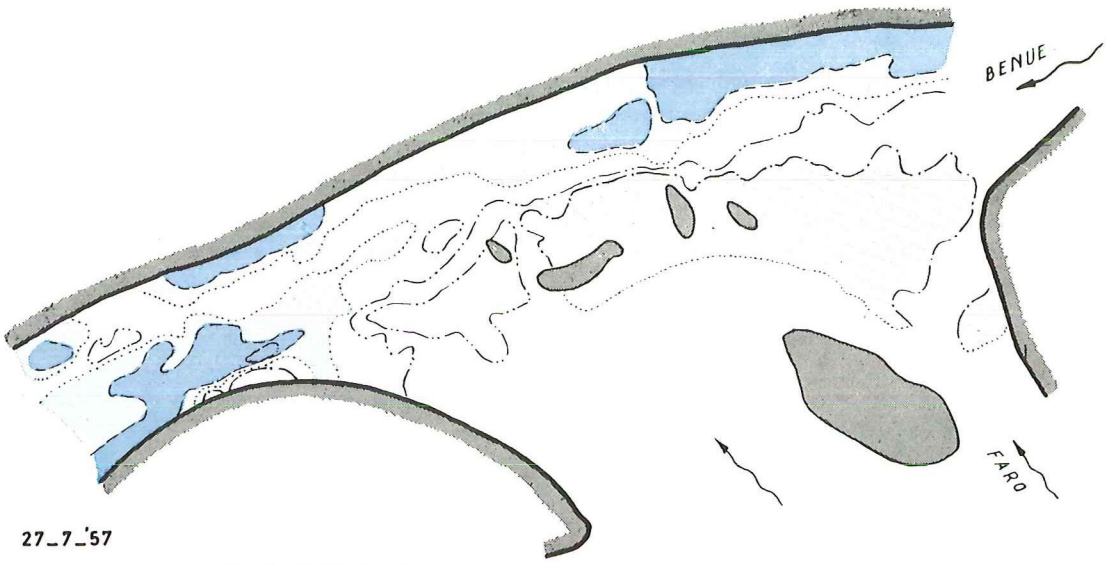
But there are other possibilities. Supply of sand from a tributary into the main river must be compensated by a corresponding increase of transporting capacity of this main river, in order to attain equilibrium at the confluence. This might come true when the tributary and main river both carry their sediment in an evenly continuous stream. The configuration of the entire confluence will adapt itself until at any place the sand supply equals the transporting capacity (see III, 5.4.5), and equilibrium is fixed. However, in a natural river the sediment discharge is certainly not constant. The water discharge of a normal tributary shows steep and irregular peaks, with quick rise and fall of its water-level. Correspondingly the sand supply is of a highly pulsatory type, bringing into the main river large masses of sand in relatively short periods. In most cases this sudden supply exceeds the transporting capacity of the lower main river, and deposition at the point of intersection is the result. In course of time, after the high peak of the tributary has disappeared, while the discharge from the upper main river remains moderate over a longer period, this buffer stock of sand is scoured again.

3.2.2. Effects

A clear example of this phenomenon is the Mimi Delta, debouching into Sacrifice Channel of the Niger some 5 miles below Lokoja, which has been described in III, 5.4.5. The Faro Confluence with the Benue also shows a wide sand-bank protruding into the Benue. After a high peak discharge from the Faro, it nearly blocks the Benue, leaving only a narrow channel along the northern bank; in course of time, the edge regresses gradually (Diagram 3.2.2-1). However, neither of these examples actually hampers navigation.

Quantitative prediction of such phenomena is not possible, since calculation on the basis of an average year is useless.

A past occurrence, however, can be analysed. Diagram 3.2.2-2 shows the results of such an analysis on the Lokoja Flats, immediately below the confluence of the Niger and Benue.



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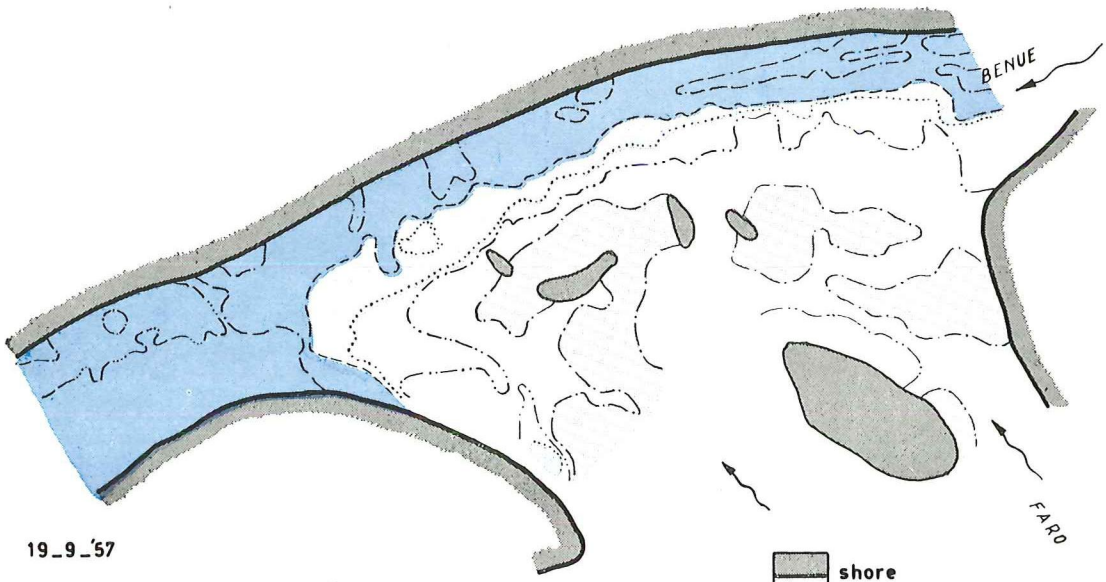
2 DAYS AFTER A HIGH FARO PEAK

remaining channel: depth 3'
width 115'
crossing below confluence: depth 2'10"



19_9_'57

17 DAYS AFTER A HIGH FARO PEAK

remaining channel: depth 4'
width 290'
crossing below confluence: depth over 4'

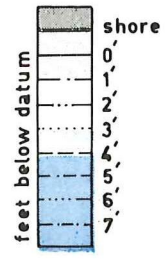


DIAGRAM 3.2.2-1

Movement of the sand-bank in the Faro Confluence

Their situation is not at the very point of confluence, as in the case of the Faro-Benue intersection, because here both the Niger and Benue are almost equal, while their discharges do not pulsate, but are merely non-synchronised. The phenomenon, therefore, is not as pronounced as the Faro sand-bank; the deformations are more gentle and slow. Yet the Lokoja Flats cause

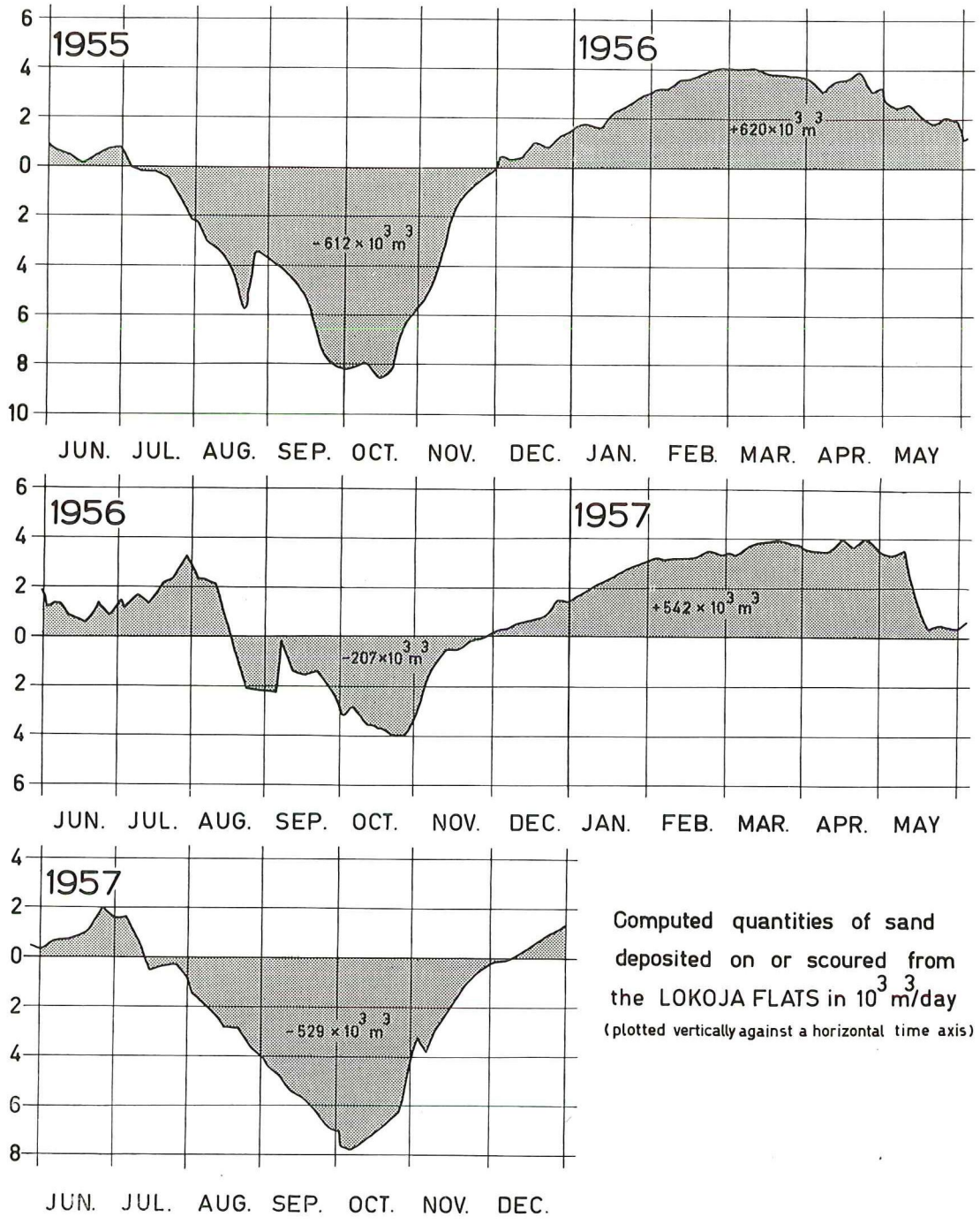


DIAGRAM 3.2.2-2

Deposits and scour on the Lokoja Flats

more problems to navigation: they form a shallow barrier in the sailing route from Lokoja downward, and at certain conditions even become determinant for the least available depth in the Lower Niger.

Their main deposition period runs from January to June, while at the same time the water-level (read on the gauge at Lokoja) continues to fall slowly. Decrease in available depth over the flats is apparent.

The graph of Diagram 3.2.2-2 has been determined as the difference of the supply of sand from both the Upper Niger and Benue, and the transporting capacity at the station Shintaku, located on the immediate downstream side of the flats. The latter magnitude follows immediately from the relation between discharges of water and sand, as given in Diagram III, 5.2.2-1, the daily water discharges being known from the daily readings on the gauge at Lokoja combined with the Q-h rating curve for Shintaku (III, 4.3.2).

The determination of the supply was much more complicated. A simple relationship between Q and S does not exist in the lowest sections of the two upper rivers, since raise or draw-down affects the sand-transport severely. However, the mean velocity v in the entrance as well as the slope i could be calculated as a function of the discharge Q, and the raize z_0. The latter has been discussed under III, 4.2.6; its daily magnitude has been computed and drawn in Diagrams 13 and 15 of that paragraph. But the discharge in the entrance is not known exactly, since no Q-h rating curve could be made for such a place. Therefore the discharge along a station located far upstream has been taken instead, and the error corrected by estimation; the discharges along Baro and along Makurdi added together (with the respective time-lags taken into account) show a deviation from the discharge along Shintaku; the difference is due to lateral inflow, storage, evaporation, etc. As no information has been obtained concerning this lateral inflow, it has been assumed that one-third of the volume is due to the Niger area Baro—Lokoja, and two-thirds due to the Benue area Makurdi—Lokoja. With the help of this assumption, the discharge at Baro could be reduced to the one at the Niger Entrance, and the discharge along Makurdi to the one in the Benue Entrance.

The Q and z_0 now being known, v and i can be determined for every day separately, and by means of the formula of MEYER-PETER and MUELLER (III, 5.2.1) the sand supply from each of the two upper rivers.

The difference of the sand supply from upstream and the sand transport downward gives the amount of deposition or erosion of sand over the flats, as has been plotted in Diagram 3.2.2-2.

Flats like these Lokoja Flats are illustrated but not fully explained by the pulsatory or non-synchronised sand supply. If this pulsatory effect were the only cause, the buffer stock would not remain so large. Other causes must therefore exist in addition. These might possibly be local phenomena: a sudden widening of the river by local erosion of the banks due to great angle of attack by the waterflow from the tributary. Such can be seen especially where the affluent joins the main river at more or less right angles, as for instance the Taraba. Here, however, a rock on the northern bank happens to obstruct further bank erosion, while the position of the rock works accidentally in such a way that the main current is crossing the river favourably and maintains a good navigable channel downstream from the confluence.

A different general cause is the effect of the annual transport downward not being able to compensate the total annual supply from both upper main river and tributary. Ultimately, the sand movement on a confluence must be in equilibrium; but by some cause the regime of, for example, the tributary might change and start to bring more sand into the confluence than usual, resulting in deposition taking place. Compensation is found in a steepening slope of the lower main river, until the increasing drag suffices to transport the new annual supply. This equilibrium on the confluence would restore normal shipping conditions. The shoals, however, are only transferred downward: there can be no adaptation of the lower main river immediately over its full length. The downward propagation of the front of the buffer stock of sand is slow. Somewhere below the confluence, the state of transition between the original (gentle) slope and the new (steep) slope must cause difficulties for navigation, since there the supply is greater than the transport. This type of flats, finding their origin in a change of regime of a tributary, is illustrated by the notorious example of the Wuro Boki Flats (see 2.4.2).

Summarising, affluents might raise difficulties for navigation by local disturbances at their confluences, by pulsatory sand supply or by changes of their regime.

PART VI

IMPROVING THE NAVIGABILITY

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CHAPTER 1

INTRODUCTION

1.1. MEASURES NOT AFFECTING THE REGIME OF THE RIVERS

1.1.1. Ships and shipping

The type of a river vessel bears a close relation to the nature of the transport and of the river itself, and also to the state of navigability of the waterway. For instance, fast-flowing, narrow and winding rivers ask for a different type of craft than wide and slow rivers. General merchandise and piece-goods require ships different in size and type from those destined for bulk transport. The same holds true for the system of shipping.

In a balanced development, the type of ships and the system of shipping will more or less be adapted to the obtaining conditions of transport and navigability. No major improvement in river navigation may then be expected from modifications to the type. But an improvement of the navigability itself will in its turn invite a response by the shipping companies, as, for example, greater depths and longer navigation periods may ask for different sizes and types of ships. Moreover, advances in the system of inland water transport are evident from developments on many rivers in America, Asia and Europe (1 as well as on the Niger and Benue (2, which show the effects of an application of recent findings.

The following measures show the possibilities of adapting the types of ships and shipping to the obtaining conditions:

a. the *size* of craft depends on the nature of the cargo as well as on the characteristics of the channel;
b. the *draught* of the ships may be limited in order to increase the length of the season during which they can be employed on the river, but on the other hand deeper drawing ships may be operated more efficiently;
c. the *speed* of ships may be increased within the limits of economy which in turn depend on the time the towboats are idle due to poor navigability or under-developed river management;
d. the *manoeuvrability* of the ships negotiating difficult stretches may be improved, which may appear more efficient than improving the channel characteristics at these stretches;
e. the *type* of ships may be varied: there is a choice between self-propelled barges, tugs towing dumb barges, push-tows and semi- or fully-integrated tows which resemble in shape the self-propelled barge but consist of a towboat pushing a stream-lined tow;
f. the *number* of ships may be increased: it is obvious that the transported volume of cargo on a certain river may increase by employing more ships, but it remains to be seen whether this would be the most economical way of improving river transport; and

(1 UNITED NATIONS, 1954. TRP. 5
(2 Chapters 4 and 5 of Part IV

g. lastly, the *system* of transport may be adapted by applying various kinds of shuttling to ensure the most efficient use of the towboats and barges.

In the next Chapter these possibilities will be dealt with in more detail. No recommendations will be made, however, as it is considered that these measures should be the natural response by shipowners to a development of the river trade and to improvements of the navigability.

1.1.2. Guiding the navigation

Although river vessels, as all ships, may be independent from the presence of man-made navigational aids, such assistance will be a great contribution towards a more efficient and less hazardous navigation, especially on untrained rivers as the Niger and Benue. These means of improving the navigability without affecting the regime (channels, water-levels, discharges, etc.) may originate from the shipping companies as well as from the authority in charge of the river management.

The shipping companies operating on the Niger and Benue Rivers employ their own locally-trained pilots for guiding the vessels. Until recently, only a few river gauges were available, which were read on behalf of various departments and firms. The river operators used these readings, when and where available, for estimating the available depths as their experience made them establish certain rules of thumb.

Communications were rather poor: the larger river stations offer telegraph facilities, but the masters of the river vessels were mostly left to their own initiative and the headquarters of the shipping companies received only scanty information on the conditions of the river or the whereabouts of their ships.

The former Marine Department maintained a number of large buoys marking dangerous rocks between Lokoja and Etobe on the Niger, and near Makurdi and the Taraba Confluence on the Benue. These duties have now been taken over by the Inland Waterways Department.

Very few maps and charts of the navigable rivers existed (see Section 4.1 of Part II of this Report), and as most of these maps were out-dated they were not used by shipping.

The exact position of the navigable channel between the sandy shoals was neither marked on the river nor shown on the maps. Pilots had to rely on their memory, local knowledge dating from their previous trip or from a low-water reconnaissance from the previous year. In addition, they used remarkably sound judgment of the river and usually managed to find a deep channel even when the situation had completely changed since their last voyage.

It is evident that an improvement of the aids to navigation will greatly assist shipping and will result in a more efficient use of the available natural channel-depth.

The following measures for an improved guidance of the navigation may be mentioned:

a. *Maps* as a general reference, indicating the channels, sand-banks, landmarks, towns and villages.

b. *Buoys and beacons*, to be used for marking the channel. The advantage of these navigational aids is evident when there are fixed obstructions in the channel such as rocks or wrecks. When the position of a channel liable to frequent shifting has to be marked, care should be taken that the buoys and beacons are re-positioned as required, which means that they should be of a type that can easily be handled.

c. *Lights or luminous buoys* will make it possible to navigate at night, which naturally will extend the period of navigation and thus increase the efficiency and capacity of the river fleet.

d. *Channel patrols* are essential for maintaining and re-positioning the channel markers. In addition, these patrols will provide valuable information on the depths and conditions of the

channels, snags may be removed where necessary and assistance can be given to ships whenever required.

e. *Pilots* may collaborate with the channel patrol officers and eventually be trained and/or licensed by the river authorities.

f. *Stage and discharge measurements* yield data on the navigability of the rivers, whilst a prediction of the water-levels will also become possible — provided that a fair number of gauges, at regular intervals along the rivers, be read frequently.

g. *Communications* are of great importance, both to the operators of the river fleets and to the river authorities. Ship-to-shore and ship-to-ship radio telephone systems may be used to pass on information about available depths, on expected rise and fall of the river, and on the positions of channels, buoys and snags. The positions of the various ships are of interest to the shipowners, to those responsible for the operations of ports as well as to the channel patrol officers.

In Chapter 3 of this Part, these measures will be further explained and recommendations be made where necessary. Several items have already been introduced during the past few years, some by the shipowners, and others in the course of the NEDECO Investigation. In the latter case a beginning was made on an experimental basis and the responsibility has subsequently been taken over by the Inland Waterways Department.

1.2. MEASURES AFFECTING THE REGIME OF THE RIVERS

1.2.1. Improving the bed

The navigability of rivers flowing in easily-erodible alluvial sediments such as the Niger and Benue can generally be ameliorated by deepening the channel in a direct or indirect way, without improving the natural stages and discharges of the rivers. The following range of solutions may be considered:

(i) recurrent dredging;
(ii) other temporary improvements;
(iii) channel regulation; and
(iv) channel normalisation.

Ref. (i). Local dredging at reputedly bad places or crossings will usually be a recurrent operation, with the amount of maintenance dredging depending on the extent of possible regulation-works. The main object would be to clear the Niger crossings after the rapid fall of the river and thus assist the natural scouring process.

Ref. (ii). The dominating bottle-necks for navigation may also be eliminated by provisional river-works, effecting greater depths during one low-water season only and with the influence disappearing again during the high-water period, These light works may consist of timber screens (bandalling), floating guide-vanes, or artificially-created roughness on the shallow sand-banks by a system of grooves and ridges.

Ref. (iii). Channel regulation aims at a permanent elimination of these dominating bottle-necks by giving the river a more regular course. It involves normally a fixation of the bed by means of bank protection, guiding walls or groynes, the closing of minor branches, the stabilisation of concave bends, etc. By guiding the river in this way, the crossings will be made more gradual and no high sills need be formed. In other words, the river is given over great parts the appearance and characteristics of its most favourable natural sections.

Ref. (iv). Normalisation involves an artificial narrowing of the bed along the entire stretch that has to be ameliorated. The narrowing is accomplished by means of groynes or training-walls that confine the discharges to a narrower channel, thus provoking greater depths by scouring action. Normalisation of rivers is usually preceded by a channel regulation.

1.2.2. Improving the water-levels

A weir across the river will raise the water-level on the upstream side, thus giving a greater depth of water even when discharges are low. The amount of raising is at a maximum just above the weir and decreases gradually farther upstream (backwater curve).

The logical continuation of this principle is a complete canalisation. It comprises a chain of weirs built along a section of the river in such a way that another weir is placed upstream of the place where the raising of the water-level by the downstream weir will no longer be adequate.

The minimum discharge to make a canalised river navigable would be very low indeed, as water has only to be supplied to balance leakage and evaporation losses. For evacuating a far greater flood discharge of the river, the weirs may have to be made movable. Locks will have to be provided at each weir enabling ships to pass.

1.2.3. Improving the discharges

When a river shows a deficient discharge in a certain season whilst it discharges an excessive quantity of water during another season, then a regulation of the discharges may be considered as a means of improving the navigability.

Reservoirs for storing the water may effect such a discharge regulation by distributing the available annual volume of water more regularly. Such reservoirs are usually constructed in the upper reaches of the main river or in the affluents, where gorges and sparsely-populated areas offer opportunities for building large dams with more or less extensive reservoir areas.

When a dam with a reservoir can be constructed in the navigable reach of the river, then the advantage of raising the water-level on the upstream side goes with the advantage of a regulated discharge below the dam. However, difficulties might arise through deposition of sediment in the upstream part of the reservoir.

As in the case of a weir, a lock will have to be constructed enabling ships to pass.

CHAPTER 2

SHIPS AND SHIPPING

2.1. RECENT VIEWS ON RIVER VESSELS

2.1.1. The size and draught

The size and draught of a river vessel is normally restricted by available depth, width and curvature of the channels as well as being further determined by the quality and nature of the cargo offered for transport. The right balance is usually a compromise which aims at the optimum efficiency and economy; it will be sought in a fleet of ships of different sizes to suit different purposes. In this light a few points will be considered here for the Niger and Benue river vessels.

The actual nature and origin or destination of the cargo offered over the year and the prospects of future developments can, of course, be only obtained through a market survey, and some remarks with regard to this item have been made in Part IV, Chapters 1 and 2. Briefly, however, the picture of annual river transport in downward direction can be sketched as below:

Baro	70,000 tons
Onitsha	40,000 tons
Rest of the Niger	35,000 tons
Garua	25,000 tons
Benue above Gamadio	15,000 tons
Benue below Gamadio	25,000 tons

The average yearly increase can be estimated at 5—7%.

Only the downward traffic of ships is considered here as it exceeds the upward traffic by 100 to 200%.

The power-unit of the river vessel has a draught largely determined by the propeller size, which will be fitted in a tunnel. These units must serve on the Niger as well as on the Benue, as the short navigable period of the Benue alone would not make it an economic proposition to operate a river fleet. In view of this, the number of days on which Baro can be reached with different draughts will then determine the maximum draught of the power-unit. Even more important is the number of days when Baro can be reached after the crop-yields are available for transport, i.e., from November to May (Diagram 2.1.1-1). This period is calculated from the least available depths in different stretches of the Niger (see also Sections III, 4.3 and 6.4 and IV, 3.2 and 3.3).

From the Diagram it follows that the draught of the power-unit should not exceed 5′ as a greater draught would sharply reduce the sailing period. From 4′0″ to 4′6″ seems the most efficient draught for a push-tug.

At present 1,200 h.p. can be taken as an economic maximum for a power-unit of 4′6″ draught, and as the horse-power/tonnage ratio for the Niger and Benue is from 1 : 2 to 1 : 4, about 4,500 tons can be considered as the maximum load for an efficient push-tow on the Niger and Benue.

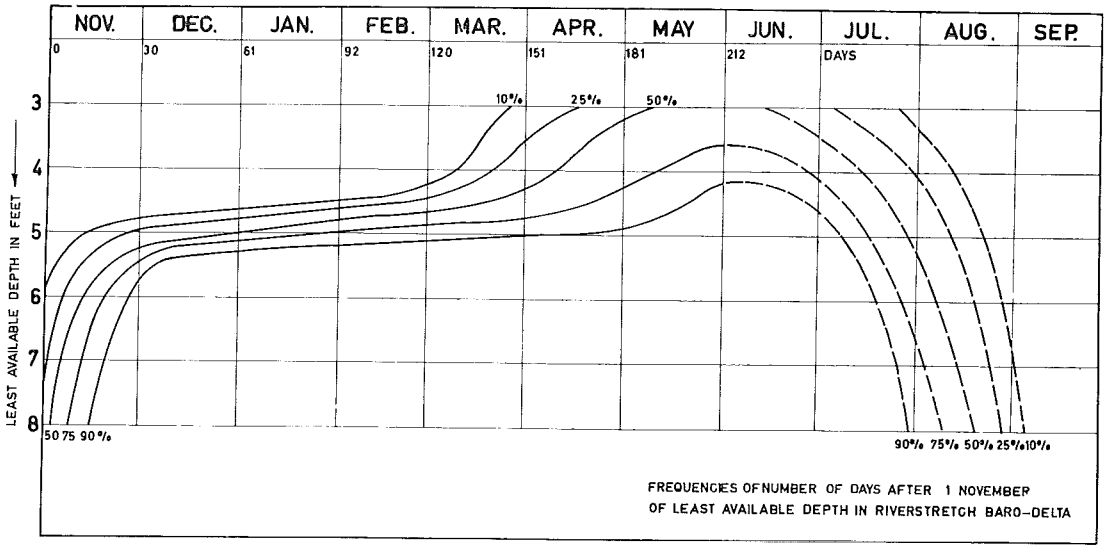
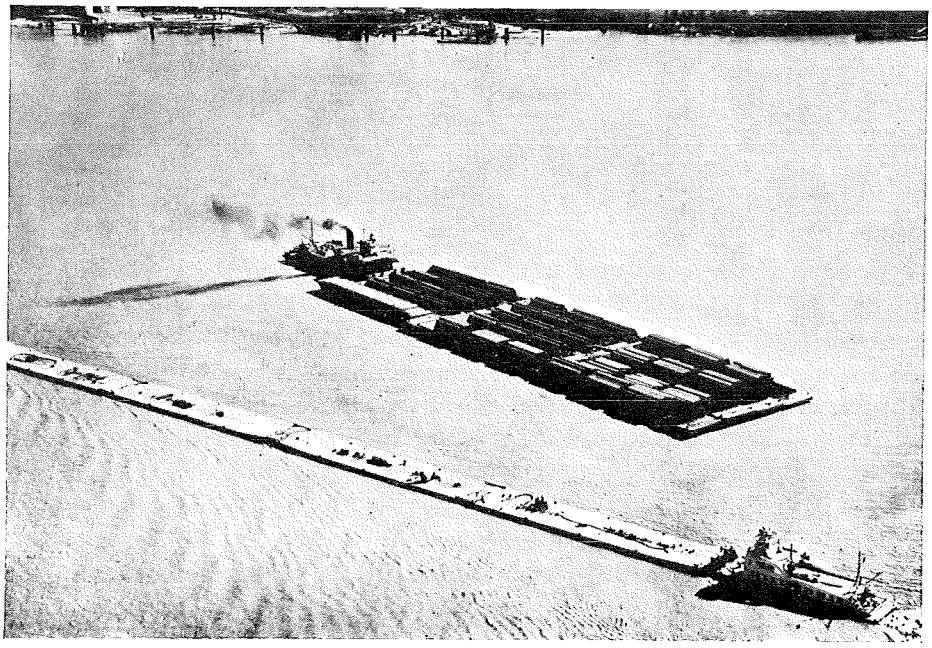


DIAGRAM 2.1.1-1

Accessibility of Baro Port

The tendency is to increase the total tow length as much as possible, as the total resistance per ton of cargo decreases with the increasing length of an integrated or semi-integrated tow. As has been explained in section IV, 3.1, the curvature of the channels and the cross-currents will restrict the total tow-length to about 600—700 feet, leaving for the barges 475—550 feet.

About 80—100 feet width of barges in front of a push-tug would be possible on the Niger



PHOTOGRAPH 2.1.1-2

Integrated and non-integrated tow on the Mississippi.

from: CORPS OF ENGINEERS, 1956, GEN. 8.

and the greater length of the Benue. Such a wide tow is not desirable, however, as this would be out of proportion. Also it would be difficult to obtain a proper flow of water around the tow and near the propellers. Therefore, some 50—70 feet width of barges pushed in front of the tug is normal for large tows, and the maximum draught is in the order of 7'0" for 4,500 tons in barges 500 feet long by 60 feet wide.

Another consideration is important when determining the draught at full capacity of the barges belonging to a tug. A barge built for a maximum of 8 feet draught carries at 4 feet draught only 36% of its maximum capacity, while a barge built for 5 feet carries at 4 feet 72% of its maximum capacity under conditions in which a light draught of 1'9" for an 8-foot barge and of 1'3" for a 4-feet barge has been taken into account (see Diagram 2.1.1-3). The power-unit in both cases must be built for the maximum capacity of the barges. It is clear that the average load-factor throughout the sailing period for barges with a maximum draught not much larger than that of the push-tug is much more favourable than that for barges with deeper maximum draughts (Diagram 2.1.1-3).

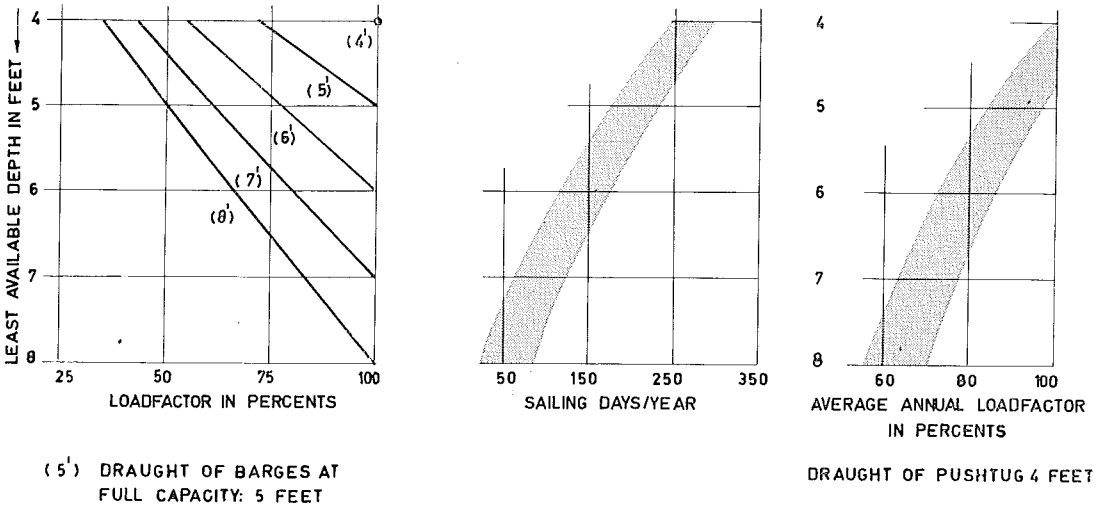


DIAGRAM 2.1.1-3

Use of barges at different draught

A tug of 4' draught will always be able to utilise barges of 4' to full capacity, while the maximum load-factor over an average year for a barge of 8' would be between 55% and 70%. The power-unit is more efficiently used when the design is restricted to maximum barge draughts of 5 to 6 feet.

The above sizes and draughts for a 4,500 tons tow are the maximum possible as can at present be foreseen under the prevailing conditions on the Niger and Benue. But such large ships should not stand alone, as they could not operate economically.

A tow of 1,000 tons is still considered a large one on the Niger and Benue, whilst tows less than 300 tons are small. Although such small tows alone may finally prove uneconomic, they can still be operated under the present navigation conditions.

The obvious advantage of small tows is that they:

(i) ply longer periods;

(ii) reach more ports at an earlier date;

(iii) ply on tributaries;

(iv) do not ground easily; and
(v) offer a flexible operation of terminal ports, which is of importance for the present unsatisfactory river conditions.

2.1.2. Speed, manoeuvrability and engine horse-power

The lower limit of *speed* for ships would theoretically be slightly more than the maximum speed of the current encountered (5 knots between the piers of the bridge near Makurdi). In practice, it should at least be 1 knot higher than this maximum current speed and 2—3 knots higher than the average speed encountered. This means that a minimum speed in still water of 6 knots for the Niger and Benue Rivers is a necessity.

An increase of the maximum ship-speed is accompanied by a progressive increase of resistance and drag and thus of power, fuel consumption and initial costs of such a faster vessel. A faster ship can, however, handle a greater tonnage per time-unit. The economic speed of a tow on the Niger and Benue Rivers will probably be between 7 and 8 knots in still water under the present circumstances. The economic speed can vary considerably and depends on numerous factors, among which are quality of service demanded, number of sailing days in a year, initial costs of the tow, fuel costs and depreciation allowed per year.

In shallow waters shipping is hampered by squatting. This phenomenon, which becomes more severe with increasing speed, is caused by the increase in speed of water around and underneath the vessel. The result is a drop of the water surface around the ship and an equal drop of the vessel. Depending on the tow dimensions and the speed and the depth of water underneath the keel, this drop does not vary much and is something in the order of 6 inches. During low water slackening of speed is the only counter-measure which can be taken above the sills to decrease this drop as much as possible. The danger then is the decrease in manoeuvrability when the ship's speed decreases.

High *manoeuvrability* is of prime importance for tortuous talwegs. The manoeuvrability of a tow partly determines her maximum size and this is certainly the case on the Niger and the Benue. In general, a larger tow is more economic and the shipbuilder will be requested to increase manoeuvrability as much as possible.

Very little has been published about manoeuvrability. The total horse-power of the engines, the dimensions of the tow, the number and positioning of the rudders and the positioning of shaft and propeller influence the manoeuvrability under different service conditions. Model tests may prove advantageous and further research on this subject is certainly necessary.

TABLE 2.1.2-1
PROPULSION POWER UNDER VARIOUS CONDITIONS

	slope in 10^{-5}	h.p./ton		slope in 10^{-5}	h.p./ton
Lower Rhine	5— 15	0.15—0.20	Canal tows	0— 5	0.10—0.20
Upper Rhine	60—100	0.80—1.00	River tows	0— 100	0.10—1.00
Mississippi	5— 15	0.10—0.25	Self-propelled river vessels	0— 100	0.40—1.00
Niger/Benue	8— 30	0.25—0.50	Sea-going vessels	0— 5	0.40—0.80
			Diesel train	0—1,000	appr. 3

The amount of *horse-power* which the engines develop is often given in relation to the tonnage of the cargo capacity by the h.p./tonnage ratio. This ratio is brought about by efficiency considerations, and thus includes all the factors which play a rôle in the design, as well as the weight which each of these factors is given.

Different rivers have different characteristics, and the ratio will be influenced by them. Specially the current speed and the slope of the river affect the h.p./tonnage ratio. On the Lower Rhine, for example, this ratio is 1 : 5 or 6, increasing to 1 : 1 or 2 in the upper reaches of the Rhine. On the Mississippi the ratio varies between 1 : 4 and 1 : 10. The latter ratio can only be reached with very large tows, going downstream or sailing in canalised stretches. On the Niger and Benue Rivers, the ratio is 1 : 2 to 1 : 4. In this connection Table 2.1.2-1 is interesting for comparison.

2.1.3. Propulsion organs

Paddles (Photograph 2.1.3-1) have long been the propulsion organs of a ship and still are on several rivers in the world. The use of paddles for restricted-draught vessels is advantageous as the submerged area is large, thus reducing the paddle load and increasing the efficiency, whilst repairs to paddles can be made with relative ease and without the necessity of slipping the vessel. A disadvantage of paddle-wheels has always been the heavy weight. Stern-wheelers as well as side-wheelers become very large for the push which they develop.

PHOTOGRAPH 2.1.3-1

Paddle propulsion, a common sight on the Niger and Benue Rivers

The development in combustion engines and propellers have gradually ousted the paddle propulsion. Tunnels and the use of more than one propeller have increased the submerged area of propellers. Propeller speeds are higher than paddle speeds, which implies less reduction gear and/or faster running engines. This results in a decrease of weight in the push-tug, which for shallow rivers is very important. Also the ever-increasing technical progress and facilities

have gradually made the special advantages of the paddles less striking, the more so as at the same time river depth is being increased by river improvements.

The use of Kort nozzles can increase the efficiency of propellers for relatively slow ships by up to 35%, although above a speed of 7 knots the advantage is less. The use of these nozzles, however, decreases the propeller dimensions and as the Kort nozzle is vulnerable, they have not so far been used on the Niger and the Benue Rivers.

Voith-Schneider propellers, the method of cycloidal propulsion, give extreme manoeuvrability, but the initial installation is expensive and it requires high-quality maintenance. Voith-Schneider propellers are used in a few units on the Niger and Benue, but it is doubtful whether this will be extended without major improvements to this system. The efficiency may be slightly higher than of screw propellers, but the system is very vulnerable, and repairs necessitate the slipping of the vessels.

2.1.4. Propulsion methods

Push-towing is the normal practice on the Niger and Benue, even as on the Mississippi and Ohio Rivers in America it is also almost exclusively the propulsion method. On the Congo, Danube and the large rivers in the U.S.S.R. push- and pull-towing is practised. On the Rhine pull-towing (Photograph 2.1.4-1) is normal and only recently was the first push-tow introduced. Self-propelled vessels can be found on all these rivers, but these ships normally serve only special demands.

Push-tows attach the barges firmly in front of the tug and a pull-tow draws the barges behind it, each on one cable. The former becomes a large rigid frame in the river, the latter a more elastic but longer body. The self-propelled vessels have usually a smaller capacity with a high h.p./tonnage ratio. They require a very quick turn-round to make them an economic proposition, as the engine cannot be separated from the carrying capacity. On the Rhine, many self-propelled vessels are in use as oil-tankers, as these can be very quickly loaded and discharged by pumps. At present, there is very little cargo which demands this speed in Nigeria, and also there is a tendency for push-tows to take over many of the qualities of self-propelled vessels. On the Mississippi hardly any self-propelled vessel is in use.

Moreover, the draught of a self-propelled vessel would be such that operation only during 3—4 months a year would be possible on the Niger and Benue and slipping would be very difficult in Nigeria. Therefore, there is little prospect that self-propelled vessels would be able to take a considerable part of the transport on these rivers (Photograph 2.1.4-2).

As a temporary measure chartered coasters of 600—700 tons have plied on the Lower Niger and Benue Rivers. These vessels may be considered as self-propelled vessels of relatively great draught (12 feet) and speed (9—11 knots). Although as an emergency proposition these coasters have not been without success as river vessels, there is no tendency of the river operators to continue this system. A few self-propelled sea-worthy oil-tankers carry oil from Lagos along the coast and up the Niger as far as Onitsha and Lokoja.

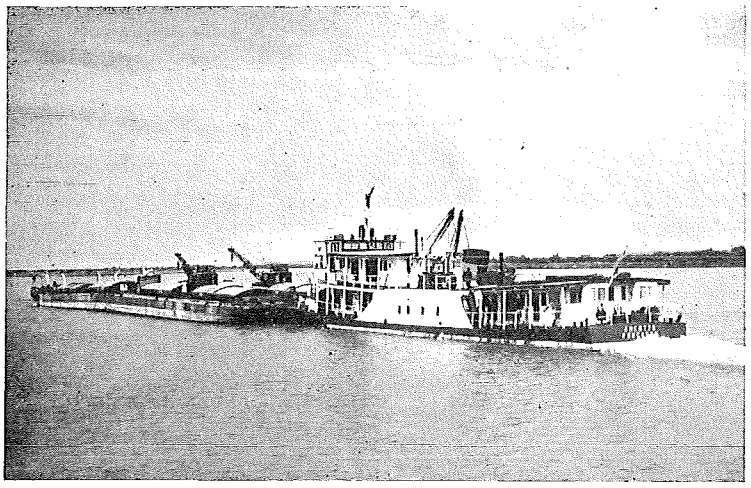
Push-tows combine many advantages of the self-propelled vessels with a higher flexibility. By integration or semi-integration, i.e., streamlining the tow or the barge-train only, the resistance can be reduced, whilst the barge-units and the motor-unit do not reach unmanageable sizes, which is specially of great importance for slipping. Self-propelled ships and push-tows are more manoeuvrable than pull-tows. The rigid construction is better controlled and stopping while going downstream can be effected by the engines, without having to swing the tow round.

In narrow channels, the large rigid construction can be a disadvantage and pull-towing may then be preferred. Rough water is a danger for the lashes and can damage the barges, but these

PHOTOGRAPH 2.1.4-1

Pull-towing on the Rhine.

One tug pulls a line of barges. In the foreground, a self-propelled vessel pulls a barge in the lower reaches of the river.



PHOTOGRAPH 2.1.4-2

Push-tow on the Niger

circumstances do not prevail on the Niger and Benue Rivers. On most of the other rivers where pull-towing is still in practice it has been the natural development from the time barges were pulled by man-power. Pull-towing has maintained its existence for a long time, largely because of the huge investment needed for a switch-over to push-towing and probably, too, because rivers operators have been conservative.

Although the picture sketched above would be sufficient to conclude that push-towing is the obvious system on the Niger and Benue, a few other advantages of this system should be mentioned:

(i) simple and cheap construction of barges, standard sizes, simple maintenance;
(ii) no rudders and steering equipment, no anchors and anchor winches, no riggings and hawsers for all the barges;
(iii) smaller crew in relation to the carrying capacity compared with pull-towing;
(iv) compared with pull-towing 20—30% saving on propulsion; and
(v) in case of night navigation safer than pull-towing and one set of navigation aids suffices.

2.1.5. Conclusions

Summarising, the following may be outlined as the requirements of river vessels for the present conditions on the Niger and Benue Rivers:

(i) the size of a tow should in general not exceed 4,500 tons; the length may be 600—700 feet, the width 60—80 feet;
(ii) the efficient draught of power-units is between 4 and 5 feet and the efficient draught of barges between 5 and 7 feet;
(iii) the manoeuvrability should be excellent;
(iv) the speed should be at least 6—7 knots in still water, the maximum being determined by considerations of economy;
(v) propellers in tunnels appear to be the most modern solution for shallow-draught towboats; and
(vi) push-towing is the obvious method of propulsion.

It goes without saying that the present operators of the Niger and Benue river-fleets are fully aware of the above considerations. Recent additions to the fleets all show the suitable characteristics that have been explained in the previous paragraphs.

Only with regard to the principle of push-towing is there a — perhaps temporary — deviation as the power-units (towboats) are seldom separated from their barges, which implies that these integrated tows show the same disadvantage as self-propelled vessels. The expensive towboat is thus idle during the loading and discharging of the barges. Only when additional barges are used (see 5.1.5) can full advantage of the integrated tow (immediate turn-round of the towboat) be achieved.

2.2. SHIPPING SYSTEMS

2.2.1. Introduction

Ships and shipping should be adapted to the circumstances encountered in a given area on a certain waterway. These circumstances vary widely over the world and considerably on the Niger and Benue Rivers.

Each type of ship and each system of shipping has its own characteristics and suits its own purposes, and the combination of ships and shipping systems should be so organised that they provide for the most efficient transport in the given circumstances. This, however, is a very complicated matter, and judgment of the weight of each factor which plays a rôle in the organisation of efficient transport can only be gained after long experience, and will even then always remain subject to the personal views of those concerned.

The picture of freight transport lines on the Niger and Benue is at present, insofar it concerns motorised transport, not very complex. Nearly all cargo shipped by the river-fleets has an overseas destination or is of overseas origin. There is very little internal transport between ports along the Niger and Benue by ships as opposed by canoes.

Burutu, Warri, Sapele and partly Lagos are the ocean ports of the Niger and Benue. If the Delta entrance of Escravos had not restricted the draughts of sea-going vessels, Lagos would not have been brought in. It is, however, necessary to maintain a service between Lagos and the Delta ports, either through the creeks or via the open sea, to make full use of ocean-going ships. This is a great disadvantage, but it is expected that the Escravos entrance will be improved considerably in the near future which will no doubt strongly stimulate river transport.

To transport goods from a port along the Niger or the Benue to one of the Delta ports or vice-versa it is not always advantageous to ship direct from port to port. There are several systems in use to effect the most economic transport; these depend on:

(i) the composition of the fleet, large or small units with greater or smaller draught;
(ii) the number of days per year that a certain stretch of river can be navigated by a certain type of vessel; and
(iii) the distribution of transport quantities over the year and over the different ports.

The systems are described in more detail in the next paragraphs to illustrate the various possibilities on the Niger and Benue. As the shipping companies are obviously in the best position to judge the merits of each system, no recommendations will be made on this subject.

2.2.2. Direct transport

This hardly needs explanation; it is the transport between two ports along a river directly accessible to the transport unit. This system will be used when between two ports a large flow of goods exists and when the navigability over the entire river-stretch between the two ports is approximately uniform for a certain transport unit. On the Niger and Benue this system is used for the bulk of the cargo. During high-water, when the ports of the Benue can be reached, most ports are accessible with the large draught and size of tows. Also during the Baro season there is not much difference in the available depth in stretches above and below Lokoja, so that there is no reason to change the composition and draught of a tow between the two ports.

2.2.3. False shuttling

False shuttling can be described as indirect transport with temporary storage ashore. This transport system can be used when a port is accessible only during a short period of the year. Cargo is then conveyed to a port which is accessible over a longer period and later shipped to the final destination. This system is practised with petroleum products destined for Garua. Temporary storage in tanks at Lokoja enables shipment of a larger quantity to Garua with a given fleet than would be possible with direct shipment between Sapele and Garua during the short navigable period of the Upper Benue.

Another application of this system is practised where small units are employed instead of large units which cannot easily navigate a tributary, for example, and when the quantities of

cargo at ports are small. It would be ineffective to use these small units on river-stretches where larger units operate more economically. The small units then convey goods to ports which large units can reach and where they can be loaded to a maximum. Makurdi and Numan are examples of ports where after temporary storages of cargo from the Katsina Ala and the Gongola respectively, the cargo is taken over by larger units.

A disadvantage of the system just described is the extra handling involved.

2.2.4. True shuttling

The system of true shuttling is that of false shuttling as described in the previous paragraph without temporary storage ashore. The cargo remains in the barges, but at certain points, where permitted or necessitated by the navigability, tows are combined or broken up. The obvious advantages of this system is that it does not involve extra handling, although it asks for a high degree of standardisation and careful planning to prevent idling of tugs and loaded or empty barges. On the Niger and Benue, where shipping conditions cannot always be foreseen, such a system is liable to break down at times and the transport management must be able to improvise, as experience on the Benue has shown (see Chapter IV, 5).

This kind of shuttling is often used on the Mississippi River, especially at the confluence of the navigable Ohio and Middle Mississippi. As the navigation seasons of the Niger above Lokoja and of the Benue do not normally coincide, there is at present no opportunity of applying this co-called confluence-shuttling. It may, however, be used advantageously in a later stage of development when barges from Baro might be assembled with tows from the Benue into a single tow for the trip from Lokoja to the Delta.

Another variation of true shuttling can be applied where a reasonable portion of the cargo originates from, and is destined to, intermediate ports. Barges can be left at various stations during the upward voyage and re-assembled during the downward trip. This has the advantage of reducing the size of the convoys in the upper reaches of the rivers, where this is often an essential requirement for safe navigation. This is normal practice on the Rhine and also on the Mississippi River and could be called the "pick-up-and-leave" system. For the Benue this system has so far been less suitable, where during the short Garua and Yola season all convoys serve these important stations; downward ports are being served separately later in the year. It is, however applied at Onitsha on the Niger, and it is understood that, with the development of the Benue intermediate ports, river operators will consider the use of the same system.

2.2.5. Additional barges

The use of an over-capacity of barge tonnage with respect to the total horse-power of the fleet's power-units aims at the independency of tugs from barges. In this way it is possible to utilise tugs during the period when barges are being loaded or discharged. This system can be applied in direct as well as in indirect shipment and is a more specialised form of shuttling.

The simplest example of the use of additional barges is that of a large flow of cargo between two ports. A tug delivering barges at the port should be able to return directly with other barges. The number of additional barges depends on the number of sailing days between the two ports and the number of days used for discharging and loading in a port. A schedule can then be drawn up so that the fullest use is made of barges and tug-boats, the former being underway or in port loading or discharging and the latter almost continuously sailing between the ports.

On the Niger and Benue, it has been companies' practice not to seperate their barges from the power-units, which is tantamount to using the integrated tow as a single large self-propelled vessel.

Much depends on the ingenuity of the schedule in the case of more complicated transport flows to determine how far the number of additional barges can be restricted.

2.2.6. Conclusions

The managements of the various shipping companies will choose between a combination of these different systems. To attain the most economic transport within the limits given by their fleet, the often badly predictable river conditions and the freight offer, a good and reliable communication system such as a ship-to-shore radio is of the utmost importance. The introduction in recent years of such a communication system has proved a success, and there is no doubt that the river operators will respond to improvements in the navigability by a further application of the above-described shipping systems, so that the maximum efficiency will be attained. The appearance on the Niger and Benue of modern towboats in recent years and the expected introduction of more of these modern vessels in the near future may be seen as a proof of the confidence from the side of the river operators in the development of the Niger and Benue system into a better transport route.

CHAPTER 3

RIVER MANAGEMENT

3.1. MAPS

3.1.1. General: purpose and examples

As a means of improving navigability, maps serve the dual purpose of being an aid to navigation and of providing basic data for buoyage and channel improvement schemes. The requirements, however, are different in each case.

a. *Navigation* is best served by maps on a fairly small scale, each sheet showing some five to fifteen miles of river length and a part of the adjacent riverain area. A scale of 1 : 20,000 to 1 : 50,000 would then give handy-sized maps in view of their use on board ships.

Landmarks such as hills, conspicuous trees, towns and buildings are of importance to the river navigators, as also are minor creeks, confluences, typical river bends or crossings, and islands — all these characteristic features indicated by name — and river training-works, hidden rocks, bridges and overhead wires. Lastly, the mileage system should be indicated on the maps for reference to locations and for measuring distances.

The exact position in alluvial rivers of the navigation channel or talweg should not be marked on navigation maps, as this would soon be out-dated and might result in a dangerous confusion. Such shifting channels should be located by the pilots, assisted where necessary by channel markers. But the position of the large sand-banks or shoals that are exposed during low water may be shown on these maps, as this gives general information on the topography of the river-bed at the time when the maps were prepared. Even one or two years later these maps would still give an idea of that topography as the navigators will be aware of the more or less uniform downstream propagation of the shoals during the flood season (about 500 to 1,000 feet per annum on the Niger and Benue Rivers).

Such navigation maps provide good orientation of the general situation, as they show the main characteristic features of the river and enable easy reference to be made to the position of river vessels, buoyed areas, snags, etc. They will therefore be of great value to all concerned with the river, i.e., shipowners, river-masters and pilots as well as the civil engineers of the River Management authority. Sometimes third parties, dealing with forestry or public works, etc., and interested in the riverain areas will also require river-maps, although these authorities may be better served by flood-plain maps (see 3.1.4).

b. *Survey charts* show more details which are required for a thorough study of the channel characteristics on behalf of river improvements. The position of the banks and islands has to be given with a considerable degree of accuracy, for which scales of 1 : 10,000, of 1 : 5,000 or even larger are desirable. Land-marks are still essential on these charts as they provide good bearings for the surveys.

Such survey charts are indispensable when channel improvement is considered, when dredging has to be carried out or where bandalling or permanent regulation-works are contemplated. Buoyage, channel patrol and dredging operations often require the details contained on such charts.

c. *Flood-plain maps* also serve the purpose of river studies, as the storage of water during high stages is of importance for calculations of water-flow. Predictions of water-levels depend on the amount of storage, and the effect of an artificial reduction of that amount by constructions in the flood-plain (dikes, reclamation) on the stages of the river can only be found when an accurate contour-map of the flood-plain is available.

But these maps will also serve many other purposes, for all valley development projects in the spheres of agriculture, flood-protection, and building will require this detailed information.

A few *examples* of river mapping may be given here, and as well-developed rivers will provide the best comparison, some of the available maps of the Mississippi and Rhine Rivers will be briefly described.

(i) *Mississippi River* ([1

Flood Control and Navigation Maps of the Mississippi River from Cairo, Illinois, to the Gulf of Mexico. Bound sets of charts, size 13″ × 20″, scale 1 : 62,500 (approximately 1″ = 1 mile). Published annually showing Mississippi River, with navigation sailing line, navigation lights, bridges, aerial and submarine crossings, ferries, roads, levees, topography adjacent to the river, etc.

Maps of the Mississippi River from the Mouth of the Ohio River to its Headwaters at Lake Itasca, Minnesota. In 26 sheets, size 15″ × 24″, scale 1″ = 1 mile (1 : 62,500). Showing the main river and chutes, soundings, topography within a mile or so of the river-banks, landings, levees, mouths of tributaries, and old river lakes.

Navigation Charts, Middle and Upper Mississippi River. Bound set of charts, size $8\frac{1}{2}$″ × 14″, scale $\frac{3}{4}$″ = 1 mile (1 : 84,480; the lateral scale is distorted). Same information as above, but neither topography nor soundings are shown. Positions of navigation aids (lights, daymarks and lighted buoys) are shown with the restriction that their location or type may be changed from time to time.

Hydrographic Survey 1948—1951, Lower Mississippi River, and Mosaics, 1948—1949. Bound sets of charts, size 14″ × 22″, scale 1 : 20,000, showing river soundings and aerial mosaics. The elevations are in feet referred to Mean Sea Level. Countours are shown in feet above and below 1947 Low Water Plane; contour interval 5 feet. The detail maps show latitude and longitude lines, also names of islands, "towheads" ([2 and sand-bars, bends, lakes, bayous, creeks, levees and station numbers, towns, cities, railways, highways, counties, cut-offs, canals, benchmarks, sketches of bridges, river revetment locations, etc. Previous surveys were made in 1881, 1913, 1925 and 1937.

These maps may be procured from the U.S. Engineer's Offices, North Central Division and Lower Mississippi Valley Division, Corps of Engineers, U.S. Army, where also many other maps, charts or information for general or other purposes may be made available.

(ii) *Rhine River in Holland*

River Maps of the Rhine River and branches (Waal, Lek and IJssel). Printed in four sets, size 0.5 × 0.8 m (20″ × 30″), scale 1 : 10,000. Showing in two colours the topography of the

([1 CORPS OF ENGINEERS, 1956. GEN. 7
([2 "towhead" is used on the Mississippi to describe a small island.

river, flood-plain and adjacent areas; embankments, groynes, revetments, bridges, syphons, locks and sluices, all with names and heights relative to Datum.

Hydrographic Maps as above, supplemented with river-bed soundings across the river every 100 metres (330 feet). Depths are shown in centimetres referred to ordinary low water.

Detail Maps are prepared as and when required for special design or study purposes, either by enlarging from the river maps above, or from special aerial photography and terrestrial measurements. The scale is usually 1 : 2,500.

The river maps of the Rhine may be procured from the Landsdrukkerij (Government Printer), The Hague, whilst requests for Hydrographic and Detail maps should be addressed to the Rijkswaterstaat Offices, The Hague.

3.1.2. Navigation maps

In the course of the Niger and Benue Investigation complete series of river maps have been prepared by NEDECO, as described in II, 3.9. These general-purpose maps on a scale of about 1 : 20,000, constructed from special air photographs, show the topography of the river. No ground control was available, but on each map heights of exposed sand-banks, islands and riverain areas are given relative to the water-level on the date of photography.

From these maps, which were neither intended nor are very suitable for use on board river vessels, navigation maps have been prepared by reducing the scale by pantograph to 1 : 50,000. The resulting Book of River Charts, including an Index Map and a Table of Distances, is appended to the present Report. The 1 : 50,000 maps measure 0.31 × 0.65 metres (12″ × 25″); the Niger from Baro to Burutu is shown in 20 sheets, and the Benue from Garua to Lokoja in 35 sheets. A supplement shows the Niger from Jebba to Baro, but these maps have been sketched from air photographs and are, therefore, less accurate than those of the main navigated sections.

Scale, size and detail as shown on these maps have proved suitable for the purposes of navigation as described in the previous paragraph. It is therefore recommended that the Government should continue the edition of these navigation maps, whilst taking full account of any remarks from the users of the maps.

To keep the maps up-to-date, they should be revised at least every two years. For this, a single-strip aerial photography of the Niger and the Benue respectively should be carried out at first in alternate years, and later every year if that would prove desirable. The photography should be scheduled in the months of March or April when the river-stages are low and great parts of the sand-banks are exposed. A scale of photography of 1 : 20,000 would seem appropriate.

With this schedule it will be possible to have the navigation maps corrected before May or June when the shipping season begins. To facilitate these corrections, it is advisable to have transparent master-copies of the 1 : 50,000 river maps in which the sand-banks and the channel configuration are not shown, leaving only the shore-lines, the islands and the riverains. With an adjustable episcope appliance, it will then be possible to project the air photographs, with their scale optically reduced to 1 : 50,000, on the transparent master-copies of the maps. The sand-banks can then be plotted directly on these transparencies, whilst appreciable changes in the positions of shore-line and islands will become evident so that they may be corrected in the same process.

From the filled-in and corrected master-copies prints can be directly made, and then, before the H.W.-season, be issued to shipowners, to the masters of upward-bound vessels and to other interested parties.

Corrections in the general-purpose maps (1 : 20,000) may prove necessary for certain areas

where the topography has been essentially changed by the formation of new islands, major erosion or because of break-throughs.

3.1.3. Survey charts

Because of the highly variable nature of the beds of the Niger and Benue Rivers, the channel configuration may change completely within a short period, sometimes even within a single flood season. Survey charts showing the contours and depths of the river-bed will, therefore, soon be out-dated and consequently there would seem to be no point in having full sets of these charts, covering the entire river, prepared in advance for some future purpose.

But for hydrological studies it will be interesting to have surveys of the depths for general reference. As and when required these may be repeated at intervals ranging from a single month to several years, so that the changes in the channel topography may be studied. These changes are particularly important for the planning of river training-works. Examples of such series of repeated soundings with some resulting conclusions are given in III, 6.5.3 and III, 6.5.8.

For the Niger below Baro it appears, therefore, desirable to have eventually available sounding charts covering the entire river down to Burutu, i.e., a distance of 400 miles. During the NEDECO investigation, large areas of special interest to the studies have already been surveyed. These sections are shown on Diagram 3.1.3-1, whilst Diagram III, 6.3.1-1 gives an example of one of these sounding charts, which have generally been made on a scale of 1 : 5,000. It is recommended that the remaining gaps in the charting of the Niger below Baro be filled within the next few years. Transverse profiles have already been measured at intervals of $1\frac{1}{2}$ miles in these gaps.

There appears to be no urgent reason for having survey charts of the entire Benue River, as no river training-works are being considered here in the near or distant future. As Diagram 3.1.3-1 shows, separate crucial areas have already been charted, some of them repeatedly.

For buoyage operations it will sometimes be essential for a sounding chart of an intricate area to be prepared at short notice. For this purpose a fully-equipped survey team should always be made available to each channel patrol unit if and when required. These teams may at other times be employed in making routine surveys as above described.

When recurrent dredging (see Chapter 4) is introduced as a means of improving navigability, it will be necessary to have such a survey team available for making pre-dredging and post-dredging surveys of the channel.

As to the procedure of river soundings, it has been found from experience that on the Niger and Benue Rivers echo-sounding apparatus, supplemented by pole-soundings wherever depths are less than six feet, yields the best results. The positions may be fixed by using sextants measuring double angles to landmarks or shore beacons. The plotting can then be done by station-pointer or, in repeatedly sounded areas provided with permanent beacons, by using plotting-sheets with intersecting arcs. Range-finders have proved useful in rivers less than half a mile wide. These methods, however, have been described in greater detail in II, 3.6.3.

3.1.4. Flood-plain maps

Few detailed maps of the Niger and Benue flood-plains were available when NEDECO studies commenced in 1955 (see Section 4.1 of Part II). During the course of the NEDECO investigation there was no urgency for having such maps prepared of the entire area concerned, as this would have been beyond the immediate aims which were the providing of general information on the regime of the rivers and the making of recommendations for improving the navigability.

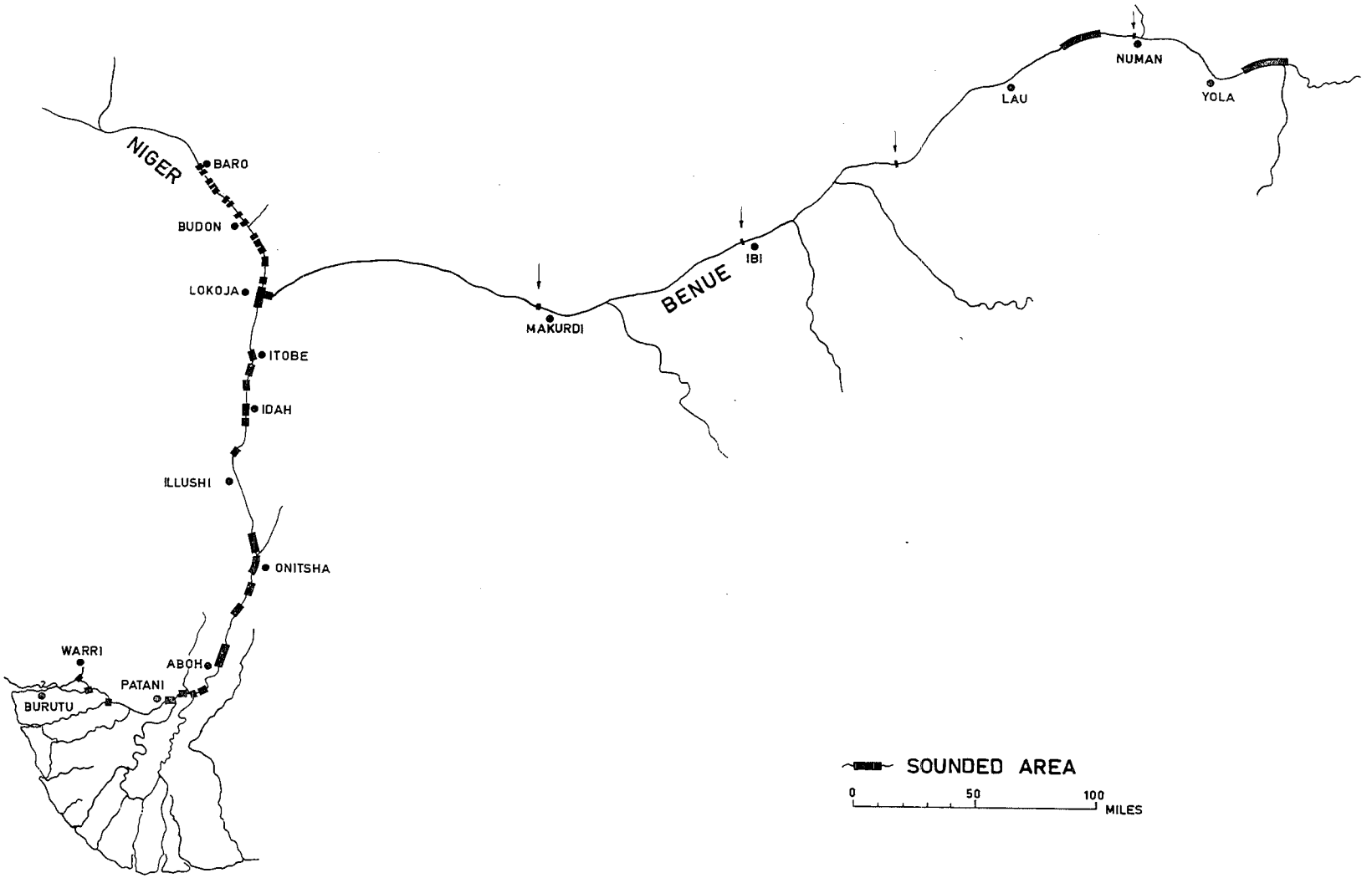


DIAGRAM 3.1.3-1

Sounded areas on Niger and Benue

Therefore only of three areas of special interest have maps of the flood-plains been prepared:
(i) From Garua to Yola, an area of about 30 × 60 sq.miles has been mapped on a scale of 1 : 50,000 with a limited ground control. This was done on behalf of the study of a reservoir dam on the Benue River (see 8.5.1).
(ii) From Asaba to Onitsha, an area of about 6 × 9 sq.miles was mapped on a scale of 1 : 12,500 with full ground control, on behalf of the investigation into the practicability of constructing a bridge across the Niger ([1.
(iii) The intricate delta zone between the Taraba and Donga Confluences with the Benue River has been mapped on a scale of 1 : 20,000. This area is nearly 35 miles in length with a width varying from 8 to 13 miles. No ground control has been provided and therefore no heights in the riverain areas could be given here.

These maps have been constructed by NEDECO (K.L.M.-Aerocarto) from aerial photographs specially taken by the Federal Survey Department.

The Survey Department are issuing uncontoured maps of Nigeria (series FN 15) on a scale of 1 : 100,000, based on air photographs. From those sheets already available, the following numbers cover flood-plains of the Benue ([2:

173 Kaltungo	193 Muri	212 Shendam
174 Guyok	194 Lau	213 Amar
175 Shellen	195 Dong	215 Jalingo

whilst sheet No. 247 covers the Niger-Benue Confluence.

The Niger flood-plain from Yelwa to Jebba is partially covered by the following uncontoured maps on a scale of 1 : 62,500 (series FN 16):

118 Yelwa (2 sheets)	160 Leaba (4 sheets)	182 Mokwa (2 sheets)
139 Warra (4 sheets)	181 Jebba (3 sheets)	

Flood-plain maps of the Niger Valley between Bussa and Jebba are now being prepared on a scale of 1 : 50,000 in connection with the investigation into the feasibility of a reservoir dam ([3. This mapping, which covers an area of 80 miles in length, is based on a limited ground control. Contour intervals will be 20 feet. The flood-plain downstream from Jebba will also be mapped in the course of the investigations for this multi-purpose project.

It has been pointed out in Paragraph 3.1.1 that it is desirable to have the disposal of flood-plain maps for such future purposes as detailed predictions of flow and constructions in the riverain areas as well as for development projects in the valley.

Therefore, it is recommended that in due course maps be prepared of the entire part of the main river valleys which is less than 10 or 15 feet above the highest flood-level on record. Scales of 1 : 50,000 to 1 : 100,000 would seem to be suitable for this purpose. The maps should be constructed from air photographs, supplemented by terrestrial measurements sufficient for drawing contours with 5 or 10 feet intervals.

Unless there is a special reason for giving priority to a certain area, it would seem most appropriate to commence this programme of flood-plain mapping in that area where coverage of air photography, or also uncontoured maps, is already available. Of the Benue Valley from Yola to Ibi, i.e., 290 miles of river length, photographs were taken on a scale of approximately 1 : 30,000 between 1946 and 1951 by the Royal Air Force. Several uncontoured maps on a scale of 1 : 100,000 are already available here, as stated above. Large areas are annually flooded in this region, where the storage of flood-water is considerable and the hydrological balance is complicated, as has been explained in Chapter 4 of Part III.

([1 NEDECO, 1957. GEN. 22
([2 FEDERAL SURVEY, 1957. GEN. 13
([3 joint investigation by BALFOUR, BEATTY & CO. and NEDECO

Flood-plain maps of this area should be prepared within five years unless other priorities for such mapping prevail. As special apparatus is required for the plotting, it may be profitable to have this work carried out on contract.

3.2. PILOTS

3.2.1. General: purpose and examples

It is common practice for vessels entering restricted waterways to employ a pilot who assists in navigating with his greater local knowledge and experience. Sometimes the use of a pilot within a particular stretch is prescribed either by the waterways authorities or by the insurance company of the shipowner. Although the Captain remains responsible for the ship, he will usually follow the advice of his pilot concerning the course and speed of the ship and sometimes also whether or not navigation in a certain section is at all possible.

A great part of the required advice can, however, also be given in other ways than verbally by a pilot. Channel markers and patrols, together with a system of communications, are of great assistance to navigators, and these aids will be dealt with in the next sections of this Chapter. Although maps (see the preceding section) and Pilot Books contain general information on the river and channel conditions and are, therefore, of value to the stranger on the river, such guide books cannot substitute the other navigation aids. Part I of the Admiralty's Africa Pilot (edition of 1953) already contains valuable information on the Niger and Benue Rivers and their ports; but it is recommended to include in future editions of this Pilot Book some of the information which has recently become available and is described in the present Report.

But for navigation on untrained rivers, as the Niger and Benue are, it is of special importance to have the benefit of up-to-date local knowledge of the rivers and channels and their special characteristics. Most of the vessels navigating the Niger and Benue are confined to these rivers only, and although they usually operate over long distances totalling one thousand miles, the Master and crew of the river vessels gain a wide, though general, experience of the navigated stretches. Yet this knowledge cannot compete with that of the Section Pilot who guides vessels through a difficult stretch of limited length only, and thus travels many times up and down over the same section.

The following examples will show how practice on other rivers has often led to a combination of the duties of pilot and deck-officer in the same person on board river vessels.

On the waterways in the *Mississippi Basin*, the situation is interesting as it has grown from conditions comparable to those on the Niger and Benue. MARK TWAIN ([1], for instance, describes the duties and performances of the pilots in the early days of steam-boating, when the Mississippi was still a virgin river over the greater part of its course. As on the Niger and Benue Rivers, a marked difference between the pilot and the Master of the vessel existed. The pilot and his partner (co-pilot), with whom he worked in shifts, were solely responsible for the navigation and piloted over river-stretches, that were as long as the navigable Niger and Benue combined at a time when no buoys or beacons existed and no channel patrols were established. The administration and maintenance of the ship, the cargo handling, etc., were the duties of the Master, who was ignorant of the channels and their vagaries, and who had to rely completely on the navigation of his pilots.

Nowadays, the Masters of commercial river vessels on the American rivers are at the same time licensed pilots. In view of the day-and-night navigation, which is current practice on those

([1] TWAIN, 1874. GEN. 35

rivers, the Captain is relieved by another licensed pilot who is also in the permanent employment of the shipping company and a member of the crew, but holds no responsibility for the administration or maintenance of the ship.

Whilst the Captain has general responsibility for the ship and navigation, the pilot is responsible for the navigation only when on duty, and a mate assists the Captain in running the administration and upkeep of the ship. Day-and-night sailing is achieved by a double crew working in six-hours' shifts; therefore the Captain and the pilot relieve each other at the control levers of the ship every six hours. The pilot (for historical reasons often still called Partner) is usually on duty from midnight to 6 a.m. and again from noon to 6 p.m.

Pilot Tickets are issued by the United States Coast Guard for separate sections of the rivers after candidates have passed an examination, which includes the drawing of a sketch of an arbitrary section of the river with all details relevant to navigation such as lights, beacons, bridges, pipe-lines, etc. Up-to-date information regarding channel conditions and positions of buoys is supplied by Navigation Bulletins (see Section 3.5 hereafter). As the river maps must be known by heart by the Captains and pilots, a Book of River Maps (see 3.1.1) is not normally used for navigation purposes and therefore it is not available on board commercial vessels, unless a trainee would require it for his studies.

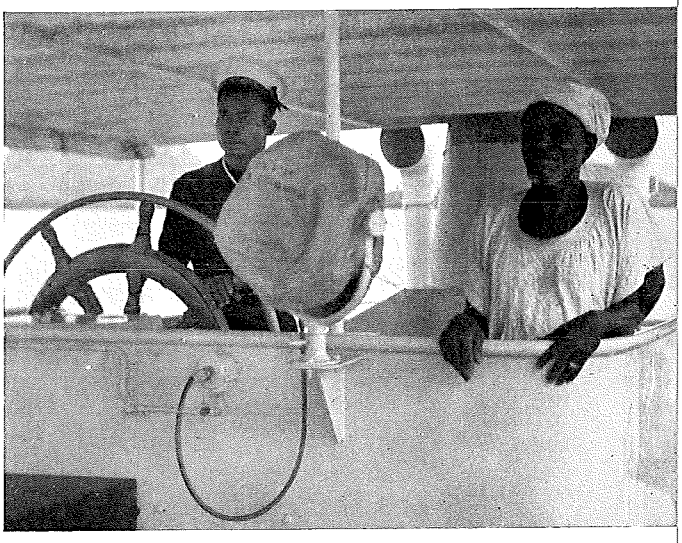
The Pilot Tickets have to be renewed at regular intervals, but when the pilot can prove that he has frequently sailed that section, no new examination is required. Some Captains hold valid licenses for a total of one or even two thousand miles of river length.

Contact Pilots, employed by the U.S. Corps of Engineers, embark on commercial vessels for short trips to exchange views and information on the channel conditions (see 3.2.4). They submit reports weekly to the Channel Maintenance Department of the Corps of Engineers.

On the *Rhine River* the Captains of river vessels usually hold licences (issued by a Government Agency) for the sections of the river which they normally navigate. Special piloting is not necessary except for Captains who seldom use the river (coasters) or have no licence.

On the Lower Rhine patrolling "beacon-masters" may on request indicate a particular location of the channel by leading the way with their survey vessel.

PHOTOGRAPH 3.2.1-1
Mississippi pilot



PHOTOGRAPH 3.2.1-2
Niger pilot

On the middle reaches of the Rhine there is piloting over short reaches, namely, in the rocky part near Bingen where the channel is fixed in a rocky bed but where navigation is endangered by outcropping rocks and cross-currents, and on the reach above Mannheim where mobile gravel banks cause shifting of the channel.

In these sections the pilot is also a welcome addition to the ship's crew, as steering the vessel in the intricate channels with strong currents is strenuous work. The pilot usually takes his turn at the wheel, thus relieving the Captain. Neither on the Mississippi nor on the Rhine is a special helmsman used when sailing, contrary to the custom in Nigeria.

On the *Niger* and *Benue Rivers*, the shipping companies employ their own locally-trained pilots for guiding the vessels (Photograph 3.2.1-2). These pilots gain their knowledge about the location of the navigable channel by:

(i) long experience (often from father to son) about the shifting of the shoals during high water;
(ii) the flow-ripples along the edges of the shoals, the presence of caving banks, the behaviour of the ship in shallow water, local soundings and sometimes the presence of grounded ships;
(iii) examining the beds of the channels during the previous low-water stages (on the Benue a trip is made along the river by canoe before the river rises); and
(iv) some exchange of information with other pilots.

In general, the pilot's stretch is a long one here, even many hundreds of miles, and only for a few special short reaches with notorious shallows are section pilots taken on board.

3.2.2. River pilots

At present, the river pilots are remarkably conversant with the different shallows, but it cannot be expected that they can carry all the details in their memory. The present tendency of the shipping companies to increase the speed and turn-round of their towboats will be beneficial to an up-to-date knowledge by the river pilots, and buoyage, maps and channel patrols will facilitate their task of guiding the vessels.

It is felt that the present system, where the shipping companies supply and employ their own pilots, should not be altered, as this undoubtedly provides the most elastic and smooth organisation.

The decision whether or not the duties of pilots and deck officers on board river vessels may be combined in one person should be left to the shipowners, as this is a matter of internal organisation.

Government may decide at a later date to institute an examination for river pilots, followed by the issue of a licence or Pilot Certificate. Such a decision to license the river pilots may be taken in response to a request by the shipping companies who could desire general and equal requirements to be established for their navigators. It may also result from consideration of a safe navigation on the rivers, because the possibility of accidents leading to an obstruction of the channel will naturally increase with a more intense traffic which may be expected as a consequence of river development.

It is felt that the training of pilots can best be done on the river, where knowledge of the channels and navigation can be most easily obtained.

3.2.3. Section pilots

Section pilots are being stationed by the shipping companies along the notoriously difficult stretches of the rivers. In particular at the frequently shifting channels of the Wuro Boki and Gamadio Flats and also at Akpanaja (Mile 505), all on the Benue River, are special pilots

taken on board who are well-informed of the latest channel topography, a knowledge obtained from their frequent trips and soundings.

The value of these section pilots will decline in proportion as the buoyage and channel patrol services increase, as these latter services are planned to indicate the best channel and its characteristics in a clear and unmistakable way.

During the transitional period, when the channel patrol service would not be working to its full extent or with its full equipment, it is recommended that section pilots, when still stationed at difficult places by the companies, should closely co-operate with the channel patrol officer concerned to their mutual benefit. Section pilots should, for example, be invited on board patrol vessels to exchange information on the channel topography.

3.2.4. Contact pilots

The buoyage of an untrained river with its shifting shoals and cross-currents is difficult and remains for each separate crossing to a certain extent a matter of personal view, feeling and experience, as will be explained in Section 3.4. Close contact between the Channel Patrol Service (see Section 3.4) and the users of the waterway is essential for a good performance of the buoyage, patrolling and information services.

For this purpose it is recommended that Government should appoint an officer of the Channel Patrol Service as a contact pilot. His duties would be to make frequent trips on board various commercial ships, and to report on his findings at regular intervals to his Department, e.g., every one or two weeks. His duties may alternate with those of a Channel Patrol Officer.

The contact pilot may explain the reasons for a certain method of buoyage and the characteristics and peculiarities of a certain channel. He may, on the other hand, learn the requirements of the various vessels, which are different when going up or downstream, and also vary for each type depending on its size, draught and manoeuvrability. He may discuss the merits of a certain buoyed channel with the men who have to use it and any criticism can be accepted or dealt with on the spot.

Such an exchange of views with the Captains and pilots of river vessels should assist in creating an atmosphere of confidence and have a stimulating effect on the performance of the buoyage service as well as on the response by shipping.

3.3. CHANNEL MARKERS

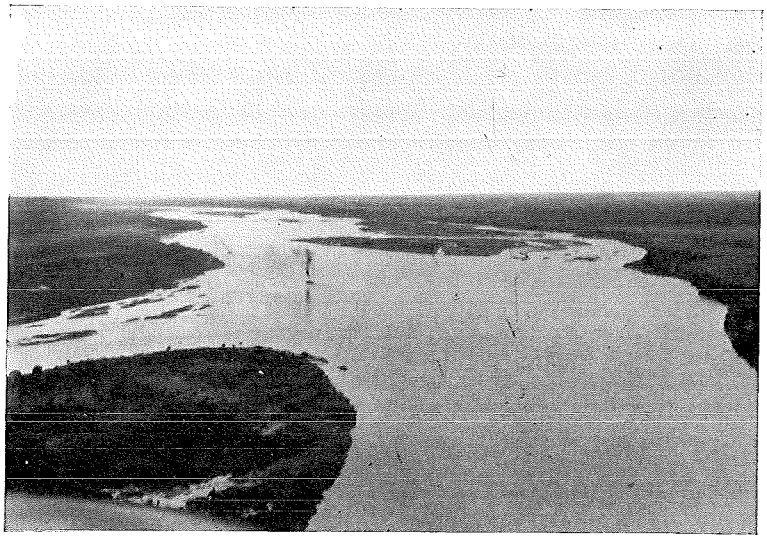
3.3.1. General

In consequence of the vagaries of the river-bed, navigation experiences the following difficulties:

At low water on the Niger — the Benue at that time is not navigable by larger ships — the navigable channel is less pronounced at crossings and confluences, and often situated in a wide and shallow expanse of water, although the channel on the whole is more clearly discernible than at high water. It also happens that in a divided or braided low-water bed the fairway switches occasionally from one channel to the other. In several locations, moreover, the navigable channel is narrow and sinuous, so that it is very difficult to navigate without running aground owing to the absence of indications of the edges of shoals.

At high water ships may still run aground, although in general the depth is fully adequate in many stretches of the river. The explanation is that several sand-banks are so high that they

lie only a few feet below the water-level. The wide expanse of water and the rapidly shifting banks when the river is in spate make orientation difficult.



PHOTOGRAPH 3.3.1-1

Wide expanse of water

Under such circumstances it is impossible to determine by sight the position of the navigation channel. And because the low-water shoals may be shifted several hundred yards downstream during every high-water season, the course of the navigable channel changes every year.

Buoys and beacons on those stretches of the river which are difficult for navigation through lack of orientation marks or because the channel is narrow and winding will present a major improvement provided the buoyage is kept up-to-date by frequent soundings and, when necessary, repositioning of the buoys. A closer general orientation can be achieved by means of such signs as mile-boards marked both on the charts and on the shore nearest the navigable channel.

Where there is heavy traffic the best solution can generally be found in beaconing or buoying: beaconing only if the river is not too unstable and not too much divided so that indications can be given from the shore, and buoying if the river-bed is wide and has many parallel channels.

When the volume of shipping is not great, an uninterrupted beaconing and buoying system is not efficient. Only the worst places along the route should be indicated by markers, leaving the rest of the reconnoitring to the pilots.

But to render night navigation possible, it will be necessary to provide a continuous demarcation of the navigable channel at all navigable stages by means of lighted or reflecting beacons and buoys.

3.3.2. Conclusions and recommendations

On the Niger and Benue the traffic volume justifies buoyage, the more so because easier evacuation of the produce facilitates development of the country. In view of this, an experimental buoyage was inaugurated by NEDECO in 1956, and from subsequent experiences on the Niger (1957) and Benue (1957 and 1958) it is concluded that continuation and extension of the buoyage should be recommended.

The importance of making it possible to steam throughout the hours of darkness cannot be over-emphasised, as this will have a most marked effect upon existing fleet capacity. It is appreciated that at present only a minority of the commercial ships is equipped and prepared to undertake night navigation, but this may change within a few years. It is, therefore, recommended to extend the day-buoyage into night-buoyage by adding more buoys and providing all buoys with reflecting strips.

Summarising, channel marking on the Niger and Benue Rivers offers the following advantages:
(i) a better use of the available natural depths will be made, as the talweg channel with a maximum depth will be indicated;
(ii) the safety clearance between the ship's keel and the river-bed may be reduced, as the least available depths that can be expected in the buoyed channels are published;
(iii) the number of groundings will be greatly reduced, thus avoiding the considerable loss of time in re-floating and assembling grounded barges;
(iv) the safety and reliability of navigation will increase; and
(v) night navigation will become possible, thus greatly augmenting the transport capacity of the fleets.

Reference may be made to that part of the Final Report by the French Cameroun investigators ([1 which deals with a buoyage scheme for the Upper Benue. The proposals in that section are in full agreement with the views expressed in the present and subsequent paragraphs of this NEDECO Report and are therefore to be recommended.

3.3.3. Examples of buoyage on other rivers

On the *Lower Mississippi* the navigation channel is indicated by shore beacons as well as by buoys. The beacons consist of tripods on which a kerosine or battery-fed electric light has been mounted. A small sign with a number shows the mileage from the Head of Passes (the Mississippi mouth in the Gulf of Mexico). The intensity of the light and the size of the mileage number make it evident that the use of binoculars is widespread. Generally, along-side or near each light day-marks are placed, which consist of 6′ × 6′ square boards on which a clearly visible pattern is painted.

The shore beacons are placed in the direction of the axis of the channel where it crosses the river. When this axis has shifted, the beacons are not immediately repositioned but instructions are issued for vessels to cross at a certain distance upstream or downstream from the beacon. The beacons are maintained at regular intervals by the U.S. Coast Guard.

Buoys on the Lower Mississippi are 30″ in diameter, 11′ long and weighing 450—500 lbs. Formerly, a smaller size of buoys was in use, but that type is being replaced by the larger ones in view of their better visibility, especially at night and on radar screens. The buoys are of two types, viz., red conical nun buoys and black cylindrical can buoys; all buoys have their top ends fitted with reflecting tape (scotchlite) in red and white respectively. The buoys are anchored to one or more concrete sinkers 2′ square and 8″ high. During one season up to 100% of these sinkers and sometimes 30% of the buoys may get lost during the operations of repositioning the buoys. The marking of the channel is done by the U.S. Corps of Engineers with buoys supplied by the Coast Guard. An impression of the density of buoyage is given by the fact that in the 270 miles of the Vicksburg District the 67 crossings are marked during low water by about 450 buoys; during high water some 50 or 60 buoys are sufficient for indicating the shoals ([2.

([1 ELECTRICITÉ DE FRANCE, 1958, Part III, B. 1. GEN. 11
([2 CORPS OF ENGINEERS, 1955. GEN. 8.

The *Congo* has relatively deep channels in all seasons, due to the geographical position of its drainage basin which extends both north and south of the equator so that there is no pronounced low-water season. The problems are, therefore, not so much concerned with the finding of the deepest channel during a low-water period as providing a general orientation in difficult and intricate sections as well as in the remaining part of the river so that a day and night navigation could become possible. The system applied has been described in the January, 1956, issue of "Dock and Harbour Authority" from which the following may be quoted here:

"Establishment of a complete system of marking, including buoys, shore-marks, semaphores, etc., information stations and navigation books was completed around 1930. The pilot service has been abolished. The marking of the channels is now such that a Master who possesses only a summary knowledge of the waterways can navigate from one mark to the next all along the route. The present system, therefore, not only serves to mark difficult passages but consists of a continued series indicating the route over its entire length.

"In general, the channels available to navigators have a minimum width of 200 m (650 feet). In case where this width is not available, marks are provided indicating exactly the limits of the channels. The marked route does not necessarily follow the line of the greatest depth in the river but rather stays near the bank in order to avoid as much as possible the use of buoys which are exposed to floating islands and may be displaced by collision with barges in a tow. It has been found that shore-marks offer the safest solution and that their upkeep is less costly than that of buoys. Every Master of the vessels navigating on the Congo River must have the official publication in which the buoyed channel is indicated and in which also additional information has been given to facilitate finding the marks in times of poor visibility. The marks do not necessarily indicate the nature and location of snags and shoals, but they do guide the navigator through safe channels. As a rule, and with the exception of sections located near a bank, a navigator will always see the next mark before having to leave the previous one.

"The possibility of night navigation on the Congo River and the Kasai River has often been considered. Around 1933, it was proposed to fit metallic mirrors on the buoys and on the shore-marks and to fit the buoys with reflecting prisms so that the rays of the searchlight would be reflected. This system, however, had to be abandoned because the mirrors were stolen and the prisms were too heavy for the buoys. Later experiments with fluorescent paint were also unsuccessful because the fluorescence was insufficient at night, and in day-time the yellow colour of the paint made the marks poorly visible. Even at that time, in spite of the absence of lights or luminous shore-marks, night navigation was often practised. With the aid of powerful searchlights, the Masters were able to find shore-marks and buoys at least in certain sections of the waterways, but this obviously meant a heavy strain on the navigator, and an added risk factor. The introduction of tugs equipped with diesel engines and screw propellers which did not have to stop frequently to load their wood fuel, the recent crises in transport which necessitated improved turn-round of vessels, and the ever-increasing capital investments required with modern equipment have led to the introduction of a continuous series of marks for night navigation which offer practically the same degree of safety as those used in day navigation.

"Originally, plans were made based on the use of light buoys and beacons. However, these plans had some serious disadvantages and the investments required were exorbitant whilst the anticipated maintenance cost and depreciation were very considerable. In view of this, the Administration decided to go back to the principle of using material with a reflecting power and leaving the light sources on board the vessels. In 1951 and 1952, after experiments which were carried out in co-operation with the transport companies, orders were placed for 300 ordinary buoys, 10 light buoys and 70,000 patches of aluminium with scotchlite reflecting paint. The principle of the new system is to give the same indications for night navigation as are available for navigation by day. Therefore the navigator must not only be able to pick up the marks but also to identify them at the required distance. This has been made possible by arranging the reflecting material in a special manner. The system adopted has proved satisfactory except on one large expanse of water where acetylene light buoys are being used for additional

guidance, especially when visibility is poor. The marks for night navigation were installed rapidly. The work was started in 1952 and finished in the first half of 1953.

"The marks for navigation by day have been reproduced as well as possible both in shape and colour. The marks for night navigation, which are fitted with reflecting patches, can be seen in the light of a 1,000-watt searchlight with narrow beam at distances varying from 3 to 5 km (2 to 3 miles) depending on the size of the mark and the colour of the scotchlite. On long stretches where the distance between marks is more than 2 km, light buoys have been used not because they are indispensable but to facilitate navigation in bad weather.

"Orientation at certain points is achieved by numbered marks. The marks for day navigation are provided with wide-angel scotchlite which has the capacity to reflect light even at an angle up to 80°. Transits for night navigation are also provided with reflecting patches."

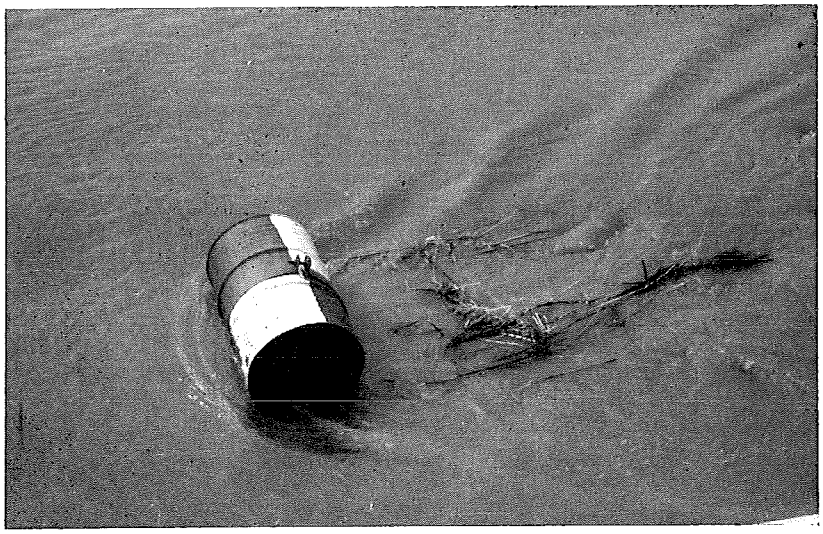
On the *Lower Rhine* beaconing and buoying are the most important of the aids to navigation. Along the entire navigable length of the Rhine (over 1,000 kilometres or 620 miles) distances are indicated every kilometre (about 0.6 mile) by a continuous system of kilometre-boards, on which the distance to the Rhine Bridge at Constanz is shown in large painted figures. Every tenth of a kilometre (330 feet) is marked by a small white board.

3.3.4. Channel markers for the Niger and Benue

a. *Buoys and buoyage*

In the course of the NEDECO investigation, experimental buoyage has been carried out on the Niger and Benue Rivers to determine the feasibility and requirements of a comprehensive scheme of channel marking and also to study the benefits to navigation arising from such a scheme.

During the 1956-1957 Baro shipping season experiments were carried out on the 125-mile stretch between Baro and Idah. Later in 1957, during the Garua shipping season, the notorious flats of Wuro Boki and Gamadio on the Benue were experimentally buoyed. These experiments proved successful, and during the subsequent Baro and Garua shipping seasons buoyage was



PHOTOGRAPH 3.3.4-1

Port buoy with grass

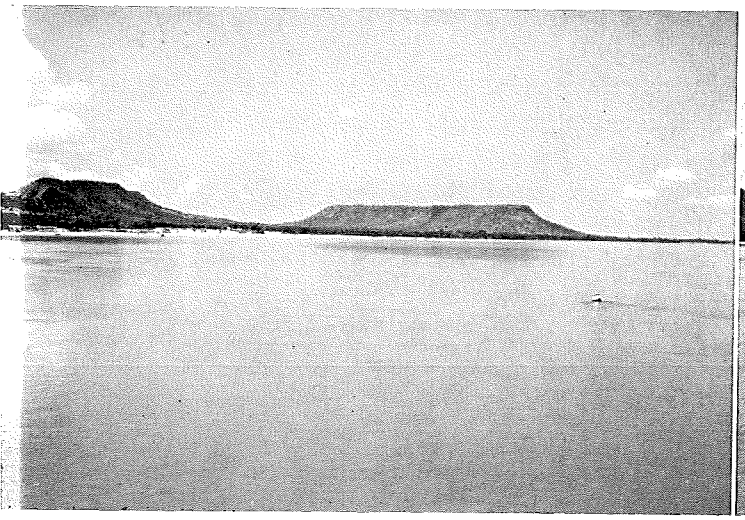
established as a service by the Inland Waterways Department, although it is recognised that this service is still in a stage of development. As and when continued experience and new special equipment become available, the present technique of buoying may be slightly modified, and it is recommended that the Buoyage and Channel Patrol Services (see also the next Section on Channel Patrols) should for some years still remain a subject of careful study and deliberation.

The present experience and the resulting recommendations are here summarised:

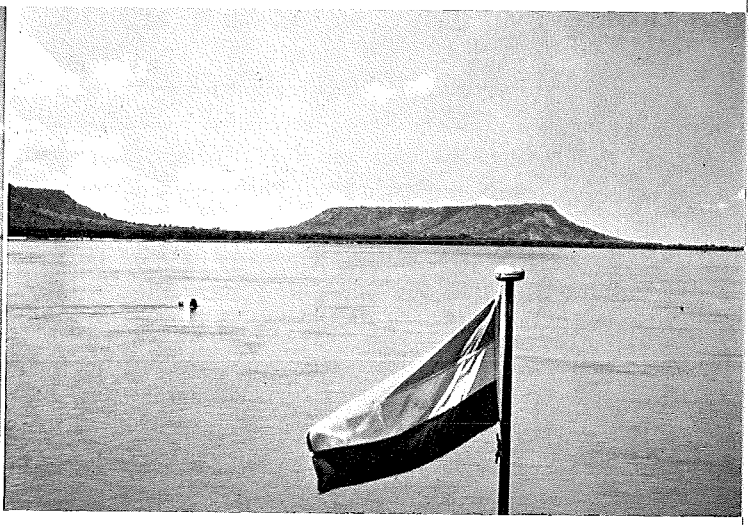
Buoys are to be preferred as main channel markers. Empty 45-gallon oildrums have proved suitable and cheap material for buoys. Complicated constructions made to diminish the nuisance of floating debris accumulating around buoys have not been a success on the whole; it has proved more efficient to detail separate small vessels for the duty of keeping the buoys clear of grass and weeds.

In the recommended lateral system (i.e., marking the lateral limit(s) of navigable channels) port and starboard are determined by the general direction taken by the navigator when proceeding inland.

The drums are painted red and white chequered (port), and black with a narrow white band around the top (starboard). The starboard buoys are made to float vertically by filling them with about 15 gallons of water. A sand fill of equivalent weight is, however, to be preferred with a view to the stability of the buoys.



PHOTOGRAPH 3.3.4-2
Starboard buoy (Mile 397, Niger)



PHOTOGRAPH 3.3.4-3
Port buoy (Mile 397, Niger)

The difference in shape between the vertical and horizontal buoys makes them reasonably discernible even when the colours are less visible (see Photographs 3.3.4-2 and 3.3.4-3). An improved visibility of the deeper-floating black buoys will be obtained by adding steel cones to the upper end of the drums. The buoys then conform entirely to the United Nations' system recommended for inland waterways in Asia and the Far East and to the League of Nations "Uniform System of Maritime Buoyage" ([1].

The present practice is to anchor the buoys to 100-lbs concrete sinkers by $1\frac{1}{2}''$—$2''$ steel cable pennants, although it is recommended to consider the use of $\frac{3}{8}''$ or $\frac{1}{2}''$ galvanised iron wire

([1] UNITED NATIONS, 1957. TRP. 6

instead of the more expensive and less pliable steel cable. The number of sinkers to be used depends on the circumstances, but in most cases three sinkers will be required. The length of wire between the buoys and the first sinker will be some ten fathoms. As soon as it appears impracticable to retrieve the sinkers of buoys that are no longer in the correct position, it is suggested that the wires be cut and the sinkers abandoned. Experience on the Mississippi proves the obvious assumption that these abandoned sinkers will not create a danger to navigation.

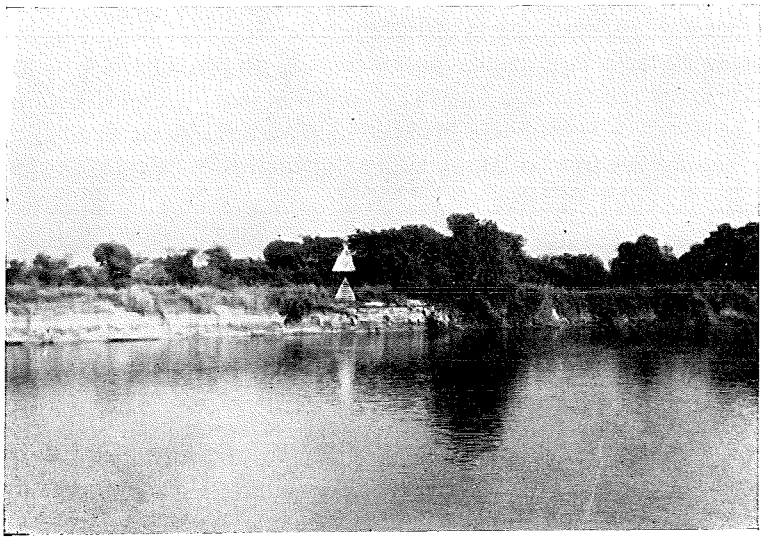
Buoys for day-time navigation should mark the channel only in cases where the course of the navigation channel is not self-explanatory or where certain difficulties for shipping may be expected. For night-navigation more buoys will have to be positioned, supplemented by shore-marks, at distances between two marks or buoys of not more than 1 or 2 miles. The buoys must in this case be provided with reflecting patches of red or white scotchlite tape; experiments with this have commenced during the 1958 Benue season.

Buoyage must be carried out in the form of turning buoys generally, with a few buoys between them as required by shipping for an easy and safe navigation. A single line of buoys is to be preferred; the downstream side of the shallow areas will be the most suitable place in most cases. Buoyage on both sides of the channel is necessary if the width of a six-feet channel is less than 200 feet in which case the buoys must be laid alternately on the two sides of the channel.

The marking of a tortuous channel must be avoided as much as possible, even if this means that the least available depth has to be reduced at that particular section. The fact that ships have passed upstream successfully is not an indication that the same ship will easily manoeuvre through the same channel on the downward trip, so that buoyed channels should be widened and straightened as soon as a rise of the water-level permits. Contact pilots (3.3.4) will be in a position to learn the particular requirements of the several vessels.

b. *Beacons*

During the experiments several transit-beacons have been tested at places along the Niger and Benue. They consisted of two large wooden triangles within the axis of the channel over a crossing, placed at an adequate distance from each other (see Photograph 3.3.4-4).



PHOTOGRAPH 3.3.4-4

Transit-beacons near Igumu on the Niger (Mile 376)

Beacons at crossings are not, however, favoured by the Masters of river vessels, as they cannot be seen during periods of bad visibility such as rainy weather and even in bright weather it is often difficult to orientate on beacons more than one mile away. They also give little indication of the channel's real width. If a unit is steaming over a long crossing across the current, a line of buoys gives a far truer indication of the amount of drift to allow for than transit-beacons. Beacons are only considered useful along the Niger and Benue at places where ships can either run directly with the current or stem the current.

In this case, with stable channels running along the shore-line, beacons may be useful for night navigation as channel-markers in addition to buoys at crossings and mile-boards at regular intervals. It is recommended to adopt in this case the "in-and-out" beacons as suggested for the Benue by the French Cameroun investigators in their Final Report ([1.

c. *Lights*

More maintenance is required for lights than for reflecting buoys and beacons, because in addition to the repositioning in accordance with the shifting of the channels, care has to be taken that the lamp is always lighted.

It is not recommended to establish lights as channel markers along the Niger and Benue Rivers in their present stage of navigation and riparian development.

d. *Mile-boards*

A closer orientation with the help of mile-boards is desirable for those parts of the route which have no specially outstanding features or which give particular difficulty to navigation. Unmistakable reference can then be made in navigation bulletins to certain crossings or positions of channels. Along stable channels these mile-boards may also substitute channel marks for night navigation.

It is recommended that these boards be placed every five miles, and even at every mile along special sections of the route. The extension of the buoyage to night navigation purposes, however, should not be delayed by the construction of these boards. In the first stages of this mile-marking, a beginning could be made at the notorious sections of the river; the system may then be gradually extended to include the remaining parts of the river.

The boards must be fairly large and be placed on stilts on the high river banks along the side of the navigable channel. The mileage should be shown in large figures (2 or 3 feet high) giving the distance to the Escravos Light-house in accordance with the Book of River Charts annexed to this Report. The figures and boards should be fitted with reflecting patches of wide-angle scotchlite.

3.4. CHANNEL PATROLS

3.4.1. General: purpose and examples

The experience gained in other countries that the buoying of fairways should be effected by and under the responsibility of the Government authorities applies equally for Nigeria. A special service within the Inland Waterways Department is required for this purpose, equipped and organised as effectively as possible and conforming to the particulars, peculiarities, and circumstances of the water-courses.

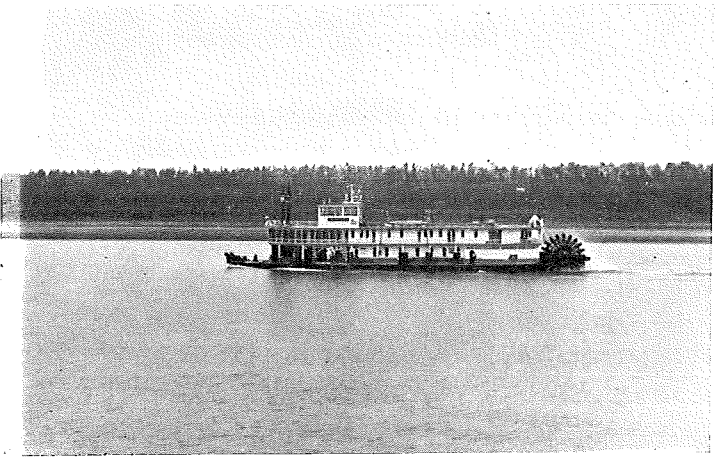
([1 ELECTRICITÉ DE FRANCE, 1958, Part III.B.1.a. GEN. 11

Channel marking on the Niger and Benue Rivers implies an almost constant maintenance of the buoyage after the buoys have initially been positioned. Therefore this service should undertake regular patrols of the channels at short intervals during the navigation seasons. The Channel Patrol Service is then in a favourable position to supply valuable information on the channels regarding the least available depths (L.A.D.'s) and the numbers of buoys of separate crossings, as well as the L.A.D. of a certain section between two ports as a whole.

Such a channel patrol service will remain desirable even after other channel improvements have been carried out, such as dredging, channel training-works or discharge regulation. For although the channel will then have become deeper, its course will not become better discernible. An established channel patrol service, therefore, should certainly not become redundant: on the contrary, it would prove still more useful.

On the *Mississippi River*, in the United States of America, the Coast Guard is in charge of buoying and beaconing, and this Government Department also has police powers on the rivers. In the canalised sections of the rivers, where little maintenance is required as the buoys are mostly in a permanent position, the buoyage is performed entirely by the Coast Guard. But in the downstream districts of the river, where the channels are more intricate and liable to shift, the positioning and repositioning of buoys is done by the Mississippi River Commission (Corps of Engineers) who are reimbursed for this work by the Coast Guard Department.

The various districts of the Corps of Engineers employ licensed pilots for the survey of the channels and the buoyage. Several types of craft are being used, ranging from 185 feet stern-wheelers with steam-engines to small diesel-propelled launches (see Photographs 3.4.1-1 and -2).



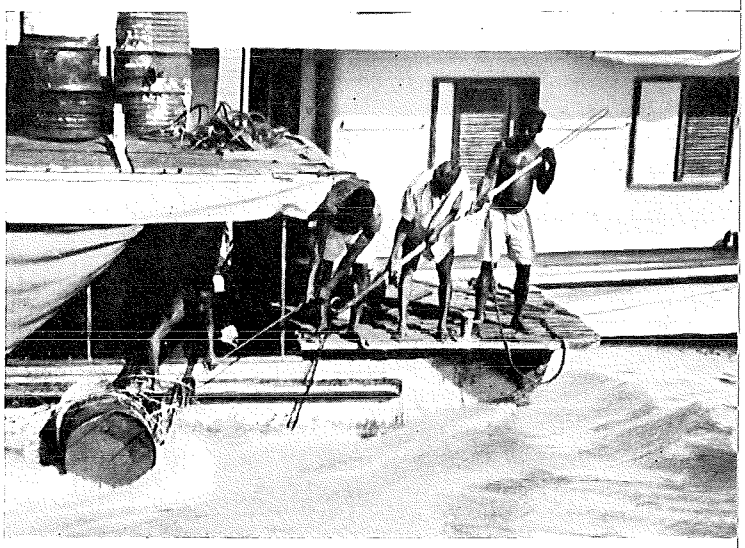
PHOTOGRAPH 3.4.1-1
Channel patrol boat "General John Newton"

PHOTOGRAPH 3.4.1-2
Channel patrol launch "Pathfinder"

These vessels are equipped with echo-sounding gear, radio transmitters, radar, and hoisting apparatus for lifting the buoys and for the removal of snags. With three shifts an almost continuous patrol is made. When proceeding upstream over a crossing, first the line of the port buoys is sounded, and buoys are repositioned, cleaned or replaced as necessary. Then the centre-line of the channel is taken, going downstream, in order to check on the depths that should be at least the same as along the line of buoys. Lastly, going upstream again, the starboard line of buoys is dealt with, after which the patrol boat proceeds to the next buoyed stretch. After the entire section has been treated in this way, the patrol boat turns round and sails in a downstream direction (i.e., the most difficult way to navigate) along the channel which has just been rebuoyed. The echo-sounder is still switched on and during this trip the buoyage is checked on its adequacy, whilst a navigation bulletin is prepared which describes the alignment of the channels and states the available depths and numbers of buoys for each crossing.

On the *Rhine branches* in Holland, a large number of small channel patrol services has been instituted, a system which has an historical background. These small services are each responsible for a short reach of the river of about 15 or 20 miles. The heads of these services each have a comparatively small boat in which they regularly examine the navigable channel and, where necessary, remove or replace buoys and beacons.

PHOTOGRAPH 3.4.1-3
Launch "Wagtail" with buoyage barge



PHOTOGRAPH 3.4.1-4
Handling a buoy on the Benue

On the *Niger and Benue Rivers*, patrols have so far been carried out with ordinary survey launches, and as these offered no special facilities for handling the buoys, a barge was towed alongside (Photograph 3.4.1-3).

Man-handling the buoys in the fast-flowing waters of the Benue, with a poorly manoeuvrable pair of ships, proved a cumbersome task (Photograph 3.4.1-4), and it is indeed remarkable that with these makeshift vessels a reasonable performance of the channel patrol and buoyage service could still be achieved.

But it is of prime importance that a number of special patrol and buoyage vessels be constructed for the Niger and Benue to increase the range and efficiency of the buoyed districts.

3.4.2. Patrol vessels

A special study has been made of the buoyage experiments on the Niger and Benue, and comparison with channel patrol work in other countries has resulted in a programme of requirements for buoyage vessels that will match the schedule of patrols which is proposed (see 3.4.3). A report on these matters was submitted to the Director of the Inland Waterways Department, Lagos, in January, 1958, and from the findings of that report with respect to the patrol vessels some considerations may here be quoted.

Velocity and manoeuvrability. More time will be available for the proper buoying work as the vessels can develop a greater velocity and are better manoeuvrable. In proportion to the possibility of operating more quickly with a vessel, the district to be served may be greater. Calculations show that the advantage of a great velocity, however, decreases in proportion to

an increase in the density of the buoying. But it is shown that the cruising speed with respect to the water should not be less than 12 knots, although if possible and practicable within reasonable financial limits, a greater velocity should be welcomed. On the other hand, the vessel should also be capable of sailing at a low speed of one or two knots, for example, when stemming the current during buoyage operations. The manoeuvrability should be as good as possible at all speeds. All controls should be in the wheel-house in order to avoid loss of time while manoeuvring, and to reduce the crew.

Accommodation. It is thought that a crew of 8, i.e., Patrol Officer, Quartermaster, Driver, 4 Able Seamen and a steward should be able to cope with all the work to be done. The regular return to a base will permit a certain limitation of the accommodation and the capacities of fuel and water tanks. Nevertheless, these limitations must not be overdone, as the vessel should also be able to undertake longer trips whenever these might be necessary or desirable.

Equipment. An echo-sounder is essential, as well as a hoisting-apparatus for the lifting of buoys and snags (see Photograph 3.4.2-1). Searchlights with narrow beams that make buoys or beacons visible at distances of some two miles are necessary, as well as a radio-telephone transmitter. Provision should be made for a radar set to be installed at a later date.

These and other requirements may be summarised as follows:

1. *General.* Very great reliability and working security; greatest possible simplicity; independency of shipyard facilities.
2. *Speed.* Maximum not less than 12 knots; minimum 1—1½ knots.

PHOTOGRAPH 3.4.2-1

U.S. Corps of Engineers Snagboat "Charles H. West"

3. *Manoeuvrability.* Very good.
4. *Draught.* 2'6" to 3" as a maximum.
5. *Stability.* Great (wind gusts up to 110 m.p.h.).
6. *Engines.* Air-cooled.
7. *Batteries.* Reliable: NiFe.
8. *Navigation.* Entirely from the bridge, where also the engine-controls should be placed.
9. *Accommodation.* Similar to Government "Wood"-class launches. Adequate for trips of one or two weeks.
10. *Electricity.* Foolproof system. Light, radio (eventually radar), echo-sounder, searchlights, 2 refrigerators, and ventilation. Spare generating set.
11. *Water.* Drinking water and river-water systems. Hydrophores or daytanks and hand-pumps. Capacity of tanks 300—500 gallons (10 days).
12. *Fuel.* Capacity of tanks for 50—60 hours full-speed steaming.
13. *Working deck.* Low (1'—1½') above water-level. Preferably on fore part of the ship.
14. *Anchors.* Similar to Government "Wood"-class launches. Stern-anchor with hand-winch.
15. *Hoisting-apparatus.* Mechanised derrick 1½ tons.

It is recommended, in view of the suggested schedule of patrols (3.4.3), that at least three of these special patrol/buoyage vessels be ordered for day-time buoyage on the Niger below Baro and on the Benue within Nigeria. For maintaining a continuous night buoyage, at least one additional vessel is required, but a fifth vessel will lessen the strain on the service and may, on the other hand, be seen as a reserve.

The Senior Channel Patrol Officer, supervising the work of the several Patrol Districts, will require a fast launch (such as a pinnace of some 15 knots speed) with sufficient accommodation for a few nights. An echo-sounder and a radio-telephone transmitter should be fitted in that launch.

These recommendations are based on the thesis that the cleaning of the buoys from floating debris, etc., will not be the normal task of the buoyage vessel, but will be done by means of special cleaning vessels of which at least one should work in conjunction with each patrol vessel.

When continuous day and night buoyage is effected, this cleaning procedure may develop into a cantoning of the rivers, comparable to the practice in Holland of having small services. Each separate cantonment would carry out minor maintenance works in a river-section, such as cleaning and storing buoys, beacons, mile-boards and gauges, but the cantonment would not be responsible for the positioning of the navigational aids, which should be left to the patrol officers on their special vessels.

The cantonments might cover sections of between 20 and 50 miles of river-length, depending on the density of the buoyage. Similar to the Public Works Department Road Camps, the personnel of a River Cantonment may consist of a headman and a number of labourers, who have a small self-propelled cleaning vessel and a number of canoes at their disposal.

3.4.3. Schedule of patrols

The length of daily permitted working time naturally plays an important part when considering a schedule for the patrols. When, for instance, by a system of shifts the daily working time could be fixed at 12 hours, as is usual in many countries for these purposes, instead of at about 8 hours, then an extension of the districts at a rate of 50% will be possible. It does not, however, seem advisable to create accommodation on board for a double crew, as this would necessitate a larger ship than the actual work requires, meaning a large displacement, more powerful engines, and

increased cost of building and operation. As the need for a double crew is obvious, a solution may be found in the accommodation of the entire crew (and their families) on a shore basis, and in shifts of a 4-days' (of 12—13 working hours) scheme.

Relief of the Patrol Officer, the Quartermaster and the Driver, respectively responsible for the fairway, the ship and its good working condition, should not take place for short periods. The continuity of the personal and local knowledge of the river-stretch, as well as a continuous perfect working order of the ship are indispensable factors for good results, according to the responsibility of the authorities for reliable aids to navigation.

It seems acceptable that these persons should be on board their vessel during every patrol and must not be relieved during the periods when the service works under great strain.

Such a maximum strain will occur during the Benue season on the river above Lau, where the shifting channels require frequent patrolling. Channel patrol services on the Lower Benue and on the Niger will during the high-water period in general be restricted to the controlling of buoyage for night navigation.

It is suggested that three districts be instituted on the Benue during the shipping season on this river. Two of these would be in the upper reaches, covering together about 200 miles and each containing a difficult and laborious stretch; the bases could be at Yola and at Jen or Lau. A third district would cover the remainder of the Benue.

These three teams, each with a separate vessel, will suffice for day-time buoyage on the Benue. During the present Niger season (November to April), three teams will be ample for day-time buoyage, leaving time for maintenance of ships and leave of crews.

For a continuous night buoyage, which will require patrols on the Niger also during the flood period, at least one additional district will be required but, as has already been explained, a fifth vessel may prove necessary to lessen the strain on the service. In that case the organisation could be, apart from the two Upper Benue districts: district 3 from Lau to Makurdi, district 4 Makurdi—Lokoja—Baro, and district 5 the Niger below Lokoja. It is evident that these 5 vessels will be more than sufficient for a continuous low-water buoyage, even from Jebba to Burutu/Warri.

With the required speed of at least 12 knots, the patrol vessels can control the small districts on the Upper Benue and the Niger districts (day-time buoyage) in 4-day schemes, i.e., corresponding with the shifts of the crews. Each part of the channel is then being controlled on an average every other day, which normally will prove sufficient. The longer districts, i.e., the Lower Benue and the high-water Niger (night-time buoyage) districts, could have a frequency of control of about once a week or, in the case of five districts, about once in 4 or 5 days, which may in practice also prove sufficient for the more easy channels during high water.

The Upper Benue offers a good opportunity for an inspection of the channels and a terrestrial positioning of the first buoys during the low-water period, i.e., in the months of April and May. This implies that the buoys should be left in the river-bed here during the entire low-water season.

3.4.4. Duties

The task of the Channel Patrol Service may be outlined as follws:

a. to find the best channel by soundings;
b. to place and maintain buoys and beacons at those parts of the river where they are needed;
c. to clear away snags and obstacles; and
d. to compile Navigation Bulletins which give information on the depth and situation of the channels.

The work of compiling river charts and the soundings needed for this work should not be part of the duties of the Channel Patrol Service, although co-ordination with the Hydrographic Service is very desirable. If necessary, the maintenance and check-reading of the river gauges can be performed by the Patrol Service; but as this service will have to work mainly to meet the many needs of the moment caused by local conditions, it is not advisable, in principle, to assign to it tasks which are bound by time and place.

Rough surveys are required to find the exact position of the navigation channel and the least available depth therein. It is necessary for the patrol launch to sound frequently and accurately; a diamond pattern of soundings across the channel may give the best results.

When the area is intricate or where there exists more than one possibility as to a suitable navigation channel in the river-bed, every possible channel must be investigated. A survey chart may then have to be prepared, and for this purpose a separate and self-supporting survey team should be made available at short notice to the Channel Patrol Service (see also 3.1.3).

The above Channel Patrol duties require officers who are highly experienced in the river-work and who consequently should remain in this Patrol Service for a long time. Their duties may only alternate with those of a Contact Pilot (3.2.4) and they should be considered specialists in Niger and Benue navigation who are not normally available for other work within the Inland Waterways Department.

In view of the importance of this work, it is recommended that a number of suitable and qualified Nigerian river-navigators should be selected as soon as possible to receive further training as a Patrol Officer, e.g., by serving as Quartermaster on the patrol vessel.

3.5. STAGE INFORMATION

3.5.1. General: purpose and examples

Stage-hydrographs are basic data for all hydrological studies and river improvements. People concerned with river navigation also are very interested to know the stages and their trend along the various river-stretches.

Quartermasters and pilots know by experience what difficulties they can expect during certain river-stages while navigating their ships. A particular bend may need more than normal attention because of the force or the direction of the stream. The tactics of mooring very often depend much on the river-stage.

The velocity of the stream increases with the stage, and by experience those in charge know how much time a ship will need to reach a station, as this depends on the river-stage.

When it is known that river-stages are falling in the headwater area, it is also known that after some time a fall may be expected further downstream. Although this knowledge can only be expressed in vague terms as 'some fall' and 'some time', it can nevertheless be very useful for the short-term planning of ship movements. The same, of course, holds for rising stages.

To meet the demand of stage information along the *River Rhine*, a river-stage announcement is broadcast daily at 9.30 a.m. as part of the programme of the Dutch broadcasting services: water-levels read the same morning at 08.00 hrs are given for 16 stations along a river length of 500 miles. This means broadcast water-levels for, on the average, one gauge per 30 miles, out of a system of main gauges of one per 20 miles. With the actual gauge reading, information about rise or fall since the previous day is also given.

For the *Mississippi* and its tributaries, a daily river bulletin is published by the United States Weather Bureau, giving water-level readings of a number of gauges corresponding to about one gauge per 70 miles length of river. Taking all existing main gauges into account, the average distance between two gauges on that river is 30 miles. At the same time information about the trend of the river-stages and the weather forecast are given. The river bulletin is published simultaneously in a number of places along the river and is offered for sale in many towns. The river-stages are also broadcast.

3.5.2. Main gauges

In III, 4.2.1. a list is given of the gauges which have been established or maintained or used by NEDECO and which were handed over to the Federal Government in April 1958. These gauges are:

Jebba, Egwamama, Budon, Shintaku, Idah and Isara-Aboh on the Niger;
Wuro Boki, Yola, Numan, Lau, Angwan Taru, Ibi, Makurdi, Loko and Umaisha on the Benue;
Dadin Kowa and Bare on the Gongola;
Beli and Gassol on the Taraba;
Donga and Nyankwola on the Donga; and
Katsina Ala and Sevav on the Katsina Ala River.

The gauges at Baro, Lokoja and Onitsha on the Niger have been maintained first by the Nigeria Marine Department and later by the Inland Waterways Department, which has since taken measures to provide them with a more permanent construction.

In view of future studies (see III, 7.2.1) it will be necessary to extend the network of river gauges and, in addition to this, a recording gauge will have to be installed at a number of stations.

3.5.3. Organisation of gauge readings

With a view to the immediate use of gauge readings (short-term planning of ship movements) and for use in the future (see III, 7.2.1.) it is of great importance that the organisation of the gauge readings — readings, despatching, and filing — is such that a continuous, up-to-date and highly-reliable stage-record can be obtained.

Experience during 1955—1957 has shown that a regular inspection of the position of the gauge and the readings made by the gauge reader is necessary. Even when a recording gauge is used, it will still remain necessary to have a staff gauge read daily.

For the purpose of assisting navigation (daily river-stage information) it will generally be sufficient if gauges are read once a day. Further hydrological studies, however, will require 2 or 3 readings a day, depending on circumstances. In some remote stations it might be necessary for the local gauge reader to do the routine work on the recording gauge. For this a careful instruction will be needed. Gauge readers must be supplied with a written instruction of their duties, and a special note-book to keep the records of their observations.

To make it possible for water-levels to be published daily for the information of navigation, water-level readings must be sent daily to a central station. To ensure a continuous good record it is advisable that readings be sent in as quickly as possible so that measures can be taken whenever there is some doubt about their being correct.

It is therefore advised that, where possible, daily use be made of the existing telegraph facilities, whilst the radio network mentioned in 3.7.2 will in this connection also render good

services. In some cases it might be necessary to instal a radio-telephone set or an automatic transmitter at the gauge station.

Water-level records of all gauges must be kept in central water-level archives where arriving records will be checked immediately, and put into a clear form.

3.5.4. Publication of gauge readings

River-stages of interest for navigation should be transmitted daily by radio (see also 3.7.2).

As water-level records made for the purpose of river study and navigation will generally serve other interests as well, they should be made easily available by being published yearly in a synopsis of water-level records.

3.6. PREDICTIONS

3.6.1. General: purpose and examples

River-stage predictions give information on the fall or rise which can be expected to occur at a certain place along the river during a certain interval of time. To establish prediction procedures, an intensive study of river-stage records is generally necessary.

The general purpose of river-stage predictions consists of assisting the navigation (see 3.5.1) and of warning riverain interests of the occurrence of high floods.

In Holland, stage-predictions for the *Rhine River* are made by a Government agency during low and during high river-stages. The prediction during low stages is mainly of interest for the navigation, because of the least available depths. During high river-stages they are made because the stability of levees and embankments should then be watched, and because navigation along certain river stretches becomes then rather difficult or even impossible. The prediction will also enable the commercial interests to remove merchandise in time from those quays that are liable to become flooded. Along the Dutch stretch of the Rhine, predictions during high river-levels are made 4 days beforehand, whilst during low stages they are made about 6 days in advance. For the prediction the data of 16 gauges (in Germany) are used.

On the *Mississippi River* forecasts are made daily for the three following days and published in the River Bulletin and by radio. The interests here are also the navigation and the flood protection of riverain towns and industries.

The length of time over which a stage-prediction can be made in advance depends on the physical properties of the basin drained by the river and on the properties of the valley through which the river flows. Diagram 3.6.1-1 gives the travel-time (time-lag) in days of a flood from the various up-river stations along the Niger and Benue to Onitsha on the Niger, during medium river-stages. The sailing time for modern river-craft from the Niger Delta Ports to stations along the Niger and Benue is also shown on the diagram.

Because of the difficulties met by the navigation on the Niger and Benue during low and medium river-stages, stage predictions together with a prediction of available depths will prove very useful. It is advised that the Inland Waterways Department be charged with the responsibility of making and publishing such predictions. Close contact with the commercial shipping interests will ensure that this Department is always kept informed about the existing need of stage-predictions.

3.6.2. Niger water-level predictions

a. *Niger above Lokoja*

The close relation between the discharges of the Niger in the Interior Delta in the French Soudan and those at Baro in Nigeria during the months of January to May inclusive creates a good possibility of predicting the water-levels at Baro during that period. The fact that the shipping companies operate their fleets on the Benue during the wet season and only start to evacuate the produce via Baro during the months from November onward, makes a prediction of the water-levels of this so-called "Baro season" very interesting.

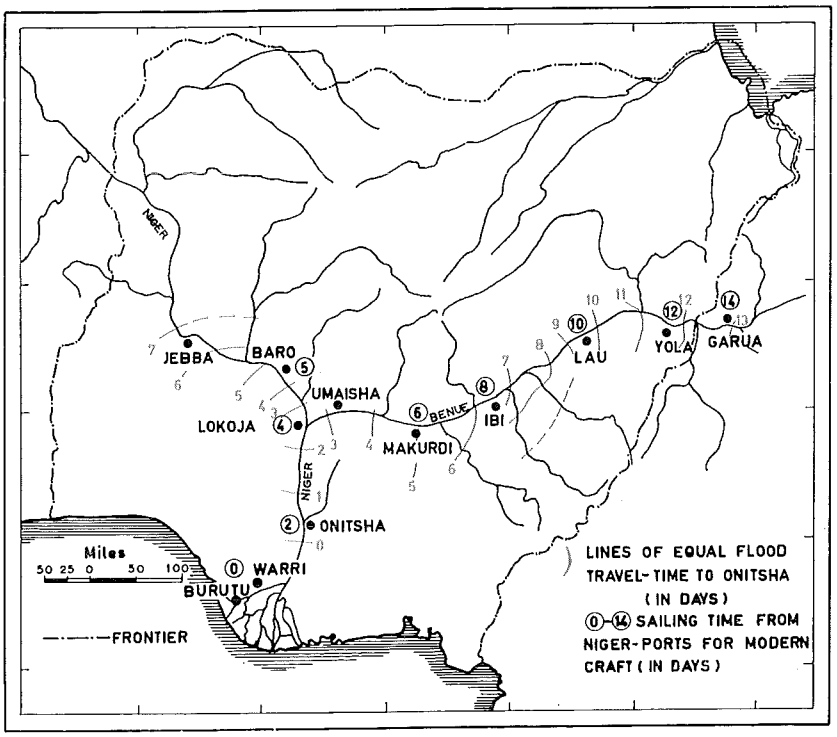


DIAGRAM 3.6.1-1

Propagation of flood and sailing time of ships

First of all, it will be possible with the use of the figures as found in Table III, 4.5.4-7 (columns 1 and 4) to predict the maximum water-level at Baro to 4 months ahead. Fortunately also a rather good relation can be found between the maximum water-levels of the flood at Mopti and Diré respectively, and as the crest of the flood needs about 2 months to cover the 190 miles between Mopti and Diré, this means a prolongation of the term of prediction to about 5 to 6 months. The relations between the maximum water-levels at Mopti, Diré and Baro respectively are given in Diagram 3.6.2-1.

Secondly, it will be of value to predict the fall of the river after the Black Flood period. For this purpose the figures from Table III, 4.5.4-9 (columns 5, 9, 13 and 17) have peen plotted as a function of the maximum water-level at Diré, and average curves have been drawn. This prediction can also be extended by another two months when based on the maximum water-

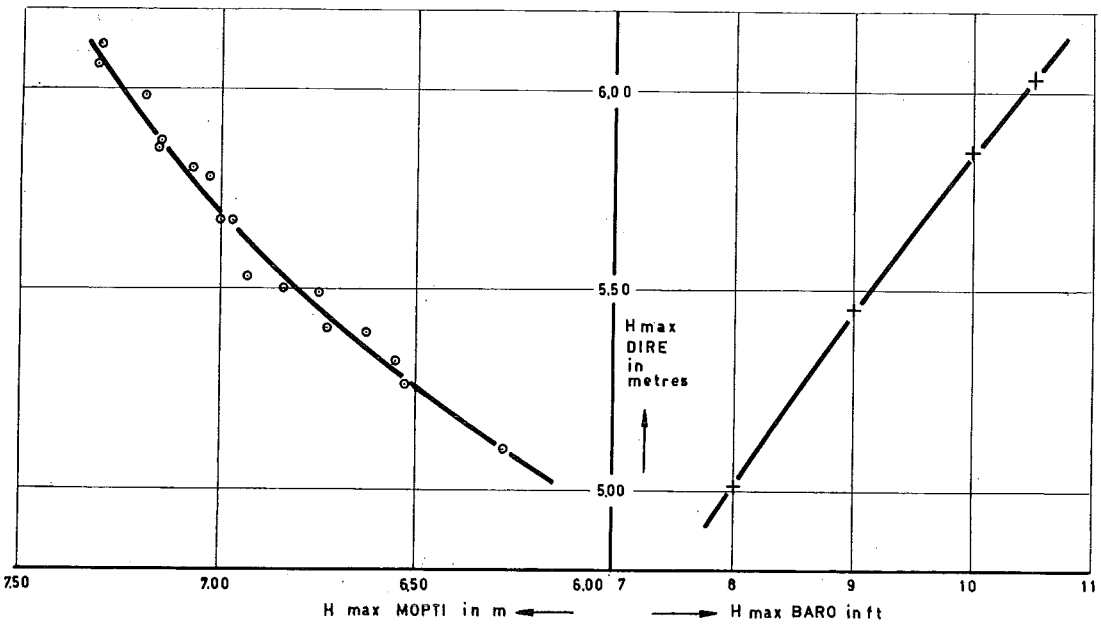


DIAGRAM 3.6.2-1
Relations between maximum water-levels at Mopti, Diré and Baro

levels at Mopti. The results of both computations are shown in Diagram 3.6.2-2. These graphs can also be used for the prediction of the moment of the maximum water-level at Baro as derived from Diagram 3.6.2-1.

With regard to the accuracy of the prediction, the maximum water-level has a divergence of three inches and the time-lag is accurate up to one week when the prediction is based on water-level readings at Diré. Where it concerns a prediction based on observations at Mopti, these figures are five inches and 10 days respectively. Good results have been obtained with predictions for the 1958 and 1959 Black Floods.

b. *Niger below Lokoja*

There are three distinct periods during which stage-prediction on this river-stretch may be of interest.

The first is the period during which there is intensive navigation to Baro. A study of the combination of the procedure used for the prediction of the Baro water-levels and of the recession curves of the Benue will enable the prediction of water-levels for February and March on this river-stretch about 2 months in advance. Further study of the recession curves of the Benue during the low stages will be necessary.

The second period is during June, the beginning of the Benue shipping season. Prediction on the Niger below Lokoja will become of interest when the Benue Entrance is improved. At present shipping on the Niger below Lokoja is already possible before the Benue Bar can be crossed, and ships are then waiting at Lokoja (see V, 3.1.2).

Early in the season the increase of stages on the Niger is mainly due to the increased discharge of the Katsina Ala River, whilst shortly afterwards discharges increase on the Donga River and on the Taraba. Because of the time-lag (see Diagram 3.6.1-1) predictions on the Lower Niger during this time will not be possible more than 4 or 5 days in advance. However, to enable even this prediction a more detailed study of storage on the Benue is necessary.

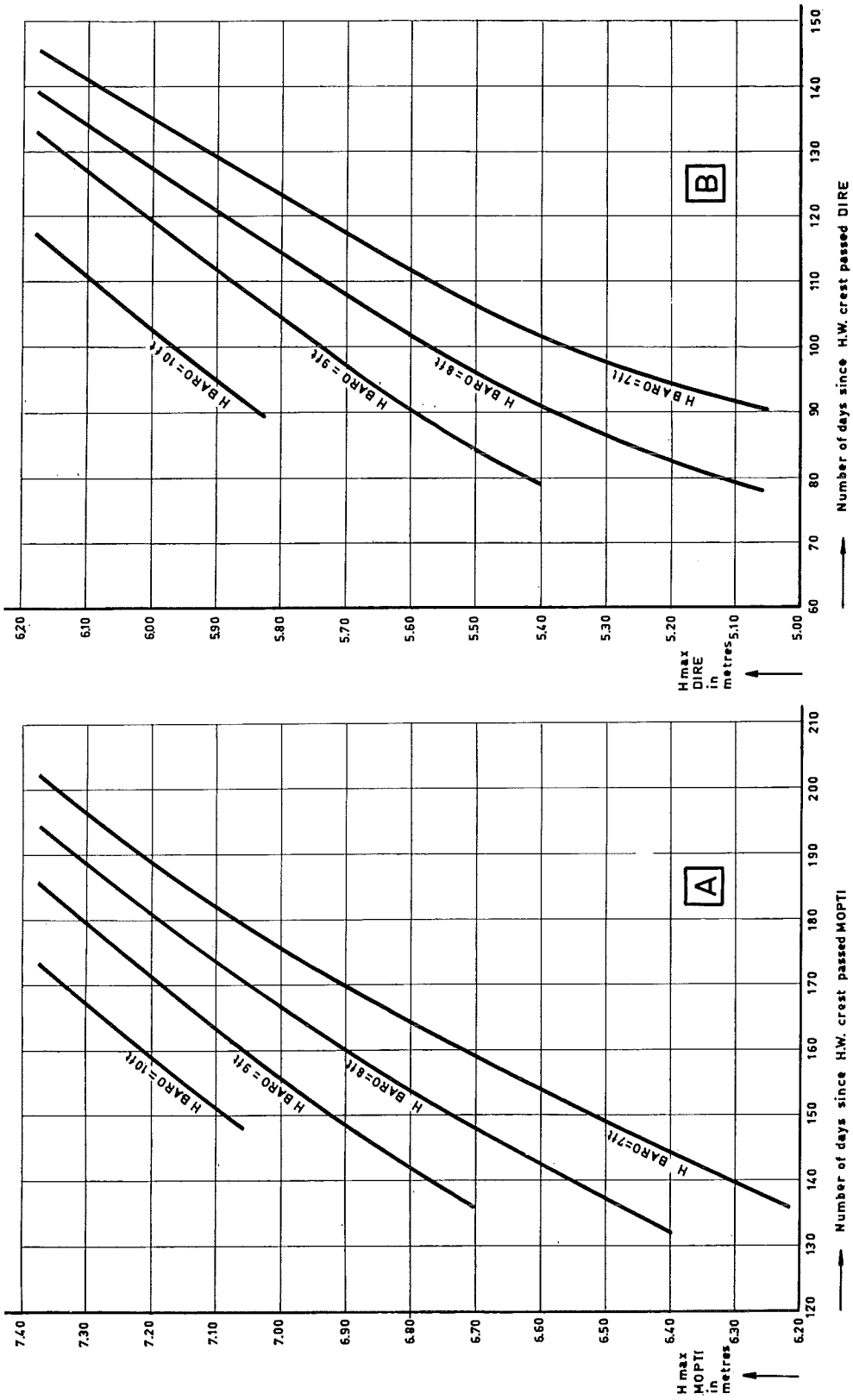


DIAGRAM 3.6.2-2

Prediction of Baro water-stage

The third period during which stage-prediction on the Niger can be of value is during the high stages in September and October. Especially when very high floods are expected will commercial firms with sheds liable to flooding be interested.

3.6.3. Benue water-level predictions

a. *Benue above Lau*

After river-stages have started to rise during June and July, a fall occurs in some years during July and/or August which can be very awkward for the navigation between Lau and Garua. A stage-prediction will then enable short-term planning of ship movements. It can, for instance, be decided that a ship must leave Garua or Yola for Lau in order to be loaded there, or a ship may make use of one or two days before the river falls to pass the Wuro Boki flats and to await the rise while loading at Garua.

At the end of the season water-levels generally fall very fast. To avoid the risk of grounding (which may involve the ship having to be left behind until the next season), shipping may leave this river-stretch before it is really necessary. Prediction can assist the navigation in getting the benefit of the whole length of the navigable period.

Because Yola is situated relatively close to the headwater area, predictions for river-stages at this place can be made only 2 or 3 days beforehand. When stages are falling after the maximum water-level has passed, the period of prediction may become 10 days, but shipping may then already be impossible.

Predictions of very high floods can be important for the commercial stores.

In the wet season the water-levels at Garua (Mile 972) and at Wuro Boki (Mile 916) are predicted by a service installed by the "Ports et Voies Navigables" of French Cameroun to aid navigation on Garua. The recorded water-levels and the predictions on the water-levels for the next day are broadcast daily together with the expected trend for the next two days. These predictions are the result of stage-interpretations of the upper reaches. These water-levels are, of course, transmitted to Garua via a special radio connection. The accuracy of the predictions proves to be good, certainly when considering the whimsical aspect of the streams (Faro, Mayo Kebbi and Benue) in its upper reaches.

At Garua 65% of the predictions in 1958 were less than 4 inches out; 75% were less than half a foot out; and only of 8% was the error more than 8 inches (Diagram 3.6.3-1). At Wuro Boki the respective figures were: error in 75% of the predictions less than 4 inches; in 85% less than 6 inches; and in 95% less than 8 inches (Diagram 3.6.3-2). On July 8 and 9, 1958, when the error in the prediction of Garua water-level was one to two feet, the water rose rapidly (6'6" on July 7, 11'2" on July 10) resulting in too low a predicted water-level.

The predictions of the water-level at Garua and Wuro Boki might be extended another one or two days, but in that case more gauging stations will have to be installed as well as a fairly dense system of recording rain-gauge stations.

Between Lau and Numan, where the Gongola joins the Benue, the Gamadio Flats are situated. Navigation can be difficult over these flats in the beginning of the season and during the August fall. Considering the time-lag, discharges and water-levels on the Gamadio Flats could be predicted about three days in advance by making use of river-stage data from both the Benue above Numan and the Gongola in its headwater area.

b. *Benue below Lau*

In the beginning of the Benue season the depth on the bar at the entrance near Lokoja determines the moment at which this river becomes accessible. So it will be of interest to predict

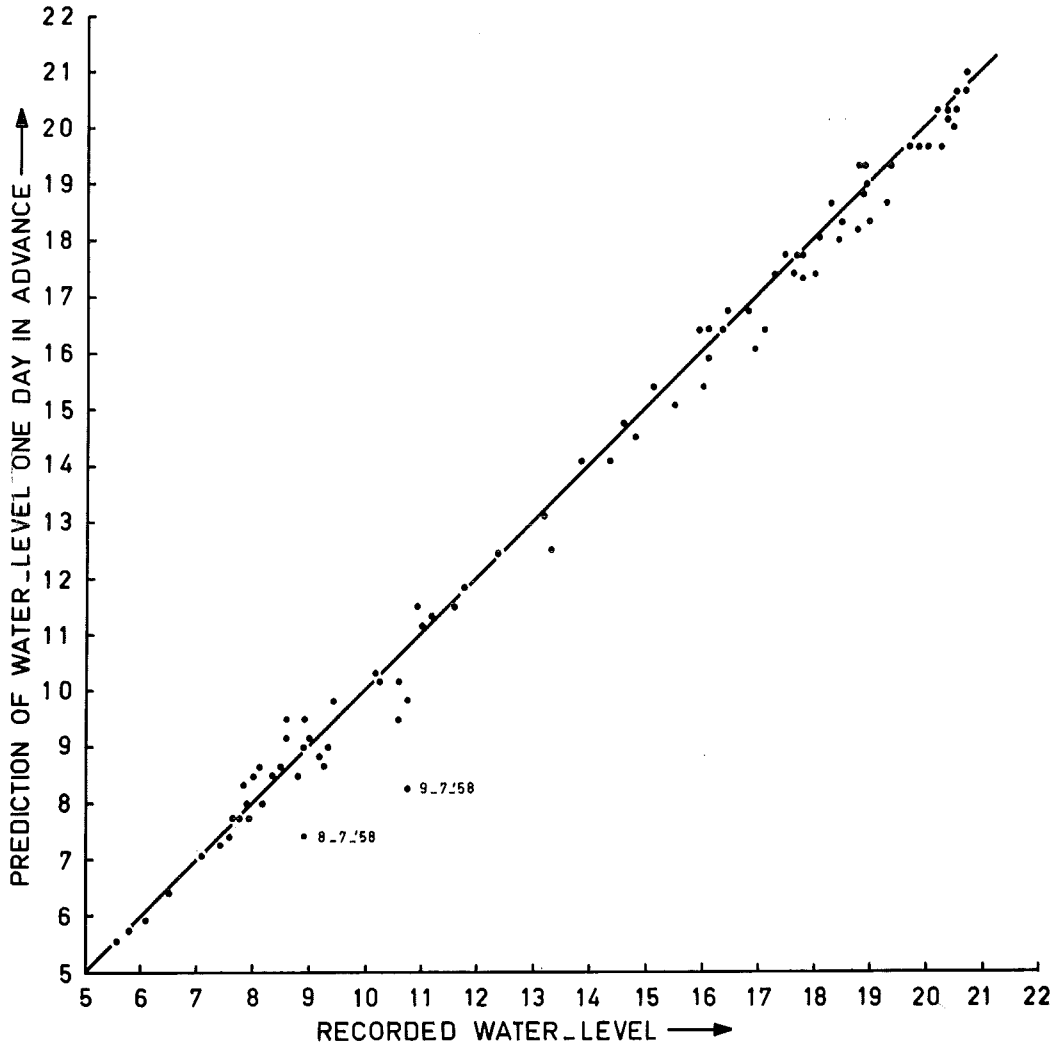


DIAGRAM 3.6.3-1

Water-level prediction, Garua, 1958

the river-stage at the confluence with the Niger. The variations of this stage are at this time of the year mainly a result of variations of the Benue discharge. It has already been said that discharges are in the beginning of the season arriving mainly from the Katsina Ala River. So, considering the time-lag, it will not be possible to forecast stages at the confluence more than 4 or 5 days in advance, but to do this a more detailed study than has been possible up to now will be necessary.

Diagram 3.6.1-1 shows that the sailing time from the Niger Delta Ports to Lokoja is 4 days. So when a certain water-level (and depth) for the Benue Entrance has been predicted 4 days in advance, ships can be loaded to a draught corresponding with the available depth. At Lokoja no waiting will then be necessary, and ships can proceed for the Benue immediately.

During the so-called August fall, when navigation above Lau is difficult because of small depths, stages below Lau remain generally high enough for navigation.

After the fall has commenced on this part of the river, stages can be predicted with the help of recession curves. It will be possible to predict some 10 days in advance a minimum water-level: this means that although water-levels may exceed those predicted, they will not be lower.

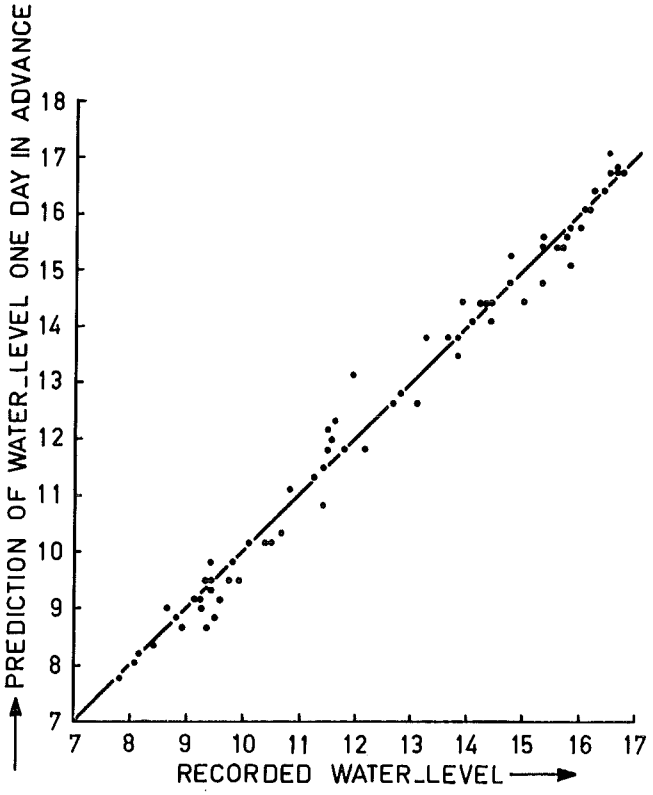


DIAGRAM 3.6.3-2

Water-level prediction, Wuro Boki, 1958

Such a prediction will enable navigation to use the whole length of the navigable period. Up to now ships have been generally leaving too soon because it was not known how fast the river would fall.

3.6.4. Predictions and reservoir operations

The present prediction of the water-levels at Garua and at Wuro Boki will have to be extended when a reservoir at Lagdo, at Yola or at both places is envisaged.

For a dam above Jebba, a fair prediction of the Black Flood (December to March) is already possible (see 3.6.2). But an extensive network of gauges would have to be installed along the tributaries (such as the Sokoto River) and their headwaters to enable a prediction of the floods resulting from the local rains.

The efficient operation of a reservoir needs a reliable and radio-equipped network of stations not only in the catchment area but also on the main tributaries and their headwaters in the area downstream of the dam to determine the amount of water to be released from the dam. When, by means of a sound system of prediction, this can be calculated with fair accuracy, the efficiency of the reservoir with regard to navigation and flood control will increase considerably.

Predictions should be extended as far as possible in the catchment area above the dam, whereas downstream of the dam the extent of prediction is related to the distance along the river, measured in flood-propagation time. For instance, as a change in the discharge at the Yola dam-site causes a reaction at Makurdi 7 days later (Diagram 3.6.1-1), also the discharges of the tributaries Gongola, Taraba, Donga and Katsina Ala should be predicted at a time-distance of 7 days from Makurdi. Gongola water-levels at Bare would not be sufficient, but Dadin Kowa as well as Garkida on the Hawal should be taken instead. An exact prediction 7 days in advance of the influence of the Taraba, Donga and Katsina Ala on the Makurdi water-levels would not be possible, as the propagation from the headwaters of these tributaries to Makurdi is generally less than a week. However, a combination of recession curves, up-to-date water-levels and a knowledge of the general behaviour of those stages at a certain time of the year will yield a useful result.

It will be clear that, when operating a reservoir, a good system of radio-equipped gauging stations on the main tributaries is to be recommended.

3.6.5. Prediction of depths

If the relation between stages and least available depths is known, it seems simple to predict the available depth on a certain river-stretch from the predicted water-levels.

But, as discussed in III, 6.4.3, the relation between least available depth and the discharge of the river must be handled with great caution. First of all, there is, for a certain depth, the difference in limit discharge during rise and during fall and, secondly, the effect of retarded scour has to be taken into consideration.

On the Niger, for instance, the prediction of depths becomes interesting in late November and early December, when the flood due to the local rains abates, and the influence of the Black Flood begins. The least available depth, as found from the graphs in III, 6.4.3, must be decreased during this period as a result of the retarded scour. It is only during the real Black Flood period, i.e., mid-January to April-May, that the relation between discharge and depth can be used more accurately. But even then there is a possible divergence which is related to the height of the preceding flood-period, as in general a high flood will yield a high position of the crossings and, adversely, low sills will be found after a low flood.

During the rise of the Niger, the relation between discharge and available depth depends largely on the water-levels and the duration of the preceding low-water period. A very low and long-lasting low-water period will effect a rather important scour on the crossings and during the first period of the rise this will, with a certain discharge, result in greater depths than in the case of a short-lasting low-water period and a relatively high low-water level. The prediction of the available depth on the Niger during the rise, will, therefore, be rather complicated and will need careful study.

On the Benue the situation is different, as here the fall of the river does not retard half-way as on the Niger, but continues throughout. A prediction of the depths during this rather short period of fast-falling water-levels is not so very important, as the water-level falls 9″ to 1′3″ per day, while the accuracy would be only one to two feet.

Of more importance is the prediction of depths during the rise. First of all, the restricting depth of the Benue Bar is of vital importance to shipping, as it determines the beginning of the Benue season. The behaviour of the bottom configuration of this Bar is rather complex and depends on the respective raise and draw-down of the Niger and Benue as described in detail in V, 3.1.2. A sounding of the Bar just before the rise of the Benue, put together with the predicted water-levels of the Niger and Benue into a complicated calculation of raise and draw-

down in the confluence area, will after some experience give a short-term prediction of the least available depth on the restricting sill.

On the Benue, fortunately, the relation between discharge and least available depth during the rise is not so intricate as on the Niger, because of the rather small divergence of the height and duration of the low-water periods; and a careful study of the least available depths during the first rise of the Benue has given a series of graphs showing the relation between the discharge and this depth (III, 6.4.3). Taking this with the possibilities of predicting the water-levels on the Benue, a certain potential possibility exists of predicting the depths to be expected on the first trip up river.

The prediction becomes more complicated, however, during the so-called August fall ([1]. The height of the crossings has changed after the beginning of the rise and depends on the shape of the hydrograph since the rise. A prediction on theoretical grounds is, therefore, hardly possible, and only the Channel Patrol Service can give a fair estimate of what is to be expected. Especially on the Benue above Lau no rules can be given to predict anything accurate up to less than two feet.

3.7. COMMUNICATIONS

3.7.1. General: purpose and examples

The value of making river information available to all those concerned with navigation has been made evident in the foregoing sections of this Chapter.

This information may consist of maps or Pilot Books which remain valid for a reasonable long period. But there are also many data, valid for a short time only, for which it is highly important that they should be transmitted without delay to the users of the waterways. This second group comprises:

(i) stages of the rivers and predictions thereof;
(ii) least available depths of separate crossings as well as of river-sections between ports; and
(iii) details regarding the channels, the buoyage and the possible presence of wrecks or snags.

A third group of navigation data concerns mainly the shipping companies and the port authorities, but is also partly of interest to the agency responsible for River Management:

(iv) positions and movements of ships; and
(v) data on draughts and cargo of the ships.

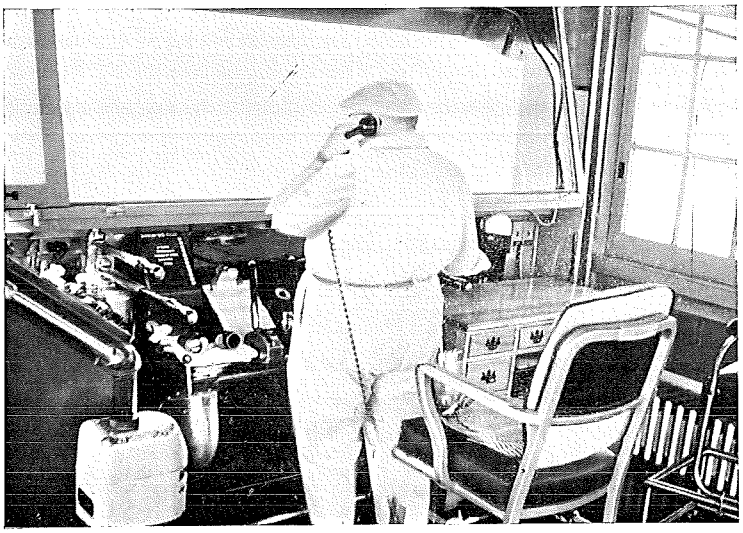
For the efficient performance of the River Management services and also for the river transport, a fast and reliable communication system is indispensable. It is therefore recommended to extend and consolidate the systems now in use along the Niger and Benue Rivers which have been developed during the past three years. The recommendations are further explained in the following paragraphs, after some examples have been given of the present practice of communications along the Mississippi, Rhine and Niger/Benue Rivers.

On the *Mississippi* almost all ships are equipped with a radio-telephone set, each with several channels. One channel is used for short-range ship-to-ship navigation messages: before entering one of the many bends a ship normally calls any oncoming vessel and if necessary discusses the procedure for their taking that bend (see Photograph 3.7.1-1).

Other radio channels are used for longer discussions such as those between shipowners and

([1] due to "the little dry season", as described in III, 4.1.3.

the masters of their vessels. A radio station at St. Louis offers its services for this purpose to the shipping companies concerned.



PHOTOGRAPH 3.7.1-1

Mississippi Captain, using ship-to-ship radio

Stage information and prediction are given in daily bulletins as described in 3.5.1, whilst channel information on depths, buoys, etc. is communicated in frequently-issued navigation bulletins of the various Districts. These bulletins can be obtained at a great number of places along the river, such as ports, docks and even mailboxes on the river-banks.

In the Netherlands, river-stages of the entire *Rhine River*, and the least-sounded depths of its branches in Holland, are daily transmitted at a fixed hour in the normal programme of one of the medium-wave broadcasting stations; this information is also published in the evening papers. Many ships have a V.H.F. public-call telephone transmitter (mobilophone) for ship-to-shore calls to and from any telephone subscriber.

Until recently the only means of communication for river information on the *Niger and Benue Rivers* was the public telegraph service. Messages could be transmitted by telegram from only a dozen river-stations, spread over a thousand miles of river-length.

In 1955 NEDECO erected a radio-telephone transmitter at Lokoja (Mile 362). Two-way conversation was then possible with the French Cameroun stations of the "Service des Ports et Voies Navigables" at Garua (Mile 972), and with NEDECO field headquarters in a house-boat which was stationed during the Benue season at Numan (Mile 846) and during the Niger season at Aboh (Mile 178). Later, also a survey launch was equipped with a radio-telephone set. One-way communication was possible to those river vessels that had a normal broadcasting receiver on board, including all survey launches.

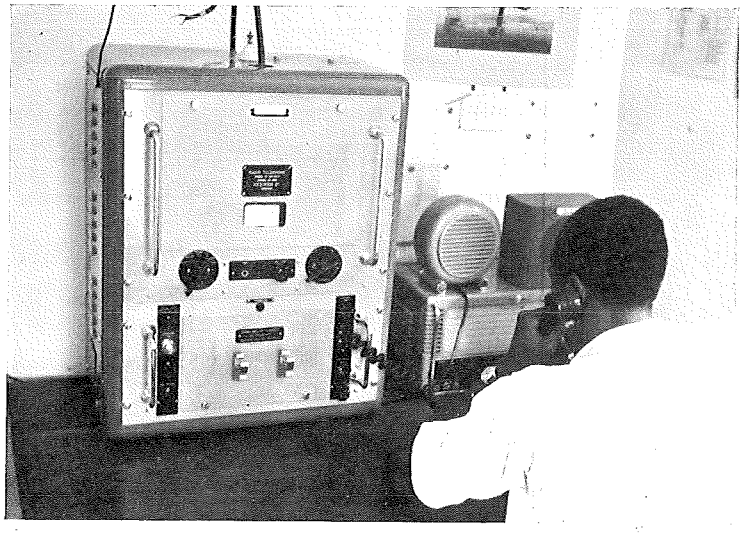
Soon afterwards the largest shipping company operating on the Niger and Benue established similar R/T sets at various river-ports as well as on a number of its tow-boats. An efficient co-operation between the R/T stations of NEDECO and of the shipping company, all operating on the same wavelength (39.1 metres or a frequency of 7663 kc/s), has developed for transmitting

the information on rivers and ships. At present (1958) this combined system comprises ten shore-stations at the main ports along the rivers and over a dozen ship-stations. At fixed hours, gauge-readings are collected from stations along the rivers; they are subsequently broadcast with the predictions (if any), followed by the broadcasting of navigation bulletins in English and vernacular (Hausa) (see Photograph 3.7.1-2). The remainder of the time is available for service messages from and to ships.

The above information is also written out in bulletins, which are made available to ships and shipowners.

3.7.2. Radio network

It has appeared that 50-watt radio-telephone transmitters are capable of maintaining a reliable connection on the 7663 kc/s frequency between stations several hundreds of miles apart along the Niger and Benue. So it is recommended that all Government survey and channel patrol launches be equipped with such transmitter/receiver sets.



PHOTOGRAPH 3.7.1-2

Nedeco wireless station, Lokoja

A certain congestion on this allocated frequency has occurred, notwithstanding the fact that separate hours were used for messages regarding river-conditions on the one hand and ships and cargo on the other. The allocation of an additional frequency (i.e., wavelength) for river communication is therefore recommended; but this frequency should show the same favourable qualities as the 7663 kc/s, namely, an undisturbed reception over distances up to several hundreds of miles, barring abnormal meteorological propagation difficulties. One of the frequencies should then be used for transmitting messages of general interest and for monitoring and calling. The other channel will then be available for the more lengthy two-way discussions between stations that have established contact through the general frequency. All radio stations in use for river communications should be equipped with channels for both frequencies.

3.7.3. Bulletins

Whenever necessary through the availability of fresh data, a navigation bulletin should be issued on behalf of the Government organisation in charge of River Management. This bulletin may contain the following information:

(i) gauge-readings, and predictions of stages;
(ii) available depths of river-sections between two ports;
(ii) buoyed crossings, least available depths thereof, and numbers of buoys; and
(iv) any other information regarding the river which will be of interest to navigators or shipowners.

Item (i) will necessitate daily bulletins, owing to the rate of daily rise and fall of the Nigerian rivers.

Because of the importance of making fresh data available as soon as possible, these bulletins will have to be transmitted by radio at fixed hours to ensure that everybody concerned will listen in. To keep the bulletins in a clear style and to reduce the time required for their transmission (at dictation speed and in two languages), it is recommended to adopt a standard form of bulletin. It may even be considered to prepare loose-leaf books in which the names of the gauge-stations, time of observation and the sections for which least available depths should be given, are printed, with columns left open for filling in the mileage and name of buoyed crossings, number of buoys and L.A.D. An example of such sheets is given in Diagram 3.7.3-1; they can easily and rapidly be completed by the various radio operators and will enable the presentation of the information in a clear way.

Copies of the bulletins will have to be made available by the Government to ships that have no radio receiver. Various agencies may also require copies of these bulletins.

It should be noted that navigation bulletins should not include instructions on an advised way to pass a certain buoyed channel. The buoyage should explain itself, and channel buoys in the recommended lateral system should have the uniform significance that ships can sail in straight lines from one buoy to the other and pass the buoy at a short distance on the side indicated by colour and shape. Only in emergency cases may the bulletin advise to keep clear of a certain buoy.

3.7.4. Ships' movements

The positions of ships are naturally of interest to shipowners and to port authorities. But the authority in charge of River Management, too, is interested in shipping movements, as this information will indicate when ships of a certain size may be expected in a river-section that has to be buoyed or re-buoyed. The movements of ships also indicate when and where difficulties have occurred with a certain ship, whilst on the whole they will give an insight into the navigability of river-sections. Lastly, the movements of ships are of a statistical interest as they show the density of traffic on the river.

It is advised that the Government authority in charge of River Management should centralise all information regarding the movements of ships on the Niger and Benue Rivers. That information may be obtained from observations of survey and patrol launches, from shore-stations and directly from ships that radio their position. A close co-operation between the various agencies, for the benefit of all, will be required for this purpose.

The positions of the ships at a certain time, for example, at daybreak, may then be listed in a bulletin which can be transmitted by radio later in the morning.

A clear picture of the movements of ships is obtained by composing diagrams of ships' movements, as shown in IV, 5.1. Government should prepare these diagrams and keep them up-to-date for their own use and benefit.

NAVIGATION BULLETIN. DATE ...../...../19...

RIVER-SECTION: GARUA — LAU

WATER-LEVELS at 0600 hrs:	yesterday ft. ins.	to-day ft. ins.	PREDICTIONS to-morrow ft. ins.	GENERAL:
Garua				
Wuro Boki				
Safaie				
Yola				
Numan				
Gamadio				
Jen				
Lau				
Makurdi				

LEAST AVAILABLE DEPTH:

To-day:	Restricting Crossing:
Garua — Yola ..... ft.	Mile ..... — .....
Yola — Numan ..... ft.	Mile ..... — .....
Numan — Lau ..... ft.	Mile ..... — .....

CHANNEL INFORMATIONS

Channel Mile	Channel name	Sounded	Date	Gauge	Buoys etc.

SPECIAL NOTES:

.....

Officer i/c CHANNEL PATROLS.

....., 19..

DIAGRAM 3.7.3-1

Example of a standard form of bulletin

3.8. ORGANISATION FOR RIVER MANAGEMENT

3.8.1. Introduction

As river management produces benefits to the entire economy (Chapter 9), it is in most countries a governmental task. In 1954, the World Bank recommended in their Report (1 that a Government Department be established to "collect detailed information about the behaviour of Nigerian rivers and to hold this information ready for studies of flood control, irrigation and reclamation projects, as well as for navigation and hydro-electric schemes".

In 1956, the Federal Government of Nigeria established the Inland Waterways Department, which is in charge of river conservancy, after the now abolished Nigeria Marine had for a long time been the only Government Department on inland and coastal waters. In the "Statement of Policy proposed by the Government of the Federation for the Establishment of an Inland Waterways Department", issued as Sessional Paper No. 7, 1956, the principal duties of the new Department were summarised as follows:

(i) the operation and maintenance of Government craft;
(ii) maintenance and improvement of channels; control of navigation;
(iii) wrecks, lights, buoys and piers, licenses, examinations and surveys of craft;
(iv) hydrological and hydrographic surveys, including map production; and
(v) hydraulic engineering.

It was also proposed that the Department should consist of a Navigation Branch, an Engineering Branch and a Hydrological Branch. The Navigation and Hydrological Branches have already been established.

3.8.2. Duties

The following subjects of river management that are directly connected with an improvement of the navigability of the Niger and Benue Rivers can be mentioned here:

a. *studies and observations* on hydrology (stages, discharges, rainfall, evaporation) and morphology (sediment, channel depths and behaviour) as meant in III, 7 (Future studies), VI, 3.5 (Stage Information) and VI, 3.6 (Predictions);
b. *water-levels*, archives and publications (3.5);
c. *hydrographic surveys* (3.1.3 and 3.4.4);
d. *mapping* (and drawing office) (3.1);
e. *channel demarcation* (buoys, beacons, mile-boards, patrols, contact pilots, buoy-cleaning) (3.3 and 3.4);
f. *dredging* (Chapter 4);
g. *communications* such as radio and bulletins (3.7);
h. *hydraulic engineering*, i.e., the design, execution and maintenance of temporary and permanent training-works, groyning, bank stabilisation, and eventually also the operation and maintenance of dams, reservoirs and locks (Chapters 5, 6 and 8); and
i. *traffic statistics*, research and development (3.7.4).

Each of these items, having a direct bearing on the navigability, should be a responsibility of the Inland Waterways Department (hereafter referred to as the I.W.D.), as follows from Paragraphs (ii), (iv), and (v) of the summary of its principal duties in the Statement of Policy (3.8.1).

(1 WORLD BANK, 1954. GEN. 41

The I.W.D. will extend its hydrological activities regarding subjects (a) and (b) over the entire Niger/Benue drainage basin within Nigeria, being the first Government Department to gain experience in such a wide field of hydrology.

The Hydrological Services of the I.W.D. should, therefore, be in a position to take a leading part in national inter-departmental consultations on hydrological matters. In international consultations on the same subject, and more in particular on measures affecting the run-off of the Niger and Benue, the I.W.D. will be the obvious organisation for discussions on a technical level. In fact, few inter-Governmental consultations have so far taken place on the subjects of hydrology and navigation within the Niger drainage basin, but a certain international co-ordination cannot be avoided when the river potentialities will be developed.

It is, therefore, recommended that the Government should take the initiative over such international consultations whenever measures are contemplated inside or outside Nigeria that would affect the regime of the Niger and Benue Rivers.

The duties of the I.W.D. as described in Paragraphs (i) and (iii) of the Statement of Policy will not be discussed here, as they are beyond the terms of reference of this Report. But it is assumed here that (i) will include the operation and maintenance of survey, patrol and other launches required for the various subjects of river management, as well as eventually the maintenance and crewing of a dredger fleet.

3.8.3. Functional sub-division

The duties stated in the previous paragraph (exclusive of the maintenance and operation of the necessary vessels) may at first all be dealt with by the Hydrological Branch of the I.W.D. The reasons for this are that the several items are all based on, or deal with, the hydrology and morphology of the rivers, whilst the extent of the developing river management and improvement works will still be such that they can be handled by one branch in the first period.

But it may soon become necessary to make a further sub-division. When considering the duties of the previous paragraph, the following subjects will be evident:

1.	*hydrology*	a) observations, studies, research; b) archives and publications;
2.	*hydrography*	c) surveys and mapping;
3.	*channel demarcation*	d) channel demarcation; e) communications;
4.	*hydraulic engineering*	f) dredging; g) training-works, dams, locks, etc.;
5.	*statistics*	h) traffic statistics and related economic research.

These five principal subjects connected with river management and improvement of the rivers may develop into separate units. Later it may become necessary to establish a separate Engineering Branch.

3.8.4. Geographical sub-division

In the Statement of Policy it was decided that Lokoja will be a suitable place for the Headquarters of the I.W.D. This town, situated at the confluences of the Niger and Benue Rivers in the centre of these major waterways of Nigeria, is in a very favourable position, indeed, for guiding the many activities of the Department.

But in view of the great amount of field work to be done in the extensive drainage basins of the main rivers, a certain amount of decentralisation cannot be avoided. As a Government agency with a rather specialised task in a large country, the organisation has to be built up according to geographical as well as functional lines. By reason of the extensive areas involved, the numerous and long rivers, the difficult communications, etc., it is quite impossible to deal with inland navigation and with hydrological affairs with only one strictly centralised organisation.

It is recommended to establish separate divisions and districts, the boundaries of which should coincide with the watersheds of rivers; the divisions are supposed to cover a wider range of activities than the districts.

The duties of the divisional and district staff may include the following activities within its particular area:

hydrological observations and minor studies;
hydrographic surveys;
channel demarcation;
communications;
dredging; and
minor river improvement schemes;
the last two items concerning divisions only.

Other activities such as major hydrological studies and research, hydrological archives and publications, hydrographic map production, major river improvement schemes, traffic statistics and related economic research, should be the duty of the Headquarters itself or of separate units which are closely connected to the Headquarters.

For a close contract and a good co-ordination between the various divisions, districts and H.Q. it may be advisable for the Engineer in charge of a division (district) to be stationed at

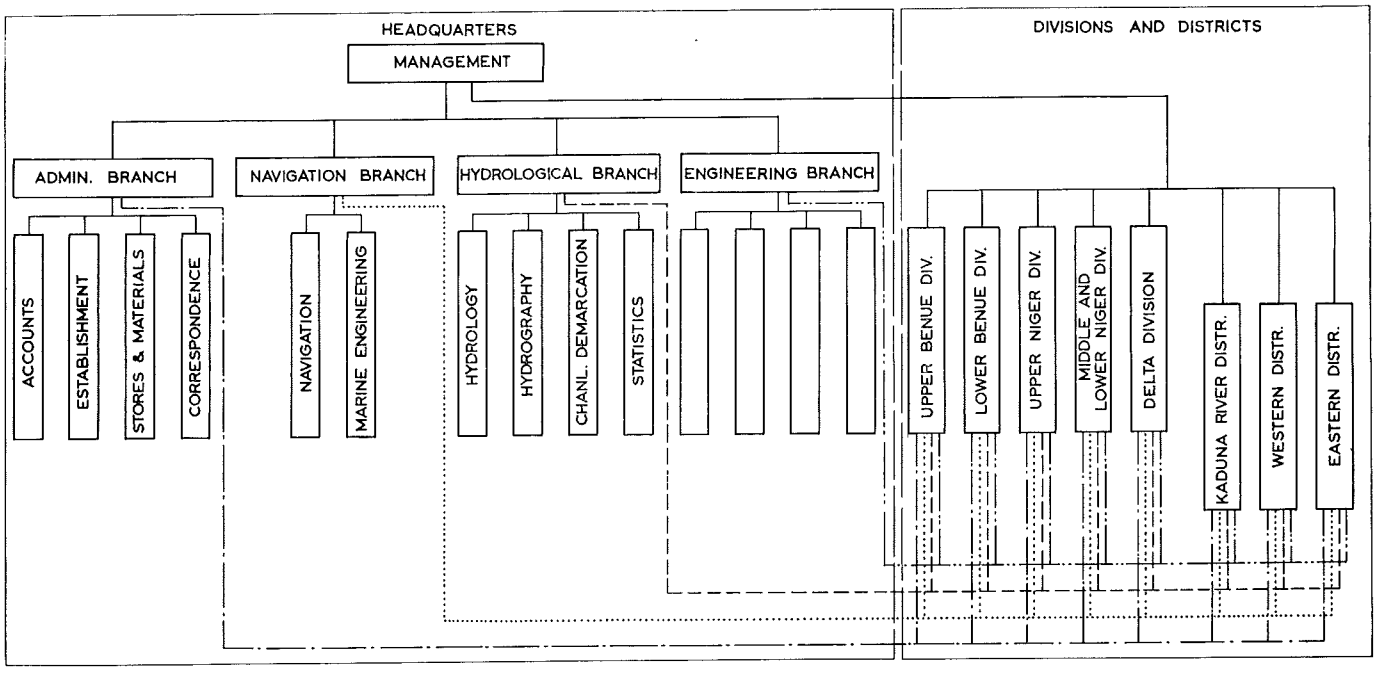


DIAGRAM 3.8.4-1

Tentative scheme of functional and geographical sub-division

Lokoja, although he would, of course, spend a considerable part of his time in the division (district).

A tentative scheme for decentralisation is:

Upper Benue Division:	drainage area of the Benue upstream of Amar;
Lower Benue Division:	drainage area of the Benue between Amar and Lokoja;
Upper Niger Division:	drainage area of the Niger upstream of Jebba;
Middle and Lower Niger Division:	drainage area of the Niger between Jebba and Aboh, exclusive of the Kaduna, Gbako, Gurara and Benue Rivers;
Delta Division:	the delta area downstream of Aboh and between the Benin and Imo Rivers;
Kaduna River District:	the drainage area of the Kaduna, Gbako and Gurara Rivers.

Apart from these Niger and Benue Divisions and the Kaduna District it may become necessary to make a further sub-division of the part of Nigeria outside the Niger Basin. It may then be considered to establish the following two Districts:
Western District: remaining area in the south-west.
Eastern District: remaining area in the south-east.

In the Chad Basin there are no Federal waters at this moment so that the establishment of a Chad Basin District need not be considered at present.

It is recommended that such a system of divisions and districts will be established within the coming period of 5—8 years. In some cases a division may start as a district and, moreover, it seems to be advisable that the establishment of a division or district is sometimes preceded by a preliminary hydrological investigation of the watersheds concerned.

3.8.5. Integrated organisation for river management within the Inland Waterways Department

The further organisation of the Hydrological Branch cannot be discussed without taking into consideration the other tasks and branches of the I.W.D.

The Navigation Branch of the I.W.D. has been decentralised already to a great extent and the Engineering Branch will certainly follow the same pattern, once it has been established as a separate branch.

There seems to be no serious objection against a similar decentralisation of the Navigation and Engineering Branches as has been suggested for the Hydrological Branch. Anyhow, the situation will soon exist that the Navigation, Hydrological and in future Engineering Branch units will be operating in more or less the same areas, each with the same kind of administrative problems regarding accounts, establishment, stores and materials, correspondence, buildings, transport, etc. Also the problem of the co-ordination of the several activities in each area of the I.W.D. arises, especially when working together with other Government Departments, etc., in efforts to build up an integrated development of the water resources in that particular area. It seems to be advisable, therefore, to bring the decentralised sub-divisions of the Navigation, Hydrological and Engineering Branches under one head in each area.

The heads of the divisions and districts covering these areas should have at their disposal administrative, navigation, hydrological and engineering units if and when necessary. In connection with the fact that the I.W.D. will concentrate especially on hydrological and civil engineering problems and also in connection with the favourable influence on the integrated development of water resources which may radiate from a local agency of the I.W.D., the heads of the divisions and preferably also of the districts should be highly qualified civil engineers.

The picture will be then that the divisions and districts will act as local agencies of the Department, whereas the Headquarters will deal with the major problems and the overall management. All the administrative, navigation, hydrological and engineering problems, which are referred to the Headquarters by the units in question of the divisions and districts, will be dealt with by their own branch at the Headquarters, whereas these branches at the Headquarters will have at their disposal sufficient staff or centralised separate units to deal with the major problems.

The importance of an adequate administrative unit assisting the divisional and district heads to administer their divisions and districts can hardly be overestimated. The experienced, technical staff, expensive and difficult to recruit, should not be obliged to devote more time to administrative questions than is absolutely necessary. The same applies to the Headquarters and, therefore, the establishment of a separate Administrative Branch might be considered (see also Diagram 3.8.4-1).

3.9. SUMMARY

3.9.1. Recommendations

Hydrological and morphological studies (III, 7.2) should be continued for the benefit of navigation and of river improvements.

River-gauges (3.5 and 3.6) should be erected in greater numbers; their maintenance and the organisation of the readings deserve special attention.

Water-levels (3.5) of the main gauges should be daily transmitted by radio; a synopsis should be published annually.

Predictions (3.6) of stages and if possible depths should be prepared where feasible for the separate sections of the rivers; special studies must be made for this purpose.

Navigation maps (3.1.2) on a scale of 1 : 50,000 (as appended to this Report) should be revised every two years, which implies that new Niger and Benue maps should be issued alternately every year in June. Single-strip aerial photography averaging 500 miles of river-length per year is required for this, as well as a suitably-equipped drawing office.

Survey charts (3.1.3) of those sections of the Niger below Baro not yet covered by NEDECO sounding charts should be prepared within the next few years. Special survey charts should be made when necessary for the construction of river training-works, for buoying purposes and eventually for dredging operations.

Flood-plain maps (3.1.4) of the area between Yola and Ibi should be prepared within five years, unless other priorities for such mapping exist. In due course these maps should be produced of the entire flood-plain of the Niger and Benue Rivers.

Special buoyage and patrol vessels (3.4.2) should be ordered; three of these will be required for a day-time buoyage of Niger and Benue, and a total of four, preferably five, vessels will be adequate for a complete night-signalisation.

Small motor-launches (3.4.2) should be made available for the purpose of cleaning buoys from floating debris and one or two of them should work in conjunction with each patrol vessel.

One fast launch (3.4.2), suitably equipped, should be made available to the Senior Patrol Officer.

Day-time buoyage (3.3) of the difficult sections of the entire Benue within Nigeria (June to October) and of the difficult sections of the Niger below Baro (November to June) should be effected as soon as the necessary patrol vessels are available.

Night-signalisation (3.3) of the entire Benue within Nigeria (June to November) and of the Niger below Baro (year-round, with increased density from November to June) should be effected as soon as the necessary patrol vessels become available.

Channel patrols (3.4) should be well-organised, each unit running a separate patrol vessel. In view of the operational requirements for a small manoeuvrable vessel, the optimum crew will be found to be a Patrol Officer, Quartermaster, Driver, and two shifts of four Able Seamen. One or two cleaning vessels should be detailed to each unit. Adequate housing facilities on a floating or permanent shore base should be made available in the various districts. The training of Nigerian Patrol Officers should commence at an early date.

A Contact Pilot (3.2.4) should be appointed as a liaison between shipping and patrols.

Mile-boards (3.3) should be placed every five miles along the rivers with placing commencing along difficult sections of the rivers, the distances between them being here one mile.

Communication (3.7) should be further improved by allocating a second wavelength (radio-frequency) for the use of river information, and by close co-operation between shipping companies and the Inland Waterways Department. All survey and patrol launches of the I.W.D. should be equipped with a radio-telephone transmitter/receiver.

The *organisation* of the Inland Waterways Department should at all times be adequate to meet the requirements imposed by the foregoing recommendations. A functional and geographical sub-division will be necessary for this, which implies a decentralisation along the rivers of a part of its activities.

Inter-departmental consultations (3.8.2) should take place to co-ordinate the observations and investigations regarding the use and utilisation of the water of the rivers.

International consultations (3.8.2) with the other countries bordering the Niger and Benue Rivers should be initiated by the Government whenever measures affecting the regime or navigability of these rivers would be contemplated.

3.9.2. Resulting improvements

River management improves the navigability by offering the following advantages resulting from a demarcation of the channels, improved communications and the availability of maps:

(i) a better use is made of the available natural depths, as the talweg channel with its maximum depth will be indicated;
(ii) the safety clearance between the ship's keel and the river-bed may be reduced as the least available depths that can be expected in the buoyed channels are published;
(iii) the number of groundings will be greatly reduced, thus preventing the considerable loss of time in re-floating and assembling grounded barges; and
(iv) there will be an increase in the safety and reliability of river navigation.

These advantages will result in a greater permissible draught of about six inches, and in a gain in time by avoiding groundings and utilising the full length of the navigable period, a gain which may be estimated to give a 10—15% increase in the transport capacity of the present fleets.

When night navigation is introduced as a result of night-signalisation, the transport capacities of the fleets will be further greatly augmented. It is estimated that 60% more cargo can then be transported by the present commercial fleets.

River management will also be essential for further improvements in the navigability by supplying basic data on the regime and on the navigation.

Lastly, river management has an incalculable value by establishing confidence in the future of river transport, and may therefore be responded to by measures taken by the shipping companies, as discussed in Chapter 2.

3.9.3. Expenditure

As the Hydrological Branch of the Inland Waterways Department is already in existence, no further expenditure will be stated here. But it should be taken into account that an annual increase in the recurrent cost of this Branch is essential as during the coming ten years it will certainly expand and decentralise along the lines mentioned in 3.9.1.

For mapping an amount of £ 75,000 has already been applied for. This should be sufficient, to cover the expense of mapping and charting the main rivers and of mapping the flood-plains as stated in 3.9.1.

Buoyage vessels are estimated to cost each about £ 35,000. For housing, office, field-bases and workshop an investment of about £ 50,000 is required for day-time buoyage, and £ 80,000 for a full night-signalisation.

The annual cost of operating Channel Patrols is calculated at £ 20,000 per unit, including amortisation and interest on capital investment, repairs, maintenance, cost of running, salaries and emoluments of officer and crew, housing, overhead for shore services, and buoyage material. To this amount should be added a sum of £ 3,000 per annum for extra services to be rendered by the Hydrological Branch in connection with surveys and other observations.

For day-time buoyage (3 units) the capital expenditure would, therefore, be in the region of £ 150,000; the recurrent cost would be about £ 70,000.

For a complete night-signalisation (maximum 5 units) the capital expenditure would be in the order of £ 250,000 and the recurrent cost would come to about £ 115,000.

The latter figures for a complete night-signalisation include the cost of a day-time buoyage. Thus, to extend a day-time buoyage into a night-and-day signalisation, an additional investment of about £ 100,000 would be required, whilst the recurrent expenditure would rise from £ 70,000 to £ 115,000.

CHAPTER 4

IMPROVEMENT BY RECURRENT DREDGING

4.1. GENERAL

4.1.1. Principles and methods

Some of the defects in navigability mentioned in Chapter 2 of Part V can temporarily be improved by removing soil from the river-bed. Dredging offers a direct way to realise this. Modern dredging equipment, such as a bucket or a suction dredger, is able to remove large quantities of river-bed materials and deposit them in places where they are of no hindrance to shipping. The mobility of dredging equipment ensures the elastic nature of this method of improvement and is an obvious advantage for rivers which show yearly differences in the places where difficulties for naviagtion occur.

Dredging proper, however, does not cure the causes of the defects in the navigability, but is only a means to combat some of the effects of undesirable qualities of the river. Consequently the improvements realised by dredging are only of a temporary nature.

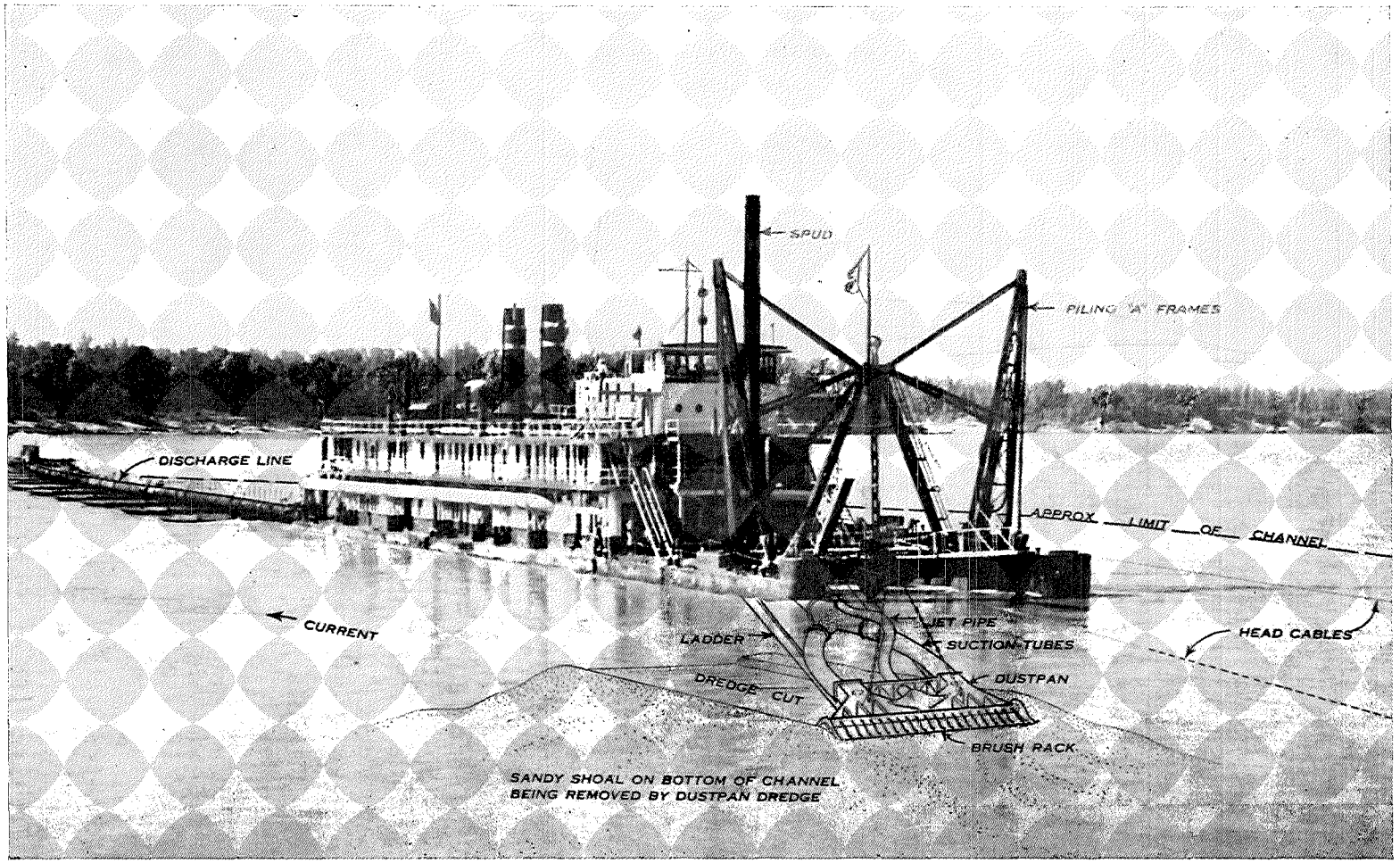
The effects of undesirable qualities of a river where improvement by dredging is feasible are, for instance, retarded scour, wide and shallow crossings, and sharp bends. In other words, dredgers can be used to clear away sills on crossings, dredge channels through flats, and improve sharp bends in channels.

In both the Niger and the Benue, the river-bed consists of fine sand which moves in large quantities during high water. At low-water stages, when navigation is still possible (least available depth 4 feet), sand movement is reduced in speed and quantities but does not come to a standstill on the shallow crossings. The cohesion of the material is not very great: no clay has ever been found on the crossings.

A channel dredged during the fall or low-water stages of the river may maintain itself during the low-water period, but will be completely filled up during the high-water period when the sand-transportation in the river is high and the direction of the flood current, especially on crossings or flats, is different from the direction of the current during low water. Even the question whether a channel dredged during the fall or low-water stages of the river will maintain itself needs careful consideration, as explained in III, 6.6.1.

Little reliable information on this subject is available. On parts of the Mississippi River system, however, extensive channel dredging is carried out yearly to maintain channels of a certain minimum depth and width for navigation. Results over a considerable number of years are reported to have been satisfactory: channels dredged during falling stages or low water mostly maintain themselves during the entire low-water period provided that site and direction of the channels to be dredged have been chosen with good hydraulic insight.

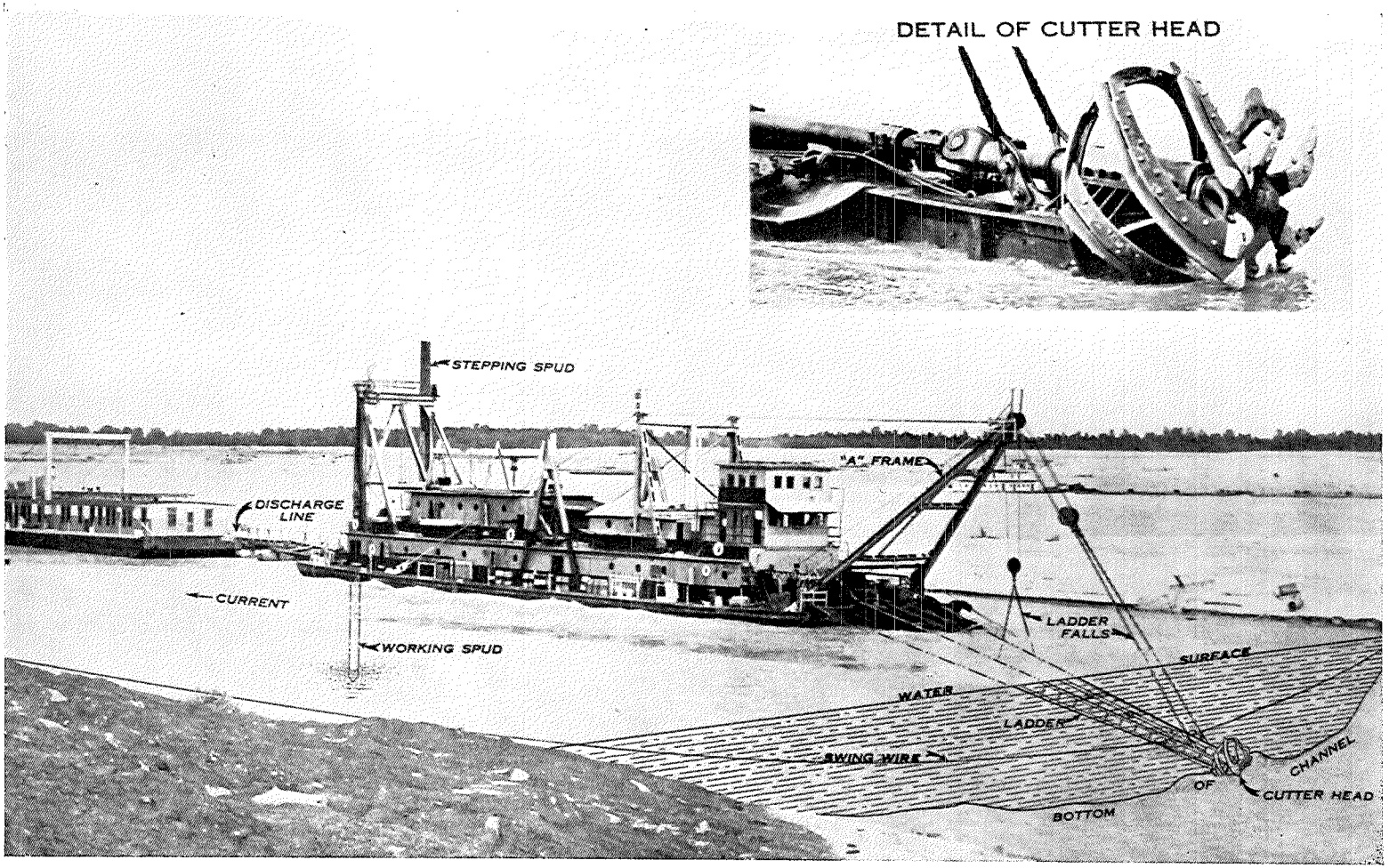
The best results of dredging will probably be obtained when the channel follows the flow-lines. Cross-currents loaded with sediment will then not be given the chance of evening out the channel.



PHOTOGRAPH 4.1.1-1

Dustpan dredger

from: CORPS OF ENGINEERS, 1956. GEN. 8



PHOTOGRAPH 4.1.1-2

Cutterhead suction dredger

from: CORPS OF ENGINEERS, 1956. GEN. 8

Under such circumstances the dredging plant will also be most easily handled and ships can best navigate the channel.

A channel width of 150 feet seems at present the minimum for safe navigation, whilst the length must be determined by the situation. Dredging such a channel width can be effected in two ways, dependent on the type of dredging plant:

(i) Dredging several cuts parallel to the axis of the channel. This system must be followed with the normal suction dredger and the dustpan dredger and can be followed by the bucket dredger.

(ii) Dredging with the dredging plant swinging constantly so that the suction-pipe reaches over the total width of the channel. This system is applied with the cutterhead suction dredger. The sand is brought to the head of the suction-pipe by the cutter-blades which dig sideways. The bucket dredger is often operated in the same way.

A basic feature of dredging on crossings in rivers for the benefit of navigation is that the cut is not very deep compared with dredging a harbour or a canal or dredging as a means of obtaining sand. The cut should be as even as possible to prevent dredging too large quantities without a corresponding improvement in depth in the dredged channel.

For instance, the system mentioned under (i) has the disadvantage of making a number of deep cuts which must smoothen out, but the extent to which this will happen in a particular situation always remains a guess and must be found by experience. Normally the sides can be expected to have a slope of 1 in 3 or 4. This means either many cuts with dredged quantities a little larger than the theoretical cut would necessitate, or fewer cuts of a greater depth with quantities dredged far over the theoretical amount. Dredgers with a swinging movement as mentioned under (ii) remove the soil evenly and the quantity dredged is not much larger than the theoretical quantity. The advantages and disadvantages of different types of dredgers will be discussed in more detail in 4.1.4.

When the cohesion of the soil is too large to reach an effective production with the suction-pipe only, the production of the suction dredgers can be increased by working the soil loose and bringing it to the head of the pipe.

Two principles are normally used to achieve this:

(i) by means of mechanical devices such as a rotating head with propeller, crown-shaped blader or small buckets; or

(ii) by means of water injected under pressure around the head of the suction-pipe (principle of the waterjet).

Ref. (i) is normally applied in clay or firm sand, the rotating head being adapted to the type of soil.

Ref. (ii) has been developed for the dustpan dredgers on the large rivers in America, where sand of very small particle size is dredged. The very wide head of the suction-pipe of this type of dredger is developed to minimise the quantities to be dredged above the theoretical quantity of the desired cut without reverting to a swinging movement.

A further principle of dredging channels should be to dispose of the spoil in a place where it will not hinder shipping and if possible where it has a beneficial effect on the dredged channel. As the cause of the shoal lies in the extensiveness of the crossing, it follows that the spoil should be brought on the crossing at the downstream sides of the channel to be dredged. In this way the flow is concentrated in the channel over the crossing.

Finally, dredging for navigation purposes implies the removal of great quantities in a short period. On the Niger, where a certain improvement in navigability can be expected from dredging, the period available is from November until April, but if possible the channels should be ready in December or January, while the rest of the low-water period should be used to maintain the

channel. Dredging operations for clearing bottle-necks and improving existing channels should be carried out in close co-operation with the Channel Patrol Services.

Channel patrols will be able to give timely indication where difficulties for shipping will occur and will direct dredging operations accordingly.

4.1.2. Examples

Dredging channels through shoals in a river for the benefit of navigation is being done on the Mississippi and her tributaries and on the Congo and it has also been tried in Nigeria on the Niger. But very little is known about dredging channels through shoals in other rivers, particularly on the subject of the quantities which must be dredged, the shoaling of these channels and the gains for navigation which result from the efforts. This is, of course, also very difficult to evaluate.

On the *Mississippi* dredging has been carried out for many years, from which it can be concluded that it is a success for navigation.

On the Upper Mississippi, which is a canalised river with low or moderate flow velocities, dredging is still necessary for maintaining a 9-feet channel. In the Rock Island District, 353 miles long, annual dredged quantities range from 500,000 to 2,500,000 cubic yards, for a 300 feet wide channel. Dredging is here carried out by a 20″ cutterhead suction dredger with a maximum capacity of 2,500 cuyards per hour; the dredged cut goes to a depth of 13 feet below reference datum.

Between St. Louis and Cairo on the Middle Mississippi, i.e., some 250 miles of river-length, about 100 crossings are maintained to a depth of 9 feet (by dredging to 14 feet below reference L.W.) by two 21″ cutterhead suction dredgers. Working day and night with three shifts, each dredger has an output of about 15,000 cuyards per day, at a cost of $ 4,500. The total quantity dredged in a year is about five million cuyards at a cost of roughly $ 1,000,000.

The 67 crossings in the 270 mile long Vicksburg District on the Lower Mississippi are being maintained by a dustpan dredger and a 12″ cutterhead suction dredger. The output of the day and night working dustpan dredger is about 1,000,000 cubic yards a month, at a cost of $ 80,000. The Memphis District, also on the Lower Mississippi but where the river offers more difficulties owing to shifting channels, operates four of these dustpan dredgers for maintaining its 350 miles of river length. In the two districts together, comprising 740 miles of the Lower Mississippi between Cairo and Baton Rouge, the dredging required to maintain a channel 9 feet deep and 300 feet wide ranges from 30 million to 70 million cubic yards in one year; the five dustpan dredgers move the bulk of this material.

All dredgers are owned and operated by the United States Corps of Engineers.

It is said ([1] that the number of crossings dredged and re-dredged, and the amount of dredging required in any one low-water season, depend largely upon the duration of that season and the frequency of stage fluctuations during the low-water season. All of these factors directly affect the stability of the dredged cuts in the sandy bed of the Mississippi River.

On the *Niger* dredging has already been tested by the Government-owned and operated suction dredger Quorra in the years between 1909 and 1913. The target of this test dredging was to create a year-round navigable depth of 6 feet to Baro. The Quorra averaged 900 cuyards per hour and removed large quantities of soil (approximately 400,000 cuyards during the 1913

([1] CORPS OF ENGINEERS, 1956. GEN. 8

season). However, the target proved to be too ambitious for the available equipment and the project was abandoned.

It is not known whether the Quorra was operated in particularly dry years. It is also possible that mistakes were made in the choice of the site of the channel and place for deposition of the

PHOTOGRAPH 4.1.2-1

Dredger Quorra at work on the Niger

soil. Nor is it clear why a year-round navigation of 6 feet was thought to be feasible. Such a target, even now with modern equipment, would certainly not be reached during the months of April and May between the end of the Black Flood and the rise of river-levels at the new rains.

4.1.3. Administrative organisation

In principle, public works are carried out under one of the following three ways of administrative organisation:

a. A *contractor*, under a contract with Government, carries out the works according to Government specifications and under Government supervision. Before contracts are made, contractors

are either publicly invited to submit tenders or only a selected group is invited. Also a private agreement may be made without tender.

b. An *agreement* is made with a contractor to put the necessary staff, equipment and sometimes also materials at the disposal of Government on a cost-plus base. The works are carried out by Government.

c. *Government* carries out the works with its own staff, equipment and materials.

The question arises as to which of these administrative types of organisation best suits the execution of channel-dredging works. The choice of a certain form of organisation depends to a great extent on the character of the works envisaged. Where possble, the method mentioned under (a) is to be preferred, as competition means greater efficiency and a lower cost of the works. Moreover, in such a case Government is not involved in the actual execution of the works, but has only a supervising task.

But if (a) is to be applied, the character of the works must enable the Government to draw up specifications acceptable to both contractor and Government. This, however, will meet with grave difficulties where channel-dredging is concerned and especially in the early stages, when the operations will also be of an experimental character. The following uncertainties will exist:

(i) The tenability of the established channel is unknown, as well as the extent of maintenance dredging needed during the same season;

(ii) the exact location where dredging is most effective cannot be indicated long beforehand;

(iii) the number of places where dredging is necessary and the quantities to be dredged depend on the discharges, which are not predictable;

(iv) the output of dredging equipment depends to a certain extent on the qualities of the river-bed materials; and

(v) the depth and width of the cut after the dredging has been completed are no reliable measures for the dredged quantities, as sand may have scoured or deposited during the dredging operation.

Some years of test-dredging will greatly reduce these uncertainties, but as long as the regime of the river is not artificially changed, the extent and the sites of dredging operations will remain unpredictable and show great variations each season.

These considerations lead to the conclusion that it is not feasible to draw up sharply-outlined specifications for such dredging works, so that the form of organisation mentioned under (a) does not appear to be applicable. A choice has to be made out of the two more elastic methods (b) and (c).

For the first stages of channel-dredging works, where the stress is laid on the experimental character, preference must be given to utilisation of the apparatus of an experienced dredging contractor. The advantage of co-operation with an expert firm, sufficiently interested in the job and keen to solve the problems, cannot be under-estimated. A wide range of up-to-date dredging equipment with experienced crews will be available, so that a varied selection can be made. It may be expected that in this way experimental dredging will have the greatest chance to attain its ends successfully.

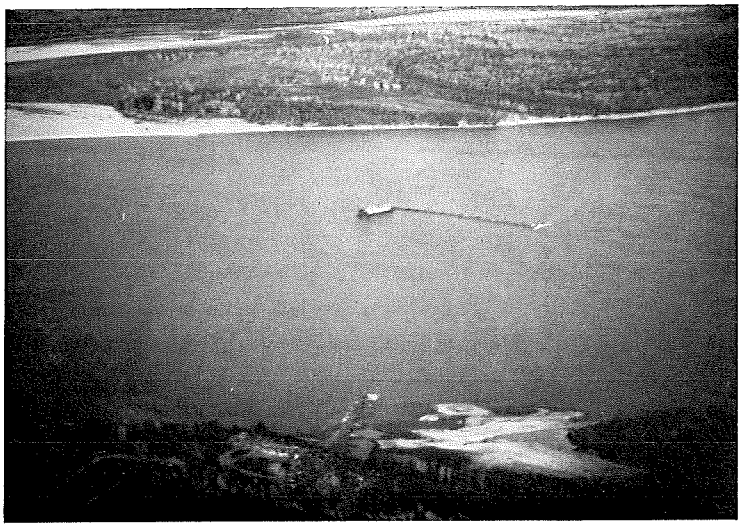
After channel-dredging has outgrown its experimental stage and the possibilities of the method and the design of the most suitable apparatus can be more sharply defined, Government could decide whether or not to take channel-dredging operations entirely in its own hands. A Government dredging service would by then have been gradually built up and sufficient experience could have been acquired to justify such a decision, but there are, of course, also disadvantages.

In conclusion it may be stated that during the experimental stage of dredging operations co-operation with an experienced contractor is advisable, which may result in a sufficient

experience of Nigerian Government staff and adequate insight into the possibilities of the method to enable Government to decide:
(i) whether the resulting assistance to navigation justifies further development of the dredging operations; and
(ii) whether Government should build up its own dredging organisation or continue to utilise the apparatus of a contractor.

4.1.4. Type of dredgers

To dredge means to remove soil from under water, and a large variety of equipment exists to achieve this. Dredging for the purpose of improving navigability by removing alluvial obstacles from the river-bed must necessarily be recurrent because of the nature of the obstacles, which consist of small particles to a greater or lesser extent moving in the flow. As the rate of cohesion of the particles determines the methods to work them loose, an indication will now be given regarding the most suitable equipment for the special job of channel-improvement by dredging on the Niger; but undoubtedly during the course of test-dredging operations a clearer picture of the most suitable equipment will be obtained.



PHOTOGRAPH 4.1.4-1
Dredger with floating discharge pipe-line of the unanchored type

The choice of a dredger type is already greatly narrowed when the question of how to dispose of the dredged spoil is solved. Disposal as a water and soil mix through a floating pipe-line outside the channel is undoubtedly the simplest and cheapest and is adopted on all waters of the world where channel-dredging occurs. Especially attractive seems the new design of floating pipe-line, which requires no anchoring but which has the discharge terminal kept in position outside the dredged channel by the force of the discharge jet on a kind of rudder. Now for the types of dredging equipment which remove soil by means of shovels, grabs or buckets, no completely satisfactory solution of the problem of the disposal of the originally solid soil as a soil-water mix through a pipe-line has yet been found. Trials in this field have resulted in rather complicated

and not completely effective equipment. The suction dredger, however, which removes the soil as a soil-water mix, is ideally suited to discharge its spoil through a pipe-line, and from the many variations of this type of dredger the choice will have to be made.

The desired capacity of the dredgers should be large for the following reasons:

(i) Upto a certain limit it can be stated that the cost of dredging a cubic yard of soil will decrease with the increased capacities of the equipment;

(ii) in case of the sudden appearance of "bottle-necks" on a river-stretch, large dredgers will clear them more quickly;

(iii) less supervision and crew are required per cuyard;

(iv) large units can be made more self-supporting and may have their own workshop which makes them more independent;

(v) fewer dredgers at work on the river present fewer obstacles to shipping; and

(vi) full employment of a few large dredgers can be more easily realised and needs less organisation.

The hourly output of these large dredgers needs further specification. Test-dredging will certainly give more definite data on this subject; but in the meantime dredgers of an extremely large output should be avoided, mainly because the ratio of productive days against transport days from one site to another should be within reasonable limits, and also because dredging operations would then be less elastic. An hourly output of 1,000 to 1,400 cuyards, enabling the dredger to cut a channel through an average crossing in a week's time, seems a fair standard. Under normal conditions such an output can, with suitable bottom materials, be obtained by suction dredgers with a suction-tube diameter of from 24 to 30 inches and an engine driving the sand-pump of 1,000 to 1,200 h.p.

The dredgers will have to move frequently from one crossing to another. They should therefore preferably be self-propelled and from the previous Chapter it follows that their draught should not exceed 5 feet. Although dredgers with the above-mentioned output will as a rule have a greater draught than 5 feet, the combination of these two requirements can certainly be realised. The advantages of self-propulsion are obvious, as the engine driving the sand-pump can also be used to drive the propeller, thus obviating the cost of a large tug and extra crew.

For the realisation of a test-dredging programme it will, however, be almost impossible to find dredgers which will meet all requirements of output, draught and self-propulsion. However, for the purpose of test-dredging self-propulsion is not essential, while a compromise between the other requirements can be found by accepting, for instance, a somewhat smaller output with a slightly larger draught. But the ability of some types of dredgers to cut their own channel is an important point for dredgers operating on rivers where available depths may drop below the draught of the dredger. If, in such a case, the dredger were not able to dredge its own channel, its activities would come to an untimely end. This, of course, is unacceptable.

In this connection a short description of the main types of suction dredgers will be useful:

(i) Ordinary suction dredgers of orthodox design.

These dredgers are equipped at the bow with a suction-tube which is adjustable to different dredging depths, and through which the sand-pump sucks large quantities of water. The velocity of the water flowing into the mouth of the tube loosens the bottom materials so that a mixture of water and soil, the so-called spoil, flows through the suction-tube and pipe-lines and is discharged at the end of the floating pipe-line. The percentage of soil in this mixture, in other words the output, depends on the contexture of the soil. Hard or tough soils such as loam, clay and peat are difficult for suction, while loose sands or mud give a large output. Sand may even be so easily picked up by the suction-tube that considerable deepenings below the level of dredging occur. On the other hand, cohesive soils may resist the suction force of the dredger to such an

extent that the output of the dredger drops below a reasonable level. This sensitivity to the quality of the soil and the unevenness of the produced cut is a disadvantage of this type of dredger. Another disadvantage, especially for the special job of channel-dredging, arises from the typical method of working of a plain suction dredger. The dredger moves straight forward while dredging a groove of the desired depth in the river-bed. The width at the top of this groove depends on the depth of the dredge-cut. After finishing this groove the dredger is brought back to its original position, moved slightly sidewards and then dredges another groove parallel to the previous one. This is repeated until the desired width of the channel is attained. When a shallow cut is to be dredged, as will be the case with channel-dredging on the Niger and Benue where the depth of the cut needs seldom to be more than 3 to 4 feet the width of one cut will be less than the breadth of the dredger. This means that a plain suction dredger will only be able to cut its own channel when an excessively deep groove is dredged. The depth of this groove depends on the natural slope of the soil, but may be 15 feet or more. As this extra depth is of no benefit to shipping, this can be considered a mere waste of capacity. To overcome these disadvantages of the suction dredger, the following types of modified suction dredgers have been developed:

(ii) Dredgers equipped with a set of parallel suction tubes.

These multiple suction-tube dredgers can make a cut slightly wider than their own breadth, although this modification has not overcome the disadvantage of its output being dependent on the contexture of the soils.

(iii) The dustpan type suction dredger.

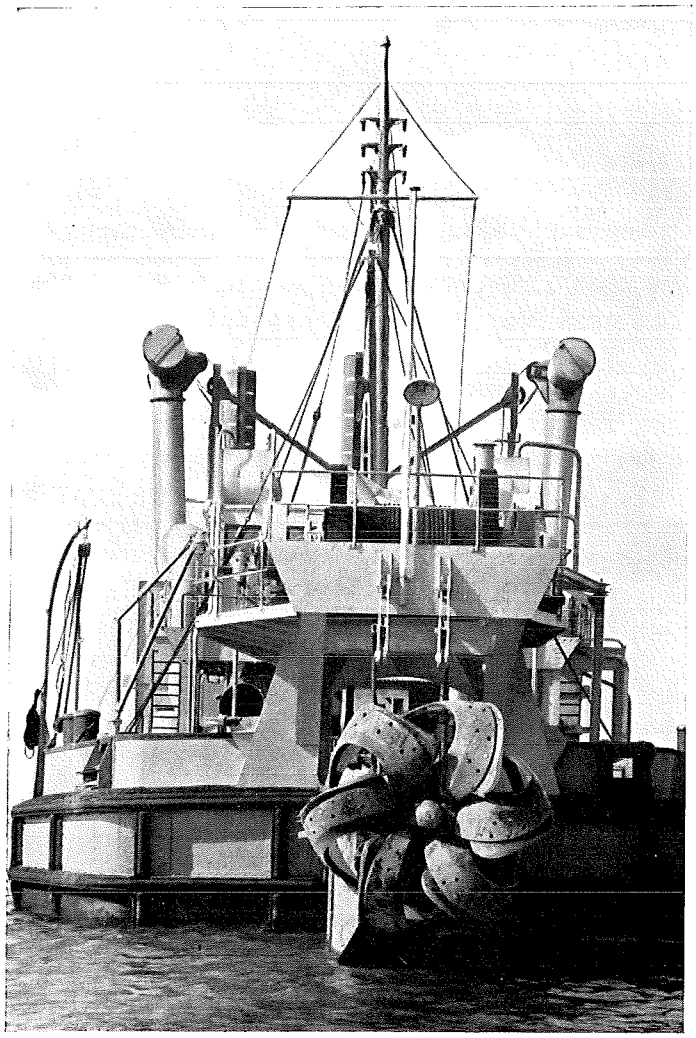
This type of dredger with a modified suction-tube, shaped broad and flat like the nozzle of a vacuum-cleaner, loosens the soil in front of the suction mouth by a number of waterjets. This type, operating on the Mississippi River system and especially built for channel-dredging, makes a wide and flat cut, but is only effective when working in fine sands and mud. It must be expected that the dustpan dredger will not be a suitable tool to dredge the slightly coarser sands in the Niger and Benue.

(iv) The cutterhead suction dredger.

This is a suction dredger of which the suction-tube is equipped with a rotor on which a number of knives is fitted. These knives (the cutterhead), driven mostly by an electromotor and via a shaft on the suction-tube, revolve in front of the mouth of the suction-tube and loosen the bottom materials. The loosening of the soil by mechanical means renders the output of the cutterhead suction dredger less dependent on the quality of the soil and a more even dredge cut is obtained. There is a basic difference between the working method of this type of dredger and the before-mentioned types. Instead of working straight ahead, the cutterhead suction dredger makes sweeps to left and right while moving forward and is able to dredge a channel of a width more than its own breadth.

It may be concluded that in the cutterhead suction dredger the disadvantages of other types of suction dredgers have been largely overcome, and that this type of dredger appears to be the most suitable for channel-dredging operations in Nigeria. This opinion may even be strengthened by some further considerations.

The system of anchoring of dredgers should obstruct shipping as little as possible. While the other types of suction dredgers are anchored by a system of bow, aft and side cables, the anchoring of cutterhead suction dredgers consists of two side cables or swing lines and two spuds, placed in the port-hand and starboard corners aft. Spuds are long heavy steel poles, often filled with concrete and running vertically through holes in the hull of the dredger. When a spud is lowered, it enters the bottom and keeps the dredger firmly in place. By means of the swing lines the dredger pivots around the spud and the suction nozzle with cutterhead makes



PHOTOGRAPH 4.1.4-2
Cutterhead suction dredger
from: IHC Holland

a sweep, carrying out an arched cut. When the end of the sweep is reached, the second spud is lowered and the first spud pulled up. The dredger now pivots around the second spud and sweeps its second cut in the opposite direction. Later developments of the spud system feature spud-lorries or spud-rotors, situated at the middle aft of the dredger, and which permit the dredger to make parallel arched sweeps. In this way the dredger moves forward step by step. Only the two swing lines may obstruct shipping, but as these swing lines are attached to the bottom end of the suction ladder, release of the tension of a cable is sufficient to bring it to the bottom of the river. This system of anchoring probably gives a minimum of hindrance to shipping.

A last argument in favour of the cutterhead suction dredger is provided by the fact that the channel-dredging operations will only take place during the period from November until April. The rest of the year it is essential, in order to lower the cost of the channel-dredging operations, that the dredgers can be put to work on other jobs, such as reclamation works and harbour and channel improvements in the Delta. Although different soils and circumstances will be encountered, it is believed that cutterhead suction dredgers, because of their versatility, are also the most suitable for these other works.

In connection with these miscellaneous jobs the dredgers should be able to dredge at greater depth than the 8 to 10 feet required for channel-improvement dredging. Ladders and suction-tube should be long enough to permit dredging depths of 30 feet.

Summing up the foregoing, it may be stated that, while experimental dredging on the Niger is essential in order to arrive at a clearer picture of the most suitable dredging equipment, the cutterhead suction dredger now appears to be a recommendable tool.

This dredger should have the following specifications:

1. output 1,000 to 1,400 cubic yards per hour;
2. draught not exceeding 5 feet;
3. self-propelled;
4. discharge through floating pipe-line, preferably of the unanchored type; and
5. maximum dredging depths up to 30 feet.

It may finally be remarked that dredging equipment for test-dredging purposes need not necessarily answer all these requirements completely. From available equipment the nearest compromise should be put to the test.

4.1.5. Cost

As long as so many uncertainties regarding the method of dredging for channel-improvement exist, a reliable estimate of the cost of this method of improvement is difficult to give. It can, however, be stated that a dredger more or less answering the requirements as stipulated in the foregoing paragraph, chartered in working condition from a contractor, inclusive fuel and crew will cost in the region of £ 4,000 per week. It depends on the desired improvement how long and how many dredgers are needed (see next Section 4.2).

A reasonable improvement may be obtained with two of these dredgers during the months of November till April inclusive. This means that carrying out this programme will need between £ 150,000 and £ 250,000. It will, however, be possible to lower this expenditure if Government is able to give contractors long-term securities and a full-employment guarantee.

4.2. DREDGING THE NIGER

4.2.1. Frequencies of depths and increase in least available depth versus quantities to be dredged

A frequency curve of depths along the talweg must always be tied to a water-level. Nevertheless such a frequency curve at a certain water-level will differ from year to year and will also be dependent on the scour and silting which takes place in a single hydrological year (see III, 6.4.2). Compared with the depth of a dredge-cut, these differences can be so marked that the frequency curve of depths of the talweg is not directly suitable for the calculation of the quantities to be dredged.

However, the frequency curves of depths, as they are given in Diagram 4.2.1-1 calculated from the talweg profiles in Diagrams III, 6.4.1-1 and -2, give an indication of the variation in bottom height in each river-section, as a uniform slope of the water-level may for this purpose be assumed. The frequency curves have been made for separate river-sections of about 30 miles. For each section is given in percentages that part of the talweg which in that section is higher than a certain number of feet below Low River Level (L.R.L.). For the river-section Baro—Lokoja the measurements have been taken in early November, 1957, i.e., in a period when the talweg

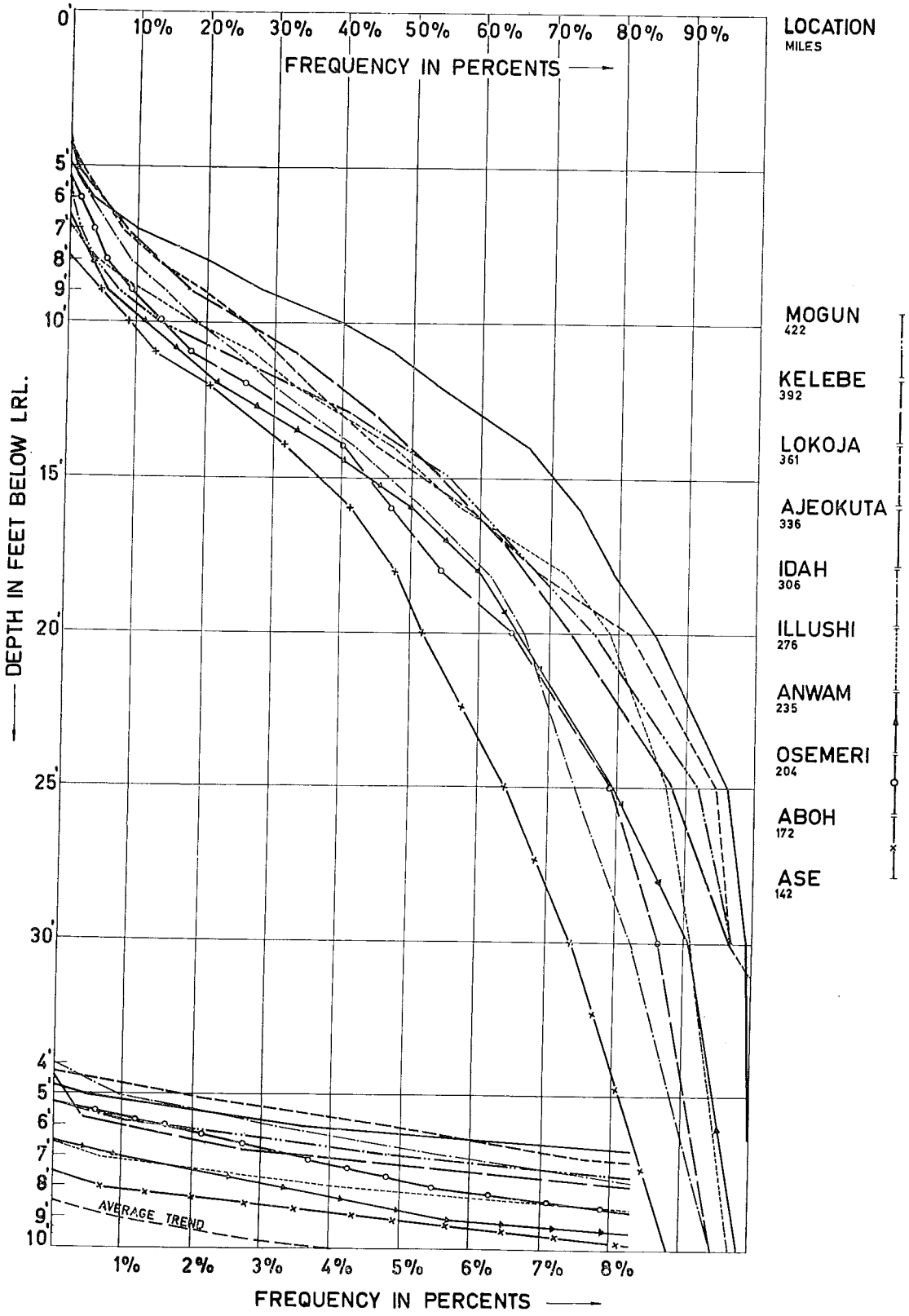


DIAGRAM 4.2.1-1

Frequencies of talweg depths

bed on the crossings is high. The measurements on the Niger below Lokoja have been taken in June/July, a period in which the scour on the crossings has probably not yet been annihilated by the renewed sand movements caused by the rising water.

To establish the quantities to be dredged the following line of thought has been developed:

From the frequencies of the bottom height in the different river-sections the average increase in minimum depth on a river-section can be determined, when 1%, 2%, 3% and 4% respectively of the length of each section is dredged in the shallowest spots. From the calculations this appears to be respectively 6 inches, 10 inches, 14 inches and 17 inches (average values from Diagram 4.2.1-1). The water-level on the crossings will hardly be influenced by such dredging (see III, 6.6.1).

The dredge-cut on a crossing will be 4—5 feet deep at the shallowest spot of each crossing and theoretically approaching to zero at the upstream and downstream sides of the cut. In practice a cut of two feet will be a minimum for dredging. Allowing for a certain unevenness in the dredge-cut, it will be safe to say that an average cut of 4 feet will give at least an improvement of 3—4 feet on the dominant spot of the crossing.

The minimum width should be 150 feet at the basis of the cut; the sides are estimated to have a slope of 1 in 5, which gives the cut an average width of 170 feet. The average cross-section over the cut will then be 680 sq.feet or 75 sq.yards.

The length of the channels to be dredged is a function of the improvement in depth (see above) and that length multiplied by the average cross-section of the cut determines the quantities.

The average quantities to be dredged on each river-section for certain increases in depth are then:

length dredged	increase in depth	quantity to be dredged
1 percent	6 inches	0.75 L cubic yards
2 „	10 „	1.50 L „ „
3 „	14 „	2.25 L „ „
4 „	17 „	3.00 L „ „

(L is length of river-section in yards)

The navigability of the Niger at low-water stages in an average year is given in Diagram 4.2.1-2, which is an extract of Diagram IV, 3.2.2-1. Three river-sections are normally distinguished, i.e., Baro—Lokoja (72 miles), Lokoja—Onitsha (131 miles) and Onitsha—Patani (101 miles). Downstream of Patani in the Delta, maintenance dredging for low-water navigation on the Niger will not be necessary.

In all dredging programmes an attempt will be made to maintain over these three river-sections a constant least available depth from November onwards to ensure the most effective evacuation of produce from Baro. This implies that the maintenance in an average year of a 5'0", 5'3" or 5'6" channel requires dredging of the Niger above Lokoja as a first step in November and December, supplemented by dredging of the Niger below Lokoja from December to March, while maintenance dredging should be continued until the end of March.

The total quantities to be dredged for the different programmes follow from the number of inches to be dredged. To determine this, the available depth at the end of March has been

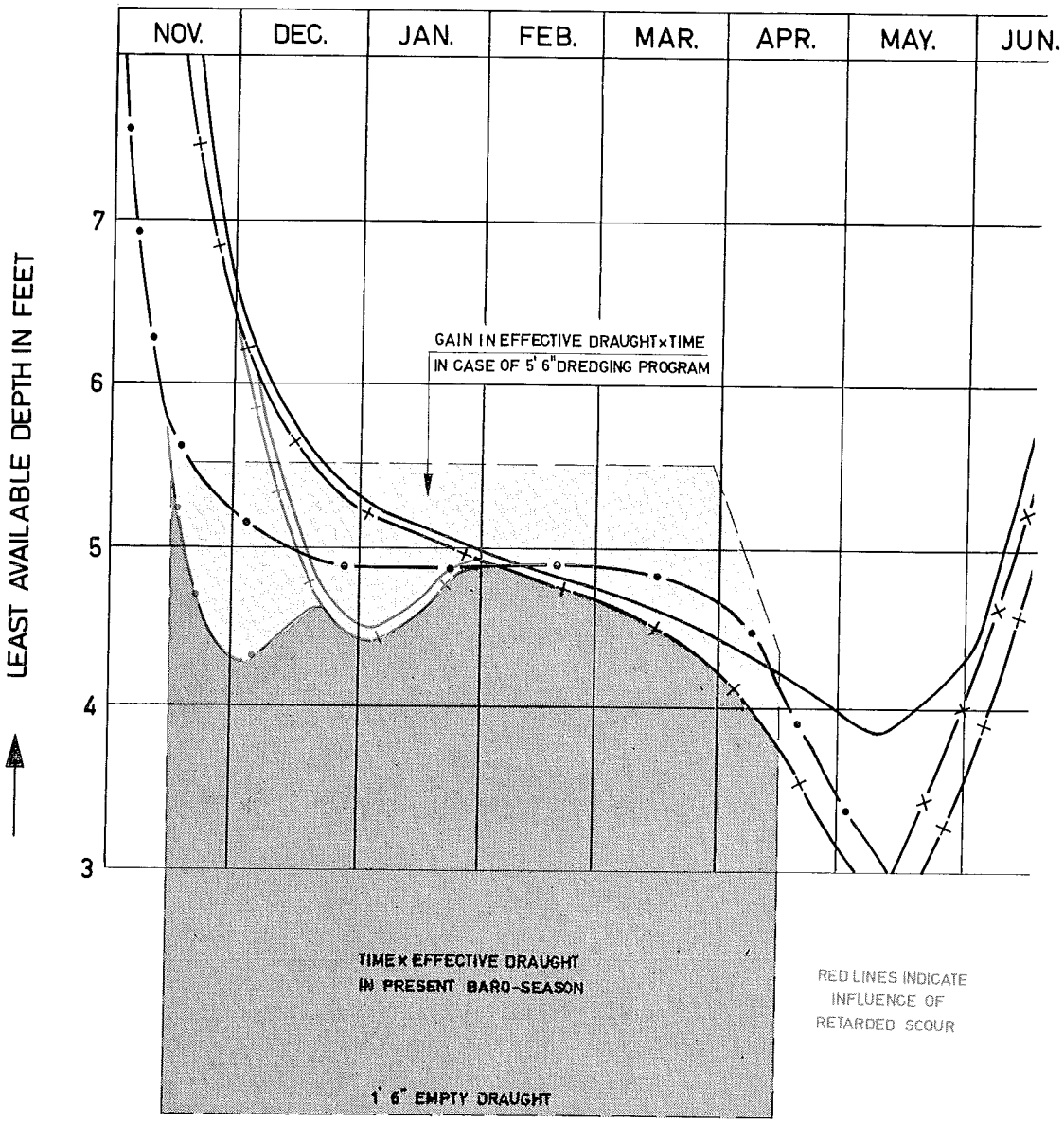


DIAGRAM 4.2.1-2

Navigability of the Niger before and after a 5'6" dredging programme

subtracted from the programme depth, leaving the number of inches to be dredged in each river-section (see Table 4.2.1-3).

A different approach to the quantities to be dredged results from experience during the observations on the river. Many crossings, of course, hamper navigation, but only 7 to 9 crossings are extremely bad. These crossings are dominant for the navigation depth or at least one of them is, although each of them may be dominant during a part of the season. The crossings have been mentioned in III, 6.4.2. By retarded scour these crossings may improve during December and

TABLE 4.2.1-3
DREDGING PROGRAMMES

Depth in all river-sections Delta — Baro	BARO — LOKOJA in inches	BARO — LOKOJA in cuyards	LOKOJA — ONITSHA in inches	LOKOJA — ONITSHA in cuyards	ONITSHA — PATANI in inches	ONITSHA — PATANI in cuyards	Total quantities to be dredged in cuyards
5′0″	3	48,000	9	300,000	6	133,000	480,000
5′3″	6	92,000	12	430,000	9	230,000	750,000
5′6″	9	165,000	15	570,000	12	330,000	1,070,000

January, but when at the end of the high-water period these crossings are recognised and then cleared in November and December, the least available depth will certainly improve by one foot. In December and January a least available depth of 5′6″ could then be attained, but the dropping water-levels in the Niger below Lokoja (as a result of decreasing discharges from the Benue) will then cause new crossings to become dominant and 5′6″ cannot be maintained here without dredging.

It is, however, likely that the number of crossings which will need dredging to maintain 5′6″ until the end of March will be large. This can be seen from Diagrams III, 6.4.1-1 and -2 if taking into account that this Diagram gives the depth on the crossings at L.R.L., while at the end of March water-levels in the Niger below Lokoja are on an average 1′6″ below L.R.L. It then appears that some 20 crossings need dredging to maintain a depth of 5′6″. Although it is difficult to forecast the circumstances in future years, it appears from 1956 and 1957 observations that dredging another 8 crossings in January—March will leave the possibility of 5′0″ navigation to Baro at the end of March. The total quantities to be dredged with an average crossing length of 700 yards and a cross-section of the channel of 75 sq.yards will then be $16 \times 700 \times 75 =$ 840,000 cuyards. This will allow navigation with 5′6″ during December and January, gradually diminishing to 5′0″ at the end of March.

The water-levels fall in an average year in April so rapidly that continued dredging over the entire river below Baro does not then seem practicable. But the water-levels and the navigable depth in the river below Onitsha do not decrease as much and as quickly in April and May, due to early rains in the south of the Niger drainage area and a small rise in water-levels of the Benue. It will certainly be possible, with the equipment necessary to carry out the above programmes, to maintain throughout the year 5′0″—5′6″ available depth as far upstream as Onitsha.

Repeated maintenance dredging must be provisionally estimated at one-third to one-half of the total quantities to be dredged.

Calculating along the same lines as above, it is possible to indicate quantities to be dredged in an average year for a 6′0″ and 7′0″ programme up to the end of March. These will be 1,800,000 cuyards and 4,200,000 cuyards respectively (exclusive of possible re-dredging).

It must be mentioned that each year has different discharges. Therefore an average year must be taken as the criterion to obtain an indication of the quantities to be dredged and to be able to estimate the required capacity of a dredging fleet. However, with a certain dredging fleet, different targets must be set from year to year dependent on the actual discharges in such a year. It is therefore a great advantage that discharges and water-levels occurring during January—April can already be forecast in November from observed peak discharges in the French Niger and from recession curves of the Benue. In November and December the dominant crossings which re-appear yearly and which can be recognised at the end of high water, should be cleared; then from January to March dredging will continue on other crossings. The least

available depth in the remaining months of the low-water season can then be predicted if good co-ordination exists between channel patrols and dredging operations.

Summarising, dredging an annual quantity of some 1,400,000 to 1,600,000 cubic yards will result in an overall improvement of one foot from December to March inclusive on the Baro—Delta stretch of the Niger. In an average year, this will lead to depths ranging from 5'9" to 5'6" in December to 5'6" or 5'3" by the end of March.

An overall depth of 6 and 7 feet respectively to Baro until the end of March in an average year will ask for roughly 2.5 million and 6 million cuyards dredging.

4.2.2. Improvement in navigability

The improvement in navigability obtained from the different dredging programmes follows very clearly from Diagram 4.2.1-2. A further insight into the value of dredging operations can be gained by realising that barges and tugs will be used more efficiently. If the average maximum barge draught of the river-fleets is assumed to be 6'6" and the average empty draught 1'6", a simple determination of the draught × time area in Diagram 4.2.1-2 between November 15 and April 15 indicates the quantities which can be transported with these fleets in that period when the different dredging programmes are carried out.

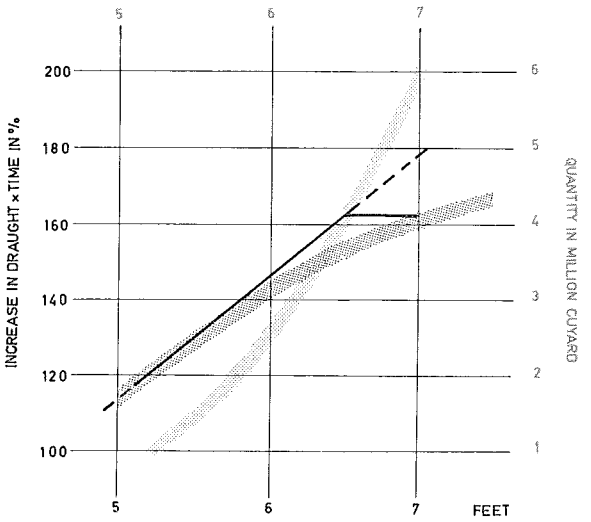


DIAGRAM 4.2.2-1

Fleet capacities and dredged quantities

When the present capacity of the fleet between November 15 and April 15 in an average year is taken as 100, then a 5'6", 6'0", 6'6" and 7'0" dredging programme would increase the fleet's capacity in that period to 130, 146, 160 and 178 respectively. The fleets consist, however, of ships with maximum draughts of between 5 and 8 feet, so that the line should be drawn fluently (see Diagram 4.2.2-1). It is also clear that as long as the fleets are not adapted to greater draughts, the execution of a 7'0" dredging programme will have little justification. The increase in fleet capacity then compares very unfavourably with the increasing quantities to be dredged (Diagram 4.2.2-1) and the diagram indicates that 6'0" is about the limit to which increase in fleet capacity

is proportional to dredge-quantities. Large fleet draught will certainly be adopted but will remain restricted by the limitation which the Benue navigation imposes on the same fleet, unless a separate Niger fleet is created. This will, however, not be necessary before the navigation season on the Benue is extended.

4.2.3. Additional improvement with discharge regulation

Even if discharge regulation is applied on the river, dredging will still have a beneficial effect. Discharge regulation produces a lengthening of the present shipping season or allows navigation with increased draught during a certain period, or will be a combination of the two. The unevenness in talweg heights will still be present, however, and dredging remains a possibility of increasing the available depth in order to improve the efficiency of the reservoir. At present it is not possible to predict whether the frequency curve of depths in a regulated river will alter much in shape. At first sight there is little reason to believe that these curves will change much in steepness in the region of shallow depths. Quantities to be dredged will then not alter much to give relative improvements in the way discussed in the foregoing paragraphs, i.e., some 1.5 million cuyards for an overall improvement of one foot.

4.2.4. Incidental dredging

The navigability of the Niger can further be improved by incidental dredging, by which is understood dredging which need not necessarily be recurrent. As an example can be mentioned the sharp bends near Gbekebo (Mile 60) and Siama (Mile 89). These bends can be cleared by a better alignment of the river, and the best way of execution is by dredging. The approaches to the ports, beaches and berths (e.g., Buturu, Warri, Aboh and Idah) may also be ameliorated by dredging. At the same time dredging may offer a cheap method of raising bank heights at places where floods may endanger port installations and other valuable properties.

The possibilities of dredging the Benue Bar at Lokoja Confluence in May or June will be discussed in Section 4.4 hereafter.

Finally, incidental dredging during high water at all those places where this can be useful (ports, bars and as means of sand-production) will improve the efficiency of the dredger, as in such a case the fixed costs of the dredging equipment may be spread over more objects and a longer period of the year.

4.2.5. The execution of a dredger programme on the Niger

A 5'6" dredging programme on the Niger (November to April) asks for roughly 1,100,000 cuyards dredging and 400,000 cuyards maintenance dredging. When 50,000 cuyards is the average amount to be dredged on a crossing and maintenance dredging is in average 20,000 cuyards per crossing, 22 crossings should be dredged, while on some 20 crossings additional dredging may be necessary.

A programme for dredging on the Niger may then be as below. The programmes are based upon 6 working days of 12 hours, while the average sailing distance between objects is taken as 35 miles. The average speed (up- and down-river) of the dredging equipment can be taken as 3.5 miles per hour.

VI, 4

a. *Dredger 1,200 cuyards/hour*

Initial dredging:

Positioning of dredger and floating discharge line	1 day
Dredging $\frac{50{,}000}{1{,}200 \times 12}$	$3\frac{1}{2}$ days
Stops for passing ships, weather circumstances, maintenance	$1\frac{1}{2}$ days
Prepare for sailing	1 day
Sailing	1 day
	8 days

Maintenance dredging:

Positioning etc.	1 day
Dredging $\frac{20{,}000}{1{,}200 \times 12}$	$1\frac{1}{2}$ days
Stops	$\frac{1}{2}$ day
Prepare for sailing	1 day
Sailing	1 day
	5 days

The total programme can be executed in five months (150 days) by $\frac{22 \times 8 + 20 \times 5}{150} =$ two dredgers of this size.

b. *Dredger 600 cuyards/hour*

Initial dredging:

Positioning of dredger and floating discharge line	1 day
Dredging $\frac{50{,}000}{600 \times 12}$	7 days
Stops for passing ships, weather circumstances, maintenance	3 days
Prepare for sailing	1 day
Sailing	1 day
	13 days

Maintenance dredging:

Positioning etc.	1 day
Dredging $\frac{20{,}000}{600 \times 12}$	$3\frac{1}{2}$ days
Stops	$1\frac{1}{2}$ days
Prepare for sailing	1 day
Sailing	1 day
	8 days

The total programme can be executed in five months by $\frac{22 \times 13 + 20 \times 7\frac{1}{2}}{150}$ = three dredgers of this size.

The use of three dredgers with a total capacity of 1,800 cuyards/hour and the use of two dredgers with a total capacity of 2,400 cuyards/hour will be approximately equal in annual cost and it is even likely that the capital investment for the former will be higher than for the latter.

4.3. DREDGING THE BENUE

4.3.1. Problems

When considering the feasibility of dredging the Benue, the following remarks can be made:

(i) The sand movements are considerable owing to the slope of the river-bed, which is 20 to 25 $\times$ 10^{-5} on the Gamadio and Wuro Boki Flats as compared to only 5 to 10 $\times$ 10^{-5} on the Niger below Lokoja.

(ii) The rises and falls at the beginning of the season deteriorate channels and probably necessitate frequent re-dredging in the same year, in contrast to the Niger where the Black Flood provides a rather even discharge. The experience in the United States has been that alterations in water-levels form one of the causes of resilting of the dredged channels.

(iii) The dredgers would have to be fairly large to compete with the difficulties (i) and (ii) and to cope with the many crossings that have to be dredged between Lau (Mile 778) and the Faro Confluence (Mile 926).

(iv) The dredgers should have a very shallow draught in order to sail upstream well ahead of the commercial ships; say two feet draught. This may be impossible, so that the dredgers would have to be left in the dry season at, say, Yola. But even then their draught should be restricted as much as possible because otherwise they should have to dredge through nearly every crossing simply to go from one point to another.

(v) A fleet of dredgers would be necessary to extend the season on Garua and Yola. This extension, however, would be a few weeks at most.

4.3.2. Improvement in navigability

The discharge hydrographs (Diagram III, 4.3.3-1) and consequently the least available depths (Diagram IV, 3.2.2-1) show a marked difference between the Niger and the Benue, the first with an extended period of middle stages (Black Flood) and the second falling abruptly from high levels and great depths when the local rains stop. Dredging the Niger for the Black Flood period would increase the navigable depth over several months, but dredging the Benue would result in a much smaller improvement or extension of the season.

As dredging on the Niger for navigation improvements is not yet quite an economic proposition (see 9.1.3) it will be clear that dredging need not be considered as a means of improving the navigability of the Benue at present.

When, however, a discharge regulation has created a period of sustained flow with depths of 5 or 6 feet, a dredger may be of great assistance in eliminating dominating bottle-necks.

4.4. DREDGING THE BENUE BAR, LOKOJA CONFLUENCE

4.4.1. Available depths on the Bar

Formation and deformation of the Benue Bar near Lokoja have been described under V, 3.1.2; available depths on the Bar have been shown in Diagram V, 3.1.2-1. It may be shortly repeated here that the main causes of the Bar are:

(i) deposition of sand from the Niger in the Benue Entrance when the Benue water-level is raised by backstage, which occurs in the period of the Black Flood from December to April; and (ii) draw-down of Benue's water-level from May to July just at the time when ships require to enter the Benue.

The Bar forms a real barrier, since the scour on the Bar, caused by the Benue current, lags behind. It has been found that the Bar can normally be passed by ships drawing 5 feet about two weeks after the Benue itself is navigable as far upstream as Makurdi.

Dredging on the Bar would be effective, provided it is carried out after the period of raised water-level on the Benue has come to an end. In this case the accelerated Benue flow maintains the dredged channel and no re-silting will take place. The data from which dredging could be effectively started differs from year to year and predictions do not seem possible. In the years 1956 and 1957 the date was June 1 and May 10 respectively; in both years this was about two weeks before the Benue up to Makurdi was navigable (see Diagram V, 3.1.2-1). Since this is in a period when dredging on the Niger, as contemplated in 4.2, will have been already terminated, the dredger could easily be made available for the work on the Benue Bar.

There seems to be no objection to starting actual dredging too early, i.e., with Benue's water-level still raised by backstage. The only consequence is that the dredged quantities are slightly greater, due to possible re-silting. While the dredger has probably no other working objects during this period, and no predictions on the theoretical starting date can be made, it seems advisable to start dredging in early May.

The ships can in this way enter the Benue some two weeks earlier, although navigation above Lau will not profit by this improvement (see Diagram IV, 3.2.2-1) and ships would then have to wait there instead of in Lokoja. However, it may prove an advantage to clear the ports of Makurdi and Ibi by a part of the fleet before the trips into the upper reaches of the Benue are made. Another part of the fleet may take advantage of incidental and temporary rises in the water-level of the Upper Benue to reach its destination earlier.

Improvement of the Benue Bar by dredging would thus permit entering the Benue on the same date as the Benue itself is navigable from Mozum to Makurdi. However, the stretch from Onitsha to Lokoja might then become the bottle-neck, as can be seen in the upper section of Diagram IV, 3.2.2-1. The 14 days' gain would in that case be reduced to some 8 to 10 days, which still seems sufficient to take action on this improvement.

It may happen that the South Channel can be passed at an earlier date than the North Channel, as in 1957 was actually the case. Such a circumstance, however, is thought to be incidental and will certainly not occur every year. Moreover, the existence of the Lokoja Flats hampers entering the South Channel, and when improvement of the situation is carried out by clearing the Sacrifice Channel for navigation, the South Channel will probably lose all importance (see V, 3.1.2).

Before such clearance, local survey of the area may indicate that in a specific year preference should be given to the South Channel, and that additional dredging there would lead to better results than in the North Channel.

4.4.2. Quantities to be dredged

From Diagram V, 3.1.2-1 it follows that a dredge-cut of some 2 to 3 feet depth is necessary to permit navigation over the Bar on the very same day as the Benue itself is navigable. In the previous sections of this Chapter it has been noted that a dredged cross-section of 75 sq.yards will be the average. The length of the cut will be some 1,000 yards, as follows from soundings of that area. The quantity to be dredged is then 75,000 cuyards, which would take some 10 days

dredging with a dredger of 1,000 to 1,400 cuyards per hour capacity. Since the theoretical starting date of dredging is about two weeks before the Benue is navigable, an improvement of the Benue Bar by dredging is concluded to be very well possible.

4.5. SUMMARY

4.5.1. Recommendations ([1

In the foregoing sections it has been shown that dredging as a means of improving the navigability meets with some uncertainties regarding the most suitable equipment, the quantities to be dredged to improve navigability and the re-silting of the dredged channels. Nevertheless, the expectation is that restricted improvement of channel depths by dredging of $\frac{1}{2}'$ to $1\frac{1}{2}'$ on the Niger between Baro and the Delta will result in sufficient advantages for navigation to warrant the expenditure, after test-dredging has proved that the assumptions have not been too optimistic and when the traffic density has increased to twice or three times that of the present traffic.

PHOTOGRAPH 4.5.1-1

Cutterhead suction dredger

from: I.H.C. Holland

The latter will almost certainly be the case as soon as river management in all its forms including night navigation have reduced the freight cost on the Niger to such an extent that the main crops of the north of Nigeria are conveyed via Baro and the Niger to the Delta, where the

([1 Some of the considerations outlined in the preceding paragraphs, including those on the most suitable type of dredger, have resulted from discussion with I.H.C. Holland.

improvement of the Escravos Bar will either precede or be coincident with the improvements on the river.

It is recommended that test-dredging should be carried out on crossings of the Niger and on the Benue Bar during one or two years to obtain data which will answer many of the present open questions. A cutterhead suction dredger of about 500 cuyards/hour capacity will prove the best equipment to start with.

On the basis of these data and the experience gained it will also be possible to establish the test-dredging programme which must follow from the ratio between actual dredging and the transport of the dredging equipment from crossing to crossing. After test-dredging has given sufficient information a large-scale dredging programme can be carried out as soon as required.

It is not recommended to try and gain an improvement of more than 2 feet on the Niger, as when that depth is reached the channel length to be dredged will increase to such an extent that other ameliorations may prove to be more remunerative if they are of a more permanent character. Dredging equipment with a total capacity of some 2,500 cuyards/hour capacity for the Niger and for the Benue Bar, divided over two dredgers, is recommended to follow the test-dredging programme. No dredging is recommended for improving the Benue as long as discharge regulation has not been carried out.

Apart from the further conclusions from test-dredging it can now be recommended that the type of dredger should be a cutterhead suction dredger of a capacity of about 1,200 cuyards/hour and of the following specifications:

(i) Equipped with a spud carriage. This is essential as the shallow cuts in the crossing ask for a quick forward move of the dredger to maintain its capacity.

(ii) Equipped with anchor derricks so that the positioning and repositioning of the forward side anchors is independent from the use of tug-boats.

(iii) Equipped with a floating discharge line of 200—300 yards length which can be kept at right angles to the flow by means of an adjustable guide-vane.

(iv) Self-propelled, with a speed of 4½—5 knots in still water. This can be effected either through the use of the sand pump engines or by the use of two harbourmaster-engines.

A small tug of approximately 150 h.p. is necessary a.o. for assistance when the dredger sails with the floating discharge line behind and for towing the sections of the floating discharge line when these must be assembled or taken apart.

4.5.2. Resulting improvements

From test-dredging only minor improvements will probably result, as the total capacity of the equipment for test-dredging will be restricted.

However, it has already been explained that the first inches improvement over a river-stretch ask for comparatively little quantities to be dredged. It may well prove possible with a dredger of some 500 cuyards/hour capacity to gain in the months of December and January half a foot available depth by dredging on the worst crossings, where scour is retarded.

With dredging equipment of some 2,500 cuyards/hour, it is expected that on the Niger in an average year 5'6"—5'9" can be maintained during December and January and thereafter 5'3"—5'6" can be maintained until the end of the Black Flood in April. This will lead to a 30% increase of the fleet capacity during the Baro season. The adaptation of the fleet to the new available depths will, moreover, lead to a cheaper exploitation of such a fleet.

The dredging equipment will be able to clear the Benue Bar in May, so that the navigation depth in the river-stretch Mozum—Lokoja will not be less than the navigation depth in the stretch Lau—Mozum. Ships will be able to enter the Benue from 10 to 14 days earlier than would

be possible without dredging. Furthermore, the available dredgers can improve on too sharp bends by cutting a better alignment and can make deeper ports and berths.

Many other projects can also be taken in hand, not directly connected with improvements on the Rivers Niger and Benue; the continued use of the dredgers during high water will improve the efficiency of the dredgers and indirectly favour navigation by offering a cheaper means of the required improvements.

4.5.3. Expenditure

Information on the expenditure of dredging has revealed that the total dredging cost of test-dredging will be £ 3 to £ 3/10/- per week for each cuyard/hour capacity of the dredger, when the dredger is of at least 500 cuyard/hour capacity and the dredging continues throughout the low-water period, i.e., from November until April. The removed quantities depend largely on the number of dredging hours and the composition of the soil. Test-dredging with a dredger of some 500 cuyards/hour capacity, as has been recommended, will cost £ 40,000 to £ 45,000 in a low-water season.

A dredger fleet of 2,500 cuyards/hours can be operated at a cost of £ 150,000 to £ 200,000 per season (exclusive of eventual contractor's profit), dependent on the utilisation of the dredgers outside the river season. Such a dredger fleet is able to dredge a quantity of 1,400,000—1,600,000 cuyards in a five months' period.

The cost of a dredger of 1,300 cuyard/hour capacity delivered in Nigeria is approximately £ 400,000, while the cost of a dredger of 650 cuyard/hour capacity is approximately £ 300,000.

CHAPTER 5

TEMPORARY IMPROVEMENTS BY OTHER MEANS THAN RECURRENT DREDGING

5.1. GENERAL

Improvements of a temporary nature can normally be made at relatively low cost. Their effect will in general be local and remain limited to the prolongation of a certain navigable depth at crossings or, expressed differently, to a reduction of the limit discharge ([1 in crucial periods, in particular at the rise and at the fall of the flood.

In some countries, notably India and the Soviet Union, methods of this nature have been applied. The basic idea is to guide the currents in such a way that there is an increased erosive action in the channel. The methods can be roughly classified into two groups. The Indian system, called bandalling, consists of the application of bamboo guiding structures and will be discussed first. In the Soviet Union rather more subtle systems of guiding vanes are used with the aim of inducing transversely-circulating currents.

Both systems have been recommended for the Upper Benue by the French Cameroun Consultants in their Final Report ([3.

Still another possible method of influencing the current, not making use of any guiding element, is to create artificial roughness in the river-bed by means of grooves dredged on the shoals bordering the channel.

A special type of river training is the so-called "river training without embankment", or rather the building up of river-banks by training works of local materials constructed on the flood-plains as used in Burma and Malaya. This method is applicable in small, silt-bearing streams only and will therefore not be described here.

5.2. BANDALLING ([2

The method of bandalling is used on the Rivers Ganges and Brahmaputra in India. Its purpose is to concentrate the flow into a channel in order to deepen it.

A "bandal" is a frame consisting of bamboo stakes planted in the river-bed at distances of 0.6 m (2′), connected by horizontal ties and strengthened at distances of 1.2 m (4′) by sloping stakes, all lashed together. Bamboo mats called jhams are tied on the frame. They have a width of 0.75 to 1 m ($2\frac{1}{2}$—3 feet).

The screens are placed on both sides of the channel at angles of 30 to 40 degrees to the main current, as is shown on Diagram 5.2.1-1.

([1 see III, 6.4.3.
([2 UNITED NATIONS, 1954. GEN. 40
([3 ELECTRICITÉ DE FRANCE, 1958. GEN. 11

Another and somewhat more solid construction is known as "cow". This is a dolphin-like structure consisting of bamboo stakes jointed together and supporting bamboo "sausages". Applied in one or more rows they form temporary and permeable groynes.

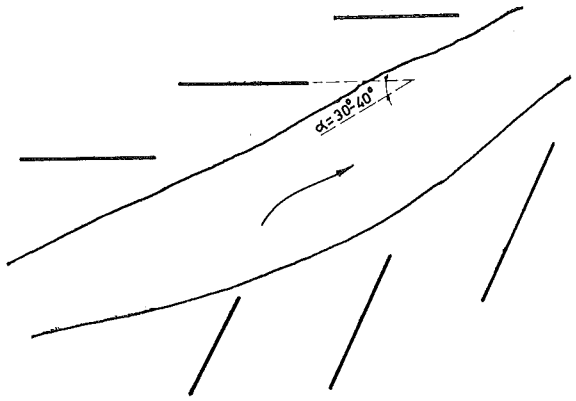


DIAGRAM 5.2.1-1

Bandals along a river

5.3. TRAINING WORKS INDUCING CIRCULATORY CURRENTS

5.3.1. Principles and use ([1]

As a rule the flow filaments in a river are not parallel. Transversely-circulating currents are superimposed on the general flow, as a result of which the surface and bottom currents diverge. Such a transversely-circulating system of currents, or spiral flow pattern, particularly occurs in a curved channel, where its effect is to erode the concave bank and to build up the convex bank (see III, 6.1.2). But elsewhere in the river the phenomenon also exists, although it is often less easily observed. Altogether it plays an important part in the evolution of channels and shoals (see III, 5.4.4).

In the Soviet Union, on the initiative of Professor POTAPOV, methods have been developed providing for the systematic utilisation of the phenomenon for various purposes, such as, for instance, prevention of deposition of sediment in the intakes of canals for irrigation or water-power and protection of banks against undermining.

The principle can also be used for improving navigation channels. For that purpose a spiral flow pattern has to be created in which the surface flow converges into the channel and the bottom flow diverges from it. Such a flow pattern, in which also downward flow components appear, has a deepening effect on the channel.

In bringing the principle into practice there must be used either a system of vanes acting on the surface flow or a system acting on the bottom flow, or a combination of both.

For a surface flow system, floats are constructed, supporting vanes placed vertically and at an angle of 15 to 20° to the main current ([2]. The vanes may simply be flat sheets or, which is slightly more effective, curved in a circle-segment. They have a horizontal length of 2 to 3 times the depth and are submerged upto 30 to 50% of the local water depth.

([1] UNITED NATIONS, 1956, GEN. 38
([2] UNITED NATIONS, 1956, page 328. GEN. 38

Their mutual distance, although varying according to circumstances, is often roughly equal to the depth. A number of consecutive vanes (8 to 10 or more) are combined into one unit, which is kept in the correct place by anchoring or by mooring to the bank. The dimensions of the vanes, as well as their arrangement with respect to the channel, must be adjusted empirically for every given case so as to obtain the best effect.

Diagram 5.3.1-1 gives an example.

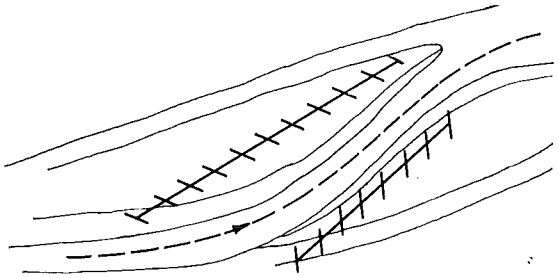


DIAGRAM 5.3.1-1

Surface flow vanes on a crossing

A system of vanes for guiding the bottom currents can be constructed by driving stakes into the bed and attaching to them vertical vanes of metal, wood or mats of bamboo or other plants, adjoining the bed and reaching upward to somewhere near mid-depth. These vanes deflect the bottom flow from the channel. Here again the dimensions and the angle to the channel axis have to be established by experience. The bottom vanes are put at a slight angle away from the channel, as can be seen in Diagram 5.3.1-2.

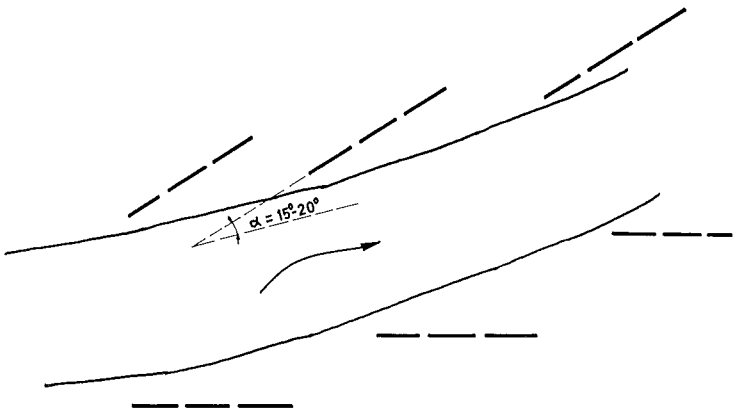


DIAGRAM 5.3.1-2

Bottom flow vanes

It must be understood that their action is entirely different from the "bandal" structures discussed in the preceding section, which simply tend to contract the flow into the channel, and thereby to obtain a greater depth as a result of higher flow velocity. On the other hand, the

flow vanes aim at inducing a spiral flow pattern favourable to the formation of a channel (Diagram 5.3.1-3).

Experiments in the Niger between Koulikoro and Ségou by the "Service des Etudes d'Outre Mer" have shown that to a certain extent satisfactory results may be obtained by means of the flow vanes.

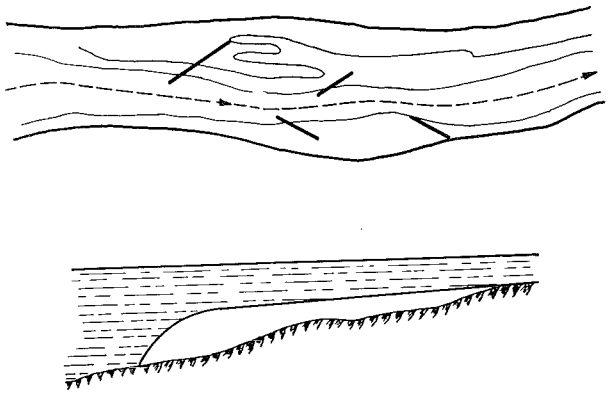
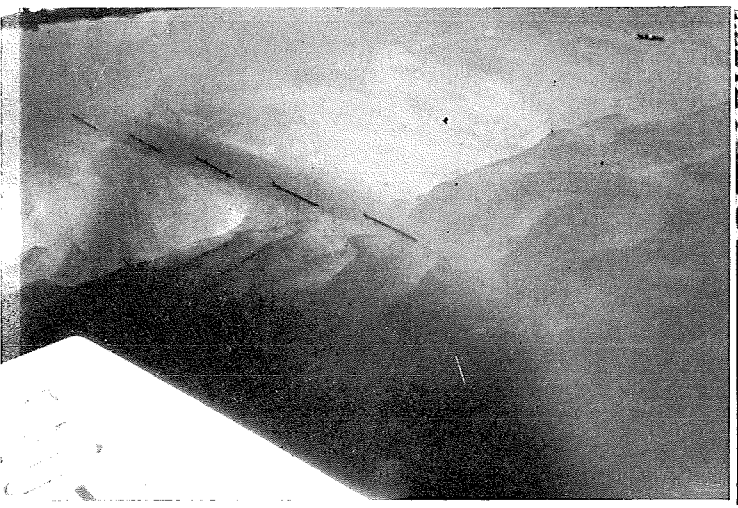


DIAGRAM 5.3.1-3

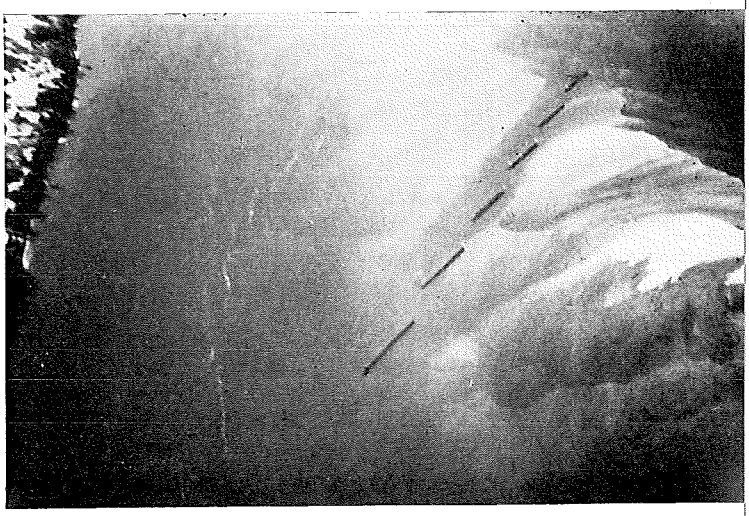
Bottom flow vanes create a deeper channel

The bottom flow vanes as used in this case had a length of about 50 m (165 feet) and mutual openings of about 35 m (115 feet). Old rails served as vertical supports. Photographs 5.3.1-4 and -5 show a channel deepened in this way by a system of bottom vanes on the right side only. A deepening of the channel by 0.5 to 0.6 m ($1\frac{1}{2}$ to 2 feet) has been gained.

A different method, which also aims at inducing a spiral flow pattern but simultaneously creates increased turbulence along the channel-bed, has been devised by LOSSIEVSKY. An artificial



PHOTOGRAPH 5.3.1-4



PHOTOGRAPH 5.3.1-5

Single row bottom vanes in the Niger near Koulikoro

from: ELECTRICITÉ DE FRANCE

sill, consisting of a submerged screen of fascine structure, is fixed to the bottom at an angle of 15 to 20° with the main current, aside of the channel (Diagram 5.3.1-6). Whereas the surface current tends to be deflected more at right angles to the structure, the bottom flow is deflected along it, carrying off the sand eroded by its increased turbulence. In addition, deflection of the surface flow can be considered by placing surface vanes as well.

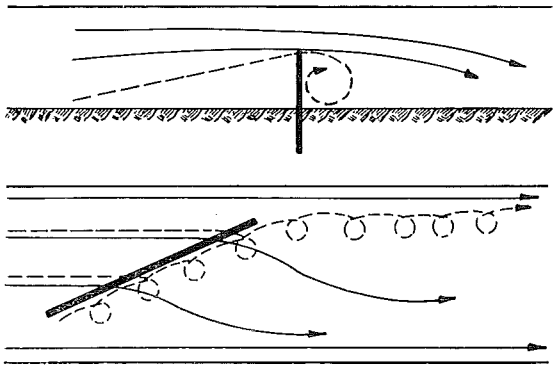


DIAGRAM 5.3.1-6

Bottom sill of Lossievsky

A special application of the spiral flow principle is a "dredging barge" designed by the Russian engineer PROSTOV. The structure, shown in Diagram 5.3.1-7, consists of a barge to which are attached four vane systems so as to obtain a spiral flow pattern behind the barge. As the vanes are surface vanes, the action is analogous to that obtained by the floating units discussed above.

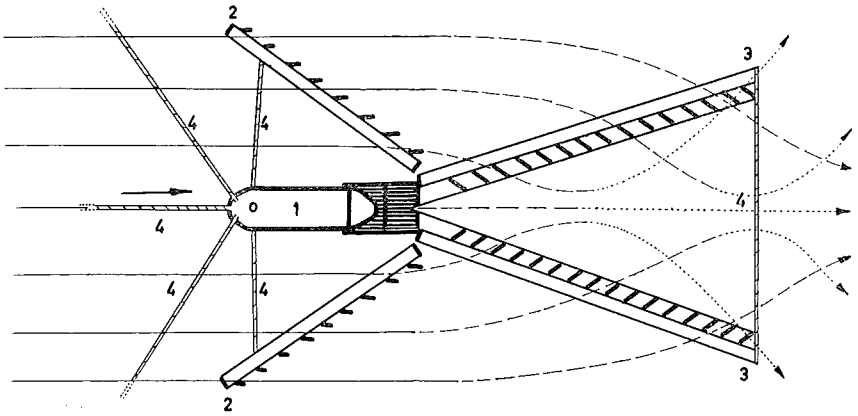
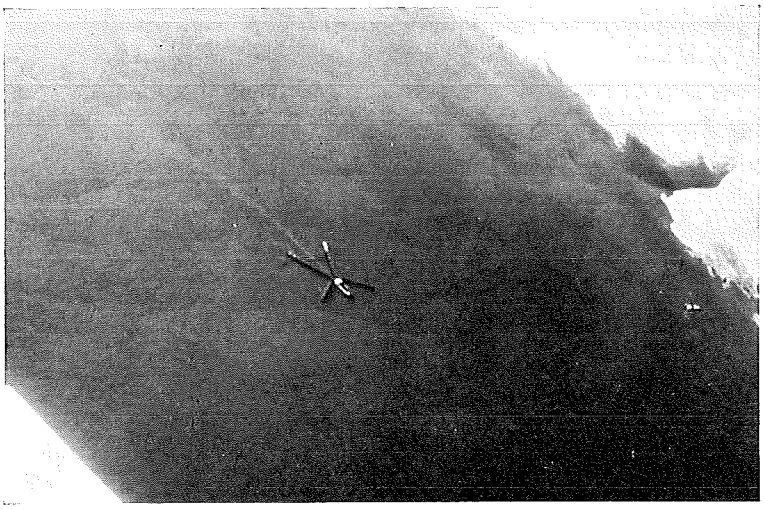


DIAGRAM 5.3.1-7

Dredging barge of Prostov

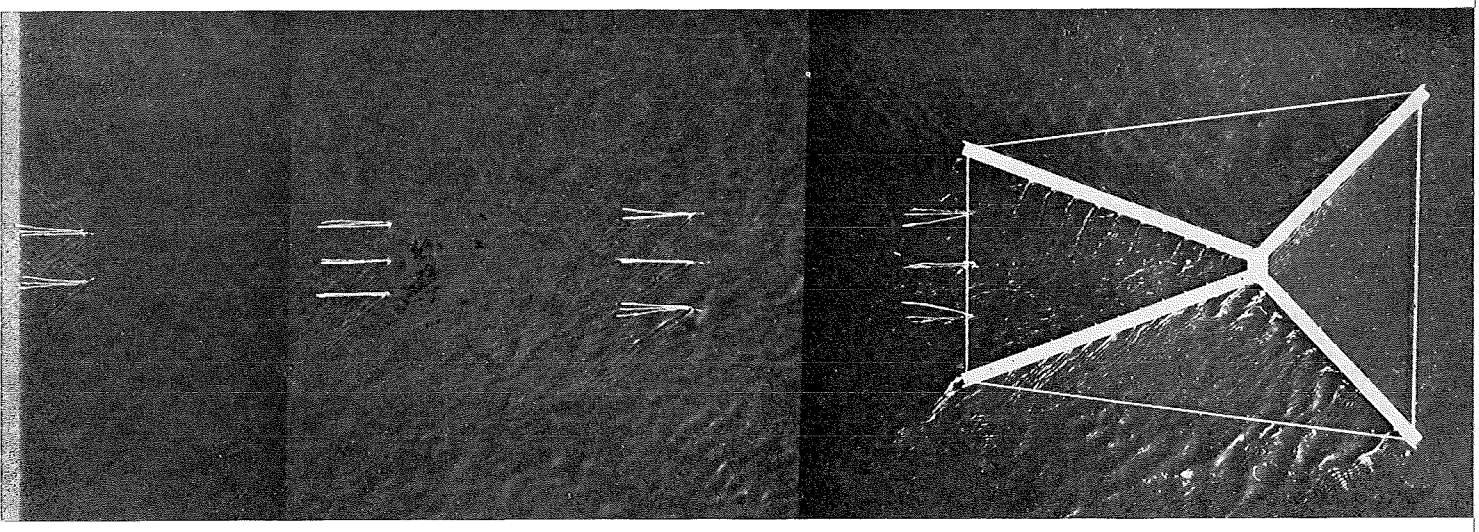
A unit of this type has also been tried on the Niger between Koulikoro and Ségou, with satisfactory, though limited, results (1. In Photograph 5.3.1-8 the concentration of the surface flow induced by the converging effect on the vanes can clearly be seen.

(1 ELECTRICITÉ DE FRANCE, 1958. GEN. 11



PHOTOGRAPH 5.3.1-8
Experiments on the French Niger
(from: ELECTRICITÉ DE FRANCE)

Experiments on a small-scale model are being carried out in the French National Hydraulic Laboratory at Chatou, near Paris, and preliminary results are reported ([1] to be fairly satisfactory. The deeper the vanes reach, the more extensive erosion they effect, but only over a short distance. An eroding action extending over several times the length of the vane system can be obtained with rather shallow vanes, in which case the depth of the erosion is less. Always, however, the width of the eroded channel is less than the width of the structure. The experiments aim at establishing the most effective combination of size, distance and depth of submergence of the vanes and their angle to the main current for obtaining the best result under different conditions.



PHOTOGRAPH 5.3.1-9
Model tests in French National Hydraulic Laboratory

([1] not yet published in 1958.

Photograph 5.3.1-9 shows the model installation from above and offers an indication of the deflection of the current on the surface, mid-depth and bottom.

Although the experiments may be expected to supply useful information regarding the most effective manner of construction and operation, it will still remain necessary to adjust the arrangement to the special conditions and requirements in each given case.

5.3.2. Method of operation

The Potapov bottom vanes and the Lossievsky sills are semi-permanent structures which have to be built and fixed onto the river-bed with sufficient solidity to ensure that they remain functioning during the period of their usefulness. They can be assembled either from prefabricated metal or wooden elements, or from local materials, put together on the spot. In either case some skilled labourers are required, as well as a leader who has experience on the river and understanding of its behaviour. Moreover, certain facilities are needed, such as vessels with gear capable of handling the weights involved, and simple pile-driving equipment.

The location concerned should be watched frequently to ascertain that the structures do not offer obstruction to navigation as a result of possible displacement or damage or of channel shifting.

The floating vane structures are more flexible and, once assembled, can easier be put into operation, although they still ask for a skilled team. Difficulties may arise when the river carries much floating debris.

The dredging barge can either be kept in a certain position for some time and then moved to another position, or towed up and down the channel.

5.4. PRACTICAL APPLICATION IN NIGERIA

5.4.1. Where and when to use

On the Niger and Benue Rivers, several circumstances exist where application of a temporary means of improvement would be suitable.

On the Niger, the long Black Flood period permits application of the method of bandalling by construction of screens along a crossing channel. The screens can be positioned at the beginning of the Black Flood period in December and possibly result in a little more depth on the crossing, effected by channel contraction. The dredging barge of PROSTOV may also offer some effective possibilities. However, it is not believed that improvement of the channel would be obtained at such a rate that navigation would be possible even during the low-water period of April—May, although some experiments are always advisable.

On the Benue, the existence of the Benue Bar near Lokoja (V, 3.1.2) forms an excellent opportunity to carry out experiments with floating training-works or bottom flow screens. Construction should take place at the end of the Black Flood period before the Benue starts rising; an accelerated scour of the Benue Bar would probably be effectuated, resulting in the possibility for ships to pass the Bar a few days earlier than normally.

It is not expected that the formation of the Benue Bar during the Black Flood period could be prevented by temporary means.

On the Gamadio and Wuro Boki Flats, where difficulties arise, for instance, during the August fall (III, 4.1.3), application of the system of flow vanes might lead to satisfactory results. In view of the rapid shifting of channels, it seems advisable not to use bottom flow vanes, but to limit experiments to floating structures.

5.4.2. Materials and cost

In the previous paragraph it is recommended to start an experiment in the entrance of the Benue River under one of the methods discussed in 5.3 aiming at an accelerated scour of the Benue Bar. As a start the choice may be the same method as already applied on the French Niger (see 5.3.1) resulting in $1\frac{1}{2}$ to 2 feet more depth. Such a result would certainly justify the cost of the experiment.

To keep the cost of the experiment as low as possible, it will be profitable to use labour and materials locally obtainable. Therefore the use of the Morelia Senegalensis is recommended. This is a shrub or small tree reaching 25′ in height with a maximum stem diameter of 8″. In the Swamp Forest Reserve between Koton Karifi, Lokoja and Okpanedu it is one of the most common species. Stems of a length of about 10 feet and of a diameter of 4 to 6 inches will be very useful as the vertical supports, while the flexible branches can be used to twist the screens.

Roughly estimated cost of a system of guiding screens for the Benue Bar made from this material, and constructed according to the sketch in Diagram 5.4.2-1, amount to £ 500.

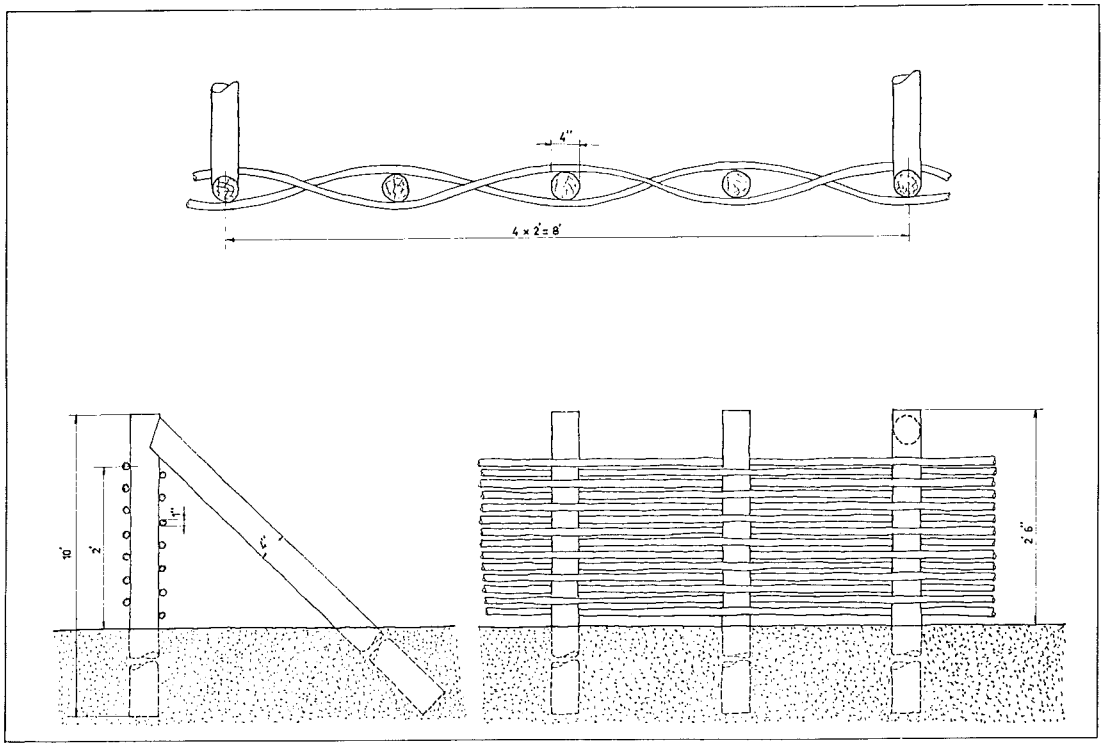


DIAGRAM 5.4.2-1

Bottom flow guiding screen designed for Nigeria

The most suitable time for execution will be at a low stage of the river, e.g., about mid-April. The duration of the work can be easily limited to two weeks if the materials have been collected beforehand.

To indicate the location of the screens after they have been submerged by the rise of the water, it will be necessary to demarcate them by a number of buoys, which can also indicate the deepened channel.

A continuous observation of the behaviour of the channel by soundings and sand-transport measurements during the rise of the river may provide guidance for further experiments.

5.5. SUMMARY

Improvement by river training of a temporary kind, such as bandalling and the construction of floating training-works, seems to be efficiently applicable on certain stretches of the Niger and Benue. Some experiments on those sections are recommended.

Such an experimental programme could attractively be carried out in particular on the Benue Bar near Lokoja. The works as well as the necessarily frequent surveys on the behaviour of the created channel can then easily and at relatively low cost be executed, as they are situated close to the I.W.D. Headquarters and Dockyard. The cost of the works are estimated at £ 500.

The effect of such works — based upon the action of a circulatory flow — is only temporary and will be eliminated by the next flood.

CHAPTER 6

BED-REGULATION

6.1. GENERAL

6.1.1. Introduction

With respect to navigation the regulation of a river might be defined as the process of eliminating dominating bottle-necks in the navigation channel of the river. Examples of such bottle-necks for navigation are:

strong or irregular currents or steep slopes of the water-level;
shallow sections in the channel;
narrow or sharply-curved channels; and
intricate and rapidly-shifting channels and sand-bars.

Sometimes there is only a small number of isolated bottle-necks in a long river-section, the greater part of the stretch being of a homogeneous type without great differences in channel depth. The improvement of such rivers for navigation is often possible at relatively low cost, and without much investigation into the morphological behaviour of the river-bed.

However, many rivers in the world — including the Niger and the Benue — have a heterogeneous bed with alternate deep channels and very shallow sections with many bottle-necks for shipping. The improvement of this type of rivers for navigation, the regulation in a more narrow sense, is a very difficult problem and asks for considerable knowledge of the character of the river and for much experience. Even then there are often failures and high revision costs.

A striking example of the first group of rivers is the rapid, caused by the remainders of rock, gravel or clay banks in the low-water channel. In such rocky sections strong currents, a steep slope, shallow and irregular navigation channels and dangerous peaks of rocks will often hamper navigation. The elimination of this type of bottle-neck will often give a considerable improvement without excessive cost, provided an adequate solution is chosen. Another example of a bottle-neck of the first group is sometimes seen in a sharp bend, resulting in a narrow or sharply-curved channel, followed by a shallow crossing. The elimination of such bottle-necks by dredging a short-cut might give a definite solution, provided the consequences of such an operation are met. A local bifurcation of the river into two branches might produce another obstacle. The closing of one of the branches might provide the remedy, but will sometimes result in many difficulties (see III, 6.6.4).

A much more difficult problem is the regulation of rivers of the second group, for the improvement of the braided and shifting type of rivers offers one of the greatest challenges to river engineering. Even with all the present knowledge of these matters — which is, however, still rather limited — a number of risks has to be accepted in the execution of improvements by regu-

lation of the low-water bed, comprising stabilisation of the low-water channel(s), banks and sand-banks in a position favourable for shipping with the aid of a minimum number of supports.

Before considering the desirability of regulating the Niger and the Benue, it is advisable to discuss the main problems and difficulties in these systems of river regulation in order to judge the applicability of any form of regulation in Nigeria.

6.1.2. Examples

Smaller or larger regulation-works of different types have been applied in many rivers of the world. The blasting of isolated peaks of rocks is one of the most simple examples. Well-known examples of more extensive channel-clearing in rocky sections are the improvements of the rocky sections of the Rhine near and downstream from the "Bingerloch" (Photograph 6.1.2-1) and of the Danube in the "Iron Gate".

PHOTOGRAPH 6.1.2-1

The "Bingerloch" in the Rhine

The dredging of short-cuts in large river-bends is another frequently applied method of improving rivers. In the Mississippi, for instance, a large number of short-cuts has given a considerable shortening of the total length of the river. This, too, was the case with a section of the Meuse in Holland (Photograph 6.1.2-2), where this system was combined with another method of river improvement, the canalisation (see Chapter 7).

The closing of small secondary branches and the linking up of islands with the bank of the river is a common phenomenon in river regulation. However, the closing of larger, and in particular of long, branches has always raised many problems and especially this part of river engineering has shown several failures, such as, for example, the improvement of a section of the River Weichsel, carried out about 15 years ago.

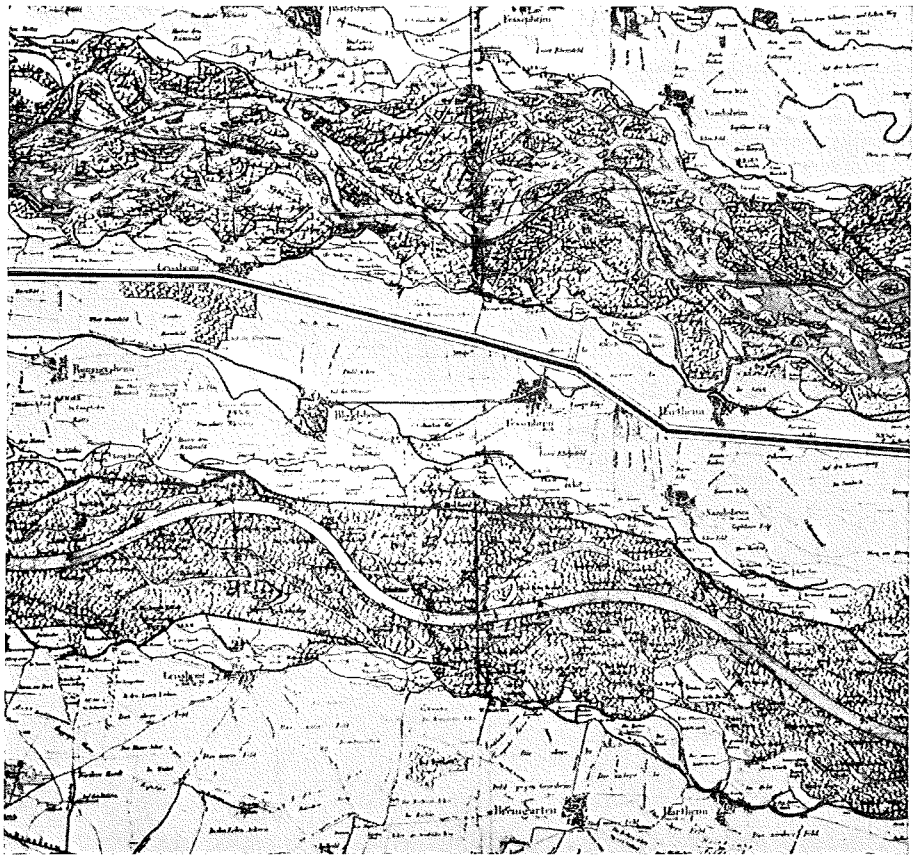
Examples of an extensive bed-regulation can be found in the middle section of the Mississippi and a large part of the Rhine. Especially the Lower Rhine shows the great advantage of this type of river improvement, i.e., offering the possibility of improving step by step. In an early

PHOTOGRAPH 6.1.2-2
Bend-cutting in the Meuse

PHOTOGRAPH 6.1.2-3
Normalisation on the Lower Rhine

stage bad crossings in sections of this river were eliminated by the construction of isolated training-works. When shipping demands grew, other crossings became important, and so gradually the whole river was regulated until all bottle-necks had disappeared. The next step to increase the depth was local contraction of the low-water bed, ultimately completed by successive further contractions, called normalisation, parallel with the development of shipping on the river (Photograph 6.1.2-3).

On the Upper Rhine in Germany, where conditions were different from those on the Lower Rhine, and where the river was of the braided type, a regulation scheme was laid out as early as about 1850 by TULLA, as is shown in Photograph 6.1.2-4.



PHOTOGRAPH 6.1.2-4

Regulation on the Rhine between Mannheim and Strasbourg

Quite a different approach to a regulation scheme was made in more recent years, when plans were drawn up to improve the shipping conditions of the River Po in Italy. Photograph 6.1.2-5 gives an aerial photograph of a section of this river, with the bank revetments under construction, together with those still to be constructed. Here also the regulation goes step by step, but the river will be navigable only when the whole scheme has been executed, as at many places the planned course of the river does not correspond with the actual situation.

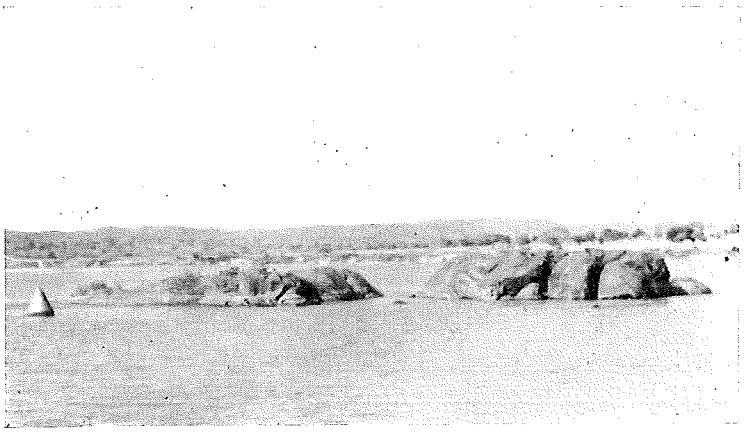
PHOTOGRAPH 6.1.2-5
Regulation of the River Po

6.2. PRINCIPLES

6.2.1. Rock-clearing

In many rivers local obstacles are formed by the presence of rocks in the navigation channel. In the Niger and Benue, too, there are obstacles of this kind. From the point of view of river engineering, a division into three types can be made:

(i) The isolated peak of rock in the river-bed. Where there are shifting channels, these peaks are situated sometimes in the centre of the navigation channel, whilst at other times they are covered by sand-banks, islands or banks. They have no influence on the situation of the bed. Examples of such rocks are found in and near the confluence of the Niger and Benue. When the navigation channel is wide, it is sufficient to mark these rocks by buoys, beacons or lights (Photograph 6.2.1-1). In the case of narrow channels, there is no objection to removing the rocks by blasting.



PHOTOGRAPH 6.2.1-1
Solitary rock near Lokoja, marked by a buoy

(ii) The rocky banks of a river-bed. The resistance of these banks is the cause of the existence of deep and stable channels as discussed in III, 6.1.5. Even in the case of a braided and shifting river, there is always a channel along these rocks. For instance, Baro, Lokoja, Onithsa and other river ports owe their existence to the rather constant presence of a deep channel along their rocky banks (Photograph III, 2.3.1-19). Underwater parts of such rocks sometimes endanger navigation and have to be removed, although this might exert influence on the stability of the channel and result in a less favourable situation for navigation.

(iii) A rocky bed of the entire cross-section of the river. This, for instance, is the case in sections of the Niger upstream from Jebba. By this bed-rock the channels are totally fixed. The high sill — high with regard to the sandy river-bed upstream and downstream — forms a rapid and often causes a bottle-neck for shipping. If important rapids or series of successive rapids are improved by rock-blasting, calculations as mentioned in III, 6.6.2 are necessary to avoid failures. This has to be considered if in future improvement of the river-section upstream of Jebba is undertaken.

6.2.2. Bend-cutting

Although the application of short-cuts in the future development of the Niger and Benue will probably be restricted to some sharp bends in the Delta Area, some remarks may be made about the main problems.

The execution of the short-cutting of a bend is in general an easy undertaking. As discussed in III, 6.6.3, the newly-dredged channel will scour and the old one will gradually silt. It is, therefore, not strictly necessary to dredge the new channel directly to its full capacity. With regard to the cost, it is wise to dredge only a small channel — a so-called pilot-channel — and to leave the rest to Nature (Diagram 6.2.2-1). If this channel has certain minimum dimensions large enough

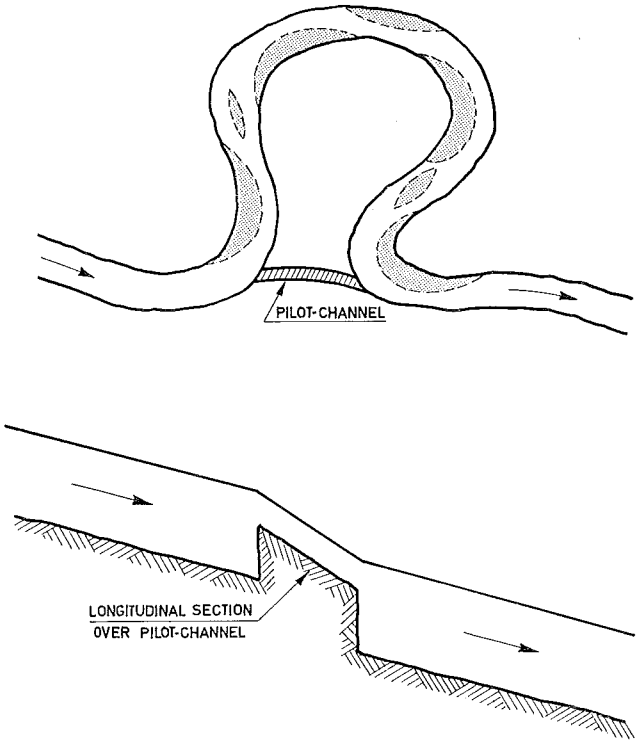


DIAGRAM 6.2.2-1
Bend-cutting by the construction of a pilot-channel

to start the process of scouring by the river itself and if no rocks or clay banks in the short-cut give a high resistance against flow, the cross-sectional size of the dredged cut will increase rapidly.

However, there are some serious objections against this method if the river upstream and downstream of the short-cut offers only a minimum of depth to shipping. In the first period after the dredging of the pilot-channel shipping will still have to take the old bend, which, however, will be gradually decreasing in capacity and in depth. So the situation will grow worse instead of better. A second disadvantage is that large quantities of sand will partly deposit in the river downstream of the short-cut (III, 6.6.3), forming sand-bars that block the navigation channel. The constant presence of a dredger for some years might then be necessary to maintain a channel open for shipping. In such cases it might be wiser, and cheaper, to dredge the new channel at once to its full capacity, that is, the capacity of the low-water channel upstream and downstream from the short-cut. The old bend must then be closed at the same time by artificial means (Diagram 6.2.2-2).

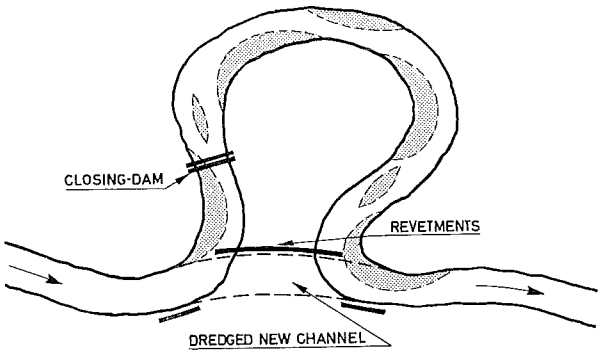


DIAGRAM 6.2.2-2

Full-size bend-cutting

In rivers like the Mississippi and the Meuse, in which as already mentioned a large number of short-cuts was executed, the scour in the upstream part amounted to several yards before an equilibrium was reached and it often appeared unavoidable to dredge over a period of years.

The large bends in rivers owe their existence to the meandering phenomenon. Making a short-cut does not mean that this meandering is stopped. Therefore it is often necessary to stabilise the short-cut by the construction of supports preventing the erosion of the banks (Diagram 6.2.2-2). Only when the banks of the future channel are strongly resistant against erosion, for instance, by the presence of layers of stiff clay, will the meandering of the new channel be such a slow process that protection of the banks can be omitted.

From this it appears that bend-cutting may seem to be a cheap and simple means of improving certain curved sections of a river, but that in reality it sometimes will give many difficulties if the available depth for shipping in the other sections is limited. Such bend-cuttings are then expensive and ask for an exhaustive investigation before being undertaken.

6.2.3. Closing branches

The closure of a number of branches in a braided river causes an increase in the capacity of the remaining channel(s) and in consequence an increase in the equilibrium depth of that channel. By this means some bottle-necks for shipping might be eliminated.

In general, the closure of a branch will be more troublesome to execute than the dredging of a new channel in case of bend-cutting. This is shown in Diagram 6.2.3-1 where one of the two branches of a river is closed. During the construction of the closing dam the cross-section in the opening is gradually decreasing, involving a considerable increase of resistance at the location of the dam, while the slope in the remaining part of the branch is decreasing. At the moment of closing the last gap, the discharge in the closed branch is stopped completely, and the water-level in the sections of the closed branch becomes horizontal. So the total difference

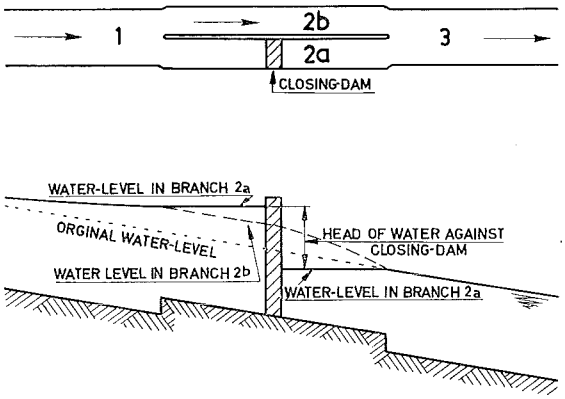


DIAGRAM 6.2.3-1

Change in water-levels after closing one branch along an island

in water-level between the ends A and B of the remaining branch is concentrated at the dam. This difference in water-level consists of the original drop between A and B before closure plus the raise of water-level upstream from the closing dam (see III, 6.6.4) due to the increased resistance by the discharge being forced into the narrow remaining branch. Therefore a calculation of the slope and of the head of water at the location of the dam during the execution of the closure is necessary to decide the method of closing or even the possibility of closing. If the head of water in the closing gap is growing over half a metre (2 feet), resulting in a velocity of the current of over 3—4 m/sec (10—13 ft/sec), closure of the last gap with mattrasses and stone-dumping will be hardly possible. Application of two successive dams, dividing the head over two gaps, will provide a solution; but it will be a very expensive one.

The drop of pressure in the ground-water across the width of the island due to the difference of water-level in both branches should also be realised, and when the island is narrow this might result in a breach.

The closure of branches will generally be executed during the low-water period. The height of the crest of the dam depends on the hydrograph of the river and on the period during which the navigation will need the shipping channel to be improved.

As discussed in III, 6.6.4, a high dam in one of the branches will improve the shipping conditions during the H.W.-period, but a bar which is formed upstream of the former island will hamper the navigation during lower water-stages. A low dam, however, will not affect the configuration of the river-bed as much as a high dam and, especially when the discharge is not too low, the possibilities for shipping are improved. It is only when the water-level drops very low that the bars upstream and downstream of the former island may restrict the available depth.

Apart from these considerations, a crest free of high water has the advantage of being safe against destruction by overflowing water during flood periods. A disadvantage, however, is that during these floods the current is concentrating on both sides of the dam with the risk of creating scour and channel formation on each side, as shown in Diagram 6.2.3-2. The construction of parallel dikes on both banks is an expensive consequence of this. A low elevation of the crest

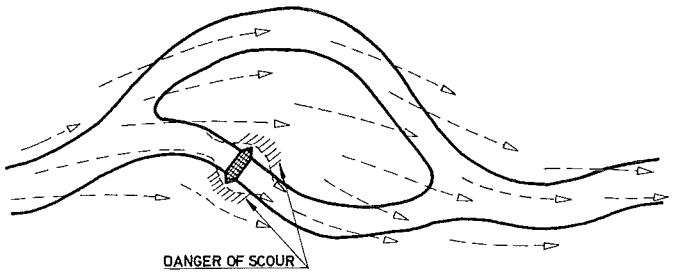


DIAGRAM 6.2.3-2

Flowlines at high water, in case of a H.W.-free closing dam

is, therefore, often preferable. If this elevation is far below the dominant level, there is the risk of sand deposition in the remaining channel during flood periods, and the consequence might be that the former semi-equilibrium is not sufficiently disturbed by the dam to change the branched river into a single-channelled river.

To avoid difficulties during the closing procedure resulting from too large a head of water in the closing gap, as well as the risks of bars upstream or downstream from the former island after one of the branches has been closed, the building of a series of open structures or low sills can be taken into consideration.

In principle the effect of such constructions is less than, although similar to, the closed one, but it will take longer for the river to adapt itself to the new situation, with the advantage of less risk of the formation of the said bars. However, a great disadvantage of open structures in rivers with floating snags is the stopping up of the open structures, and their subsequent destruction by pressure. In these cases low sills are preferable.

It will be appreciated that a simple closure of a parallel branch with a low artificial sand-bank (which is the easiest form of closure) will not achieve permanent improvement. It is, of course, possible to raise this sand-bank every year, keeping pace with the gradual bank erosion in the open branch, and with the possibility of either natural or artificial vegetation appearing. There is always a chance that in this way the island will grow together with the main bank of the river, but the tendency to island formation (III, 6.2.2), which apparently existed in that part of the river, is not outrooted and there is no guarantee of the prevention of new shoals.

If such a risk is not accepted, the only remedy is protection of the banks and the island against erosion. It might also be advisable to secure the artificial closing sand-bank against erosion and downward movement. The improvement will then have a permanent character, but is, of course, much more expensive than a simple unprotected sand-bank.

Formation of bars either upstream or downstream from the island may be prevented by local works, such as the construction of groynes, so that the sudden narrowing of cross-section by a dam in one of the branches is transformed into a gradual one (Diagram 6.2.3-3). The

deposition of sand will be spread over a larger area and consequently cause a smaller reduction of depth.

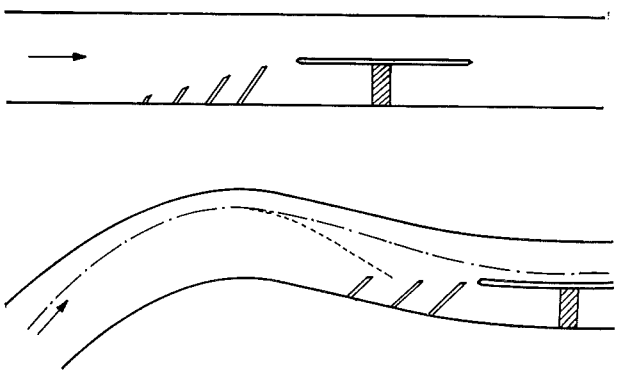


DIAGRAM 6.2.3-3

Possible solutions to prevent shoaling upstream from an island if one of the branches is artificially closed

The best solution is obtained when, possibly with the help of groynes, a connection can be made between the end of the shipping branch and a deep channel in the outer bend of the main undivided river. Any temporary deposition of sand there is unimportant.

6.2.4. Channel concentration

In III, 6.2.1. the rivers were classified into different types as distinguised to their morphological behaviour. Among these the braided, wide river with flat cross-sections, shifting and branching channels and wide, shallow bifurcations and junctions is the most difficult to understand. The Rivers Niger and Benue show in their features much resemblance to this type, although some characteristics tend to the meandering type of river and soften to a certain degree the bad shipping conditions inherent to the braided type. It has been stated that the Niger and the Benue can best be qualified as to be of the "reach" type of river.

Little is known about the factors determining whether a river belongs to a certain type, although lack of resistance of the banks against erosion seems to assist in causing a river to be braided (III, 6.2.1.). Easily erodible banks prevent the existence of steep transversal bottom gradients (III, 6.1.2.) and the concentration of water flow in a relatively narrow and deep channel. A means of improvement, therefore, is to give the banks more resistance against erosion, a method called regulation of the river-bed.

Such is achieved by protection of the banks by the cover of a revetment or by leading away the current from the banks by the construction of guiding structures such as longitudinal dikes or perpendicular dikes (groynes).

Protecting the outer bend of a rapidly-shifting channel will force the erosion from the bank to the bed. In the inner bend deposition of sand will continue until the transversal slope of the bottom has reached its equilibrium (see III, 6.1.2). The result is then a narrow channel with a steep transversal

bottom gradient and with a deep outer bend. The water discharge is concentrating into a relatively narrow channel as is shown in Diagram 6.2.4-1.

From the foregoing it can be concluded that resistant structures have to be made in places where an erosive spiral flow is to be expected, which normally is along the outer bank of a bend. Revetting a straight river-bank is of no use, because there is no spiral flow and thus no pressure to deepen the bed and concentrate the discharge. An exception can be made for the spiral flow caused by the earth's rotation (see III, 6.1.4), giving a very weak pressure on the right bank in the northern hemisphere and on the left bank in the southern hemisphere. The influence of this spiral flow, however, is very small and is often overshadowed or counteracted by other influences in the river. A stable situation of the channel by the revetting of such a straight bank is, therefore, not ensured.

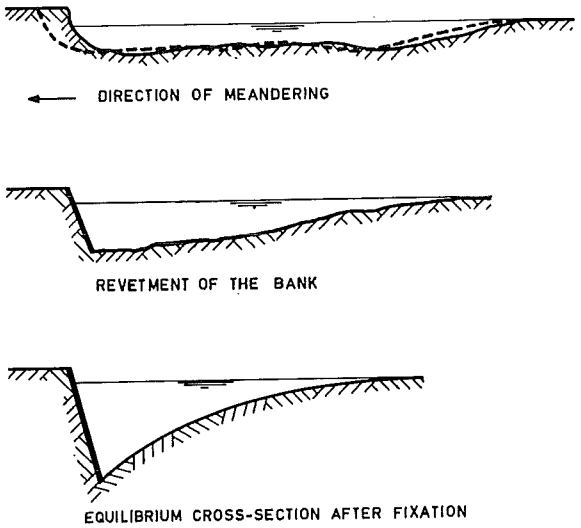


DIAGRAM 6.2.4-1

Change of a meandering cross-section by bank protection

A very important question is the stability of the channel in bends. If the radius of the bend is small with regard to the capacity of the channel, there will be a good stability after the fixation of the outer bank. The disadvantage is the strong spiral flow causing trouble for shipping, and the steep transversal bottom gradient, giving deep water at the foot of the outer bend and resulting in an expensive revetment. In a river-section with alternate bends in both directions the number of transitions or crossings — the weak points in river-regulation — will increase with decreasing radii of the bends, which is also a disadvantage. On the other hand, a bend with a very large radius is not stable: the transversal bottom gradient is small and minor irregularities, such as large sand ripples in the outer bend, might cause the channel to move away from the banks during the low-water period, while during high water a short-cut might be formed.

This problem of stability and its connection with radius, capacity and width of the channel at dominant water-level is rather intricate, and the best method, therefore, is perhaps to investigate the river in its good sections with stable bends and to derive from this the data for minimum and maximum radii, etc.

The alignment of the future stable channel is another important item on the project of a river regulation. It is useless to apply quasi-theoretical formulae like parabols. In practice, a number

of conditions have to be fulfilled to get a navigation channel without serious bottle-necks. These include:

(i) no straight or feebly-curved section between two strong curves in the same direction;
(ii) no curve with large radius downstream from a strong curve in the same direction; and
(iii) no long transitions between two curves in an opposite direction.

Experience still plays a major rôle in river regulation. A matter of dominant importance is the transition between two opposite bends. Here the minimum depth in the talweg occurs (III, 6.4.2). Downstream from a fixed bend, where the discharge is concentrated, the stream-lines are diverging and in consequence the depth is decreasing. Therefore the discharge has to be concentrated again in the next curve as soon as possible. The transversal bottom slope has to reverse in the transition zone from the upstream bend into the downstream bend, as shown in Diagram 6.2.4-2. In this transition zone the gravity centres of water-flow and sand-transport must shift from the left in the upstream cross-section to the right in the downstream cross-section.

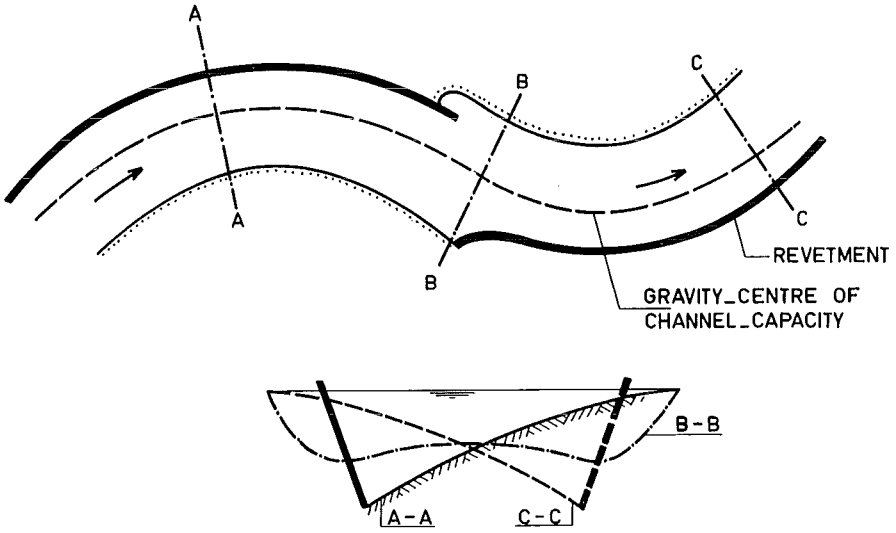


DIAGRAM 6.2.4-2

Cross-sections of a regulated river

A certain minimum length of the transition zone, therefore, is unavoidable, but a good alignment in this transition zone and a good support to limit the divergence of the concentrated water is of vital importance.

Another important question is whether it is possible to calculate the depth and the width of the channel in the bends and in the crossings. As for the bends, a theoretical approach can be made calculating the cross-section at dominant water-level, assuming that the longitudinal slope and the capacity of the river at this stage have about the same values as in the original situation. The calculation of the crossings gives greater difficulties, as the width of the widening channel and the bottom figuration in the cross-section are unknown factors. Only an approach can be made to it (III, 6.1.1), but it is better to investigate the river in good single-channelled sections and to compare the crossings in these situations with the crossings in the project.

In a good regulation project the closure of secondary branches is seldom necessary. If the channel is stable, these branches will be closed by the river itself after a certain period, although sometimes there is no objection to the existence of a secondary branch. In that case, however,

the distribution of discharge over the two branches must be stable. Here the problem of the elevation of the crests of the guiding structures arises. If at dominant discharge the flow is following mainly the route required for obtaining a stable situation, then silting and scour will certainly not influence the situation of the bed taken over a long period. So structures controlling the furcation of branches, etc., must have a crest height not too much below the dominant water-level. Other structures, for instance the heads of groynes stabilising a low-water bed, can have a lower crest-height.

Important factors here are the irregularities in the bed caused by floods. During floods the crossings in a regulated river are silting because the scour criterion ba^{α} at high water is larger in the crossing than in the bends (see III, 5.4.1), and, further, because the flow-lines during floods are more or less parallel to the banks and consequently cross the low-water bed in the transition zone between two opposite bends (see III, 6.4.2). When after the H.W.-period the water-level is falling, water is again concentrating in the channels and the equalisation of the disturbed bed starts. However, this takes time, and navigation might be hampered by the sand deposits on the crossing before the sand is removed by the river. It is, therefore, advisable to concentrate the current into the low-water bed at an early stage after the flood or, in other words, to make guiding structures with a relatively high crest. The differences in type of river, the rate of fall after the H.W.-period, the situation of the crossings in the total high-water bed, the quantity of sand-transport, etc., make it impossible to establish general rules for the required height of the crest.

One of the great advantages of river improvement by bed-regulation is the flexibility of the improvement and the possibility of changing an unfavourable alignment. During the gradual development of shipping the river can be improved step by step, starting with the regulation of the dominant bottle-necks and gradually proceeding until all unfavourable sections are eliminated.

When the regulation is completed, the entire river is guided by a series of supports in the outer bends and is artificially changed into a faintly meandering river, although at that time the river still has freedom to form its own width. Only one of the banks is fixed, giving a depth for shipping about equal to the depth in the best sections before regulation (see III, 6.6.6). So it is possible to estimate in advance the final result of regulation by channel concentration.

6.2.5. Channel contraction (normalisation)

In a totally regulated river the depth over the crossings is the restrictive factor for navigation, as in the outer curves of the bends the depth is much greater. If due to further development of navigation these depths on the crossings become insufficient, a further improvement of the river, based on the existing system of regulation, is possible by contracting the flow over the crossings by an overlap of the guiding structures of both neighbouring outer bends. The width of the crossing is then artificially reduced, so the depth in consequence must increase. By contracting the crossing more and more, the depth on the crossing approaches that in the bend (Diagram 6.2.5-1).

At this stage the width of the navigation channel in the bends becomes dominating, as the depth in the inner part of these bends become insufficient because of the transversal bottom slope. In that case a further improvement is possible by contracting also the bends, which can be done, for instance, by the construction of groynes in the inner bends.

And so, step by step, a greater depth of the navigation channel can be obtained, the limit being reached when the width of the normalised low-water channel becomes insufficient for the dimensions of the ships or the intensity of navigation.

In the regulation scheme of a river a gradual extension of the length of fixed banks is often seen. In the beginning only a small part of the length of the river-banks is stabilised in those sections where the river has limiting bottle-necks. This length is gradually extended until at the moment of total regulation the whole length of one bank, alternatively at the left and at the right, is fixed. After the normalisation of the crossings, about one and a half times the length of one bank is fixed, which is increased to double after the total normalisation.

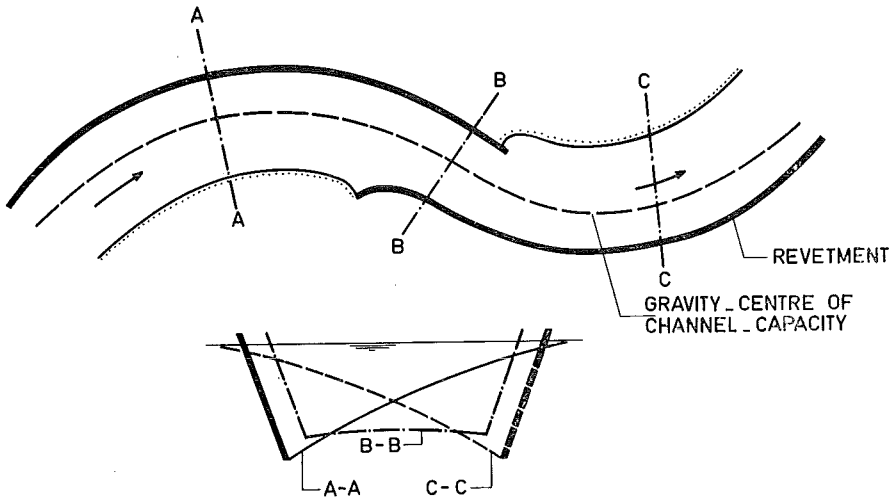


DIAGRAM 6.2.5-1

Cross-sections of a regulated river with overlapping structures on the crossings

An important question is whether it is possible to regulate and normalise any or every river. It will be clear that a river which has hardly any discharge during the low-water period cannot be made navigable during this period by regulation (channel concentration) as the depth on the crossings will not become larger than the one on the good crossings of the original situation. Nevertheless, normalisation is not advisable in that case, even if it were possible; the change from the virgin river to the totally normalised river would be too large to make it by one step. Also in the case of rivers which have great variation in discharge, with large quantities of sand supplied from tributaries, bed-regulation will present great difficulties, especially near the confluences with these tributaries, by the masses of sand brought into the main river during every high-water period (see V, 3.2).

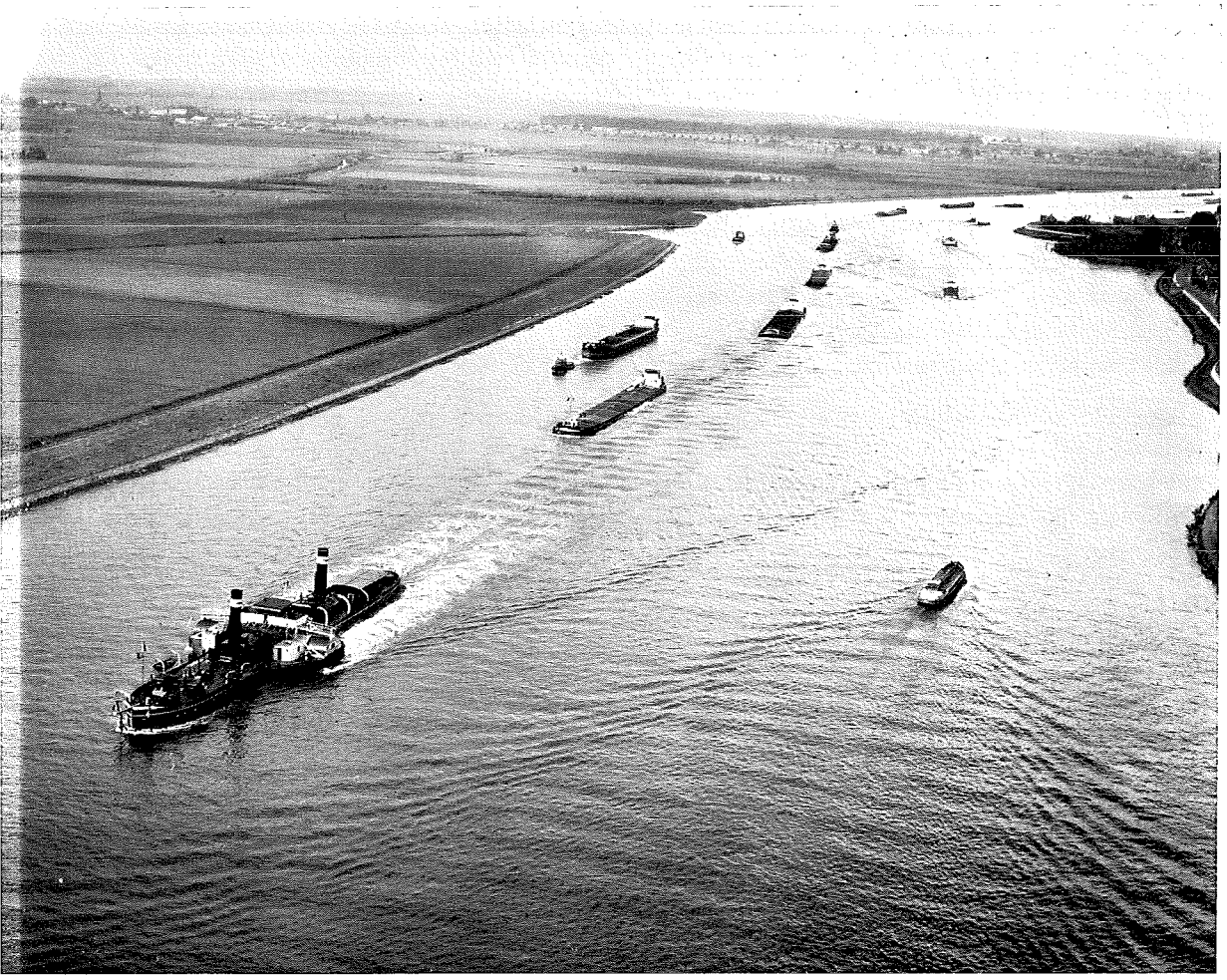
Generally it can be said that regulation and normalisation are only possible if the ratio between the high-water and the low-water river-bed is not too large.

6.3. STRUCTURES IN BED-REGULATION

6.3.1. Types and construction

The aim of the structures is to guide the current in the outer bends of the channels, or to restrict the discharge outside the channels below certain levels. The current can be guided by longitudinal structures supporting the channel over greater length, like bank revetments or longitudinal dikes (Photograph 6.3.1-1); or by isolated supports, like groynes. The application

of the various types is a matter of cost and depends mainly on the situation of the bed and the banks. If the bank coincides with the projected alignment of the outer bend of the channel, the cheapest solution doubtless will be the fixation of the present bank by a revetment. If the planned alignment is situated inlandwards, the solution of bank revetment can be applied as soon as scouring of the bank reaches the projected situation. If the alignment is situated in the existing river-bed, an artificial embankment could be constructed, connected to the bank by another dike to prevent the deviation of the current behind this longitudinal dike, although a cheaper solution in this case might be the construction of a series of perpendicular groynes.



PHOTOGRAPH 6.3.1-1

Longitudinal dike along one of the branches of the Lower Rhine

Concerning the latter type, distinction can be made between closed and open structures. The closed structures give a complete guidance to the current at water-levels below the crest height, whilst open structures only give an extra resistance to flow outside the channel. This extra resistance, due to the deceleration of the current after passing the openings of the structure, has to decrease the velocity outside the channel in such a way that deposition of sand is effected

and water concentrates in the channel. The most efficient proportion of opening in the structure can be calculated, and depends, among other things, on the velocity in the channel and the distance of the groynes.

The application of open structures, such as wooden pile-clumps on bottom-mattresses, sometimes has the advantage of cheapness. The disadvantage is the high cost of maintenance, especially when floating snags might destroy them. However, a comparison of cost determines the choice between the application of an open and a closed groyne; an open longitudinal structure is not considered, as such a solution does not answer the purpose.

The mutual distance of isolated heads necessary to give sufficient support to the flow is of vital importance. If this distance is too great, the attack against the supports will increase and the result will be a large depth in front of the head of the structure, and large maintenance cost. Moreover, the stability of the channel might become doubtful and the formation of sand-banks in the channel is possible. Experience has taught that the minimum distance between the supports of a channel should be less than the width of the channel in a rather low-water situation. However, the length of the groynes also plays a rôle.

The elevation of the crest of the structure is closely related to the type and function of the structure. Where the regulation concerns a low-water channel, it is sufficient to keep the crest low; on the Niger to a level corresponding with L.D.W. (see III, 5.2.4). But where the regulation concerns an unstable furcating river to be forced into a single-channelled flow pattern, the crest of the groynes should be high; on the Niger corresponding with H.D.W. (see III, 5.2.4). In the case of channel contraction on crossings, the crest should be made on an intermediate elevation.

Examples of the various types of structures are given in Diagram 6.3.1-2. Type A is the unprotected bank which already gives a good resistance owing to the presence of clay or rock. Only after a long period might it become necessary to protect the bank or to build out a number of groynes. The types B, C and H are longitudinal dikes, of which B must have a high crest

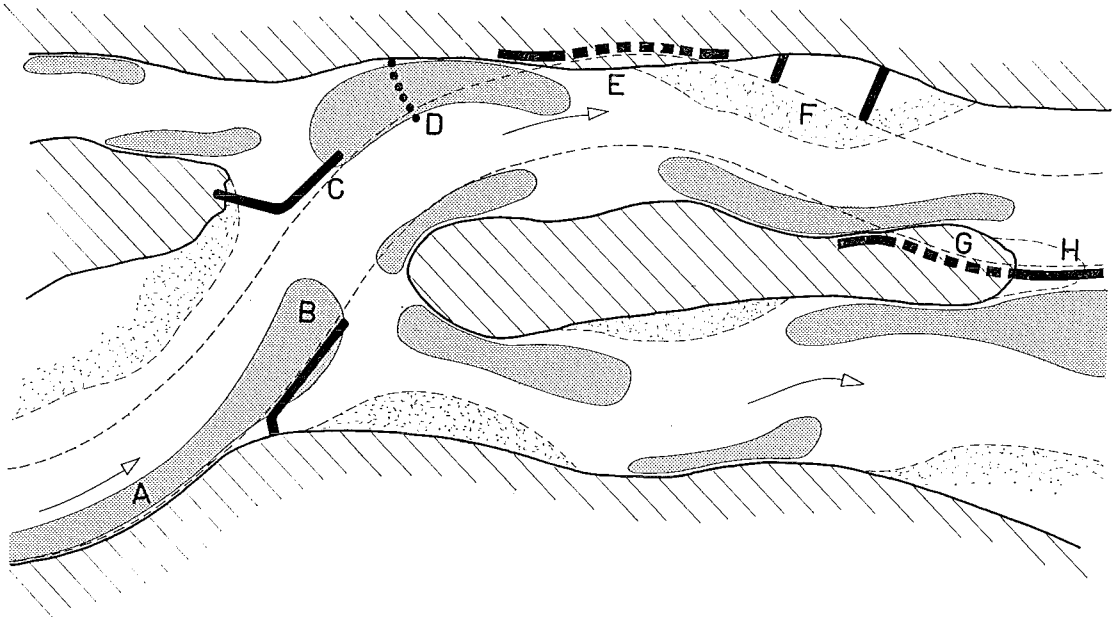


DIAGRAM 6.3.1-2

Types of regulation structures projected in a furcated river

because of the bifurcation of the channels. D is an open groyne, provisionally open with regard to the discharge of the small secondary channel. Types E and G are bank revetments, constructed partly at a later stage of the regulation after scouring of the bank. Type F is a closed groyne having a rather low head but increasing in height towards the river-bank.

The depth of the foot of the construction also has to be considered. Calculations based upon the theories of III, 6.1 will give an insight into the ultimate depth that can be expected after regulation. Mostly, this depth in the outer bends will be larger than the present depth without bank fixation, although friction of the water along the revetment will reduce the depth again. In the case of groynes, the depth in front of the head will, however, be larger owing to local contraction of the streamlines, the rate of which depends on the distance between successive groynes.

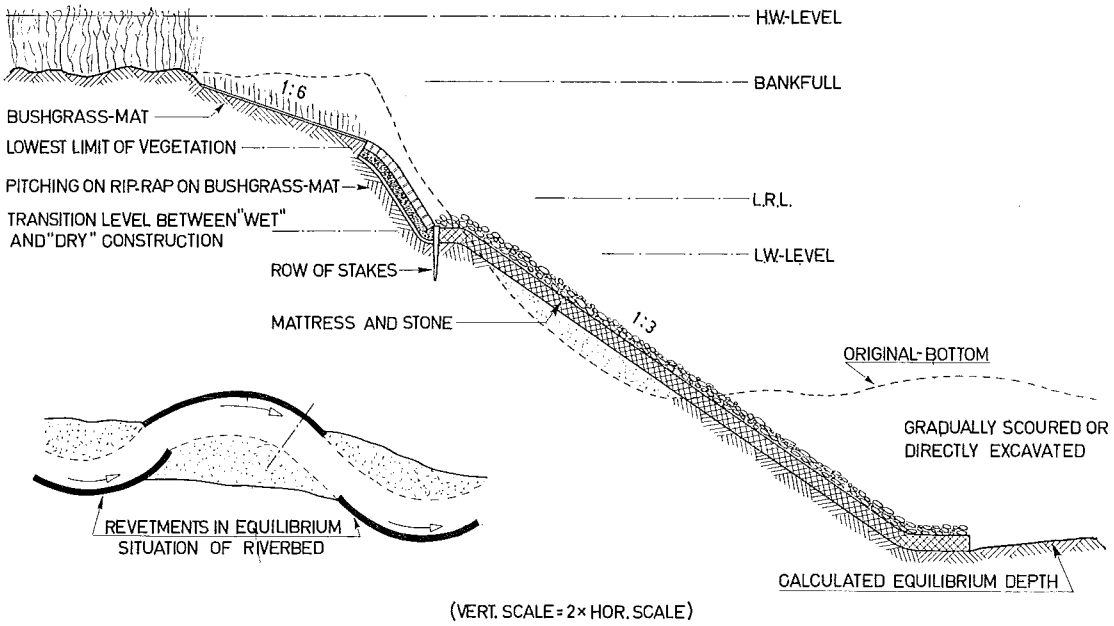


DIAGRAM 6.3.1-3

Cross-section of a suggested type of bank revetment

To construct this foot, there are two possibilities: either the foot of the construction is gradually extended during the process of scouring by sinking new mattresses in front of the revetment, or the foot of the structure is dredged directly to the calculated equilibrium-depth and protected by mattresses. In general, the first solution will be cheaper, because of the impossibility of making an exact calculation, and because of the necessary dredging. The second solution, however, gives more safety, and is chosen if a contractor is not to be continuously present. In the estimates of cost, as given in the next paragraph, the more expensive second solution has been used as a basis.

Other important levels relating to the structures are the water-level above which sufficient growth of vegetation is possible, and the level giving the boundary between "wet" and "dry" constructions. This boundary level must be projected at such a height that maintenance of the structure is possible. Often for constructions under water a material is chosen which is only durable if the construction stays under water during the greater part of the year, as, for instance

is the case with wooden mattresses. Therefore the boundary level should be positioned approximately at the height of the 2-month frequency-level, giving sufficient opportunity to construct and repair the lower part of the "dry" construction when the actual water-level is lowest.

The boundary level between artificial pitching and natural vegetation cover on the sloping sides of the banks is determined not only by the frequency-period of the vegetation being above the water-level, but also by the season of growth of the vegetation. Observation of the natural banks of the present river is the best advisor.

A very important detail of the structure is the composition of its protective cover, i.e., the material giving resistance against scour. Various different types of revetment have been applied in river regulation, depending on the local availability and cost of the materials. A distinction can be made between revetments placed in position and maintained under water and revetments constructed and maintained "in the dry". Another distinction is that between permeable and impermeable revetments. The most simple example of the permeable revetment, applicable "in the dry" as well as under water, is the dumping of stone, which forms a more or less graded layer on the erodible sand-bottom. The thickness of such a layer, however, must be large in case of fine sand, as a strong, turbulent and fluctuating current sucks the sand through the pores between the stones. This is the reason for the introduction of vegetation material under or between the stone, forming a perfect filter which prevents the sucking of sand and, in consequence, the settling of the whole structure. This combination of vegetation and stone is applied in the form of mattresses, fascines, sausages, etc. The mattresses are made of layers of brushwood, bush

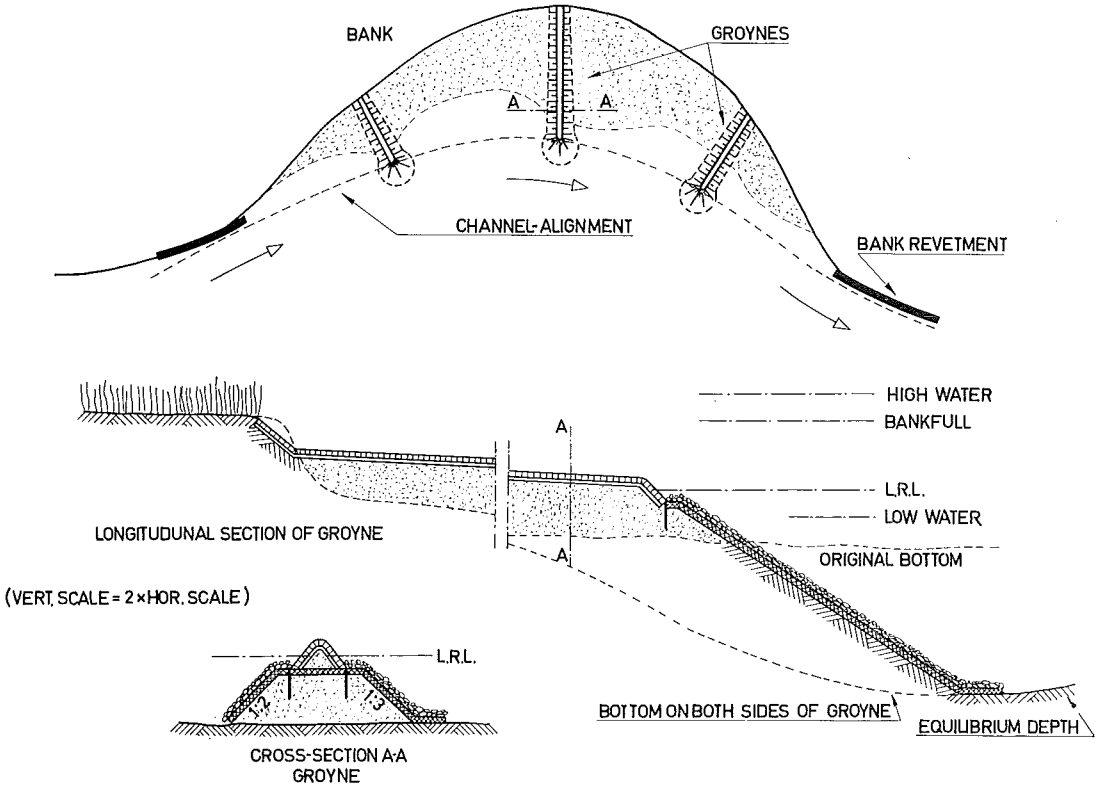


DIAGRAM 6.3.1-4

Channel fixation by groynes

or reed pressed together by a network of fascines, wire-mesh, etc. Other mattresses are made of braided board, branches, etc., but their filterworking is less favourable.

Above the water-level the application of thick layers of dead vegetation material is not recommended because of the quick decay. Here a thin layer of vegetation might have its use as a filter, provided it is carefully covered to protect it against the current. The mat, made of straw, bush-grass, etc., is therefore covered with a layer of brick, gravel or fine material from the quarry, which in its turn should be protected by stone-paving, rip-rap stones, concrete blocks, etc.

Other possibilities for the construction of revetments are given by the application of concrete, bitumen or plastics. Impermeable bituminous sand might for the Niger give a good and cheap solution for the construction of revetments "in the dry", provided a cheap bitumen is available.

The impression now to be given of the different structures as provisionally chosen for application on the Niger will be followed by a rough comparison of costs; a detailed design and an exact estimation of expenditure would be beyond the scope of this Report.

In these considerations it has been supposed that the use of the mattress, adapted to Nigerian materials, would give a cheap solution for the underwater part of the structures. For the construction "in the dry", the application of stone-pitching on a layer of fine quarry material, deposited on a mat and, if available, a layer of clay, was assumed.

In Diagram 6.3.1-3 a sketch has been given of the construction of a bank revetment.

Diagram 6.3.1-4 shows the construction of a groyne in longitudinal and in cross-section.

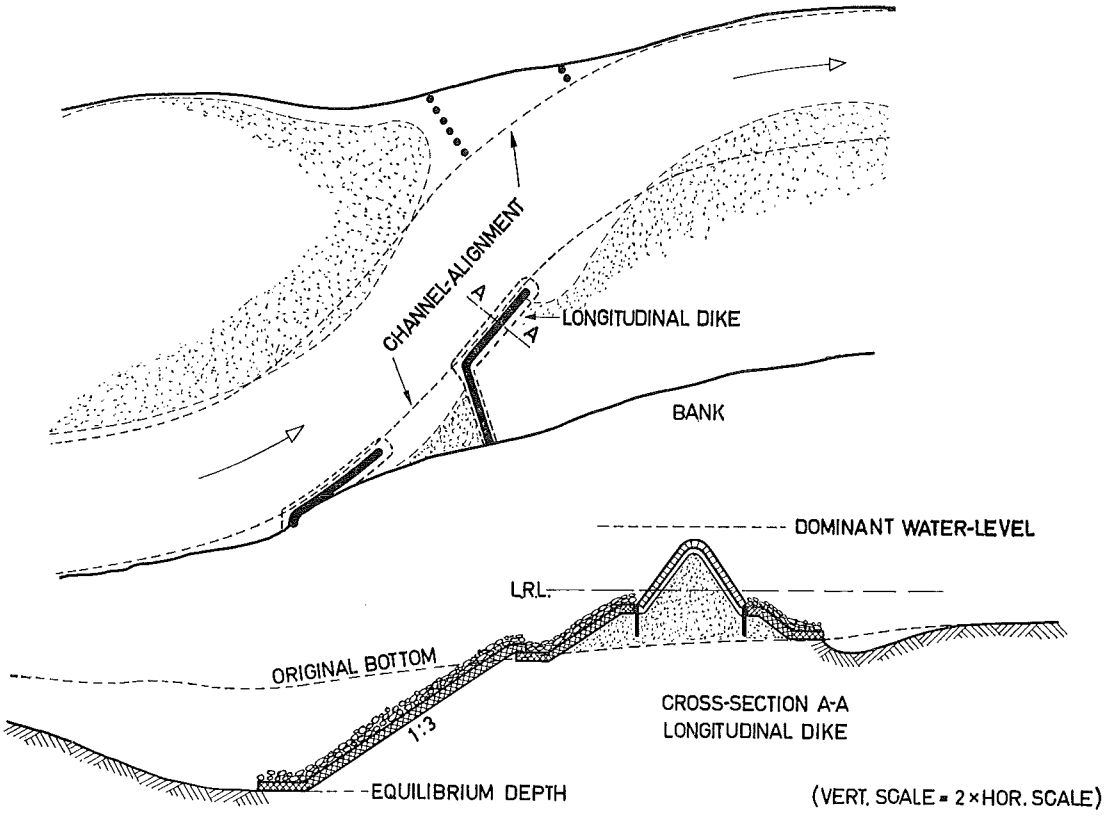


DIAGRAM 6.3.1-5

Construction of a longitudinal dike

The sand forming the body of the structure is dumped, but in exposed situations with strong currents it might be necessary to construct it in steps by using a number of mattresses, or by dumping coarse material. The construction of the crest of the groyne or the paving is done after the sand mass has settled sufficiently.

In Diagram 6.3.1-5 the cross-section of a longitudinal dike is given. In this case the advantage of the growth of natural vegetation cannot be utilised because of the strong current over the top of the structure during floods. The same might be the case with bank revetments situated in an exposed place.

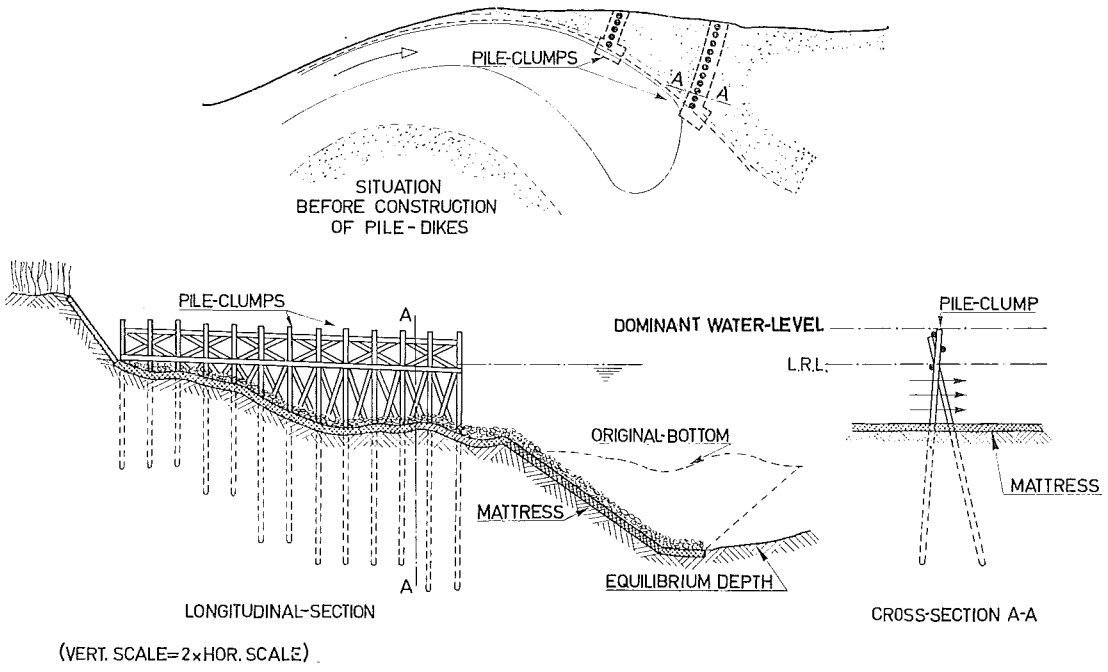


DIAGRAM 6.3.1-6

Construction of an open groyne (pile clumps)

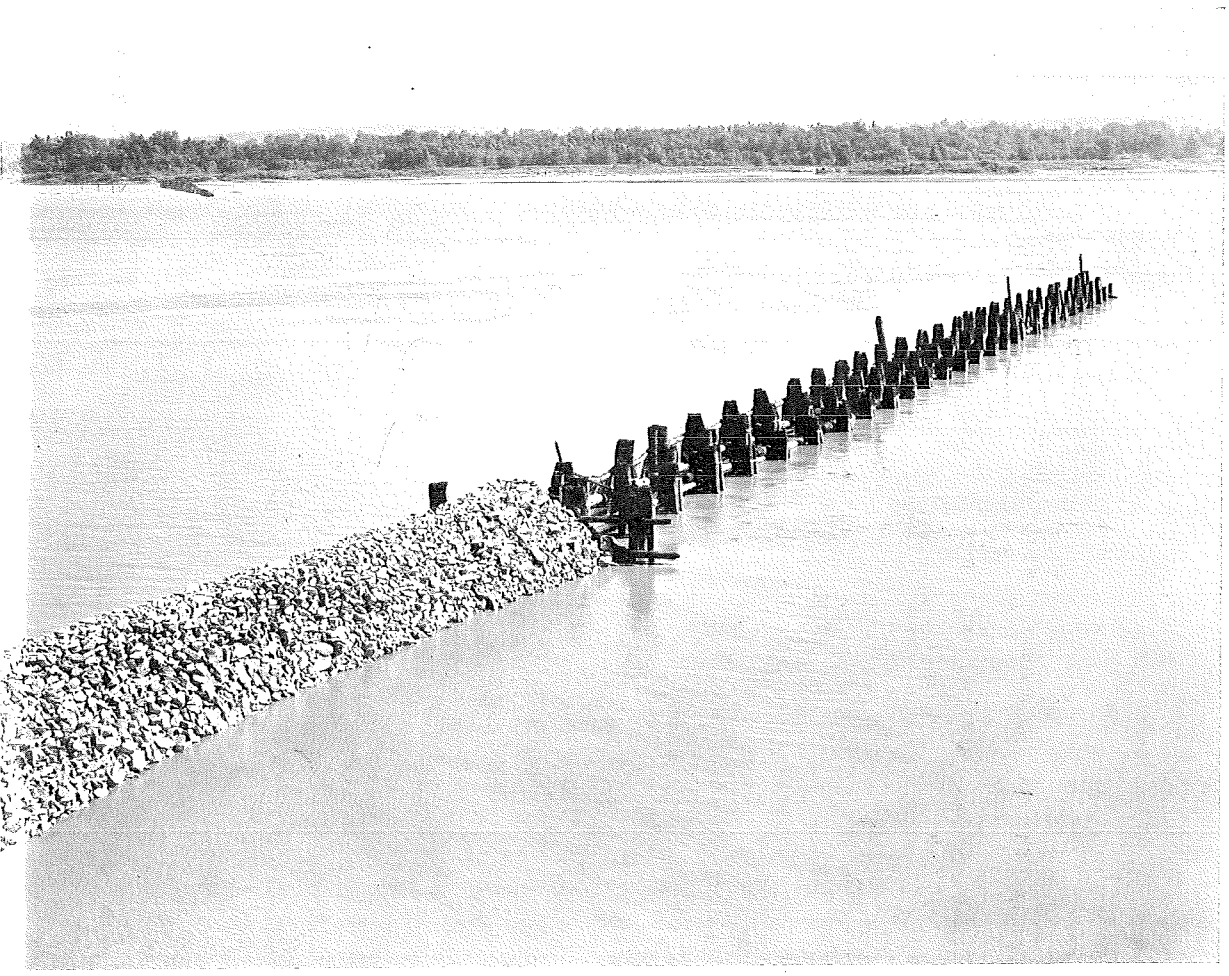
Diagram 6.3.1-6 shows the construction of an open groyne. It consists of a row of clumps of two to three piles connected by horizontal beams and crossings. To prevent scouring between and downstream of the groyne, a mattress is first sunk through which the piles are driven. The size of the mattress depends on the depth and the speed of the current between the piles. It will extend 20—30 feet upstream and 30—50 feet downstream from the axis of the groyne. At the river-side end of the groyne the attack will be larger. Direct dredging of the large equilibrium-depth in front of the head would give a safe solution, but greater length and width of the mattress will then be necessary.

It is possible to increase the resistance of this type of open groyne by dumping more stone upstream from the pile-row.

However, the application of open groynes on the Niger is not recommended, because of the yet rather high cost of construction in comparison with closed groynes, while their effect on the

concentration of the flow is less than that of closed groynes. Experience on the Mississippi shows that gradually most of the open groynes are converted into closed ones.

For use in provisional works, open groynes might serve as a cheap solution.



PHOTOGRAPH 6.3.1-7

Pile dike in the Mississippi

6.3.2. Materials and prices

If regulation works are carried out on the Niger, the questions must necessarily be answered as to the position of materials, what construction would be most suitable, what equipment and labour will be required, and what the cost of the constructions might be.

It is not the aim of this investigation to give a very exact price of all the possible types of structures; such an exact compilation would take much time and would be beyond the scope of this Report. The aim is to get an insight into the amount of capital to invest and to make a comparison of the different solutions for improving the navigability of the rivers. To this end, a short study has been made of the availability and applicability of materials (such as stone,

gravel, sand, brushwood, mats, binding materials, piles, etc.), combined with the prices in Nigeria for machinery, tools, labour, transport, etc.

With regard to oversea transport, the setting-up of headquarters and workshops, risks, etc., the assumption had to be made that regular employment is ensured for machinery and staff for at least five years ([1], even during parts of the H.W.-periods.

In the details of construction the following works can be considered:

a. removal of soil:
   1. underwater dredging of channels or equilibrium depths;
   2. underwater making of slopes and other details;
   3. above water-level grading, or dressing.

b. earth-fills:
   1. underwater with floating pipe-line;
   2. underwater by dumping sand;
   3. above water-level with pipe-line; and
   4. above water-line with floating crane and grab.

c. constructions of brushwood, etc.:
   1. mattresses for underwater revetments; and
   2. bush-grass mats.

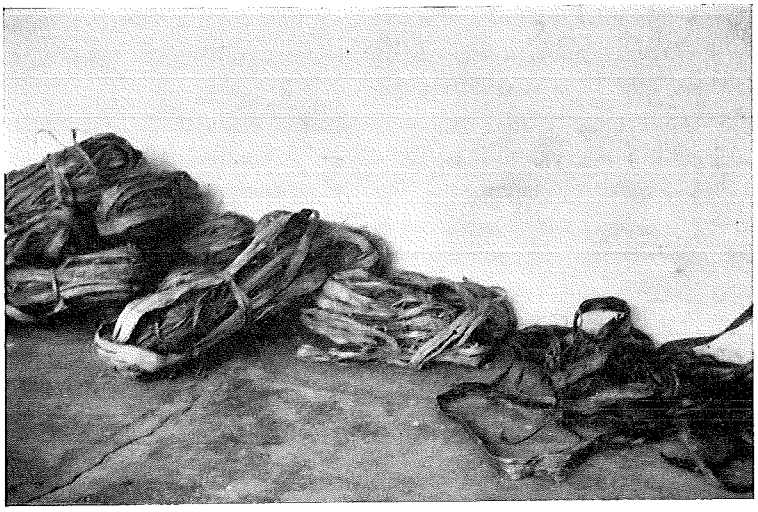
d. stone for revetment:
   1. stone-pitching of regular stones;
   2. stone-filling under the pitching; and
   3. sink- and cover-stone for mattresses.

e. constructions in wood:
   1. stake-rows in revetments;
   2. piles for pile-clumps; and
   3. timber for pile-clumps.

For the calculation, the following assumptions have been made: Dredging channels, etc.: partly by 40 cm (16″) suction-dredger with 600 feet floating pipe-line, capacity 20,000 m³ (27,000 cuyards) per week minus 25% shifting; partly by bucket-dredger with buckets of 350—400 litres (120—140 cuft), loading barges that dump the soil over a distance of 2—3 miles. Grading and dressing slopes: under water by small bucket-dredger with buckets of 150 litres (50 cuft), capacity 5,000 m³ (6,600 cuyards) per week with tug and barges; above water 800 litres (280 cuft) dragline and bulldozers.

As for the mattresses, an investigation has been made (in co-operation with the Provincial Forestry, Kabba Province) into the presence of suitable materials for making fascines, etc. A forest shrub was found with long, tough and flexible branches which appeared quite suitable for the making of mattresses. The shrub, Morelia Senegalensis, is a common tree in the Niger and Benue swamps. In the swamp Forest Reserve between Koton Karifi, Lokoja and Okpanedu, an area of about 50 sq.miles, it is one of the most common species. Another area is found on the south bank of the Benue, near Mozum (Mile 377). Along the Niger the shrub is found opposite Etikaku and at Ngori, Old Budon and Batake (Miles 368 and 407 to 417 respectively).

([1] A complete regulation of the entire Niger from Baro to the Delta would take some 20 years of full-scale work.



PHOTOGRAPH 6.3.2-1
Umfani

A suitable substitute for reed was found in the very common bush-grass which grows in lengths of 6—10 feet. Mats made from bush-grass, the so-called Zana mats, are available in several sizes.

As to binding materials, several local kinds have been tested and the following found suitable for mattress making:

Iguja Kaba (Hausa), a rope made from vegetable fibre, strong and tough. This rope comes from the Kano region and did not appear to be available in large quantities. It is suitable for binding the upper and under gratings of a mattress together.

Kwagiri (Hausa), a kind of split-bamboo, also suitable for binding upper and under gratings together.

Umfani (Hausa), a broad fibre, resembling slightly the bark of brambles. When soaked and split it is suitable material to bind the bundles or sausages of brushwood from which the gratings are made.

PHOTOGRAPH 6.3.2-2
Test mattress at I.W.D. Dockyard, Lokoja

In this connection a practical test was made in Lokoja in 1957. Labour from a nearby village cut the brushwood and, under supervision, made a good mattress, using only local materials. This mattress was sunk in the Niger near Lokoja (Photograph 6.3.2-2).

As for the stone to be applied in the pitching and on the mattresses, an investigation made into the quality of the stone from the Rocky Section of the Niger downstream from Lokoja showed that the granites are suitable for revetments, and that the opening of a quarry would meet no difficulties.

With regard to the constructions in wood, stakes might be cut from the mangrove forests in the Niger Delta. Mangrove is durable and does not require treatment with creosote oil. For the large piles local Aburu or similar woods can be used. Aburu is available in great length but as it is not a durable wood, for some of the described applications it will have to be treated with creosote oil.

The following unit-prices are based partly on experience and partly on calculation from comparable quotations, and should be seen as approximate figures:

dredging sand with floating pipe-line, per m^3	£ -/2/- to £ -/ 3/-
dredging slopes with bucket-dredger, per m^3	£ -/ 5/-
dredging and making earth-fill, per m^3	£ -/8/- to £ -/10/-
construction of a bush-grass mat, per m^2	£ -/ 2/-
construction, transport and sinking mattress, per m^2	£ 1/ -/-
quarrying, transport and sinking ballast stone, per ton	£ 3/ -/-
quarrying, transport and spreading rubble under pitching, per ton	£ 3/ -/-
winning, transport and positioning of pitching, per ton	£ 4/ -/-
winning, transport and construction of stakes, each	£ -/ 4/-
piles, delivered at site, from 7 m to 18 m length, each	£ 7/-/- to £ 35/ -/-

The required weight of stone dumped on a square metre of a mattress is about 400 kilograms. The weight of a square metre pitching should be half a ton, while the weight of the rubble under this pitching has to be about 300 kg/m^2. In a stake-row about 10 stakes per running metre are necessary. So a square metre of mattress with stone will cost about £ 2/5/- and a square metre of pitching £ 3/-/-.

With the aid of above-mentioned unit-prices, the prices of the different types of structures can be calculated, giving the following result:

Bank revetment: price per running metre (3'4" feet)

depth of the foot	height of the pitching in feet above L.R.L. + 3'	+ 6'
L.R.L. — 20'	£ 65	£ 70
— 25'	£ 75	£ 80
— 30'	£ 90	£ 95
— 35'	£ 110	£ 115
— 40'	£ 135	£ 140

Closed groyne: price per running metre (3'4")

depth of the foot	height of the crest in feet above L.R.L. + 2'	+ 6'	+ 10'
L.R.L. — 6'	£ 35	£ 50	£ 65
. . — 9'	£ 50	£ 65	£ 80
— 12'	£ 65	£ 80	£ 100
— 15'	£ 80	£ 100	£ 120

Head of a closed groyne: price per head

depth of the foot	height of the crest in feet above L.R.L. + 2' to + 4'
L.R.L. — 20'	£ 2,500
— 25'	£ 3,500
— 30'	£ 5,500
— 35'	£ 8,000
— 40'	£ 11,000

Longitudinal dike: price per running metre (3'4")

depth of the foot	height of the crest in feet above L.R.L. + 2'	+ 6'	+ 10'
L.R.L. — 20'	£ 80	£ 95	£ 110
— 25'	£ 100	£ 115	£ 130
— 30'	£ 120	£ 135	£ 150
— 35'	£ 135	£ 150	£ 170
— 40'	£ 155	£ 175	£ 195

Pile-clump dike: price per running metre (3'4")

depth of the foot	height of the crest in feet above L.R.L. + 2'	+ 6'	+ 10'
L.R.L. — 6'	£ 60	£ 80	£ 100
— 9'	£ 75	£ 90	£ 110
— 12'	£ 90	£ 105	£ 120
— 15'	£ 110	£ 120	£ 130

Head of a pile-clump: price per head

depth of the foot	height of the crest in feet above L.R.L. + 2' to + 4'
L.R.L. — 20'	£ 3,000
— 25'	£ 4,000
— 30'	£ 5,000
— 35'	£ 6,000
— 40'	£ 7,500

From these figures it can be seen that open groynes are probably not cheaper than closed groynes. Moreover, the maintenance will be more expensive.

In reality, all the prices mentioned above can be reduced considerably if some risk is taken and the river scours itself down to the equilibrium depth. In that case, however, a contractor must always be available for the execution of river-works.

6.4. NIGER AND BENUE REGULATION

6.4.1. Upper Niger

The section of the Upper Niger between Lokoja (Mile 363) and Baro (Mile 434) has favourable circumstances for bed-regulation. The normal variation in water-level and discharge is limited, and the magnitude of the L.R.L.-discharge offers a good possibility for bed-regulation. The river has two dominant water-levels (see III, 5.2.4), namely, one for the low-water bed at L.R.L. — 1′, and one for the high-water bed at L.R.L. + 8′, whilst the average dominant water-level is situated at L.R.L. + 3′. These levels are low; the crest of the structures can, therefore, be made at a limited elevation. Another advantage is the slightly meandering character of the low-water bed and the width of the river at bankfull-stage, not too wide for a bank-to-bank regulation and not too narrow for a meander regulation The clayish character of a part of the banks will reduce the total length of the structures, particularly in the first stages of the improvement.

A longitudinal profile of the concerned river-section together with the talweg depths has been given in Diagram III, 6.4.1-1. During the sounding of that river-section there appeared to be about twenty crossings between Lokoja and Baro where the depth in the channel was less than eight feet, while in some crossings the depth was less than six feet. An unfavourable circumstance was the fact that the sounding was taken directly after the flood period, so that the crossings had not yet been scoured (see III, 6.4.2). On the other hand, the water-level to which the depth has been reduced (L.R.L.) corresponds to a fairly high Black Flood (see III, 4.2.3).

In this Chapter it has not been tried to give a detailed project for regulation of the Upper Niger, but only to compare the different possibilities of improvement and to give a comparison of the cost in the different stages. These different stages are:

1. the elimination of bottle-necks;
2. the regulation of all bad river-sections to obtain a maximum regulation depth in the navigation channel;
3. further increase of depth by overlapping structures on the crossings; and, if necessary,
4. the contraction (normalisation) of the entire channel.

It would be useless to design in full detail a comprehensive project for the entire river-section; the execution of the works would take so much time that the river will have changed its bed and banks in the meantime. As for the banks, an estimate of the occurring scour could possibly be made, but the sand-banks in the river-bed move fast and irregularly and a prediction of their situation in future years cannot be made.

However, execution of regulation works should at any time be based on the momentary situation of the river-bed. Yet these river-works should fit into the entire future regulation scheme. It is concluded that a regulation project must be flexible, offering the possibility of changing the planned alignment in the course of the execution.

To obtain an impression of the possible results and of the cost of regulating the Upper Niger, a rough project has been made, based on the present situation. As representative section the

stretch between Mile 383 and Mile 397 has been chosen, having a length of 26 km (16 miles), including crossings, flats and bifurcations around islands.

The normal system has been followed, namely, to bring the low-water flow into one single channel. Only at one place (Mile 383) is the regulated channel bifurcated. The remaining secondary branches, however, would not necessarily be closed artificially; the alignment has been projected in such a way that the river itself will silt these branches in course of time. Only if the deposition of sand is not proceeding satisfactorily will artificial means have to be taken.

Important details of the project are the dimensions of the channel, the curvature, the length of the bend, the width between the regulating structures, and the elevation of the foot and the crest of the structures.

(i) Based on the condition that the discharge capacity and the slope of the channel at the average dominant water-level (D.W.) should remain unchanged before and after the regulation, it is possible to determine the size of the cross-section of the bends in equilibrium state as related to the radius of curvature. Equality of discharge and slope results in equality of the value of $ba^{\frac{3}{2}}$ under the assumption that the coefficient of de Chezy remains constant. The present value of $ba^{\frac{3}{2}}$ at D.W. is about 6,500 $m^{\frac{5}{2}}$, and this should be maintained in the regulated cross-sections.

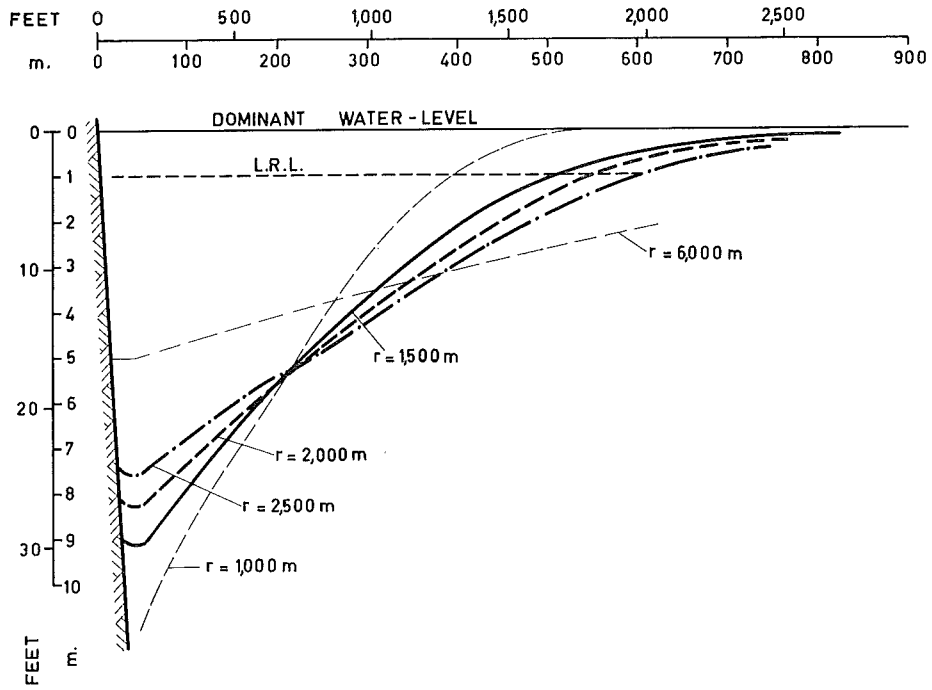


DIAGRAM 6.4.1-1

Calculated cross-sections on the Upper Niger

(ii) From observations on the present river it can be concluded that the optimum radius for a single-channelled flow pattern would be 2,000 to 2,500 m (6,700 to 8,300 feet). A radius of 1,500 m (5,000 feet) appears to be too small. For these successive radii the shape and size of the regulated cross-sections have been calculated by means of the formulae mentioned in Paragraph III, 6.1.2. The result has been drawn in Diagram 6.4.1-1.

For comparison with extreme circumstances, the situation has also been calculated for radii of 1,000 m (3,300 feet) and 6,000 m (20,000 feet) respectively. A radius of 1,000 m would give

a strong spiral flow endangering down-bound ships and necessitating a very deep foot of the revetment; whilst a radius of 6,000 m would give the risk of the formation of a chute during high water (see III, 6.1.3).

(iii) In general, the length of the bend should not be too small. If the angle of the bend is smaller than about 45°, then special measures have to be taken to ensure a stable alignment of the deep channel. However, if the length of the bend is too large, the crest of the guiding structures must be heightened.

(iv) As for the standard width of the channel, a solution with a width of 400 m (1,300 feet) is shown in Diagram 6.4.1-2, although this figure is tentative only and probably too small.

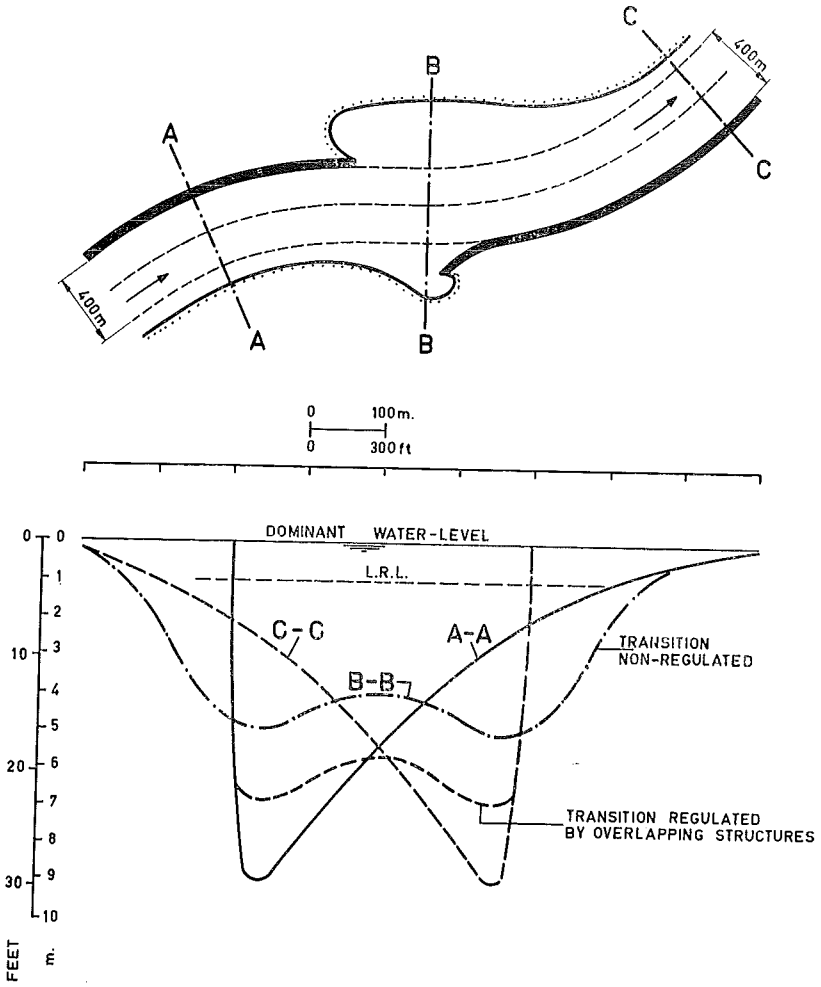
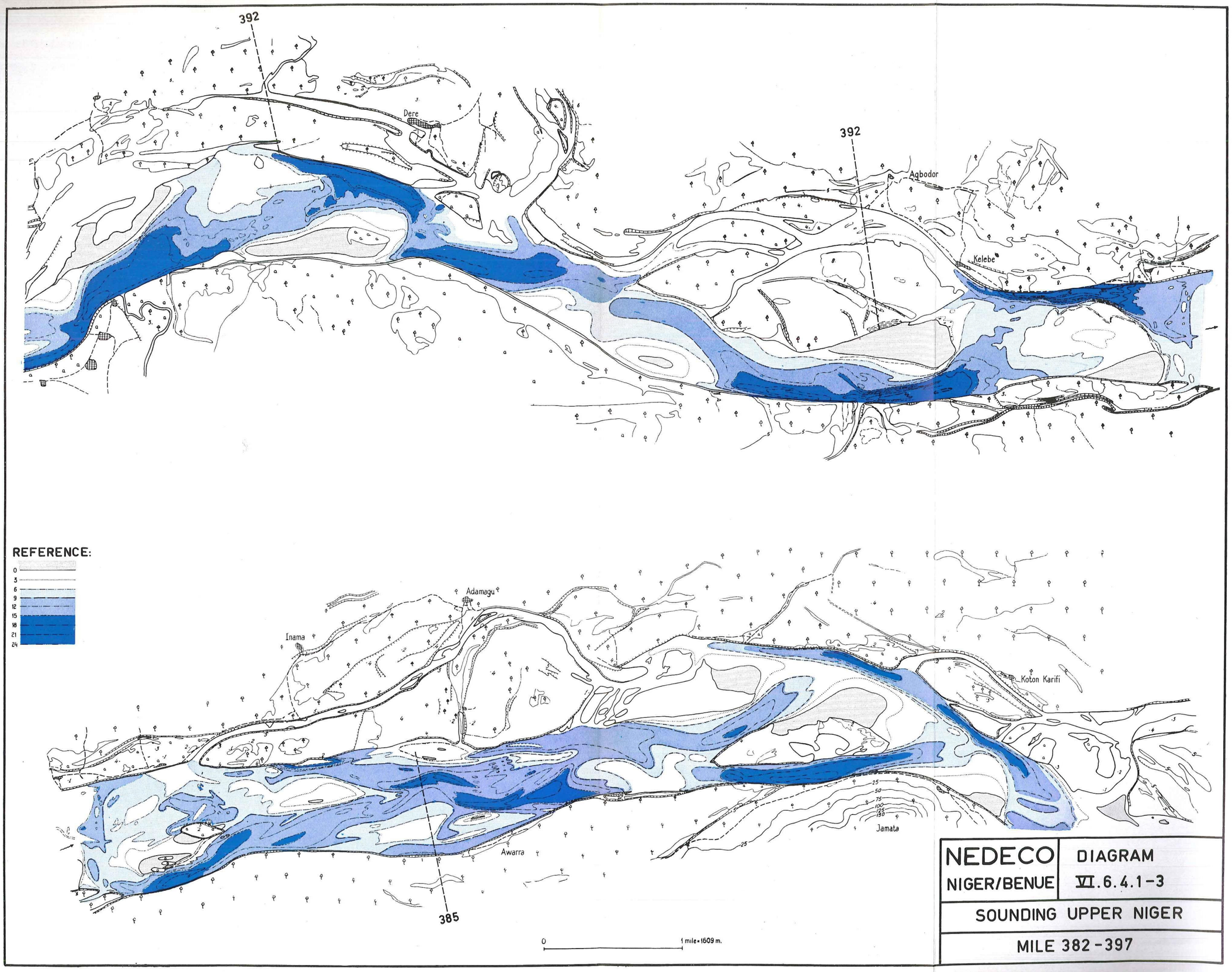


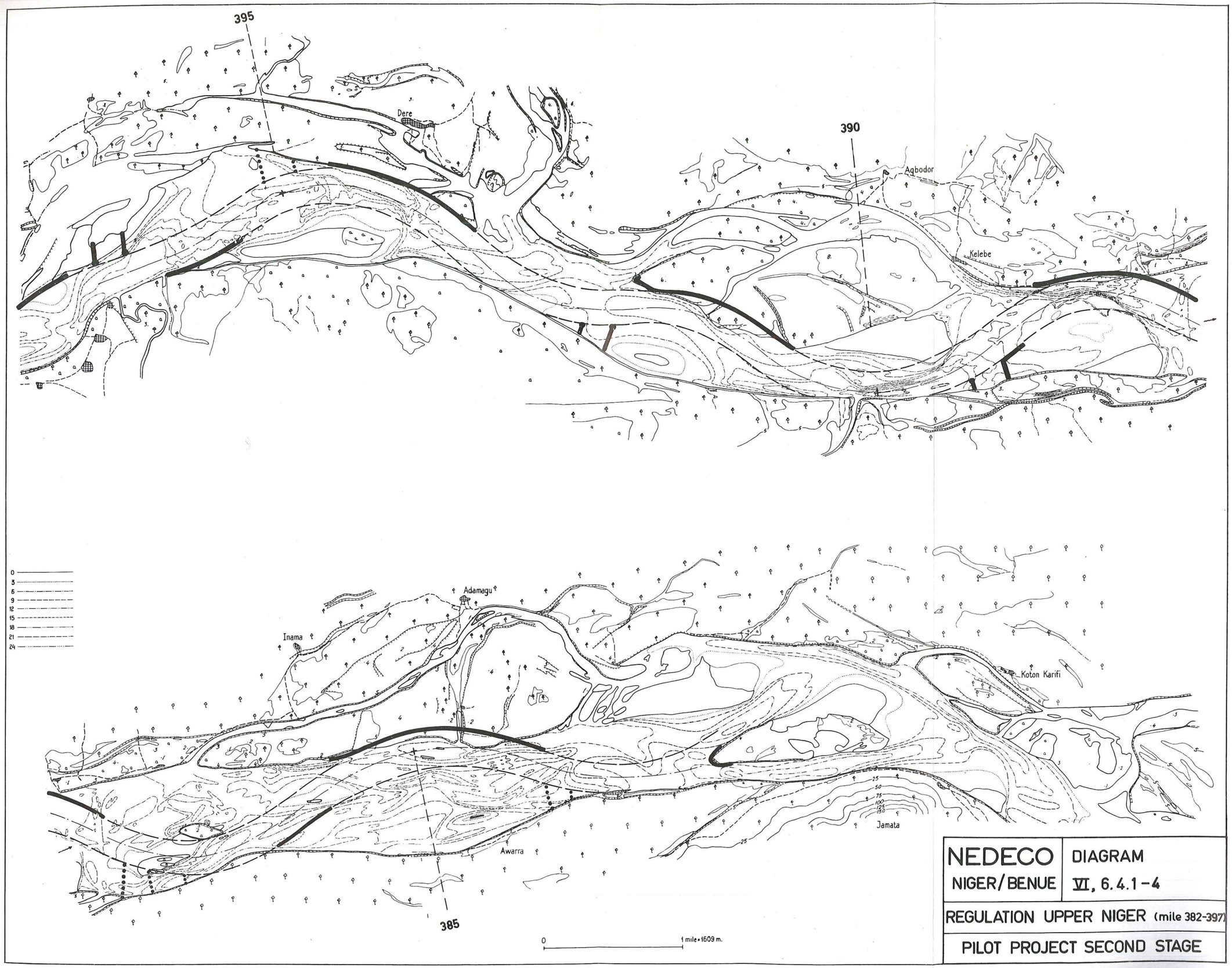
DIAGRAM 6.4.1-2

Cross-section in bends and crossings on the Upper Niger in case of a regulation width of 400 m

The advantages of a narrow transition are a larger depth on the crossing than in the case of a wider channel and the possibility of a cheaper improvement in future. The disadvantage is the necessity to lengthen the upstream end of the guiding structures in order to avoid eddies and deep scour at the head during high water.



NEDECO NIGER/BENUE	DIAGRAM VI.6.4.1-3
SOUNDING UPPER NIGER	
MILE 382 - 397	



NEDECO NIGER/BENUE	DIAGRAM VI, 6.4.1-4
REGULATION UPPER NIGER (mile 382-397)	
PILOT PROJECT SECOND STAGE	

(v) With respect to the occurring levels of D.W., H.D.W. and L.D.W. (see III, 5.4.2), the crest of the groyne-heads and a part of the longitudinal dikes has been chosen at L.R.L. + 2′, whilst the crest of high water guiding structures has been fixed on L.R.L. + 6′. Details of such structures have been discussed in Paragraph 6.3.1.

The elevation of the foot of the structures is calculated in accordance with the radius of the bend and the situation of the structure in that bend or crossing. For isolated groyne-heads an extra 5—10 feet is added, depending on the distance between the groynes.

A sounding of the river-section reduced to L.R.L. is given in Diagram 6.4.1-3, while in Diagram 6.4.1-4 a scheme of a possible regulation of this section is shown. In the first stage of improvement, only a small part of the project has to be constructed, such as indicated in Diagram 6.4.1-5. The execution of these works will eliminate the five bottle-necks in the section. With the prices given in 6.3.2, the cost of these limited works can be derived as to be about £ 400,000. The least available depth in the section would increase from 6 to 8 feet at L.R.L.

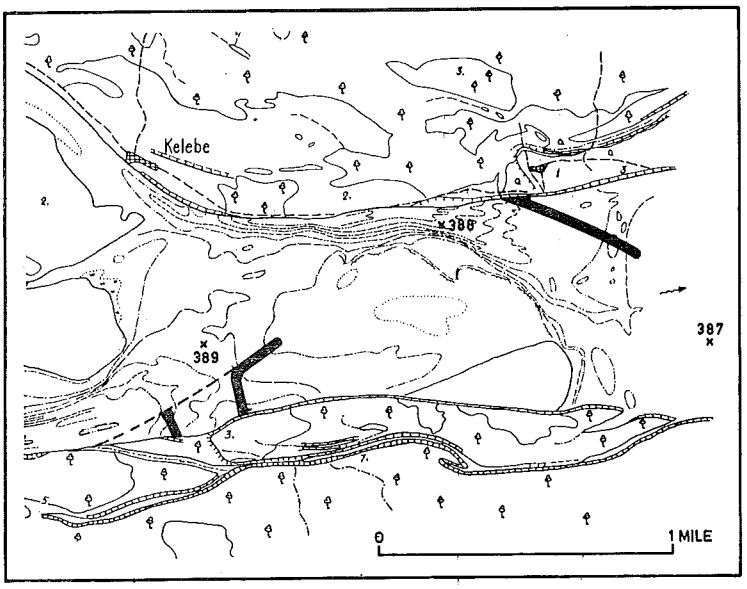


DIAGRAM 6.4.1-5

Construction scheme, first stage

Extrapolation of this price over the entire river-section Lokoja—Baro results in an estimate of about £ 2 million for the first stage of improvement.

Execution of the full project as given in Diagram 6.4.1-4 would cost about £ 1.4 million, including a quantity of dredging to clear some channels and to restore a part of the banks where the new alignment is projected in the shore-land. It is, of course, not always necessary to dredge these banks upto the alignment; mostly it is sufficient to remove those irregularities which give a risk of turning off the current.

The cost of this full regulation amounts to about £ 100,000 per mile. Of the 70 miles between Lokoja and Baro only 50 miles have to be regulated to obtain a depth of about 10 feet at L.R.L., so the total cost of a regulation of the entire river-stretch Lokoja—Baro can be estimated at £ 5 million.

In a future third stage a further improvement can be obtained by overlapping structures in the crossings. The total cost of such a regulation will be around £ 10 million (based on present prices), giving a depth at L.R.L. of more than 12 feet.

In the above-mentioned prices the possibilities of failures have not been calculated. There is also the risk that in the first stage other bottle-necks might arise. On the other hand, the prices are calculated on the assumption of a direct dredging and of full-scale bank-protection over the total length, although in reality such would not always be necessary.

Capitalised maintenance is not included in the estimates. The cost of maintenance of regulation works is rather high; certainly proportionally higher than that of weirs or dams. If this capitalised maintenance is to be included in the total price, an extra 50% of the cost for construction might give a right estimate.

6.4.2. Lower Niger

Regulation of the Lower Niger is possible in the same way as described above for the Upper Niger. However, compared with the latter, there are some disadvantages. The variation in discharge and in water-level is larger; the dominant water-level of the low-water bed is at L.R.L + 2′, of the high-water bed at L.R.L. + 22′, and of the average bed at L.R.L. + 15′, as calculated in III, 5.2.4 for the river-section near Onitsha.

From the river-maps of the Lower Niger it can be concluded that a bend with a radius of less than 2,000 m (6,600 feet) is very sharp, that a radius of 3,000 m (10,000 feet) is normal and that a radius of more than 4,000 m (13,300 feet) is dangerously large. Calculations with the aid of the existing capacity and slope give the size and shape of the cross-section. For the width of the standard-channel 600 m (2,000 feet) has been chosen and the normal distance of the successive supports about 500 m (1,700 feet). It is obvious that these figures are tentative only and possibly too small.

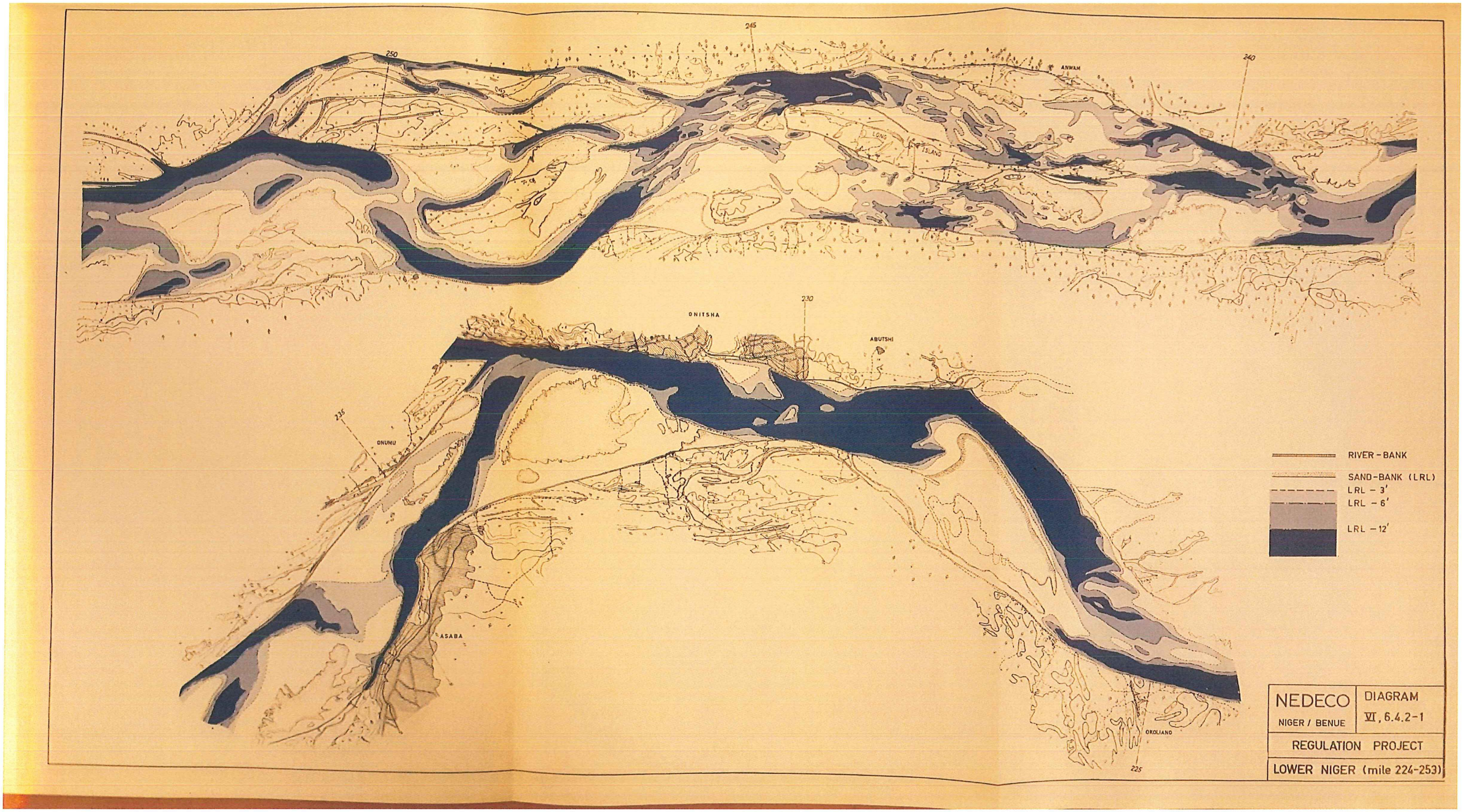
With this basic data a section of the River Niger near Onitsha has been investigated. The sounding of this section is shown in Diagram 6.4.2-1. The provisional regulation project is given in Diagram 6.4.2-2.

In the upstream part of this section the river is bifurcated in a number of channels, which will give no difficulties. In the middle section a large island is dividing the river into two large channels. The solution which has been chosen is to regulate the river in such a way that after a number of years the low-water discharge will exclusively take the left or eastern channel. More downstream the ports of Asaba and Onitsha must remain accessible. Here the presence of rocks has been made use of. Also the presence of clayish banks on the right side of the river can considerably restrict the length of the revetments.

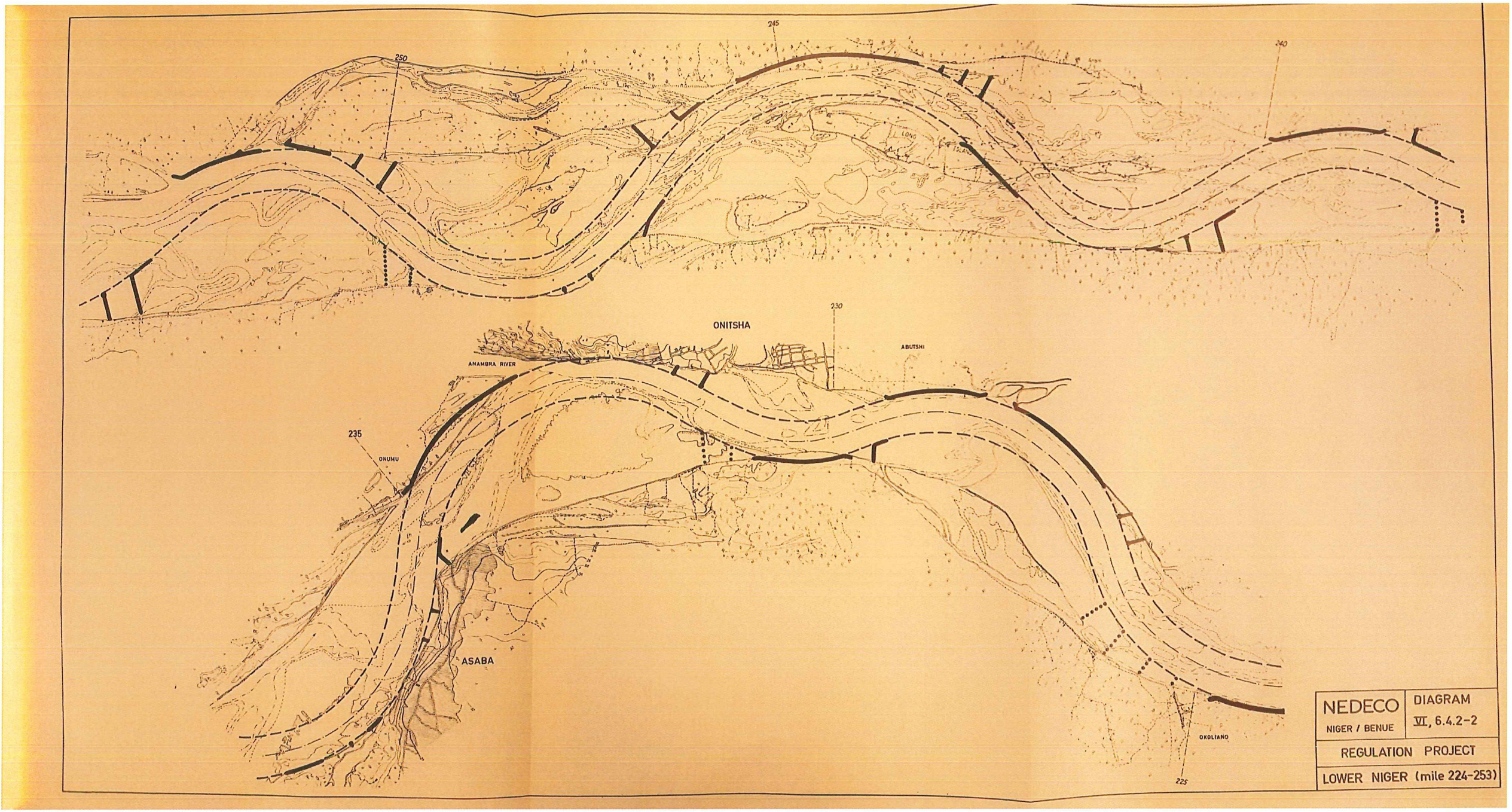
With the help of the prices mentioned in the foregoing paragraphs a calculation has been made of the cost of the projected regulation. It appears that the regulation of this section of about 30 miles will cost more than £ 4 million, which means a price of about £ 140,000 per mile.

From Diagrams III, 6.4.1-1 and 2 it can be concluded that there are a large number of bottle-necks on the Lower Niger offering at L.R.L. a draught of only 5 to 7 feet, whilst some are even worse. Particularly bad sections are those directly upstream and downstream from the Rocky Section, and the section between Mile 178 and Mile 188. It will be necessary to regulate these sections as a whole to eliminate the present bottle-necks. The total cost of these improvements, together with the elimination of a number of isolated bottle-necks, will be about £ 10 million and will result in a river offering at L.R.L. a depth for shipping of about 8 feet.

A further improvement will be the regulation of the major part of the Lower Niger down to the Nun branch, resulting in an improvement to about 10 feet at L.R.L. at a cost of about



NEDECO NIGER / BENUE	DIAGRAM VI, 6.4.2-1
REGULATION PROJECT	
LOWER NIGER (mile 224-253)	



NEDECO NIGER / BENUE	DIAGRAM VI, 6.4.2-2
REGULATION PROJECT	
LOWER NIGER (mile 224-253)	

£ 20 million. The next step can be obtained by an overlapping regulation of the whole river at an estimated cost of roughly £ 40 million. In these prices the cost for capitalised maintenance is not included; it is roughly estimated at about 50% of the price for construction.

6.4.3. Benue

An investigation about the possibility of regulating the Benue has shown that from a technical point of view, it is quite impossible to regulate this river. The very small low-water discharge offers no possibilities for regulation. Direct normalisation (contraction) of the bed is never advisable, and is in this case impossible because of the large difference between low- and high-water discharge. The high dominant water-level and the wide bed at bankfull stage would make such a work extremely expensive and hazardous. And last but not least, the five most important tributaries bring large quantities of sand into the main river during each high-water period, so that a normalisation would have to be extended upstream from the confluences with these tributaries in order to prevent the spoiling of these confluences after a high-water period.

The conclusion is that bed-regulation is not an acceptable solution for a river like the Benue in its present state.

6.4.4. Niger-Benue Confluence

The Lokoja Confluence forms a notorious place for navigation. Shoals in the Benue Entrance prevent ships from entering at the time when the Benue itself is already navigable (June), while immediately below the Confluence the Lokoja Flats hamper navigation during the Baro season early in the year. Both phenomena and their causes have been further described under V, 3.

Solution of the problem of the Benue Bar in this area can be found in various ways. As will be stated in 8.3.4 and 8.5.7, a discharge regulation of either the Niger or the Benue, or of both these rivers, would change the entire cycle of raise and draw-down of the water-level. Consequently, the features of the Benue Bar would become different. It might even be possible to prevent the Benue Entrance from shoaling or to drown the shoals at the appropriate time in the shipping season.

A second possibility of improvement is found in mere dredging. Since the difficulties are more or less the result of a type of retarded scour, dredging the shoals is easy and the dredged channel would probably not re-silt. This way of improving the Benue Bar has been dealt with in 4.4.

Lastly, it may be possible to utilise fascine screens of the POTAPOV system to create a deep channel across the Benue Bar (5.4.1).

In view of these easy and relatively cheap possibilities of improvement, it does not seem advisable to execute bed-regulation works at the Lokoja Confluence with the mere purpose of eliminating the Benue Bar.

There are, however, other arguments which seem to have large influence upon this consideration. The Upper Niger, shifting its meandering channel gradually downward, effects a very serious erosion of the left bank near Lumye, at a rate of some 300 m (1,000 feet) per year. This bank erosion has resulted already in the formation of a short-cut (see III, 6.5.8) which consolidates the existence of the Benue Bar (III, 5.4.5) and which gradually widens and deepens its cross-section and increases its discharge capacity. It seems very well possible that in the not very distant future the entire island in front of Lumye village could be washed away by the bank erosion. In that case, the main channel of the Upper Niger would be located somewhere near this present short-cut, and Lokoja, situated in the inner bend, would find a large sand-bank in front with only a narrow channel alongside the quays remaining. As a result, the entire picture

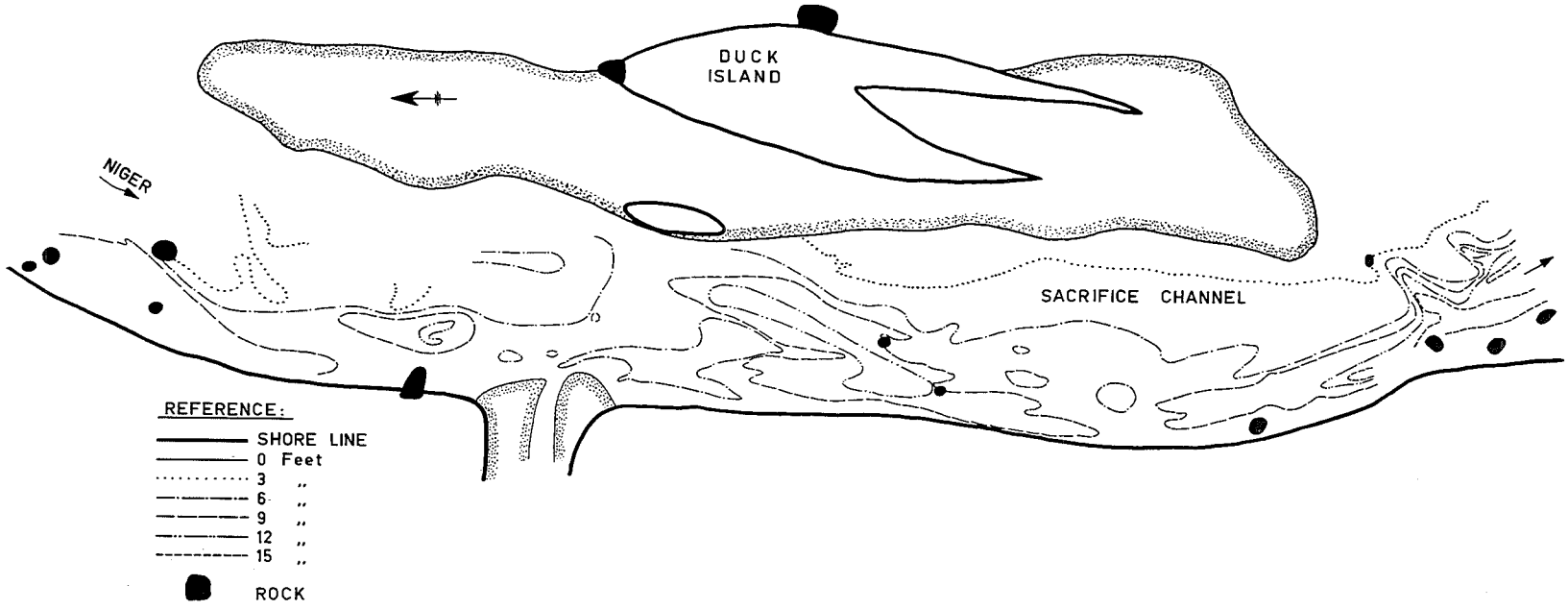


DIAGRAM 6.4.4-1

Rocks in Sacrice Channel

of the Confluence, dominated at present by the existence of the Benue Island now extending southward to somewhere opposite Mimi River, would change.

An effort to stop this serious and endangering erosion near Lumye will probably be very expensive, since the scouring channel of the Upper Niger exceeds a depth of 30 feet below L.R.L., whilst a local bank protection would even increase this depth considerably. No other possibility, however, seems to come into the picture.

In the first instance, a closing of the Lumye short-cut would be advisable, since this would retard the bank erosion at least to some extent. Such a closure could be executed without high cost, since the direction of flow through the short-cut is twice reversed in the course of the year (see III, 4.3.8) and it consequently then passes the state of being zero.

However, this will not be sufficient. Eventual works forcing the Niger flow to cross before it can attack the bank near Lumye seems inevitable, while ultimately a high-water free dam over the long and narrow spit between the two rivers must effect an exact fixation of the location of confluence. These works indeed serve this purpose only: fixation of the present situation. Actual improvement is not aimed at, and does not seem to be advisable either. Experience with execution of training-works in less complicated areas should be gained before further regulation of the Lokoja Confluence is contemplated. And by that time the situation will probably have been changed to such an extent that any plan made at present will have become out-dated.

Concerning the Lokoja Flats, an improvement appears to be near at hand. Along the western bank a secondary channel shows a reasonable depth which it has maintained from early years, as can be seen from old charts of this area; the only snags being individual rocks scattered over the place and endangering navigation. In 1933, A. L. E. DENNIS, R.N., constructed some shore beacons to indicate the best shipping route, but nevertheless the name "Sacrifice Channel" does not necessitate further comment. The channel was buoyed by NEDECO in the low-water period of 1957 and has been used by the Ferry between Lokoja and Shintaku, but in spite of the greater depths commercial ships did not venture into this channel. Rock-clearing would solve the problem of the Lokoja Flats entirely, as has been pointed out in III, 6.5.8. It is recommended to clear the rocks that have been indicated in Diagram 6.4.4-1 down to a level of L.R.L. — 9′ (0′ at the Lokoja gauge). This work should be done within 5 years.

Passage through Sacrifice Channel includes the necessity to enter the Benue via the North Channel (III, 6.5.8). But that would do away with any possibility of using a possible deeper entrance via the South Channel, unless ships would cross the Lokoja Flats again. Consequently, as the use of North Channel is then to be preferred above South Channel, any ultimate regulation should be based upon such a preference. No recommendations are made here, but it is merely stated that a good future possibility could be found in a closure of the South Channel by a low dam with its crest levelled on about M.S.L. + 118′, thus not affecting the great H.W. discharge capacity through the South Channel (for prevention of higher floods upstream). Deepening at low and medium stages of the North Channel and the very confluence will then be the result (see III, 6.6.4).

Completion of the fixation could be obtained by some low groynes built in the Niger along Benue Island opposite I.W.D. Dockyard in order to effect a higher percentage of the L.W. discharge flowing through Sacrifice Channel.

Such works, however, are offered for execution only in the distant future and would then depend largely on the result and experience obtained in works on other parts of the river. Therefore no estimate of costs is given in the present Report.

A solitary rock in the South Channel near the village of Gande should be removed if navigation wants to make use of this route.

6.5. SUMMARY

6.5.1. Resulting improvements to navigation; expenditure

One way to improve a river for navigation purpose is to regulate its low-water bed. For the Benue this type of improvement is not recommended as this river does not offer favourable conditions for such a system.

The Lower and Upper Niger offer better conditions for improvement by regulation works. As it is a special advantage of this system that the river can be improved step by step in accordance with the demands of navigation, it will be possible to improve the Niger in the first stage to a depth of about eight feet at L.R.L. In a second stage ten feet may be set as a target, while the final stage will probably give more than 12 feet available depth at L.R.L.

To visualise these increases of available depths in tonnages of ships, it can be said that with a ship of the present size of a medium-large unit of 1,000 tons capacity, 2,000 tons can be carried in case of a 8-feet channel, and 2,500 tons and 3,000 tons respectively where the channel is 10 feet and 12 feet. As for a modern vessel which at present carries nearly 4,000 tons, these figures would become 8,000, 10,000 and 12,000 tons for a 8-feet, 10-feet and 12-feet channel respectively.

In case of a complete regulation of the river, resulting in a regularly-shaped channel without sharp bends and difficult crossings, an increase in the size of the units, apart from the increase in draught, can be envisaged, which might double the tonnages of the optimum river-unit up to about 20,000 to 25,000 tons as is shown by the *Mississippi* practice.

The cost of such schemes, however, will be rather high. Very rough calculations show that the cost for a regulation of the Upper Niger, that is the stretch Baro—Lokoja, will amount to £ 2 million for the first stage and £ 5 million and £ 10 million for the second and final stages respectively. For the Lower Niger, that is downstream from Lokoja, these figures are £ 10 million, £ 20 million and £ 40 million respectively.

In these figures the capitalised cost of maintenance are not included, and for this purpose it is estimated that about 50% extra has to be added to the above-mentioned prices.

Apart from this, it must be kept in mind that a regulation scheme never can be 100% safe and therefore it will always be necessary to have one or two dredgers on hand to remove unexpected shoals.

The improvements brought about by regulating the river are to be considered independent from and complementary to buoyage and discharge regulation schemes. Channel demarcation will remain essential, although in case of a channel contraction the course of the navigation channel will become more discernible. The efficiency of a discharge regulation (which aims at the prolonged maintenance of certain water-levels by spreading out the available discharges over a longer period) will be increased by a regulation scheme of the river-bed, as this bed-regulation will increase the available depths for shipping purposes, corresponding to the sustained discharges by the discharge regulation.

Rock-clearing will obviously result in a better channel. If the rocks in the Sacrifice Channel south of Lokoja were cleared, the Lokoja Flats would be partly by-passed.

6.5.2. Additional advantages

The river valley will benefit from a regulation and fixation of the rivers because the banks of the river will become better accessible and the danger of shifting channels will have disappeared. At present many villages along the Niger have to be moved occasionally because of serious bank erosion. This will no longer happen with a regulated river. Also the river ports will be

accessible every year, without the risk of an odd sand-bank moving in front of the sheds and other shore facilities, and the threat of erosion to the installations on the banks will disappear after the execution of regulation works.

Riparian economy such as irrigation, industrialisation and urbanisation will to some extent depend on the fixation of the rivers, and, in fact, no full development of the river valley can be visualised without regulation of the river running through it.

CHAPTER 7

CANALISATION BY WEIRS

7.1. GENERAL

7.1.1. Methods

The improvement of a river as a shipping route is, from a technical point of view, almost always possible with the method of canalisation. By this method the water-level is raised by the aid of weirs or dams to such a height that adequate depth is obtained for shipping in the river, even in periods of minimum discharge. The only restriction is that this discharge must be sufficient to neutralise losses by leakage and evaporation. The average minimum discharge of the river usually is sufficient, although in certain cases an accumulation reservoir may be necessary in addition.

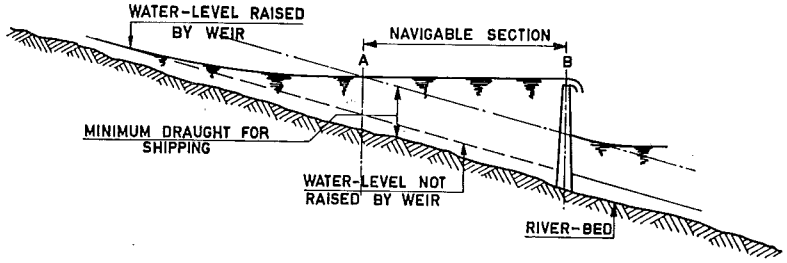


DIAGRAM 7.1.1-1

Principle of the canalisation of a river-section A—B by the construction of a weir

When the river is dammed by a weir (see longitudinal profile in Diagram 7.1.1-1), the water upstream of the dam will rise and finally be discharged over the dam, causing a very large cross-profile directly upstream of the dam. Consequently, the velocity of the water is very small, and the slope is very gentle. In canalised rivers, therefore, the slope of the water-level is smaller than the slope of the river-bed, and in consequence the depth is decreasing in an upward direction, whilst velocities and slope are increasing. This gives the so-called backwater curve which approaches, going upstream, the original conditions of the undammed river as an asymptote.

At a certain required navigation depth the river will be navigable for a certain distance upstream of the weir or dam (point A in the diagram). If extension of navigability beyond this point is required, two possibilities exist: either making the dam higher, involving the backwater curve reaching further upstream, or making another weir at the location of point A resulting

in a stepped-up condition of the water-level (Diagram 7.1.1-2). Of course, shipping must be able to pass the difference in stage above and below the weir through a lock beside the dam.

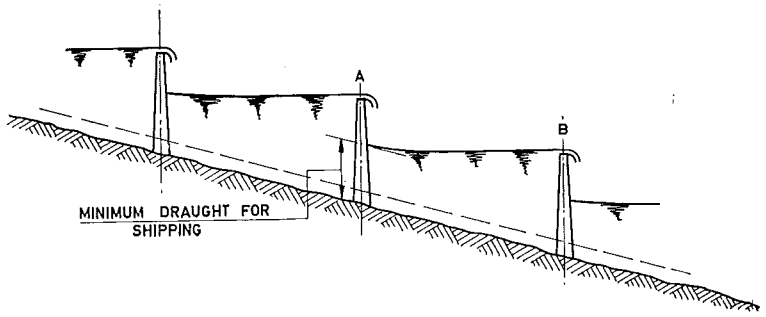


DIAGRAM 7.1.1-2

River canalised by a number of weirs and locks

When canalising a river, therefore, the method normally used is to build a number of weirs with accompanying locks which divide the river into sections producing a water-level like a staircase. There is, of course, a certain freedom in choice of the dimensions of each step. A large number of weirs can be used, each with a small head, or a smaller number can be made with greater distances between them, entailing a greater head at the dam-site. With modern weirs it is advantageous to make the distance as great as possible, although certain factors establish a limit to this distance. Such factors become especially prominent and important in wide-branched rivers with extensive flood-plains, as in the case of the Niger and Benue, which means that canalising such rivers would be very costly.

The distance between two weirs depends on the admissible drop (h) in the weir and the natural slope (i) of the river; from Diagram 7.1.1-3 it follows that

$$L = \frac{h}{i}$$

The drop h depends on downstream and upstream water-levels. The downstream water-level is fixed by the required navigation depth downstream of the dam, whilst the upstream water-level is determined by the height of the banks and adjacent land (height flood-plain = bankfull stage).

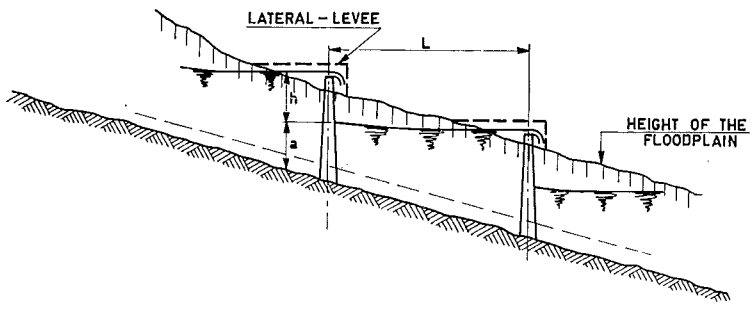


DIAGRAM 7.1.1-3

Relation between weir distance, drop of water-level and slope in canalised rivers

The downstream water-level of a meandering and branched river will be rather high because of the unfavourable crossings below the weir, although in the long run the bed downstream of the dam will be scoured, resulting in better navigable crossings. The upstream water-level of a river of the above type will be somewhat low because the flood-plain is uneven in height and perhaps still contains old and partly silted channels. In such a case, consideration should be given to continuing the dam across the flood-plain by making a transversal dike, by which the level of the dam could be made appreciably higher (solution A in Diagram 7.1.1-4). This, however, would be very costly and would also mean that a large area is permanently inundated, involving considerable increase in evaporation. In addition, difficulties could arise at high water as a result of the extra flow-resistance of the high-water bed.

A better solution would be the construction of lateral levees along the river upstream of the weir and the filling or closing of old channels and low banks (Diagram 7.1.1-3 and solution B in Diagram 7.1.1-4). In this way it would be possible to bring the water-level at the weir-site some feet above the bank. Moreover, these levees are also needed for other reasons which will be mentioned later.

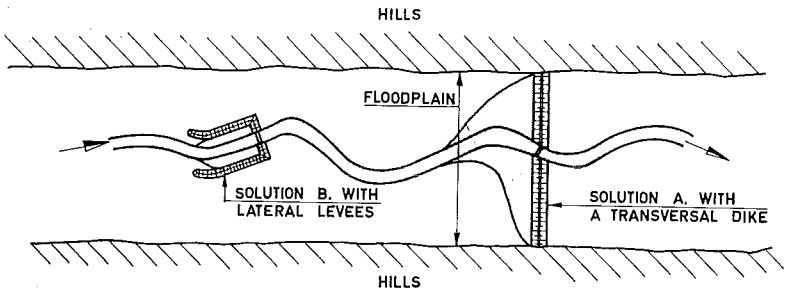


DIAGRAM 7.1.1-4

Application of levees in the case of raising headwater over flood-plain level

Such heightening must not be carried too far, because otherwise the length of the levees would be too great, whilst fixation of the banks is sometimes necessary to reduce the meandering of the river along the stretch with levees.

An important feature of the design of a river canalisation is the selection of the type of weir. The choice lies between a fixed weir or spillway where the water is discharged usually over a concrete dam with a fixed top, a movable (shipping) weir where almost the whole dam is removable, or an adjustable weir in which a part of the weir can be moved.

The fixed weir has the advantages of simplicity and cheapness, but can produce great difficulties in the river during periods of high water. Since the resistance in the stream-bed cannot be prevented or removed, the high-water levels upstream will rise, and on the weir-site a great head will be created. A large part of the water will be discharged over the flood-plain, causing scour and forming new channels through this flood-plain and eliminating the weir. This could only be prevented by continuing the dam across the flood-plain up to the hills that form the valley-wall, which would be very costly if the flood-plain is wide.

Another objection to a fixed weir is that in the long run the whole river-bed will rise, thus causing further difficulties (see III, 6.6.8).

A weir that is entirely removable with the possible exception of pillars, as with a bridge, is chosen when the river in its natural state is unnavigable only for a relatively small part of the year, so that the damming is necessary for only a short period, whilst during the remaining part of the year, owing to the larger water discharge, shipping can use the river freely without compulsorily going through locks. As such a dam is costly to construct and run, the period during which free sailing is possible will have to be extensive to make such a solution economically justified.

If this is not the case, then the choice should fall on the in-between solution of an adjustable weir in which gates only partly open during large water discharges, and navigation must continue to use the locks because the openings in the weir are either too small or have too high a sill. For typical monsoon rivers like the Benue with a very short sailling season, the adjustable weir is the most suitable.

Combinations of the above types of dam are, of course, possible, but the combination of a fixed spillway with an adjustable one is rarely applied, because it will usually be much cheaper to make the adjustable section a little larger and to make the remaining part high-water proof (for instance, with an earthen dam) than to build an expensive spillway dam.

The combination of a weir with navigation spans and an adjustable weir also presents objections. The currents in the navigation spans must not at high water be much greater than those of the river, which means that also in the adjustable openings no great speeds can occur. Therefore the total size of the openings must be about equal to the cross-section of the river between the flood-plain banks, making a very expensive weir.

Therefore rivers such as the Benue are dependent on homogeneous weirs with adjustable gates and shipping permanently passing through locks.

The determination of the minimum required size of opening in the dam and the determination of the elevation of the bottom sill now becomes a problem of river control and of comparison of costs.

If the chosen moulded cross-section is at high water much smaller than the average size of cross-section in the river upstream and downstream, then the water must accelerate while passing the weir and decelerate below the weir, causing the local slope at the weir to be steep and producing a rise of water-level above the weir which extends over the flood-plains and effects strong currents with possibilities of gully-formation by erosion.

This can be eliminated by the construction of lateral levees, which spread the local steep slope in the flood-plain over greater length. The smaller the moulded cross-section of the weir, the longer the lateral levees must be, thus presenting one of the problems of cost comparison.

According to present technique of gate-construction, a short weir with a deeply-located sill is generally to be preferred above a long and shallow weir, although it is preferable to make the width of the dam not smaller than the normal width of the main channel of the river, in order to ensure a regular discharge of water and sand.

The factors just mentioned supply the data for the total width and elevation of the sill, whilst a financial comparison answers the question of how many openings this total width must be divided into, taking into consideration, of course, the fact that floating tree-trunks and other snags must be discharged through the openings.

In addition to the weir and its lock, the levees and the training dikes, the approach channels and the bank fixations, it is also necessary to guide the river over a certain length towards the opening of the dam. The crest of these guidance works should come just under the dominant water-level produced by the new situation.

7.1.2. Examples

Among the many rivers which have been improved for shipping, a relatively large number has been supplied with weirs. From these canalised rivers well-known examples are the Seine and the Loire in France, the Main and Neckar (both tributaries of the Rhine) in Germany, the Meuse in Holland, and the Upper Mississippi and the Ohio in the U.S.A.

To give an impression of the canalisation of a river, some data now follow about two of them, the Upper Mississippi and the Meuse.

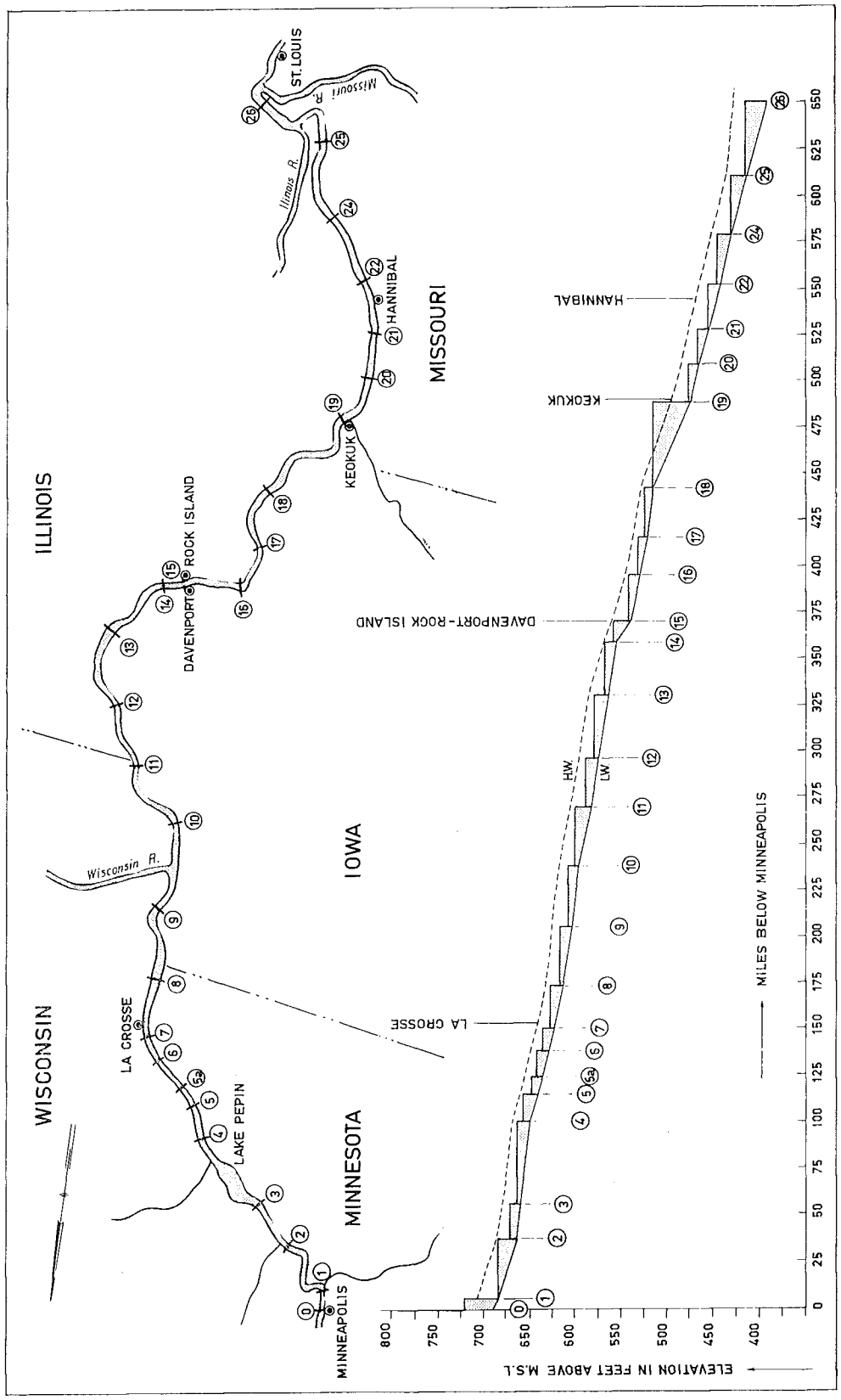


DIAGRAM 7.1.2-1

The canalisation of the Upper Mississippi

a. *The Upper Mississippi*

This part of the River Mississippi is situated upstream of the confluence with the Missouri; its length is nearly 1,200 miles, and the river is made navigable upto Minneapolis over a length of 660 miles. The river shows some resemblance to the Upper Niger. Its water discharge varies between about 300 and 7,000 m^3/sec (10,000 and 250,000 cusecs), and its slope is 10×10^{-5} except in some sections where rapids are present. After a first regulation at the end of the last century, giving a least available depth of about $4\frac{1}{2}$ feet at low water, the river was normalised at the beginning of this century. The improvement permitting 6′ draught appeared to be insufficient; so a 9′ channel was the next aim, for which a total canalisation was necessary. The main part of this improvement was carried out between the two World Wars. Diagram 7.1.2-1 shows the situation and the longitudinal section of the canalised river.

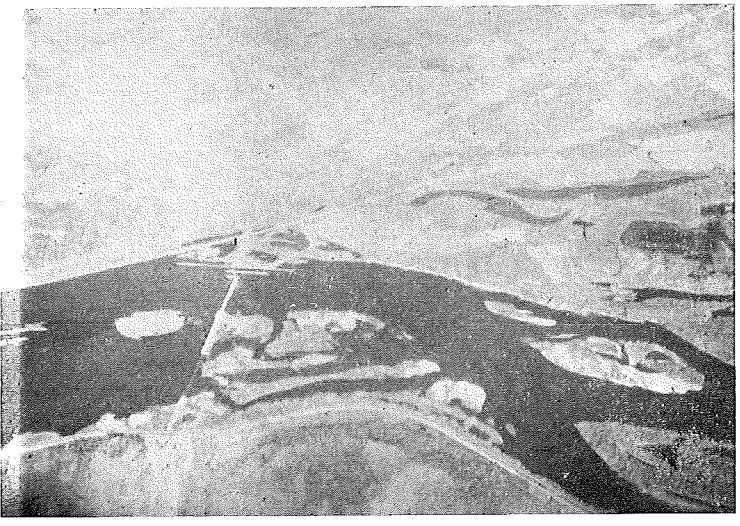
Altogether 26 weirs and locks were built over these 660 miles, with a total drop of water of 90 m (335′). The average lift per weir is about $12\frac{1}{2}$ feet.

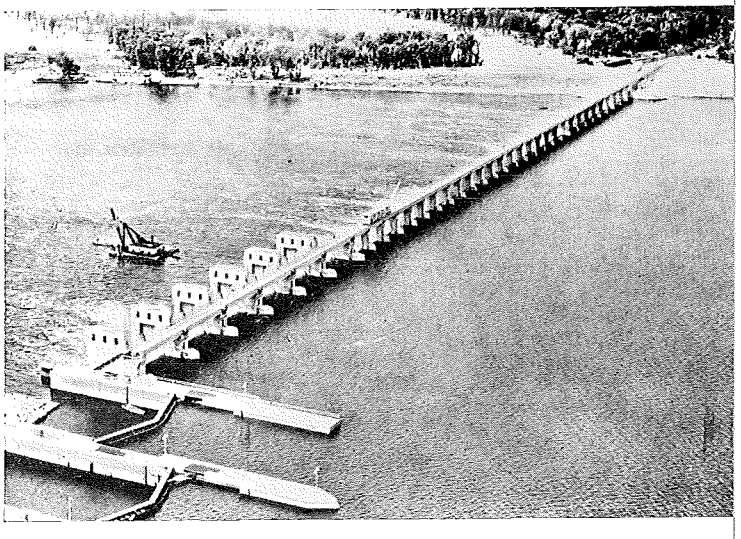
The adjustable type of gates was chosen, as navigation has to pass through the locks all the year round. The total moulded cross-section of the openings in the weirs was selected in such a way that during maximum discharge the drop of the water-level in the weir is between $\frac{1}{2}$ and 1 foot. For closing constructions the tainter-gate and the roller-gate (permitting the discharge of ice) were chosen, while some of the weirs were supplied with an additional spillway with fixed crest. The spans of the gates vary between 35 and 100 feet. The locks are adapted to push-tow navigation and have dimensions of 33×180 m ($110' \times 600'$). If necessary, these locks can in future be doubled. Photographs 7.1.2-2 and 7.1.2-3 show some of the weirs.

The total pre-war cost of the canalisation of the Upper Mississippi amounted to about £ 50 million, or £ 75,000 per mile.

b. *The River Meuse*

The history of the improvement of this river also begins with a first regulation in the second half of the last century, followed by a normalisation in different stages in the first decades of





PHOTOGRAPH 7.1.2-2 PHOTOGRAPH 7.1.2-3

Some of the dams and locks in the Upper Mississippi

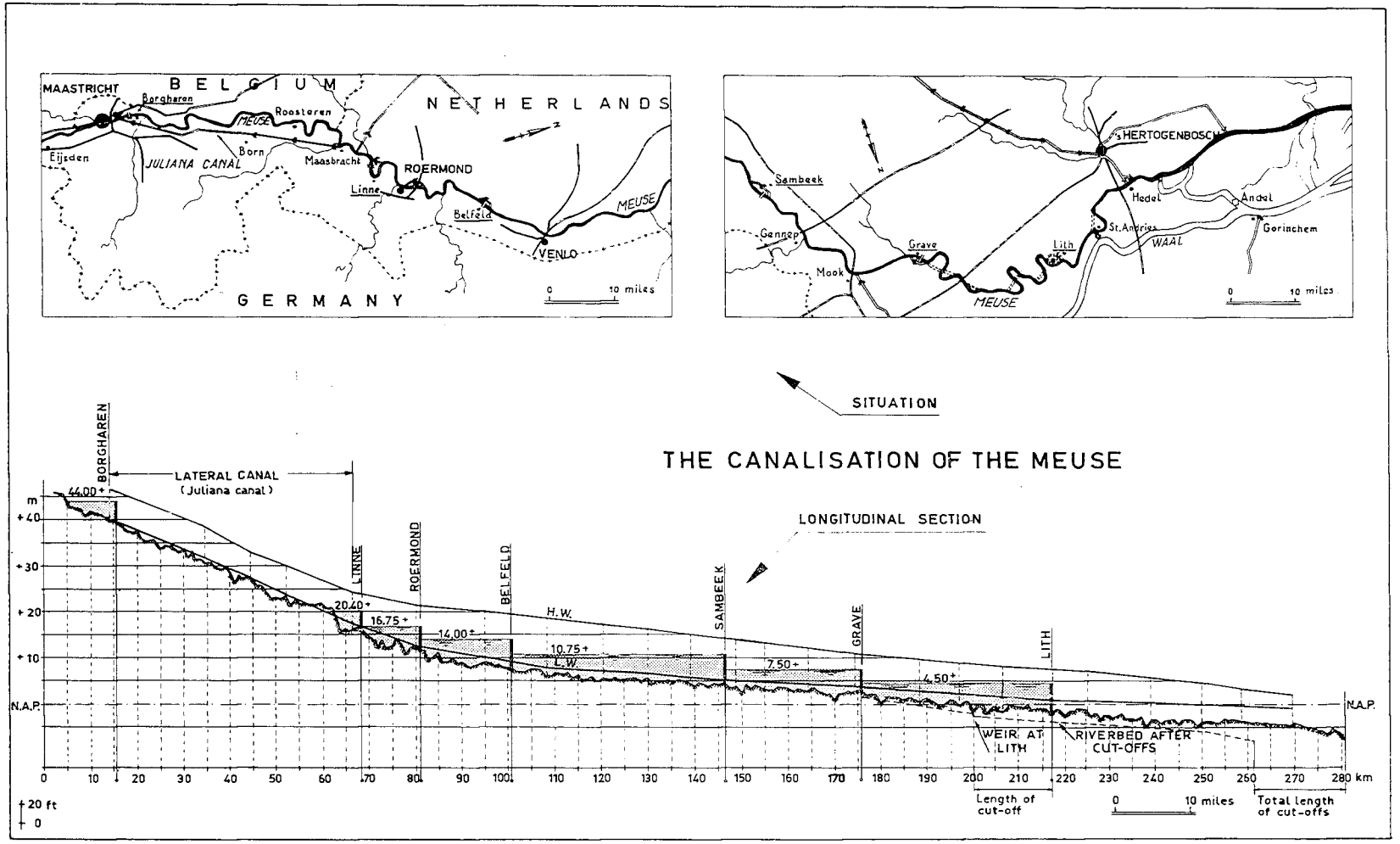


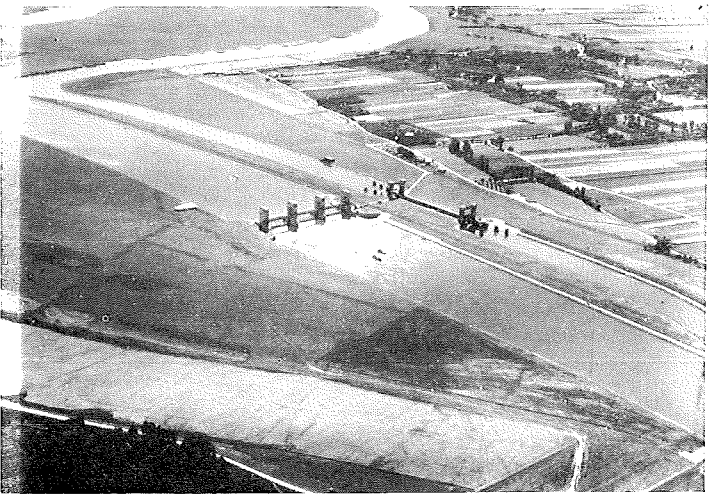
DIAGRAM 7.1.2-4

The canalisation of the Meuse

the present century. The discharge of this river varies between a few m^3/sec and 3,000 m^3/sec (about 100—100,000 cusecs), and in the dry season the navigation depth, even after normalisation, was often less than a few feet. This became intolerable in the period of the development of the coal-mines in the south of Holland, and in order to evacuate many millions of tons of coal per year the river had to be improved. Because of the small dry-season discharge of water, the only solution was canalisation. Here, too, the execution of the work took place mainly between the two World Wars.

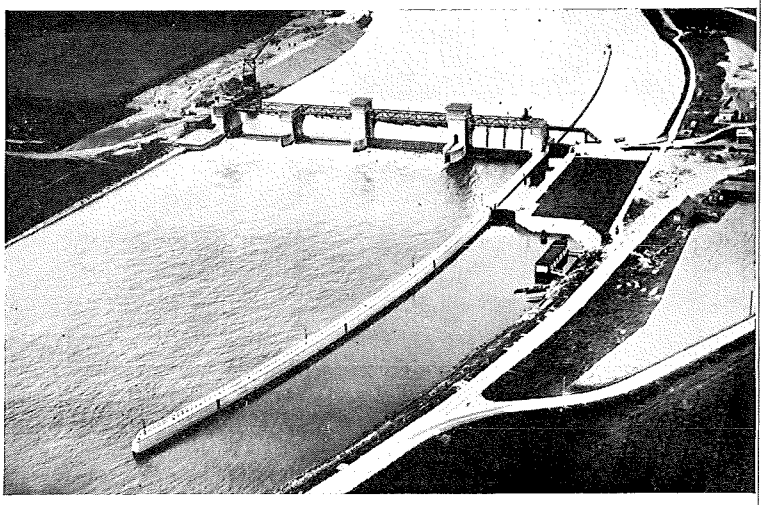
From the coal-mine area downstream to the tidal area, where the depths in the river are sufficient for navigation, the river is canalised over a length of more than 200 km (125 miles) with the exception of a section of about 50 km (31 miles) where a lateral canal proved to be cheaper. The difference in water-level between the upper and lower ends of the canalised section (about 45 m or 147′) is distributed over 7 weirs with locks, and 3 locks in the lateral canal. Diagram 7.1.2-4 shows the situation of the Meuse together with the longitudinal section over the canalised stretch.

Different types of weirs have been applied; each has a movable section for shipping during the high-water period. Because of pull-towing navigation on the River Meuse, the locks are long and narrow, e.g., 16 × 260 m (53′ × 850′).



PHOTOGRAPH 7.1.2-5

Weir complex at Lith in the Meuse



PHOTOGRAPH 7.1.2-6

Weir at Borgharen in the Meuse

In Photograph 7.1.2-5 one of the weir-complexes is shown, where the movable part of the weir is formed by 3 lifting gates for underflow with hinged flaps for overflow, each with a span of 38 m. Photograph 7.1.2-6 shows another weir in the Meuse.

7.2. APPLICABILITY ON THE NIGER AND BENUE

7.2.1. Canalisation of the Benue

The canalisation of the Benue River is undoubtedly one of the possibilities of improvement, although it is obvious that such a solution, owing to the character of the river, will be very costly.

To obtain a rough impression about the cost of canalisation, the following points have been considered:

(i) required navigation depth now and in the future;
(ii) number of weirs required, and drops of water-level at the weirs;
(iii) hydrological balance of the canalised river;
(iv) type and dimensions of the dams;
(v) type and dimensions of the locks;
(vi) additional works; and
(vii) cost of the works.

(i) The required minimum navigation depth is assumed to be 6 feet all the year round, while it is assumed that in the course of the years this depth will increase to 8 or 9 feet by scouring of the upper part of each section. It will perhaps be necessary to give some assistance by a little dredging or some regulation works.

(ii) The number of weirs required depends on the height of the flood-plain. After various observations it is roughly estimated that the sections must have a length of 40 to 25 miles on the Lower Benue and 20 to 12 miles on the Middle Benue below the Faro Confluence (corresponding to the increase in slope upwards). The number of weirs between Garua and the confluence with the Niger will be 25 to 30, whilst the drop of water at each weir will vary between 12 and 20 feet.

(iii) By damming up the sections, evaporation will increase, but this will generally not be of such a size that it will become much larger than at present, with the possible exception of the upper parts of the river in extremely dry years. The difference, however, will then be so small that the construction of a small accumulation reservoir (for example, a small Lagdo reservoir), could guarantee sufficient water supply to compensate for evaporation and leakage.

(iv) For the Benue only the adjustable weir can be considered, in view of the flood-plain which at high water takes a good part of the discharge and because the natural sailing season is very short.

The total net width of these weirs will gradually increase in downstream direction, being roughly 300 feet at Garua to over 1,600 feet near the Niger Confluence. The sill must be located deep, just under the present average bottom of the main channel.

As for the type of gates, consideration could be given to lifting gates with a width of 45′—65′, moved by a riding elevator installation. Some of them could be provided with hinged flaps for discharge during the low-water period, with the remainder having discharge along the bottom only.

(v) The locks would have vertical chamber walls with their top elevation situated above high-water level, closed by three sets of miter gates that divide the chamber into two parts of unequal length. The chamber measurements would preliminarily be established at 70 feet width and 375 feet length; ultimately, a length of 650 feet will be required.

(vi) The additional works will be levees with crests above H.W.-level, training dikes, flow guidance works, lock approach channels, etc. For many of the dams costly access roads will also be necessary for the execution of the works.

(vii) Because of the vagueness of the above-mentioned factors, it is not possible to give detailed estimates of cost. But it can be very roughly estimated that such a weir-complex in the Upper Benue will cost £ 2—3 million, whilst the weir complexes in the lower river will cost two to three times as much. Taking the respective distances between the weirs into account, this is per mile of river £ 150,000 to £ 250,000 in the Upper Benue and probably over £ 300,000 in the Lower Benue.

The total cost of such a canalisation of the Benue would, accordingly, be £ 100—200 million.

Such a huge sum, combined with the capitalised maintenance cost, is out of all proportion to the economic interests or possibilities of the next decades.

However, should there still be any idea for such a plan, consideration should be given to the possibility of making a lateral canal through the Benue Valley, as this would in some sections of the river probably be cheaper than the canalisation of the river itself.

A great disadvantage of the system of canalising the Benue is the impossibility of an execution in steps. Starting the canalisation in the Upper Benue would result in a limited lengthening of the navigable period, since navigation below the lowest dam would still be impossible. A canalisation of the Lower Benue only would not give any improvement for the main export area situated near the Upper Benue. For this reason, too, canalisation of the Benue is not recommended at present.

7.2.2. Canalisation of the Niger

The canalisation of the Niger River is also one of the possibilities for the improvement of shipping. However, in this river with its relatively large low-water discharge there are other possibilities for improvement, competing with the very expensive solution of canalisation. Though the probability of a recommendation to canalise the Niger seemed to be small, a rough investigation has been made to compare the cost of such a solution with other possibilities.

The system of canalising the Niger is, in principle, equal to that on the Benue. However, there are some special problems in the case of the Niger.

Firstly, there is the ramification in the Delta. By building a double weir with two locks at the bifurcation into Nun and Forcados, it is possible to discharge the major part of the Niger water via the Forcados River, and in consequence to improve the navigability of this river considerably over its whole length as far downstream as the Delta ports. However, as a result the navigability of the Nun River will grow worse.

Another problem is caused by the Ase and Orashi Rivers, diverting water from the Niger between Onitsha and Aboh during high-water stages. By canalising the Niger the water-levels will rise, involving an increase in discharge of the above-mentioned rivers. Therefore in the case of canalisation, some control works along the banks of the Niger between Onitsha and Aboh might be necessary.

A third problem is the confluence of the Niger and Benue. By building a weir directly downstream of Lokoja not only will the bottle-necks in the River Niger near Lokoja be eliminated, but also the Benue Bar (see V, 3.1.2) will be improved by drowning the entire Confluence during the low-water period and at the beginning of the Benue season. But if this solution would be chosen, a more detailed investigation about the behaviour of the sand-transport in the Benue should be carried out.

The type of weirs and locks of a Niger canalisation would be equal to those of the Benue canalisation. Although the navigable period on the Niger in present conditions is longer than on the Benue, it seems hardly justified to provide Niger weirs with movable shipping-spans. Here, too, a type with adjustable lifting gates would be most suitable.

For a year-round navigation on the Niger between the Delta ports and Baro 9 weirs and locks would have to be erected, e.g., a double weir at the bifurcation into the Nun and Forcados, a weir between Aboh and Onitsha, four weirs between Onitsha and the Rocky Section, a weir directly downstream from Lokoja to control the Confluence, and two weirs between Lokoja and Baro.

The total cost of such a canalisation is very roughly estimated at £ 40—80 million. It concerns a directly canalised length of 300 miles and an improved but not canalised section in the Delta of about 100 miles, involving an average of £ 100,000 to £ 200,000 per mile of river. This figure does not include the capitalised cost for management and maintenance.

Here, again, improving the navigability in one step would mean a great disadvantage for a river with a gradually developing traffic.

Therefore there is perhaps reason to confine improvements in the first instance to the section Onitsha—Delta, in view of the importance of Onitsha as a main port. A second step would perhaps be the improvement of the Lokoja Confluence by building the weir directly downstream from Lokoja. Such limited canalisation could then be combined with the improvement of other sections by, for instance, bed-regulation. Especially the Upper Niger below Baro, as far down as the backwater influence from the Lokoja weir, would be suitable for bed-regulation.

7.3. SUMMARY

It might be technically feasible to make the Benue a perennially navigable river with depths of 6—8 feet by means of a system of 25 to 30 weirs and locks. But the total cost of such a canalisation would be some £ 100—200 million. Should this solution ever be considered, then the possibility of making a lateral canal through the Benue Valley should also be studied, as this would for some sections of the river probably be cheaper.

A canalisation of the Niger as far upstream as Baro, resulting in similar depths, will require 9 weirs and locks, at an estimated cost of £ 40—80 million.

Improving the navigability by means of a canalisation can only be done in one step; this is a great disadvantage for a river with a gradually developing traffic. Moreover, a canalisation is never complementary to a regulation of the river-bed or of the discharge, but constitutes a separate item.

In view of these facts, canalisation by weirs is not recommended for the Niger and Benue.

CHAPTER 8

DISCHARGE REGULATION

8.1. GENERAL

8.1.1. Methods

From the foregoing, and notably from Part V, it will be clear that defects of navigability are caused, essentially and primarily, by the irregularity of the discharges which follow naturally from the seasonal irregularity of rainfall (III, 1.3 and III, 4.1).

In Chapter III, 4 it has been pointed out that the irregularities of the upper reaches are evened out to a certain extent when going downstream; this result is caused mainly by the compensating effect of a greater number of tributaries and is, therefore, dependent on the shape and size of the catchment area and the run-off conditions prevailing therein.

Furthermore, it has been indicated that the irregularities of rainfall are somewhat attenuated by terrestrial effects before the water reaches the rivers. This attenuation is effected by the holding capacity of the soil and the absorptive capacity of the vegetation.

Unfortunately, neither of these natural effects is very marked in Nigeria, and any means to compensate irregularities in an artificial way would be attractive. So a number of measures will be discussed here which takes a regulating effect on their discharges.

a. *Watershed management*

Watershed management — watershed here to be taken in the sense of drainage basin — may be considered as the natural counterpart of soil conservation and re-forestation; in III, 1.4 the interrelationship between hydrologically-improved run-off conditions and agricultural soil conservation has already been pointed out. The prevention of erosion is the main feature here, and it is of increasing importance in areas where soil exploitation is extended and intensified. The effect on the run-off is two-fold: less sediment is carried to the rivers, and the water discharges are more evenly distributed over a longer period. But it takes a long time before these effects make themselves felt on the navigability of the main river: the magnitude of the time-lag might be anything from 20 to 100 years.

Another means of watershed management would be: cutting through this watershed, whereupon the next divide comes to act as a new boundary of the basin. In this case, watershed is to be taken identical with divide. This way of enlarging a catchment area may be used to increase the total discharge of the river concerned and, with respect to the regulation, to obtain a more evenly-spread discharge.

b. *Reservoirs*

A reservoir is used for navigation purposes to set apart a quantity of water in times of flood when there is an abundance of water and to release this water in times of drought. In Nigeria, and more particularly for the Niger and Benue Rivers, discharge regulation would certainly

be a most interesting proposition. Especially on the Benue reservoir building is the only practicable way to extend the shipping season considerably, but also on the Niger discharge regulation by means of a reservoir is attractive with a view to year-round navigation and increased depths.

Regarding reservoir building in Nigeria the following remarks can be made:

Firstly, discharge regulation must be studied seriously when considering the improvement of the navigability of the Niger and the Benue.

Secondly, electricity may be generated at the dams of the reservoirs. When an electricity demand exists, the generation of hydro-power may very well be the stimulating factor in a multiple purpose scheme, but care should be taken to evaluate the various requirements in a justified way and regarding the economy of the country as a whole.

Thirdly, a number of by-effects are caused by regulation of the discharges, of which the influence on the morphology and the effect of flood-control are the most important.

The influence on the morphology has been discussed in III, 6.6.9 and the main conclusion has been that the channels will improve because of the evened discharges. On the other hand, difficulties might arise due to deposition of sand at the confluences of major sand-transporting tributaries.

The flood-control, effective when the reservoir is large enough to cope with the peak discharges, will have its beneficial effect on the development of the riverain areas and more particulary on the flood-plains that will no longer be erratically and excessively flooded. In fact, very often flood-control has been the main consideration for the construction of a reservoir, with improvement of navigability taking second or third place. In Nigeria, no study has yet been undertaken to evaluate the benefits of flood-control to riverain economy, but the prospects appear to be favourable.

8.1.2. Examples

In this connection it may be useful to study examples of discharge regulations carried out in other parts of the world. Usually, realisation of such regulation schemes is difficult, and so both failures and successes are instructive.

a. *Watershed management*

The embodying of neighbouring catchment areas has been realised in a few cases in the United States, in France and in Australia.

In the Niger-Benue case, French investigators have for a moment contemplated the diversion of the Upper Faro into the Upper Benue, some hundred miles above Lagdo. In the longer Upper Benue bed the diverted water would carry less sediments than in the steeper Faro River. Thus, apart from a more even supply of water at the Faro-Benue Confluence, the supply of sand at this point would be appreciably reduced, and the notorious Wuro Boki Flats would improve naturally. Unfortunately, this plan proved impossible for practical reasons.

Another idea was the embodying of the Logone River into the Benue system. This idea is not new; such a connection actually existed during two geological periods, as shown on the geological time-table (Table III, 3.1.1-1), and it could be realised again if the low natural levees and the swamps along the Logone were cut by a canal. However, in that case the future of Chad Area would be destroyed. Reinforcing the natural levees is considered a sounder plan.

In fact, nowhere along the boundaries of the Niger and Benue Basin can a possible extension of the drainage area be imagined.

Soil conservation and re-forestation are being realised in many parts of the world. An example can be found in Ceylon, where the World Bank is supporting a large scheme on a modified T.V.A.-base.

In Nigeria, soil conservation would be a very suggestible proposition. In the first place, local agriculture would benefit from such measures, although it is anticipated that operations would have to be carried out on an enormous scale before, after scores of years, the effect would be noticeable on the main rivers. At present, a tendency to soil destruction is stronger than a striving for soil conservation.

b. *Reservoirs*

Many reservoirs have been constructed all over the world, but rarely to serve shipping conditions alone. One example, however, is Fort Peck Reservoir ([1] in the middle course of the Missouri which debouches into the Mississippi, and even here it has not yet come to full employment. As usual other interests, less flexible or better organised, have prevented the complete evaluation of the scheme, and scientific observations have not yet revealed what effect can be derived from such an undertaking.

On the other hand, the number of multi-purpose dams, serving power, navigation and irrigation at one time, is steadily increasing, but here operation of the reservoirs is not governed to suit exclusively an improvement of the navigability.

Summarising, watershed management is an elementary means for run-off conditioning. As the effects, however, would take scores of years to develop on the main rivers, short-term means for discharge regulation must be found in the building of reservoirs.

The average annual discharges of the Niger and Benue are sufficient for year-round navigation. A complete regulation by constructing many reservoir dams in the main tributaries and the Niger and Benue would allow for year-round shipping of 6 feet and over; only in the Benue upstream of the Taraba River would this figure be $4\frac{1}{2}$ feet. Of course, the practicability and advisability of such measures remain to be considered.

8.2. POSSIBLE DAM-SITES

8.2.1. Bussa to Jebba (Niger)

Between Bussa and Jebba many sites appear favourable for the construction of a dam in the Niger.

The maximum/minimum flow ratio is already most favourable on the Upper Niger, but if peak discharges could be retained somewhere in this section, more water could be supplied during the navigation season for the evacuation of produce from November onwards, and during the crucial period of April and May when shipping upstream of Onitsha usually comes to a standstill owing to lack of water. Baro-bound traffic could then be given greater depths during the produce evacuation season, and possibly be continued all the year round, whilst Benue-bound traffic could have a good start encountering no difficulties as far as Makurdi and Ibi (see IV, 3.2.1).

The favourable hydrological conditions could also be exploited for the generation of electricity. The Electricity Corporation of Nigeria, facing an increasing demand, has already been considering the further development of generation possibilities, and early in 1958 a preliminary investigation into the feasibility of a power-project in this region was initiated, which subsequently grew into a joint commission to Messrs. Balfour, Beatty & Co. Ltd. and NEDECO to investigate

([1] CORPS OF ENGINEERS, 1946. MOR. 4

the feasibility of a multi-purpose project on this part of the Niger. The joint report was due by the end of 1958, and as full details will be given there, only an outline will be given here, followed in 8.3 by a preliminary discussion of the hydrological merits of an eventual project.

As far as navigation is concerned, the ideal location for a dam in the Niger would be above Baro with its railhead, and below the confluence of the influential Kaduna River. As, however, no suitable site has been found there, a place more upstream is designated. In making the choice, a number of considerations must be taken into account:

(i) the dimensions of the dam should not be excessive;

(ii) the stored amount of water should be sufficient to bridge fully or partly the temporary gaps of deficient discharge;

(iii) ships must be able to pass the dam, which means that locks have to be constructed; and

(iv) the lay-out and the operation scheme of the reservoir should be planned in such a way that the interests of both the Electricity Corporation and the navigation companies are satisfied, while fully taking into account the interests of riparian economy.

Pending the current investigation nothing can be gained by expressing premature opinions. It is certain, however, that the possibilities are confined to the river-stretch from Jebba to Bussa, descriptions of which have been given in III, 3.4.

8.2.2. Igbo (Niger)

The 30-mile stretch below Lokoja, indicated as Niger Rocky Section, has been geologically described in III, 3.4.3, where it was pointed out that rocks suitable for building material are abundant in this area. There is also the important fact that the valley is sufficiently narrow and enclosed to offer opportunities for the construction of a reservoir dam.

The granites and porphyric granites, if not too strongly affected by weathering, would form an excellent foundation rock of a relatively high bearing capacity sufficient for a concrete dam and of an extremely low permeability. Fracturing by tectonic processes having taken place only on a small scale, the strength of the granites is assumed not to have suffered, and it may be said that conditions for the construction of a concrete dam would seem most promising but for the alluvial fill below the present river-bed. However, as the bottom of the old river-bed is expected to lie at 80 or 90 m (250 or 300 feet) below the present river-bed, excavation of the unconsolidated deposits is quite out of the question. Therefore, should a dam project be considered, the unfavourable characteristics of the alluvial deposits, which would have to serve as a foundation for the dam, would restrict the choice of type of dams to a rockfill dam or an earth dam.

Rock is available in large quantities; the aspects of opening quarries in the Rocky Section have been discussed in III, 3.4.3. Also sand is available in large quantities, but it is very doubtful whether clay for an impervious core of a dam can be found in the immediate neighbourhood. Probably the nearest areas for exploitation of suitable clay are to be found near Idah further downstream, or else upstream of Lokoja.

The most suitable site in the Rocky Section will probably be found at or near Igbo (Mile 346) where the occurrence of a bypass channel around a granite rock would be a favourable condition during both the constructional and the operational phases.

But a total length of dam of over a mile would still be required, and the spillway would necessarily have enormous dimension. The flow of the Niger is almost at its maximum here just below the Benue affluent and a spillway would have to discharge many hundreds of thousands of cusecs as the average flow is about 200,000 cusecs and the maximum discharge nearly a million cusecs. The reservoir thus created should be of enormous size because of the required rate of flow regulation.

So it is anticipated that for a foreseeable future the construction of a dam in this area cannot be taken into consideration, as it would be too ambitious in respect of the requirements of both navigation and of water power.

8.2.3. Onitsha (Niger)

The Niger Valley near Onitsha (Mile 235), considerably narrowed and bordered by consistent rocks, seems to present favourable conditions as a dam-site, the more so because the very wide valley upstream would provide a large reservoir area. However, the dam, spillway and gates would have to be of enormous dimensions because, as at Igbo, the average flow is about 200,000 cusecs and the maximum discharge almost a million cusecs.

The possibilities have been considered in a previous report of NEDECO ([1] from which the following information is drawn. It must be emphasised, however, that the figures are still tentative and that an extended investigation would be required if ever the construction of a dam were to be considered.

The site would allow a dam with a crest height of 47 m (154 feet) above Mean Sea Level and of some 3,000 m (10,000 feet) in length, whilst the bed-level would be 7 m (23 feet) above M.S.L.

Assuming a reservoir level variation of between 30 m and 40 m (100 feet and 130 feet resp.) above M.S.L., a useful capacity of some 35 milliard cubic metres (30 million acre-feet) has been estimated. This would allow a year-round discharge of 4,000 m^3/sec (140,000 cusecs) with an average head varying between 16 and 25 metres (55 and 80 feet). Regarding an eventual combination with hydro-power, the electricity output would be considerable (well over 750 MW), but as at present the Jebba Scheme prevails, a scheme which could meet the electricity demand for the near future, an eventual dam at Onitsha should be kept in mind as a possibility for the more distant future.

The reservoir area would be of the order of 4,000 km^2 (1,500 sq.miles), extending to Idah or Lokoja, according to its degree of filling.

The geological conditions, and consequently the foundation conditions, remain fundamentally the same from Asaba downstream to some distance south of Onitsha. The choice of a dam-site will depend on the width of the valley and thus upon the most favourable cross-section, where the length of a dam to be constructed would be reduced to a minimum.

In the entire area the near horizontal or slightly-folded sandstones with intercalations of lignite, clay and shale are suitable as a foundation rock for an earth dam. They are probably slightly pervious, however, and when preparing a dam-project this feature will have to be taken into account.

The deep ancient buried valley below the present river-bed, filled with unconsolidated and very pervious fluviatile sandy sediments, calls for special precautions. As the depth of the buried valley will prevent the loose sediments being entirely excavated, a provision will have to be made (for instance, a vertical screen through the alluvial fill made by cement injections) in order to reduce seepage losses and water pressures which might endanger the stability of a dam.

Sand of good quality may be dredged from the river-bed of the Niger. Gravel also occurs at a few places in the river-bed, but only in small quantities. Hard rock has not been found in the Onitsha area. Ironstone has been used as building stone and for the preparation of concrete, but the concrete thus obtained is of a very mediocre quality. As a building stone it is also of poor quality, and it would be especially unsuitable for river-works. Should large quantities of gravel as well as good rock be wanted, it will probably be justified to exploit gravel occurrences and quarries in the Rocky Section of the Niger Valley north of Idah. Clay suitable for an impervious core of a dam is also expected to be present in sufficient quantity in the marshy area north of Onitsha between the Niger and Anambra Rivers.

Of course, more detailed geological investigations would be required it a definite dam-project were to be prepared. These investigations would have to include reconnaissance drilling to test the composition, thickness and quality of the sandstone formation with the intercalated lignite beds and clays and shales and to determine the thickness and exact composition of the alluvial

([1] NEDECO, 1957. GEN. 22

fill of the buried valley. Geophysical methods might prove useful to reduce the drilling programme. During these geological investigations attention should also be paid to the presumed existence of faults, which might influence the design of the project.

8.2.4. Shiroro (Kaduna River)

A dam in the Kaduna River is interesting from the point of view of a development of power supply. The most suitable site for this purpose has been found where the river breaks through Shiroro Gorge and where an attractive head can be obtained. At present, the scheme is being investigated and a report from the Consultants (Sir Alexander Gibb and Partners) is due early in 1959. Therefore the project is only briefly mentioned here.

The Kaduna River is practically empty during the dry season which is rather extended on that latitude. During the years 1955—1958 an appreciable flow was recorded only between the middle of July and the beginning of November, viz., for three and a half months. Year-round generation of electricity will require the utilisation of storage water during eight and a half months but the available reservoir volume is limited.

It is intended that at the beginning of the rainy season the first part of the fresh run-off will be used to replenish the reservoir, so as to produce the most economic head as soon as possible.

These conditions are of interest for the discharge pattern of the Niger below the mouth of the Kaduna River. When trying to evaluate these interests it appears that, irrespective of the exact figures of the ultimate project, any delay of the first flood in July would be unfavourable for shipping on the Niger. During this crucial period of the first attempt to reach the Benue, shipping is usually hampered by lack of water, and it is obvious that those early contributions from the Kaduna River are most welcome.

On the other hand, the continuation of the Kaduna discharge at the end of the season is considered favourable but is relatively unimportant.

The most favourable consequence would be obtained if the peaks of the Kaduna River flow could be evened out by the reservoir. The resulting benefits of reduced peak discharges have already been indicated in III, 6.6.9 but it is not evident whether the spare capacity of the reservoir required for the purpose could be made available.

Summarising, the realisation of a Shiroro Scheme would produce both favourable and adverse influence on the Niger. The weight of such influence can only be evaluated after the figures of the scheme have become available in the relevant report.

The possibility of combining the Shiroro Scheme with the larger Jebba Scheme is another development which could be considered, as it appears attractive for improved navigability as well as for the generation of electricity. But a discussion on it would be premature in this Report.

8.2.5. Lagdo (Benue) ([1

It has been set out in III, 3.4.5 that 40 miles above Garua the Upper Benue flows through a gap which seems designated by Nature for the construction of a dam. Not only is the gap narrow (180 m or 600′) and does the boundary consist of sound rock, but also the level country upstream of the site offers ample room for a reservoir of reasonable capacity.

The capacity of the Lagdo Reservoir has been determined at 6 milliards of m^3 (5 millions of acre-feet) at an estimated cost of about £ 6,000,000. This volume is higher than recommended in former French reports, as it has appeared advisable to have a slight over-capacity in wet years.

For a draught of 5 feet the average shipping season of the port of Garua would be extended

([1 ELECTRICITÉ DE FRANCE, 1958. GEN. 11

to 3 months, which is 1 to 1½ months more than at present. In dry years, the season would still be 2 to 2½ months and in many years the August fall would be overcome (see also 8.4).

The Lagdo Scheme might be influenced unfavourably by the Faro River. The unregulated Faro will continue to discharge its water in peak floods involving huge quantities of sand brought into the Benue; as the latter river might not be able to clear this sand because of its regulated discharges, a deterioration of the channel at the confluence and on the Wuro Boki Flats might result. Although it is thought that this effect may not be too serious, a final answer can only be given after testing the situation in a model. A combination of a Lagdo Scheme with a subsequent dam near Yola solves this problem, as the Wuro Boki Flats and the Faro Confluence will then be drowned under many feet of water even at the lowest retention level.

8.2.6. Cossi (Mayo Kebi)

The most suitable place for damming the Mayo Kebi (a tributary of the Benue above Garua) is found near Cossi, where the river flows between two rather low hillocks. A geological description of this site was given in III, 3.4.6.

According to a French project, a dam of 18 m (60 feet) height and 300 m (1,000 feet) length would form a reservoir of 150 km² (60 sq.miles) and 0.5 or 0.6 milliard cubic metres (0.4 or 0.5 million acre-feet) at a level varying from 211 to 213 m (643 to 650 feet) above M.S.L.

However, not only would the regulating effect of a dam on the Mayo Kebi be rather unimportant for hydrological conditions on Garua Creek (M.Kebi contributing only one-fourth of the total discharge), but the effect on the Wuro Boki Flats and below (where M.Kebi's influence would amount to one-sixth only) would be virtually negligible.

This dam, at the time, was estimated at some 75% of the cost of the Lagdo dam, against a storage capacity of 10 or 15%. Obviously Lagdo deserves priority, and Cossi is only mentioned as a remote possibility.

8.2.7. Yola (Benue)

Although a dam at Lagdo may be considered the first step towards discharge regulation on the Benue, a Lagdo dam on its own does not appear quite satisfactory because:
(i) Faro River, the main cause of trouble, has been left out of the scheme, so that the effects of the intended regulation on Wuro Boki Flats may not be fully adequate; moreover
(ii) the intended regulation would have a limited effect; it was calculated that instead of 6 milliard cubic metres (5 million acre-feet) about twice that amount would be required to satisfy the demands also on the middle part of the Benue.

Therefore, whilst fully recognising the merits of a Lagdo reservoir scheme, it must be appreciated that such a scheme would yield its full value only as a Cameroun counterpart of a scheme which should be constructed below the confluence of the Faro and the Benue. The most obvious place that offered itself here was to be found in the "Rocky Section" of the Benue between the Faro Confluence and Yola.

In order to prospect the possibilities of constructing a dam in this section a geological reconnaissance was carried out which decided in favour of a site near Dasin Hausa (Mile 904). The relevant report is given in III, 3.4.7, whilst the topography and the geology of the reservoir area will be discussed in Section 8.5 of this Chapter.

Here, it will only be summarised that a Yola Scheme would solve the present problems of Benue navigation to a great extent and that its cost, estimated at from £ 10 and £ 14 million according to the size, would become justified in a not too distant future. Also, flood damage

in the Benue Valley below the dam would be considerably reduced, and the agricultural output increased, especially where irrigation will be applied ([1].

Nevertheless, the return of investment will be relatively slow, as there seems to be no demand for electricity generation and no need for a (toll) bridge exists. Moreover, electricity demands and shipping requirements would be very much opposed to each other.

The improvements and additional effects will be further discussed in 8.5.

8.2.8. Makurdi (Benue)

Going down the Benue the only possible dam-site apart from Dasin Hausa is found near Makurdi, at Mile 509. The river at this point has grown to its full size: only a few minor tributaries debouch in it before the Benue unites with the Niger at Lokoja (Mile 362).

The river valley near Makurdi, considerably narrowed and bordered by hills, seems to present favourable conditions for a dam-site, the more so because the very wide valley upstream would provide a large reservoir area.

When discussing the possibilities for the construction of a reservoir dam near Makurdi, the following items should be kept in mind:

The geological conditions, and therefore the foundation conditions, remain fundamentally the same from about ½ mile upstream of the railway bridge to about 1 mile downstream of the bridge. The choice of a dam-site will depend on the width of the valley and thus upon the most favourable cross-section, where the length of a dam to be constructed would be reduced to its minimum.

In the entire area the nearly horizontal or slightly folded cretaceous sandstones are suitable as a foundation rock for an earth dam. They probably are slightly pervious, however, and while preparing a dam-project this feature will have to be taken into account.

The deep ancient buried valley below the present river-bed filled with unconsolidated and very pervious fluviatile sandy sediments calls for special precautions. As the depth of the buried valley will prevent the loose sediments from being entirely excavated, a cut-off will have to be made to reduce seepage losses and water pressures which might endanger the stability of a dam.

Sand, and probably also gravel, for construction purposes will be available in sufficient quantities. Clay suitable for an impervious core of a dam is also expected to be present in the flood-plains upstream of the site. Rock, however, can be found only in a very few places. A basalt outcrop, for instance, is known to exist at some distance upstream of Makurdi to the north of the river, but no information is available concerning its quality or the possibilities for exploitation.

More detailed geological investigations will be required if a dam project is to be prepared. These investigations will have to include reconnaissance drilling to test the composition, thickness and quality of the cretaceous sandstones and to determine the thickness and exact composition of the alluvial fill of the buried valley. Geophysical methods have been proved useful to reduce the drilling programme.

The saddle which is situated 1½ miles south-west of the railway bridge might represent a former course of the River Benue. To ensure that considerable water losses are not to occur through this gap in the hills, additional surveying will have to be executed. At the present time sufficient topographical data of this area is still lacking and therefore it cannot yet be concluded whether an auxiliary dike would have to be constructed in this saddle.

The construction of a reservoir scheme near Makurdi has been given serious consideration, but present conditions do not seem to warrant the expenditure. However, a brief summary of the considerations follows:

The advantageous points would be:

(i) the site is suitable for the construction of a dam and a reservoir; in fact, the cost per acre-foot of storage capacity might compare favourably with other sites with the possible exception of Jebba;

(ii) year-round navigation on the Lower Benue as well as on the Lower Niger would be possible; the Makurdi Scheme would bear full fruit if combined with Yola and Jebba discharge regulation schemes;

(iii) water-power could be generated in large quantities; and

(iv) irrigation could be introduced to some degree.

([1] RICE MISSION, 1948, p. 41. GEN. 33

The greatest disadvantage is the considerable area of land that would be covered by the reservoir. The value of this cannot be estimated, but certainly a great amount of good high flood-land would be affected by the lake, which might extend as far as Ibi (Mile 614).

If dams are constructed at Jebba and at Yola, the Makurdi reservoir would be of great importance when operated in conjunction with others. Both navigation and electricity, the latter when the hydro-stations are coupled in one grid, would benefit from a combination of Jebba and Makurdi.

Although the possibility of a dam at Makurdi should certainly be kept in mind for the future, a recommendation at present would be premature.

8.2.9. Benue Tributaries

Regulating the discharge of one or several of the tributaries of the Benue would be preferable to constructing reservoirs on the main river. The advantages are obvious: firstly, the tributaries would deliver a cleaner and more regular flow which would not spoil the navigation channels in the main river; and secondly, the regulation-works would be kept out of the navigation route where no locks would be required.

From the outline following below it may be clear that possibilities for flow-regulation do exist on some of the tributaries, but not on those most requiring it. Giving numbers for feasibility, the position may thus be put: 1 for the Gongola and 2 for the Taraba; whilst if priority-numbers are based on the hydrological importance or the magnitude of the difficulties caused by these affluents, they should read: 1 for the Faro, 2 for the Katsina Ala, 3 for the Gongola, 4 for the Taraba and 5 for the Donga.

a. *Faro River*

However badly needed, no proper dam-site has been found along the Faro, and no reservoir of any appreciable size can be constructed in the river-bed.

There remains, however, the possibility of a peak reservoir off the river, which might fill during floods on the river and empty again at low river stages. This would have an equalising effect on the discharges of the Faro and, more important still, the sand ejections on the Wuro Boki Flats would be greatly reduced.

It is estimated that to have a wholesome effect a storage capacity of such a peak reservoir should be 0.3 to 0.4 milliard cubic metres (250,000—330,000 acre-feet).

It is not sure whether a suitable site, low-lying and of sufficient extent, could be found for this purpose.

b. *Gongola River*

There are three possible dam-sites considered along the Gongola. Two of them, Dadin Kowa and Kombo, are situated upstream of the confluence with the Hawal River whilst Kiri-Bobore is below that confluence. This might influence an eventual choice, as the Hawal, though perhaps one-third or one-quarter of the size of the Gongola, is much more irregular in its discharges.

In III, 3.4.8 descriptions have been given of the three mentioned valley narrowings. In considering the construction of a dam and reservoir the following comments should be noted.

(i) *Dadin Kowa site* (see Diagram III, 3.4.8-1)

The geological conditions, and consequently the foundation conditions, remain fundamentally the same over a distance of about 7 km (nearly 5 miles) upstream of Dadin Kowa. So the choice of a dam-site will depend mainly on the width of the valley and thus upon the most favourable cross-section.

The Bima sandstones form a suitable foundation for a rockfill dam or an earth dam. The sandstones have a low permeability, owing to their arkosic constitution. The foundation quality of the sandstones and their permeability will vary with the presence and the intensity of faults and joints. When making a choice for a dam-site, the influence of faults and joints on the behaviour of the rocks should be taken into account and if possible the dam should be located away from important fault zones.

In the river-bed of the Gongola sandy alluvial deposits occur, the thickness of which is as yet unknown. In view of the fact, however, that the major rivers and some of their tributaries at several places proved to have deeply-entrenched and sometimes canyon-like buried valleys lying underneath their present bed, it may well be that the valley of the Gongola shows similar characteristics. To prevent seepage losses underneath a proposed dam and water pressures which might endanger the stability of the works, a cut-off([1 should be made through the alluvial fill of the valley.

The arkosic sandstones are not suitable as a building material. Basalt, however, has been observed about 3 miles to the west of Dadin Kowa in a hill crossed by the Gombe road, whilst granite is found at not too great a distance to the east of Dadin Kowa. Sand occurs in the valley of the Gongola River. Clay, suitable for an impervious core and for a cover of a dam, can probably be found in sufficient quantities either on the plains along the Gongola River downstream of Dadin Kowa or upstream of the gorges towards Bajoga.

(ii) *Kombo site* (see Diagram III 3.4.8-1)

The height of a dam to be constructed near Kombo would be restricted to that of the ridge, which reaches only about 10—12 m (33 to 40 feet) above highest high-water level of the river, as mentioned in Paragraph III, 3.4.8.

Apart from the dam to be constructed near Kombo, two more embankments would have to be made in order to close other gaps situated to the east and to the west of the modern valley. The length of the dam near Kombo would have to be about 200 metres, the dike to the west of the river would probably have to be about 300 metres long, and the dike to the east of the river should have a length of about 200 metres.

A dam to be constructed near Kombo would have to be founded on arkosic sandstones. They have sufficient bearing capacity to serve as a foundation for a rockfill dam or an earth dam, although their strength has been unfavourably affected by their steep downstream dip which is the result of a fault and by the well-developed sets of joints which cut across.

Owing to their composition the arkosic sandstones generally have a low permeability.

Future studies will have to indicate the thickness of the alluvial deposits in the modern valley of the Gongola as well as in its abandoned river courses. To prevent dangerous seepage losses or pressures which might endanger the stability of the works, a cut-off([1 would have to be made through these alluvial deposits.

The arkosic sandstones are not suitable for building material. Rock might possibly be obtained either from the Basement Complex of the Kwaba Hills or from volcanic plugs situated upstream. Sand and clay of a good quality might probably be found in sufficient quantity both to the north and to the south of Kombo.

(iii) *Kiri-Bobore site* (see Diagram III, 3.4.8-1)

Prior to any decision for a dam to be constructed near Kiri, a survey should be made of the reservoir area, and mainly of the watersheds which extend from Kiri westward towards the Longuda Plateau and from Bobore eastward towards the Kaji Hills and Song, to ascertain that low-lying saddles and gaps, which would prevent the creation of a reservoir with a sufficient capacity, do not occur.

([1 a vertical screen, made by cement injections

The valley near Kiri is considerably wider than that near Dadin Kowa or at Kombo; a dam near Kiri would have a length of about half a mile.

The geological conditions, and hence the foundation conditions, remain fundamentally the same over a distance of about a mile downstream of Kiri. The choice of a dam-site will depend on the width of the valley and thus upon the shortest cross-section.

The arkosic sandstones which form the sides and the underground of the valley near Kiri are very much fractured and jointed, which unfavourably affects their strength, bearing capacity and permeability. When designing a dam these features have to be considered and measures have to be applied to prevent water circulation and pressures through the fractures and joints in the sandstones, which might endanger the stability of the works. For this purpose a detailed mapping will have to be carried out of all fractures and sets of joints and of all other geological features which could be of importance for the design of a dam.

In the river-bed of the Gongola sandy alluvial deposits occur, the thickness of which is as yet unknown. In view of the fact, however, that the major rivers and some of their tributaries at several places have proved to have deeply entrenched and sometimes canyon-like buried valleys lying underneath their present river-bed, and taking into account that this portion of the Lower Gongola Valley might represent a very ancient drainage line, the site of which has been determined by tectonical processes, it may well be that the valley of the Gongola here also shows a buried valley underneath the present river-bed. To reduce seepage losses underneath a proposed dam and to prevent water pressures which might endanger the stability of the works, provisions should be made, for instance by a vertical screen through the alluvial fill of the valley, made by cement injections.

The arkosic sandstones are completely unsuitable as a building material. A number of volcanic cones, however, has been observed in the area east and west of Kiri-Bobore and two more volcanoes occur about 5 miles to the north of Kiri on the west side of the Gongola River. Basalt suitable for building purposes might be found near one or more of the volcanoes (with the exception of the small volcanic vents situated to the east of the river). Sand occurs in the valley of the River Gongola. Clay suitable for an impervious core and for a cover of a dam can probably be found in sufficient quantities either in the flood-plains upstream of Kiri or in the flat area downstream towards the confluence of the Gongola and Benue Rivers.

It is clear that more data are required to determine which site eventually should be chosen. Each site has its favourable and unfavourable points, but they must be evaluated before they can be weighed against each other.

On the other hand, the requirements are not fully known. Even for the navigation on the Benue it is not sure whether peak storage or seasonal storage would be preferable.

It is understood that agricultural potentialities are very considerable in this area, and not only may they ask for dry-season irrigation but possibly also for an open shipping connection with the Benue to facilitate the evacuation of produce.

At the present time the Gongola is worse than it was 50 years ago, and navigation is reduced to a very low intensity; but a certain improvement in the navigability might be envisaged after the construction of a dam.

Under these circumstances, it is believed that discharge regulation of the Gongola is an interesting proposition, as it will benefit both the region of the Lower Gongola and the navigability of the Benue. The regulation, however, should be part of a multi-purpose scheme, and much further study is required for this.

An improvement of the Benue navigability will not as a first stage entail a Gongola discharge regulation, as that would not solve the problems of the Garua trade. Therefore, any further

studies for Gongola schemes have been considered to be beyond the scope of the Niger and Benue Investigation.

c. *Taraba River* (see Diagram III, 3.4.9-2)

One site on the Taraba is found suitable for the construction of a dam, i.e., near Dalli, and which has been discussed in III, 3.4.9. In case a dam should be constructed there, the following remarks are made:

The porphyric granites, if not too strongly affected by weathering, would form an excellent foundation rock with a relatively high bearing capacity (sufficient for a concrete dam) and an extremely low permeability. Depth and intensity of weathering, which in Nigeria in granite areas may reach to a depth of more than 100′ below ground-level, and fracturing by tectonic processes may, however, influence strength and permeability of the rocks.

If further investigations are to be undertaken, full attention should be given to the depth and degree of weathering of the granites in the entire foundation area of the dam. Furthermore, a detailed mapping should be carried out of the veins, dikes, faults, fractures and lineations cutting across the granites, which also influence their consistency. At the same time, it will be indispensable to determine the depth of the alluvial fill in the valley bottom by means of boreholes or a combination of geophysical investigations and boreholes. The sedimentary fill of valley bottom normally forms a foundation of very inferior quality and of high permeability, requiring the construction of an expensive cut-off(1 below the foundations of a dam.

The sound granites provide a good building material, both for a rockfill dam and for concrete aggregates. Sand and gravel are present in large quantities. Clay to be used for an impervious core of a rockfill dam, however, will be more difficult to find in sufficient quantity.

It is obvious that much more information is required to design a dam and a reservoir here. At present it would seem that the situation for a reservoir is more appropriate than for a dam, the gap to be bridged still being of the order of 1,500 m, or nearly a mile.

In the foreseeable future no navigation on the Taraba is anticipated. Agricultural interests in the Taraba Valley, as far as known, are not considerable. Nor is electricity in very much demand, as no public supply is in existence at present.

Therefore the sole justification for a regulation scheme for the Taraba should, to-day, be found in the beneficial influence on the navigability of the main river, the Benue.

d. *Donga River*

No site has been found on the middle and lower courses of the Donga where an appreciable amount of water could be stored.

e. *Katsina Ala River*

Near Kasimbilia, in the middle part of the Katsina Ala, a site has been found which is suitable for the construction of a dam. Nevertheless such a venture is not recommended as, in the first place, only a part of the total discharge can be regulated, as much more water is collected in the lower course of the river, while secondly the feasible reservoir capacity would probably be inadequate for the ultimate purpose of the Katsina Ala debouching a fully-controlled amount of water into the Benue.

(1 a vertical screen trough the alluvial fill made by cement injections

8.3. JEBBA RESERVOIR

8.3.1. General

Some general remarks on this scheme can be made here, although bearing in mind that the figures and the ideas are still subject to further studies. More detailed information is obtainable from the Report on the Feasibility of a Jebba Scheme (1.

The average monthly discharges, as well as the outflow needed to maintain a certain least available depth from the Delta to Baro, can be seen in Diagram 8.3.1-1. The required outflow has been calculated for limit discharges occurring after the "retarded scour" (see Diagram III, 6.4.3-1), thereby assuming slightly improved river conditions because of the capture of the peak flows. Comparison of the required outflow with the actual discharges in the past years then reveals slightly greater calculated depths than actually have occurred.

Hydrographs show that a fairly small reservoir of about 4 milliard m^3 (3 million acre-feet) would be sufficient for supply during the months of May, June and July, thus extending the Black Flood period and creating all-the-year-round navigation. However, the groundnut crop, the main transport business on the Niger from Baro, arrives at Baro from November through to March or April. Navigation economy, therefore, would welcome in the first instance a raising of the Black Flood to increase the least available depth by one or two feet. Year-round navigation on these draughts, although perhaps it will be a "must" in future, is at present regarded of secondary importance.

To meet these navigational demands, a large reservoir is necessary. If a useful capacity of between 10 and 15 milliard m^3 (8—12 million acre-feet), which is still only 15 to 20% of the average annual run-off, would be used solely for navigational purposes, an increase of over a foot draught during the Black Flood period, and also an extension of the navigable season into the present low-water period, would be possible. But contrary to a Yola Scheme on the Benue, the benefits here would never meet the costs, owing to the different form of the discharge hydrographs and the length of the river (more ton-miles on the Benue for equal amounts of water).

A multi-purpose scheme, however, also mentioned in the NEDECO Interim Report, 1956, is very attractive, and fortunately the increasing demand for electricity has promoted an investigation into the feasibility of a Jebba project (see 8.2.1).

In the next paragraphs several sections of the Feasibility Report 1958/1959 will be quoted.

8.3.2. The alternatives

The investigation proved that the storage basin directly upstream of Jebba, where two dam-sites are possible, was not as favourable as expected. To obtain the desirable storage volume a dam 180′ high would be required.

At the same time the new contour maps indicated the existence of six more dam-sites, of which at least three proved feasible and were investigated in as much detail as time permitted.

The sites going upstream from Jebba are (see Diagram 8.3.2-1):

1 and 2 near Jebba
3 near Yankyadya (29 miles upstream)
8 near Donko (40 miles upstream)
4 near Kurwasa (66 miles upstream)

The total potential can be developed by 6 alternative combinations of the above dams (Table 8.3.2-2). Of these alternatives D and E are single dam developments at dam-sites 2 and 3 re-

(1 joint report by BALFOUR, BEATTY & CO, and NEDECO, 1958/1959.

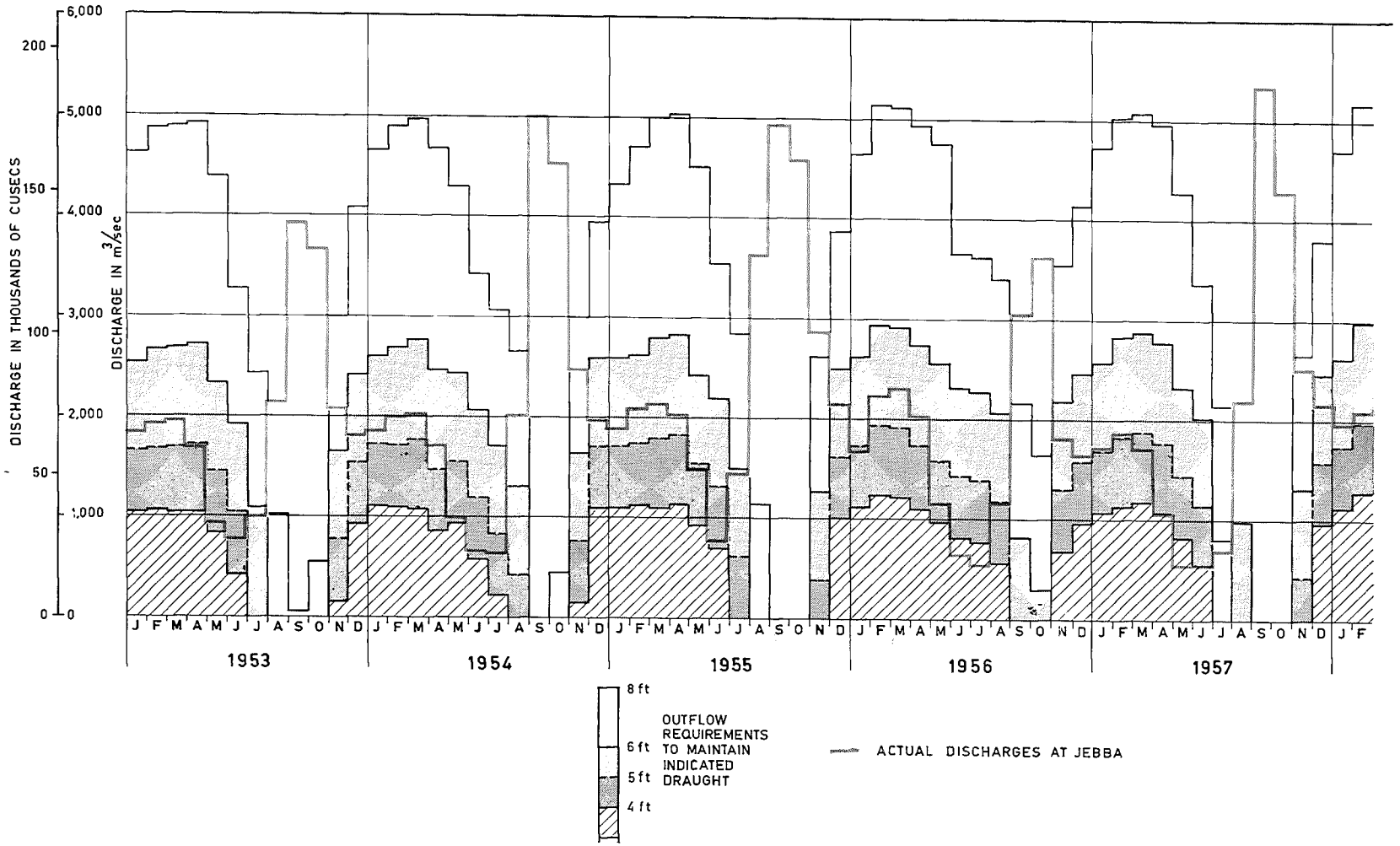


DIAGRAM 8.3.1-1

Average monthly discharge at Jebba and outflow requirements for various draughts

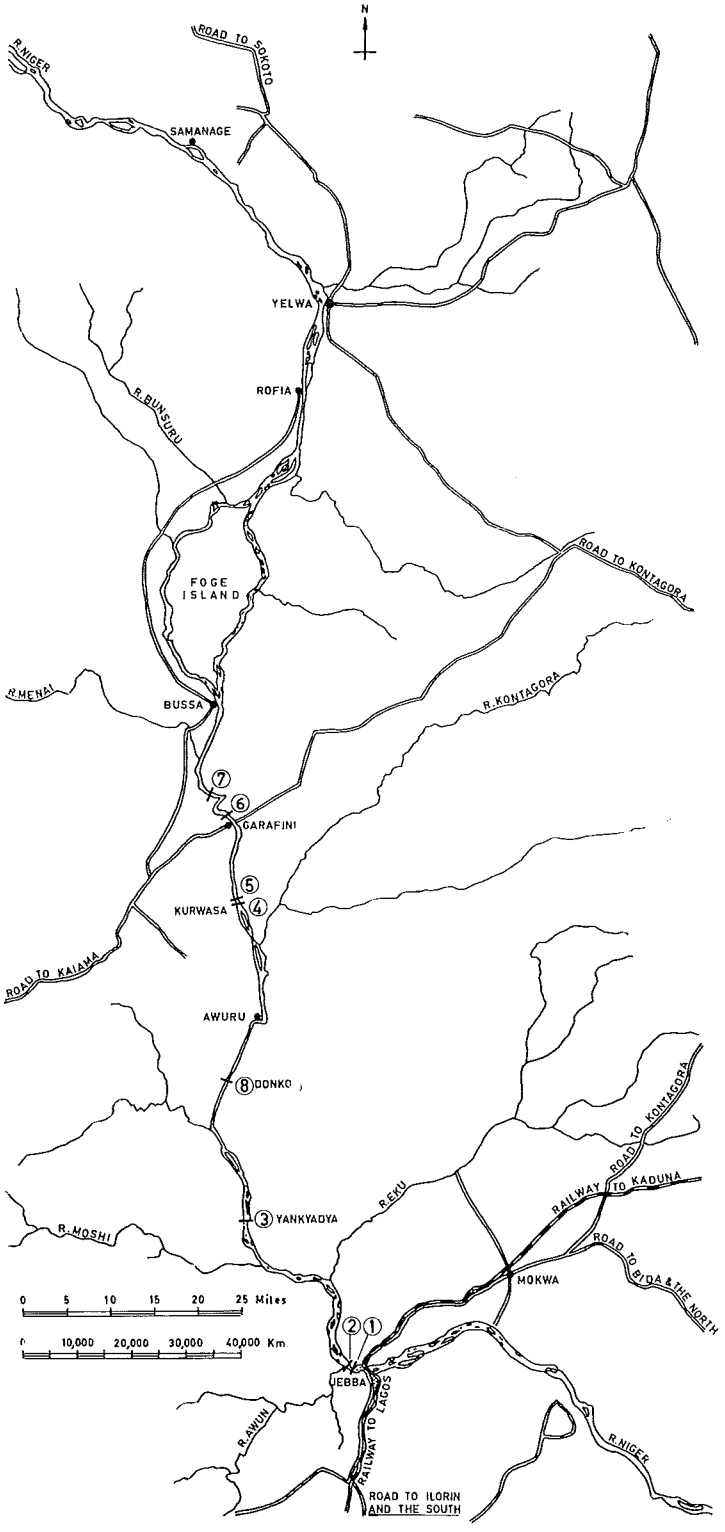


DIAGRAM 8.3.2-1

Alternative dam-sites

spectively. Due to the lesser average head, their output is some 20% less than for the alternatives A, B and C and therefore relatively more expensive.

TABLE 8.3.2-2
ALTERNATIVE DEVELOPMENTS

Alternative	Dam No.	Height	Average operating head	Storage capacity		Annual load-factor at final stage	Demand capacity	Spare	Total installed capacity	T.W.L.
				× 10^6	× 10^9					
		feet	feet	acrefeet	m^3	%	MW	MW	MW	feet
	4A	130	120	10	12	44	1,000	100	1,100	460
A	1A	90	80	1.5	1.8	80	360	40	400	335
	Total	220	200	10.5	13	55	1,360	140	1,500	
	1B	90	80	1.5	1.8	80	360	40	400	335
B	4B	130	120	10	12	44	1,000	100	1,100	460
	Total	220	200	10.5	13	55	1,360	140	1,500	
	8	50	45	—	—	80	200	25	225	340
C	4C	130	110	10	12	43	950	100	1,050	460
	1C	50	45	—	—	80	200	25	225	295
	Total	220	200	10	12	55	1,350	150	1,500	
D	2D	180	160	11	13.5	55	1,060	100	1,160	426
E	3E	180	165	15	18	55	1,100	100	1,200	454
	3F	70	68	0.3	0.4	80	300	30	330	340
F	4F	130	110	10	12	45	900	100	1,000	460
	Total	190	178	10	12	55	1,200	130	1,330	

The other four alternatives have the dam-site at 4 in common: combined with a 90′ high dam at site 1 (for A and B), with 50′ high dams at sites 1 and 8 (for C), and with a 70′ high dam at site 3 (for F). The last alternative has less head than A, B and C and is therefore also relatively more expensive. The difference between A and B is only the sequence of construction of the dams.

Because, furthermore, alternatives A, B and C make co-ordination of the several interests possible to practically the fullest extent, alternatives D, E and F were discarded and only the first three are further discussed.

8.3.3. The consequences of the scheme

Whichever alternative is adopted, when fully developed its results for the several interests are:
(i) On the assumption of a load factor of 55%, a firm capacity of 1,350 MW could be installed; with about 10% spare this becomes an installed capacity of 1,500 MW.
(ii) If the Jebba project is *designed* to operate in conjunction with other hydro sources like the Shiroro Gorge Scheme, it would enable the capacity in these other schemes to be increased manifold as well as the capacity of the Jebbas although to a much lesser extent.
(iii) Regulation of the flow will improve navigation conditions by
a. increasing the low flows considerably so that depths will be increased throughout the Niger below the dam to 5½ to 6 feet the year round;
b. developing a more regular river section and profile, possibly increasing the depth by another foot to 6½—7 feet, at least to the junction with the Kaduna River.
(iv) By drowning all the rapids, the Niger becomes navigable to beyond Niamey.
(v) Flood control reduces the inundation of the fadamas considerably, thereby making these available for agriculture over a potential area some 10 miles wide and some 200 miles long.
(vi) Cheap power would be supplied possibly in 1966 for industry and for pump irrigation.
(vii) Water will be made available at a head of 40 feet above river-level for irrigation of areas adjacent to the river.
(viii) Roadway(s) would be provided across the Niger.

The most important facts and figures, including the year when they might become valid, are shown in Table 8.3.5-1. From these the following conclusions can be drawn:

Alternative A is the only one of the three under consideration by which *all* interests are satisfied early in the development; 1967 is possible.

The only limitation is in navigability past the rapids between dam 4 and Jebba. The main obstacle to this, the Awuru Rapids, can be overcome by a bypass-channel and lock at a cost of some £ 500,000; the remainder would be navigable for two-thirds of the year.

Disadvantages of this alternative are that the expenditure of this bypass would cease to earn any return when dam 1A is built, while the initial expenditure is considerably higher than on the other two alternatives.

Alternative B has a lower initial expenditure but postpones flood control, regulation of flow and drowning of all rapids until 1977.

Alternative C has the lowest initial expenditure, produces electricity a year earlier than A or B and only postpones flood control, regulation of flow and drowning of all troublesome rapids until 1970, i.e., only 3 years later than for alternative A.

An important advantage of C is that because it is a three-dam development, the construction of the middle one can be put in hand before the design of the whole scheme is complete. Any adjustment which may be required can be made at a later date by altering the design (both in height and in installed capacity) of the upstream and downstream dams with the assurance that full advantage can be taken of the potentialities of the site.

The extra time devoted to records and study will greatly improve the reliability of the data on which the design must be based and will result in the production of a more economic scheme.

This will be especially true if other hydro sources, such as Shiroro Gorge or the Plateau rivers, are to be integrated with Jebba.

At 400 MW installed at a load factor of 55%, the cost per kWh sold will be under 1.1d for all alternatives. In the final stage the corresponding cost will have dropped to about 0.5d per kWh sold. These figures compare favourably with the estimated 1959/1960 cost of thermally-generated units.

8.3.4. Improvements for the navigation

a. *Increase of available depth*

The production of electricity requires a useful storage as given in Diagram 8.3.4-1. The volumes between the lines through the maximum storage (12×10^9 m^3) and the curves representing the electricity requirements are the volumes utilisable for navigation and flood protection purposes. It follows that the average monthly discharges that can be released for shipping purposes, additional to the inflow and when the reservoir is filled to its capacity before April 15, are:

April	1,300	m^3/sec
May	810	,,
June	540	,,
July	770	,,
August	270	,,

In many years the reservoir can be filled in or before November, so that the Black Flood can pass the reservoir unaffected. Prediction of the discharges of the Black Flood allows the distribution of the amount of water of that period equally over the months, so that during December

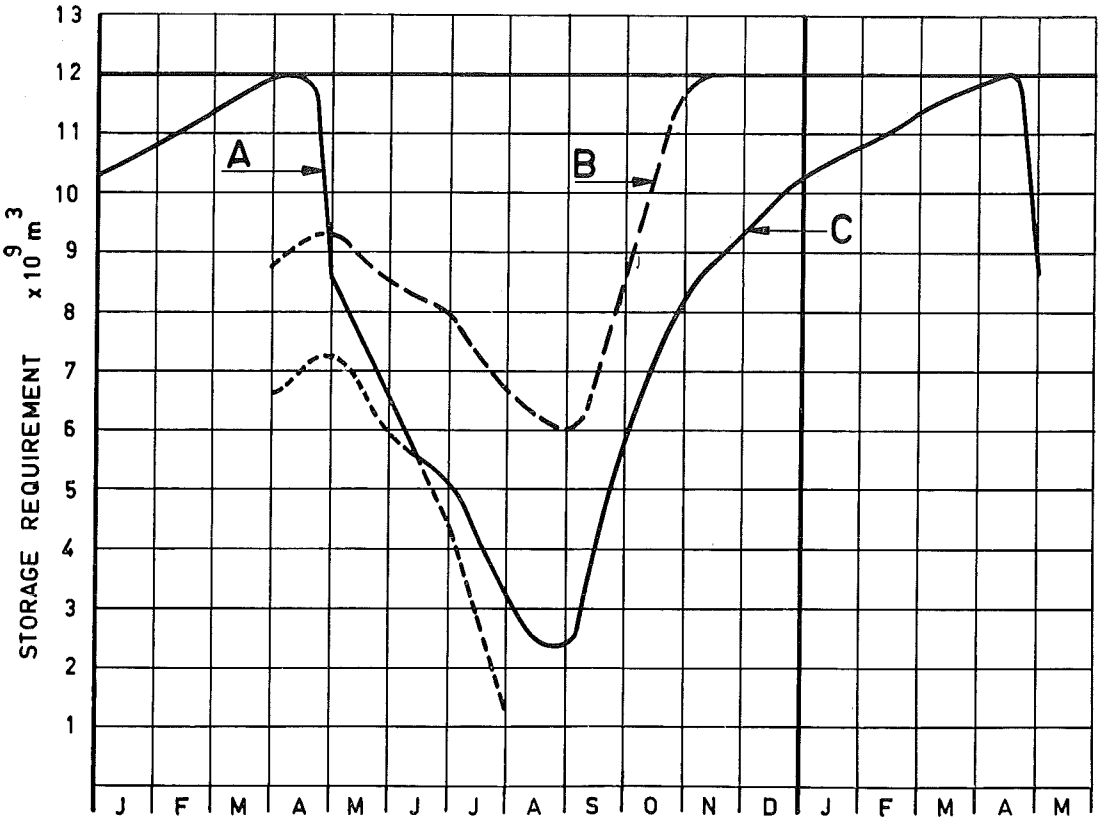


DIAGRAM 8.3.4-1

Storage requirements for electricity production

A. Emptying curve. Storage can be emptied at any date to the corresponding volume without danger of failing in a hundred year drought.
B and C. Filling curves. If the storage volume is maintained above these values, filling of the storage before November 15 (for B) and April 15 (for C) is ensured.

to April inclusive an average of 260 m^3/sec, in addition to the inflow, can be released each month, raising the least available depth from Baro to the Delta by about a quarter of a foot.

During the low flow period from April to August, the increase of the outflow will raise the least available depth between Baro and the Delta by at least a foot, thus bringing the least available depth for all-the-year-round navigation to between 5 and 6 feet in average years.

In dry years, when the local flood has failed to fill the reservoir by November, the discharges of the Black Flood may have to be decreased to prevent a failure of the electricity output. But as the said 260 m^3/sec will be added again to the discharges, the actual outflow will be less than the present ones only on rare occasions (the frequency of which needs some further study).

To some extent the lowering of the flood-peaks has been taken into account when calculating the outflow requirements with the least measured limit discharges, although the expected but incalculable improvement of the river channels resulting from the evened discharges has not yet been considered. This effect will be pronounced between the dam and the Kaduna River, still noticeable above Lokoja, but hardly perceptible on the Lower Niger where especially the Benue will still contribute to high floods.

The additional release of water during June and July will also raise the water-level at the

Lokoja Confluence, thereby increasing the depth on the Benue Bar. Consequently the start of the Benue season will be advanced some days (see under c of this paragraph).

Summarising, the navigation to Baro will become all-the-year-round for draughts between 5 and 6 feet in normal years and the Benue season will be advanced a few days.

The dates at which the advantages to navigation will accrue are listed below for alternatives A, B and C:

	Alternative		
	A	B	C
Increase in draught to 5½′—6′			
(a) Below Baro for 10 months of year	1967		
(b) whole river downstream of Yelwa for whole year	1984	1977	1970

Further improvement of the draught can be obtained if the dam at Site 4 is increased 10′ in height, thereby providing an extra 7×10^9 m³ storage volume, the cost of which is estimated at £ 2,500,000. But owing to the fact that this extra volume cannot be filled in drier years, the full benefits will only be reaped in 1½ to 2 out of every 3 years on an average.

If the Jebba Scheme is designed to operate in conjunction with the Kaduna or Plateau hydro stations, it might be possible to fill the excess storage practically every year and the release from the stations might be higher from November to June, thereby increasing the draught by an additional 0.2 to 0.4 feet to slightly over 6 feet.

b. *Navigation beyond Jebba*

Navigation past the rapids will be made possible because the dams will eventually drown all rapids between Jebba and Yelwa. Thus the Niger will become navigable from the Delta right into French territory.

The dates at which navigation upstream of Jebba becomes possible for alternatives A, B and C will be:

	Alternative		
	A	B	C
Navigation possible from Jebba upstream to above Yelwa:			
(a) for two-thirds of year, by the provision of the Awuru bypass canal (cost £ 500,000)	1967		
(b) for whole year	1984	1977	1970

c. *Effect on the Lokoja Confluence*

A discharge regulation on the Niger by the construction of a storage reservoir near Jebba would doubtless affect the Benue Bar near Lokoja, which hampers navigation while entering the Benue in about June (see V, 3.1.2) and causes a delay of some two weeks. It is originated by deposition of sand from the Niger during the Black Flood period and by draw-down of Benue's water-level at the very moment when ships want to pass the Bar.

On the one hand, with the Niger discharge regulated, deposition of sand would take place

at about the same rate as at present, since the raise of the Benue levels in December to April will be only slightly different. But, on the other hand, draw-down of the Benue water-levels would no longer occur, or would at least be very small, since the Niger would not fall to its present low water, and the reduction of available depth would therefore be less than now. There is even the possibility of giving more water from the Jebba storage during the short period of about two weeks when the Benue itself has already sufficient depth, while the Bar is determinant for navigation possibilities. If the Niger discharge would be increased to some 2,200 m^3/sec corresponding to a reading on the Baro gauge of 11 feet, involving that the Benue water-level would be raised $1\frac{1}{2}$ feet instead of drawn-down as the situation is now, the deposited sand masses would be covered with enough water to permit ships to pass. Such temporary increase of discharge from the Niger would be necessary during some two or three weeks only, as after that period the discharge from the Benue is so large that the Bar does not play any rôle.

The deposited sand masses in the entrance, which are now scoured away during the period of draw-down on the Benue in the period from April to June when the Niger is low, would then remain there because in that period no draw-down of the Benue takes place. However, in September and October the Benue discharge without any regulation would still be as high as it is at present, while the Niger discharge would be greatly moderated by the filling of the storage reservoir in Jebba. The present raise of the Benue's water-level would then possibly be reversed into a draw-down, which would have a relatively large effect upon the equilibrium state of the river-bottom (see III, 6.5.8) and probably result in a lower bottom-height of the lowest section of the Benue. Such a situation would be very favourable for the Benue Bar conditions.

However, formation of a bar in the Upper Niger entrance is then likely to occur during high water, when the (artificially maintained) moderate Niger is strongly raised by the high Benue; but the bar will be scoured by draw-down in the Niger during the dry season, when the Niger has still a moderate discharge and the Benue is almost dry. The new equilibrium of the Upper Niger river-bed is determinant for whether these variations will hamper navigation. The equilibrium has not been computed, but it is estimated that a shoal may become an impediment for navigation when the Niger is drawn-down to its maximum rate, i.e., during February to April.

Summarising, discharge regulation on the Niger affects the Lokoja Bar in the Benue Entrance favourably, but might lead to less depth in the Niger Entrance, while near Suli on the Upper Niger some 9 miles upstream from the Confluence a shoal will probably hamper navigation even more than at present.

However, a decision on whether or not a discharge regulation would be carried out should not depend on considerations about the Lokoja Bars, because temporary dredging and local training-works can always solve the navigation problem at these particular areas.

8.3.5. Time and order of construction

The estimated time to construct each of the dams and power-stations and the order and rates of commissioning the three alternatives would be as in Table 8.3.5-1.

TABLE 8.3.5-1
TIME AND ORDER OF CONSTRUCTION

Alternative	A		B		C		
Dam	4A	1A	1B	4B	8	4C	1C
Construction time in years	5	5	5	5	4	5	4
Year of commissioning	1967	1984	1967	1977	1966	1970	1988

8.3.6. Cost and their allocation between the several interests

A preliminary allocation of capital cost between the several interests in proportion to the expected direct benefits is given in Table 8.3.6-1.

TABLE VI, 8.3.6-1
ALLOCATION OF CAPITAL COST
(in £ 1,000 and in percents)

Alternative A

Dam No.	4A		1A		total	
Hydro-electric generation	66,096	93.0%	39,161	96.1%	105,257	94.1%
Navigation	3,162	4.5%	1,500	3.7%	4,662	4.2%
Irrigation	866	1.2%	—	—	866	0.8%
Fisheries	900	1.3%	75	0.2%	975	0.9%
Total	71,024	100%	40,736	100%	111,760	100%

Alternative C

Dam No.	8		4C		1C		total	
Hydro-electric generation	22,070	96.2%	64,427	93.2%	23,844	96.4%	110,341	94.5%
Navigation	846	3.7%	2,912	4.2%	846	3.4%	4,604	4.0%
Irrigation	—	—	866	1.3%	—	—	866	0.7%
Fisheries	25	0.1%	900	1.3%	50	0.2%	975	0.8%
Total	22,941	100%	69,105	100%	24,740	100%	116,786	100%

8.3.7. Further investigations required

Before construction can be put in hand, a more thorough investigation of all aspects of the project will have to be carried out. This can be divided into the following categories:
(i) *Hydrological, meteorological and biological investigation*, such as fisheries and health hazards. These are matters which in a more developed country than Nigeria would be available as part of the normal scientific services, and are not reasonably chargeable solely to the Jebba Scheme or any other project.

Much of this information should be based on long-term records properly evaluated which are irreplaceable and cannot be quickly acquired. For example, if it were not for the work on the Niger and Benue Rivers which the Government of Nigeria wisely commissioned in 1953, the present evaluation of the possibilities of the Jebba area would be much more hazardous. It is therefore suggested that the expansion of these services should be put in hand at the earliest possible date as being a matter of very great importance.

The additional cost can certainly be covered many times by the development of Nigeria's resources.

(ii) *Investigations upstream of Jebba* to prove beyond doubt the capacity of the reservoirs and the competency of the selected dam-sites. These must comprise air photography, topographical survey, geological survey and drilling.

If it is desired to hasten the production of a general design, an interim report on this investigation should be issued as soon as sufficient information is available.

If the Jebba stations are to operate in conjunction with other hydro sources such as the Shiroro Gorge or stations on the Plateau, the study thereof should be incorporated in this investigation. Failure to do so would reduce the benefits to the other stations to a small fraction of what is possible.

(iii) *Investigations downstream of Jebba* are required to establish what areas are available and suitable for agriculture. They will entail both air and ground surveys, as well as soil surveys and crop tests.

(iv) *General design* of the selected alternative to enable a decision to be reached on the preparation of contract documents. This cannot be put in hand until the results of the investigations upstream of Jebba are known.

8.4. LAGDO RESERVOIR ([1]

8.4.1. Description

In the Upper Benue, 40 miles upstream from Garua, an excellent dam-site (see Photograph 8.4.1-1) has been found and prospected by the French investigators of Electricité de France,

PHOTOGRAPH 8.4.1-1
Lagdo defile ([2]

([1] ELECTRICITÉ DE FRANCE, 1958. GEN. 11
([2] ORSTOM, 1955, GEN. 27

on behalf of the Cameroun Government. About 75% of the Benue water that passes Garua is passing through this "gap", the remaining 25% being supplied by the Mayo Kebi, a more impulsive river than the Benue which debouches into the Benue at some 12 miles upstream from Garua.

The gauging station for Lagdo is situated at Riao, 3 miles below the dam-site. Discharge measurements and water-level records exist from 1950 onwards; they are published in the "Annuaires Hydrologiques" ([1. The following annual totals are given:

Annual run-off

year	milliards m^3	millions acre-feet
1950	7.9	6.4
1951	7.1	5.8
1952	—	—
1953	6.3	5.1
1954	8.7	7.1
1955	11.9	9.7

The drainage area covers about 30,000 km^2 (12,000 sq.miles). In the dry season the discharge may be in the order of 0.1 m^3/sec (3 cusecs). The maximum discharge in 1955 amounted to 3,150 m^3/sec (111,000 cusecs) but in 1951 only 1,200 m^3/sec (42,000 cusecs) was reached.

The Benue originates from the Adamawa Plateau, descends from it under a slope of 4% through gneisses, and continues in a northerly direction for some 200 miles, on its way passing several rocky sills, though the average slope is moderate. The longitudinal profile is shown in Diagram III, 4.2.5-2. After turning north-westward, it reaches the Lagdo defile, a distance of 50 miles with an average slope of about 25×10^{-5}.

In this section the Benue receives most of its affluents, such as the Mayo Rei, China and Boki. These tributaries, of equal length and running fanwise, contribute largely to the sudden rises of the Benue. This tendency is weakened by the action of the Mayo Kebi which has a rather different regime, but is accentuated again by the contribution of the Faro.

A geological description of the dam-site has been given in III, 3.4.5. Diagram 8.4.1-2 shows a cross-section of the river at the dam-site. The situation would allow the construction of a dam

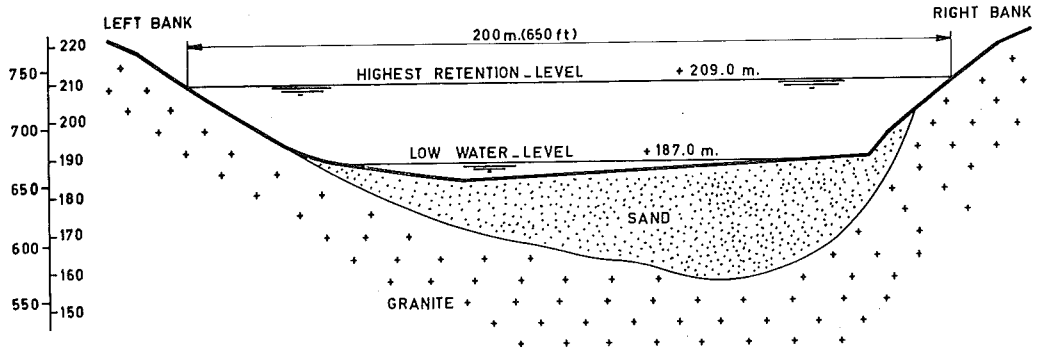


DIAGRAM 8.4.1-2

Cross-section of the Benue at Lagdo defile ([2

([1 ORSTOM, 1950—1955. HYD. 6
([2 ORSTOM, 1955. GEN. 27

32 m (105′) in height, yielding a reservoir basin of 6.5 milliard cubic metres (5.3 million acre-feet).

At first a moderate scheme of 4.5 milliard cubic metres (3.7 million acre-feet) was envisaged, which could be effected by constructing a dam 27 m (90′) high. As the river-bed is situated at 183 m (600′) above datum, the crest would be at + 210 m (+ 690′). The length of the crest would be 210 m (690′).

In the 1958 project ([1] the dam was raised 1 or 2 metres (3′ or 7′) and the capacity brought to 6 milliard m³ (5 million acre-feet).

The cost of the project was estimated at 1.9 milliard Francs CFA (about £ 3.8 million) in 1954 for 4.5 milliard m³, and at 3 milliard Francs CFA (about £ 6 million) in 1958 for 6 milliard m³.

8.4.2. Regulation programmes

The gauge readings at Riao, Garua, Wuro Boki, Yola and Numan have been transformed into discharge hydrographs, which indicate the amounts of water available passing the several stations.

From numerous extensive soundings the relation between least available depths and discharges resulted and limit discharges could be determined. The limit discharges (see also III, 6.4.3) represent the amount of water necessary to obtain a certain depth. The discharge hydrographs together with the limit discharges determine the regulation programmes of a reservoir with a certain size.

As to the extension of the navigation season, different programmes have been studied, resulting in the following proposal made in the Consolidated Report of 1958 ([1], submitted by Electricité de France to the Cameroun Government:

The gates of the Lagdo Dam will be opened 8 days before the navigation on Ibi (Mile 814) would become possible under present conditions. At the end of the season, the reservoir will supply water as long as the navigation on Ibi and Makurdi would be possible as at present. As an example, July 15 has been taken as the date of commencement for Ibi navigation. The sluices would be opened on July 7 and the shipping season of the port of Garua was thought to start on July 21. The August fall would be overcome in many years by supplementary discharges from the reservoir, and for a draught of 5 feet the average Garua season would be extended to 3 months, which is 1 to 1½ months more than at present. In dry years, the season would still be 2 to 2½ months.

The programme has been calculated for the limit discharges before high-water, given in Table 8.4.2-1. Discrepancies appear to occur between the figures under (a) and those of (b) and (c) due to the different principles governing the regulation with a small Lagdo reservoir or with a large Yola reservoir. The figures used by Electricité de France are derived from observations of the most unfavourable years.

The limit discharges at the beginning of the season depend to some extent on the characteristics of the previous year. When the previous flood has been excessive, the low-water channels are greatly deteriorated and subsequently the limit discharges will be high, in contrast to a preceding dry year when the low-water channels remain more intact. It happened that the run-off in 1955 was rather high (only surpassed once in 20 years), so that the limit discharges in 1956 were higher than normally. But as 1956 was an average year, the limit discharges of 1957 were generally lower than in the preceding year. The first French limit discharge at Wuro Boki (1,200 m³/sec or 42,500 cusecs) was related to 1955 measurements, whereas the limit discharges of the Consolidated

([1] ELECTRICITÉ DE FRANCE, 1958. GEN. 11

TABLE 8.4.2-1

LIMIT DISCHARGES BEFORE HIGH WATER

Draught		3 ft.	4 ft.	5 ft.	6 ft.	7 ft.	
Garua — Faro Confluence	a	350 12,400	425 15,000	500 17,700	600 21,200	700 24,700	m³/sec cusecs
Faro Confluence — Numan (Wuro Boki Flats)	a	800 28,300	1,175 41,500	1,600 56,600	2,000 70,800	2,400 84,500	m³/sec cusecs
	b			1,200 42,500			m³/sec cusecs
Numan — Lau (Gamadio Flats)	a	1,000 35,400	1,300 46,000	1,600 56,500	1.925 68,000	2,225 79,500	m³/sec cusecs
	c	555 19,400	820 29,000	1,100 39,000	1,360 48,000	1,650 58,500	m³/sec cusecs

a. from French Consolidated Report, 1958
b. from French Interim Report, 1955
c. NEDECO (III, 6.4.3)

Report refer to the unfavourable 1956 circumstances. NEDECO has been using data of several years, but determined the limit discharges according to the figures showing the greatest depth, which afterwards proved to be in concordance with 1958 experiences.

The French have been using their method rightly for a Lagdo Scheme because the Wuro Boki Flats might even deteriorate when regulating the Benue. The adverse influence of the Faro sand on the navigability of the Benue has been, to some extent, taken into account by very conservative assumptions. This method has also been used for the Gamadio Flats. Although the arguments here are not so strong, the method certainly yields safe results.

When a large Yola reservoir is in operation, or a combination of a Lagdo reservoir and a small Yola reservoir, the problems round Wuro Boki and the Faro Confluence are immediately solved by raising the water-level. Moreover, the discharges below the dam and over the Gamadio Flats will be very much equalised and consequently the channel of the Gamadio Flats will no longer be deteriorated by high discharges. It is quite reasonable, therefore, to reckon with the limit discharges as occurred in the most favourable years, i.e., after a low H.W.-period, when the sills were not much raised. Even then the results remain on the conservative side.

8.4.3. Additional effects

The realisation of a reservoir-dam near Lagdo and the introduction of a discharge regulation programme would have a number of additional effects.

Upstream of the dam, a large area would be submerged extending over 70 km (43 miles) along the river. In the reservoir lake silt and sediments would be deposited, and rather clear water would be released.

Immediately downstream of the dam this clear water will resume its sediment-transporting action, and in the river-bed scour will develop. This kind of bed-erosion will propagate downstream very slowly, but will probably in due course include Garua. However, the channel between the dam and Garua is expected to improve if devastating flood peaks can be avoided.

Above Garua the Mayo Kebi debouches, and its influence would make itself felt more seriously after the Benue has been regulated. It could mean that the sediments which are carried

down by the Mayo Kebi would deposit in the bed of the Benue, as this river would no longer have its original sand-transporting capacity (see III, 6.6.9). Again, this influence will not soon make itself felt near Garua.

Taking all effects together, it is expected that the navigation channel at and below Garua will improve slightly as a consequence of the prevention of peak floods.

At and below the confluence with the Faro, the same effects will develop as described for the case of the Mayo Kebi. But considering the fact that the Faro is of about the same size as the Benue and carries perhaps five times the amount of sediments, the effects will develop on a much larger scale, and here inside the navigation channels.

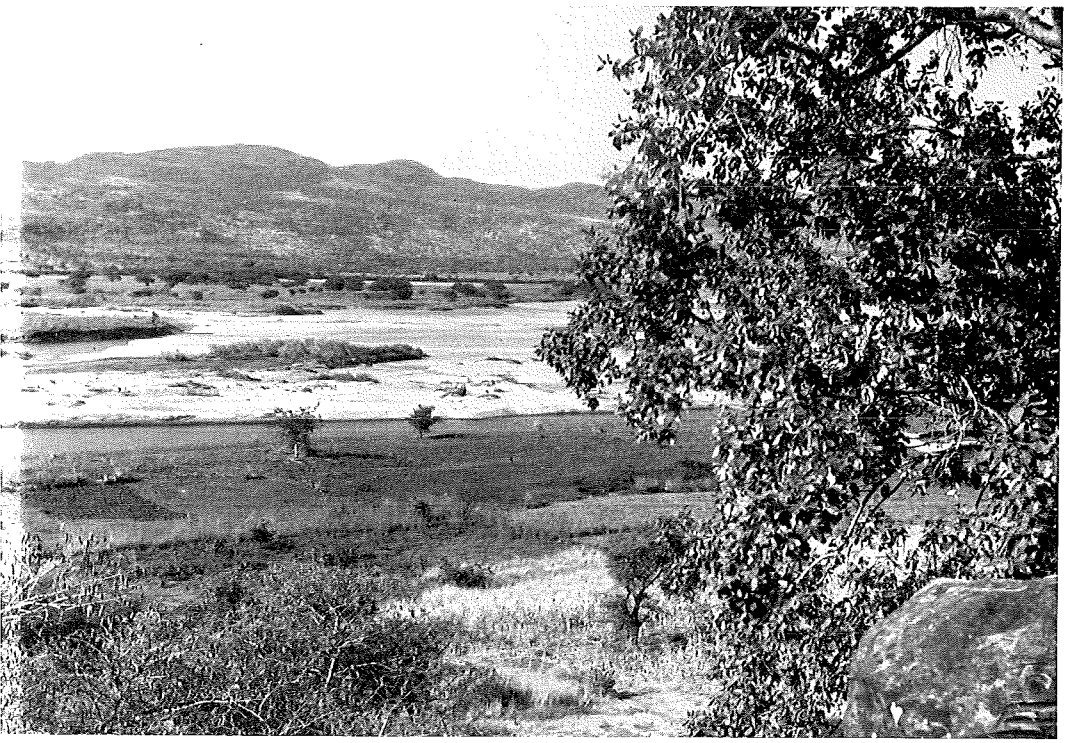
It may be true that the irregular discharges of the Faro can be more or less counterbalanced by regulating the supply from Lagdo, and that the development of a more regular channel can be expected. But the same amount of sediment as before a Lagdo regulation will be delivered by the Faro at the confluence, an amount which could no longer be coped with if the combined peaks were reduced. The issue seems uncertain: more regular channels on the one hand, and increased siltation on the other. This problem should be thoroughly studied, as it appears to be the weakest point of a Lagdo Scheme, unless at the same time, or not too long afterwards, the Wuro Boki Flats are drowned by a Yola reservoir.

Downstream of the Wuro Boki Flats only beneficial effects are anticipated from a Lagdo discharge regulation.

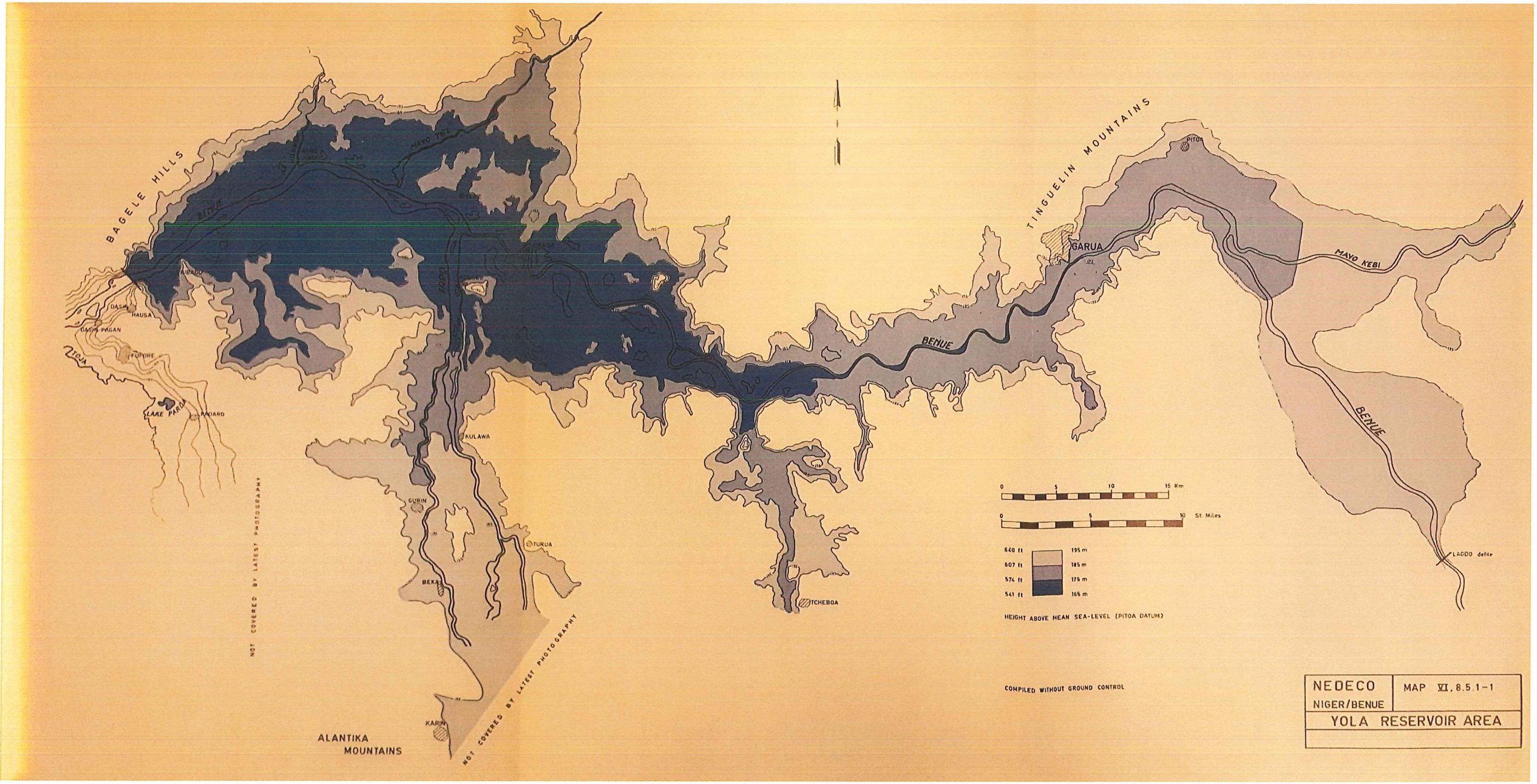
8.5. YOLA RESERVOIR

8.5.1. Topography of the Yola Reservoir

Fifteen miles above Jimeta (the port of Yola), in the valley narrowing near Dasin Hausa, a reasonably good dam-site exists (Mile 904). In 1956 at NEDECO's request the Federal Survey Department made aerial photographs of the area covered by a possible reservoir that would be created by a dam at this site. From the photographs, maps have been compiled in Holland showing contour-lines at 5-metre intervals from 165 to 200 m (541 to 656 feet) above datum. All heights have been reduced to the Pitoa datum (6 miles north-east of Garua) which, according



PHOTOGRAPH 8.5.1-2
Dam-site Dasin Hausa


BAGELE HILLS
TINGUELIN MOUNTAINS
BENUE
MAYO KEBI
BENUE
LAGDO defile
GARUA
PITOA
YOLA
DASIN HAUSA
DASIN PAGAN
FUFORE
LAKE PARO
RADARO
KULAWA
GURIN
TURUA
BEKA
KARIM
TCHEBOA
ALANTIKA MOUNTAINS
NOT COVERED BY LATEST PHOTOGRAPHY
NOT COVERED BY LATEST PHOTOGRAPHY
0 5 10 15 Km
0 5 10 St. Miles
640 ft 195 m
607 ft 185 m
574 ft 175 m
541 ft 165 m
HEIGHT ABOVE MEAN SEA-LEVEL (PITOA DATUM)
COMPILED WITHOUT GROUND CONTROL
NEDECO
NIGER/BENUE
MAP VI.8.5.1-1
YOLA RESERVOIR AREA

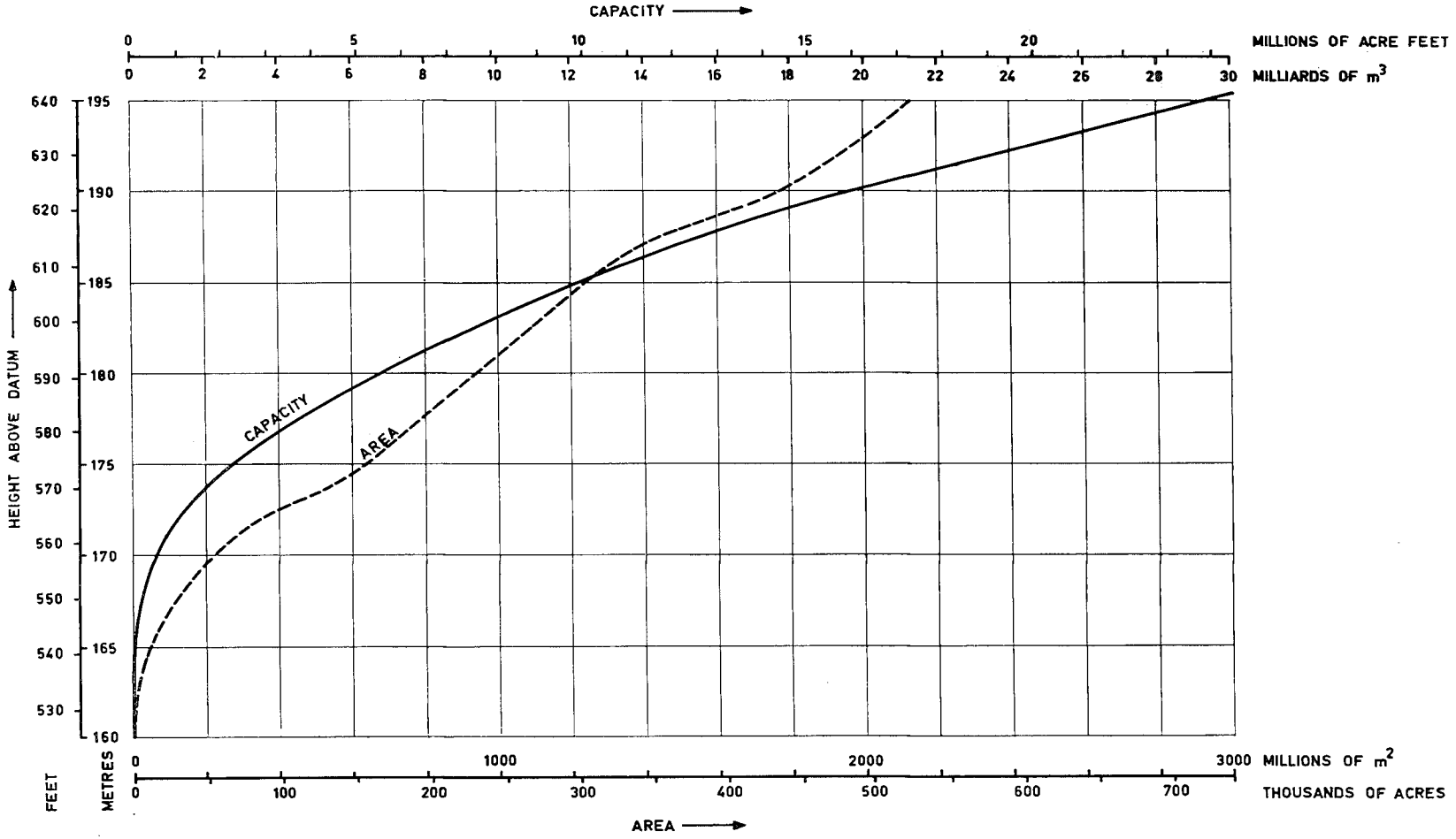


DIAGRAM 8.5.1-3

Reservoir area and capacity curves

to the French primary levelling, will be about mean sea-level. Apart from the heights of the water-levels in the Rivers Benue and Faro, which are known with fair accuracy, the maps had been compiled without ground control.

From the maps and from the special geological survey in 1957 it became apparent that near Beka the watershed on the left bank of the Faro River might be at a decisive height. To ascertain the correct levels of this region, which is just outside the photographed area, the Federal Survey Department early in 1958 levelled from Yola over the dry season road along Lake Parda to Gurin, Beka and Karin. The watershed near Beka proved to be 193 m (633') above datum. To the west of it a large, almost horizontal plain extends, slowly rising to higher ground somewhere between Beka and the Toja River. The report of the geological survey also mentioned a ridge, only slightly higher than the surrounding country, which is the watershed between the Faro and the Toja. The results of the levelling have been used for drawing the contour lines on Diagram 8.5.1-1.

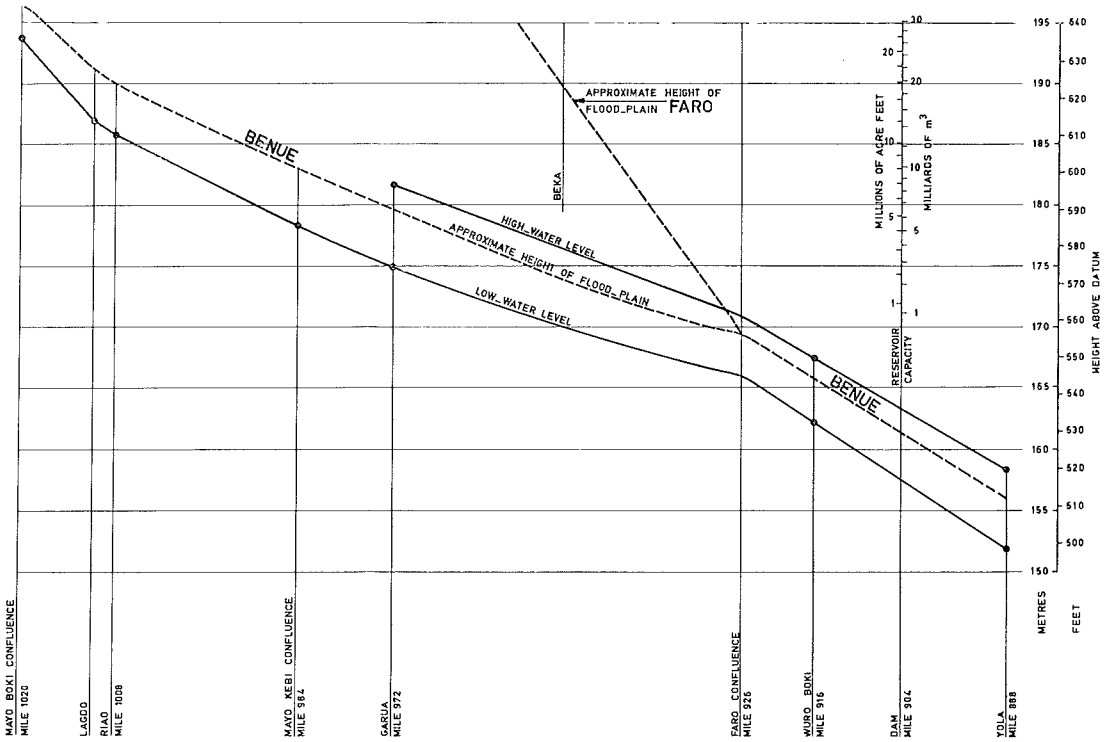


DIAGRAM 8.5.1-4

Water-lines above dam-site

The aerial photographs, covering nearly the complete reservoir area downstream of Garua, did not include the territory above Garua. This extension of the reservoir map has been compiled from the 1 : 200,000 map of the Service Géographique de l'A.E.F. et du Cameroun, together with calculated river-levels and flood-plain heights.

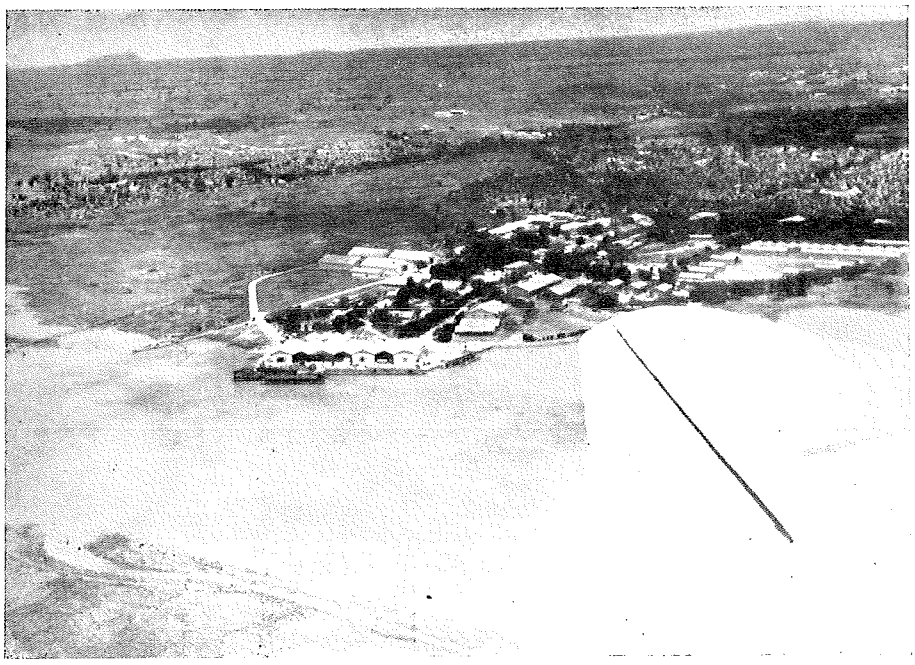
The approximate reservoir surface and volumes have been plotted in Diagram 8.5.1-3 and in Diagram 8.5.1-4 the present high-water and low-water levels are shown. The present water-levels at Garua, the only port on the Benue with a concrete embankment, are between 175 and

182 m above datum (574′ and 597′ respectively). The wharf has a low quay at + 179.9 m (590′), a high quay at + 182.9 m (600′) and four sheds at + 182.9 m floor-level. The sheds and stores of the commercial firms are situated close by on a slightly higher level (Photograph 8.5.1-5).

A water-level of + 185 m (607′) would inundate the port area and the water would then have risen to the edge of the native quarters. About half the area of the present native settlement will be covered at a stage of + 190 m (623′), but to affect the senior service and government areas the water would have to go up higher than + 200 m (656′).

In the reservoir area downstream of Garua very little land is under cultivation and only some minor settlements would have to be removed. Ribadu, three miles upstream of Dasin Hausa, lies between + 175 m and + 190 m (574′ and 623′). Wuro Boki, on the right bank at Mile 916, Tepe near the Faro Confluence, Bilachi (r.b. Mile 919) and Kinada (l.b. Mile 930) will be unundated at a level of + 175 m.

Between + 175 m and + 185 m (574′ and 606′) Kossel on the Faro and some small settlements between the Faro and the dam will be covered. Chikito, Gurin and Beka on the left bank of the Faro are between + 185 m and + 190 m, whilst Muninga, Turua and Kulawa for the greater part lie above + 190 m.



PHOTOGRAPH 8.5.1-5

The port of Garua in 1954

The Benue in spate. Lower quay, to the left of the sheds in the foreground, submerged

In contrast to the flood-plains downstream of Garua, agricultural use of the seasonal flooded area above Garua seems to have developed to some extent. Round Garua the flood-plains are at about + 180 m (590′); they gradually rise to + 184 m (603′) near the Mayo Kebi Confluence and to about + 190 m (623′) just below the Lagdo defile. The flood-plains bordering the Mayo Kebi rise to + 190 m and + 195 m about 5 and 8 miles from the confluence with the Benue.

Communications will be improved by the creation of the lake. In the reservoir area bush-tracks and a few minor dry season roads are the only means of communication apart from canoe

traffic. Lack of water in the rivers during the dry season, however, restricts canoe traffic to very light craft, but when during the rains the river has overflowed its banks and tracks and dry season roads become impassable, then canoes are the only means of getting from place to place.

The only major road affected by the heightening of the water-level is the north-south road passing through Garua. Construction of a dike, two miles long, through the flood-plains (about + 180 m or 590 feet above datum) will be necessary if a bridge is contemplated, or else the ferry will have to be used over this distance.

The lowest possible water-level of the reservoir is the present low-water line (Diagram 8.5.1-4). Sanitation, fishing and navigation require higher future minimum levels. At present, the lower quay at Garua is accessible to ships drawing 5′ when the water-level is at least + 177.85 m (584′). As it certainly has advantages to maintain year-round navigation on the lake, a minimum storage-level between + 175 m (574′) and 180 m (590′) seems advisable. If the quays are to be used at a water-level of + 175 m, the channel leading to the port of Garua will have to be dredged some feet at some places. To maintain the channel, however, recurrent dredging will be necessary, because sand is likely to deposit in the environment of Garua (see Paragraph 8.5.5).

The normal highest and the maximum retention levels, depending on considerations of economy, which in their turn are based on many different factors, will be discussed in Paragraph 8.5.4.

8.5.2. Geology

The general topography, morphology and stratigraphy of the dam-site area and, roughly, of the reservoir area have largely been discussed in III, 3.4.7. The geological survey had a special bearing on the site of the dam, the permeability of the reservoir walls and the availability of building materials for the construction of the dam. In this sequence the results of this preliminary investigation can be summarised as follows:

a. *The site of the dam*

A dam could be constructed either near Dasin Hausa or near Dasin Pagan, the first site being the more favourable because of a narrower cross-section of the river valley. The geologically determined foundation possibilities are the same at either site.

The gently dipping cretaceous arkosic sandstones are suitable as a foundation rock for an earth dam, as they are very homogeneous and relatively impervious. No complex tectonic disturbances which would complicate the planning and construction of a dam near Dasin Hausa were observed.

Reconnaissance drilling underneath the river-bed of the Benue proved the existence of a buried valley filled with coarse, very permeable sands, with some thin clayey intercalations. The presence of this alluvial fill in the Benue Valley to a considerable depth will necessitate the construction of an expensive cut-off and drainage system underneath the dam, in order to prevent water losses, phenomena of piping or internal erosion and pressures, any or all of which might endanger the stability of the dam. Therefore prior to designing a dam, extensive investigations will have to be made into the thickness and composition of the alluvial fill. Geophysical (geo-electrical) methods in addition to test drilling might be of much use for these investigations.

b. *The permeability of the reservoir walls*

The amount of water that would drain away through the sides of the reservoir — mostly relatively impervious cretaceous arkosic sandstones with some intercalations of shales and clay beds — cannot be calculated without a more thorough investigation all over the area. It is assumed,

however, that after saturation of the surrounding soils the actual losses are included in the estimates for losses through evaporation taken over the lake area (see III, 3.4.7 and Diagram 8.5.3-9).

Of special interest is the estimated amount of drainage water that flows back into the Benue Valley. The results of the survey work and the topographical and morphological conditions of the area between the Faro and the Benue show that an ancient river-bed exists to the south of the Benue River, connecting its valley near Jobolio with the Faro Valley near Beka. The altitude of the watershed, which crosses the ancient valley to the east of Padaro, probably exceeds the 220 m (726′) level and near Beka the ground-level is 193 m (633′). It was found that near Gurin and Beka, in the Faro Valley, the walls of the proposed reservoir consist of permeable alluvial deposits, being the fill of the ancient Benue-Faro Valley. However, in view of the slope of this ancient valley of an average of about 3 feet per mile, seepage losses, if any, will be only negligible. Even allowing for very unfavourable conditions, which are not believed to exist, the water losses through the fill of this valley will not exceed one million cubic metres per year or about 30 litres/sec (one cusec).

Seepage through the permeable sand-layers under the dam, after the construction of a vertical screen, will also be negligible for operational purposes.

c. *Building materials*

For the construction of the dam and additional works local materials are available. No complete inventory has been made, but the following particulars may prove useful:

(i) *Basalt* suitable for building purposes has been observed in several localities. Slightly weathered basalt, occurring in rounded blocks up to 40 cm (16 inches), forms a volcanic cone about 25 m high, lying west of Wuro Boki at a distance of about 2.5 km (1.6 miles) from the Benue, the base of which is about 500 m (1,500 feet) in diameter. Basalt with a strongly-developed jointing occurs in columns attaining 2 m (6′) in length with a diameter of 40—50 cm (about 1½′) in a volcano near Ngurore, in the neighbourhood of the road from Yola to Numan. The base of the volcano is about 300 m in diameter (1,000 feet) and it is nearly 60 m (200′) high. Two more volcanoes with the same type of rock occur in the same area.

A large number of basalt blocks suitable for rock-fill as well as for rock-dressing is available in the Yola region.

(ii) *Granite* exposures are found only at the foot of the Vere Hills, near the Yola—Karlahi Road.

(iii) *Gravel* has been found only in small quantities in the Yola region. Along the Karlahi Road near Beti gravel accumulations up to 2 m (6½′) thickness were observed, which form the residue of weathered cretaceous sandstones with intercalated coarse-grained sediments. The gravel contains quartz pebbles with a diameter of upto 5—10 cm (2—4 inches).

Sieving of the deposits will be necessary to obtain gravel of a suitable size for building purposes. The gravel accumulations were found over a distance of about 3 km (2 miles) along the road.

(iv) *Sands*, of all grain-sizes, occur throughout the whole region, especially in the present and former river-beds of the Faro and Benue. Grain-size diagrams of a few samples have been prepared (see Diagram III, 3.4.7-6).

(v) *Clay* deposits were found at many places in the Yola region. The clay beds lying on the surface between Jobolio and Fufore reach a thickness of at least 4 m (13′). Some soil mechanical data have been obtained for a few clay samples from this region. In the following list, values of Attenberg's limits of consistency, expressed in water content in percentage of dry weight, are given.

Dasin Hausa 2;	liquid limit	38.8
depth 10′6″	plastic limit	22.2
	plasticity index	16.6
	adhesion limit	37.1
	shrinkage limit	20.1

Jobolio; depth 3′	liquid limit	44.9
	plastic limit	18.4
	plasticity index	26.5
	adhesion limit	40.2
	shrinkage limit	16.7
Bank of River Toja between Jobolio and Fufore; 2 m (7′) below soil level	liquid limit	37.7
	plastic limit	15.2
	plasticity index	22.1
	adhesion limit	31.1
	shrinkage limit	15.2

These few tests give an impression of the quality of the clay, but about the quantity of the occurrences no information can be given. If clay should be required either for core fill or for dressing purposes, stock should be taken of the available material and many soil tests should be carried out. This would enable the extent and method of transport and application of that clay to be determined.

(vi) Neither the *sandstones* nor the *limestones* found in this region are of interest as a possible source for building materials.

d. *Ground-water development*

Although entirely beyond the scope of the present investigation, the results of the studies incidentally permit some interesting conclusions on the possibilities of ground-water development in the Yola region. The reconnaissance drilling carried out by the Geological Survey Department in the Yola-Jimeta area shows that the authorities are already concerned about this problem.

The cretaceous sandstones, because of their poor permeability, are not very promising from the point of water supply. The geological constitution of the ancient Benue-Faro Valley, however, forming a very dry area with the exception of the marshes of Lake Parda, offers much more favourable conditions. As a matter of fact, the coarse sandy deposits which fill the ancient valley below the topmost clay beds form an excellent aquifer at a shallow depth only. Considerable ground-water reserves are available because of the size of the valley. Moreover, in case of a development of the ground-water resources of the area, a sufficient natural recharge can be counted upon by water infiltrating from the Faro River near Beka and Gurin as well as from the River Toja and other streams which have cut their courses through the clay beds into the sands. This might be of importance when reclamation of this area, now very poorly populated for hygienic reasons, will be planned.

8.5.3. Reservoir programmes

a. *The amount of water available; not-regulated discharges*

Over a reasonable period and with fair accuracy water-levels have been read at Yola and at Makurdi. At Makurdi the Nigerian Railway Corporation established a gauge in 1914, and there are records of uninterrupted daily readings during the wet season and weekly readings during the dry season from 1932 onwards.

From the gauge at Yola, erected and read by the United Africa Company, wet season water-level records are available from 1934 onwards.

In 1954—1957 discharges have been measured at Yola and Makurdi, enabling the determination of stage-discharge rating curves for the present situation. Taking into account known changes over the years, and assuming that there were no other changes in gauges or in the river-bed, the discharges over the period of water-level records were calculated (Diagram 8.5.3-1).

DISCHARGES MASS RUN-OFF IN m^3/sec. (CUSECS)

THOUSANDS OF CUSECS

THOUSANDS OF m^3/sec.

MAKURDI

YOLA

1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945

MILLIONS OF ACRE FEET

MILLIARDS OF CUBIC METRES

5,000 (177,000)
4,000 (141,000)
3,000 (106,000)
2,000 (70,700)
1,800 (63,700)
1,600 (56,600)
1,400 (49,500)
1,200 (42,400)
1,000 (35,300)
800 (28,300)
705 (25,000)

705 (25,000)
600 (21,200)
400 (14,100)
200 (7,100)
0

YOLA MASS RUN-OFF REDUCED ON 705 m^3/sec. (25,000 CUSECS)
705 m^3/sec. = 22.2 MILLIARDS OF CUBIC METRES PER YEAR
25,000 CUSECS = 18.0 MILLIONS OF ACRE FEET PER YEAR

THOUSANDS OF CUSECS

THOUSANDS OF m^3/sec.

MAKURDI

YOLA

1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957

MILLIONS OF ACRE FEET

MILLIARDS OF CUBIC METRES

NEDECO	DIAGRAM
NIGER / BENUE	VI 8.5.3 – 1
DISCHARGES MAKURDI AND YOLA	
REDUCED MASS CURVE OF RUN-OFF AT YOLA	

The discharges of Yola can be determined only for the wet season, because no dry season readings were taken from 1934 to 1954. Irrelevant as these dry season water-levels might be for the direct use of the shipping companies, they are indispensable when calculating the necessary reservoir volume. Therefore in a conservative way the following discharges are assumed to have occurred:

Average discharges in m³/sec

	observed values			assumed values for 1934—1954
	1955	1956	1957	
January	105	130	70	50
February	40	70	30	30
March	20	40	20	20
April	20	40	20	20
May	80	45	90	45
June	290	330	450	200

The discharges of tributaries, as far as necessary for the calculations, were measured or assumed in the same way.

b. *The amount of water needed; regulated discharges*

For any river-stretch a certain discharge is required to negotiate that stretch with a ship of a certain draught. These discharges and least available depths are discussed in III, 6.4.3, and the results of the measurements and calculations are to be found in Diagram 8.5.3-2.

The limit discharges refer to conditions on the Benue in 1956 and 1957. It is possible that there have been years in which the conditions were worse; but after construction of a reservoir, it is highly probable that the circumstances will improve. When comparing two rivers with the same sort of river valley and the same annual discharge, the river with the more uniform discharge will have the greater depth for corresponding discharges, when compared with a river characterised by high peak discharges. This expected improvement has not been taken into consideration, to ensure remaining on the conservative side when computing the future limit discharges and least available depths.

It will be seen that the Yola reservoir cannot effect year-round navigation from Yola (Garua) down to the coast. But for the period without navigation the reservoir still has to supply some 20 m³/sec discharge for purposes of sanitation and fishing.

It has been assumed, when calculating the regulation programmes, that the Niger-Benue Confluence and the Niger below Lokoja are passable when the Benue is made navigable. Naturally these river parts will improve by the additional discharge from the Benue, but in between the end of the Black Flood and the beginning of the local rains the discharge of the not-regulated Niger above Lokoja may fall considerably, with the result that navigation below Lokoja, where the limit discharges are much higher than on the Benue, will be restricted to lesser draughts than on the regulated Benue.

In addition to discharge regulation on the Benue, dredging or other means of improvement on the Niger should then be undertaken to ensure navigation for the same draughts on Benue and Niger.

c. *Pre-extension or post-extension of the high-water season*

The time of water supply depends to a great extent on the harvest time of the various crops and on the time they are delivered from the production areas to the river ports. The crops are harvested between November and February (see IV, 1.1.3). Some time passes before that crop, which has to be dried, sorted and transported, becomes available at the river ports, so that regular delivery may not be expected before the end of November. If the Benue season were opened on December 1, a part of the crop could be evacuated, but as the reservoir cannot realise year-round navigation on the Benue, the rest of the crop would have to be stored to await the wet

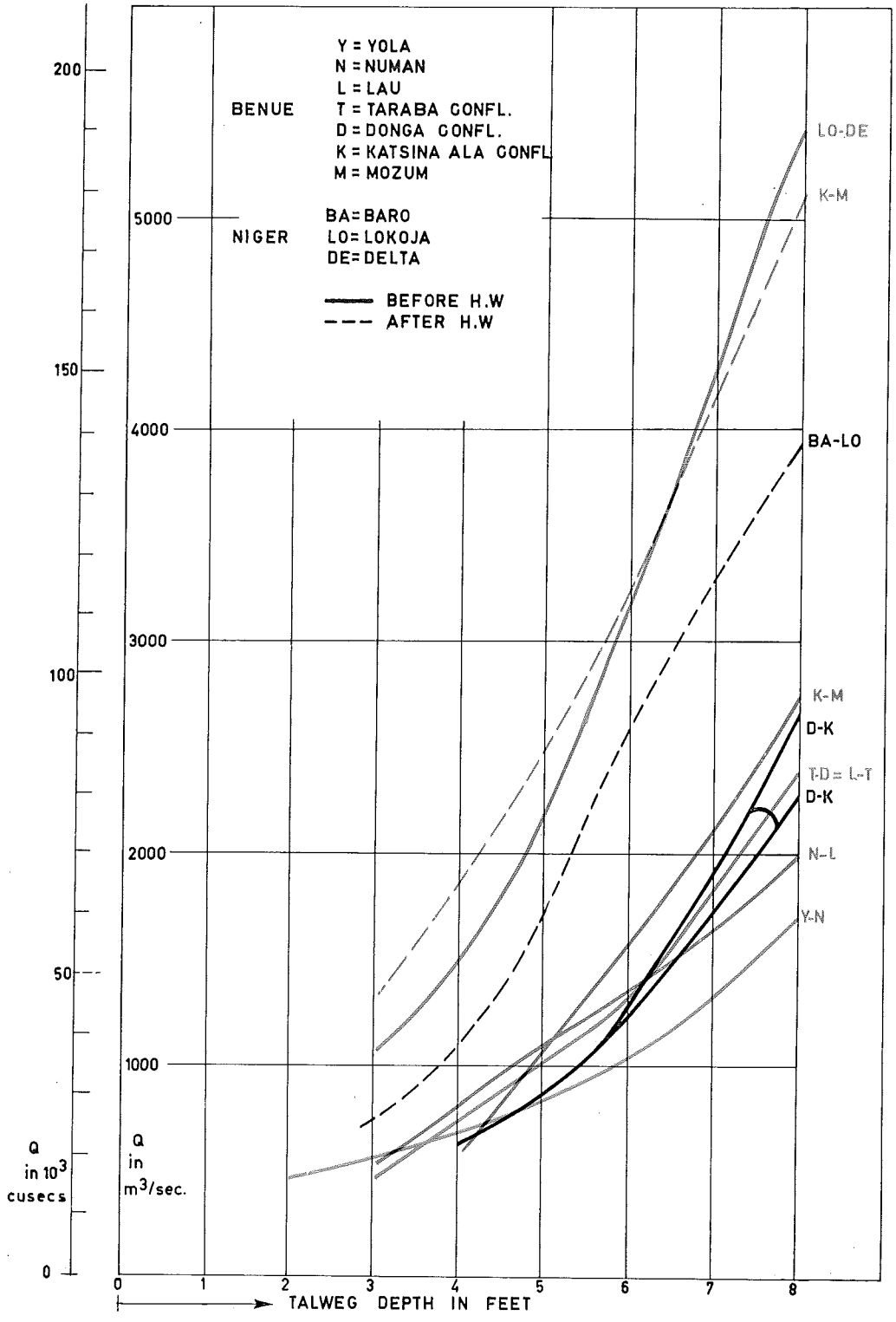


DIAGRAM 8.5.3-2

Limit discharges

season. Splitting the Benue season into two seasons certainly has disadvantages, even apart from the fact that this programme would coincide partly with the present Baro season. The conclusion from this is that pre-extension of the shipping season is more desirable than prolongation.

Also as to the point of economic utilisation of storage water, pre-extension is advisable, for when using a certain amount of water before the present season, more weeks can be gained than with the same amount after the season.

The inflow into the reservoir decreases rapidly after the season, whereas over a considerable period before the shipping season the inflow is just insufficient to balance the necessary outflow. Thus, to raise the discharge just before the season to the outflow necessary to obtain sufficient navigation depth, less storage water is needed than would be after the season. For a reservoir of restricted capacity (the useful capacity of the Yola reservoir will be less than half the average annual run-off), the result will be that when releasing equal amounts of water before and after the high-water season, the period of navigation will be more extended in the first case, Moreover, the outflow, the water required for navigation, needs to be more after than before the season, for equal depths. This effect is discussed under III, 6.4.2 and results in the two lines for Makurdi in Diagram 8.5.3-2.
Thus a more economic use of the stored volume of water is obtained in the case of supplying before the season.

The more uniform the flow, the better the channel. Especially for the upper reaches of the Benue, where the discharges after the building of a reservoir will be almost equalised, it is important to avoid the relatively high discharges needed for supply after the season. Pre-extension is therefore advisable.

A disadvantage of pre-extension is the evaporation of reservoir-water in the dry season, but the afore-mentioned effect outweighs this loss of water.

A disadvantage of a pre-extended season is the long time elapsing between the moment when the gates of the reservoir are opened and the dates on which the ships can start their voyage

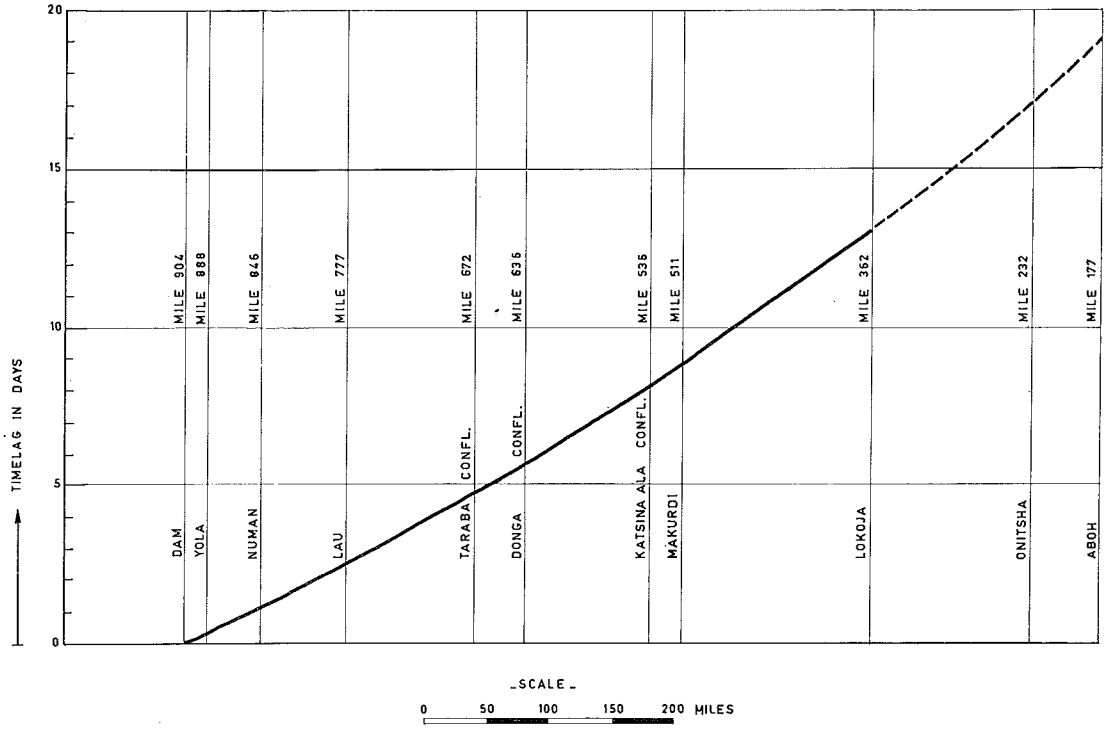


DIAGRAM 8.5.3-3

Propagation of discharge released on the opening date

upstream. At present the ships are sailing upstream as far as Makurdi on water mainly coming from the Katsina Ala River and to a lesser degree from the Donga and Taraba Rivers. The rainy season starts later in the upper reaches than in the lower reaches, so that at the time the ships leave the Delta area, the Upper Benue is not yet navigable. By the time the fleet reaches Makurdi, there is a fair chance that the upper reaches of the river carry sufficient water to allow further upstream sailing.

But in the case of water supply from the reservoir, supplying may commence at a time when none of the tributaries has yet had much rain. In many years the Niger in this period will not be navigable either, and the ships can only start their voyage by the time the water from the Yola reservoir arrives at the Delta area. Supply after the season will not involve such loss of water.

The number of days elapsing between the moment at which the gates are fully opened and the time at which the water arrives at the various stations is given in Diagram 8.5.3-3.

The time-lags following from this graph are greater than those read from Diagram 3.6.1-1. In the latter, the propagation of the top of a flood-wave has been taken, whilst in the former some time has been added, taking the attenuation into account. In Diagram 8.5.3-3 the days approximately stand for the time elapsing between the release of a certain discharge and the time when this discharge has practically reached the stations given on the horizontal axis.

Another disadvantage of supplying before the season is the impossibility of calculating the exact date on which the gates should be opened, so that the amount of water stored would be just sufficient until the date that the inflow into the reservoir balances the outflow. If the gates are opened too early, the reservoir will be empty, whilst the inflow is still less than the outflow needed for shipping purposes. The ships will then have to wait somewhere on the river. If the gates are opened too late, the reservoir will still have water in storage when the inflow exceeds the necessary outflow. This water could be saved until the next season if the reservoir were large enough to contain it together with the total inflow minus outflow in the wet season. In many years, however, the storage capacity of a reservoir of reasonable size will not be large enough. The water then leaves the reservoir over the spillway and is lost for shipping purposes. In other words, if one year the season is commenced so late that water is saved, that water cannot, normally, be used next year to give the season an earlier start.

This disadvantage of pre-extension, however, is less than imagined at first appearance. At present, the date on which the rivers will rise is not known, and it will not be known in future. Every year it is a gamble whether or not the ships will have an easy or a long and difficult first voyage. Long-term water-level predictions, dependent as they are upon long-term quantitative weather forecasts, cannot be made.

In the case of a reservoir, and supply before the season, calculations by means of frequency curves permit the determination of a date on which the gates will be opened, so that with a chance of 1 in 5, 10 or 20 years, whichever will be preferred by navigation economy, the water will suffice until the rains start. This means that as soon as the reservoir is closed around November, the date on which the next season starts can be published. The August fall will be overcome and only once in 5, 10 or 20 years, whichever will be chosen, will the ships have to wait some days on the river because of an empty reservoir. The shorter this safety period (i.e., 5 instead of 20 years) the longer will be the average season, and vice-versa.

Concluding, comparison of supply *before* the season and supply *after* the season leads to:
Advantages of pre-extension:

(i) release of water more in phase with harvest time;
(ii) closing of the season every year on the same date; and
(iii) opening date calculable months ahead;

which advantages are, of course, not obtainable with post-extension.

Disadvantages of pre-extension:
(i) loss of water by more evaporation;
(ii) lag of two weeks before the water released from the reservoir can be used for shipping; and
(iii) the possibility that (in one year out of ten years) the amount of reservoir water is insufficient to maintain an uninterrupted season.

With regard to the economic use of reservoir water, supply before the season is advisable notwithstanding the disadvantages mentioned under (i) and (ii).

It is clear that the advantages of pre-extending the season outweigh the disadvantages. But to have no supply whatsoever after the season would mean that the ships will have to clear the river in the same way as is now practised, namely, when the water is still high enough to guarantee a safe return. The buoyage of the rivers will be of great help in those periods, but the uncertainty of the end of the season would still remain and planning would be, as a matter of course, based on much improvisation, long-term prediction being equally difficult as at the beginning of the season.

A reservoir is the instrument with which an exact date for the end of the season can be determined long ahead (see d.).

The above-mentioned considerations lead to main supply before the season and only so much after the season as is necessary to guarantee water upto a previously fixed date. At the closing of the shipping season, the opening date of next season and its total length can be calculated.

d. *The closing date*

Closing the season at too early a date results, when the reservoir is already full, in a waste of water, and thus of season length. Closing the season too late costs much water which could be used more economically for the supply before next season.

To determine a reasonable and fixed closing date of the season, frequency curves have been prepared of the discharges at the end of the season. From these curves Diagram 8.5.3-4 has been plotted.

When a certain depht has to be guaranteed, the corresponding limit discharge for the Gamadio Flats can be read from the red line in Diagram 8.5.3-2. This discharge has to be used in Diagram 8.5.3-4 to read the date of closure on the 90 % Yola-line. For instance, a talweg depth of $4\frac{1}{2}'$ needs a discharge of about 1,000 m³/sec (Diagram -2). Using the 90 % curve of Yola in Diagram -4, the closing date then is November 8 for a discharge of 1,000 m³/sec.

If (see Diagram 8.5.3-4) the 90 % recession curve for Yola is chosen as a measure for the closing date, the outflow necessary for the limit discharge will exceed the inflow into the reservoir in 9 out of 10 years. The outflow equals the highest additional discharge on any river-stretch. The additional discharge is the required limit discharge minus the inflow of the affluents between the dam and the river-stretch under consideration. In most years the additional discharge for the Gamadio Flats between Numan and Lau appears to be decisive at the time of closure. Because of the rather late closing date (90 % Yola recession curve), the Gongola discharge is practically negligible at that time, which means that the additional discharge for the Gamadio Flats equals the limit discharge. Therefore the limit discharge for the Gamadio Flats, in combination with the 90 % Yola recession curve, has been used in calculating the closing date. It will be of interest to know whether the inflow between Yola and Makurdi is sufficient to compensate for the higher limit discharges for the same navigation depth at Makurdi. Comparison of the required inflow between Yola and Makurdi with the 10 % discharge recession curve (at Makurdi) of the drainage area between Yola and Makurdi, shows that only in 1 out of 10 years will a higher discharge than necessary for the Gamadio Flats have to be supplied. For instance, when a discharge of 1,000 m³/sec, needed for a least available depth of $4\frac{1}{2}'$ on the Upper Benue, is released at the dam, the closing date, determined by the 90 % recession curve of Yola, will be November 8 (see Diagram 4). About 8 days later, on November 16, this discharge will have arrived at Makurdi, where the limit discharge for a least available depth of $4\frac{1}{2}'$ is 1,300 m³/sec higher than at Yola, as represented by the dotted line in Diagram 4. The dotted line appears almost to coincide with the 10 % recession curve of Makurdi minus Yola, which implies that in 9 years out of 10 years the release of 1,000 m³/sec at the dam will be sufficient also for a least available depth of $4\frac{1}{2}'$ near Makurdi.

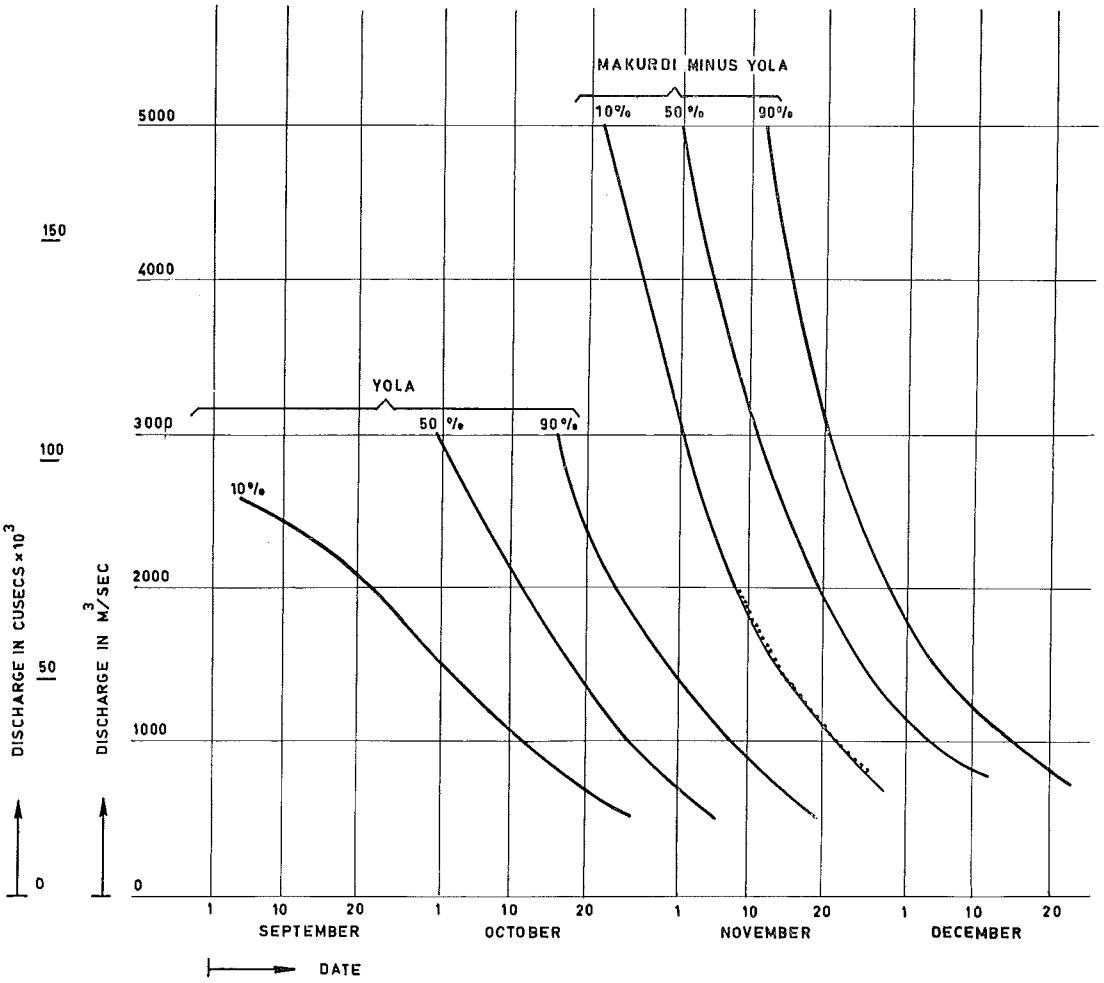


DIAGRAM 8.5.3-4

Recession lines for Yola and for Makurdi minus Yola

Thus, if the 90 % curve of Yola (Diagram 8.5.3-4) is chosen to determine the closing date, the inflow into the reservoir is sufficient to balance the necessary outflow in 1 out of 10 years. Nine years out of 10 the outflow exceeds the inflow, and only once in 10 years does the outflow exceed even the limit discharge for the Gamadio Flats in order to maintain sufficient depth downstream of the Katsina Ala Confluence.

e. *The opening date*

The opening date depends on the amount of water assembled in the reservoir on the closing date, on the evaporation losses minus the inflow after the closing date, on the required least available depth, and on the taken risk that the reservoir water does not suffice until the inflow again balances the outflow.

The dates on which the gates can be opened in order to have just enough water to maintain an uninterrupted season have been calculated for various talweg depths and various quantities of water available on the opening date. These calculations were made for the years 1934—1954. If long-term water-level predictions could be made, these dates would be the opening dates of the seasons. But such predictions in this case would have to rely on long-term quantitative weather

forecasts, which is an impossibility. Therefore recourse must be taken to statistical methods.

The above-mentioned dates have been transformed into frequency curves for various talweg depths and various quantities of water available. The date on which in 1 year out of 10 years the amount of water is not sufficient to guarantee an uninterrupted season is chosen as the opening date. Thus once in 10 years the ships will have to wait somewhere on the river, some days in June or July, because in that particular year the inflow into the reservoir remains less than the outflow for just as long a time as the useful amount of reservoir water is deficient.

Diagram 8.5.3-5 gives the result: when the useful quantity of water in the reservoir amounts to, say, 10 milliards of m^3, and when a scheme for 5′ is envisaged, the date on which the sluices at the dam are opened will be March 25.

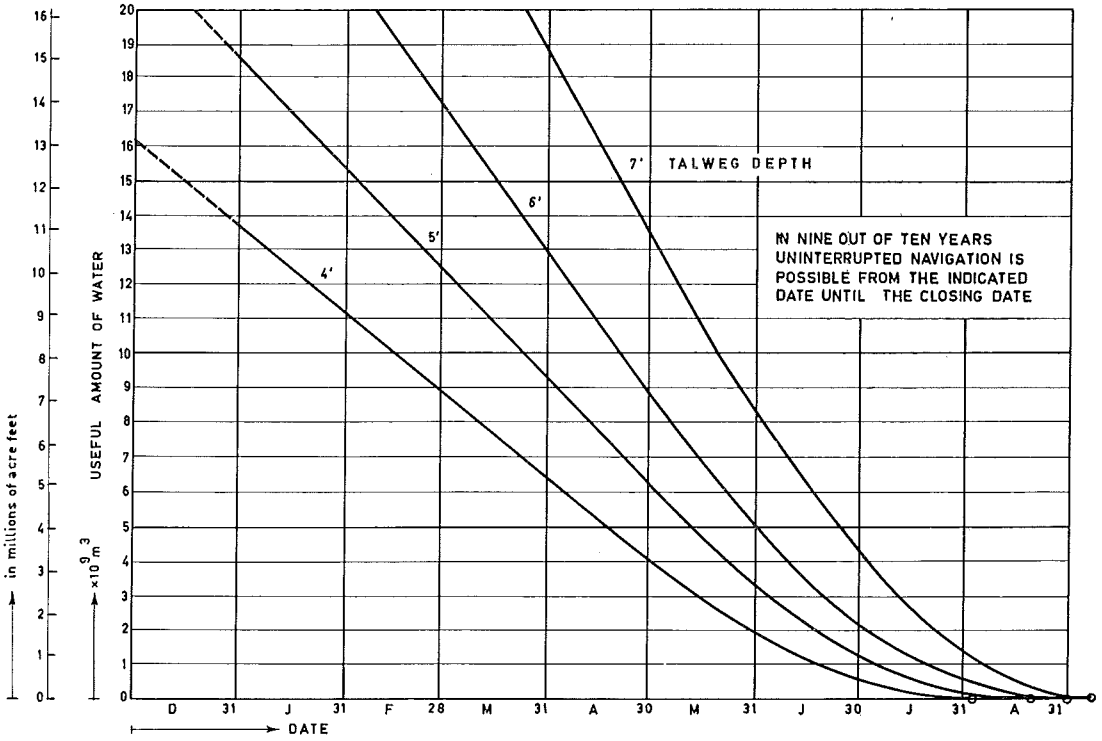


DIAGRAM 8.5.3-5

Date opening gates at Yola dam

Evaporation losses minus inflow after the closing date can be calculated fairly accurately; the useful amount of water in the reservoir on the closing date is a direct function of the water-level of the reservoir, hence the opening date of next season will be known on the closing date.

f. *The average length of the navigable season*

Diagram 8.5.3-8 shows the relationship between reservoir volume, minimum talweg depth and the average length of the navigation season for the river downstream from the dam. As for navigation above the dam, when supplying before the season, the reservoir being filled in the preceding wet season, navigation on the lake to and from Garua will be possible all the year round.

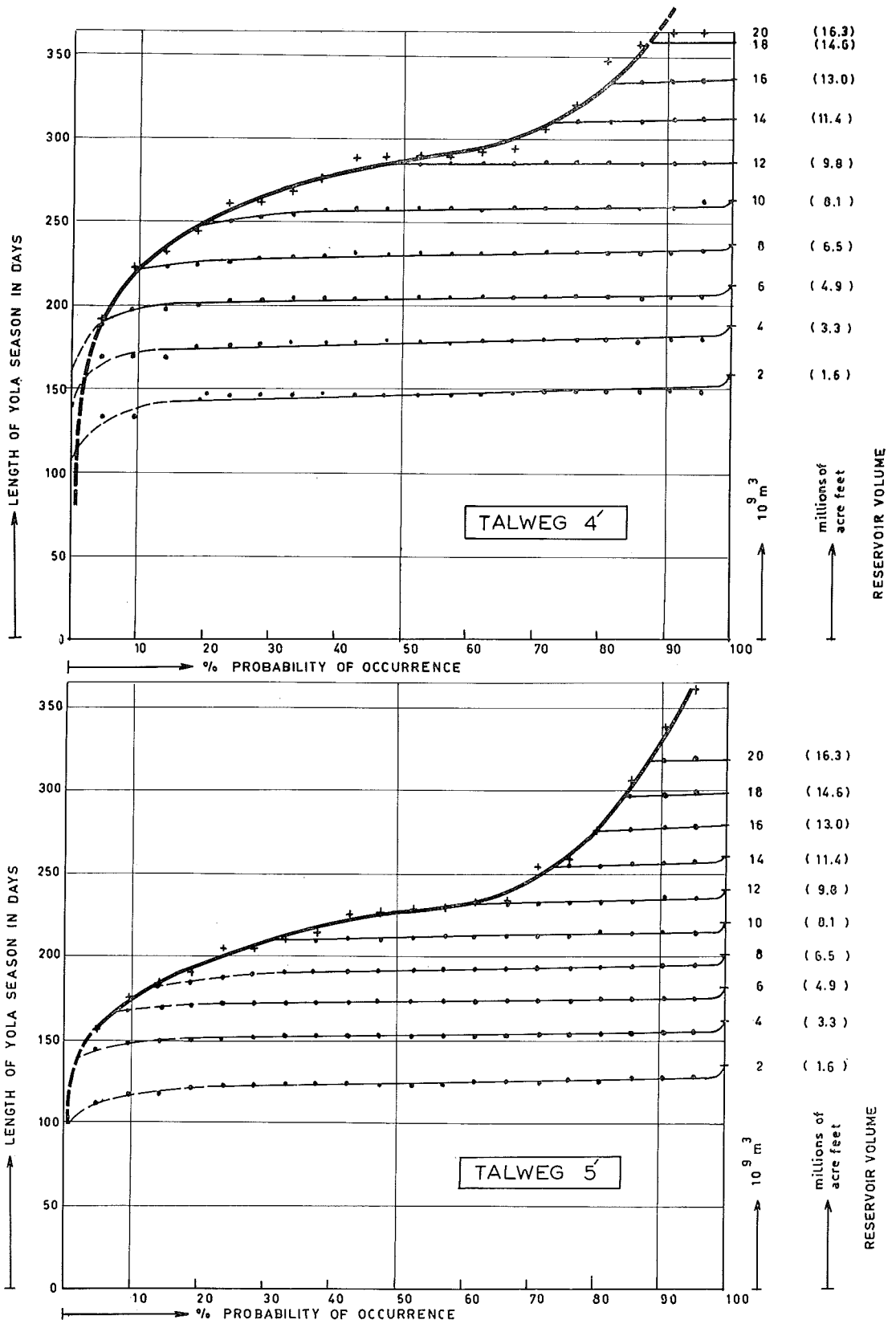


DIAGRAM 8.5.3-6

Frequency curves of length of Yola season

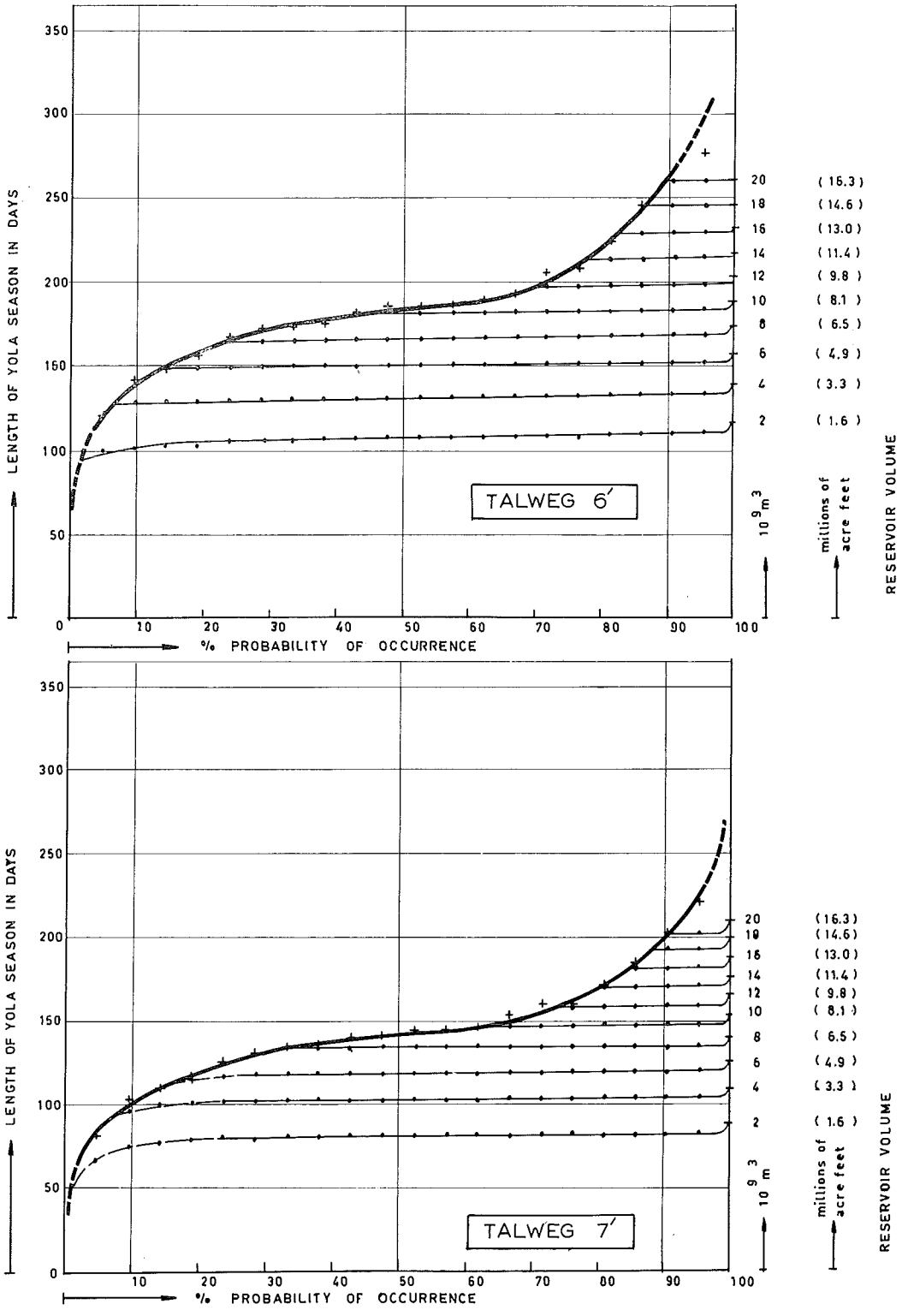


DIAGRAM 8.5.3-7

Frequency curves of length of Yola season

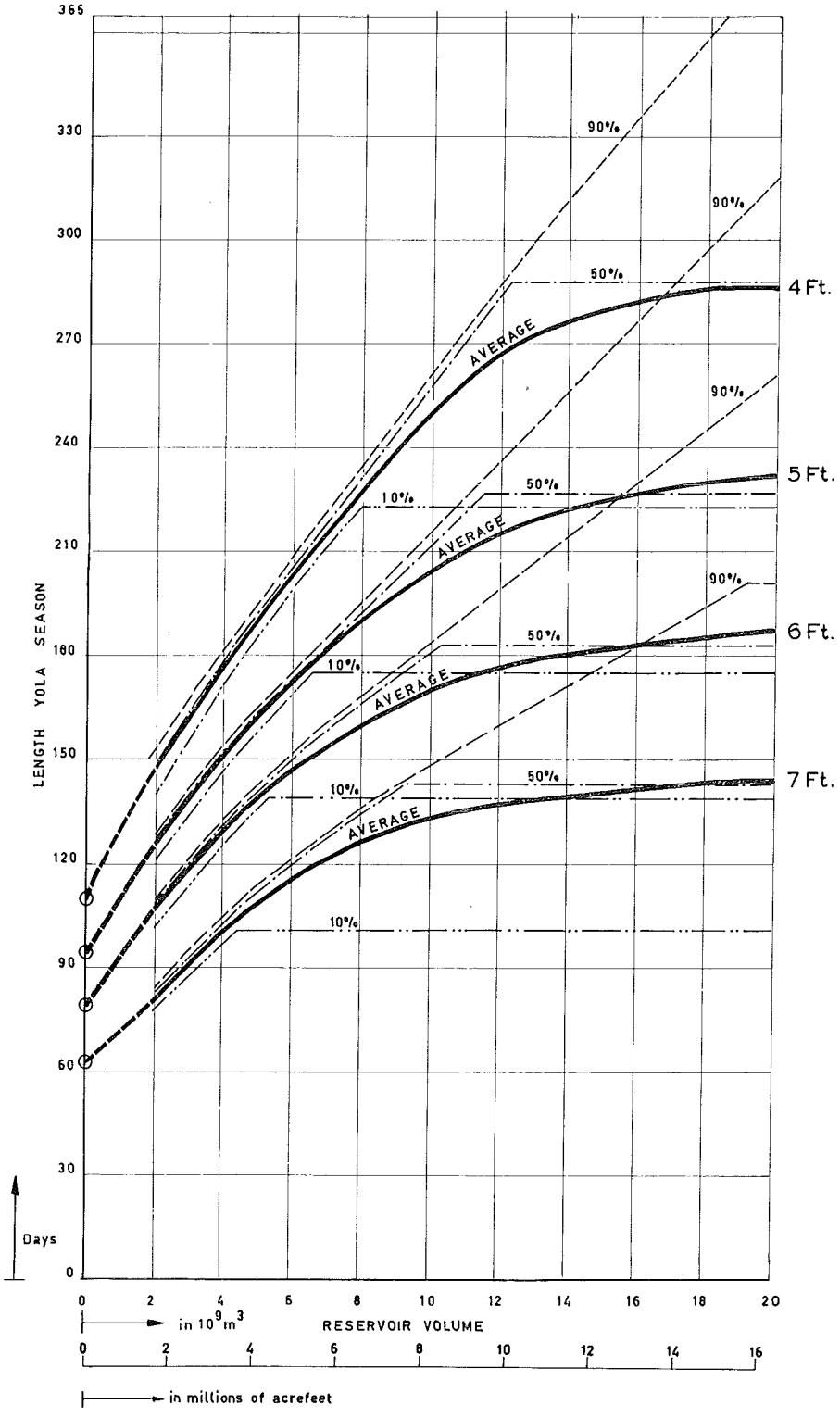


DIAGRAM 8.5.3-8

Length of Yola season

The reservoir volume is a direct function of the costs of the reservoir. Capacity, area and water-level have been plotted in Diagram 8.5.1-3. The costs and the recommended size of a reservoir are discussed under 8.5.4.

The navigation depth is related to the minimum talweg depth. When that depth is given as 5′, it means that everywhere in the channel, except in one or two places along the Benue (for instance, Gamadio Flats), the depths exceed 5′. This single difficult spot can be cleared with only very few inches of water under the ship, as is proved by practice nowadays. The navigation depth, therefore, is some inches less than the talweg depth. But if a dredger could be put into operation on the few spots which are nowadays determined as being dominant for the least available depths, the talweg depth and least available depth could certainly be increased by one foot. In these considerations, however, the river downstream of Mozum (16 miles above Lokoja) is not taken into account. Calculations are made on the assumption that the necessary depths on the Niger-Benue Confluence and on the Lower Niger are sufficient, either by operation of a Yola reservoir only or by a combination of the Yola reservoir and other means (see 8.5.5-c).

The lines of Diagram 8.5.3-8 have been constructed under the following considerations.

The reservoir operating scheme for a minimum talweg depth of 5′ will now be calculated.

The outflow necessary to maintain a minimum talweg depth of 5′ over the total length of the river depends upon the limit discharges and on the affluence of the tributaries. The limit discharge of the river-stretch Numan—Lau (Gamadio Flats), for talweg depths between 3′ and 5′, outweighs every other limit discharge in the Benue before high water. Thus, regarding the supply before the season only the limit discharges of Yola—Numan and of Numan—Lau, as well as the affluence of the Gongola, need be taken into account. When the discharge of the Gongola exceeds the difference of the limit discharges Yola—Numan (e.g., 810 m³/sec for 5′ depth) and Numan—Lau (1,100 m³/sec for the same depth), the outflow can be kept as small as the limit discharge of Yola—Numan. When the Gongola becomes dry, the outflow should be raised to the limit discharge of the stretch Numan—Lau. In calculating a reservoir operating scheme with data of 1934/1954, the discharges of the Gongola had to be estimated because no useful water-level records of this river are existing before 1955. A conservative estimate based on 1954—1958 observations yielded a discharge 0—300 m³/sec from June 1 to August 1, a discharge exceeding 300 m³/sec from August 1 to October 1, and a discharge decreasing from 300 to 0 m³/sec from October 1 to November 1.

According to Diagram 8.5.3-4, the closing date for a limit discharge of 1,100 m³/sec is November 6. But decreasing the discharge abruptly from 1,100 m³/ sec to 20 m³/sec would create undesirable situations. Instead of changing the outflow abruptly from 1,100 m³/sec to 20 m³/sec on November 6, the outflow therefore will be decreased gradually from 1,100 m³/sec on November 3 to 20 m³/sec on November 9. From November 9 onwards the reservoir will supply water only for sanitation and fishing purposes.

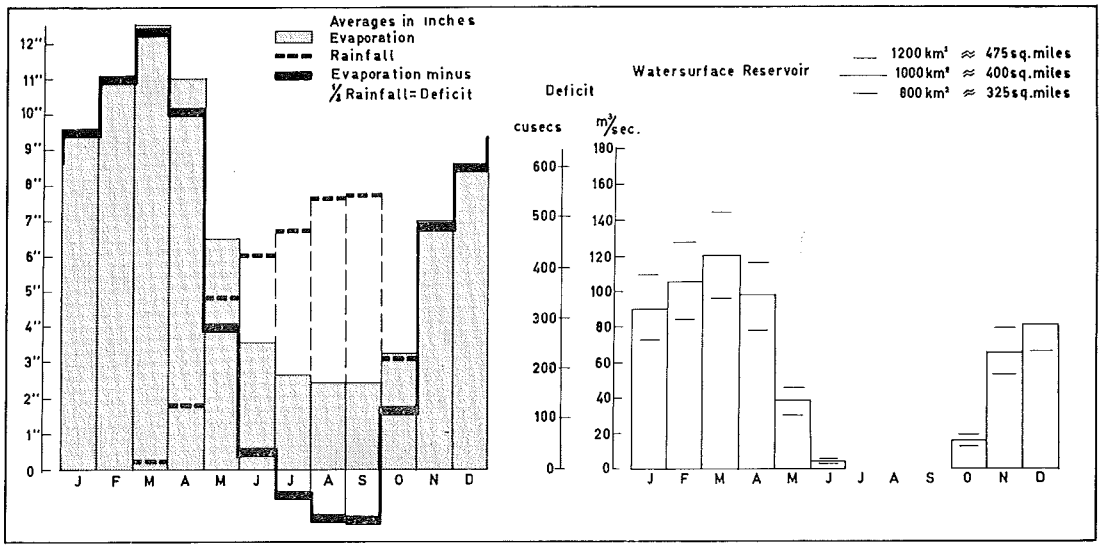


DIAGRAM 8.5.3-9

Evaporation deficit Yola Reservoir

Thus, until November 3 a talweg depth of 5′ is maintained. In most years the outflow will equal the limit discharge of the stretch Numan—Lau, but every year the operation scheme should be reconsidered.

The evaporation of reservoir water is a function of the time of the year and of the water surface of the reservoir. The evaporation in its general aspects is discussed under III, 4.4. The evaporation from a free water surface in the Yola area has been plotted in Diagram 8.5.3-9. A certain percentage of the rainfall in the reservoir area can be subtracted from the evaporation. Of the rain falling at present, about 60 % has evaporated before the water assembles in the tributaries and rivers. This means that 60 % of the rainfall can be subtracted from the evaporation figures. To be on the conservative side, only 50 % of the rainfall has been subtracted from the evaporation, resulting in the evaporation deficit curve in m³/sec as shown in Diagram 8.5.3-9.

For instance, in April the evaporation is 11″. The rainfall is 2″, hence the evaporation deficit in April is 11″ — 1″ = 10″, which averages about 100 m³/sec (3,500 cusecs) for a surface of 1,000 km² (about 400 sq.miles).

All data necessary to calculate a reservoir operating scheme are now available.

The outflow discharges are: before June 1, 1,100 m³/sec; from June 1 to August 1 gradually decreasing from 1,100 m³/sec to 810 m³/sec; because of the Gongola supply from August 1 to October 1 810 m³/sec; from October 1 to November 1 increasing from 810 m³/sec to 1,100 m³/sec, or more if necessary; from November 1 to November 3 1,100 m³/sec or more; from November 3 to November 9 gradually decreasing to 20 m³/sec; and after November 9 20 m³/sec. The evaporation deficit should be added to all these discharges.

With this outflow scheme, calculations have been made, with the aid of Diagram 8.5.3-1, on the integrated discharges at Yola from 1934 to 1954. The lengths of the seasons are calculated for those years for various reservoir volumes (Diagrams 8.5.3-6 and -7). The curves show clearly the effect of a reservoir of limited size upon the length of the season. The S-shaped curve represents the situation with a reservoir of unlimited size. In wet years and with a small reservoir, large quantities of water will leave the reservoir by means of a spillway. A reservoir of 4 milliard m³ will be filled most of the years, whereas a reservoir of 20 milliard m³ will not be used up to its capacity in 9 out of 10 years. The difference between the 50 % season-length and the average season-length, the last depending on the area of the respective case, is illustrated by those diagrams.

Diagrams 8.5.3-6 and -7 have been combined into Diagram 8.5.3-8.

8.5.4. Size of Yola Reservoir and cost

a. *Normal lowest draw-down level*

It will be clear that if solely navigation demands downstream of the dam had to be answered, the reservoir could be completely emptied when required, and the lowest draw-down level could be the lowest physically possible, i.e., about + 160 m (525′). But during the period when the storage is used to create a navigable waterway downstream of the dam, Garua should be accessible. As this release of water happens during the dry season, when the Benue has hardly any natural run-off, the water-level at Garua will be determined solely by the water-level of the reservoir. Therefore, the minimum draw-down level should not be under + 175 m (574′) (see Paragraph 8.5.1). A further advantage of this minimum draw-down level is that navigation to and from Garua on the lake would be all the year round, whereas fishing and sanitation requirements certainly would welcome not too low a minimum level.

b. *Normal highest retention level*

To determine the normal highest retention level, a comparison must be made between the cost of a reservoir and the benefit for navigation. The benefit for navigation can be taken approximately as:

$$B = \alpha (D - d) (S_f - S_p)$$

in which B = benefit for navigation;
D = draught of a loaded barge;
d = draught of an empty barge;
S_f = future length of the season;
S_p = present length of the season; and
α = a coefficient.

The cost of a dam are, very roughly, and within certain limits

$$C = \delta H^{2\frac{1}{2}}$$

in which C = the cost;
H = the height of the dam; and
δ = coefficient.

The highest percentage of return occurs when $\frac{B}{C}$ reaches a maximum It appears that such maximum gain will be attained when the reservoir capacity is greater than 10 and probably between 10 and 14 milliards of m³ (between 8 and 11.5 millions of acre-feet). This, of course, must be checked by exhaustive studies when the dam comes into a planning stage. In this first approach, the cost of the reservoir additional to those of the dam have been assumed proportionally to the cost of the dam.

The drowning of the flood-plain and the inundation of the villages does not impose heavy costs or problems as long as the normal highest level is kept under + 180 m to + 182 m (590′ to 597′) (see also Paragraph 8.5.1), as the flood-plains downstream of Garua are only sparsely inhabited. Storage levels between + 175 m and + 182 m (574′ and 597′) result in a useful capacity of 6 milliards of m³ (5 millions of acre-feet) as is shown on Diagram 8.5.1-3.

Above Garua, between + 180 m and + 190 m, fertile and extensive flood-plains are cultivated. The influence of high storage levels on these flood-plains depends on the reservoir programmes (see Paragraph 8.5.3). In the recommended programme, the reservoir will be full from November to somewhere between March and May (inclusive); it reaches the lowest level in July or August and will be full again in or before November. It might be possible to use the period between March/May and July/August for cultivation of a special crop such as rice. At any rate, the fear that the creation of a reservoir in this area would annihilate the agricultural use of the soil seems to be premature. But if a reservoir of over 6 milliards of m³ useful capacity is to be planned, a close study of the effect of various reservoir programmes on these affected regions and their development will be necessary. In the first instance, however, a reservoir of 10 to 12 milliards of m³ (8 to 10 millions of acre-feet), with normal highest retention levels of + 185.5 m to + 187 m (608′ to 613′), has to be considered a possibility.

The height of the quay and the floor-level of the sheds on the embankment of Garua being + 182.8 m (600′), measures will have to be taken when raising the water above this level, as flooding of the sheds would damage the stored groundnuts and cotton. Also the edge of the native settlement would have to be removed to sites above this level.

At present, two concrete quays exist. Building a third one on a higher level, say at + 190 m (623′), will certainly be possible. The present quays may still be used when the water-level is lowered to medium and low retention levels between April and September, but the sheds and some other buildings under the + 190 m level would have to be removed.

c. *Maximum retention level*

At this stage of investigation, the highest level of retention has not been decided on, determinant as this is on spillway design, crest height of dam and flood control in and below the reservoir.

d. *Cost*

It will be clear that construction of two heights of dams and consequently two sizes of reservoirs may be envisaged:
(i) a reservoir of some 6 milliards of m³ (5 millions of acre-feet) useful capacity, the normal highest retention level being around + 182 m (597′) and which in discussions with the French Cameroun Consultants has been termed the Yolette Scheme. When this reservoir of limited size should work in conjunction with a Lagdo reservoir, the total available useful capacity would be raised to 12 milliards of m³ (10 millions of acre-feet).

(ii) a reservoir of some 12 milliards of m^3 (10 millions of acre-feet) useful capacity, the normal highest retention level being round + 187 m (613') and known as the Yola Scheme.

As to the choice of the type of dam, the circumstance of a deep alluvial fill of the river-bed points strongly towards an earth or rockfill dam. In addition to this dam, a structure with gates capable of discharging the limit discharge also at the lowest retention level has to be planned, and finally a lock and a flood spillway.

The cost of the dams including the above items have been estimated roughly at the following amounts:

	Yola-12 (Yola)	Yola-6 (Yolette)	Lagdo-6
Cost in millions of £	14	10	6 (1
Useful capacity in milliards of m^3	12	6	6 (1

The French agency has assumed the Yola dams to cost about 20% more than the figures just given, a discrepancy which should be considered acceptable in view of the rather rough way in which these estimates had to be made.

It appears that a combination of the Lagdo dam and the Yola-6 dam will cost more than the Yola-12 dam, whilst the total useful capacity will be equal, but building in stages, and raising the invested capital when the transport-economy justifies it, makes the combination scheme of Lagdo and Yola-6 (or perhaps Yola-8) more attractive than the Yola-12 proposition, a conclusion also arrived at by Electricité de France in their Report (1. Moreover, in the Lagdo-Yolette Scheme the port of Garua and the flood-plains above this town are not so severely affected as in the Yola Scheme.

8.5.5. Effects on the morphology of the Benue

a. *Upstream of the dam*

The reservoir releases water but withholds most of the solid material. At present, about 0.4 million cubic metres of sand and 3 million cubic metres of silt pass Yola in an average year, which is less than 0.1% of the volume of a small Yola (Yolette) reservoir. For all practical purposes, therefore, the useful capacity of the Yola reservoir will not be affected by siltation.

The navigation channels, however, may be adversely affected by siltation, but the main sand deposits (see III, 6.6.9) will be somewhere on the Faro at the beginning of the backstage, where they will be well out of the shipping route. The Faro, main source of the vagaries of the river-bed at Wuro Boki, and which will still be exerting an unfavourable influence when the Benue is regulated with a reservoir at Lagdo, will be completely tamed in a Yola reservoir.

But the situation at the port of Garua, also near the limit of the backstage, will deteriorate to some extent. The lowest retention level will be such that the reservoir extends only a short distance above Garua at the beginning of the wet season. When the rains start filling the reservoir,

(1 ELECTRICITÉ DE FRANCE, 1958. GEN. 11

the Benue discharge increases and sand is moved towards Garua. As the velocity decreases in the reservoir, the sand deposits in the neighbourhood of Garua. This effect should be studied in more detail when a reservoir is planned, and measurements of sand and water in various cross-sections between the Faro and Lagdo as well as on the Mayo Kebi will have to be made.

It is not thought that these sand-deposits near Garua will create a major problem, as a channel can easily be maintained by a small dredger.

b. *Downstream of the dam*

Rather clear water will leave the reservoir, and below the dam this water will pick up material to the extent of its transporting capacity. The inevitable result is scour below the dam, fast at first and more gradual later.

As soon as the dam has been built, scour will occur immediately downstream of the dam, and gradually the affected region will increase. However, differences in grain-size and the influence of tributaries, as well as the vastness of the alluvial plains, restrict the effect of scour to a limited zone.

When planning a dam at Dasin Hausa, the amount of scour, in depth as well as in extent as a function of time, should be studied. The affected region will almost certainly not extend beyond Numan, but will probably in due course include Yola.

The local maximum scour just below the dam, which is of importance for its foundations, may be several tens of feet.

A second influence on the channels below the reservoir results from the changed discharges. When the discharge hydrograph is altered, the annual sand-transporting capacity alters, although the total annual run-off remains equal, because sand-transport S is more than proportional to the discharge Q (see III, 5.2.1). The discharge peaks move much larger quantities of sand than medium discharges and when the discharge is evened out over the year, the transporting capacity drops considerably. There is also a possibility of increasing the annual sand-transport, namely, when the water of the smaller discharges is stored to be released as a high discharge over a shorter time. Electricity programmes always give the first effect, but programmes for short periods of navigation with a great draught could have the second effect. The proposed programmes of the Yola reservoirs, however, result in a reduction of the annual sand-transporting capacity.

This effect of changed discharges is felt much farther downstream of the dam than the above-mentioned scour which was caused by the clear water released at the dam.

At present, the bed of the Benue is determined by the sequence of different discharges, but the higher ones are very much more responsible for the general shape than the lower ones. The transporting capacity of the high-water discharge is so much greater than that of medium discharges that the so-called Dominant Discharge (see III, 6.1.1-b) has a rather high value and nearly coincides with bankfull discharge (see III, 5.2.4).

Bankfull between Yola and Numan is about 3,500 m^3/sec and downstream of Numan 4,500 to 5,000 m^3/sec (120,000 and 160,000 to 175,000 cusecs). When regulating the Benue with a reservoir of reasonable size (over 10 milliard cubic metres or 8 million acre-feet) these values will be reduced to about half the present ones.

Model tests of FRIEDKIN ([1] proved that doubling the discharges did not cause deepening of the channel. Translating this into Benue circumstances, it would be: decreasing the discharges will not cause a shallower channel; which would mean that the future channels will have a depth equal to the present, when comparing the present bankfull (= dominant) discharge

([1] FRIEDKIN, 1945. MOR. 9

with the future dominant discharge. This phenomenon is also corroborated by theoretical considerations (III, 6.1.1-a).

Thus the channels may improve considerably. As already mentioned in 8.5.3, this expected improvement has not been taken into account when calculating the efficiency of the Yola Scheme.

Diagram 8.5.5-1 shows schematically the effect. The river-bed scours and the excess material is deposited on the sides. The future river-bed herein is lower than the present one.

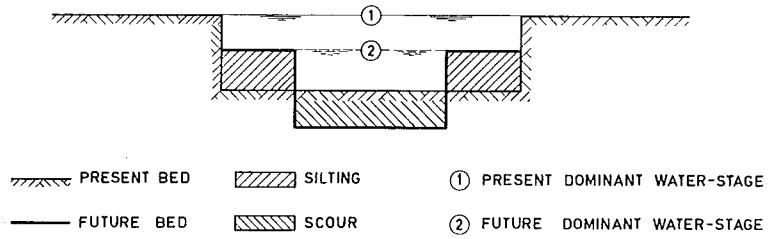


DIAGRAM 8.5.5-1

Effect of modified discharges

A combination of the scour and the effect of changed discharges will cause a lower river-bed and lower water-levels at Yola. When locally rocks prevent scour, these rocks may become troublesome to navigation; so when planning a dam at Dasin Hausa, the situation at Yola should be studied in detail, giving regard to this phenomenon.

c. *Effect on the Lokoja Confluence*

Also the Benue Bar near Lokoja will doubtless undergo influence from a discharge regulation of the Benue.

Phenomena on the Lokoja Confluence in general, and the Bar in particular, depend on two hydrographs, the one from the Niger and the one from the Benue. As especially the difference in phase between the hydrographs is very important for the results on the confluence, it is impossible to work with an average year. So the situation of 1956 and 1957 will be considered, based upon a navigation depth of 5′.

High water of both 1955 and 1956 was amply sufficient to have filled the Yola Reservoir completely, and it can be concluded that supply of water could have started at March 22 (see 8.5.3). Time-lag between Yola and Makurdi involves a rise of water-level in Makurdi on March 30; the new situation has been drawn in Diagram 8.5.5-2. The dash-line gives the situation as it actually occurred in 1956 and 1957; the full line indicates the shape of the hydrograph with the Yola reservoir working.

With the method developed in III, 4.2.6 the water-level at Lokoja as well as raise and draw-down in the Benue for this new condition have been computed. The results are given in the bottom section of the diagram. Considerations with respect to V, 3.1.2 lead to the following conclusions:

(i) Deposition of sand from the Niger in the Benue Entrance has already taken place before supply from the reservoir is started, since the whole of the Black Flood period is not changed. Due to this deposition, the navigation depth in the entrance — without raise or draw-down of Benue's water-level — is about two feet less than the L.A.D. on the Benue itself.

(ii) In the first instance, the water-level of the regulated Benue is still raised by backstage from the Niger, which is in the last period of its Black Flood. This raise would have been 2′

in 1956, and in 1957 only 1′. However, the already deposited mass of sand nullifies this raise. As a result, the available depth on the Lokoja Bar would have been:
in 1956: $5' - 2' + 2' = 5'$
in 1957: $5' - 2' + 1' = 4'$
the first figure being the L.A.D. between Makurdi and Mozum, the second the deposition of Niger sand in the Benue Entrance, and the third the raise of water-level of the Benue, due to backstage from the Niger.

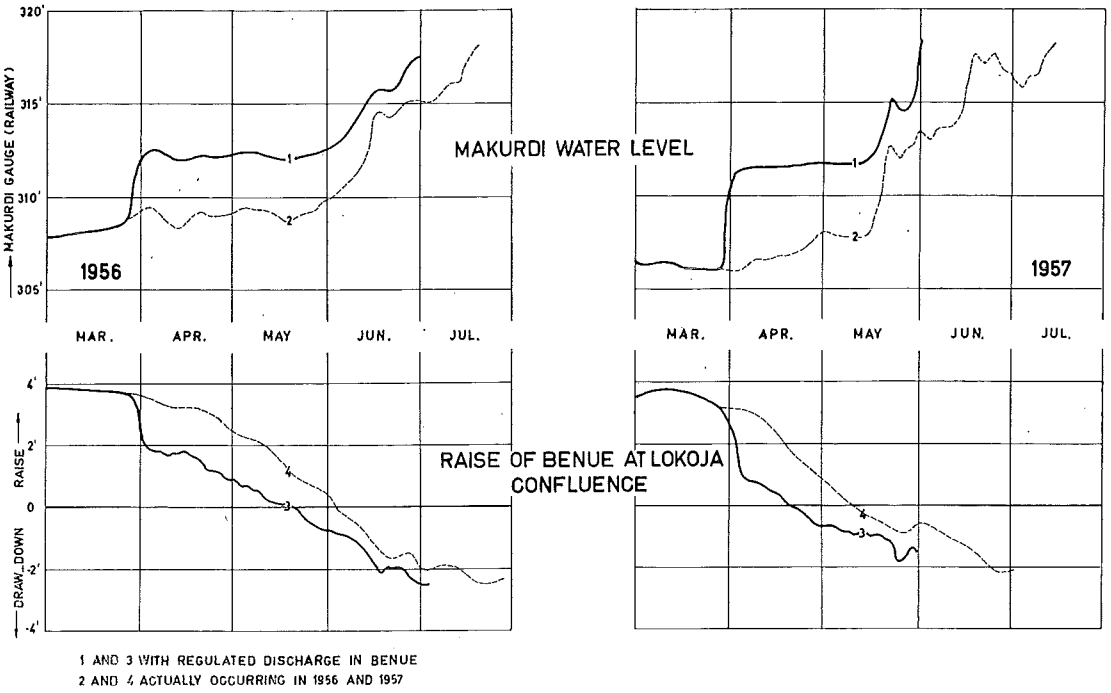


DIAGRAM 8.5.5-2

Conditions on Lokoja Confluence with Yola Reservoir in operation

(iii) Owing to fall of the Upper Niger, the raise of water-level in the Benue is gradually reversed into a draw-down. Again a reduction of navigation depth on the Bar takes place, although this is partly compensated by a scour on the deposits effected by the greater velocity of the current due to the draw-down. When it is assumed that this scour amounts to one foot, the remaining available depth on the Bar would be three feet for both years 1956 and 1957.

(iv) When further rise of the Benue occurs, due to natural increase of discharge from the drainage area between Yola and Lokoja, the Lokoja Bar is covered with sufficient water, so that from then on, the Bar does not restrict navigation.

It is concluded that a regulation on the Benue with supply of water from the storing reservoir starting in the second half of March shows only clearly the presence of the Lokoja Bar. Although the reservoir permits navigation on the Benue itself, the Bar restricts the available depth unless other measures for improvement of the Benue Entrance are taken, such as dredging and training.

However, if it were possible, commencement of supply from, for instance, January 1 will give much better results. In this case, during the entire Black Flood period on the Niger a moderate

discharge on the Benue is maintained, — more or less a "Black Flood of the Benue". Raise of the water-level in the Benue Entrance, therefore, is strongly reduced, if not completely suppressed; deposition of sand from the Niger will take place on a very reduced scale; and navigation in the entrance of the Benue will be possible during the whole period.

When in the Niger in the month of April the Black Flood comes to its end, there will be a period of draw-down of the Benue, resulting in a reduction of the available depth over the Lokoja Bar. But since this bar will have hardly been formed, difficulties will be considerably less than at present. There might, however, be some weeks of unfavourable circumstances.

A reservoir in the Niger near Jebba would probably result in possibilities of year-round navigation on the Upper Niger. The low-water period in April and May would then be compensated by supply of water from the storage. If this regulation is combined with the Benue regulation, just discussed, starting its supply on January 1, there would no longer be difficulties on the Lokoja Bar. Deposition in the Benue Entrance would not occur owing to the absence of a raise of the Benue water-level in the period from January to April; whilst there would be no draw-down in May and June as the Niger does not fall. Navigation in the Benue Entrance would thus be possible at all times.

If the Benue regulation is combined with the Niger regulation, the first starting its supply at the end of March, formation of the shoals in the Benue Entrance will have already taken place but draw-down of the Benue water-level would be less or even nil; and reduction of depth on the Bar would be only due to the deposition, which is less than the present reduction. However, reduction will still be occurring, and the only alternative will then be other measures, as, for instance, a temporary extra supply of water from the Jebba reservoir, as mentioned under 8.3.4-c.

Summarising, the improvement of navigability on the Lokoja Bar effected by discharge regulation on the Benue will be some feet less than on the rest of the Benue if supply starts in the second half of March. With a much earlier starting date, for instance in the beginning of January, the Lokoja Bar will only act as a restrictive crossing in May and June when the Niger has fallen. Discharge regulation on the Benue combined with a discharge regulation on the Niger would affect the Lokoja Bar in the Benue Entrance favourably.

8.5.6. Resulting improvements for navigation

The calculation of the reservoir programmes of 8.5.3 can be summarised in the Tables 8.5.6-1 and -2.

Here, the first column gives the sizes of a reservoir at Yola in milliards of cubic metres (1,230 cubic metres equals 1 acre-feet). Capacity zero refers to the present situation. A useful capacity of 6 milliard cubic metres (5 million acre-feet) approximately stands for the small Yola Reservoir (Yolette) and 12 milliard cubic metres (10 million acre-feet) for the large Yola Reservoir (Yola) or for the combined Lagdo and Yolette Schemes.

The date in column 2 is that on which the gates at the dam are opened to the required discharge. The date on which the gates begin to close is given in column 3. Subtracting column 2 from column 3 yields column 4.

Subtracting from column 4 the propagation time of the water from the dam-site to Lokoja (13 days) and 5 days sailing time Lokoja—Yola (night navigation with modern craft) gives the length of the season of the port of Yola in column 5.

A zero capacity gives equal figures for columns 4 and 5 because at present the first ships

TABLE 8.5.6-1
SEASON FOR FIVE FEET DRAUGHT

Capacity Yola Reservoir milliards m³	average opening date	closing date	average length in days	average effective length of season, port of Yola	
				days	percentage
0	Jul. 23	Oct. 20	91	91	100
6	May 16	Nov. 3	171	153	168
8	Arp. 29	Nov. 3	188	170	187
10	Apr. 14	Nov. 3	203	185	203
12	Apr. 2	Nov. 3	215	197	216
14	Mar. 27	Nov. 3	221	203	223

TABLE 8.5.6-2
SEASON FOR SEVEN FEET DRAUGHT

Capacity Yola Reservoir miliards m³	average opening date	closing date	average length in days	average effective length of season, port of Yola	
				days	percentage
0	Aug. 7	Oct. 10	62	62	100
6	Jun. 27	Oct. 20	115	97	156
8	Jun. 17	Oct. 20	125	107	173
10	Jun. 9	Oct. 20	133	115	185
12	Jun. 5	Oct. 20	137	119	192
14	Jun. 3	Oct. 20	139	121	195

arrive at Yola when the limit discharges are just sufficient. The ships sail from Lokoja on water mainly from the tributaries below Numan and when they reach the Gamadio Flats they often have to wait. Once the discharge is high enough to clear those flats, the ships arrive at Yola normally one or two days later.

The length of season at zero capacity is slightly longer here than those read from Diagram 3.2.2-1 for the length of the present season. This is explained by the different way of determining that season. The longer zero capacity season has been used in Tables 8.5.6-1 and -2 to remain on the safe side when calculating the precentages in column 6.

Apart from the extension of the season, another navigational improvement is the prediction of the dates of the next season. The opening date of the season depends on the amount of storage water. As this amount can be calculated in November, the opening date of the next season can be published in that month. At the end of the season the gates are closed on a fixed date, so that also the length of the next season is known in November. This guaranteed season gives advantages for the operation of ports, for feeder and distribution lines and for ocean traffic from the Delta Ports.

8.5.7. Additional effects

Measures will have to be taken to prevent an increase of insect life (malaria) in the reservoir area.

Flood-plains in the reservoir area are lost for agricultural use, but most of them are not cultivated because of the present excessive and unpredictable flooding.

The creation of a reservoir will be welcomed by the fisheries as there exists a good demand for protein food. At present, dried fish from the Chad Basin is imported into Nigeria as far as Lagos. The fish seems to be non-migrating, and a good set-up may give considerable quantities of good fish from the reservoir area.

Perhaps equally as important as the improvement for the navigation may be the flood control. At present, large fadamas are not cultivated because of the excessive seasonal floodings. Also the need for this land is not yet great. But in a forseeable future the increase in population in Nigeria and in the world will certainly result in a more intensive soil use and in the opening up of fertile but inaccessible regions.

Quoting from 2.4.75 of the Report of the Rice Mission ([1]: "Control of the Benue and its tributaries would release enormous areas, now subject to erratic and excessive flooding, for the production of very large quantities of paddy along both banks of the main Benue. These areas, now growing nothing but grass, must total at least 200,000 acres."

The flood-protection extends between the dam-site (Mile 904) and the Taraba Confluence (Mile 672) in a region of vast flood-plains. Downstream of the Katsina Ala Confluence, flood-protection cannot be effected by a reservoir in the Upper Benue reaches because of the influence of the not-regulated Taraba, Donga and Katsina Ala tributaries.

8.6. SUMMARY

8.6.1. Recommendations

A Jebba multiple-purpose scheme (8.3.2) will have beneficial effects on the navigability of the Niger and will also assist in an indirect way a discharge regulation of the Benue. The generation of electricity will produce a substantial economic return. It is recommended that such a multiple-purpose scheme be fully investigated.

To achieve a major improvement of the navigability of the Benue, a regulation of its discharges is the only feasible method. As a first step a dam at Lagdo, as contemplated by the French Cameroun investigators, should be considered. This scheme will have to be supplemented by a dam above Yola, which has been described in 8.5.

Ultimately a dam at Makurdi might prove desirable.

8.6.2. Resulting improvement

One or more dams and reservoirs above Jebba will be used in the first place for power requirements. Nevertheless, an extension in navigability to all-the-year-round in average years can be expected and the available depths during the Black Flood period will be increased by a half or perhaps a whole foot. Drowning of the rapids will render navigation possible beyond Jebba and Yelwa right into French territory. Agricultural use of the flood-plains between Jebba and the Kaduna Confluence will be feasible because of flood-protection and irrigation possibilities.

A Lagdo Scheme for the partial regulation of the Benue discharges is of interest for the Upper Benue stations Lau, Numan and Yola, whilst Garua-bound traffic in particular will

([1] RICE MISSION, 1948, p. 41. GEN. 33

benefit by it. The Garua season will then be almost doubled and the navigability during the season, at present uncertain owing to the unpredictable August fall, be safe-guarded.

A second and larger reservoir above Yola will improve the navigability further by extending the season at Garua to roughly four times its present length, whilst also doubling the Yola season. The combination of a Lagdo and a Yola reservoir will facilitate flood-protection, thereby enabling the agricultural use of some 200,000 acres of flood-plain.

8.6.3. Expenditure

The dam at Lagdo has been estimated to cost £ 6 million, and an additional dam upstream from Yola £ 10 million.

The annual operation and maintenance cost of a dam and reservoir may be estimated at 10% of the capital investment.

CHAPTER 9

THE RECOMMENDED PROGRAMME OF IMPROVEMENTS

9.1. JUSTIFICATION OF SEQUENCE OF IMPROVEMENTS

9.1.1. General

Before a short explanation can be given of some of the economic aspects of each of the above described improvements, a summary of the present situation in river transport, as well as an indication of the future trends, is essential.

The accessibility of ports is given in Diagram IV, 3.2.2-1. The river fleets are alternatively used on the Niger and Benue, respectively during low and high water. From the total time available in one year about 50 % is not used, as neither night navigation nor night shifts ashore are common practice at present. An analysis of the available day-hours for navigation show the following division:

Steaming	35—40 %
In ports loading and discharging	20 %
Lost due to non-availability of cargo	15 %
Lost due to unnavigable river during April and May	15 %
Grounded or waiting due to river conditions	5—7½ %
Repairs	5—7½ %

In the middle 1950's river transport on the Niger and Benue reached a volume of 250,000 tons producing 115 million ton-miles. At present (1958) 125—130 million ton-miles are transported along the Niger and Benue system, while the yearly increase over the last decade has been 6—7 %. A faster development of river transport is for a large part dependent on the interest taken in this transport route, i.e., on the employment of capital to improve the transport route.

At present, the average freight rate of river transport (2.5d per ton-mile) is very little below the average freight rate of the railways (2.9d per ton-mile). This difference between rail and river transport costs is determinant for the question whether goods are preferably transported by rail or by river, as in the natural economic development the cheapest way is followed. Based on this principle, areas of economic influence can be determined for any ratio of transport costs by rail and by river: on the boundary of such region of influence the average costs of transport by rail and by water are equal, whichever way is chosen. Such has been done in Diagram 9.1.1-1. For the calculation of these lines, the following rough assumptions have been made:
(i) road transport to and from railway stations and river ports is roughly estimated to cost 5.8d per ton-mile (twice the railway freight);
(ii) for each transshipment an extra cost of £ -/5/- per ton has been included;

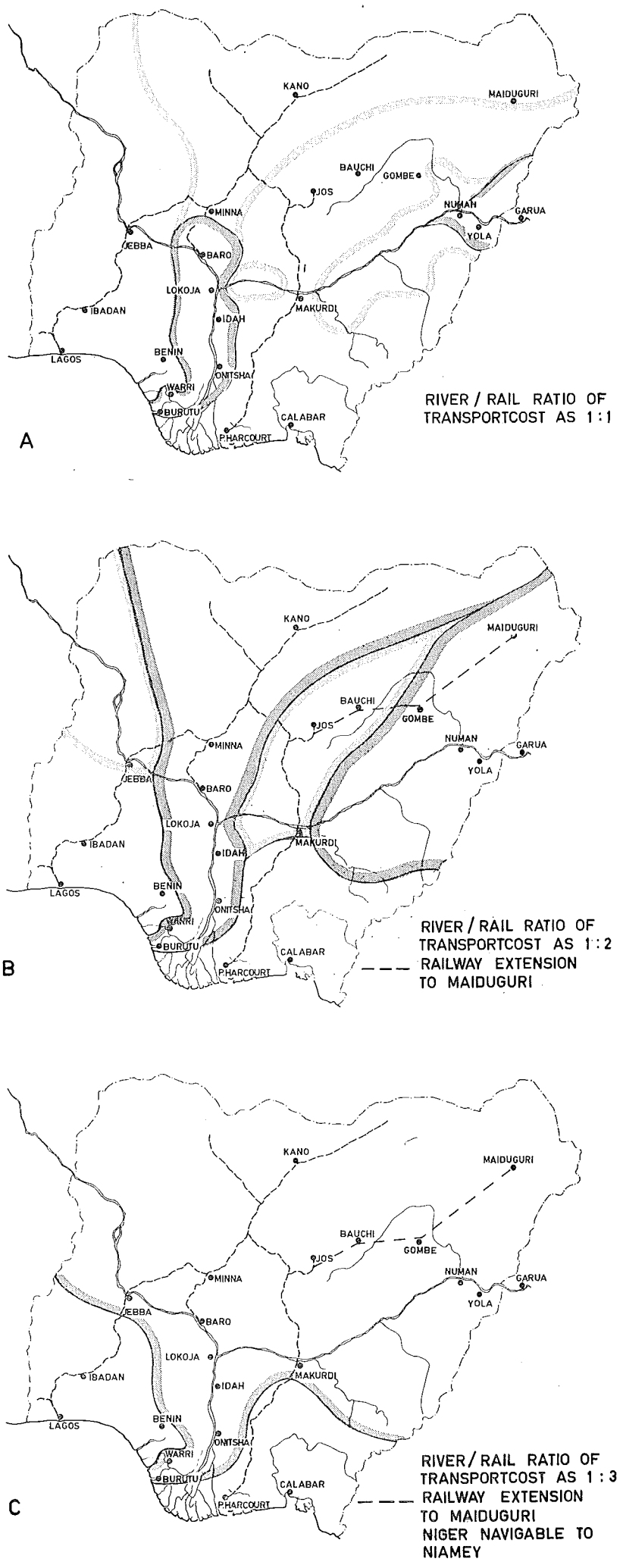


DIAGRAM 9.1.1-1

Regions of Economic Influence of Niger and Benue for Transport to and from Delta Ports

(iii) on the Benue above Makurdi additional expenses for river transport at an average of £ 3 per ton have been taken into account, due to cost of storage and loss of interest;
(iv) it has further been assumed that after the improvement of the Escravos Entrance — an essential condition for the development of river transport — the ports of Lagos, Burutu and Port Harcourt will have equal tariffs for calling ships;
(v) calculations have been based on average freight rates although they do not exist; in so far the influence areas are theoretical.

When under these circumstances river and rail transport tariffs have a ratio of 1 to 1, 1 to 2 or 1 to 3 (in some countries with a well developed transport system it may even reach 1 to 4), different areas of economic influence appear (Diagram 9.1.1-1). Dark shaded areas indicate the part of the country from where traffic is mainly concentrated on the river, as this way of transport is cheapest. To and from light shaded areas traffic can, however, also be by river under special circumstances, such as lack of proper road connections. At present, for instance, between Calabar and an area south of the Benue above Makurdi no direct roads exist and transport from the latter area is partly attracted by the river. From the North of Nigeria a limited amount of cargo is railed to Baro and shipped via the river. This is often a matter of policy. Also between Lokoja and Makurdi the river does attract some traffic.

The ratio 1 to 1 (Diagram 9.1.1-1A) reflects the present situation very well as follows from Diagrams IV, 1.1.3-2 to -4.

When river transport becomes cheaper it will happen that to and from Jebba and Makurdi rail and river transport is approximately equal in price. Large areas in the North will then be indirectly affected by the possible water-route (shaded in Diagram 9.1.1-1B).

In Diagram 9.1.1-1C is assumed that the ratio of river to rail transport cost has changed into 1 to 3, which is only possible after large improvements have been executed. Navigation throughout the year as far as Niamey on the Niger and during 6—8 months on the Benue should then be possible. The Niger and Benue will then have become the master transport route of West Africa.

If, in this way, the areas of economic influence of the Niger and Benue would increase, the transport quantities drawn to the river would increase. It is clear from Diagram 9.1.1-1 that only a slight reduction in transport cost will draw a large part of the goods conveyed by the railways north of Minna into the influence area of the River Niger. The whole north of Nigeria, with its important groundnut and cotton crops will then have the benefit of a cheap waterway for a part of the evacuation route. This cheap transport will gain even more importance when the Escravos Bar is improved, so that seagoing vessels can reach the Delta ports as easily as Lagos and Port Harcourt. At the same time, it will relieve these two latter harbours, where from time to time congestions occur due to the rapidly increasing transport. The benefits of an improvement are not only dependent on the freight reduction but also on the quantity of goods conveyed along the river. Cheaper transport will result in a sharp increase of transport and consequently show a sharp increase in the benefits.

The cost of improvements can often best be expressed in annual cost. The annual cost of permanent river-works consists for the greater part of interest on invested capital. The annual cost of the temporary improvements must mainly be evaluated from the direct cost to be made to attain the improvement.

The benefits of a certain river improvement should be expressed in social benefits to the country, but the evaluation of these benefits meets with some particular difficulties some of which are:
(i) the decrease in transport cost as a result of the improvements;
(ii) the total transport volumes for which this decrease applies in a succession of years;

(iii) the increase of production as a direct result of the improved transport facilities; and
(iv) the number of years which is a fair base for rentability calculations.

As this would be beyond the terms of reference, the present Report does not deal with an economic study of the improvements which are of such wide importance to the whole country. However, the advantages of some of the improvements are so clear that a rough calculation of cost and benefits can give an indication of the sequence of the necessary improvements, now and for some time in the future.

9.1.2. The required improvements

First and foremost is the improvement of the Escravos Bar necessary. The execution of this work, to be taken in hand in 1959, will open the Niger hinterland and tremendously stimulate river traffic. The second step will be to make river traffic less hazardous, more regular and suitable for larger units, all with the aim of decreasing transport cost and extending the use of the cheapest mode of transport.

To decrease the risks in navigation and to increase the optimum use of the available natural depths, leading to greater permissible barge draughts on the Niger and Benue, guiding is necessary. This can be given by maps, pilots, channel markers and patrols, communication, stage information and prediction, as well as by all research directly or indirectly connected with river management.

A more regular river traffic, by which the river-fleets can be used to the full extent, will be reached when:
(i) night navigation is introduced, depending on a proper night-signalisation and buoyage;
(ii) the river fleets can navigate throughout the present navigable seasons without delays, with barge draughts close to their maximum, which should be taken as 6 feet and which can be effected in a practical way on the Niger by dredging, local river training-works and a reservoir dam or a combination of this and on the Benue by a reservoir upstream of Yola.

For the future is required a depth of some 8 or 9 feet to continue the decrease in transport costs and to have river traffic maintain its position of cheapest mode of transport among the other competing means of traffic, for the benefit of the country. For the Niger a dam and reservoir as well as river training-works along a large part of the river would then be required, while for the Benue a dam in the upper reaches near Yola and a dam near Makurdi are required to attain this target.

A modernisation and enlargement of the commercial fleets is considered a logical response by the shipping companies to improved river conditions. In this way the river operators will obtain the maximum effect of the improvements. Already river operators have recently made a beginning with modernising their fleets. Modern tows have appeared on the Niger and Benue, and old tugs have been converted from coal-burning to oil-burning, which proved a considerable amelioration.

A more efficient operation of the feeder lines, especially of the Minna—Baro railway, in order to avoid losses of time, is one of the requirements of an improved transport, but above all it is required that the river fleets obtain more upward cargo.

9.1.3. Comparative merits and sequence of improvements

River management, consisting of all measures to guide navigation as has been described in the preceding chapters, leads directly to a decrease in transport costs. As an example, there may be mentioned the radio communication system recently introduced by one of the large shipping

companies; in co-operation with three radio transmitter-receiver sets of NEDECO (later taken over by the Inland Waterways Department) this has in a very short time paid for itself.

Many items of river management are imponderable. Studies and research, for instance, must always precede all improvements. How much such research will save is not calculable, but such an approach to problems is generally felt essential. The formation of a Hydrological Branch of the Inland Waterways Department, as was decided upon in 1956, is in this spirit.

However, the direct effects of channel demarcation and channel patrols, combined with stage information and water-level prediction, can be roughly calculated. In the two years during which such a system has been in use and although it has not yet attained full size and shape, it has been experienced that half a foot can be gained in usable draught. Navigation draughts are always between $3\frac{1}{2}$ and 7 feet, averaging 5 feet, due to the fact that during low-water shipping concentrates on the Niger and during high-water shipping concentrates on the Benue, where then depths remain restricted to this extent. The average degree of loading in a year may, therefore, increase by 10% as a result of channel demarcation, patrols and information. Also the number of sailing days may increase due to the stage information and prediction, which prevent a premature descent from the Benue and the Niger when water-levels tend to drop. At the same time, the number of groundings is considerably reduced as a result of a demarcation of the channel and information on its depths. This increase in sailing days could be estimated at 15%, so that the total capacity of the fleet increases to 1.10×1.15 or 126% of the present capacity even though no other measures are taken. Assuming 60% of the annual expenses of transport cost as fixed and 40% variable with transported volume, the cost per ton-mile will decrease by $12\frac{1}{2}$% ([1.

At the present volume of traffic (130 million ton-miles) and the present freight rate (averaging £ 1/-/- per 100 ton-miles excluding loading and discharging), the annual potential savings will be $0.125 \times$ £ 1,300,000 or £ 160,000, while the annual cost of these services will almost certainly be less than this amount. The net benefit will increase with the increasing volume of transport, as the cost will not increase. The adaptation of the fleet to the new circumstances will probably lead to an even higher efficiency than has been calculated above.

Night navigation can be made possible by a good system of night buoyage and night signalisation. The number of sailing hours for a certain fleet can then be increased by at least 60% over the present number of sailing hours (see 9.1.1). Buoyage and signalisation for night navigation will follow day demarcation, so that the increase of 60% is in addition to the increase of 15% due to stage information and prediction and the 10% due to the increase in degree of loading. Over the benefits of day demarcation an extra decrease of $22\frac{1}{2}$% ([2 in transport cost can then be expected if the same assumptions as above about fixed and variable costs of river transport are made. The annual potential savings reach, with the present volume of traffic, $22\frac{1}{2}$% of £ 1,300,000, or £ 290,000 which is certainly much more than the cost of night buoyage, while the net benefits will increase rapidly with the growth of traffic.

Dredging operations on the Niger with annual quantities of over 1.5 million cuyards (see Chapter 4) do not seem very effective at present, as the quantities to be dredged rise sharply

([1 This figure is arrived at by the consideration that, when originally 100 units are transported at a cost of 100 (60 fixed and 40 variable), now 126 units will be transported at 60 fixed and 40 $\times$ 1.26 variable. The decrease of cost per ton-mile is then

$$1.0 - \frac{1.0 \times 0.6 + 1.26 \times 0.4}{1.26} = 12\tfrac{1}{2}\ \%$$

([2 $1.0 - \frac{1.0 \times 0.6 + 1.6 \times 0.4}{1.6}$; see also ([1.

against equal additional improvements. Dredging operations for 1.5 million cuyards are estimated to cost in the region of £ 200,000 in an average year, although this amount may decrease by 25% if sufficient other objects with the dredger can be carried out during high water.

In 4.2.2. it has been explained that dredging 1.5 million cuyards will result in an increase of 30% in efficient fleet capacity during the Baro season from November 15 to April 15. On the same basis, calculated as above, this could lead to a reduction in transport cost of 14% ([1 during this period. The total ton-mileage on the Niger ports during that period can be taken as 40 million, with a transport cost of £ 400,000. So the annual potential savings from the dredging operations are thus in the order of £ 56,000.

Apart from dredging the Niger, the Benue Bar could also be dredged at the beginning of the Benue season. From this improvement a 5% increase of the capacity on the Benue for the river fleets is estimated and the freight reduction would then be 3%. On the Benue 90 million ton-miles are transported, and the annual potential savings from dredging the Lokoja Bar will then be 0.03 × £ 900,000 or £ 27,000. The total annual potential savings of some £ 80,000 from dredging do not warrant the execution of such a dredging programme as an economic enterprise until the volume of traffic increases.

This is in turn dependent on the improvement, and it seems at present that the combination of channel demarcation, channel patrol, stage information and prediction, night navigation and dredging operations will reduce the cost per ton-mile of river transport on the port of Baro to 60 or 65% of the present cost. No doubt this will be even more when upward transport of merchandise to the port of Baro increases. At present this up-river traffic is only a few percents of the down-river traffic, while the average for all ports along the Niger and Benue is about 30% and the ratio of import and export in the coastal ports is 1 to 1. The increase of up-river traffic to the port of Baro is thus very likely and from a viewpoint of efficient operation of railway and river fleets this is very necessary.

All this leads to the conclusion that during the months of December to April a considerable part of the produced crop will be conveyed via Baro along the river to the Delta ports when the above-described improvements are carried out and when the Escravos Bar is no longer a restriction for ships calling at the Delta ports. Under such circumstances 300,000 tons downward shipped from Baro, being about 50% of the total groundnut crop, and 100,000 tons upward shipped to Baro is a fair estimate, and then also would dredging be a paying proposition. It is understood, however, that the present capacity of the Baro—Minna Line is 120,000 tons in each direction, so that capital investment is necessary to increase the capacity of the line accordingly.

Discharge regulation asks for very large investments, and the benefits of such schemes must be calculated over a large number of years. Two such schemes should be considered:

(i) one or two dams and reservoirs upstream of Jebba where good sites exist; the reservoir size could be 12—15 milliard cubic metres, or 10—12 million acre-feet, according to rough estimates; and

(ii) a dam or two smaller dams with reservoirs in the upper reaches of the Benue, where good sites exist upstream of Yola and near Lagdo; the most suitable reservoir size is 10—12 milliard cubic metres, or 8—10 million acre-feet, according to preliminary calculations.

The present volume of river transport does not warrant these dams as long as they are not a part of a multi-purpose plan, but certainly future transport will to a considerable extent contribute to a sound economic base of these multi-purpose plans.

([1 $1.0 - \frac{1.0 \times 0.6 + 1.30 \times 0.4}{1.30}$; see note on previous page.

A Jebba dam will have a beneficial effect on a river-stretch of 500 miles below the dam and the Yola and Lagdo dams may improve even 1,000 miles of river. A Jebba dam will open a very long stretch of the Niger above Jebba, while a Yola dam will not increase the navigable length of the Benue above Garua. Future transport will develop fast over a short period after completion of the dams, and to a great extent this will be due to attraction of traffic to the Baro and Garua ports.

Traffic to and from Baro may from 30 million ton-miles reach within a few years 160 million ton-miles (300,000 tons of produce downward shipped and 100,000 tons general merchandise upward shipped) after which a normal yearly growth of traffic of between 5% and 7% will follow.

Traffic to and from Garua will, in the first instance, increase as a result of the prolongation of the navigation season and not of an increase of hinterland, as in the case of the Baro port (see also Diagram 9.1.1-1). The period of accessibility of the Garua port will be doubled even when no improvements on the Niger below Lokoja are executed and nearly trebled when the Niger below Lokoja is navigable with 5—6 feet during April, May and June. In the first instance traffic to and from Garua will increase from a small 50 million ton-miles to 100 million ton-miles, after which a normal growth of river traffic may be expected. To attain this it will still be necessary to dredge the Benue Bar which hampers navigation considerably when the rest of the Benue would already be navigable.

When comparing a Jebba and Yola scheme, the conclusion is that the benefits will be approximately equal from a viewpoint of navigation. However, a Jebba scheme has four important advantages above a Yola dam. They are:

(i) the better situation (from the viewpoint of consumption) to generate and distribute large quantities of electricity as a part in a multi-purpose scheme;
(ii) the opening of the River Niger above Jebba as far as Niamey, which will render accessible a complete new hinterland of the Niger and eventually be of great importance;
(iii) the effect of a Yola dam depends on the improved navigability of the Niger below Lokoja in April—June, which can best be improved by construction of a Jebba reservoir first; and
(iv) a dam and reservoir near Yola is not suitable for the generation of electricity as it cannot supply power throughout the year; apart from navigation only, flood control and subsequently irrigation would benefit from such a dam, whilst a Jebba project will produce all these beneficial effects.

River training-works will be only applicable on the Niger as has been outlined in Paragraph 6.4.3. These works aim at navigation depths of 8 or 9 feet. The large cost will be off-set by the considerably more efficient fleet exploitation than the use of a fleet with 5—6 feet draught. A condition is again a large volume of transport on the river, but there is little doubt that traffic will have increased sufficiently in the 30—50 year period required to carry out the complete regulation of the Niger from the Delta as far as Lokoja or Baro. It must be realised, however, that it will be difficult to exploit effectively a river-fleet in a combined operation on the Niger with 8 or 9 feet available depth and on the Benue with 5 to 6 feet available depth. A further improvement of the Benue with a second dam near Makurdi would be indicated to follow such river training-works on the Niger when in this 30—50 year period transport on the Niger remains largely dependent on agricultural crops. The agricultural crops cause a peak in transport over a comparatively short period. If industrialisation has developed sufficiently for a river-fleet solely for the Niger to be efficiently exploited during the whole year, it will prove even easier to decide on river training-works for the Niger.

From the above the following *sequence of improvements* can be summarised:

(i) River management, including research, channel demarcation, channel patrols, stage information and stage prediction combined with communications. This has already proved to give a net benefit, and the organisation already existing should be extended so that full profits of these relatively cheap measures are obtained.
(ii) Night navigation should be introduced as soon as the necessary buoys, beacons, etc. can be installed, as this improvement also will pay for itself as soon as it has reached full effect.
(iii) Dredging of dominating sills in the Niger as well as of the Benue Bar should be the third step of improvement, as it will be economically justified in combination with (i) and (ii) as soon as the decreasing transport cost attracts sufficient additional water-borne traffic, which may be in a few years' time. Meanwhile, test-dredging should be carried out as described in Chapter 4. Further, tests should be carried out with floating training-works and bandalling (Chapter 5).
(iv) A dam and reservoir upstream of Jebba, which as a multi-purpose project may soon prove economic and then precede:
(v) A dam and reservoir upstream of Yola to supplement a dam near Jebba. Through a combination of the water release of these two dams, the most effective navigation channels can be created. Extension of the navigation season and increase of available depth can from year to year be combined to serve the river-fleets with the best transport route, depending on the distribution of the freight market over Niger and Benue in each year.
(vi) River training-works on the Niger should be completed within 30—50 years, which will ask for the first steps to be taken in the near future.
(vii) A dam near Makurdi will eventually bring about the further improvement of the Benue to a river navigable below Makurdi throughout the year with an available depth of 8 or 9 feet and a further extension of the navigation season between Makurdi and Garua to 8 or 9 months with 4 feet draught, or 5—6 months with 6 feet draught, or 3—4 months with 8—9 feet draught will then be the least result.

In conclusion it may be stated that the improvements (i) and (ii) should be carried out without delay, as they are already economic propositions. At the same time, test-dredging should be started to establish whether the results of dredging will be in accordance with the assumptions in Chapter 4. If this proves to be so, dredging proper should follow the improvements (i) and (ii) directly.

The other improvements can be carried out when the volume of traffic has increased to such an extent that the costs are smaller than the benefits. The opposite reasoning is that the improvements result in a large increase of transport, which will make them remunerative. Which approach is to be taken is a question of policy; but if the first is followed it will mean that the improvements are carried out too late, which will mean a loss to the country. Improvements (i) and (ii) are clear examples of this; they should have already been carried out, as the net benefits of such improvements over preceding years can no more be realised.

In the long run, all the above-suggested improvements will prove remunerative. This may in the first years appear to be partly at the expense of other means of traffic (railway and road transport) but the overall traffic will develop so quickly, partly as a result of the river improvements, that eventually also the other means of transport will benefit. The impressive revival of the Mississippi navigation of the past decades had no unfavourable effects at all on the railways running parallel to that river. The Rhine and other European rivers are frequently flanked by railways; together with road transport, these transport systems are complementary to each other, and the only effect of a normal and free competition should be that the most efficient means of transport is provided for any type of goods.

9.2. RECOMMENDATIONS

9.2.1. River Management

An increasing number of hydrological and morphological observations and studies (III, 7) will have to be made as this is essential for the benefit of navigation (3.5 and 3.6) as well as for further river improvements.

More river-gauges have to be erected in the upper reaches of the rivers and the organisation of their readings and the publication thereof should be further improved (3.5). Predictions of stages and depths (3.6) should be prepared where feasible.

Navigation maps have to be revised every two years, and survey charts and flood-plain maps of certain specified areas have to be prepared within the next five years (3.1).

Day-time buoyage of the difficult sections of the Niger and Benue Rivers (3.3) should be effected as soon as possible. A number of special vessels, forming three independent units, will have to be built for this, and an adequate system of channel patrols, comprising a number of shore-bases (3.4) will have to be established.

This system should be extended into a comprehensive night-signalisation (3.3 and 3.4) as soon as practicable. One, preferably two additional channel patrol units are required for this.

The existing system of radio communication should be improved and extended (3.7).

The Hydrological Branch of the Inland Waterways Department should be expanded and decentralised in order to be at all times adequate for meeting the requirements imposed by the foregoing recommendations (3.8).

Inter-departmental and international consultations on the hydrology and the navigability of the Niger and Benue (3.8) should take place to co-ordinate observations and projects.

9.2.2. Dredging

When the transported tonnages on the river system have increased to a two or threefold of the present volume, dredging the Niger and the Benue Bar will warrant its expenditure. It is likely that river management including night navigation will cause this increased transport in a few years (9.1).

It is therefore recommended to commence test-dredging by a contractor as soon as possible, in order to establish the uncertainties of dredging, to gain experience and to be able to develop a dredging scheme for the execution of a large-scale dredging programme of the River Niger and of the Benue Bar. This should be done with a cutter-head suction dredger of about 500 cuyards/hour capacity (4.1).

In the near future a dredging programme of approximately 1,500,000 cuyards is foreseen in an average year to maintain a 5'6" navigation channel from the Delta to Baro during the months of December to April and to open the Benue 10—14 days earlier than ships can at present enter the Benue. A 2,500 cuyards/hour capacity of the dredger fleet will be sufficient to reach these targets and it is not recommended to try and gain a larger improvement than 2 feet during the Baro season as this would better and at less cost be obtained by other river works (4.2).

Improvement by dredging of one to two feet can be obtained on the Benue after a discharge regulation will be carried out (4.3).

It is recommended that the dredger fleet should consist of cutter-head suction dredgers, as these dredgers are most suitable for the rather coarse sand of the Niger and have the widest application in dredging work other than cutting channels through shallow shoals in the Niger. A spud-carriage system, anchor-derricks and self-propulsion are recommended for these dredgers,

while the floating discharge line should not need anchoring. All these specifications should be met to obtain the maximum effect of the dredging fleet (4.5).

9.2.3. Other temporary improvements

It is recommended that, after the results of current experiments regarding the Soudanese Niger have become available, experiments be carried out to deepen the Benue Bar near Lokoja with the use of fascine screens of the POTAPOV system (5.4).

9.2.4. Bed-regulation

In view of the fact that an ultimate regulation of the Niger-bed cannot be avoided when the river and its valley will be fully developed, and because of the long period of time required for making such a regulation, it is recommended to commence within the next ten years with such works (9.1).

It is further recommended to give priority to a regulation, by means of groynes, training-walls and bank-stabilisation, of the difficult crossings and flats in a 30-mile stretch of the Niger below the Rocky Section (i.e., about from Mile 340 to Mile 310). Such a regulation may take some 15—20 years before it is completed (6.4).

This regulation should be followed by a further programme of bed-regulation, but as circumstances and priorities are hard to predict some 20 years ahead, only a sketch of such a programme should be given.

A regulation of the 10-mile stretch between Lokoja and the Rocky Section (Miles 360—350) may subsequently be undertaken, to be followed by the section between Odugri and Aboh (Miles 187—177). Lastly, several scattered crossings between Idah and Odugri (Miles 310—187) have to be regulated. This programme, with some complementary dredging, will result in depths of some 8 feet below Low River Level between Lokoja and Samabri (Nun Fork, Mile 155).

Alternatively or simultaneously a regulation of the Baro—Lokoja section (Miles 434—362) may be carried out. The first step would here be to eliminate the difficult sills, which will result in depths of about 8 feet below L.R.L. Next, a regulation of this section to 10 or 12 feet may be considered.

In view of the first target, it is recommended to prepare a series of detailed survey charts of the area between the Rocky Section and Idah (3.1).

It is further recommended to improve the channels of the Niger just downstream of Lokoja by clearing the rocks from the Sacrifice Channel (Miles 358—361), in order to eliminate the Lokoja Flats, and from the South Channel of the Benue at its confluence with the Niger. This should be done within the next five years (6.4).

9.2.5. Discharge regulation

A Jebba multiple-purpose scheme (8.3.2) will have beneficial effects on the navigability of the Niger and it will also assist in an indirect way a discharge regulation of the Benue, whilst the generation of electricity will produce a substantial economic return. It is recommended that such a multi-purpose scheme be fully investigated.

A Lagdo scheme (8.4) for the partial regulation of the Benue discharges is of particular interest to the navigation on the port of Garua, but Yola-bound navigation, too, would benefit.

It is recommended that a Lagdo scheme should precede a further regulation of the Benue discharges by a dam at Mile 904 above Yola (8.5).

Meanwhile, studies should continue to consolidate and extend the basic information required for such a Yola regulation scheme.

9.2.6. Conclusion

It is concluded that the improvement of the navigability of the Niger should be carried out in four major steps, namely, (i) river management, (ii) dredging, (iii) bed-regulation and (iv) discharge regulation. Improving the Benue navigability should within the foreseeable future be done in two steps, viz., (i) river management and (ii) discharge regulation.

These steps are for each river supplementary to one another and their respective improvements should be added together. But each separate step in itself is sub-divided into a number of phases, which may overlap in time with phases of other steps. Also, each step will in general increase the efficiency of the previous one.

In this way, a flexible programme of river improvement is obtained, so that at any time the rivers may be developed to a stage that meets the demands of navigation in particular, or of the country's economy in general.

9.3. EXPENDITURE

9.3.1. Capital and recurrent expenditure

River observations and studies will ask for annual increases in the present recurrent expenditure over a period of at least ten years.

An amount of £ 75,000 will cover for the coming 3—5 years the expense of mapping and charting the rivers.

Day-time buoyage on the Niger and Benue requires a capital expenditure of some £ 150,000; the recurrent cost will be about £ 70,000.

Night-signalisation on the Niger and Benue requires over and above the cost of a day-time buoyage a capital expenditure of £ 100,000; the additional recurrent cost will be about £ 45,000.

Test-dredging will require a sum of between £ 40,000 and £ 50,000 per season, during two years.

A dredger-fleet, when Government-owned, would require a capital investment of between £ 800,000 and £ 900,000. The annual recurrent expenditure for river improvement by dredging would be between £ 150,000 and £ 200,000, depending on the use and ownership of the dredger-fleet.

For experiments with light provisional training-works a total sum of £ 500 should be allocated. If successful, the expenditure should be gradually increased to £ 10,000 or £ 15,000 per annum, for improving the Benue Bar and the Wuro Boki and Gamadio Flats.

A summary regulation of the difficult crossings of the Niger to L.R.L. — 8 feet between the Rocky Section and Idah will require a capital investment of about £ 4.5 million, to be spread out over 15 or 20 years. The recurrent cost, composed of maintenance and amortisation, is estimated at about 5% of the cost of the completed works, rising to £ 200,000 or £ 250,000 after all crossings in this section have been regulated.

A further regulation of the difficult stretches of the Niger between Lokoja and Samabri would require additional capital investment of £ 5.5 million spread out over perhaps 10 or 20 years, with annual cost of maintenance etc. rising to some £ 250,000 or £ 300,000.

A complete regulation of the Niger between Lokoja and Samabri to attain depths of 10 feet below L.R.L. as a sequence to the elimination above of difficult stretches, would require another £ 10 million investment, whilst the additional recurrent cost would be £ 500,000.

A regulation of this section, with contracted crossings to reach depths of 12 feet below L.R.L. would ask for an additional £ 20 million investment and £ 1 million recurrent cost.

A summary regulation of the Baro—Lokoja stretch to 8 feet below L.R.L. would ask for an investment of £ 2 million; a complete regulation to L.R.L. — 10 feet would cost £ 3 million more and a regulation with contracted crossings to L.R.L. — 12 feet would cost an additional £ 5 million. Recurrent cost may again be estimated at about 5%.

The cost of a discharge regulation through a Jebba scheme will not be given here, being a part of a multiple-purpose scheme.

The cost of a Lagdo dam, for a regulation of the discharges of the Benue and effective between Garua and Ibi, has been estimated by the Cameroun investigators at £ 6 million.

The cost of a Yola dam will be between £ 10 and £ 14 million, depending on its size. The annual recurrent cost, composed of maintenance, operation and amortisation, is estimated at about £ 1 million.

9.4. RESULTING BENEFITS

9.4.1. Improved navigability

The improvements just described each lead to an improved navigability, which may be shortly summarised thus:

River management can be properly organised in 1961 or 1962, effecting half a foot gain in utilisable navigation depth throughout the present shipping seasons. Not only will the number of groundings be greatly reduced, but the prediction of water-levels and available depths will enable the maximum use of these available depths until the end of the Baro and Benue seasons. The estimated lengthening of the serviceable season is from 10 to 15%.

Night buoyage and signalisation, as a part of river management, will increase the capacity of a fleet by some 60% compared with the present situation.

Dredging by a dredger fleet of some 2,500 cuyards/hour capacity will increase the available depths by one foot in the Baro season, i.e., from December to April and entering the Benue will be possible 10 to 14 days earlier in an average year. Dredging the Benue would mean excessively large expenditure and is not recommended as long as the Benue season is not extended and the water-levels be kept partially in hand by discharge regulation. Test-dredging during a couple of years should precede the building of a special dredger fleet, but navigation can in the meantime benefit to a small extent from such dredging. This experimental dredging could start immediately, if it is to be carried out by a contractor.

Temporary training-works will probably not give any real improvement, although trials should give a definite conclusion on this subject. Locally, it can in some places achieve the same effect as dredging and reduce the dredging programme, thus in combination with dredging attain the same improvements in navigability as dredging only. On the Wuro Boki and Gamadio Flats it could lead to channels through these flats which would permit passing of ships perhaps a fortnight earlier than at present. This would lead to an improvement of the accessibility of the ports Yola and Garua by half a month, which would be a far from negligible lengthening of the navigable season for these ports.

Bed-regulation is only feasible on the Niger, and the execution of a complete regulation of this river between Baro and the Delta will probably enable navigation with 8 or 9 feet throughout the present season, i.e., excluding April, May and June, when draughts would be limited to 5 or 6 feet. Execution of these works will take from 30 to 50 years, and it is very likely that a dam and

reservoir upstream of Jebba will have been built before this time has elapsed. If that is so, 8 or 9 feet navigation throughout the year will then be possible, meaning an improvement of 4 feet and an extension of the Baro season by two to three months as compared with the present situation. During the execution of the training-works the amount of dredging could gradually decrease, although this would be ineffective when the dredger fleet is not used to full capacity. A little more depth can then be gained by full-capacity dredging each time a part of the river training-works has been completed.

Discharge regulation on the Niger by means of dams and reservoirs of upto about 12 milliard cubic metres (10 million acre-feet) upstream of Jebba will be used in the first place for power requirements. Nevertheless, an extension in navigability to year-round navigation in an average year can be expected and the Black Flood can be heightened some inches. Moreover, the crossings and the channels will to a lesser extent be exposed to the deteriorating effect of the flood-peaks and consequently the total increase in available depth during the Black Flood period will rise to $\frac{1}{2}$ or 1 foot. Further improvement of the available depth can be obtained when the storage volume is raised by some 7 milliard cubic metres to almost 20 milliard cubic metres (16 million acre-feet), the cost of which is estimated at only £ 2.5 million. But owing to the fact that this extra volume cannot be filled in drier years, the full benefits will only be reached in $1\frac{1}{2}$ to 2 out of every 3 years on an average. Lastly, navigation upstream of the rapids between Jebba and Yelwa will get an outlet to the sea, as the dams will eventually drown all rapids.

A Yola dam or a combined Lagdo and Yola (Yolette) Scheme with a reservoir capacity of between 8 and 10 million acre-feet will lengthen the navigable period at ports in the upper reaches of the Benue. The season at Yola will be doubled, whilst the Garua season will be extended to roughly four times its present length (see Table 8.5.6-1). The Yola (Dasin)—Garua stretch will be navigable throughout the year. On an average, navigation will gain from this improvement a 100% increase of cargo shipped to and from the Benue without enlarging the present fleet capacity. When the fleet is adapted to the new possible draughts, a much more favourable exploitation of the fleet will result.

An eventual dam in Makurdi may provide for a year-round 8—9′ navigation channel downstream from the dam, and conditions on the Niger below Lokoja would also greatly benefit from this regulation. But between Yola and Ibi the navigation channel cannot be more than 8—9′ during 3 to 4 months, or 6′ during 5 to 6 months or 4′ during 8 months, according to conservative assumptions for the discharge hydrographs and to the present limit discharges. However, a Yola dam will precede a dam near Makurdi by many years, and there are good grounds to expect considerable changes in the morphology in the Yola—Ibi stretch as a result of a discharge regulation (see 8.5.5). The river-bed may narrow and the limit discharges may considerably decrease, so that it may very well be possible that large depths over longer periods will be available on this stretch.

9.4.2. Increased and improved transport

All the measures taken to improve the navigability of the Rivers Niger and Benue aim at a cheaper exploitation of the river-fleets by minimising the time of idleness of invested capital in ships and by increasing the available depths, which reduces the invested capital and, to a smaller extent, the recurrent expenditure per ton-mile of carried transport. It is beyond the scope of this Report to investigate further the reduction in transport cost per ton-mile, but there is no doubt that the measures described above will bring water transport cost per ton-mile in the same position as in more developed countries, i.e., in the order of 1 to 2 or 1 to 3 compared with rail transport cost per ton-mile.

The results of these reduced exploitation costs can be partially understood from Diagram 9.1.1-1. The influence area of the railways north of Minna will be drawn into the Niger River influence area via the railway-line Minna—Baro. Furthermore, the direct influence areas of the rivers will considerably increase. New developments of the railway and road transport routes cannot, however, be overlooked, so that the influence on river transport is very difficult to estimate. However, if the river transport will remain cheaper, bulk transport will mainly follow the water route provided port facilities in the Delta are equivalent to those in Lagos and Port Harcourt.

Rough estimates made of the increased tonnages moved by the cheaper river transport following the improvements are:

(i) Resulting from river management, night navigation, dredging and the expected response from sh'pping and port agencies:

1. an extra increase of transport from Baro of 250,000 tons/year and up-river to Baro of 100,000 tons;
2. an extra increase of 20 to 40% of the present transported tonnages from the increasing Niger influence area; and
3. an extra increase of 60% of the tonnage handled during the Benue season.

(ii) Resulting from a Jebba dam subsequent to (i), and from a further increase of the Niger influence area:

an extra increase of 10% over the increased transport mentioned under (i) 1, and 2.

(iii) Resulting from a dam near Yola following (i) and (ii):

a doubling of the Benue transport as has been mentioned under (i) 3.

A further normal annual increase of 5—7% can be expected over all the above tonnages.

A necessarily inaccurate extrapolation of the transport into the future has led to the estimate of a 10 to 15-fold increase of the present transport within 40 years, i.e., between 1,300 and 2,000 million ton-miles transported per year between the Delta ports and the ports along the Niger and Benue. This is excluding local traffic between ports along the Niger and Benue, which may also become very important, as can be realised from the fact that the ratio of exported to total volume of agricultural produce is at present about 1 to 15 and that Nigeria has a considerable industrial potential. Important raw materials such as oil and iron have been localised.

In the decreased cost of transport due to improvements will also be found expressed the more reliable, shorter and year-round transport which will be possible. All transport from and to places within the present area of influence of the river will benefit to the full extent by the improvements. Places within the enlargements of the influence area will benefit only partly and at places situated at the new periphery of the influence area nothing will be gained until further improvements are made. From Diagram 9.1.1-1 it can be seen that approximately 65% of the country will profit from the improved transport facilities and from the reduced transport cost when the ratio of water and rail transport cost has become as 1 to 2.

9.4.3. Additional advantages

The recommended programme of improvements will bring about many additional advantages not directly connected with improved navigation. The most important of these are:

(i) the stimulation of production in cultivated and not yet cultivated areas above the present annual increase in production, as a result of the improved and cheaper transport facilities;

(ii) the generation of power, which will be the main interest of a dam and reservoir near Jebba, as well as the flood-control made possible by dams including the irrigation prospects;
(iii) the agricultural and industrial development of the river valleys which will become increasingly attractive as the rivers are being brought under control;
(iv) the opening of a water-route along the Niger as far as Niamey;
(v) the creation of employment by the execution of the river-works for a group of the population in skilled labour of different levels; and
(vi) the imponderable advantages of hydrological research beyond the direct results for navigation.

All these extra advantages should be added to the calculation when seeking to find an economic basis for the improvements. This is not necessary when the benefit for navigation only already surpasses the expenditure as in the case of river management and night navigation, but it certainly is necessary for those large-scale projects as dams and reservoirs or river training-works for which the economic justification must be sought in all their aspects and over a large number of years.

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LIST OF UNITS

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LIST OF SYMBOLS

Generally used throughout this Report

a depth of water
a_e hydraulic depth
a_n navigation depth
b width of stream-channel, measured at the surface
c concentration; velocity of propagation
d grain-diameter: d_m, d_{50}, d_{90}
f function of
g acceleration of gravity
h water-level related to any arbitrary datum, for instance, M.S.L.
i water-level gradient, or slope
k channel roughness, distinguished into k_r = roughness of the bed
k_s = roughness of the grains
l wave-length, for instance of bed-ripples
n frequency (number of days); Manning's coefficient
p percentage (in particular regarding the sieve-curve of a sand sample)
q discharge of water per unit width
r radius of a bend
s sand-transport per unit width
t time
u momentary water velocity on a certain position in the cross-section
$\bar{u}$ local velocity averaged over a certain period of time
v mean water velocity, averaged over the full cross-section and over a certain period of time
v_c pick-up velocity
x co-ordinate along the river-axis
y co-ordinate in transversal direction
z co-ordinate in vertical direction

A area of wetted cross-section
B width of storage
C coefficient of De CHEZY
D deficit as regards to rain
E energy; evaporation
E_p potential evapotranspiration
F function of
G function of
H total-head, related to the same datum as h; $H - h = \frac{v^2}{2g}$

L wave-length (for instance of meanders); length of a river-section
P precipitation
Q discharge of water over the full width of the cross-section
Q_d dominant discharge
R hydraulic radius; run-off
S sand-transport over the full width of the cross-section

α angle; coefficient
β angle; coefficient
γ specific gravity
ε coefficient of Strickler
ϑ angle; coefficient
μ ripple factor
ν kinematic viscosity
π 3,1415
ρ density; ρ_w = density of water
ρ_s = density of sand
τ tension = ρgai
φ function of
χ function of
ψ function of
ω angular velocity (in particular regarding the earth's rotation)
Δ increase; relative density of sand under water = $\frac{\rho_s - \rho_w}{\rho_w} = 1.68$
Σ sum

Indices

c critical, for instance in v_c
d dominant, for instance in Q_d
e equilibrium, for instance in a_e
m mean or average, for instance in d_m
n navigation, for instance in a_n
r ripple, for instance in k_r
s sand, for instance in k_s or ρ_s
w water, for instance in ρ_w
0 initial stage
1, 2, 3 various stages in the development of a magnitude, with respect to time as well as to place

In addition, various symbols have, in a single Section or Chapter, been used to express different magnitudes. Such has been clearly explained in the concerning paragraphs.

LIST OF UNITS

1 metre = 1 m = 3.281 ft = 39.37 inches
1 centimetre = 1 cm = 0.01 m = 0.03281 ft = 0.3937 inch
1 millimetre = 1 mm = 0.001 m = 0.003281 ft = 0.03937 inch
1 kilometre = 1 km = 1000 m = 0.621 mile

1 square metre = 1 m^2 = 10.764 square feet = 10.764 sq.ft
1 square kilometre = 1 km^2 = 0.386 square mile = 0.386 sq.mile

1 cubic metre = 1 m^3 = 35.3 cubic feet = 0.0008107 acre-feet
1 litre = 1 ltr = 0,001 cubic metre = 0.001 m^3

1 cubic metre per second = 1 m^3/sec = 35.3 cubic feet per second = 35.3 cusecs
1 litre per second per km^2 = 0.0914 cubic feet per second per sq.mile

1 gramme = 1 gr = 0.03527 oz
1 kilogramme = 1 kg = 1000 gr = 2.2046 lbs

1 foot = 1 ft = 12 inches = 0.3048 m
1 inch = 25.4 mm = 0.0254 m
1 (statute) mile = 5,280 ft = 1,609 m = 1.609 km

1 square foot = 1 sq.ft = 0.0929 m^2
1 square mile = 1 sq.mile = 1.589 km^2

1 cubic foot = 1 cuft = 0.0283 m^3
1 acre-foot = 1,233.5 m^3

1 cubic foot per second = 1 cusec = 0.0283 m^3/sec
1 cubic foot per second per sq.mile = 10.941 litre per second per km^2

1 ounce = 1 oz = 28.35 gr
1 lb = 16 ozs = 453.59 gr

All references to tons are to long-tons of 2,240 lbs unless otherwise noted.

GLOSSARY

A list of terms which could cause confusion or misunderstanding is given below, together with the number of the page which could best be consulted for further elucidation. The descriptions indicate the sense in which the relevant words have been used in this book and are not intended to be authoritive decriptions of a general validity. The mark * to a word indicates that this word, too, has been listed in this glossary.

Accretion: Local heightening of the river-bed * caused by local deposition of sediment *.

Aggradation: Gradual and slow but continuous heightening of the river-bed * over a rather long stretch of river.

Alluvial river: A river with the essential characteristic of flowing through its own sediment *, and therefore capable of adjusting bed * and banks * according to physical laws; rocks or other very cohesive materials not originating from the river itself are absent. *512*

Apex: The place in the main river from where it starts to ramificate * into various distributaries forming the delta *. *262*

August fall: Temporary discontinuity in the gradual but irregular rise of river-stages * after the rainy season starts; it is caused by a temporary decrease in rain intensity. *398*

Axis: See *hydraulic axis.*

Backwater: Deviation of the water-line * from its equilibrium * state by any influence, creating a so-called back-water curve in the river-section immediately upstream from the point of disturbance. See also *raise* and *draw-down. 366*

Bandal: Temporary bamboo guiding structure in the river-bed * to effect a small deepening of the channel by contraction of the flow *; the structure itself as well as the effect are demolished by the next flood. It is originally applied in India. *856*

Bank: Lateral boundaries of the river-flow * in its normal stage *. Banks are often flooded by high water. *577*

Bankfull: That stage * of the river which just does not overflow the banks *. *577*

Bar: Excessively shallow sill * or ridge in the river-bed *, blocking the navigation route.

Beacon: Sign erected on the bank * for the purpose of guiding navigation or for survey purposes. *803*

Bed: That part of the river which is situated below bankfull * stage.

Bed-load: Transport of sediment * (sand *) by the river flow * close along the bed * by rolling and sliding grains. This type of movement is limited to a restricted zone above the bottom, which is here arbitrarily taken to be 4 inches high. *464*

Bed-ripples: More or less regular sand-dunes or ridges occurring on the river-bed * with their crests at about right angles to the flow direction. *498*

Bed roughness: Roughness of the river-bed * forming the total resistance against water flow * and including the grain roughness * as well as all irregularities by ripples *, sand-banks *, bars *, etc. *589*

Beheading: See *capture.*

Benchmark: Artificially-erected fixed point on a bank * for levelling purposes. *123*

Black Flood: Moderate discharge * occurring on the Middle and Lower Niger during the months of December till April and originating from the rains in the drainage * basin along the upper * reaches of the Niger above Timbuctu; the run-off * from this area is retarded and flattened out by the extensive flood-plains * around Timbuctu and arrives in Nigeria some 5 months late. It is called Black Flood because it contains little silt * and has therefore a dark appearance, as opposed by the normal high-water flow * (originating from the rains falling in the drainage basin below Timbuctu) which has more light-coloured water and which is called White Flood. *345, 446*

Braided: The type of river showing multiple bifurcations and junctions, wide and shallow cross-sections, relatively steep slopes*, rapid shifting of channels* and sand-banks* and mainly a generally straight alignment of its banks*. *553*

Buoy: Drum or any other suitable floating object positioned in the river and moored to an anchor or anchoring structure with the purpose of guiding the navigation. *801*

Capture: Extension of a river (affluent) in upward direction by erosion into the drainage* basin of another river, resulting in the discharge* of that river running through the first-mentioned river; the latter river is then said to have been beheaded. *288*

Catchment area: See *drainage basin.*

Central delta: The flat area between Ségou and Timbuctu, probably once an inland sea, and now consisting of marshes, lakes and annually flooded land intersected by many distributaries. *200*

Channel: Deeper part of the river-bed* where the flow is more or less concentrated, *501.* Sometimes used in the sense of the entire river-bed taking part in the discharge* of water, *533*

Chute: A short-connection along the inner part of a bend, originating from variations in the discharge* and disturbing the regular alignment. *557*

Coriolis (acceleration of): Acceleration exerted on any moving particle by the earth's rotation, on the northern hemisphere directed to the right. *538*

Crossing: More or less straight transition zone between two consecutive opposite bends, where the flow* during low water must cross over from one side of the river to the other. The bed configuration on a crossing is like a saddle, sloping gently downward in the direction of the flow and upward perpendicular to the flow direction. *601*

Cut-off: 1. Vertical impermeable screen under the foundations of a dam or weir made, for instance, by cement injections. *922*

2. Short-cut across a loop of a meandering* river. *647*

Datum: Imaginary plane to which all depths or heights are reduced for the purpose of:

1. preparing sounding* charts or flood-plain* maps; the datum can be horizontal or inclining more or less parallel to the water-line* of the river at a certain stage*. The latter method has been used by NEDECO; for the Niger it corresponds with L.R.L.*. *389*

2. establishing a reference elevation for gauge* readings. This datum is mostly mean sea-level but could theoretically be any arbitrary elevation. *364*

Defile: River valley narrowing.

Degradation: Gradual and slow but continuous lowering of the river-bed* over a rather long stretch of river.

Delta: Seaward section of the river where it bifurcates into various branches which debouch into the sea; zone of deposition of the sediment* carried down by the river flow*. *262*

Density: Fluid mass per unit of volume.

Discharge: Volume of water or sometimes of sand* carried by the river per unit of time.

Dominant discharge: Representative quantity of discharge* as determined in the case of a non-steady* discharge for a certain characteristic of the river-bed*. In this Report, the average depth has been used for the calculation of the dominant discharge. *519*

Dominant water-level: Representative water-stage* corresponding to dominant discharge*. *520*

Drag: Tractive force exerted by the water flow upon a movable sand* particle on the river-bed. *465*

Drainage basin: Area of land which drains into the river. *228*

Draw-down: Negative disturbance by which the water-stage* upstream is kept below its level of equilibrium*. *389*

Duration: Period during which the magnitude of a phenomenon remains below or above a certain value.

Duration curve: Graph indicating the relationship between the duration* of a certain phenomenon and the magnitude of that phenomenon; it is an integrated frequency* curve, but is often itself termed frequency curve. *351*

Equilibrium state: Static: the situation which occurs when all forces exerted upon a particle compensate each other in magnitude and direction. *270, 544*

Dynamic: situation in which the movement of particles (for instance sand* particles) is such that for a certain location the supply equals the removal. *270, 544*

Erosion base: Fixed elevation serving as a maximum possibility for erosive powers. *270*

Evapotranspiration: Evaporation of water from between the grains which consitute the soil, together with the transpiration from the vegetation. *437*

Fall: The lowering of river-stages* by decrease of discharge*.

Fall velocity: The vertical downward velocity of a sand particle in water, moving under the combined influence of gravity and resistance. *466*

Flats: A relatively wide and shallow river-section with undistinguished and frequently shifting channels *. *753*

Flood-plain: That part of the river valley which is regularly flooded by high water and which has, therefore, a storage function. *235, 439*

Flow: Moving mass of water.

Flow-line: Intersection with the water surface of an imaginary vertical plane parallel to the river-axis with the characteristic that the total transversal flow * through this plane averages zero. However, as such a flow-line is difficult to determine, surface flow-lines are often used instead; these indicate the paths of water particles at the surface. *607*

Frequency: Period during which a certain phenomenon occurs within a limited range of values.

Frequency curve: Relation between the frequency * of a certain phenomenon and the magnitude of that phenomenon. *350*

Gauge: Vertical scale or instrument to determine the water-level * elevation. *122*

Gradient: Tangent of inclination; in this book expressed in units of 10^{-5} (a hundred-thousandth or a centimetre per kilometre). *362*

Grain roughness: Roughness of an imaginary river-bed * consisting of regularly settled sand-grains on an even plane without any other disturbances as ripples *, etc. See also *bed roughness. 589*

Grain-size: Average diameter of sand-grains, as determined by sieve-analysis. *457*

Groyne: Structure for guiding the water flow * built in the river-bed * more or less perpendicular to the direction of the current.

Guide vane: Structure either on the surface or on the river-bed * with the object of creating a circulatory current with a deepening effect.

H.D.W.: High dominant * water-level *, occurring where two dominant water-levels on one river-section exist. *477*

Headwater area: More or less mountainous catchment * area near the source of the river. *225*

Helicoidal flow: Transversal circulatory current. *526*

H.W.: High water.

Hydraulic axis: The line formed by connecting the centres of gravity of the mass of flowing water in consecutive cross-sections. *584*

Hydraulic depth: The natural depth of a simplified river in its state of equilibrium *; its magnitude can be expressed as $\sqrt[3]{\frac{q^2}{C^2 i}}$. *644*

Hydraulic radius: Wetted cross-sectional area divided by the perimeter of the zone of contact between river-bed * and river-water. As for most rivers the width is very great in comparison with the mean depth, the hydraulic radius can often be replaced by this mean depth. *391*

Hydrograph: Graph obtained by plotting stages * observed on a river-gauge * against the time at which they occurred (stage hydrograph), *344*. Also used is discharge * hydrograph, *398*.

Hydrography: 1. description of the water courses;
2. description of the morphological pattern and preparation of sounding * charts;
the latter being used in this book.

Hydrology: 1. science of the water movements in, on and above land;
2. study of the regime * of rivers and their drainage * basins;
the latter being used in this book.

Hydrological cycle: General circulation of water from the sea to the atmosphere, to the ground and back to the sea again. *437*

Hydrological year: Period of one year between two points of annual minimum discharge *. For the Niger between Diré (F.W.A.) and the coast it runs approximately from June 1 to May 31, and for the Benue it is roughly between April 1 and March 31. *439*

Interflow: Horizontal flow of soil-moisture * above the ground-water table. *438*

Intertropical front: The boundary between the Equatorial Maritime (monsoon) and Tropical Continental (harmattan) air masses ([1]. *208*

Isohyet: Line formed by connecting places with equal rainfall. *332*

L.A.D.: Least available depth, i.e., the least sounded talweg * depth on a given river-stretch. *611*

Lag: The time elapsing between the origin of a phenomenon and its effect. Mainly used in this book as the time required for propagation * of a flood-wave along a certain river-stretch. *381*

Lateral inflow: Not measurable amount of water flowing into or from a certain river-stretch between two measuring * sites, possibly including direct precipitation and evaporation. *384*

([1] BUCHANAN and PUGH, 1955. GEN. 3

L.D.W.: Low dominant * water-stage, as opposed by H.D.W. *

Least available depth: See *L.A.D.*

Levee: Lateral dike along the river-bed * with its crest well above the flood-plain * elevation, either naturally made by the river itself, *628*, or artificially constructed, *902*.

Level: Elevation of water-surface or of ground-surface relative to datum*.

Limit discharge: The discharge * required to maintain a certain L.A.D. * on a river-stretch. *611*

Little dry season: Period in the middle of the rainy season with relatively less rainfall, especially remarkable in the south of Nigeria. *335*

Littoral drift: Transport of sediment * along the coast primarily generated by waves and tides. *268*

Local sand-transport: The movement of sand * in the river-bed * which causes the sideward shifting of the meandering * channel. *495*

Longitudinal profile: Simplified graph indicating the elevation of bed * (and water-level *) as a function of the distance to the river-mouth measured along the talweg*. *269*

Lower reaches: The lowest part of the river from where the effect of intermittent rainfall is evened out by storage * capacity and by the increasing number of affluents from various drainage * (and rainfall) areas. *622*

L.R.L.: Low River Level, i.e., reduction plane for sounding * purposes. On the Niger L.R.L. was originally established as to the water-line * of what was thought to be the average Black Flood *. Later it was discovered that it corresponded with a rather high Black Flood, the difference from the average being about $1\frac{1}{2}$ feet. On the Benue. where no significant water-level in that region exists an arbitrary plane has been chosen. *389*

L.W.: Low water.

Meanders: More or less regular windings of the river, alternately to the left and to the right. *553*

Meandering river: River that flows to a certain extent through a succession of meanders *, although in Nature the alignment of a very complex pattern may still be termed meandering. A meandering river is characterised by erosion of its outer bends and accretion of its inner bends, thus propagating * the entire winding pattern either sideward or downward. *553*

Meander coefficient: The ratio of the length of the sinuous talweg * and the rather straight centre-line of the bankfull * river. *586*

Measuring site: Location along the river where observations of any kind are being taken. In particular, used for indicating cross-sections where regular measurements of sand and water were taken.

Navigation depth: Depth over a sufficient width available for navigation, following a not too crooked course which is navigable without complicated manoeuvring even in downward direction. *694*

Oscillation: General expression for river-windings, either regular or irregular, but mostly used in the restricted sense of sinuous channels * in a straight high-water bed *. *554*

Percolation: Soil-moisture * entering into deeper layers and joining the ground-water. *438*

Pick-up velocity: Minimum water velocity capable of moving sand * particles along the river-bed * (in the form of bed-load *). *490*

Prismatic river-section: River-section of which the consecutive cross-sections are equal in size and shape. *519*

Propagation: Movement of a phenomenon (such as a meander * pattern, or a flood) downward along the river. *381*

Raise (by backstage): Positive disturbance by which the water-stage * upstream is kept above its level of equilibrium *. *389*

Ramification: Branching of a single river into two or more distributaries; in particular, used for the multiple branching in the Delta * Area.

Range: Zone of interval between highest and lowest water-levels * at a certain site *. *123, 262*

Rapid: Location with relatively steep local slope * and fast current velocities due to the existence of a rocky sill in the river-bed *. *243, 647*

Rating curve: Relation curve between the discharge * and water-level *, both observed at a certain site *. *393*

Reach: Type of river intermediate between 'braided' * and 'meandering' *; it is characterised by more or less straight high-water banks * with an oscillating * flow-channel * in between. *554*

Recession curve: The part of the hydrograph * after the crest of a flood-wave has passed. *423*

Regime: The combination of all conditions which characterise the river. It includes the distribution of discharge * over the year, the quantity of sediment * transported by the flow *, and the size and shape of the sand-grains, etc.

Regulation: Intervention in the natural conditions obtaining on the river, for the purpose of improving its navigability. Regulation can be bed-regulation, i.e., the fixation, or even the changing of alignment by the construction of guiding structures or bank revetments, *874*; or it can be discharge regulation, i.e., the elimination of the irregularity of discharge which follows naturally from the seasonal irregularity of rainfall, *911*.

Relation curve: Graph indicating the relationship between two magnitudes.

Relative density: Dimensionless number obtained by dividing the density* of a sand-grain in water by the density of the water itself. *992*

Reservoir: Artificial lake created in the river valley by the construction of a dam in order to set apart a quantity of water in times of flood when there is an abundance of water and to release this water in times of drought. *911*

Ripple: See *bed-ripple.*

Ripple factor: Dimensionless coefficient indicating the influence of the roughness* of the river-bed* upon the magnitude of sand-transport*. *591*

Rise: Heightening of water-level* at a certain site* due to increase of discharge*. *389*

River-bed: See *bed.*

River-stage: See *stage.*

Roughness: See *bed roughness* and *grain roughness.*

Run-off: Discharge of precipitation.

Run-off coefficient: The ratio of the run-off* from a drainage* basin to the amount of precipitation over that basin during the same period. Normally, the period taken into consideration is one year. *440*

Saltation-load: Transport of sediment* in the form of saltating sand-grains. The zone of saltation-load is arbitrarily taken to be between 4 and 16 inches above the bed*. Saltation-load is often included in bed-load* for the purpose of morphological considerations. *455*

Sand: Quartz grains with an average diameter between 2 mm and 0.02 mm, and forming the most important part of the material composing the river-bed*.

Sand-balance: Quantitative considerations on the origin and destination of the sand* transported by the flow*, based upon the law of continuity. *476*

Sand-bank: A sandy part of the river-bed* which has its top-level in the range* between the H.W.-level and the L.W.-level of the river. Sand-banks are normally not (or only temporarily) covered by vegetation, and are often moved downward as a part of the gradual propagating* general meander* pattern. *500*

Sand-spit: Narrow and long sandy peninsula between two joining rivers or branches. *575*

Sand-transport: Movement of sand-grains by the water flow; properly used, it would include bed-load*, saltation-load* and suspended* load, but it is often restricted to the first-mentioned two as it is mainly these two types which determine the morphological behaviour of the river. *465*

Sand-transporting capacity: The maximum possible quantity of sand* which can be transported by the flow* under obtaining conditions. *465*

Scour: Erosion of material from the river-bed*. *490*

Scour criterion: Condition under which scour* just does or just does not occur; state of transition between deposition and scour. *491*

Sediment: Material originating from erosion of the drainage* basin and transported down the valley by the river flow, including gravel, sand*, silt* and clay particles. *454*

Short-cut · Breach through the land dividing two rivers or two river-branches. It can be natural, *637*, or artificial, *870*.

Sieve curve: Graph indicating the grain-size* distribution of a certain sediment* sample. *457*

Sill: Shallow spot on a crossing*. *601*

Silt: Small-size grains of sediment* with an average diameter less than 0.02 mm.

Site: Location along the river.

Slope: See *gradient*; slope is mostly used for the water-surface gradient.

Soil-moisture: Rainwater infiltrated into the soil but remaining above the ground-water table. *438*

Sounding: Measurement of the water depth in a great many locations for the purpose of preparing a survey* chart. *135*

Sounding chart: See *survey chart.*

Spate: High stage* of the river.

Specific discharge: Run-off* per unit of time per unit of area. *421*

Spiral flow: Superposition of transversally helicoidal* current upon the normal (more or less parallel) flow* pattern along the x-axis. *526*

Stage: River-level; mainly used in the restricted sense of water-level* at a certain site*.

Steady discharge: Discharge* with a constant magnitude in the course of time.

Steady motion: Motion with a constant direction and magnitude with passage of time at any fixed point. Streamlines*, however, may be curved, but their form must remain the same from one instant to the next.

Storage: 1. The amount of water in the river valley, included the ground-water, above lowest level. *439*
2. The capacity of a reservoir*. *928*

Stream-bed: That part of the river valley which takes part in the actual discharge* of water, not including the storing part of the valley.

Stream-line: See *flow-line.*

Survey chart: A chart which shows the depths and contours of the river-bed*. *791*

Suspended (sand-)load: Transport of sediment* by fine sand-grains kept in quasi-suspension by the turbulence* of the moving flow*. *455*

Talweg: The line connecting the deepest points in consecutive cross-sections. *584*

Through sand-transport: The net longitudinal component of the transported sand* (bed-load* and saltation-load*) which does not exert any influence upon the sideward shifting of the meandering* channel. *495*

Time-lag: See *lag.*

Tow: Combination of a towboat* with one or more barges. *783*

Towboat: Tug or power-unit either pushing or pulling a number of barges.

Turbulence: Frequent and continuous disruption of a smooth and gently-flowing (laminar) stream pattern into a complex movement, including an intensive transversal exchange of particles.

Uniform flow: Flow with a constant direction and magnitude along the x-axis at a given instant. Stream-lines* must be straight and parallel.

Upper reaches: The most upstream part of the river where stages* or discharges* are highly influenced by the intermittent rainfall, and where sudden peaks in the hydrograph* are common phenomena. *622*

Velocity: Current speed of water particles in the flow*; mostly used for the magnitude 'mean velocity' either in the vertical or in the entire cross-section. *693*

Wash-load: Transport of sediment* in suspension including silt* and clay, and for a minor part also fine sand which bears no relation to the composition of the river-bed*. *479*

Water-balance: Quantitative considerations on the origin and destination of the water, based upon the law of continuity.

Water-level: Elevation of the surface of the water, in relation to any arbitrary datum*.

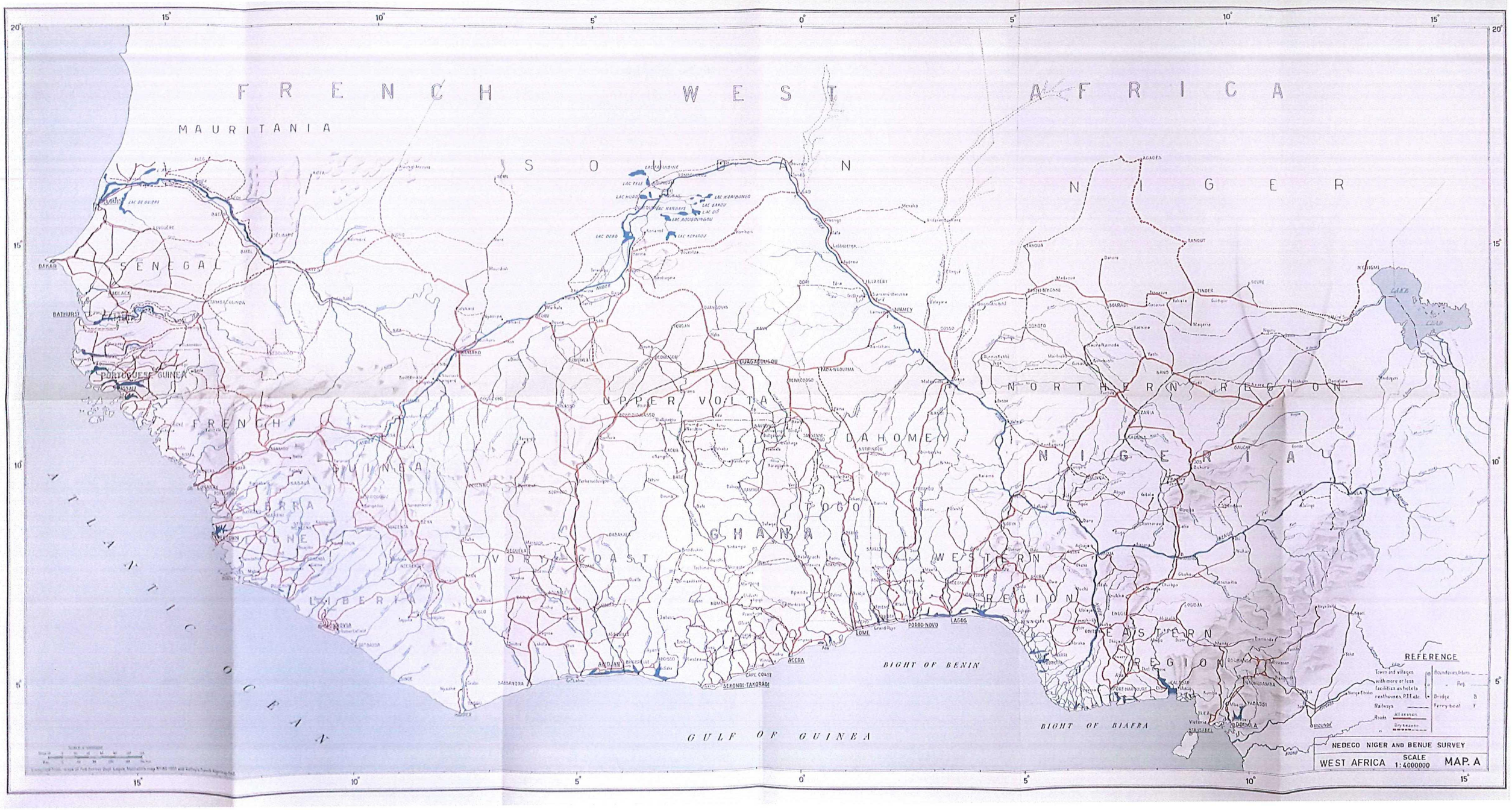
Water-line: Longitudinal connection of instantaneous water-levels* along the river, all levels being related to the same datum*.

Watershed: Division between two drainage* basins, generally corresponding with a line along the highest points of the topography. *226*

Water-stage: See *stage.*

Weir: Structure across the river for the purpose of damming up the water-level* upstream and/or creating a head of water; often movable. *900*

W.L.: Water-level*.


FRENCH WEST AFRICA
MAURITANIA
SENEGAL
PORTUGUESE GUINEA
FRENCH GUINEA
SIERRA LEONE
LIBERIA
IVORY COAST
UPPER VOLTA
MALI
NIGER
DAHOMEY
TOGO
GHANA
NIGERIA
NORTHERN REGION
WESTERN REGION
EASTERN REGION
ATLANTIC OCEAN
GULF OF GUINEA
BIGHT OF BENIN
BIGHT OF BIAFRA
DAKAR
BATHURST
BISSAU
CONAKRY
FREETOWN
MONROVIA
ABIDJAN
ACCRA
CAPE COAST
SEKONDI-TAKORADI
LOME
PORTO-NOVO
LAGOS
PORT HARCOURT
BAMAKO
BOBO-DIOULASSO
OUAGADOUGOU
NIAMEY
AGADES
KANO
ZARIA
KADUNA
IBADAN
ENUGU
ONITSHA
CALABAR
YABASSI
DOUALA
YAOUNDE
LAKE CHAD
LAC DE GUIERS
LAC TELE
LAC HOUNDE
LAC KANSARE
LAC DEBO
LAC FAGIBINE
LAC MARIBONGO
LAC BARGU
LAC DJO
LAC BOUGOUMGOU
LAC KOMADOU
NIGER
BENUE
REFERENCE
Towns and villages with more or less facilities as hotels resthouses, P.T.T. etc.
Railways
Roads All seasons
Dry seasons
Boundaries, Inter.
Reg.
Bridge B
Ferry boat F
NEDECO NIGER AND BENUE SURVEY
WEST AFRICA SCALE 1:4000000 MAP. A
20°
15°
10°
5°
0°
5°
10°
15°
20°

NIGERIA

SCALE: 1:2.000000 OR 1 INCH TO 31,57 MILES

MILES 20 0 20 40 60 80 100 120 MILES
Km. 32 0 40 80 120 160 Km.

REFERENCE

Boundaries, International		Headquarters, Provincial	▣ WARRI
,, Provincial		,, Divisional	◉ IDAH
,, Regional		Principal Towns	• Igbor
Boundary, Nigeria-Cameroons		Minor Towns & Villages	○ Onya
Railways		Bridge	B
Roads, Main Trunk		Ferry-boat	F

NEDECO NIGER AND BENUE SURVEY

NIGERIA	SCALE 1:2.000000	MAP. B

Compiled from maps of the Fed. Survey Dpt. Lagos.