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THE REALIZATION AND FUNCTION OF THE NORTHERN BASIN OF THE DELTA PROJECT

BY

DELTADIENST OF RIJKSWATERSTAAT

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DIRECTIE WATERHUISHOUDING EN WATERBEWEGING

THE HAGUE — NETHERLANDS

Contents

Introduction

The western part of the Netherlands, part of the low lying Rhine-Meuse Delta, lies, with the exception of the thin ridge of dunes, below mean sea-level (MSL). This means that each day more than half of the population lives and works below this level.

This land was gradually gained from the sea, slowly at first, when the means to build dykes and drain the water from the polders were non-existing or very primitive. In Roman Times, spades and wicker baskets were used to build 'terps', man-made mounts on which the simple farms protected both men and cattle against the storm-surges. By linking some terps with primitive dykes and by draining the water from the enclosed polder at low tide, land was reclaimed. With the improvement of the windmills even lands below the water level could be drained and gradually Holland reached the shape and area it has now.

The history of the Netherlands is characterized by a continuous fight against the sea, the building of dykes, canals, the reclamation of land gained but ever so often lost again. It seems an endless succession of catastrophes, set-backs and renewed efforts, perseverence and success.

In or about the year 1000 the Zuyderzee, in the heart of Holland, cut into the low lands and again in 1421, the 'St. Elisabeth Flood' drowned parts of the south-western area. They were lost and never regained only leaving on the maps the former names of polders and lands that were. For more than a thousand years the people in the threatened country have fought against the sea, an unequal fight from the start. Chances turned however when it became a national cause and when the means to defend ourselves improved (when the spade and wheel barrow were replaced by dredgers). Moreover, the need to concentrate on this problem was urgent, as the sea-level kept rising whereas the land kept sinking. The resulting effect, however small (8″ per 100 years), in a country which is in fact only protected against flooding by dykes, means a serious threat.

The situation of the Dutch low lands has become more and more vulnerable. Hundreds of miles of dikes must defend lands, lying many feet below sea-level, while their foundation is threatened by the scouring caused by strong tidal currents and the stability of their crowns by water overflowing during severe stormsurges.

This defence line appeared to be inadequate to withstand stormsurges of exceptional strength. In 1916 a heavy storm caused severe floodings and damage in the north-western part of Holland, a disaster which led to the closing of the dangerous Zuyder-zee. And in 1953 a stormsurge of even greater strenght, with a floodlevel which sur-passed all the floods of the past, hit the south-western delta, formed by the rivers

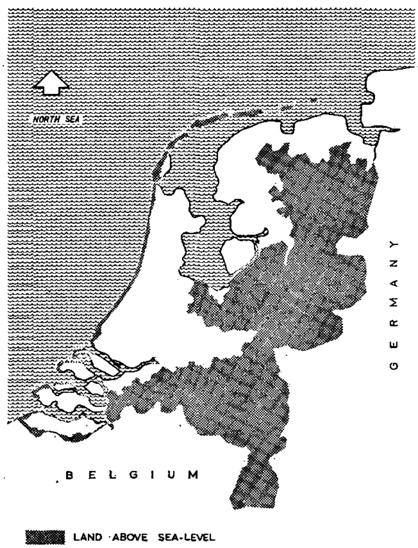
Scheldt, Meuse and Rhine. After this new disaster a plan was immediately adopted, a plan somewhat similar to the Zuyderzee project, providing in the closing of three dangerous inlets, the Haringvliet, the Brouwershavensche Gat and the Eastern Scheldt. The location of the dams was planned as close as possible to the sea, thus achieving maximum shortening of the coast-line and the largest protected area behind the dams. Needless to say that both the entrance to the ports of Antwerp (Western Scheldt) and Rotterdam (Nieuwe Waterweg) should remain open for the ever increasing shipping, which entailed however that the dykes along these waterways should be modified and/or improved in accordance with the new stormsurge criteria. The dykes mentioned above and of course the new dams are to be made to withstand a 'superstorm' having a frequency of occurrence of once in 10,000 years, (1% in 100 years).

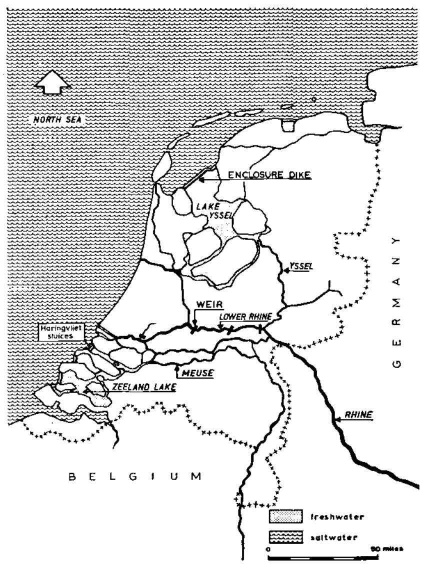
Once built, the plan ensures the safety against an attack on the south-western part of the Netherlands (see figure on pages 6 and 7).

Naturally the main purpose and the leading policy of the plan is safety but other advantages are:

the shortening of the coast-line, meaning less maintenance and fewer risks, whereas the existing dikes along the enclosed basins form a secondary defense, strong enough to withstand floods;

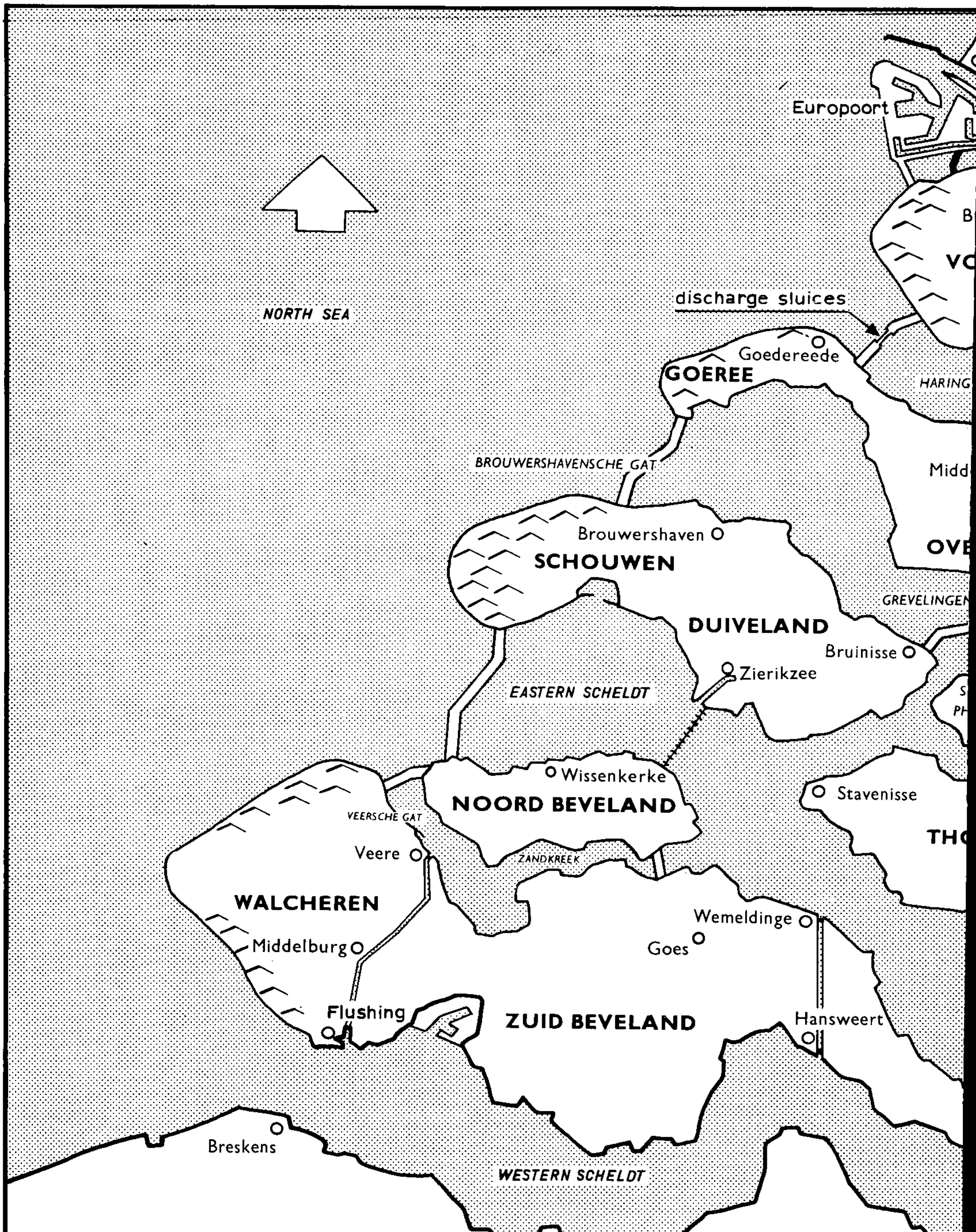
the improvement of the watermanagement by restricting the salt intrusion from the sea; with the sluices in the Zuyderzeedike and three weirs in the lower Rhine (Lek) the Haringvlietsluices form a system by which the freshwater from the Rhine and the Meuse can be distributed according to the needs.

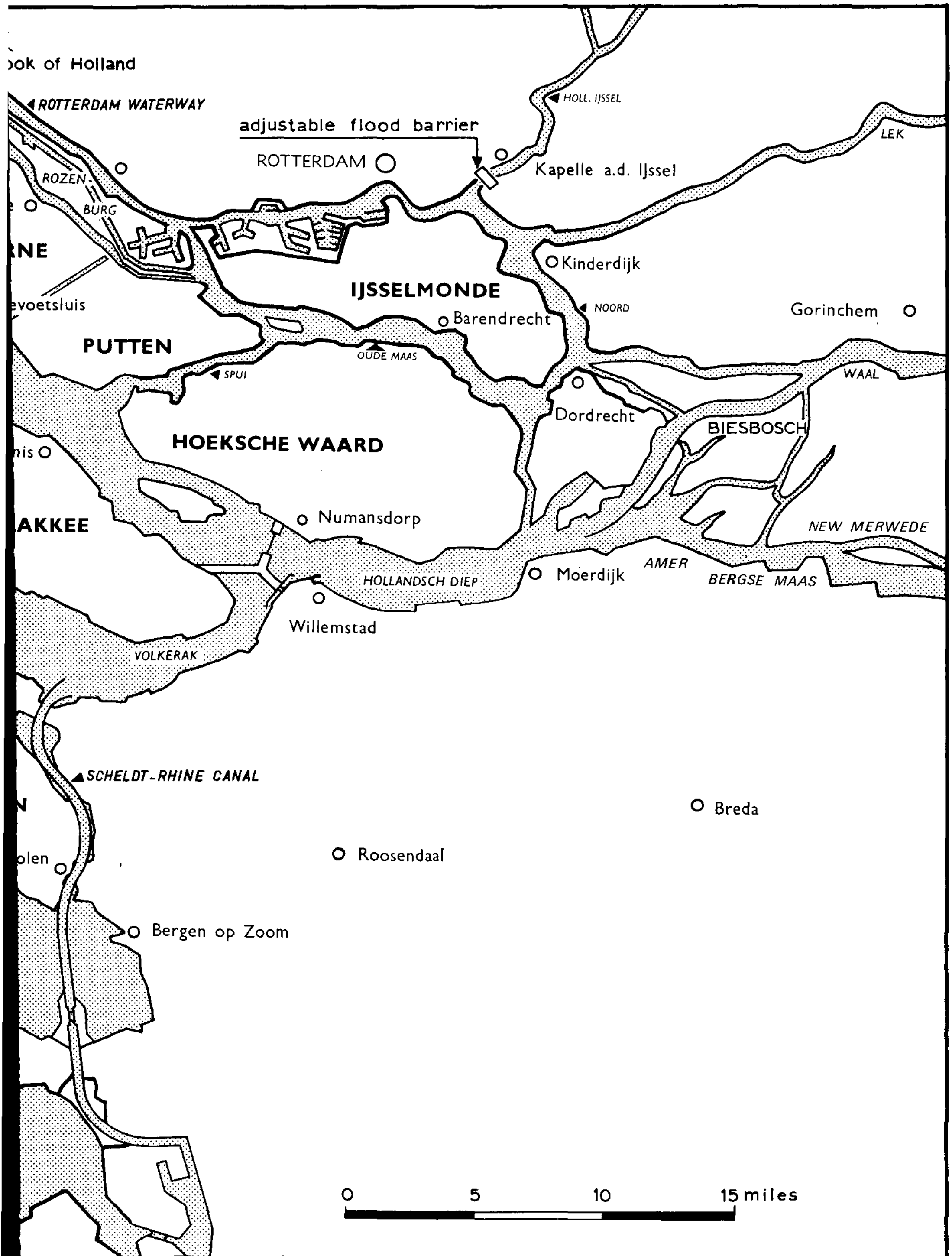




The Netherlands
1 Higher and lower parts

2 Parts with fresh- and salt water

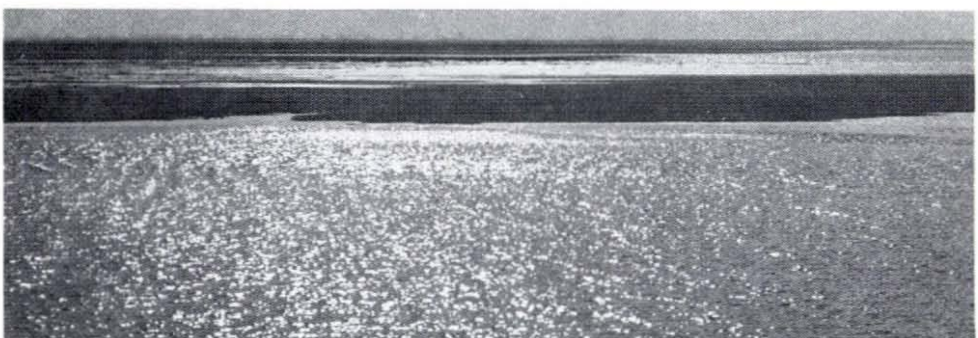

Europoort
discharge sluices
NORTH SEA
Goedereede
GOEREE
HARING
BROUWERSHAVENSCHE GAT
Midd
Brouwershaven
SCHOUWEN
OVE
GREVELINGEN
DUIVELAND
Bruinisse
Zierikzee
EASTERN SCHELDT
Wissenkerke
NOORD BEVELAND
Stavenisse
VEERSCHE GAT
Veere
ZANDKREEK
TH
WALCHEREN
Wemeldinge
Goes
Middelburg
Flushing
ZUID BEVELAND
Hansweert
Breskens
WESTERN SCHELDT
ZEEUWSCH
Braakman
Terneuzen
VLAANDEREN

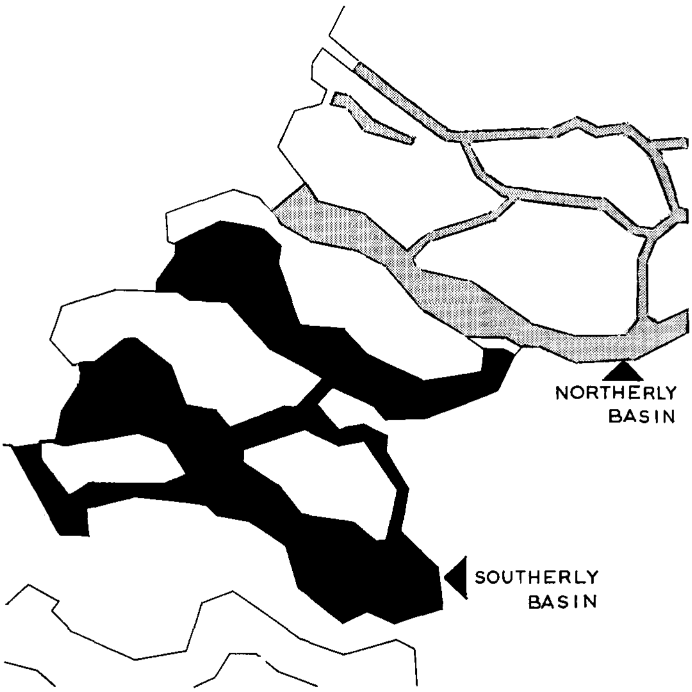


ɔok of Holland
ROTTERDAM WATERWAY
adjustable flood barrier
ROTTERDAM
HOLL. IJSSEL
Kapelle a.d. IJssel
LEK
ROZEN-
BURG
NE
evoetsluis
IJSSELMONDE
Kinderdijk
NOORD
Barendrecht
Gorinchem
PUTTEN
SPUI
OUDE MAAS
WAAL
Dordrecht
BIESBOSCH
HOEKSCHE WAARD
Numansdorp
AKKEE
NEW MERWEDE
AMER
Moerdijk
BERGSE MAAS
HOLLANDSCH DIEP
Willemstad
VOLKERAK
SCHELDT-RHINE CANAL
Breda
Roosendaal
Bergen op Zoom
0
5
10
15 miles

1. Earlier plans and execution

The closing of the Volkerak and the Haringvliet, two schemes which can be regarded as forming a single, more or less integrated whole, and which were therefore planned to fit in with each other from the point of view of timing, signified the end of an important stage in the realization of the Delta Project. The completion of the Volkerak dam in 1969 meant that the northern part of the delta of the Rhine, Meuse and Scheldt was permanently cut off from the rest of the delta. The whole Delta area is now split into three sections, each with a character of its own. The Scheldt estuary in the south is still more or less in its natural state; the middle section with its deep, wide estuaries, although still largely at the mercy of tidal currents, will shortly be completely cut off from the sea; and finally, in the north, there is the delta of the Rhine and Meuse itself, with its complex network of, for the most part, relatively narrow river branches. The evolution of the structure of the Delta, leading up to this tripartite division, took several centuries. A glance at a map of the period round about 1300, reveals a hotchpotch of scattered islands, both large and small, bearing little resemblance to the present structure. Since that time the picture has been considerably simplified. Many small islands have merged to form larger ones, while the areas of water have similarly developed into larger reaches. Man's influence in this hydrographic transformation should not be overestimated, however inclined one might be to ascribe the simplification and clearer delineation of the Delta structure to human intervention. This was not a case of man consciously striving to achieve any particular simplified configuration, but of his simply making adjustments here and there, where nature afforded him



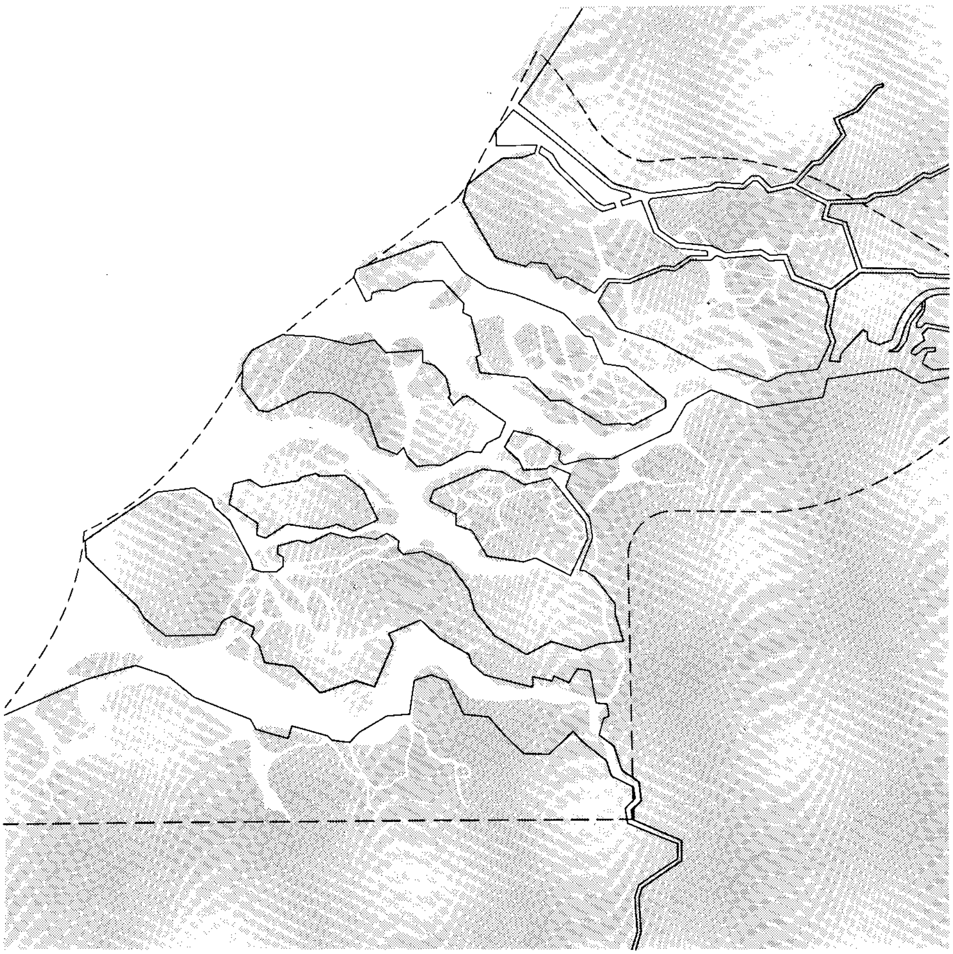


The basins of the Deltaplan

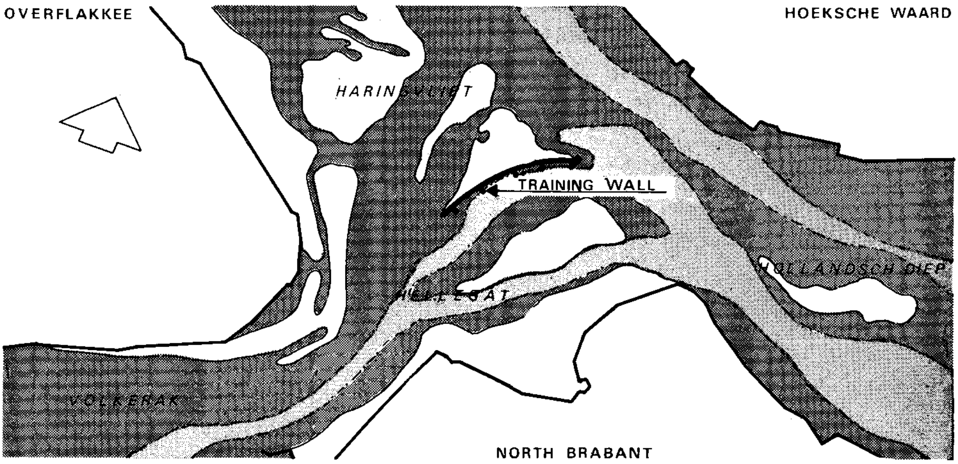
the opportunity, with the still relatively primitive means available to him at the time. Human intervention, confined for the most part to building dykes round land raised to a sufficient height by alluvial deposit, had, to a great extent, followed a course parallel to natural hydrographical developments.
Thus the merging of the two islands Goeree and Overflakkee, which can now be regarded as the first step towards the later separation of the northern and southern Delta basins, could only come about because of the gradual silting up of the channels between the various islands from which Goeree-Overflakkee was formed. In the southern part of the Delta the separation of the Eastern and Western branches of the Scheldt by the damming of the Sloe and the Kreekrak at the end of the last century was facilitated by the fact that both water courses had been reduced in size by natural silting up from sand and mud.
In this way a relatively balanced pattern with a number of large elements evolved during the course of time. The further this natural process of simplification proceeded, the harder it became for man to make important changes to the basic structure, until the point was reached where it would only have been possible to interfere by resorting to very strong measures, which would certainly have run violently counter to the character of the system.
The formation of natural barriers in the Delta area had virtually come to an end. It

was unlikely that there would be further developments in the form of a simplification of the system due to silting up, such as had taken place in the south, and in particular that any convenient separation of the central from the northern delta area could be brought about by silting up of the Volkerak. Such a development would certainly receive no assistance from nature, nor were efforts made to bring it about artificially. On the contrary as late as 1931 steps were taken to improve the stability and depth of the Hellegat, connecting the northern and middle part of the Delta, for the benefit of shipping to and from the south, by building a training wall there to guide the current (see figure on page 11).

Although the closing of the Sloe and the Kreekrak in the south had a similar function



The Delta area around 1300



The training wall in the Hellegat

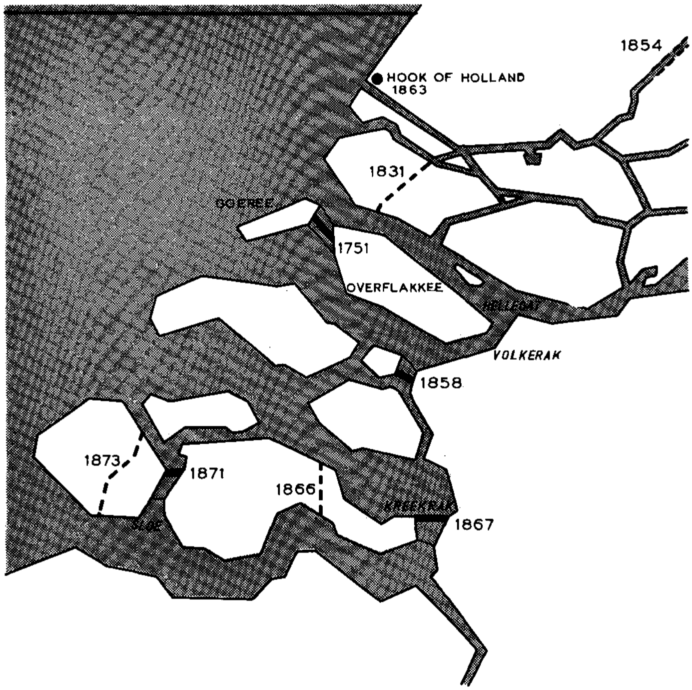
in the hydrographical development of the country as the later closing of the Volkerak in the north, from the point of view of water engineering the latter was an event of quite a different order. The 'forcible amputation' of the Volkerak has, therefore, had a far greater effect on tides in the adjacent stretches of water on both sides of the dam than did the separation of the Eastern from the Western Scheldt. The consequences of closing the Volkerak will, indeed, continue to be felt on the south side until the Eastern Scheldt is finally closed.

On the other hand the repercussions arising from the closing of the Volkerak on tidal movements in the northern basin were only of a very temporary nature, being of negligible significance in comparison with what has now been achieved by the closing of the Haringvliet.

It was stated above – and as a generalization it is correct – that human agency had very little effect on the main structural features of the Delta area in comparison with natural forces. However in the northern part of the Delta where the waterways are on a smaller scale and are more river branches than estuaries, more effective human intervention has been possible. Hydraulic engineers were already putting forward ideas for substantial changes and improvements to the river system in this area during the last century, as witness the 'Consideratiën' by Christiaan Brunings, in which, as early as 1804, he was urging the systematic improvement of the courses of the Meuse and Waal.

Beginning with these earlier studies and projects, understanding of the complex northern tidal river system has steadily matured, until finally, in recent decades, knowledge in this field has advanced by leaps and bounds.

The first important step to affect tidal movements and the distribution of water in the river system of the northern Delta basin to any great extent was the digging of the



Connecting dams built and canals cut in the 18th and 19th centuries

New Waterway, replacing the old route along the Brielse Maas, by which the northern branch of the Rhine had previously reached the sea, by a shorter channel emerging at Hook of Holland.

Construction of the training walls at Hook of Holland began in 1863, actual excavation of the channel in 1866, and the Scheur – the earlier link with the mouth of the Old Meuse – was closed in 1879.

The execution of this project was accompanied by many difficulties and disappointments, caused principally by large quantities of sand being deposited between the training walls. Dredging alone – at that time – could not solve the problem. The situation did not improve until 1907, when the navigable channel between the main piers was reduced in width by the construction of submerged groynes.

This bold project was, in reality, ahead of its time. This was the first occasion on which dredging was carried out on a large scale in a coastal river mouth, and the first on which the complex flow phenomena arising at the point where fresh river water and salt sea-water meet were encountered. Furthermore the steadily increasing size of ships also made ever-increasing demands on the navigability and particularly the depth of the New Waterway; the engineers were continually being faced with new problems. The New Waterway became an important 'training school' for Dutch hydraulic engineers and investigations carried out there made an important contribution to knowledge of tidal currents and the accompanying sand movements in a mixed, freshwater and salt-water condition.

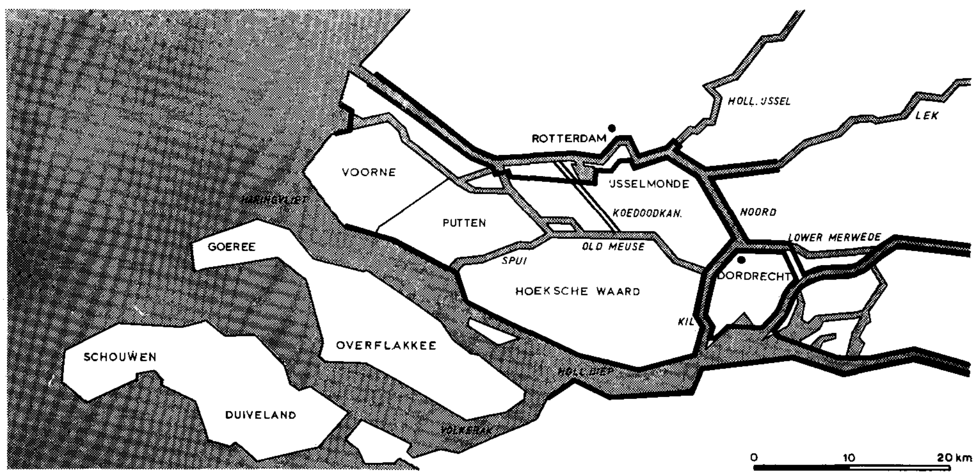
The next important project in the northern basin that calls for mention is the excavation of the New Merwede, the object of which was to improve the flow of river water through the small channels of the Biesbosch. This major new river branch was formed in the period 1851-1885 by enlarging and joining up a number of existing channels.

The separation of the Meuse and the Waal followed not long afterwards. This involved excavating the Bergse Maas, regulating the level of water in the Amer, widening the Heusdens canal, closing the Heerewaarden spillways, raising the level of the Waal dykes, damming the Meuse at Andel, and making provision for the drainage of North Brabant. The execution of this extensive and complex project extended over the years 1888-1907.

Next can be mentioned the work of improving the Old Meuse for shipping to and from Dordrecht. Between 1925 and 1929 much of this river branch was enlarged and otherwise improved, an operation which was accompanied by the excavation of the Krabbegeul, linking the Old Meuse with the seaport at Dordrecht. The last important improvement to be carried out in the northern Delta basin in the period before the Second World War was the construction of the training wall in the Hellegat, already mentioned above, the purpose of which was to stabilize the shipping channel connecting the Hollands Diep and the Volkerak. This work was completed in 1931.

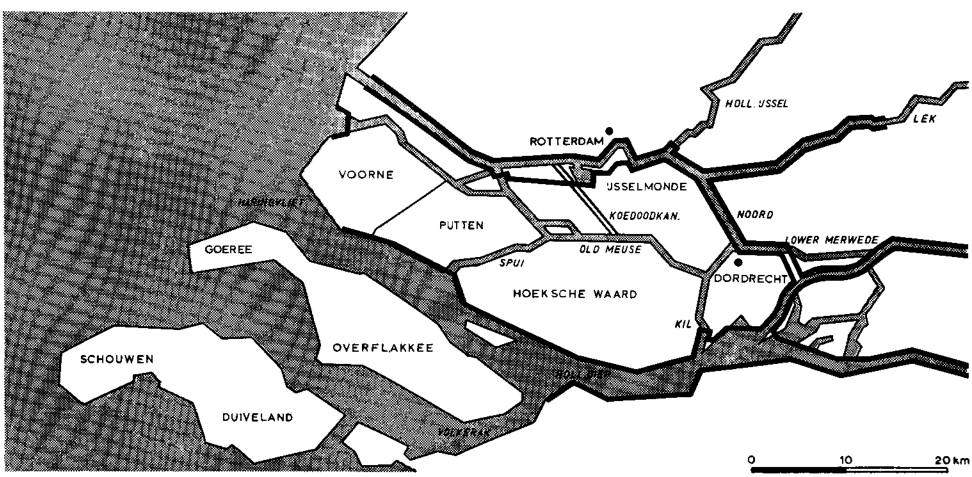
It was about this time that the collection and study of data on tidal movements, and related phenomena such as sand transportation in rivers, tidal channels and estuaries, became more systematic. As a result, engineers began to get a much better understanding of these difficult problems. The studies carried out formed the basis of the

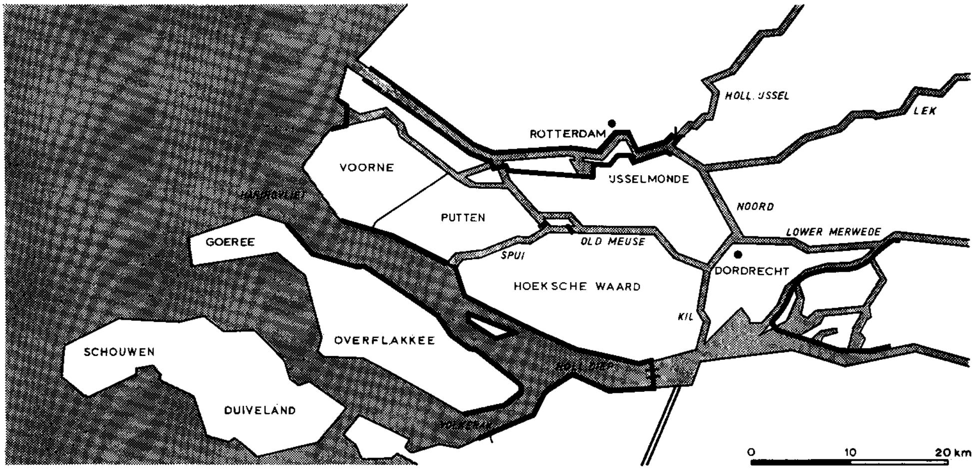
The Four Island Plan of 1938



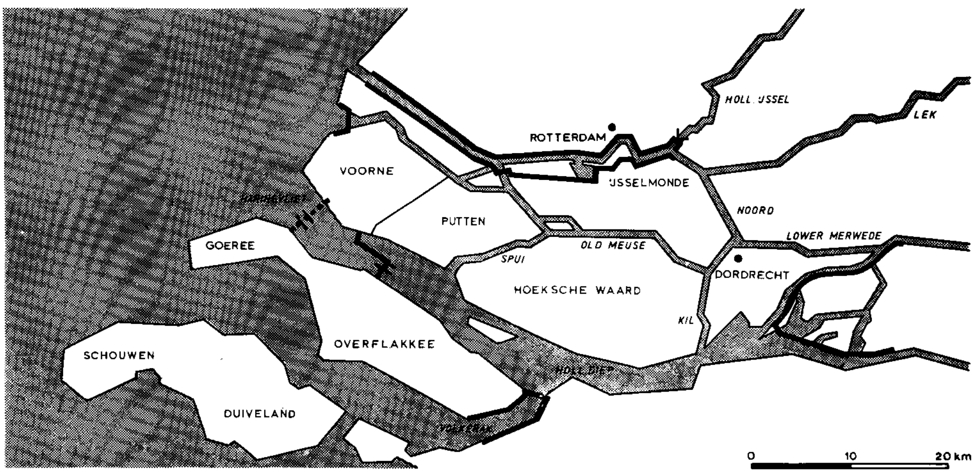
first far-reaching plans for further, radical improvements to the river system of the northern Delta basin. The main aim then – as later also in the Delta Project – was to provide greater security in the event of storm tides and better protection against salt intrusion from the sea. The idea of shortening the total length of the sea defences and river dykes by joining the islands together was beginning to take root.
This new approach first found expression in the 1938 Four Island Plan, which provided for the merging of the islands of Rozenburg, Voorne-Putten, the Hoekse Waard and Ysselmonde. This would have shortened the dyke frontage by about 170 kilometres, while the reduction in the volume of tidal water would have helped to limit salinification. This plan also envisaged the closing of the Brielse Maas and the Botlek by dams, behind which a freshwater basin would be formed for the benefit of agriculture on Rozenburg and Voorne-Putten. This part of the plan was, in fact, carried out in 1950 and 1951. One objection to the Four Island Plan however was that it implicated two locks between the port of Dordrecht and the sea. Various modified versions were therefore drawn up, of which only the Five Island Plan shall be mentioned here. This provided for the inclusion of Dordrecht in the group of islands which would have a joint system of water defences. However, in this case too, the level of general river dykes would have had to be drastically raised, and this proved to be impossible, especially in the vicinity of Dordrecht. For this reason, an attempt was made in a later design, drawn up after the end of the Second World War, to achieve a collective system of water defences in a different way. The idea was to build four moving storm-tide barrages near the mouths of the Lek, the Kil and the Noord, and somewhat further upstream on the Lower Merwede, in order to prevent high floods entering the lower river area, so that the existing dykes would provide adequate security without their height having to be raised. Subsequently a plan was devised that

The Five Island Plan of 1942





Plan with barrage at Klundert (1950)



Plan with barrage at Hellevoetsluis (1952)

was based primarily on the construction of a storm-tide barrage in the Hollands Diep near Klundert.

Further study of the possibilities afforded by such a barrage led to its relocation – still only on paper – at Tien Gemeten, and later to its being moved further downstream to the vicinity of Hellevoetsluis. After 1951 the plans began to include proposals for closing the Haringvliet and the Volkerak. Hydraulic studies in connection with these plans had already reached such an advanced stage by 1952 that one can say that, as far as the northern area was concerned, the main features of the Delta Plan had already in principle formal shape before the disaster of 1953.

In the Hydraulics Laboratory in Delft a hydraulic model of the lower river area had been built long before, while, in addition, an analog computer of limited power had already been constructed. Consequently, the designers of the Deltaproject had a well advanced study and an arsenal of scientific aids to call on when they were suddenly put before their task in 1953. It was only possible to complete the plan for shutting off this area from the sea at such relatively short notice because of the detailed experience, and thorough knowledge and understanding of the working of this complex system of tidal channels and river branches which had been gained over a period of many years, but particularly during more recent decades. A cardinal feature of the plan was the construction of a large sluice, which, in conjunction with a carefully calculated discharge programme, would enable tidal movements in the area to be adequately controlled, and at the same time allow the water management requirements of the area to be taken into account as far as possible.

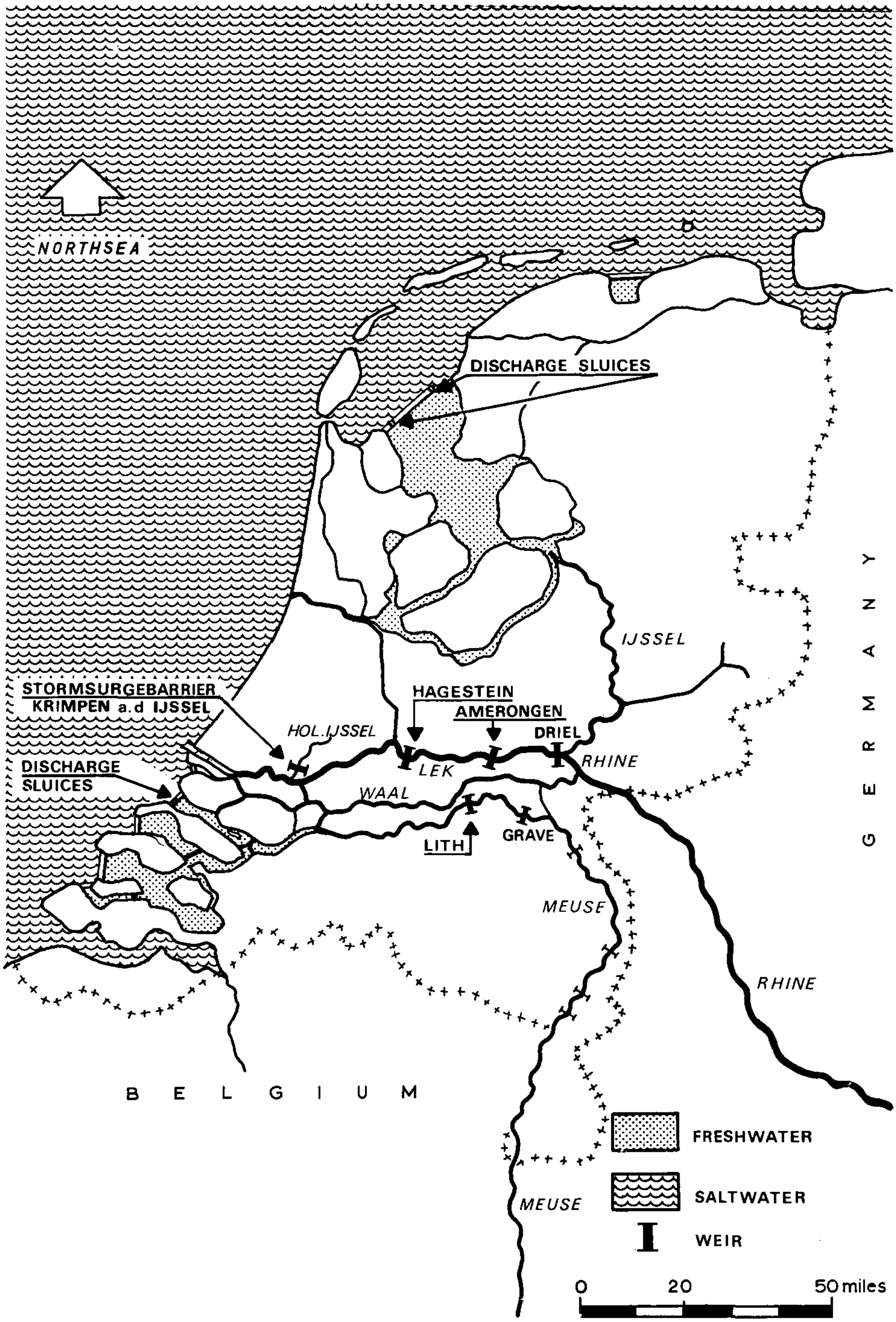
2. Water movements in the Delta region to the north of the Volkerak dam after the closing of the Haringvliet

Since the damming of the Scheelhoek Rak, the last open channel in the Haringvliet, great changes took place in the water movements in the Delta region north of the Volkerak dam. After the Haringvliet and the Volkerak have been closed the tide coming in from the sea can only penetrate freely into the lower river area by the mouth of the New Waterway. The mouth of the Haringvliet is permanently closed to the incoming tide, while fresh water is only discharged into the sea during ebb tide.

The extent to which the Haringvliet sluices will be opened during ebb tide depends, on the one hand, on the discharge of fresh water carried by the Rhine and the Meuse and, on the other hand, on the fresh water requirements for agriculture and industry, the restriction of salinity prevention in the Waterway, and also for flushing out of saline and polluted inland water. When the rivers are low the fresh water available from the Rhine and Meuse must be used as economically as possible, which obviously means that the discharge of fresh water at the Haringvliet into the sea must be kept to the minimum. A constant loss of 40 cu.m. per second through the salt-water culverts built into the sluices is unavoidable, due to the need to expel saline water trapped in the sewer directly behind the sluices as a result of overspill, leakage and seepage. When the water in the Rhine is low it will reach the sea almost exclusively via the Waterway, except for the natural discharge through the Gelderse Yssel to the Yssel lake (the former Zuyder Zee), that can be artificially increased to some extent by the weirs in the lower Rhine.

The lowest Rhine discharge so far recorded at Lobith is 600 cu.m. per second. The Haringvliet sluices however should be closed before this condition is reached, namely whenever the Rhine discharge falls below 1,500 cu.m. per second. If discharge rises above this critical point, the sluices can be opened at ebb tide, the extent depending on the actual discharge.

During high discharge periods the sluices will remain fully open for the whole duration of the ebb tide. At the same time, however, care must always be taken to ensure that the current velocities in the lower river area do not become too great for shipping. Added to this, when the current changes direction at low tide, water containing more than 300 mg. of chloride ions per litre must not be allowed to penetrate further inland than the point where the Hollandse Yssel joins the Lek, being the important intake of fresh water for agricultural purposes. Inasmuch as the sluices are opened when the level at sea is lower than on the Haringvliet basin, operation will cause the level of the water in the Haringvliet to fluctuate. This fluctuation has some effect further inland, and, in combination with the tide flowing up the Waterway, will affect the tidal movements in the network of waterways in the lower river area and in the adja-

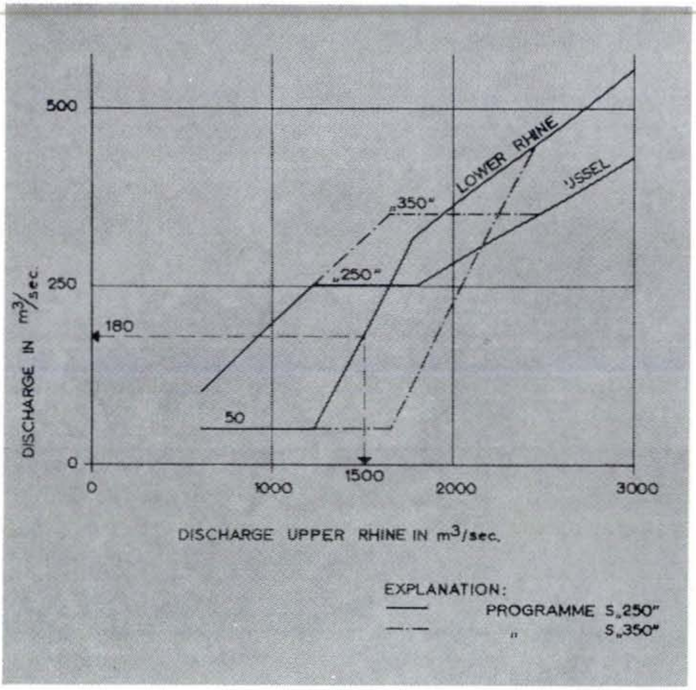


Netherlands main system of watermanagement cent, lower reaches of the upper rivers. Daily tidal movements in the lower river area are thus determined by the tide in the open sea near the Hook of Holland and in the mouth of the Haringvliet – the latter depending on the discharge programme of the Haringvliet sluices – and, in addition, by the discharge from the Rhine and the Meuse as regulated by the programmes for the movable weirs. Changes in these tidal movements may still be brought about by modifications to the configuration of the lower river area which are being made in order to improve the waterways used by shipping, combat salinity and reclamation of storage regions.

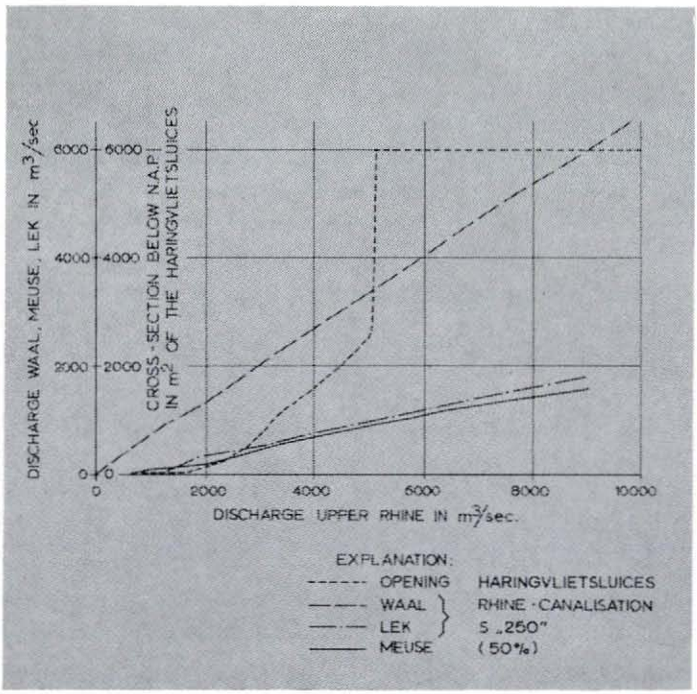
So far we have only considered the normal tidal movement north of the Volkerak dam. In order to assess the extend of safety in the lower river area however we have to account of the less frequent conditions of high and extreme high water levels. Storm winds blowing from the sea, especially the notorious north-westerlies, cause the waterlevels to rise, the extent to which this occurs naturally depending mainly on the force and duration of the winds. During such periods it may be almost or completely impossible to use the gates for sluicing. For the duration of such a storm, the sluices will have to remain closed until the falling level of the water outside the dam equals the level inside, where-upon the sluices can be reopened – unless the wave attack is too great. During storms of this kind the water-level in the lower river area and the feeding upper rivers is determined not only by the change of water-level at the mouth of the Waterway and the discharge from the Lower Rhine, Meuse and Waal, but also by the effect of the wind on the waters of the lower rivers themselves; this effect will be particularly marked in the case of the New Waterway and the Haringvliet because the direction in which they lie runs very nearly from north-west to south-east, in other words, in the exact direction by the north-westerlies blow. As the discharge from the Rhine and the Meuse can be influenced by a system of weirs a closer look into this factor may be useful.

The canalized Lower Rhine has three movable weirs; in sequence in a downstream direction these are at Driel, Amerongen and Hagestein. The one at Driel is used for regulating the distribution of Rhine water to Lake Yssel and the south-west of the country. By operating this weir, Rhine water can be directed along the Gelderse Yssel to Lake Yssel. According to the requirement the programme used is '250' or '350', referred to for the sake of brevity as S250 and S350. Under S250 the Driel dam is used to maintain the discharge along the Lower Rhine at 50 cu.m./sec. until the Yssel discharge reaches 250 cu.m./sec. If the rate of discharge from the Rhine continues to rise the gates of the Driel weir are raised so that the Yssel discharge remains at 250 cu.m./sec. If the Rhine discharge is large enough the gates are left fully open. Under programme S250 the Driel gates are not raised until the rate of discharge of the Yssel has reached 350 cu.m./sec. As a rule programme S250 is used, the possibility of S350 being required to bring Lake Yssel up to its Summer level only arising in a dry spring. Unless stated otherwise it is presumed that the Driel weir is operating according to programme S250.

When the rate of discharge of the Upper Rhine is 1,500 cu.m./sec. the Driel weir



Discharge distribution between Lower Rhine and Gelderse Yssel



Opening of the Haringvliet sluices as function of the Rhine discharge gates are almost closed, allowing only 180 cu.m./sec. to pass. If the gates at Driel are fully opened, increasing the discharge to the Lower Rhine and the Lek, the Amerongen weir gates can then also be raised. Finally, when the rate of discharge of the Rhine is high, the gates of the Hagestein weir can also be fully opened, with the result that the whole system functions as an open river. When the weirs in Lower Rhine and the Lek are in operation the discharge at Hagestein dam takes place through an underwater by-pass which can be regulated. The consequence of this is that tidal influence can still be felt to a very small degree in the first reach immediately above this weir.

When the discharge from the Rhine is low the operation of the weirs on the Lower Rhine reduces the discharge by way of the New Meuse. This could result in the salt boundary intruding too far up the Waterway. The closed Haringvliet sluices, however, will cause the fresh water that previously flowed into the sea through the Haringvliet to be diverted along the Old and New Meuse to sea. Were it not for the damming of the Haringvliet, canalization of the Rhine would hardly have been possible. The discharge along the Waal is also affected by the Rhine canalization in that it is increased when the weirs on the Lower Rhine are operated.

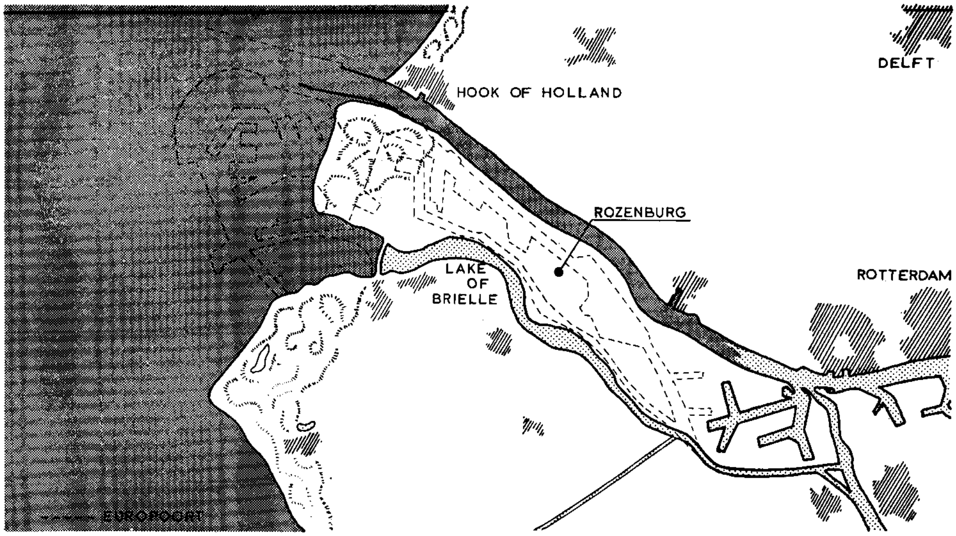
The distribution over the lower river system of the Waal discharge, supplemented by the discharge from the Meuse, will depend on the sluicing programme for the Haringvliet gates and the outflow from the Hagestein weir on the regulated Lower Rhine.

The canalization of the Meuse meant to serve a different purpose from that of the Lower Rhine. It is intended exclusively to aid navigation by controlling the river level and does not provide a means of controlling the outflow from the Meuse into the lower river area. Water discharges from the Meuse at Lith over an adjustable overflow weir, the aim here being to maintain the level of the Meuse immediately above the dam at 4.6 metres above N.A.P. (Amsterdam Ordnance Datum).

The downstream tidal movement is kept from propagation in the upper reach by the overflow weir. The weir at Lith is opened when the discharge rate is high – of the order of 800 to 1,000 cu.m./sec. – but also when there is ice floating on the river, and in case of maintenance and repair work.

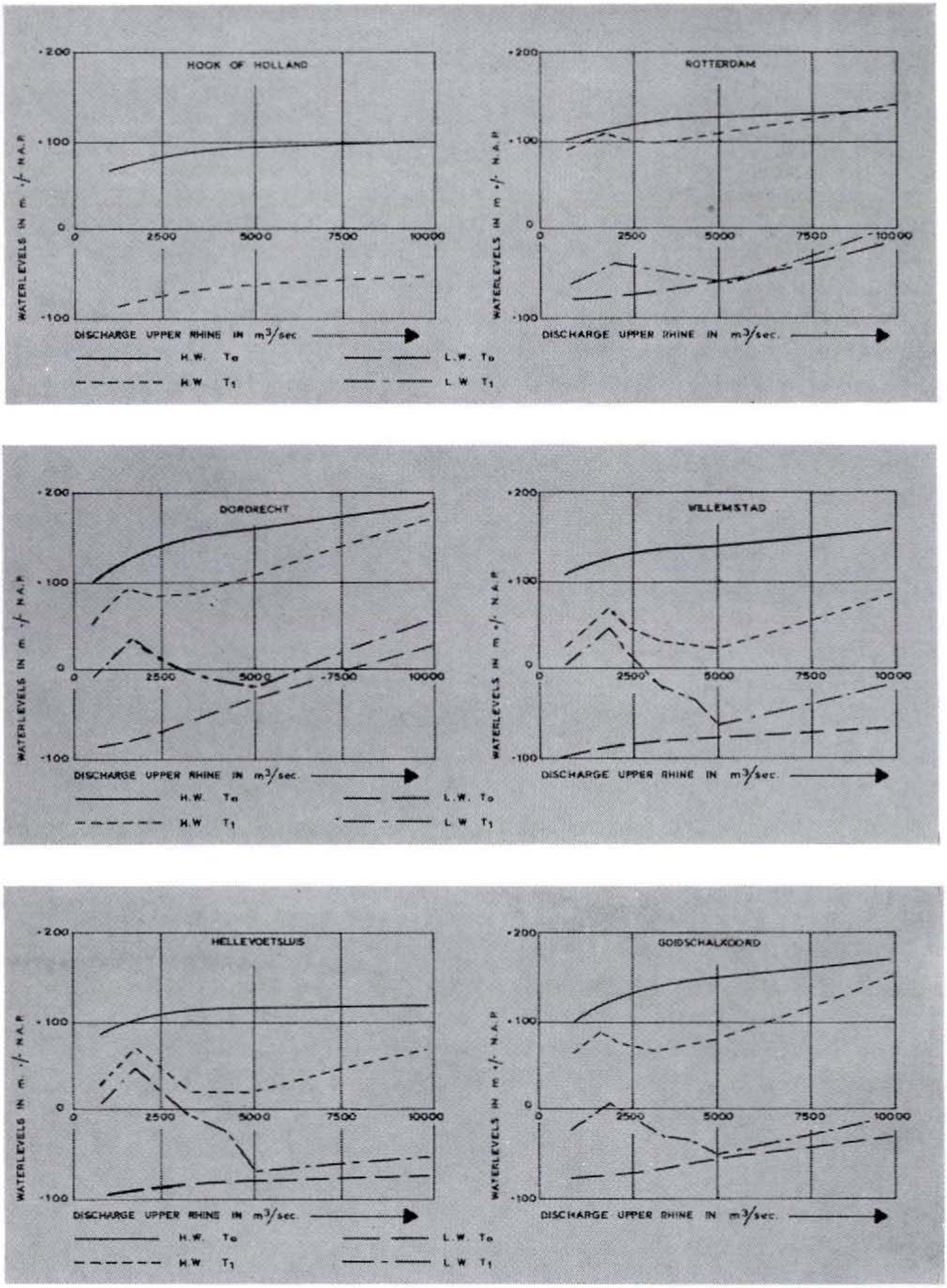
The amount of water extracted for industrial purposes in the lower river area varies, but, in view of expected developments, is likely to increase. An extraction rate of 60 cu.m./sec. from the Hollandse Yssel is a reasonable estimate for the water requirements in the middle and western part of the Netherlands. Until the Eastern Scheldt is closed, water extraction for Lake Zeeland will not be of any great consequence, the only requirement presumably being a relatively modest quantity of water to combat salinity near the Volkerak sluices. Water extraction for Lake Zeeland will therefore not be taken into account, hereinafter, although in the future, water extraction when the Rhine discharge is over 1,000 cu.m./sec. could certainly reach an average rate of 300 cu.m./sec. after 1978.

Here mention must be made of the difference in the character of the discharge patterns



The Europoort harbour project

of the Rhine and the Meuse. The Rhine is glacial in origin. Its discharge is determined not only by rain-water run-off in its drainage area, but also to a considerable extent by snowfall in Germany and Switzerland. The Meuse, on the other hand, is a rain river and its rate of flow is mainly determined by the rainfall in its drainage area in France and Belgium. Consequently there is hardly any relationship between the discharges from the two rivers. A graph would show that the manner in which the discharge curves deviate from one another follows no regular pattern. When the Rhine discharge is quoted henceforth, the corresponding figure selected for the Meuse is such that there is an even chance of the discharge from the Meuse lying above it as below it. This is called the 50% probability Meuse discharge. The distribution of water discharge over the lower river system can thus be controlled at two points, the Driel weir and the Haringvliet sluices. A further influence will be felt by extraction points like the one in the Hollandse Yssel at Gouda and those to be built in the Volkerak Dam to enable water to flow into Lake Zeeland. The tidal movement of the sea, which also plays an important part in the distribution of the water discharged throughout the lower river area, varies from day to day. For the sake of simplicity however we shall assume here that the sea tide is always average. This mean tide as the term is used here is the average between high and low tide and is obtained by averaging the high water and low water readings taken over an extended period, while the times of their occurrence are obtained by averaging the times of all the high and low tides relative to the culmination of the moon at the point of observation. Even so it is not certain whether this average tide can be used for our purposes. The reason for this is that there is still an uncertainty as to how the vertical tides at the Hook of Holland



High and low water lines for some stations in the Lower Rhine area in relation to the river discharge; condition (T_0) before closure of Volkerak and after closure of both Volkerak and Haringvliet (T_1) are shown and in the mouth of the Haringvliet will be affected in the near future by the construction of the new harbour mouth – with moles reaching out to sea several kilometres further than at present – by other Europort developments and by the natural adaptation of the bottom configuration in the mouth of the Haringvliet as a result of the closing of the estuary further inland. This general explanation will now be followed by a consideration of the changes in tidal movements in the lower river area on the basis of given discharge flows for the Rhine and the appropriate 50% probability figure for the Meuse discharge, the average sea tide, programme S250 for the Rhine weirs and the discharge programme for the Haringvliet sluices. It is assumed that the sluices will stay closed until the Rhine discharge reaches approx. 1,500 cu.m./sec., the opening being increased for higher Rhine discharge rates in such a manner as to ensure that the 300 mg. chloride ions/litre limit remains downstream of the Hollandse Yssel.

In recent years forecasts of water movement in the lower river system subsequent to the completion of the northern section of the Delta project have been compiled using hydraulic models and on the basis of calculations. The studies of water movement in the lower river area are indeed still continuing. In order to illustrate the changes in water movement graphically we have drawn the high water and low water lines for a number of gauging stations, firstly before the closing of the Volkerak and secondly after the closing of both the Volkerak and the Haringvliet, these situations being subsequently referred to as T_0 and T_1 (see figure on page 23). The stations concerned are at Hook of Holland, Rotterdam, Dordrecht, Willemstad, Hellevoetsluis and Goidschalxoord.

Since the high and low water figures at the Hook of Holland are still influenced slightly by the Rhine discharge, the vertical tide at the Hook of Holland cannot, strictly speaking, be accepted as a constant tidal boundary condition.

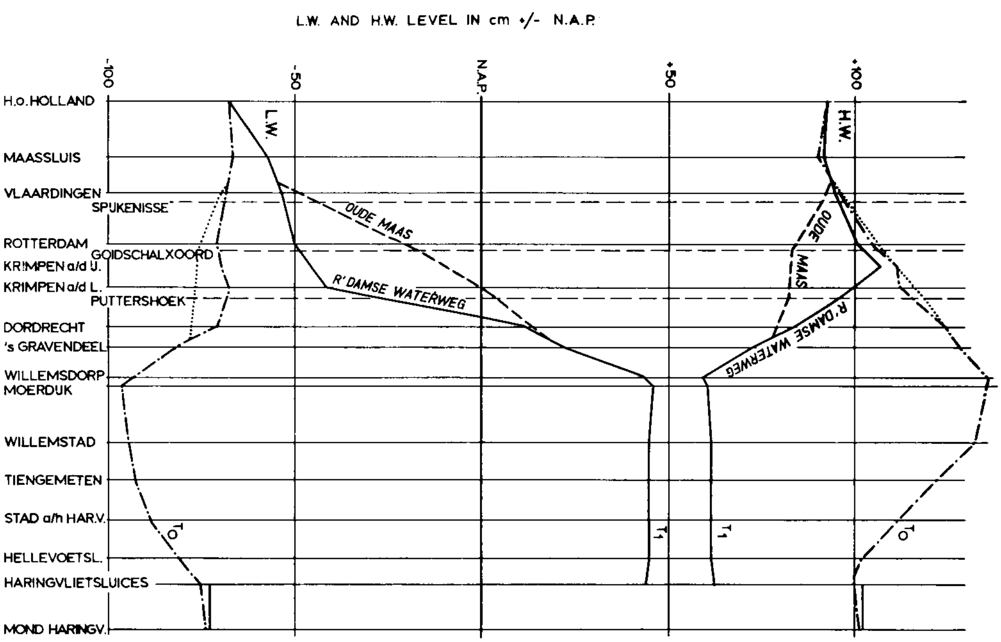
For this reason the figure for the seaward end of the present north jetty has been introduced as a boundary condition for the purposes of the study.

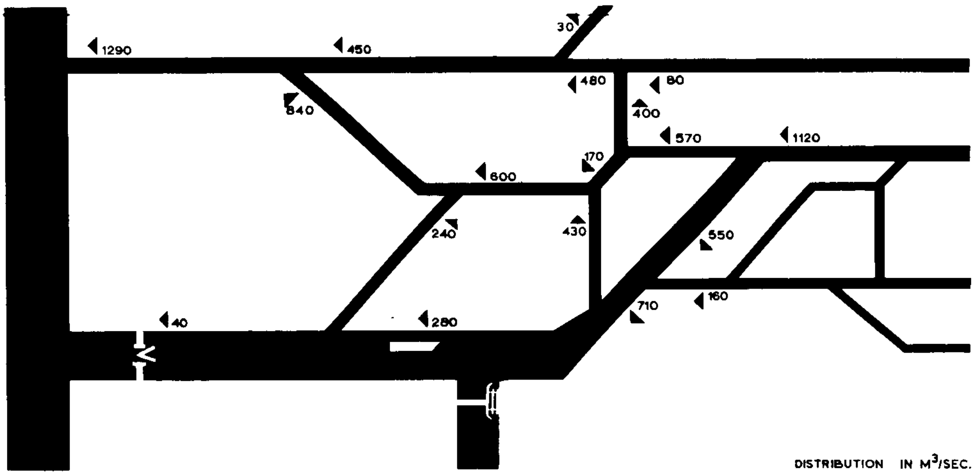
At Rotterdam the closure of the Haringvliet and the discharge programme for the Haringvliet sluices have a perceptibly greater effect on the high and low water lines already. At Dordrecht the effect on high and low water levels are even more pronounced than at Rotterdam. With an Upper Rhine discharge of 1,500 cu.m./sec., the Haringvliet sluices being shut, the low water level will be 85 cm. above previous levels and will no longer fall below N.A.P. The high water level will also be effected to a marked degree, falling by 40 cm. in relation to the level prior to the closing of the Volkerak. For the above Rhine discharge the tidal range will thus have changed from 190 cm. to 65 cm. The greatest effect on high and low water levels will be observed in the Haringvliet basin. When the Haringvliet sluices are closed the tidal range at Willemstad will be no more than 20 cm. For a Rhine discharge of 1,500 cu.m./sec. the high water level will have fallen by 70 cm. and the low water level risen by 130 cm. as compared to the figures prior to the closure of the Haringvliet.

When the Rhine discharge is high and the sluices are opened during the ebb period the tidal ranges will gradually increase again as is also shown by the graphs for the other gauging stations. If the Rhine discharge is greater than 5,000 cu.m./sec. and the Haringvliet sluices are fully opened during the outflow period, the tidal range at Willemstad will become approx. 85 cm. – still very different from the erstwhile 210 cm. Finally, the graph for Hellevoetsluis shows that the high and low water marks are very closely related to those recorded at Willemstad. During periods of high Rhine discharge the tidal range at Hellevoetsluis will be about 10% greater than at Willemstad, since at low tide there the water will fall to a lower level when the sluices are discharging at full capacity. The high and low water lines for Goidschalxoord are simply included for the sake of completeness.

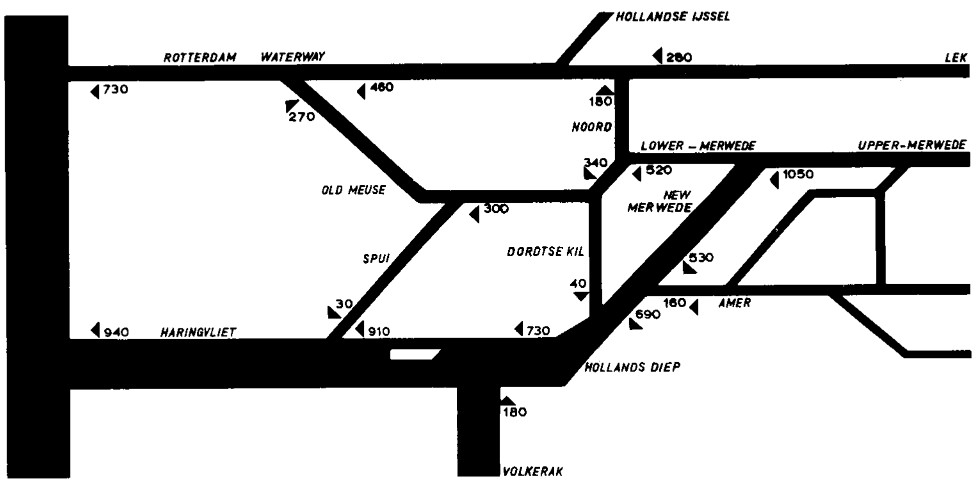
In the figure the high and low water marks recorded for a Rhine discharge of less than 1,500 cu.m./sec., i.e. when the Haringvliet sluices remain shut, are plotted as a function of geographical distance, beginning at the Hook of Holland and proceeding inland, by way of the New Waterway, the New Meuse, the Noord, the Old Meuse and the Kil, to the Hollands Diep and the Haringvliet as far as the mouth of the Haringvliet. The corresponding high and low water lines are plotted for the stretch of river represented by the New Waterway and the Old Meuse and subsequently for the route along the Kil and the Hollands Diep and the Haringvliet as far as the closed sluices. The high and low water levels on the two sides of the sluices differ considerably. The tide

High and low water levels as a function of the distance with an Upper Rhine discharge of 1,500 cu.m./sec. M.S.L. at sea and closed Haringvliet sluices



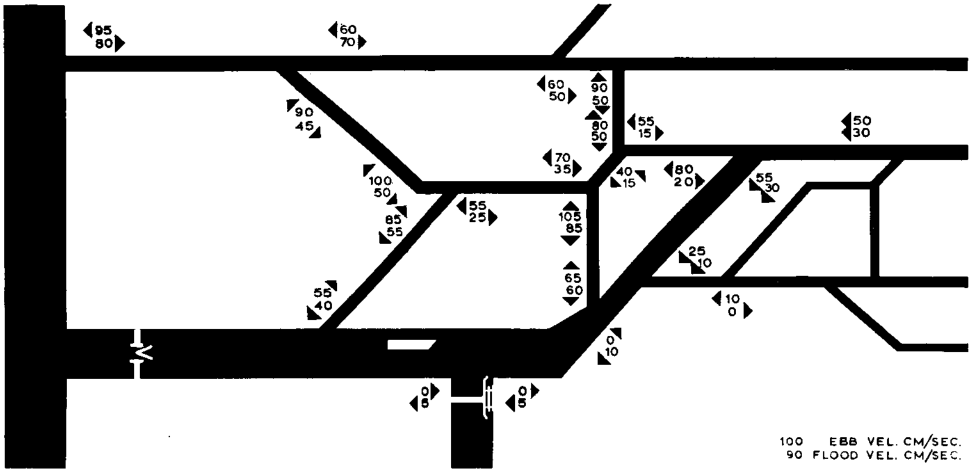


a



b

The distribution in the lower river area with an Upper Rhine discharge of 1,500 cu.m./sec. Figure a for condition T_0 and b for T_1. The Haringvliet sluices are closed. The currents are reversed in Spui and Dordtse Kil



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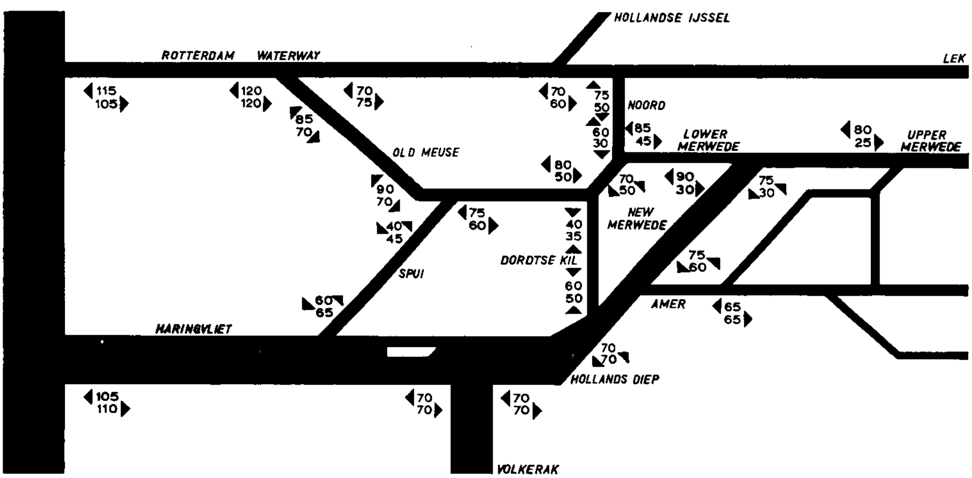


b

Velocity and direction of the maximum flood and ebb currents in the lower river area with an Upper Rhine discharge of 1,500 cu.m./sec. Figure a for condition T_0 and b for T_1. The Haringvliet sluices remain closed

on the inside of the sluices is of course a consequence of propagation of the tidal movement at the mouth of the Waterway via the lower rivers to the Haringvliet. Due to friction, inertia and tidal storage in low-lying areas the amplitude and phase of the vertical tidal movement undergoes a significant change during its propagation to the Haringvliet. The currents arising in this way in each of the tidal rivers in the lower river area are supplemented by their share of the discharge from the Waal, Lek and Meuse. The figure on page 26 gives both velocity and direction of the combined discharges from the Waal, Lek and Meuse for each of the lower rivers, for both situation T_0 and T_1. The most striking change is that the direction of the discharge from the upper rivers through the Kil and the Spui is completely reversed. For T_0 the upper water discharge by way of the Kil and the Spui runs from north to south and for T_1 from south to north. This change makes the tidal current in the Kil and the Spui in the vicinity of the Old Meuse greater than at the Haringvliet end.
When the discharge from the Upper Rhine exceeds 1,500 cu.m./sec. and the sluice openings are gradually increased during the ebb period the discharge along the Spui and the Kil will at first decrease, and then, when the sluices are opened wide enough, finally flow in the same direction as in the T_0 situation.
The same phenomenon could arise if the Haringvliet sluices were widely opened during a period of low Rhine discharge. The discharge through the Noord would then flow in a southerly instead of a northerly direction. In this case a permanent current would be created from the mouth of the Waterway to the Haringvliet basin and from there into the sea. Such a circulating current would soon lead to salinization of the whole lower river area. Until the Haringvliet sluices became operational for water control purposes they were left open during the whole tidal period. As a result of the closing of the Rak van Scheelhoek virtually the only way the tide was able to enter the Haringvliet was through the fully opened sluices. This reduced tidal movement inland from the sluices. The tidal range at Willemstad decreased from 165 cm. to 145 cm. and at Dordrecht from 170 cm. to 155 cm.
The Haringvliet sluices will only be used for discharge when the Rhine discharge exceeds approx. 1,500 cu.m./sec.; this means that the sluices will remain closed for an average of about 150 days a year. In summers when the Rhine discharge is low, as it was in 1947 and in 1949 and lastly in 1971, the sluices will scarcely be opened for months at a time, or not at all. Finally one further point must be made about the situation during high discharge periods. If the Rhine discharge exceeds approx. 5,000 cu.m./sec. the sluices will presumably remain fully open during ebb tide. At times of extremely high Rhine discharge, such as the 12,500 cu.m./sec. recorded in 1926 the sluices will only be closed for a limited number of hours during each tidal sequence; in other words they will still, therefore, be partially open during flood tide. In the case of even higher Rhine discharge the sluices will be closed for shorter and shorter periods until a situation is reached where the discharge from the Rhine and Meuse is passing through what is in effect an open gap with a discharge opening below N.A.P. of approx. 6,000 square metres.

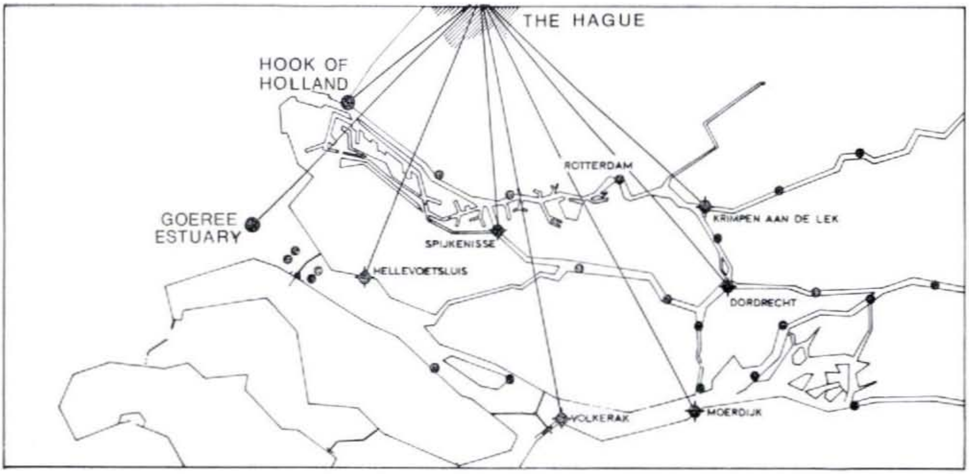
Photo of movable weirs and lock near Amerongen

Needless to say that the weirs in the Rhine and the Meuse will also be fully open in such circumstances.
The critical water-levels for the safety of the country around the upper rivers themselves are determined by the extreme discharge rate of 18,000 cu.m./sec. The frequency of this occurring are on an average of one day per 1,000 years. The water-levels associated with such extreme discharge rates will hardly be influenced by the Delta project, although they will be affected by artificial and natural changes in the configurations of the upper rivers and their beds. In the lower river area proper, below Schoonhoven and Werkendam, the water-levels will indeed be influenced by the Delta project. In this area the maximum critical storm flood levels are determined by the situation arising on the occurrence of a super storm such as the Delta project is designed to give protection against.

3. The water management system in the northern Delta basin: practical considerations

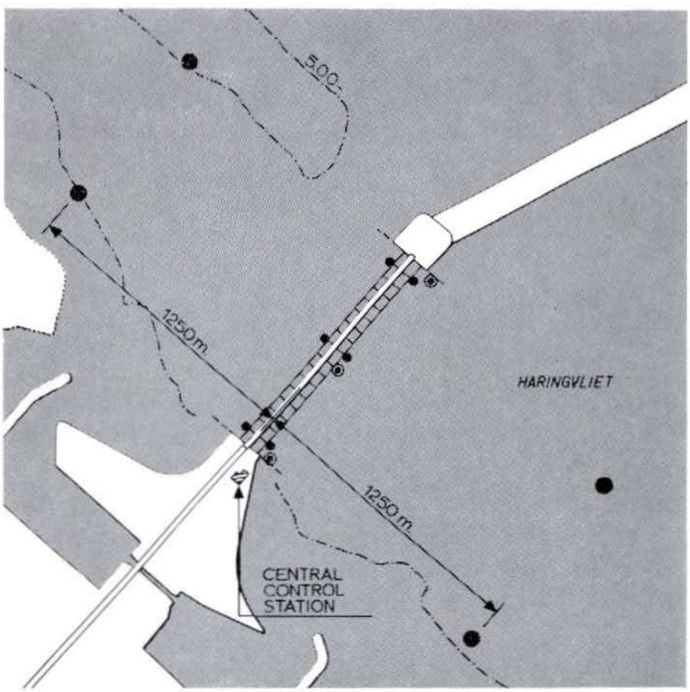
The Haringvliet sluices and the weirs on the Lower Rhine and Lek will, within certain limits, enable the water brought down by Holland's great rivers to be distributed more effectively to different parts of the country. In this chapter we shall deal with the practical aspects of the water management system, devoting particular attention to the instrumentation techniques.

The first year of the water management system has to be considered as an experimental phase. The experience gained during this trial period will be used in drawing up the final scheme which, however, it will not be possible to implement until all the necessary inlet sluices, weirs and discharge systems are built. For the next few years the distribution of river water over the northern Delta basin will depend on the discharge sluices in the Haringvliet and the movable weirs on the Lower Rhine and Lek. The sluice in the Volkerak dam intended to be used for combating salt-water intrusion via the locks next to this dam, are expected to become available in about 1974 and be added as a third regulating point in the overall water management system.
All the sluices, weirs and outlets constituting part of the system will be operated according to a pre-determined plan. Thus, the Haringvliet sluices have their own twinfold outflow programme. Proceeding from the assumption of an average tidal movement of the sea, the normal programme lays down the aperture of the sluice gates during low tide for different water discharges of the upper rivers. Allowance is made for the fact that the tidal movement of the sea always differs from the average, though any deviation will usually be so small that for a substantial part of the year the programme can be adhered to.
This programme is therefore known as the standard discharge programme.
A different programme must be followed, however, when there are Western storms, when the east wind has lowered the water level or when the water in the river is badly polluted. When the water management system has been fully implemented, its operation must be continually checked according to its results. Although during development of the system tests were carried out with hydraulic and electronic analogue models and use was made of theoretical and empirical calculation techniques, we certainly may not assume that under natural conditions, water, salt and sediment movements will conform to the predicted patterns.
The water management system for the northern Delta basin was drawn up on the assumption that the control station for the Haringvliet sluices could carry out the standard outflow programme on its own. For this purpose the control station needs a wide range of information. To determine how far the sluice gates should be opened,



- Boundary condition stations with permanent cable connection
- Gauge stations with direct cable connections
- Gauge stations - selfrecording

▲ Gauge stations in the northern Delta basin



Position of gauges and pressure indicators on or near the Haringvliet sluices

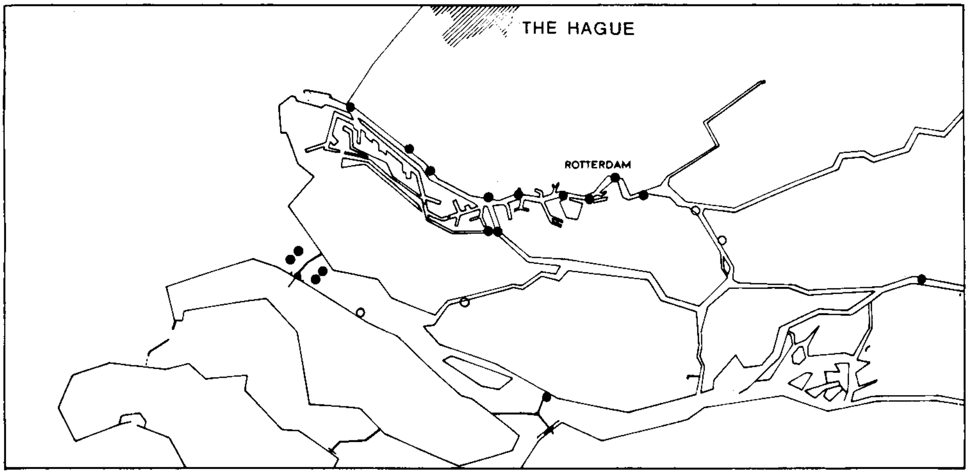
- Gauges transmitting vertical tide and salinity data to Haringvliet control station by wireless
- Pressure indicators with cable transmission of pressure differences to control station
- Conductivity meters in salt trap linked by cable to control station

it is necessary to know the rate of discharge from the upper Meuse and Rhine rivers at any given moment and, in addition, the causes which lead to this discharge. Continuous information of this kind is only obtainable in the case of the Rhine and its tributaries, a number of monitoring measuring stations having been set up there for the purposes of the Rhine canalization scheme. The data acquired in this way can be transmitted by direct line to the Haringvliet sluices. The rate of discharge from the Upper Rhine and its tributaries can usually be determined from the water level readings at the Lobith and IJsselkop stations as there is a known relationship between the levels recorded there and the rate of discharge.

Endeavours are being made to determine the discharge from the Meuse automatically, but until this has been achieved it will have to be derived from the position of the three sluice gates of the movable overflow weir at Lith ascertained at 8 a.m. daily and from the water level of the reach immediately above them, or, when the gates are opened, from the water level at Grave. However, although the water discharged from the Meuse is important enough as regards quality, quantitatively its contribution is small, so that the fact that information is received only once every 24 hours does not constitute a serious drawback.

The water takes one or two days to reach the Delta area from the stations mentioned above, which allows ample time for determining in advance how far the Haringvliet sluices should be opened. The control station must in the meantime be provided with information about the volume of water discharged into and drawn off from the main river and route, e.g. the in- and outflow at polder pumping stations.

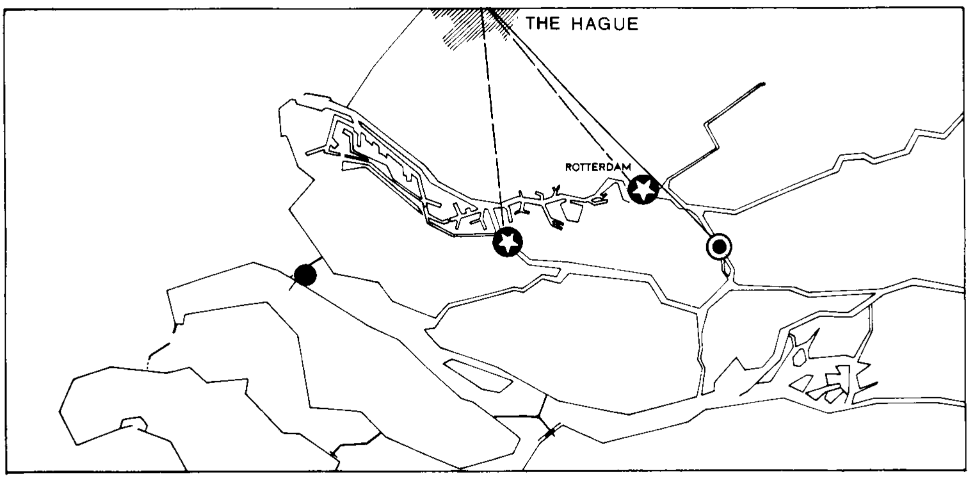
The water flow which has to be discharged must now be distributed over the available sluices, viz. the 17 large gates, the 5 salt sewers in the abutments and the fishways built into six of the piers. The purpose of the salt-water sewers is to discharge into the sea the salt-water which has leaked through or splashed over onto the upstream side of the sluices and collected in the deep-lying salt-water trap on the upstream side of the sluices. Two of the drains are in the north abutment and three in the south. The cross-sectional area of a salt-water drain is 7.84 sq.m. To avoid any risk, during discharge, of fresh river water being drawn over the salt-water collected in the trap, the valves are adjusted to ensure that the water velocity through each drain does not exceed 20 cm. per second. This in turn limits the amount of water that can be discharged via the salt-water drains. A velocity meter inside each drain is coupled to the valve to enable its setting to be altered if the water velocity begins to deviate from the required value. Conductivity meters at various depths in the salt-water trap, which are connected to the recording equipment in the sluice control station, provide a check that only water with a sufficiently high salt content is passing through the salt-water drains. The six fishways enable eel, smelt and other fish to move from the sea into the Haringvliet. A small current has to be maintained in the fishways to lure the fish. The limitations imposed by the above considerations on outflow through the salt-water drains and fishways mean that these outlets are not capable of ensuring the minimum average discharge rate per tide through the Haringvliet of 40 cu.m. per



Installations in the northern Delta basin for the measurement of the salinity

● Conductivity meters already installed

○ Conductivity meters to be installed



Current meters in the northern Delta basin

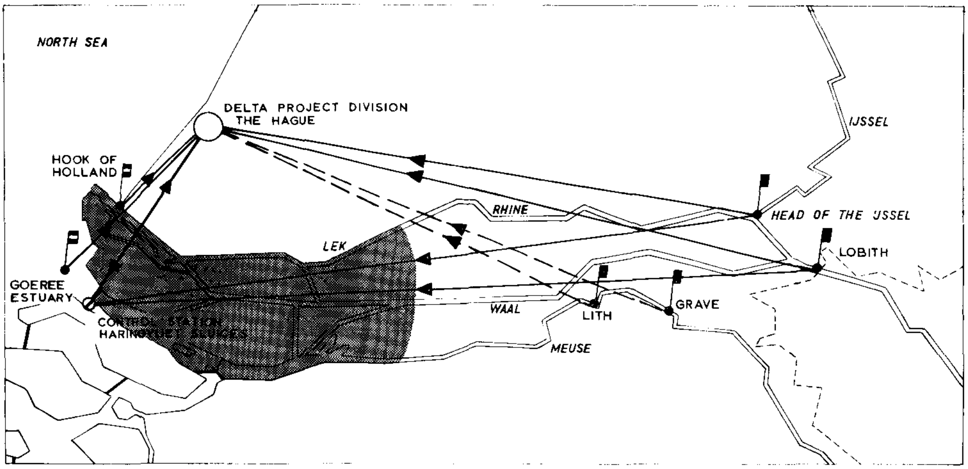
◉ Current meters with permanent links

✪ Current meters to be installed

● Discharge determination based on water-level data

second which is necessary when the discharge from the Rhine is at a low level. It follows therefore that one or more of the main sluice gates need be used.

The Haringvliet sluice control station will also have to determine when the main sluice gates and the valves in the salt-water drains and fishways have to be opened or closed; they are only operated when the inside water level is higher than outside.



Stations providing data on boundary conditions of river water outflow and tidal movements, and their links with The Hague

Stations registering boundary conditions of river discharge

Stations registering boundary tidal conditions in the open sea

Northern Delta basin

Theoretically these times are fixed, as they must coincide with the times of equal water pressure on both sides of the sluices. In practice in order to determine these moments four monitoring gauges are used, two on each side, these being placed in the water at a distance of 1,250 m. from the sluices. The point chosen had to be far enough from the sluices to escape the effect of changes in the current velocity and turbulences due to the sluices themselves. The use of two observation stations on each side is a precautionary measure, which reduces the chance of no data being recording owing to technical defects and furthermore cancels out the effect of cross fall, i.e. the surface slope at right angle to the direction of the current. The stations, embodying a tide gauge and a conductivity meter, are placed in positions where the depth of water always averages at least 5 metres, this being necessary for the proper functioning of the equipment. Water level and salt content readings are transmitted by wireless to the sluice control station, where they are registered by recorders and a tape can be punched.

These data can now be used to compute the water pressure on both sides of the sluices. In addition pressure gauges are fitted to all the sluice piers at a height of 3.15 m below N.A.P. The pressure gauges on piers 1, 8 and 16 are connected to differential pressure meters. The pressure difference thus measured will also be registered at the control station, giving additional information for determining the moment to open or close the sluice gates.

4. Testing the discharge programme

The available data recorded at the control station must also be used to check the discharge programme. The changes in the water levels on both sides of the sluices give an indication of the total outflow through the sluice gates. The observation stations which have been described above form part of an extensive measuring system, covering the entire northern Delta basin, which provides continuous information on the fluctuations of the vertical tide and the salt content throughout the area as well as on the current data in some of the tributaries. The tidal range and the salt content are registered at a large number of points by local recording stations. In addition along the Noord and the mouth of the Old Meuse a number of current meters give on the spot readings from which the average current velocity, and hence also the outflow into the tributaries, can be determined. Similar meters are shortly to be installed in the estuary of the Old Meuse and possibly also in the New Meuse. This measuring network will enable the effect of the Haringvliet sluice discharge programme on water movement to be checked. If the changes in water movement and salinity do not correspond to calculations or expectations the standard discharge programme will have to be modified.

In special circumstances, as for example during storms or when the river is extremely low, immediate information will be required on water movement and salinity. For this purpose permanent line connections have been established between a number of gauges and a centre in The Hague. As a further consequence, it is desirable that the recording of the current and salt readings be transmitted to The Hague as soon as possible. When operational guidance on the control of the Haringvliet sluices is required from the analogue computer 'Deltar', the latter must have direct access to data on boundary conditions, like tidal movement in the open sea and the discharge from the rivers, for the purposes of its calculations. Boundary conditions of the tidal movement in the open sea is obtained from readings taken at the Hook of Holland and a tide gauge in the Goeree estuary, 5 to 6 km. to seaward of the Haringvliet sluices. The Lobith and IJsselkop gauges provide the answer as regards discharge of the Rhine and its tributaries, while stations at Lith or Grave do the same as far as the Meuse is concerned. All the data mentioned, apart from those relating to the Meuse are relayed by direct line to the centre at The Hague.

The monitoring system which has been described will thus enable an effective check to be carried out on the discharge programme during the experimental stage, and provide operational support for the control of Haringvliet sluices. In order to obtain a deeper understanding of all the factors involved and to enable further testing of the discharge programme to be carried out, the regular measurements described here will be supplemented from time to time by measurements of water, salt and sediment movement made from survey ships. An extensive survey programme has been drawn up, with the prime object of accurately determining the water distribution at the various points where the river divides and to measure water, salt and sediment movements simultaneously in practically the whole of the lower river area. In addition water samples are taken at a large number of predetermined points, for the measurement of the temperature, chloride content and, in some cases, oxygen content of the water.

5. The design of the Haringvliet dam

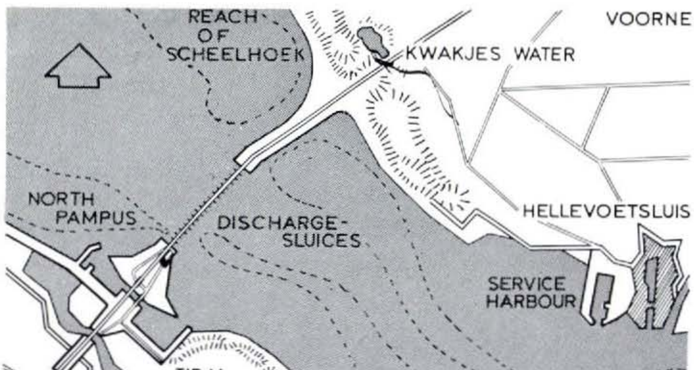
Of the three major estuaries whose closure was provided for in the Delta Plan, the Haringvliet had the smallest tidal volume, namely 260 million cu. m., as against 360 million cu. m. in the Brouwershavensche Gat and 1,100 million cu. m. in the Eastern Scheldt. But the actual construction of the dam across the Haringvliet was in fact much more complicated than in either of the other two cases, since it had to incorporate a discharge system about one km/wide and a shipping lock. The time taken to build the discharge sluices would determine the total construction time of the dam. This was one reason why it was necessary to make an early start on the Haringvliet dam, which was to take no less than 13 years to complete.

The closing of an estuary as large as the Haringvliet presented the Dutch hydraulic engineers with problems they had never had to deal with before to this extent, either in the Delta area or anywhere else. The nearest comparison, from the point of view of the extent of the project, was the closing of the Zuyder Zee, completed in 1933. But the characteristics of that project were different in a number of respects. Though in the case of the Zuyder Zee the dam was of greater length, the channels in the Haringvliet were deeper, and much more exposed to wave-action, while the tide is stronger. For that reason a new strategy had to be worked out for closing this estuary. Because of the loose sandy bottom and the relatively strong tidal current, the structure of the estuary is very unstable. Slight natural or artificial changes in the conditions may cause considerable alterations to the pattern of channels and shoals. If the damming operations had been carried out without due caution there would have been a risk that the current pattern would have been radically affected as soon as operations began. This would then have meant that the situation on which the plans were based would irreversibly change, completely overturning the design. If the main channels, for instance, would have been closed first, new channels would certainly have developed rapidly and the originally shallow areas of sandbanks would have been swept away and scoured out in a very short time.

It was therefore necessary to leave the existing tidal channels relatively intact for as long as possible, and to start work in those parts of the cross-section which were of least importance to current flows in the estuary.

These considerations resulted in a design whereby the sections of the dam on the shallow flats would be built first, to be followed only at a later stage by those in the main channels in between, construction of which would then have to proceed as rapidly as possible. However, in view of the fact that the damming of the shallow parts would also give rise to shifts in the current pattern and to further concentration of current flow in the main channels, it would generally be necessary to guard the main channels the dam would have to cross against changing course or being eroded further, and to stabilise them by laying a protective covering on the bottom.

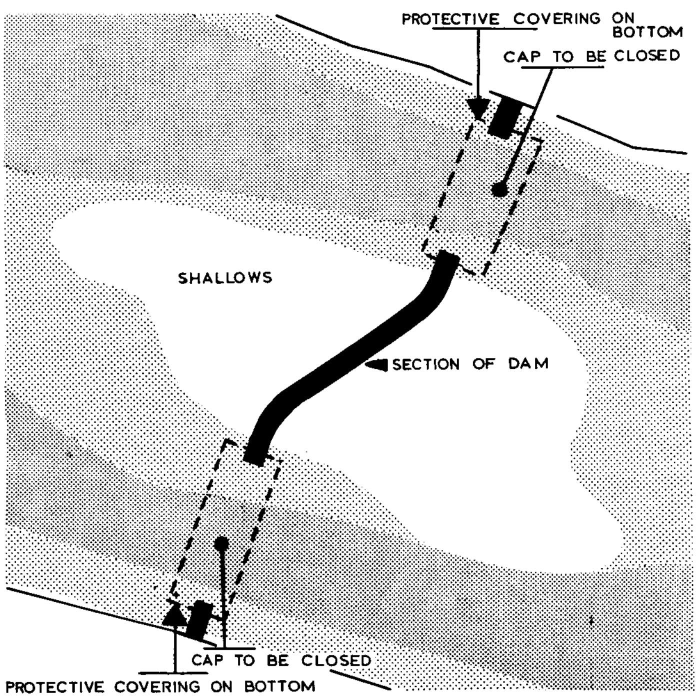
The special characteristic distinguishing the Haringvliet from the other estuaries was that large quantities of water would still under certain circumstances have to be discharged from it into the sea even when the dam had been completed. Thus it would have to partially retain its function as a link between the river system and the sea. The structure of the estuary would ultimately have to be adapted to meet this new requirement, and in such a way that the sluice complex forming part of the dam would ultimately be situated on a through channel. The logical conclusion to this line of thought would be to choose the main channel of the estuary as the location for the sluice complex. The final situation would then coincide as nearly as possible with the initial phase. But in order to build the sluices in that channel the latter would first – that is at an early stage of the whole damming operation – have to be closed, with all the undesirable repercussions this would have on the general situation in the estuary. The only solution therefore was to situate the sluice on a shoal between the channels. At a later stage the water could be admitted by clearing away the surrounding dike and be allowed to pass through the sluices, which would then be able to take over the function of the main channel, thus limiting the velocity of the current through the gap still to be closed.



The Haringvliet dam

In fact the cross-sectional current flow in the Haringvliet as a whole at the time of commencement of operations in the main channel, the Rak van Scheelhoek, turned out in practice to be only 500 square metres less, with the sluices open, than it had been in 1956 when work started.

There was also the problem of finding the best place in the Haringvliet for the realization of this ambitious project. Of the three sites for the closing dam which were considered, the most westerly proved to be unsuitable due to the powerful waves to be expected there, which would have created difficulties not only during the actual construction work but also with regard to the design specifications of the sluice complex. In the case of the easternmost site the estuary was not wide enough to allow a building pit $1\frac{1}{2}$ kilometres wide to be constructed without endangering the shores of the islands. The middle site, extending from Stellendam on Goeree to Kwakjeswater on the island of Voorne, had neither of these disadvantages. At this point there was a shallow section in the middle of the cross-section, where the ringdike for the sluice complex could be sited. Further south, in the direction of the Noord-Pampus, there was enough room for the construction of a shipping lock, also in a building-pit. These factors determined the ultimate shape of the cross-section. After the completion of the construction work, a channel would have to be dredged beyond the discharge sluices in order to adapt the hydrography of the closed estuary to the new situation.



General diagram showing method of closing an estuary

Although this, admittedly, meant extra work, only a partial increase in costs was involved, as part of the spoil was of good enough quality for the work to be done under a sand excavation concession.

The first operation in the Haringvliet project, then, was the construction of a ringdike for the discharge sluices. This dike, which was of no mean proportions, extended for a distance of 1,400 metres at right angles to the current and 560 metres parallel with it. Although the dike was built on a shallow part of the cross-section, the obstruction caused maximum current velocities to increase by about 25‰. That was no surprise, as calculations and experiments with models had pointed to such a development. The only question was whether the strong currents created in this way could be given free play, since they were almost certain to cause considerable deepening of the existing channels.

Because of the length of time required to build the sluices, the obstruction would be in existence, and thus continue to influence conditions, for 8 consecutive years. The stability of both the ringdike itself and of the vital water defences on the adjacent shores of the islands might, therefore, be threatened by developments. It was decided to wait and see what happened. As long as the situation did not get out of hand it would certainly be preferable to simply allow events to take their natural course; action would only be taken to intervene where warning of unfavourable developments showed it to be necesssary. The services of an extensive and well-equipped survey and research team were available on the spot, so that there would be no delay in becoming aware of any danger that threatened. There were also adequate resources available to enable steps to be taken at short notice, where necessary. Experience has shown that this was a sensible procedure to adopt. The deepening of the channel which occurred did not give rise to any dangerous situations, and the shores of the estuary were not affected. Only on the northern side of the building pit extra measures had to be taken to ensure the stability of the surrounding dike. Despite extensive deposits of ballast an unstable trough developed to a depth of 22 metres below N.A.P. (Amsterdam Ordnance Datum about mean sea level).

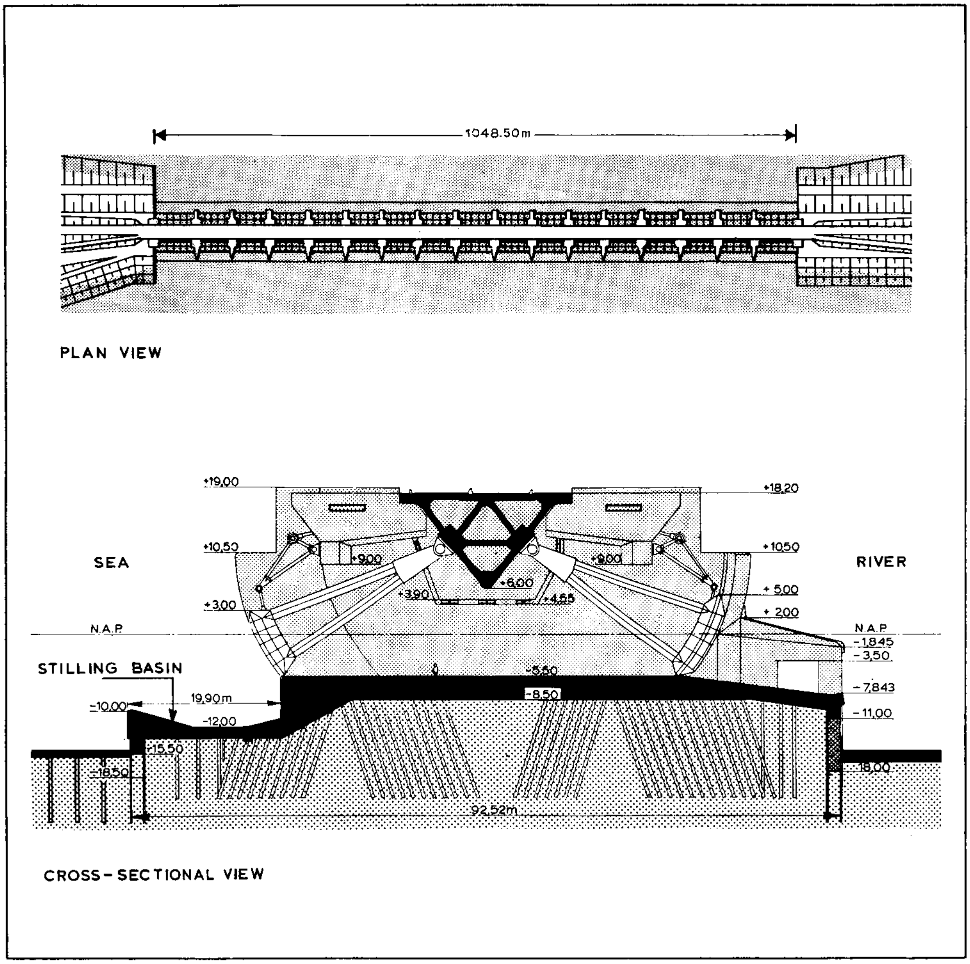
6. Designing the discharge sluices

The design of the gigantic discharge sluices in the Haringvliet raised many problems. The dimensions of the structure and the complexity of the problems involved in its design went beyond the range of experience gained previously with similar structures. It is easy to see that a hydraulic engineering project is, as a general rule, bound to have an effect on its environment, due to its provoking certain reactions on the part of the water, which manifest themselves in changes in the pattern of currents and wave action. These changed conditions in their turn react on the structure, so that it is one of the tasks of the designer to take such effects into account from the very start of his work. In the case of the Haringvliet sluices interaction of this sort was present to a very high degree. The complex series of problems which had to be faced and which demanded the joint attention of a team of experts from the most diverse branches of science and technology, was dominated by the problem of the effect of wave action on the structure itself, and in particular on the sluice gates. In addition, there were problems in relation to the undermining of the floor of the estuary adjacent to the sluices which required careful attention, while a thorough investigation also had to be made to devise suitable foundations for the structure. The measures which had to be taken to overcome these problems determined to a considerable extent the design of the sluices themselves. The sluices would be subjected to dynamic loads by the water in two ways: by the waves, and by the current flowing under the gates. These loads would be affected by the mechanical characteristics of the gates and the beams, the water-levels on both sides of the gates, and the position of the gates. Moreover, in the case of the load attributable to waves the characteristics of the waves, including their height, length, period and direction and the form and length of their crests, would also be important. The wave research was mainly carried out in the large wind flume at the 'De Voorst' Hydraulics Laboratory in the North-East Polder. In the flume, waves could be created either by a wave generator or by artificial winds.

The effect of wave action on the sluices proved to be more serious when they were closed than when they were completely or partially open. The forces exerted by the waves were at a maximum when the waves were breaking just as they reached the sluices. To be able to estimate the frequency with which particular wave loads were likely to occur, data was needed from observations under natural conditions. At that time wave measurements in the Haringvliet had not been carried out for a sufficiently long period. Substitute data was, however, provided by the wind and wave records from the weather-ship 'Goeree', which covered a considerable period, and which could be used to calculate the equivalent values applicable to the area around the mouth of the Haringvliet.

However, this did not give a precise indication of the size and, more especially, the form of the waves that the structure would actually have to contend with when it was built, as the whole wave pattern would have been changed by the presence of the sluices themselves. Attempts to get some idea of these changes, using a large-scale wave model of the Haringvliet, failed because of insufficient knowledge at that time of the techniques required. As a result, the changes in wave movement arising from the presence of the sluices had to be determined primarily by calculation. Several teams of experts, using different methods of calculation as a check on one another's work, sought to determine the nature of the changes and the reaction of the structure to them, and to make a theoretical computation of the dynamic load to be expected. The awareness during the designing of the sluices of the inadequacy of knowledge on these matters led to the dimensions of the gates and beams being based in every case on the most unfavourable load conditions, with the result that there is every likelihood of the structure having been made stronger than is strictly necessary. For example, although it can be presumed that the waves will only strike a portion of the surface of a gate, in the design calculations the assumption has been made that they strike the whole of a gate with the same degree of force simultaneously.

It is now considered extremely important, in the interests of the design of similar structures in the future, to check the accuracy of the scale-fixing rules and calculation techniques employed. Repetition under actual operating conditions of all the measurements made in the model would enable a useful contribution to be made to the further development of model techniques. In view of this, the Rijkswaterstaat commissioned the Hydraulics Laboratory and the TNO Institute for Mechanical Construction, as early as 1962, to carry out extensive measurements on the completed sluices, where necessary supplementing their work with new experiments using models.
The method of protecting the bed of the estuary, immediately adjacent to both sides of the sluices, from undermining which would threaten their stability was the subject of intensive research using models. The concentrated discharge of large quantities of water would scour a channel in the sandy bottom on both sides of the sluices unless some special measures were taken at those points to prevent it. A scouring effect of this sort would be bound to occur sooner or later – it was simply a question of keeping it as far away as possible from the sluices. The protective covering, used to line the bottom in the vicinity of the sluices, would itself have to stand up to very high water velocities. Research with models showed that conditions would be most critical when one of the gates could not be raised, because of maintenance work or a fault.
The powerful eddies set up by the water passing through the gate proved capable of displacing heavy stone ballast weighing many hundreds of kilograms. It was, therefore, deemed advisable to construct the first part of the bottom protection in the form of an integrated concrete slab, set on piles which could absorb both upward pull and downward pressure.
As the eddies grow weaker the further one proceeds downstream, further away from



The discharge sluices, plan view and cross-sectional view

the sluices it was possible to pass from the concrete method of construction to one of a more permeable nature, using gravel and stone.

Attention then had to be given to stabilizing the edge of the lining; immediately beyond it the current would start to erode the sand, with the result that the protective lining might be in danger of crumbling away along the edge of the ensuing depression. The solution was found in the provision of a special facing along the edge of the lining, employing tetrahedrons, or pointed concrete blocks. Subsequently practical evidence has become available of the need for the protective lining, in that the depth of certain parts of the Haringvliet where no protective covering was laid has increased from between 5 and 6 metres below N.A.P. to 20 metres below N.A.P.

In order to estimate the extent to which erosion round the edges could be considered permissible from the point of view of the stability of the structure, a soil mechanics investigation was necessary.
This involved taking soundings, making borings and measuring density. The latter in particular represented a new element in this sort of investigation. Used for the first time on a large scale in the Haringvliet project, density measurements are now employed extensively in all investigations connected with the construction of a dam of this sort, and thus also in the soil mechanics survey carried out in the Rak van Scheelhoek. The measurements obtained at the site of the discharge sluices showed that enough provision had been made for the stability or the structure in its design and that the undermining expected to occur would not endanger it. At the same time regular soundings would have to be taken downstream from the sluices so that prompt action could be taken in the event of unforeseen developments in the configuration of the floor of the estuary. The subsoil underneath the concrete structure itself also required a thorough soil mechanics survey.
A preliminary survey of the site chosen for the building pit showed that the subsoil

A model being used for research into wave impact on segmental gates

Construction of the hydraulic model at De Voorst consisted mainly of sand. However, the fairly thick layer of sand under the surface contained patches of clay, which, although only shallow, were of such a size and, above all, varied so much in number that if the structure were built on shallow foundation considerable settlement, and in particular great differences in the amount of settlement, would have to be reckoned with. As it was particularly vital to avoid any difference in the amount of settlement between one pier and another, because of the need to attach the gates to them, there was no escaping the conclusion that the piers would have to be built on piles.

Although this type of foundation is widely used in the Netherlands, a number of difficult problems arose in the case of the Haringvliet, which could only be solved by means of very special experiments. First of all there was the problem of the maximum permissible tractive force that could be applied to the piles under the base of the sluice. The base might be subjected to a downward or upward pressure depending on the water-level above the base of the sluice and the level of the ground water under it. The upward pressure would have to be absorbed partly by the weight of the base and partly by the piles. In view of this a safe permissible pressure had to be laid down for each pile. The foundations of the piers also gave rise to problems, mainly owing to the fact that very large numbers of piles would have to be driven into the soil very close to one another to ensure transfer to the subsoil of the pressure exerted. Driving in the piles so close together would increase the density of the subsoil and thus the maximum permissible pressure per pile. This, too, was made the subject of an investigation by means of an extensive series of experiments, which also took account of the fact that the horizontal loads, due to water pressure and wave action on the gates, would have to be partly absorbed by the pile foundations. These loads fluctuate greatly in amplitude, causing rapid changes in the load applied to the piles, a factor which adversely affects the amount of pressure that can be permitted per pile. Here, too, the fact that the piles were to be driven into the ground in groups was an important factor.

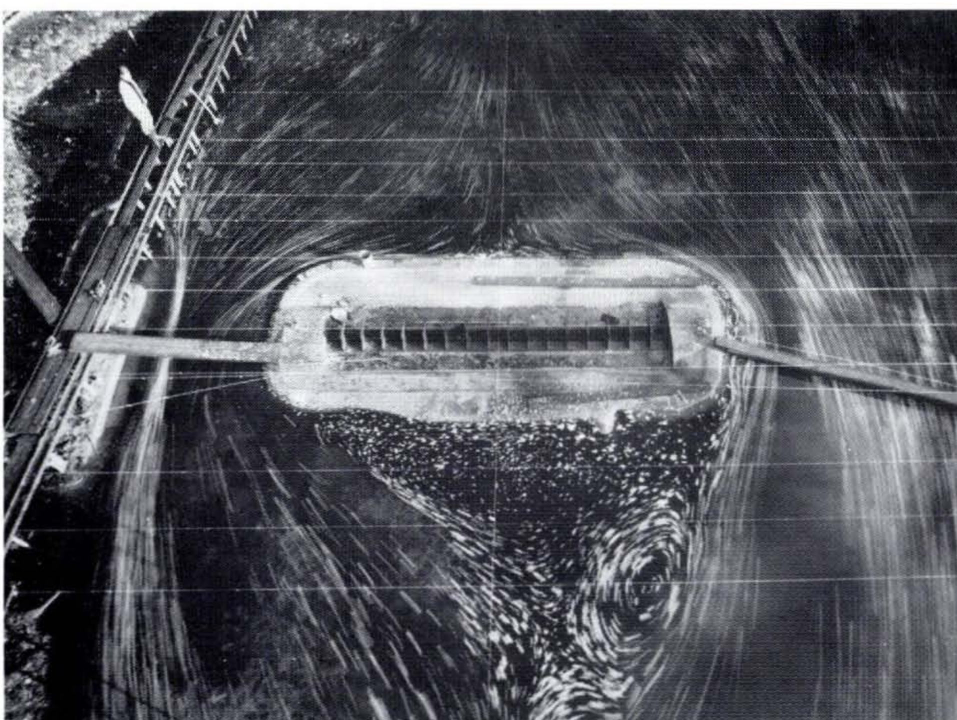
The design requirements for the sluices which emerged from the hydraulic research were in a number of respects diametrically opposed to the specifications worked out by the concrete and steel construction engineers for a power-driven sluice which would function efficiently without being too expensive. From the point of view of hydraulic engineering it was desirable that the sluice openings should be as wide as possible, mainly in order to discharge ice from the lower river area. But very wide openings would have meant excessive loads on the gates and on the concrete beam which had to absorb the loads on the gates. Balancing requirements against possibilities led to the design of a sluice complex with 17 discharge openings, each 56.5 metres wide, having a sill depth of 5.5 metres below N.A.P. The problem of how to close such large openings was only solved after long study. In view of the dimensions of the openings all possibility of constructing any type of flat vertical gate was ruled out on account of the considerable constructional difficulties involved. A solution was sought in a design in which the sluice gates would be supported by the beam which was to form a bridge between the piers. Some such bridge would have been required in any case to carry the through road traversing the Delta dams. The only type of gate for which reasonable opening and closing arrangements could be made despite its wide span was a segmental one, anchored to the body of the bridge at intervals of 15 metres by means of supporting arms. The circular form, however, is far from being the best from the point of view of hydraulic engineering, the force with which the waves strike it being greater than in the case of a vertical gate. Nevertheless, on this point water engineering requirements had to give way to those of mechanical engineering.

The disadvantage of this form from the point of view of wave action is particularly marked in the case of the gates on the seaward side which, therefore, have to withstand heavy shocks. The situation is different in the case of the gates on the river side, owing to the concave face being in contact with the water, which reduces the force of impact of the waves appreciably. On the other hand the gates on the river side are less able to absorb shock, the construction of the gates and the method by which they are connected with the main concrete structure being such that they can absorb pressure better than pull. Since, therefore, both gates have their advantages and disadvantages as regards their resistance to the pressure occasioned by waves from the sea, a way was sought to enable them to absorb these forces in combination with one another, each taking care of its own share.

The problem was solved by designing the gates on the seaward side two metres lower than those on the river side. In this way, at the highest water-levels, part of the force of the waves is absorbed by the outer gates, and the remainder, attributable to the water which runs over the outer gates, by the inner gates. And so optimum resistance to the waves has been achieved. Everything possible was done to ensure that the load on the gates should not exceed what was strictly necessary. Great attention was paid to giving the external surfaces of the gates a smooth finish, in order to avoid making it unnecessarily difficult to raise the gates in a field of pack-ice. With the same end in view powerful heaters were incorporated in the gates for melting the ice from them. Fe 52 steel, subjected to a special manufacturing process, was chosen for the gates after extensive fatigue and corrosion tests. In addition, all the gates were given cathodic protection against corrosion.

As far as the operation of the steel gates was concerned, the original design provided for very heavy gates, each weighing 500 tons, balanced by counterweights. Tests in the Hydraulics Laboratory, however, showed that they would be liable to tilt up from the sluice floor in certain circumstances for which reason the counterweights had to be abandoned. The consequences of reducing the weight of the gates were not acceptable. Hydraulic propulsion proved to be the only system suitable for accomplishing the exceptionally difficult task of operating the heavy segmental gates. To raise each gate a maximum vertical force equivalent to 800 tons is required, divided between two drive mechanisms housed in engine-rooms adjacent to the sluice piers. The cylinders required to do the work have an external diameter of 1 metre. The energy for operating the gates is supplied by a diesel installation with a capacity of $2 \times 1{,}500$ h.p. In emergencies power can be supplied by the Rotterdam Power Supply Board. For the concrete structural work it was necessary to have a detailed analysis of the compound load on the main sluice and connecting bridge structure as an integrated whole, a load coming on the one hand directly from the waves and currents, and on the other transmitted by the segmental gates via their mountings to the main concrete structure. All the forces to be absorbed were broken down into a number of multiple spring systems and various possibilities were investigated to see whether constructional changes had any effect on the forces which had to be absorbed. The outer floor of the sluices just in front of the gates on the seaward side was lowered to form a stilling basin which would help to damp down much of the energy of the approaching waves and thus considerably reduce their impact on the gates. The bridge to which both the outer and the inner gates are attached, and which are thus subject to pressures and tractive forces, was constructed as a hollow triangular beam with the apex pointing downwards and its base forming a carriageway for traffic. It proved necessary to strengthen the triangular beam by placing another triangle the other way up inside the first. A beam of this design could not be made in one-piece spans. For construction-

Current pattern round the coffer-dam

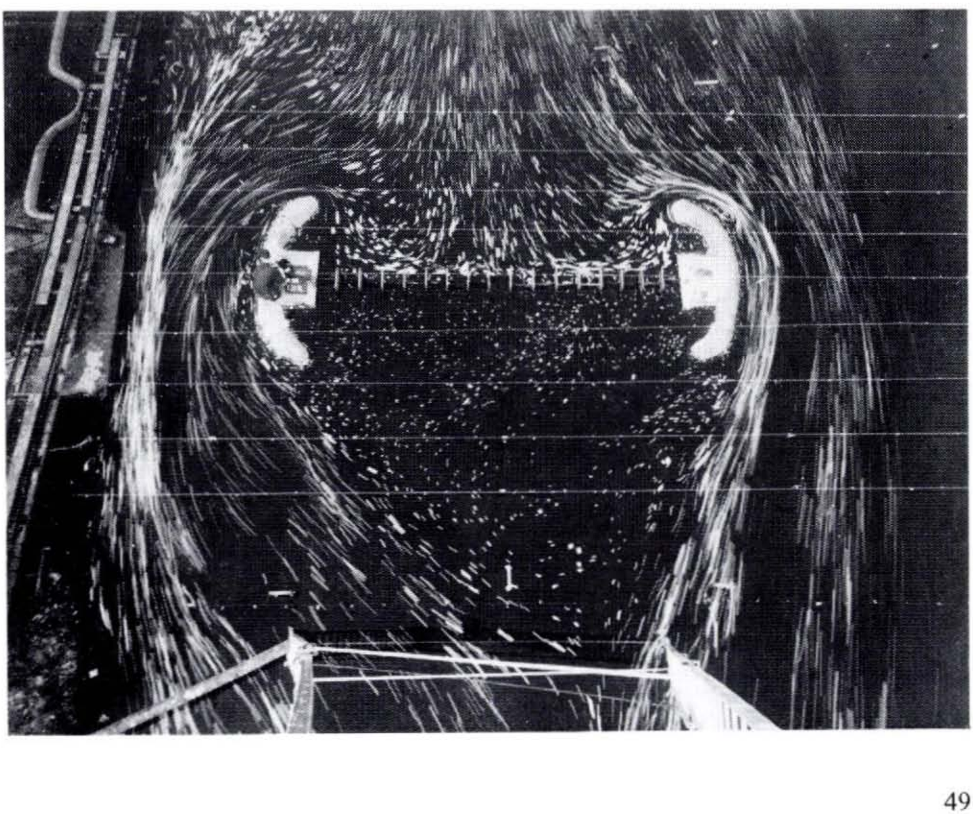


al purposes it was divided into a large number (22) of separate sections, each weighing about 250 tons; these were placed on a supporting framework and then permanently joined together by means of 200 high-tensile steel cables, which bind the separate sections of the beam together with a force of 26,000 tons.

In order to check the methods of calculation used, a 1 : 15 scale model of the whole concrete structure, as designed, was prepared in micro-concrete and clamped together using a force which was correspondingly scaled down; the model was then tested in the laboratory. The tension measured showed no significant deviation from that calculated. Resistance to cracking and rupture amply met requirements.

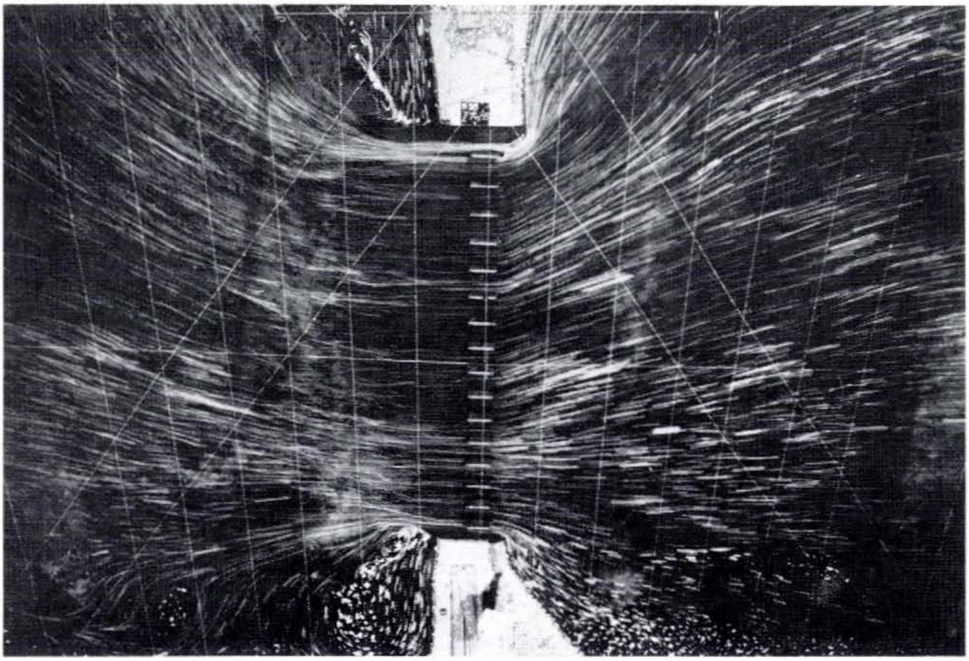
The research on which the complicated work of designing the discharge sluices in the Haringvliet was based was notable for its scope, thoroughness and complexity, requiring the maximum of attention from specialists in a wide variety of fields, and the greatest possible willingness to cooperate as members of a team, appreciate one anothers' problems and accept reasonable compromises. The problems which arose, especially those relating to wave impact and the undermining of foundations, phenomena which are still very difficult to reproduce accurately to scale in a model, neces-

The coffer-dam quadrants have not yet been demolished; the sluices are closed

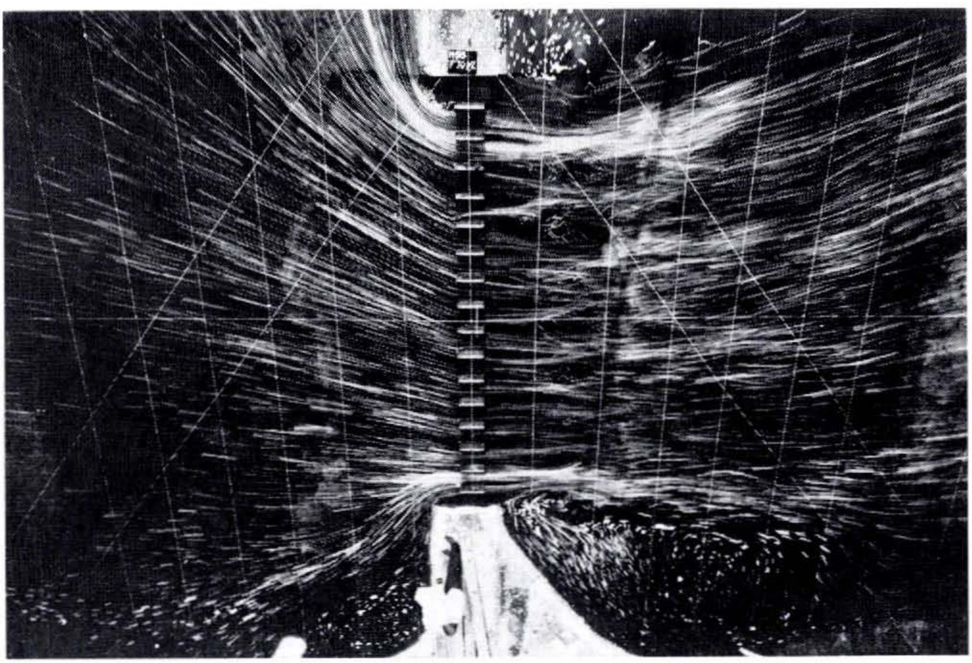


sitated fundamental research that has enabled science to make considerable progress in these fields. The wave studies in particular led to a considerable amount of material being published, abroad as well as in this country, to which Dutch hydraulic engineers have made considerable contributions by their theoretical analysis of problems. The design of the Haringvliet sluices served, for example, as a model for the design of a sluice complex in the Eider Dam, to the South of Husum in Schleswig-Holstein (Western Germany), where similar problems were encountered.
Both laboratory techniques and measuring techniques in the field have benefitted from the Haringvliet research and have improved considerably in the course of a few years. New types of wave measuring posts were evolved and a system for the telemetric transmission of data by radio and collection on punched tapes was introduced. More reliable methods were found of reproducing waves in wave tanks. The designs of several subsequent hydraulic engineering projects, in the Netherlands and elsewhere, have already benefitted from this advance; this applies in particular to the research into the stability of harbour jetties, recently carried out in connection with the design of the new jetties at Ymuiden and Hook of Holland.

The coffer-dam quadrants have not yet been demolished; the sluices are open



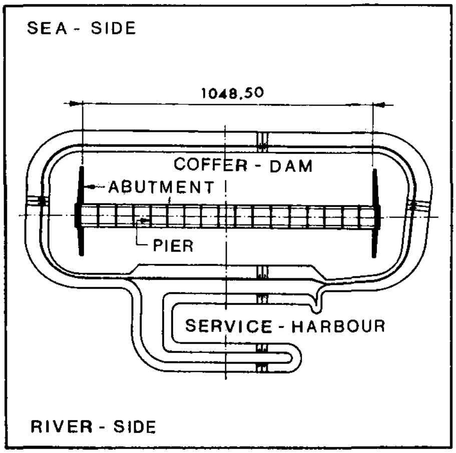
The final stage: the dam across the Haringvliet has been completed; the sluices are open



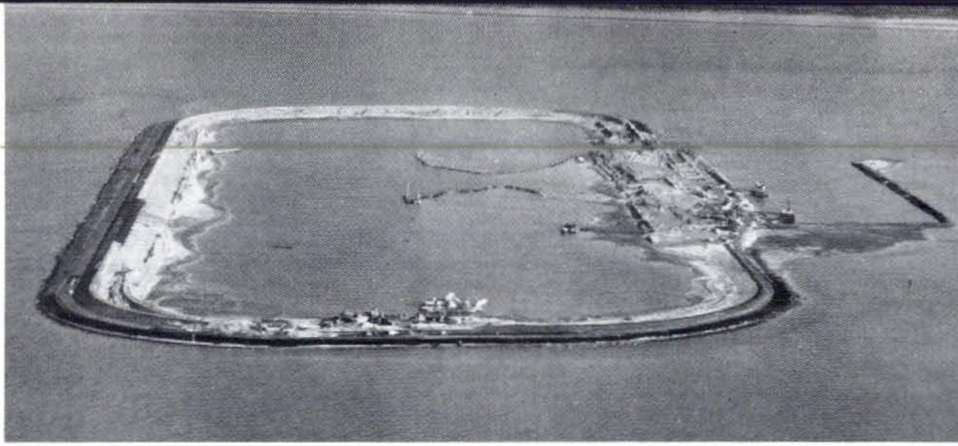
7. The execution of the Haringvliet project

The schedule of operations for the Delta Project was drawn up in such a way that as far as possible small tasks could precede large, and the relatively easy ones those which were more difficult; the small gaps to be closed were dealt with first, to be followed later by the three large estuaries and finally by the Eastern Scheldt. In this way it will have been possible to gradually acquire and extend the knowledge and skills required to bring this last and largest part of the project to a successful conclusion. In the case of the Haringvliet dam it was already possible to learn something from the preceding operations, and in particular from the experience gained with the overhead cableway during the construction of the Grevelingen dam, a cableway being of course employed once again in the construction of the Haringvliet dam.
In spite of this general plan of campaign the Haringvliet works had of necessity to be given a place fairly early in the schedule of operations. Because of the time required to construct the discharge sluices, and the consequent extended duration of the work, a start had to be made early in the schedule, the first mattresses being laid as early as 1956, to provide a foundation for the ringdike. In a sense, therefore, the Haringvliet dam paved the way for the others, since it was started earlier than that in the Veerse Gat. And so, when looking back at the Haringvliet operations, it is particularly interesting to see what lessons it has to offer that are of benefit to the other projects in the Delta Plan.
The first task was the construction of a ringdike for the building pit in which to build the massive sluices. There had been virtually no previous experience of building a ringdike of such proportions in the middle of a large estuary, where it would be exposed to big waves and tidal currents. Naturally the work had to be done in its entirety from the water, using floating equipment, and was consequently very much affected by the waves and currents, especially during the initial stages. Moreover, the shallowness of the water – the site chosen for the coffer-dam was on a sandbank – frequently hampered the operations of the large items of floating equipment, which simply cannot operate safely without a certain minimum depth of water beneath them. Again, some of the equipment, as, for example, suction dredgers with floating pipes, whose job was to build up the sand component of the ringdike, could only be used effectively in the lee of parts which had already been built up. The basic structure of the dike had to consist of some material which could offer adequate resistance to the tidal current, and thus act as a support for the sand component to follow. Good results were achieved with waste from the coal mines, and this material proved perfectly adequate for the purpose, although it offers little resistance to the wash of the waves, which causes it to level out into a fairly gentle slope. Mine waste proved to be a better

material for constructing the walls than the solid Klundert clay, which was also used here. The experience gained in using mine waste in the construction of the ringdike led to its use on a large scale in other parts of the Delta Project, and also, for that matter, elsewhere, as for example in the building of the new link between the Rhine and the Scheldt. Considerable experience was also gained in the use of gravel as a means of protecting the bottom against sand erosion. The Haringvliet operations also made a particularly useful contribution to the modernization of the whole operation of making and submerging protective mattresses. When work on the dam started it was the general custom to cover the parts of the sandy bottom that it was desired to protect from scouring with fascine mattresses woven from osiers and later weighted with stones. The making and submerging of 'classical' fascines such as this was accomplished by hand, and this is how a large proportion of this work was still carried out in the Haringvliet. It was primarily the 'classical' type of matting that was used for the construction of the service harbour at Hellevoetsluis and of the two ringdikes for the building of the discharge sluices and the lock. At the same time, however, efforts were being made to find a substitute, partly because the natural materials required for the 'classical' type of matting seemed to be getting too scarce, and partly to save labour. As the investigations proceeded, the composition of the matting underwent a gradual, but radical, change. Artificial fibres now form the main component of this sort of protective covering for the bottom, and their use has not only achieved the economics desired, but has also made the matting more impervious to sand. At the same time there have been great advances in the techniques used to submerge it and weight it down. Both these operations, which were previously carried out entirely by hand, are now fully mechanized. The use of electronic location systems has considerably improved the accuracy with which the matting can be positioned. The protective covering laid on the bottom of the Haringvliet covers over a million square metres and con-



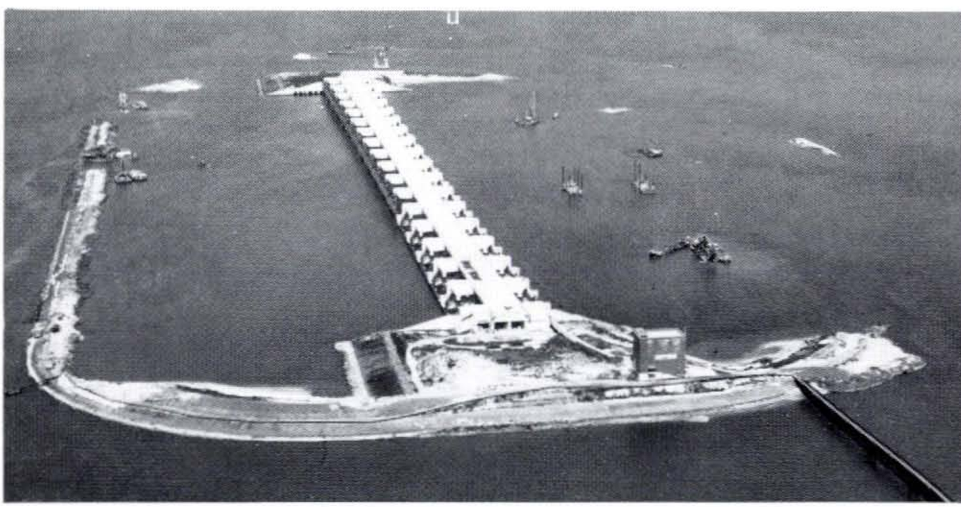
The coffer-dam for the discharge sluices



Stages in the building of the discharge sluices

2 November 1957

28 September 1964



30 May 1968

13 May 1959

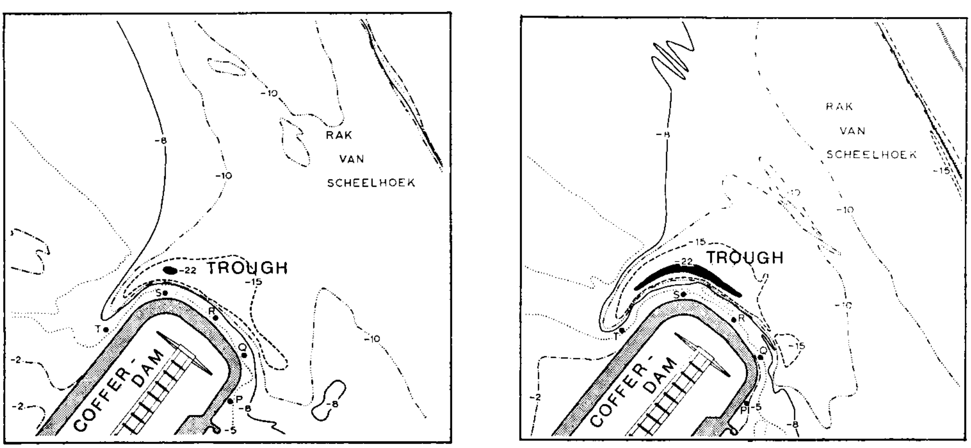
31 July 1967

2 April 1969

sists of matting of many different types and sizes, forming a veritable checker board of the results of technical developments in this field over the last fifteen years.

Finally some very useful experience was gained with a number of different methods of closing the gaps in a new dam. In the Haringvliet three channels had to be closed one after the other: the Zuiderdiep, the Noord-Pampus and the Rak van Scheelhoek. Since the scale of operations differed greatly in each of the three cases, three completely different methods were used to close the gaps. The Zuiderdiep, an independent channel opening into the side of the Haringvliet was blocked by stones transported and dumped in the required position by lorries. The Noord-Pampus, situated between the shipping lock coffer-dam and the discharge sluice coffer-dam, was closed entirely with sand, without the assistance of other materials such as stone or clay. This simple technique was based on methods recently developed for calculating the sand carrying capacity of flowing water; these made it possible to calculate the limit beyond which the current flowing in a channel as a result of tidal changes is so strong that it washes away all the sand deposited in situ by suction pumps. As long as the work was carried out within this limit it was possible to gain on the current by means of intensive sand-pumping operations and thus to close the channel. By adopting this method to close the Noord-Pampus, advantage was being taken of the experience gained during the closing of the Ventjagersgaatje, a section of the Volkerak dam, and of the Brielse Gat, part of the new harbour-mouth project at Hook of Holland, where a similar method was used. Knowledge of the extent to which sand can be used on its own in certain cases was increased as a result of the closing of the Noord-Pampus. Owing to the very great output which can be obtained from modern suction pumps, the possibilities of closing tidal channels exclusively with sand are now greater than before. The closing of the Rak van Scheelhoek could be regarded as a full-scale trial for similar future

Development of a trough on the north-western side of the coffer-dam between 1959 and 1964



Cableway across the 'Rak of Scheelhoek'

operations in the Brouwershavensche Gat and the Eastern Scheldt. Experience gained with the cableway during the closing of the Grevelingen was further broadened. In the closing of the Rak van Scheelhoek use was made for the first time of heavy materials of regular shape, in the form of concrete blocks with an edge 1 metre long and a weight of almost 2.5 tons. Blocks of this kind have since been used in the Brouwershavensche Gat, and will be used also later in the Eastern Scheldt. It is now known how such blocks stack in a dam of this sort and how porous such a dam will be. The results of this experiment, which among other things served as a check on the results from experiments with models, were fruitfully used as a basis for determining the technique to be employed in sealing the block dam in the Brouwershavensche Gat.

The construction of the discharge sluices was an extremely fascinating and spectacular project. The extraordinarily large scale of this structure naturally influenced the building operations, and even determined to a great extent the character of the whole project and the manner in which it was tackled. The enormous dimensions involved required a new approach, making great demands on technical and organizational skill, especially as regards the assembly of the very large components such as the triangular sections of the nabla beams and the steel gates. Special equipment was required, including a huge gantry crane of a size suited to the scale of the structure itself.

As, however, the actual construction of the sluice complex proceeded more or less independently of the dam building operations proper, and in any case has no further relevance to the other dam building projects, for the execution of which, therefore, it has no lessons to offer, it is not proposed to go into details in this review of the closing of the Haringvliet.

8. The hydrographic adaptation of the northern Delta basin

The protection afforded the northern Delta basis against both storm tides and salt penetration by the closing of the Volkerak and the Haringvliet far exceeds the benefits the area concerned could have derived from a four or five island plan (see introd.) As the Brielse Maas has already been closed there is therefore no reason for carrying out any further part of either of these plans. There remains, however, the question whether, with the closing of the Haringvliet, the basic hydraulic structure of the northern Delta basin has now attained its final form, or whether important modifications will still have to be made there.
The broad structure of the system of waterways in the northern basin owes its present form primarily to the natural action of river and tidal currents which moulded them over the centuries. Although there was fairly large-scale human interference on a number of occasions during the last century, it did not forcibly disturb the balance which had developed naturally. The present structure still, therefore, clearly bears the stamp of the natural interplay of currents and tides which continued relatively unhindered until recent times. But the closing of the Volkerak and, above all, of the Haringvliet has now changed the situation drastically. Tidal movements have been considerably altered by the dams at these points; what is more they can be altered at any time by changing the setting of the Haringvliet sluices. Add to this the effect of the artificial deepening of the mouth of the New Waterway and the construction of the new harbour mouth at Hook of Holland, then the question must be asked whether the old structure is suited to the new situation and whether perhaps other important corrections and alterations should be made to the river system to create a proper balance. This problem, of course, arose as soon as the possibility of closing the Volkerak and the Haringvliet was first considered as a component part of the preliminary studies for the Delta project. First and foremost there was the question of how the lower river system would react to the projected operations if left to its own devices. Would some river branches be scoured to unacceptable depths to the detriment of riparian interests and the management of fresh-water supplies over large areas? Would others perhaps suffer serious silting up with consequent damage to shipping interests? And could come some river branches be expected to have a tendency to change their course? To arrive at an answer to these questions it was not only necessary to investigate carefully what changes were likely to occur in the current patterns, but also what would be the effect of such change on the river beds of fine, shifting sand. It was thus necessary to indicate in advance to some extent where erosion and where deposition could be expected to occur as a result of these changes. Basically this was of course connected with the question as to the manner in which it would be practicable

and necessary to operate the Haringvliet sluices. After all the sluices were there to act as a safety valve and only had to be opened when the river discharge was so great that it could no longer be safely taken care of by the New Waterway and its branches. This meant considering not only the stability of the river beds, but also the safety of shipping. Luckily there was enough information available about the influence of tidal currents on sand movements in the northern Delta basin to provide clear enough answers to these questions. It proved possible on the basis of the calculations to determine the places accurately enough where erosion or deposition must be expected as a result of the building of the dams, while general forecasts were also made of the extent to which the depth would be increased or decreased. As, in general, they were expected to be of a limited nature only, there was no need to take additional measures anywhere, in advance, against erosion or silting up. It was, and still is, considered that developments can be awaited with equanimity and that remedial action can safely be left until the effects begin to appear.

One important method of combating undesired erosion is to stabilize the river bed by means of a layer of gravel, which is far more resistent to the pull of the tidal current than a bed consisting of fine sand. A layer a few decimetres thick is sufficient to keep the sand in position. Lessons can be learnt in this respect from the experience gained in the use of this material during the execution of the Delta project. Gravel is much cheaper than any other form of protective covering, and has the additional advantage that vessels can safely drop anchor in it without interfering with the protection afforded. Gravel has also already been used as a protective covering for the bottom in places in the northern Delta basin outside the Delta Project, for example in stabilizing and raising the level of the floor of the New Waterway.

A second problem was the discharge of ice. The ice which forms on large rivers during periods of hard frost can endanger river dykes when it breaks up and blocks the channel. This problem applies particularly to the Waal, which takes the majority of the discharge from the Rhine and must therefore be freed from ice obstructions as soon as a thaw sets in, to be able to carry out its function. To minimize the risk of the river dykes being breached, the ice on the large rivers must be kept floating freely as long as possible, so that it can be carried out to sea. Previously, drift ice usually reached the sea via the Volkerak. At first it was thought that the large openings in the Haringvliet would be able to take over this role from the Volkerak and thereby compensate for the disappearance of the usual exit route to the sea. Consideration was even given to the possibility of regulating the Haringvliet channel to enable the ice to get away more easily. Closer investigation and observation of the behaviour of ice floes under natural conditions, and particularly in the area concerned, showed however that the measures under consideration would not be effective enough. Present indications are that the ice from the Waal can best be discharged into the sea via the Lower Merwede and the Old Meuse. The raising of the temperature of the river – albeit at the moment only marginal – brought about by the discharge of industrial cooling water, will, in the future, reduce the risk of ice obstruction. The present view is that for this reason it will

probably not now be necessary to take special measures in the northern basin. Nevertheless, when new projects are being examined, ice discharge requirements are always taken into account when such matters as the location of bridge piers and changes in the line of the river bank are under consideration.
Various measures, some more far-reaching than others, have had to be taken to meet the requirements of shipping, especially in the vicinity of Dordrecht where the closing of the various estuaries has caused considerable alterations in the current pattern. Radical improvements have already been made in the bend at Papendrecht. An adjustment also had to be made at the confluence of the Kil-Mallegat and the Old Meuse above Dordrecht, as part of a much more extensive plan for the improvement of the course of the Kil to meet the requirements of the rapidly growing volume of shipping using this river branch. The improvement of the mouth of the Old Meuse at the New Waterway end, which involved the dredging away of Kruiteiland, was partly made necessary by the changes in the current situation, although the principal reason for the measure was the growth of river traffic.
All in all, then, only a small number of adjustments were needed to adapt the northern basin to the new water-flow situation, and to maintain the equilibrium that existed as regards the cours and depth of the rivers in the area.
The question has, however, been raised whether the present river system could be made even more suitable for water distribution and shipping by further engineering measures. Among the recommendations put forward by the Delta Commission was one for the closing of the Old Meuse by means of a moving barrier in order to secure better distribution of water when the river discharge was low. Later studies showed, however, that this would not be as effective as had at first been thought, and in particular, that it would give rise to many difficulties for shipping. This plan was, therefore, shelved for the time being, especially as the closing of the Old Meuse would have necessitated compensatory measures elsewhere in the river system, such as improvements at the confluence of the Noord, the Lek and the New Meuse at Krimpen.
The role of the Spui is still under consideration. This is a river branch of minor importance which plays a secondary role in the water movements of the northern Delta basin. However, the Spui can play a critical part in marginal situations and could tip the balance one way or the other – especially from the point of view of the water management situation, which is often very finely balanced when river discharge is low. Thus the future of the Spui is not entirely a matter of indifference. For the present, however, there are no definite plans, although the effect on the river system of closing the Spui at both ends has indeed been the subject of study. In the short term, then, no drastic changes will have to be made to the river system of the northern Delta basin as a consequence of the implementation of the Delta Project. The closing of the Volkerak and the Haringvliet has settled the water situation in the area for the time being. Other developments not connected with water control might, however, lead to new projects being undertaken in this area.

9. The effect of the closing of the Haringvliet on the mouth of the estuary and the adjoining coast

The closing of the Haringvliet and the subsequent bringing into operation of the discharge sluices means that not only will the waters of the northern Delta basin be subject to a considerable degree of artificial – i.e. human – control, but the mouth of the estuary to seaward of the dam will also be greatly affected. Previously, the tide was free to move in and out without restriction, in its characteristic fan-shaped pattern; tidal movements were mainly controlled by the fairly regular cycles of astronomical forces; meteorological factors, being essentially unpredictable, gave them a changing character without, however, altering the pattern radically. Closing the estuary has changed the influence of the tide on the area at its mouth. Out at sea beyond the estuary the tides still retain their former character, but in the estuary area itself they are now strongly influenced by new factors. The dam now prevents tidal movements to and from the area inland, which are now, in consequence, much slower; in addition, water is discharged from the sluices at irregular intervals. The times and volume of discharge are mainly determined by the river flows, principally that of the Rhine. The fact that the Haringvliet carried water from the Meuse and the Rhine to the sea was also one of the factors determining the pattern of water movements at the mouth of the Haringvliet before it was closed, and there were differences between tides at times of substantial river flows and tides when only a small quantity of river water was finding its way to the sea via the Haringvliet. Now, however, this effect has become much more pronounced, partly because the sluices are only opened during the ebb tide and the flood tide can no longer flow inland. There will be times – sometimes several months in succession – when no river water at all will be discharged through the sluices, and other times when large quantities of river water will have to be allowed to pass through. This makes the pattern of water movements in the Haringvliet less regular than before and far more dependent on fluctuations in the quantity of water from the Rhine. The extremes – no discharge at all when the sluice gates are closed and considerable flow of river water when they are fully open – are much further apart than they were before the estuary was closed. A shock effect, so to speak, is introduced.

The hydrographic situation will adapt itself to the new circumstances but in what way is not yet certain; here, too the extremes could be further apart. During periods when the sluices are opened frequently it is to be expected that a through channel to the sea will be scoured away by the current, but this channel will partially silt up again during periods when the sluices are shut. This irregularity will have an effect on both shipping and the biological environment. Certain measures may, therefore, have to be taken, or work carried out, to control the situation. In the period following the bringing into

operation of the Haringvliet sluices regular observations and extensive studies are needed to provide information for use in determining what, if any, extra measures of adaptation might be required, and what form they should take.
At the same time the effect on the adjoining coastal areas must also be studied and attention given to the relationship between the closing of the Haringvliet and the adjacent Europoort project, especially the new harbour mouth. The closing of the Brouwershavensche Gat and the Eastern Scheldt will presumably have only a minor effect on the conditions in the mouth of the Haringvliet. Meanwhile it has been found that in recent years fairly considerable changes had already taken place in the estuary area before the Haringvliet was closed, as a result of which some forecasts have had to be modified. In particular, it is to be expected that the Hinderplaat, the bar rising in the Haringvliet mouth, will move further in a seaward direction than was assumed in 1968.

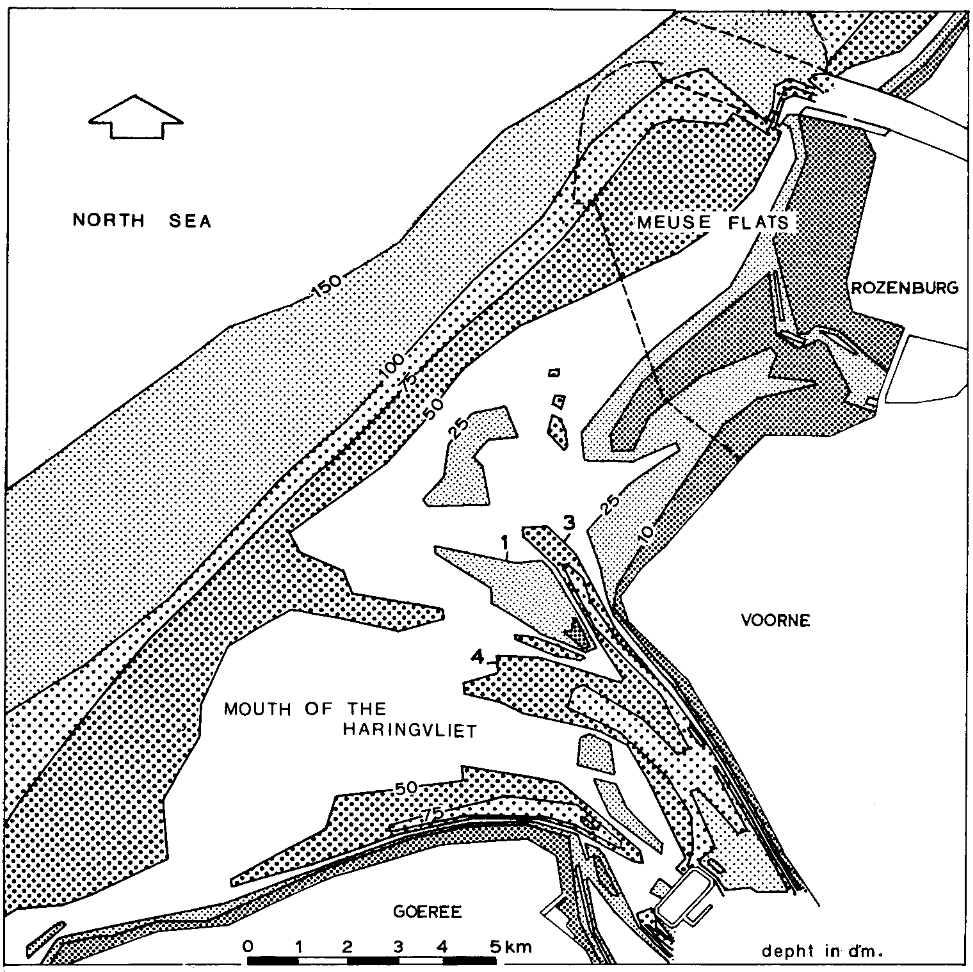
9.1. Natural developments before the closing of the Haringvliet

Since 1957 the point at which the Rak van Scheelhoek divides into the Gat van de Hawk and the Bokkegat has moved in a seaward direction. Between 1965 and 1968 the rapidity of this movement was continually increasing, but in 1969 it came virtually to a halt. The bifurcation point was then 2 to 3 kilometres away from where it had been in 1957.
At the same time the Gat van de Hawk and the Bokkegat diverged until the angle between the two channels had increased by 75°.
Meanwhile the area of the Hinderplaat was becoming shallower, changing by as much as half a metre per year over a period of several years.
Between the beginning of 1964 and the middle of 1968 6 million cubic metres of sand and mud were deposited in the raised area. The depth contour for 5 metres below N.A.P. to seaward of the Hinderplaat has hardly moved since 1956.
To the South of the Bokkegat conditions have been less liable to change. The Slijkgat remained, broadly speaking, the same. A shoal did, however, move outwards with the Bokkegat; this shoal, which was named the Garnalenplaat, gradually grew in size, and a new channel gradually developed along its southern edge. Gradual deposition has been going on in the whole estuary mouth to landward of the 10 metre N.A.P. contour line. Between 1956 and 1969 the average depth decreased by half a metre. This is equivalent to a total deposition of some 80 million cubic metres. Great changes had, therefore, occurred in the mouth of the estuary before it was closed, changes that will now be considerably accelerated. It is important that the possible ways of predicting such morphological developments should be investigated to enable some sort of forecast to be made of the future position.

9.2. The morphological development of a coastal area

The development of a coastal area is determined by the erosion, transportation and deposition of material from the bottom, i.e. of sand and mud. Transportation occurs mainly in suspension, the sand grains being swept up from the floor by the water. Bottom transportation, in which the grains move forward over the bottom, is quantitatively insignificant in comparison with transportation in suspension.
The physical processes which are involved in such phenomena have been the subject of much study, with the result that a better understanding has been gained of the influence of currents and waves on bottom configuration. However, the hypotheses postulated still frequently prove inadequate when tried out in practice, while some of

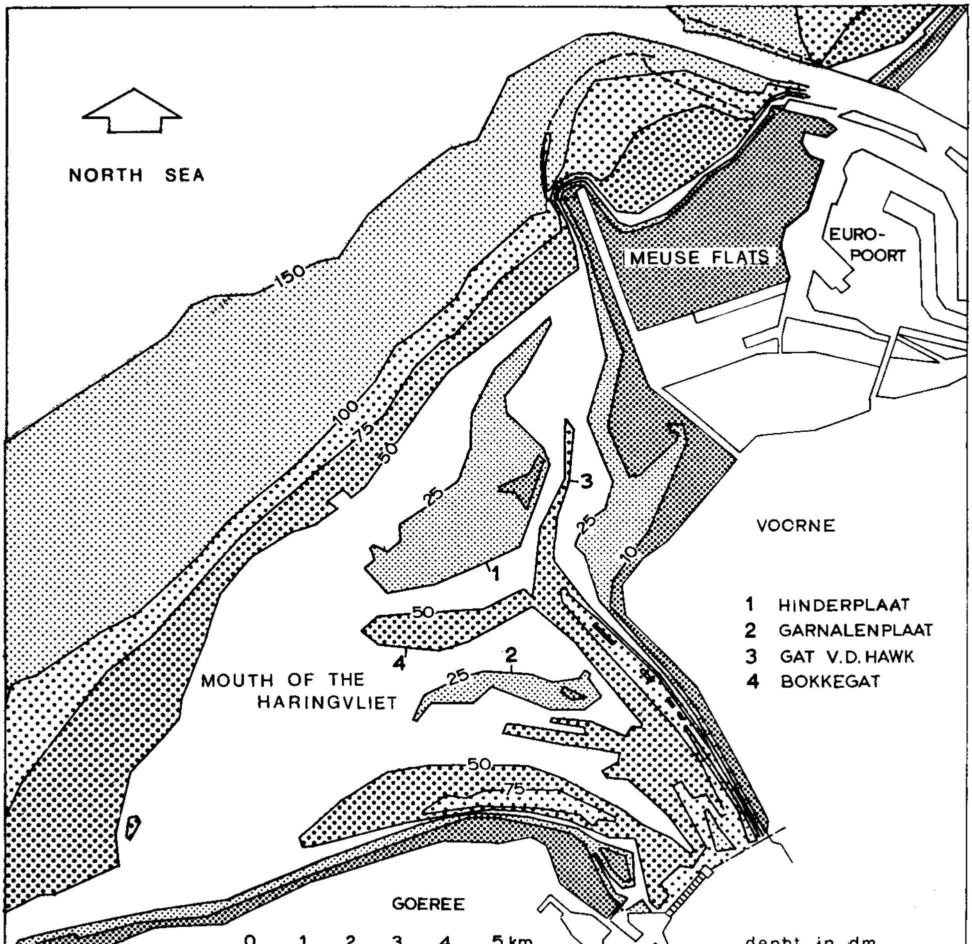
The development of channels and shoals in the mouth of the estuary between 1958 and 1969 (b)



the processes studied do not lend themselves to investigation in hydraulic models. In addition, the natural characteristics of the bottom, and the current and wave conditions influence each other, while they are liable to change continually from one place to another and in the course of time.

In order to make calculations which will be of practical value, it is, therefore, necessary to introduce simplifications and then, by actual measurements on the spot, to check whether the simplifications introduced are reliable. The importance of such measurements is beyond dispute, but there are still many technical problems attached to the methods of carrying them out. For example, it is only possible to measure the sand content of the water, and thus ascertain the volume of sand transported, in favourable weather conditions. Measurements made using radio-active tracers do

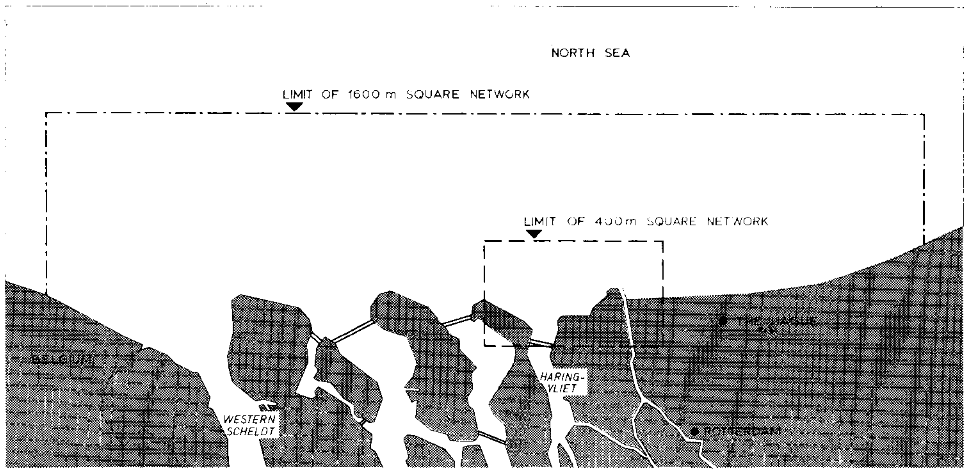
b



give some idea of the direction and volume of average sand transportation over a fairly long period, but it is still not possible to determine accurately the amount of sand transported or the relationship between the amount transported and the velocity of the current. The principal method of ascertaining the total amount of sand transported is still by regular soundings, the results of which can be compared and assessed by means of tide and wave measurements carried out at the same time. Such soundings are taken along the coast of the Delta area every three months, and even more frequently in some areas where sand movement is considerable. Meanwhile, one or two methods have been developed to enable future morphological development to be forecast. One of these makes use of the empirical relationship between the cross-section of the mouth of an estuary and the tidal volume, being based on the assumption that the type of sediment remains virtually constant. Deposition of mud instead of sand would give the floor greater resistance to erosion, and thus the cross-section for the same tidal volume would not become so large. By drawing on experience gained during earlier damming operations and on the results of tidal calculations, it is possible to make a global estimate of the area of the cross-section along a line extending to the West of, and perpendicular to the Haringvliet dam, as well as of the rapidity with which the development will take place. A second calculation method uses the Kalinske sand transport formula, which has been tested by Dutch experts for calculations in a tidal area. With this method it is possible to find indications of the changes in sand transportation likely to occur as a result of variations in tidal currents.
The calculation of sand transportation by waves however is more problematic. While a good approximation has been found for calculating the transportation along a coast caused by waves breaking on it at an oblique angle, it is doubtful whether this method is equally applicable to a shoal area like the mouth of the Haringvliet. A further complication here is the interplay of waves and tides, as a result of which the sand swept up by waves, mainly in the breaker zone, may be carried along by the tidal current. In the area where this interplay occurs only global forecasts are therefore possible, these being based on previous experience and supported by a general understanding of the subject.
Recently the calculation methods mentioned above were supplemented by important new information in the shape of the results of two-dimensional tidal calculations by the Leendertse method.

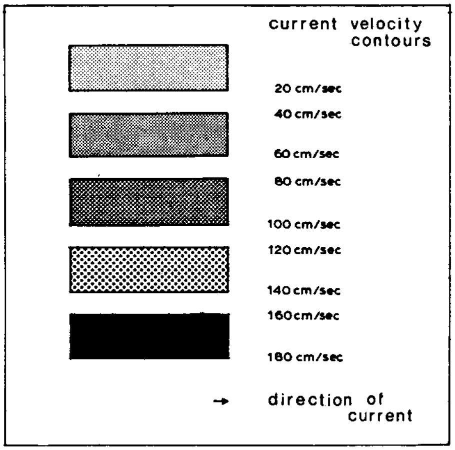
9.3. Two-dimensional tidal calculations

For the purposes of these two-dimensional tidal calculations an area is split up systematically into a large number of small squares of constant depth, where the hydraulic resistance along the bottom is either constant or dependent on the depth of water. The capacity of the computer used restricted the number of squares capable of being handled in a calculation to a maximum of 3,000. The tidal calculations for the

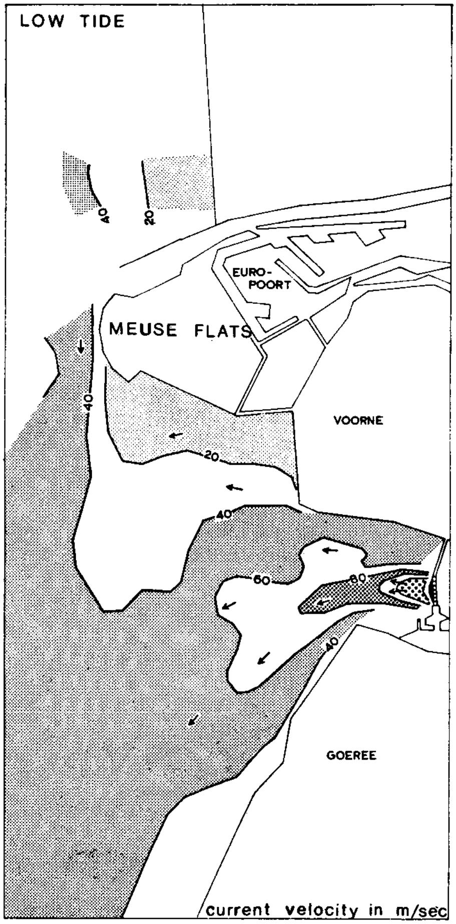


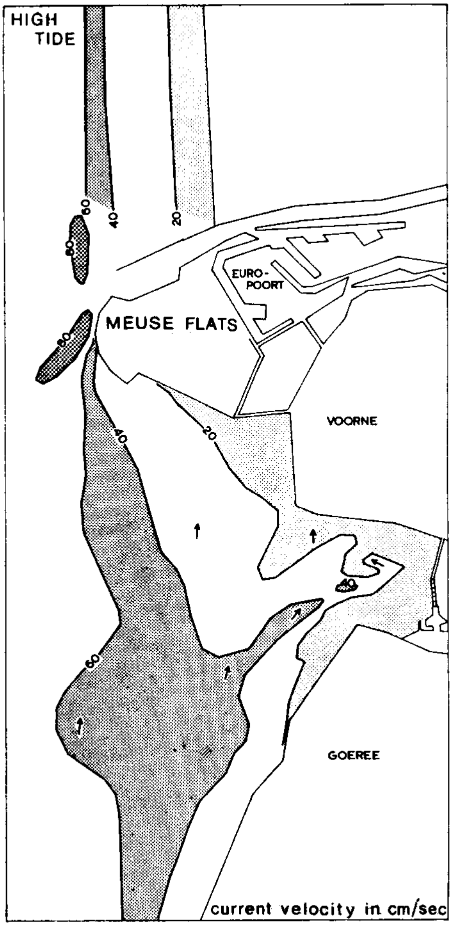
Limits of the RD and Ha models for two-dimensional tide calculations

area in question were, therefore, carried out in two stages. A start was made with a network of 1,600-metre squares in the so-called Rand-Delta, or RD, model. The sea boundaries of this model are such that the influence on it of the dam-building operations in the Delta area can be ignored. With the aid of these RD calculations, water levels and velocities were then worked out along the edge of the Haringvliet model (Ha model), covering a smaller area, which has a network of 400-metre squares. Using the Ha model, it is now possible to look into the effect of the changes taking place in the mouth of the Haringvliet in greater detail. Thus, two calculations are made for each situation – a RD and a Ha calculation. It has been found that, following the closing of the Haringvliet, the inner zone has become primarily a tidal storage area. The velocities here are so much reduced that there is nog longer any sand transportation by current. The sediment brought in by the tide is mostly deposited. In the vicinity of the Haringvliet sluices this sediment will consist mainly of mud, which will settle first of all in the deeper parts of the channels.
Velocities are dropping in the coastal area too, so that silting will take place in the Slijkgat as well as the Rak van Scheelhoek and the Gat van de Hawk. In the mouth of the estuary as a whole, up to a distance some 6 to 8 kilometres from the discharge sluices, the velocities are dropping. Sedimentation can, therefore, be expected in this area, particularly as a result of wave action.
On the seaward side, where the movement of the waves prevents the deposition of mud layers, the bottom will be built up from sand. Further in, where the effect of the waves is less, mixed layers may form.
As a result of the fall in current velocities, the shallows already in existence in this area will be built up under the influence of wave action to a more elevated area of tidal flats known as the Hinderplaat.



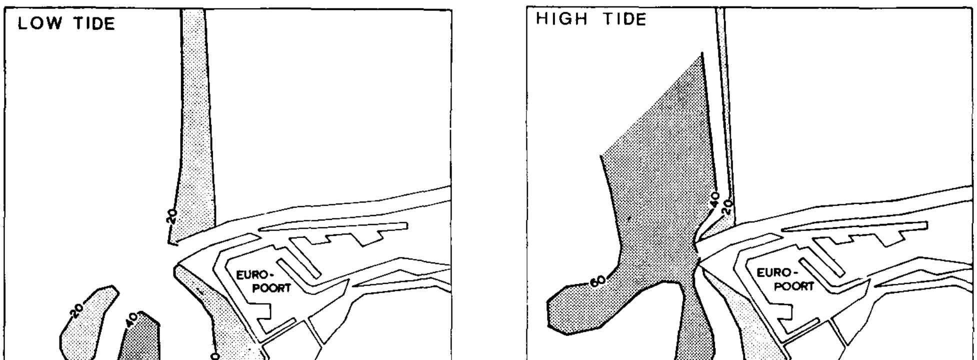
Velocity and direction of current flows in the mouth of the estuary when the sluices are discharging





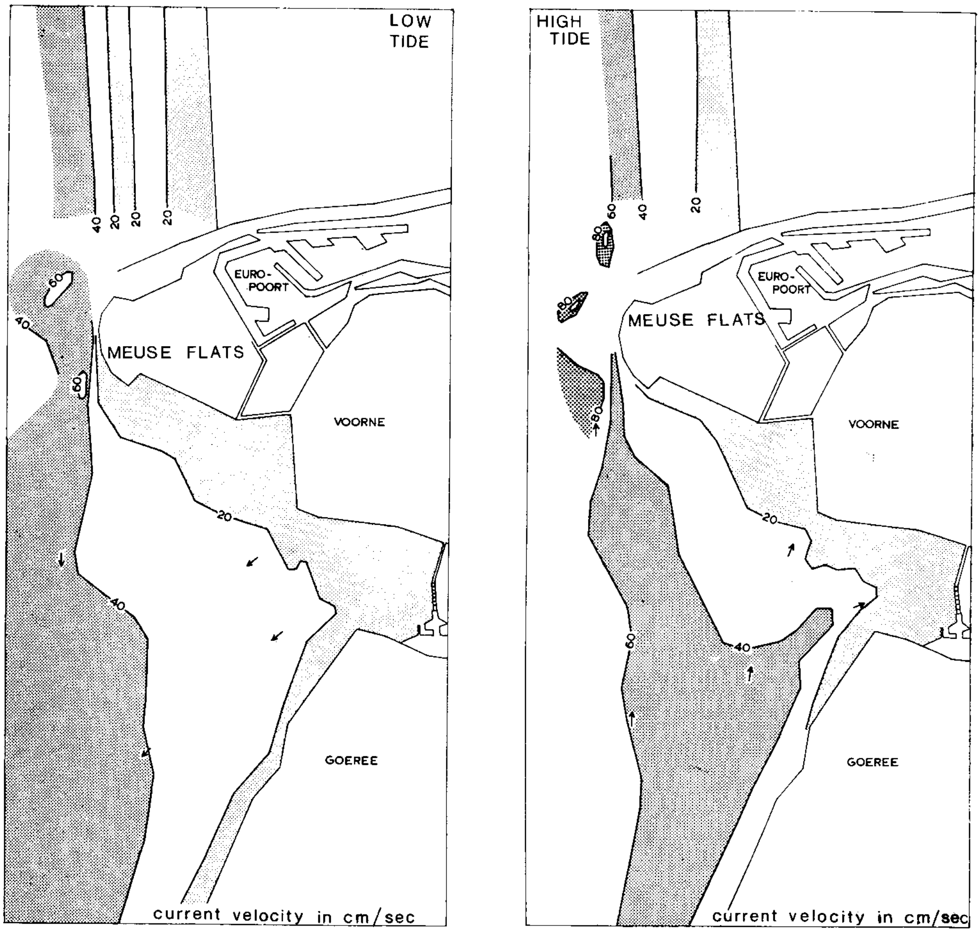
It follows from tidal calculations already made that the current velocities along the coast of Goeree, between the Flaauwe Werk and the Kwade Hoek, will be reduced when the discharge sluices are closed. No erosion of this coast is, therefore, expected to be caused by the current in the short term. The question is rather to what extent sand will be transferred from the foreshore to the channel as a result of wave action. The outcome of such a process would be some erosion of the coast until a new balance was achieved. Along the whole coastal area of Voorne wave influence will predominate over the influence of the current as long as the sluices are closed. At high or low tide the current velocities at the Groene Punt for an average tide will be virtually nil. At such times the inner zone will be filled and emptied from the Slijkgat and the Bokkegat, and the coastal area to the north-east of the Groene Punt via the Gat van de Hawk and the northern Hinderplaat area.

Current velocity and direction of current flows in the mouth of the estuary before completion of the dam



The velocities in the Rak van Scheelhoek have dropped to such an extent that mud deposits will begin to form, mainly near the Haringvliet dam. As the coast between the Haringvliet dam and the Groene Punt slopes down steeply beyond a line 2 to 3 metres below N.A.P., the levelling of this slope due to the effect of wave action could cause the coast line to recede slightly in places. However the strength of the waves along this part of the coast of Voorne will decrease as the Haringvliet becomes shallower. The higher waves in particular will then break on the shallows in the mouth. Although the developments described will take place gradually – over a period of several years – it is clear that a constant check will have to be kept on them. An extensive monitoring programme has therefore been drawn up for this purpose, which will enable prompt action to be taken should undesirable developments occur.

after completion of the dam



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