F THE DUTCH
WADDEN SEA

H. POSTMA

STELLINGEN

I

Enkele hoofdtrekken van de verdeling van kalk in diepzeesedimenten worden bepaald door de verzadigingstoestand voor calciumcarbonaat van het bodemwater.

H. Wattenberg, Fortschr. Mineral., Kristallogr. u. Petrogr., **20** (1936).

II

Variaties in de verhouding van nitraat en phosphaat in zee zijn voor een deel het resultaat van verschillend ver gevorderde oxydatie van stikstofverbindingen.

G. A. Riley, Bull. Bingham Oceanogr. Coll., **13** (1951).
F. Bernard en J. Lecal, Bull. de l'Inst. Océanogr. Monaco, **963** (1950).

III

De verhoogde concentratie aan phytoplankton in de temperatuur-spronglaag van de Noordelijke Noordzee kan zijn veroorzaakt door groei in deze laag.

J. Krey, Kieler Meeresf., **10** (1954).

IV

Het troebelingsmaximum in de beneden Elbe is het gevolg van de blokkering van de sediment-afvoer naar zee door het zoute water dat de rivier binnendringt.

H. Lüneburg, Archiv Dtsch. Seewarte, **59** (1939).

V

De bevissing van de Noordzee kan niet die invloed op de basisproductie van organische stof hebben, die door Burkenroad voor mogelijk wordt gehouden.

M. D. Burkenroad, Publ. Inst. Mar. Science, **2** (1951).

VI

Het is onwaarschijnlijk dat het uit sommige visoliën verkregen clupanodonzuur (docosapentaeenzuur) bij de destillatie uit docosahexaeenzuur zou zijn ontstaan en niet in deze oliën zou voorkomen.

E. H. Farmer en F. A. van den Heuvel, J. Soc. Chem. Ind. Trans., **57** (1938).
P. Baudart, Compt. Rendus Trav. Fac. Sciences Marseille, **1** (1941).

VII

Het IJsselmeer bevindt zich sinds de afsluiting in een stadium van toenemende eutrophie.

VIII

De bijdrage van de Theems tot de voedingsstofvoorziening van de Zuidelijke Noordzee is te gering om veel invloed te hebben op de visopbrengst van dit gebied.

K. Kalle, Ber. Dtsch. Wiss. Komm. Meeresf., **13** (1953).

IX

Het afvoeren van industrieel afvalwater naar zee is in principe even ongewenst als de lozing ervan op het binnenwater.

Adv. Gem. Groningen, N. Rott. Courant, 24-3-1954.

HYDROGRAPHY OF THE DUTCH WADDEN SEA

RIJKSUNIVERSITEIT TE GRONINGEN

HYDROGRAPHY OF THE DUTCH WADDEN SEA

A STUDY OF THE RELATIONS BETWEEN WATER MOVEMENT, THE TRANSPORT OF SUSPENDED MATERIALS AND THE PRODUCTION OF ORGANIC MATTER

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN
DOCTOR IN DE WIS- EN NATUURKUNDE AAN
DE RIJKSUNIVERSITEIT TE GRONINGEN,
OP GEZAG VAN DEN RECTOR MAGNIFICUS
JHR DR P. J. VAN WINTER, HOOGLERAAR
IN DE FACULTEIT DER LETTEREN EN
WIJSBEGEERTE, IN HET OPENBAAR TE
VERDEDIGEN OP DINSDAG 7 SEPTEMBER
1954 DES NAMIDDAGS TE 4 UUR

DOOR

HENDRIK POSTMA

GEBOREN TE ZWOLLE

Aan mijn Ouders
Aan Hans

HYDROGRAPHY
OF THE DUTCH WADDEN SEA

A STUDY OF THE RELATIONS BETWEEN WATER MOVEMENT, THE TRANSPORT OF SUSPENDED MATERIALS AND THE PRODUCTION OF ORGANIC MATTER

by

H. POSTMA
(Zoological Station, Den Helder, Netherlands)

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I. Introduction

III. Distribution and transport of suspended matter

IV. The cycle of organic matter

I. INTRODUCTION

1. DEVELOPMENT AND PURPOSE OF THE INVESTIGATION

This paper is concerned with the hydrography of part of the Dutch Wadden Sea. During recent years coastal waters and more especially estuaries have received much attention. One reason is the increased economic and social importance of these areas, which made a better knowledge of their hydrographic conditions desirable; the other reason is the advance of marine science, which contributed to an increased theoretical interest in estuarine problems.

The present investigation has been stimulated by biological work carried out by the Zoological Station at Den Helder. The chief line of research of this institution is the ecology of marine animals, which requires a profound knowledge of their environment. Bottom structure, tidal movements, temperature and salinity are among the outstanding factors regulating the distribution of these animals; the availability of organic matter and, indirectly, of nutrient salts, determines their potential growth.

Therefore, many data about these hydrographical elements (including bottom structure) have been collected over a number of years. A study of water movement and the distribution of salinity and temperature has already been published (Postma and Verwey, 1950; Postma, 1950). The seasonal variation of nutrients in the harbour of Den Helder was studied by Scheele and Verwey (unpublished). The composition of suspended matter has been analysed by Scheele at the request of the "Rijkswaterstaat", who were interested in this subject for reasons of land reclamation.

There is a close interrelation between the above-mentioned subjects, which makes it difficult to study them separately and renders it valuable to discuss them as a whole. Above all, knowledge of water movement is fundamental. Without this knowledge it is impossible to study matters of transport, to understand the reason for the actual composition of suspended matter, and to investigate the cycle of nutrients. Moreover, a study of nutrients must remain incomplete, if we do not consider how they affect the suspended organic material.

The above subjects will therefore be discussed here simultaneously, and stress will be laid on their interdependence. Chapter II is concerned with *water movement*, chapter III with the *transport and distribution of suspended matter*, and chapter IV with the *seasonal cycle of nutrients and organic matter*.

1. In studying *water movement*, the exchange of water between the

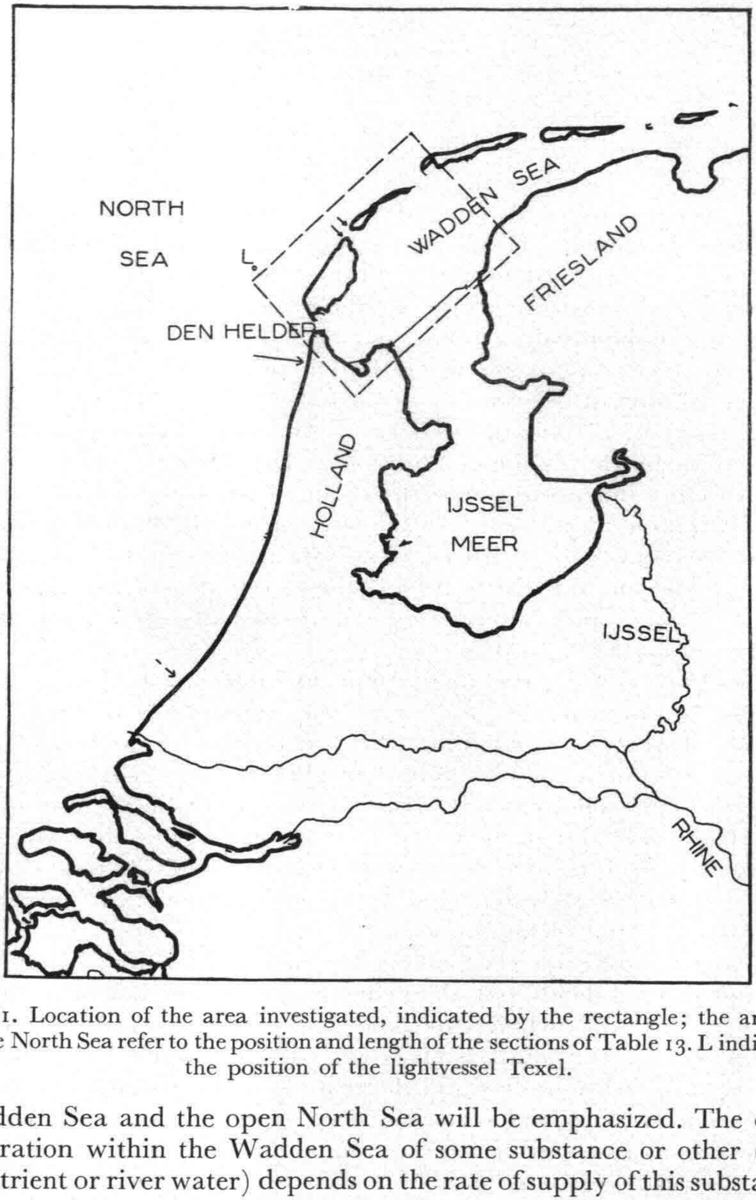

Fig. 1. Location of the area investigated, indicated by the rectangle; the arrows in the North Sea refer to the position and length of the sections of Table 13. L indicates the position of the lightvessel Texel.

Wadden Sea and the open North Sea will be emphasized. The concentration within the Wadden Sea of some substance or other (e.g. a nutrient or river water) depends on the rate of supply of this substance from, for instance, the main land, and the rate of exchange between the Wadden Sea and the North Sea. The greater this exchange, the more important will be the influence of the North Sea on the Wadden Sea. An attempt will be made to find a quantitative measure for this rate of exchange.

2. As regards *suspended matter*, superficial observations already show that the water of this region is very turbid. This becomes especially clear when the area is compared with the open North Sea. In the Wadden Sea a white disc, lowered into the water, is only visible to a depth varying between 0.5 and 5 meters, whereas the visibility in the North Sea mostly extends to ten meters or more. Exact measurements in many different parts of the Dutch, German and Danish Wadden Sea have confirmed that large quantities of material are present in suspension. In chapter III an attempt will be made to explain the presence of these large quantities of suspended matter. In this connection knowledge of the water exchange between Wadden Sea and North Sea is indispensable.

3. As part of the suspended material the *organic matter* is naturally subject to the same laws of transport as the suspension itself. The cycle of nutrient salts and the production of organic matter will be discussed in chapter IV. It will appear that a distinction must be made between the production of organic matter within the Wadden Sea itself, and the exchange of organic matter and nutrients between the Wadden Sea and North Sea. It goes without saying that here again knowledge

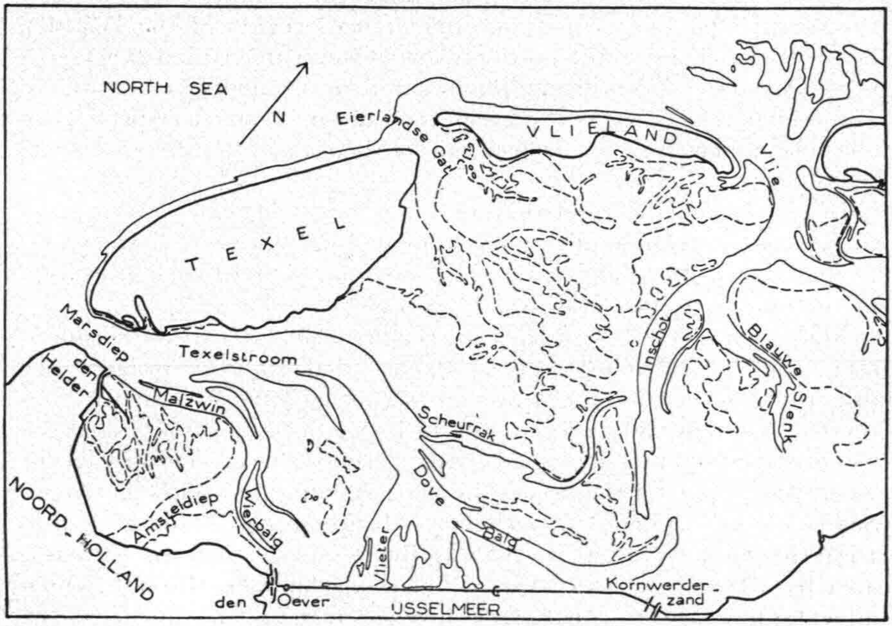

Fig. 2. Map of the western part of the Dutch Wadden Sea; intertidal flats are enclosed by dotted lines of Mean Low Water.

of the rate of water exchange is of primary importance. Of the various nutrients especially phosphorus was studied in detail.

I owe many thanks to Dr. J. VERWEY, director of the Zoological Station, for his stimulating interest taken in my work and his valuable advice. Thanks are also due to Prof. Dr. G. P. BAERENDS for his critical reading of the manuscript. The analyses of the large numbers of samples would not have been possible without the assistance of Miss E. GROEN, Mr. N. PIJL and Mr. A. DRAL. The manuscript and the tables were typed carefully by Miss T. STOLL. To Mr. J. SPIEKERMAN, den Helder, I am greatly indebted for his thorough correction of the English text.

2. DESCRIPTION OF THE AREA INVESTIGATED

Viewed as a whole the Wadden Sea is an oblong coastal sea, on one side bounded by the continental coast, on the other separated from the North Sea by a chain of islands. Its total length from Den Helder, Holland, to Esbjerg, Denmark, amounts to several hundreds of kilometers, whereas the distance between the coast and the islands is only some dozens of kilometers.

Between the islands several tidal inlets form the connection with the North Sea. Every inlet supplies a small region of the Wadden Sea with water. From the point of view of water movement every area is well separated from its neighbours and can therefore be considered an independent unit. As the areas are similar in many respects conclusions gained from research in one of them can often be applied to the others.

In every area the tidal inflow and removal of water takes place through a rather complicated system of tidal channels and creeks. Going inward the channels decrease in capacity until they gradually merge into large tidal flats (Wadden).

Many parts of the Wadden Sea receive fresh water from the mainland, some of them in large, others in small or even insignificant quantities. Generally speaking, the salinity of the Wadden Sea is therefore considerably lower than of the North Sea.

The investigations here dealt with were chiefly carried out in the westernmost part of the area. This part is connected with the North Sea by the tidal inlet of Den Helder (Marsdiep, figs. 1 and 2). Up to 1931 the Zuiderzee – as it still was then – was connected with this area by a broad open expanse of flats and channels, through which all water flowing into and leaving the Zuiderzee under influence of the tides passed. The course of the channels reminds us even at the present day of that state of affairs. In 1931 the Zuiderzee was closed off by a heavy dike, the "Afsluitdijk", which turned it into the "IJsselmeer". The Afsluitdijk thus forms the boundary of the area under discussion.

Fresh water from the IJsselmeer enters the Wadden Sea at low tide through two sets of sluices, situated at either end of the Afsluitdijk near Den Oever and Kornwerderzand. The IJsselmeer in its turn receives most of its fresh water from the IJssel, a distributary of the Rhine. Smaller quantities of fresh water reach the Wadden Sea through locks near Den Helder and at two points on the Frisian coast. Numerical data about the tidal movements and volumes of water are given in table 1. The transport of water under influence of the tide is very considerable; as compared with the total quantity present in the area, the supply of fresh water is comparatively small. The area is on the average very shallow, although depths up to 30–50 m occur in the tidal inlets.

TABLE I

Numerical data of the Marsdiep area; compare fig. 2.

1. Total area covered	0.69	$\times 10^9$ m^2
2. Dry at mean low water (M.L.W.)	0.15	$\times 10^9$ m^2
3. Average depth at mean sea level (M.S.L.)	3.9	m
4. Water volume at M.S.L.	2.7	$\times 10^9$ m^3
5. Average tidal amplitude at Den Helder.	1.35	m
6. Water volume at mean high water (M.H.W.)	3.1	$\times 10^9$ m^3
7. Water volume at M.L.W.	2.2	$\times 10^9$ m^3
8. Water volume entering the area through the Marsdiep with the flood and leaving with the ebb.	0.93	$\times 10^9$ m^3
9. Average discharge per tide of fresh water from the IJsselmeer (1949, 1950, 1951)	16.8	$\times 10^6$ m^3
10. Fresh water discharged at Den Oever	10.3	$\times 10^6$ m^3
11. Fresh water discharged at Kornwerderzand	6.5	$\times 10^6$ m^3
12. Average discharge per tide of fresh water at Den Helder	0.8	$\times 10^6$ m^3

Remarks: 1, 2, 3: derived from a chart of the Dutch Hydrographic Office; 5: from tables of the Rijkswaterstaat; 9: unpublished measurements of the Rijkswaterstaat; 10, 11: data from the Dienst Zuiderzeewerken; 12: data from the Provinciale Waterstaat van Noord Holland.

The bottom of the larger part of the area consists of sand; mud is only found in sheltered places, for example on tidal flats near the coast and in some dammed-up channels, compare p. 68.

3. SAMPLING AND ANALYSES

Several thousands of water samples have been taken over the whole area of investigation, the larger part of them between Den Helder and Den Oever.

Generally speaking, surface samples were taken with a galvanised iron bucket. In the case of samples to be analysed for suspended matter, a special water bottle was used (see below), because when a bucket is used particulate matter easily sinks down before the water is transferred to a bottle.

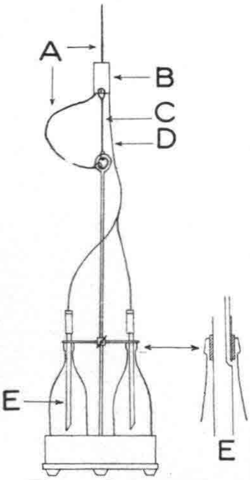

Fig. 3. Sampler for suspended matter.

Surface temperature was determined immediately after sampling with a frameless and verified thermometer divided into tenths of centigrades. Reading was accurate up to about 0.03° C; for series of observations the relative accuracy was about 0.02° C.

For subsurface samples, except for those to be analysed on suspended matter, the well-known Nansen reversing water bottle with reversing thermometers was used; the temperature readings are accurate up to about 0.01° C. Samples for determining the quantity of suspended matter were obtained with a simple water sampler of our own design (fig. 3), by means of which the sample bottles, lowered into the water, were filled on the spot.

This sampler for particulate matter works as follows. It is lowered into the sea on a steel wire (A), which is provided with a tripping mechanism (B). Bij means of a so-called messenger, lowered along the steel wire, a short rope (C), connecting the sampling apparatus (E) with B, is released from B. E drops down until the slack lower loop of A is taut. The drop stretches a third line D connecting B with the rubber hoods closing the bottles, so that the hoods are torn off. Water flows into the bottles through a long and wide tube, and the air escapes through a short narrow one; the filling of the bottle requires only a few seconds. When being pulled up, the instrument is not closed; nevertheless, no appreciable quantity of suspended matter "rains" into the bottles during that period.

The instrument functions properly at least to a depth of about a hundred fathoms.

The samples were analysed in the laboratory. The various processes of determinations will be discussed hereafter. Special attention will only be given to some newly developed or modified methods.

A. *Salinity* (Chlorinity)

A. *Salinity* (Chlorinity) was determined according to the wellknown Mohr-Knudsen method for sea water, modified by Van Dam (1940). In this modification the Knudsen pipette of 15 cm^3 was replaced by Van Dam's micropipette with a volume of about 1 cm^3. The silvernitrate solution was diluted accordingly.

The procedure has the advantage of being faster than the standard one without being less accurate. Accuracy has been maintained by using potassium chromate in the same quantity as in the standard procedure. This means a higher concentration of chromate at the end point of the titration, the volume being only half as large. Therefore, the solubility product of silver chromate is easily attained after the precipitation of chloride has been completed. Moreover, at the end point of the titration the quantity of silver chloride is much smaller than is the case in the standard method; the delay of colour change caused by absorption of chloride ions at the precipitate is therefore probably shorter.

B. Suspended matter

a. *Quantitative determination.* Suspended matter was separated from the water by filtration under suction. Ash-free filter discs with a diameter of 5 cm and of normal gradation (SCHLEICHER and SCHÜLL, nr. 589) were used. Compared with very fine-grade filterpaper 3 % at the utmost of the suspended matter was lost in passing through the filter. This was considered to be a negligible quantity. A greater loss occurs in fresh water, so that fine-graded filter paper had to be used here. In this case the filtration of one litre of water sometimes took many hours; the same volume of seawater is easily filtered within a quarter of an hour. Since very many samples had to be analysed rapid filtration was essential and a small loss of suspended matter had to be accepted.

The dry weight of the suspended matter was determined as follows. Before use the filter discs were dried at 110–120° C and weighed. The hygroscopy of the filter paper necessitated precautions against a gain in weight, by weighing in a closed glass vial. After filtration the discs were cleared of salt with fresh water, dried at 110–120° for more than 3 hours, and weighed again. The results are reliable up to about 1 mg/l. The accuracy of the method was checked regularly.

Before filtration, the suspended matter was mostly separated into a heavy and a light fraction. Separation was carried out by means of a method devised by N. PIJL, analyst at the Zoological Station (fig. 4, table 2). The sample to be analysed was transferred from the sample bottle into a strong separation funnel of one litre. A slowly rotating stirrer, performing about one revolution a second, prevented attachment of suspended matter to the glass, and kept the light material in suspension. The heavy fraction settled down and was removed from the bottom of the funnel together with a small volume of water by opening the tap for a moment. The light fraction was removed afterwards with the remaining water.

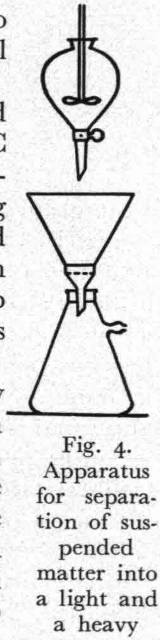

Fig. 4. Apparatus for separation of suspended matter into a light and a heavy fraction

This stirring at the rate of about one revolution a second resulted in a division at a grain size of 40–60 microns. This may seem to be a somewhat arbitrary size limit, since in soil analyses clay is customarily defined as the fraction below 16 microns. Separation of the material at this grain size would therefore have given more generally comparable results. In the Wadden Sea, however, most clay and other particles combine to form floccules larger than 16 microns. Our interest was in the first place directed towards problems of transport of suspended matter and not to its chemical and mineralogical composition. It was therefore necessary to separate the material into two fractions without breaking down these floccules. All material behaving like sand grains larger than 40–60 microns, hereafter to be called *sand*, actually proved to consist mainly of sand. Below 40–60 microns sand played only a secondary rôle and most of the material consisted of clay, iron oxide, remains of peat and shells, and organic matter. This fraction will be called *silt*.

TABLE 2

Accuracy of the determination of sand and silt.
Duplicate samples from the harbour of Den Helder.

nr. Sample	*Sand, mg/l*			*Silt, mg/l*		
	I	*II*	*difference*	*I*	*II*	*difference*
1	6.1	6.5	0.4	41.1	40.3	0.8
2	5.8	6.1	0.3	39.1	38.2	0.9
3	4.1	4.7	0.6	38.9	40.6	1.7
4	3.4	4.5	1.1	23.3	21.8	1.5
5	2.3	2.8	0.5	22.3	20.1	2.2
6	6.6	7.4	0.8	39.0	39.9	0.9
7	5.8	5.8	0.0	40.2	38.1	2.1
8	9.7	10.8	1.1	51.3	51.3	0.0
9	8.9	9.9	1.0	49.7	51.7	2.0
10	7.2	7.4	0.2	51.5	50.2	1.3
11	7.3	8.8	1.5	39.3	38.5	0.8
12	5.3	5.7	0.4	35.0	34.8	0.2
13	3.1	3.1	0.0	20.1	21.8	1.7
14	3.8	4.1	0.3	22.9	20.0	2.9
mean:			0.6			1.4

When checked under the microscope, the separation actually effected in the apparatus proved to be sufficiently complete. Some sand grains larger than 40–60 microns were often found in the silt fraction, but in negligible quantities.

The separation of the material into sand and silt had to take place within 48 hours after sampling. Further delay was undesirable because of the decomposition of organic matter and the tendency of silt particles to become stuck together or adhere to the glass of the bottle.

b. *Chemical composition of the inorganic part.* Attention to the chemical composition of the material in suspension is in this paper given only in so far as organic matter is concerned. The composition of the latter is dealt with in chapter IV. A chemical analysis of suspended organic matter, however, is only possible if also the composition of the inorganic part is quantitatively known, since the inorganic components, for example carbon dioxyde, may influence the results.

Determinations by Scheele provide some information in this respect. They only refer to material collected in the harbour of Den Helder. Analyses of suspended matter from other parts of the Wadden Sea now in progress provide evidence, however, that these determinations are roughly representative of the Wadden Sea as a whole. Scheele's data, which have been published by Verwey (1951), are summarized in table 3.

TABLE 3

Chemical composition of the inorganic part of suspended matter after ignition according to determinations obtained by Scheele in the harbour of Den Helder; Verwey, 1952, p. 186.

Depth	*SiO_2*	*CaO*	*MgO*	*Al_2O_3*	*Fe_2O_3*	*Total*
0.5 m above bottom (June 2, 3, 7, 8 and 9, 1938)	62.98	10.21	0.42	6.80	19.66	100.07
1 m below surface (June 21, 22, 23, 24, 27, 1938)	42.69	6.83	1.41	6.53	38.48	95.94
1 m above bottom (October 21, 1938)	75.6	12.8	trace	2.82	7.65	98.87
1 m below surface (October 21, 1938)	68.8	21.8	0.2	4.21	2.93	97.76

The main components are: silicate (sand and clay), iron oxide, shell sand (chiefly $CaCO_3$, some $MgCO_3$), and organic matter. Of these components clay and iron oxide may interfere with certain determinations of organic matter by loss of combined water at high temperatures; shell sand may lose carbon dioxide.

c. *Suspended organic matter.* Two different methods were followed to determine the quantity of organic material in suspension. This was necessary since both methods have their disadvantages and in this way one method could be checked with the other.

A very simple, but rather inaccurate way to determine the quantity of organic matter is by *loss of weight on ignition.* The inaccuracy is caused by simultaneous loss of carbon dioxide and water. Carbon dioxide can be determined by quantitative carbonate analyses, or removed by an acid before ignition. The first method was preferred, since the acid may also react with part of the organic matter. Filtration with 0.05 n hydrochloric acid proved to give sufficiently accurate results. Checks were carried out on some pieces of shell to make sure that ignition over a Bunsen burner removes carbon dioxide completely. – Unfortunately, loss of combined water during ignition cannot be ascertained easily, but this loss probably did not influence the results to any considerable extent (see below).

The most accurate method for the determination of organic matter is by *elementary analysis*. This procedure moreover provides information on the chemical composition of the organic matter, as it gives the proportions of some of the principal elements present. Analyses were made for carbon, nitrogen and phosphorus. However, the method is too elaborate to be used for many hundreds of samples and could therefore be applied only to a few of them. Carbon was determined according to Ter Meulen and Heslinga (1927), nitrogen by a micro-Kjeldahl method (catalyst $HgO + K_2SO_4$; Reith and Wansink, 1947; Bouman, 1949). The method of phosphorus determination will be discussed separately hereafter (part C).

A number of determinations are collected in table 4. Comparison of the vertical columns, indicating respectively organic matter determined by loss through ignition and by carbon analyses, shows that both methods give about the same results. It may therefore be concluded, that determination of organic matter by ascertaining the loss through ignition, and subtracting the loss of CO_2, produces more or less reliable values.

The data on nitrogen and phosphorus and the relation between C, N and P will be discussed on p. 71.

C. Phosphorus

For phosphate determinations the well-known colorimetric method of Denigès-Atkins (compare Harvey, 1948) was followed. In some cases a modification developed by Buch and Ursin (1948), especially suitable for brackish water, was used. According to this method all necessary reagents, with the exception of the reducing reagent stannochloride, are added to 100 ml of the sample. Before addition of the latter the phosphorus molybdate complex is transferred into 20 ml ethyl acetate by shaking twice in a separator. Reduction of the compound and development of the blue colour takes place in the acetate solution. The method is of special advantage in polluted sea water, since most pollutants are insoluble in ethylacetate. An undisturbed development of the blue colour is obtained even in fresh or brackish water coloured yellow by humic compounds. A second advantage of the method is that the phosphate of a 100 ml sample is concentrated to 20 cc, and the blue colour is more intensive accordingly. Another ad-

TABLE 4

Chemical composition of suspended organic matter. Surface samples of 10 l.

Nr. sample	*Date*	*Nr. Station*[1]	*Suspended matter, mg/l*	*A Carbonate (CO_2), mg/l*	*B Loss on ignition, mg/l*	*B-A Organic matter, mg/l*	*Organic matter, calculated*[2], *mg/l*	*Carbon, mg/l*	*Nitrogen, mg/l*	*Phosphorus, mg/l*	*C:N:P*
1	15-11-1950	17	30.7	2.2	7.4	5.2	4.7	2.0	—	0.061	33 : — : 1
			30.9	2.5	7.6	5.1	4.1	1.8	0.37	0.035	51 : 10.6 : 1
2	15-11-1950	9	43.6	3.4	8.8	5.1	5.0	2.2	0.39	0.051	43 : 7.7 : 1
			—	—	—	—	4.8	2.1	0.42	0.072	29 : 5.8 : 1
3	15-11-1950	1	60.5	4.2	8.6	4.4	4.6	2.0	—	0.036	55[5]: — : 1
			55.3	3.8	10.1	6.3	6.0	2.6	0.41	0.072	36 : 5.7 : 1
4	18-11-1950	Den Helder Harbour	23.8	1.8	5.7	3.9	3.7	1.6	0.31	—	
			27.7	2.1	6.3	4.2	3.2	1.4	0.26	0.032	44 : 8.1 : 1
5	20-1-1951	1	29.0	2.3	4.6	2.3	2.1	0.91	0.13	0.023	39[5]: 5.7 : 1
			24.7	2.6	5.7	3.1	3.0	1.3	0.32	0.048	27 : 6.7 : 1
6	20-1-1951	S. Texelstroom	16.3	1.6	4.2	2.6	2.8	1.2	—	—	
			12.8	1.3	3.4	2.1	2.4	1.05	0.21	0.019	55 : 11.0 : 1
7	13-2-1951	1	18.0	2.1	5.2	3.1	2.3	1.0	0.17	0.026	38[5]: 6.5 : 1
			12.8	1.1	3.1	2.0	2.2	0.96	0.18	0.021	46 : 8.6 : 1
8	13-2-1951	17	36.5	3.0	5.8	2.8	2.0	0.87	—	0.023[5]	37 : — : 1
			45.7	2.8	5.9	3.1	2.8	1.2	0.19	0.041	29 : 4.6 : 1
Average											40 : 7.4 : 1

[1] The numbers refer to the stations of fig. 13. [2] Calculated from carbon by multiplying with the factor 2.3.

vantage is that a small size colorimeter can be used for the determinations, whereas the original method requires exceptionally long colorimeter tubes.

Organic phosphorus was determined on the lines laid down by HARVEY (1948) by autoclaving the samples for six hours with sulfuric acid. HARVEY's original procedure was modified in some respects. Samples of 25 ml instead of 67 ml were used. This small volume was sufficiently large for an accurate determination since the phosphorus concentration of the area investigated appeared to be considerably higher than in the English Channel, where HARVEY collected his samples. The same quantity of sulfuric acid was added as prescribed by HARVEY (1 ml conc. H_2SO_4, 1 : 1). The higher concentration of sulfuric acid in the sample can only have accelerated the decomposition of organic phosphorus to phosphate; it was found that the end point of decomposition was attained within three hours.

The samples were analysed with and without the removal of suspended matter by filtration. The difference in phosphate content between the two analyses gives the phosphorus content of the particulate material. The reliability of the method was tested by filtering some samples through filters covered with a precipitate of bariumsulphate. The suspended matter retained by the precipitate was analysed separately, and the quantity of phosphate found was compared with the difference in phosphorus between the unfiltered sample and the filtered one (table 5). Both analyses gave about the same results and the methods followed are therefore considered to be reliable.

TABLE 5

Accuracy of the determination of total phosphorus. Duplicate analyses (I and II) of samples from the Marsdiep; chlorinity ± 17.5 $^0/_{00}$.

Nr. sample	*A. Total P, μg-at/l*			*B. Dissolved P,*[1] *μg-at/l*			*A-B*[2]		*Particulate P,*[3] *μg-at/l*	
	I	*II*	*Difference*	*I*	*II*	*Difference*	*I*	*II*	*I*	*II*
1	3.16	2.98	0.18	0.85	0.78	0.07	2.31	2.20	2.16	2.41
2	2.11	2.03	0.08	0.96	1.02	0.06	1.15	1.01	1.18	1.26
3	2.14	1.96	0.18	0.96	1.08	0.12	1.18	0.88	1.13	1.21
4	1.87	1.83	0.04	1.13	1.00	0.13	0.74	0.83	0.78	0.62
5	1.82	1.71	0.11	1.02	0.86	0.16	0.80	0.85	0.81	0.75
6	1.82	1.70	0.12	0.93	0.81	0.12	0.89	0.89	0.84	0.71
7	1.76	1.70	0.06	0.83	1.01	0.18	0.93	0.69	0.95	0.87
8	1.73	1.62	0.19	0.98	1.13	0.15	0.75	0.39	0.60	0.76

[1] Including phosphate. [2] Particulate P, determined by subtracting B from A. [3] Particulate P, directly determined from suspended matter after destruction with conc. H_2SO_4.

As will be discussed in chapter IV of this paper, the phosphorus content of the particulate material is considered to be a rough measure for the quantity of organic matter present, the phosphorus percentage of organic matter being more or less constant. The possibility cannot be excluded, however, that part of the suspended phosphorus is present in an inorganic state, for example as iron phosphate.

Harvey (1937, 1948) determined the dissolved phosphate content of a turbid sample of coastal North Sea water before and after removal of the particulate matter. He found respectively 0.35 and 0.12 µg-at/l of phosphate and suggested that the difference was due to particulate inorganic phosphorus dissolved by the acid reagent.

In the English Channel Cooper (1948) found a relation between "abnormal" phosphate values (values much higher than those of the other samples of the same series) and the presence of particulate iron. On theoretical grounds he assumed that iron phosphate is preferably formed in a slightly acid environment, for example in the guts of animals, and brought into the seawater in the form of faeces.

In view of these assumptions the Wadden Sea should be a favourable environment for the formation of iron phosphate. Iron hydroxide is found in large quantities in the water as well as in the bottom and there is a dense population of bottom animals, especially molluscs. According to our own determinations a water sample, containing 30–40 mg/l of suspended matter, shows a difference of 0.20–0.40 µg-at/l if treated with acid before or after filtration. If this quantity were actually present in an inorganic state, the inorganic fraction would include a considerable part of all particulate phosphorus present.

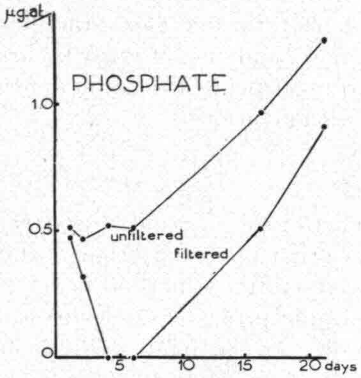

Fig. 5. Phosphate changes occurring in a water sample stored in the dark; one part has been stored with suspended matter, the other without. The unfiltered part contained about 50 mg/l of particulate material, including about 8 mg of organic matter.

In part IV of this paper it will be shown, however, that the organic carbon–phosphorus relation of the particulate matter is comparable with the relation generally accepted for phytoplankton. Moreover, in the same section evidence of a distinct seasonal variation of particulate phosphorus, which runs parallel with the cycle of organic matter, will be supplied. Both observations do not point to an important rôle of suspended inorganic phosphorus. It would seem that Harvey's suggestion, that all phosphate released from suspended matter by a short treatment with acid is of inorganic origin, is open to question. Perhaps part or even most of the phosphate is the product of easily hydrolysed organic phosphorus. This point deserves further investigation.

Phosphate and phosphorus determinations were as a rule made immediately after sampling. Therefore, no measures against decomposition of organic material were taken. The rate of decomposition in summer (temperature 17° C) appears from fig. 5. The samples were kept in closed bottles in the dark. It is interesting to note the difference between the filtered sample and the unfiltered one. In the first bottle the phosphate content rapidly decreased to zero, after which an increase took place. According to RENN (1937) this phenomenon can be explained by assuming intensive absorption of phosphate by bacteria during the first few days of storage. After this period the number of bacteria decreases and part of the phosphate is regenerated. – In the second case it must be assumed that mineralisation of phosphorus from suspended organic matter prevented the decrease of the phospate concentration.

D. Chlorophyll

Part of the suspended matter consists of living or dead phytoplankton or other plant material, containing chlorophyll. For the determination of the latter a method developed by KREY (1939) was used. A ten litre sample proved to be more than sufficient for an accurate determination, also in winter when the chlorophyll concentration is low. The suspended matter collected on a filter disc of normal hardness was dried and weighed, and chlorophyll was extracted by means of methyl alcohol (15–45 ml). The extraction mostly took place overnight.

The chlorophyll content of the extract was determined by means of a spectrophotometer at a wave length of 6660 Å and a spectral width of 200 Å. For standardization chromatographically pure chlorophyll *a* (Sandoz, Basel) was used. The pure chlorophyll was kindly supplied by Dr. J. B. THOMAS of the Biophysical Research Group at Utrecht.

II. HYDROGRAPHY; THE EXCHANGE OF WATER BETWEEN WADDEN SEA AND NORTH SEA

The main purpose of this chapter is to arrive at an estimate of the water exchange between Wadden Sea and North Sea. The calculations will be based on salinity figures and the quantities of fresh water supplied by the IJsselmeer. For the study of salinity the papers published by VERWEY and the author in 1950 could serve as a starting-point. It is proposed to follow up a summary of these papers by new observations.

Although not in open communication with a river the Wadden Sea can be considered an estuary. Therefore, the general principles of water movement in estuaries will be discussed first. Next, these principles will be applied to the Wadden Sea itself. The knowledge of water movement obtained in this way will be used to study the transport of IJsselmeer water through the area under consideration to the North Sea. It will be shown how the rate of water exchange can be computed from this transport. The system of calculation followed is generally applicable to well mixed estuaries.

I. DISTRIBUTION OF SALINITY AND TEMPERATURE

In the Wadden Sea tidal currents continuously transport large volumes of water. This transport in itself is enough to cause considerable changes in the distribution of salinity or other variables from moment to mo-

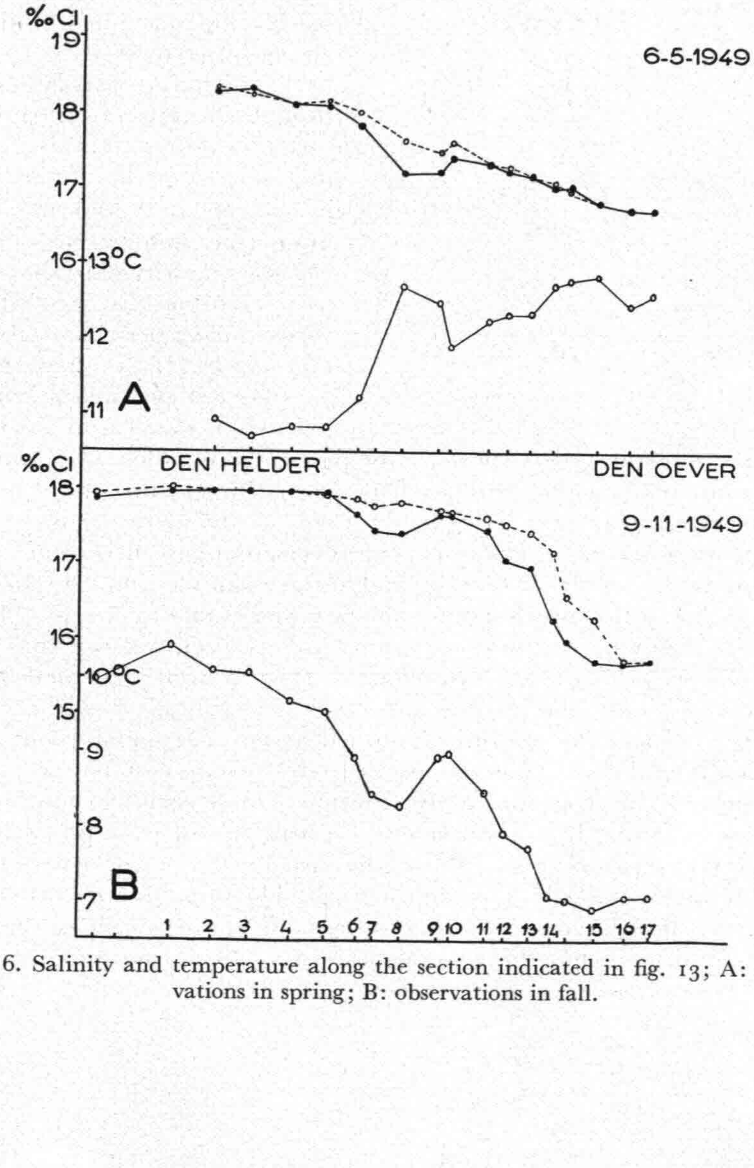

Fig. 6. Salinity and temperature along the section indicated in fig. 13; A: observations in spring; B: observations in fall.

ment. Water temperatures, moreover, vary as a result of warming and cooling, and salinity varies in consequence of variations in the supply of fresh water.

Changes in air temperature are followed by the water more closely in shallow than in deep areas. Therefore, in periods of rising temperature (Febr.–August) the water temperature increases in proportion as one moves from the tidal inlet to the coast (fig. 6 A), whereas the reverse is the case during the time of falling temperature (fig. 6 B).

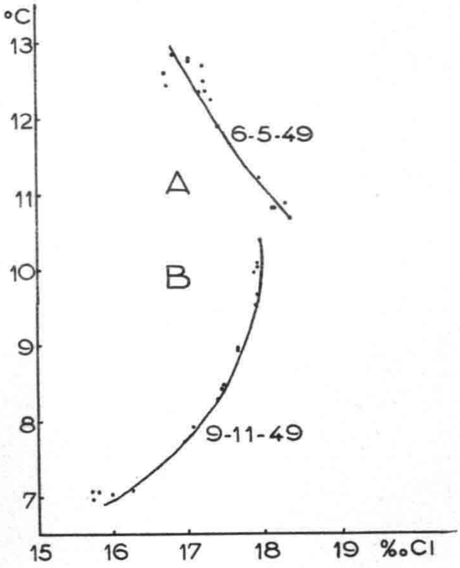

Fig. 7. T-S-relation of the observations of fig. 6.

The discharge of fresh water through the IJsselmeer sluices causes a considerable decrease in salinity from the North Sea inwards (fig. 6 A and B). The salinity gradient varies along with the quantity of fresh water discharged and is greatest in winter during periods of abundant supply. In summer there are frequent periods in which no differences in salinity occur.

If simultaneous observations in one particular Wadden Sea channel are considered, a close correlation between temperature and salinity becomes apparent (fig. 7). In summer the water temperature increases along with a decrease in salinity; the reverse happens in winter. The relation holds for both bottom and surface samples (fig. 8), but is different for different channels (Postma and Verwey, 1950). This means that mixing within one channel area is intensive, but that the water masses of adjoining channels are as a rule well separated from one another by the intervening flats.

If we compare the readings obtained at any particular point, we find that the tidal movements cause periodical changes in temperature and salinity. The geographical distribution of these variables can therefore only be found by simultaneous observations, for example at high tide, in many places. Fig. 9 shows the distribution of salinity at high water in the first few days of August, 1948. The isohalines for different dates may show large variations and the same applies to the isotherms of different dates, but the general pattern is always more or less the same (Postma, 1950).

The changes in temperature and salinity distribution in the course of the tide are rather complicated and difficult to describe in detail. A short and schematic description of some of the principles probably involved may suffice here, since the subject is discussed more extensively in the papers mentioned before.

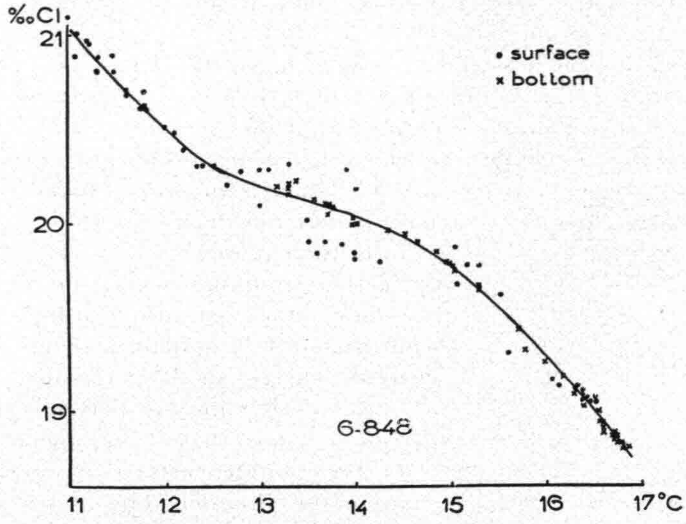

Fig. 8. T-S-relation of the observations of fig. 11.

To simplify matters we may represent the Wadden Sea as consisting

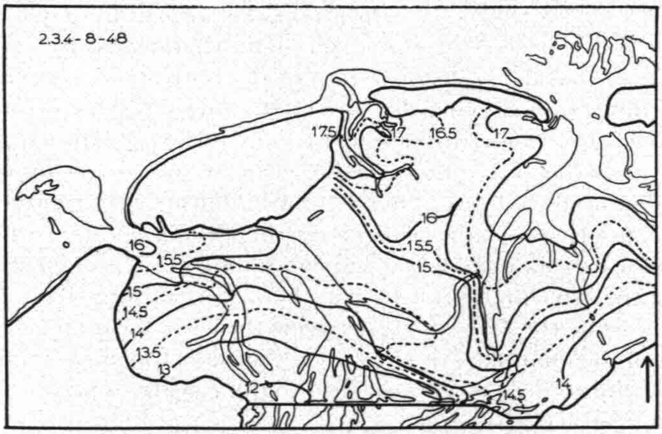

Fig. 9. Chlorinity distribution at high tide in the early part of August 1948; fresh water had been discharged at Den Oever and Roptazijl (marked by an arrow), but not at Kornwerderzand.

of one tidal inlet and one channel with shallows on both sides. The shallows are taken to emerge at low tide (fig. 10 a). The flood tide is supposed to enter the area from the North Sea and the rising water to spread over the flats. A few isohalines chosen at random will serve to illustrate the point.

Observations such as those given in fig. 9 show that the isohalines move farther inward along the channel than on the flats (fig. 10 b). To explain this it must be realized that the influence of bottom friction on water movement is relatively more considerable in shallow water than it is in deep. Hence currents have smaller velocities on the shallows than in the channel.

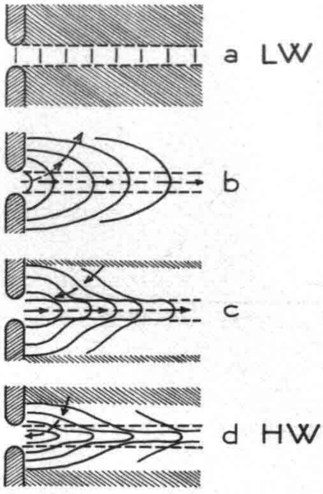

Fig. 10. Scheme of the changes of isohalines during a tidal period.

Further, in shallow water the reversal of the slope of the area surface at high tide is immediately followed by a reversal of the current, whereas in deeper water there is a considerable time lag between the two phases (compare figs. 23, 24 and 25). As a result the ebb tide starts earlier on the flats than in the channel. This must also be explained from the fact that bottom friction is more considerable on the flats than in the creeks; at the turn of the tide the energy of the flood current is used up more rapidly in shallow than in deep water.

As a result of this phenomenon the water in the channel is still running inward when the water on the shallows is already ebbing. This causes a marked transformation in the pattern of isohalines. The strongest deflection is generally observed along the edge of tidal flats, where the bottom slope is steepest (fig. 10 c). Here a salinity gradient, which forms a sharp dividing line between the water masses on either side, is generated. Salinity – hence mostly density – is greatest on the channel side of this gradient, because the channel water comes from farther seaward than the water on the shallows.

During the later phases of the ebb the water running back from the shallows pushes the boundary between the two water masses in the direction of the channel axis (fig. 10 d). Perhaps this movement is supported by differences in density, the lighter water moving over the heavier subsurface water.

After the current in the channel has also turned, the boundary is shifted seaward and disintegrates gradually. It can be observed, however, as a streak (STOMMEL, 1951) during a large part of the ebb tide. Flotsam and foam, unable to cross the boundary, are accumulated in these streaks or tide-rips, often forming clearly visible lines.

The disintegration of the streaks is caused by the strong ebb current. At the end of the ebb-tide mixing is often complete. If during the ebb-tide the water is not completely drained off from the tidal flats, new streaks may develop at low tide. After low tide they move, however, away from the channel and are therefore not observed so easily. Measurements have shown that the more saline water in this case occurs on the shallow side of the boundary.

If for a moment we consider the water on the shallows (at high tide) and the water in the channel to represent two separate bodies of water which do not mix, it is of importance to note that the phenomenon described must cause a mutual shifting of these two water masses. The water carried from the channel on to the flats by the flood tide appears, after its return, to have been displaced seaward in respect of the water that remained behind in the channel. In a deep channel as the Texelstroom this displacement may even amount to some 3 kilometres.

The seaward movement of the water returning from the shallows after high tide is more or less neutralized, however, after low tide, since then this water, after leaving the channel, becomes more or less stagnant, whereas the ebb current in the channel continues. This causes again a mutual shifting of the two water masses, but now in a reversed sense: the channel water is displaced seaward with respect to the water of the flats.

The ultimate effect as regards water movement is therefore practically nil. The process has, however, an important bearing on water exchange, since actually the water returning from the flats is mixed thoroughly with the channel water. Water masses, originally separated by distances of several hundreds of metres or even some kilometres, are thus mixed thoroughly. The horizontal exchange of water is strongly promoted in this way.

It also fits in with the above explanation that differences in salinity between bottom and surface are mostly greater during the ebb-tide than during the flood. The water returning from the nearby shallows has a lower salinity than the channel water, which originates from farther seaward. As a result, the vertical salinity gradient will therefore increase after high tide (fig. 11).

This increase, however, might also be explained as follows. The flood runs with the horizontal salinity gradient, the ebb against it, while in both cases the current velocity decreases from bottom to surface. Therefore, during the flood the surface water comes on top of bottom water of lower salinity than was originally the case, causing a decrease in stratification, whereas during ebb the upper water layer comes on bottom water of greater salinity, so that stratification increases.

In the case of fig. 11 it can be shown, however, that the latter effect cannot play an important rôle in causing stratification during the ebb-tide. Two hours after the beginning of the flooding tide the salinity rises above 15 $^0/_{00}$ Cl (14.20 h.). From this moment onwards, until slack high water, the 15 $^0/_{00}$ isohaline was carried inward along the channel axis over a distance of about 7.4 km[1]. Nevertheless, the surface salinity drops below this value nearly immediately after the beginning of the ebb movement. During this short period the surface water was carried back along the channel axis over a distance of only 0.8 km. One can therefore be sure that this decrease in salinity, and consequently also the ebb stratification, cannot have been caused by water running back through the channel, but only by the supply of less saline water from the nearby flats.

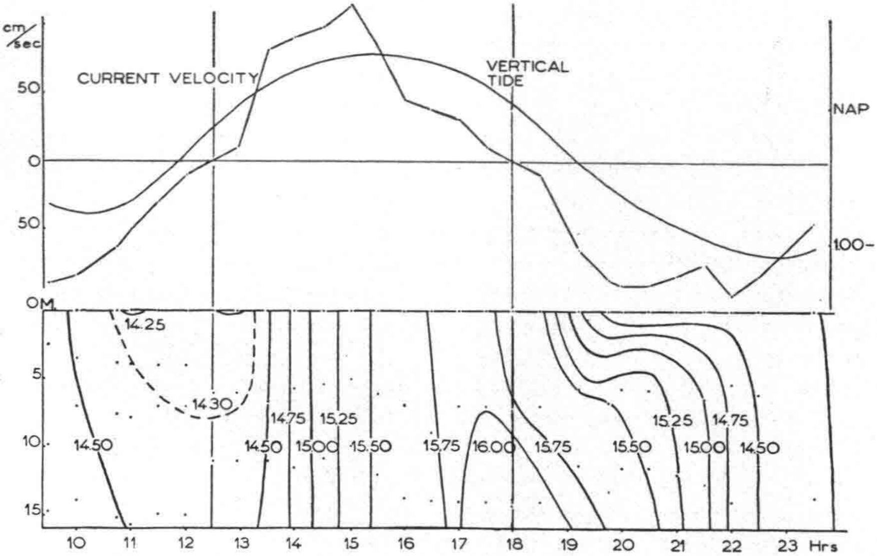

Fig. 11. Observations of vertical and horizontal tide and of salinity at station 3 of fig. 13 (30 March 1950).

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[1] The distances of 7.4 and 0.8 km have been calculated by means of the current velocity curve on the assumption that this curve is the same over the whole of the distance; actually, current velocity will decrease toward the Wadden Sea interior, so that the distances calculated will be somewhat too high.

2. THE INFLUENCE ON WATER MOVEMENT OF DIFFERENCES IN DENSITY

Hydrographically the Wadden Sea, being a transition area from river conditions to the conditions of the open sea, may be defined as an estuary. The water movement within estuaries has been studied among others by Alexander, Southgate and Bassindale (1935) in the inlet of the river Tees (England), by Tully (1949) in the Alberni inlet (Canada), by Ketchum (1951) and Stommel (1951) in the New York Bight and other areas, by Pritchard (1952) in Chesapeake Bay, and by Rochford (1951) in several estuaries of the Australian coast. Water movements in estuaries are to a considerable degree influenced by the density differences caused by the supply of fresh water. The relatively light river water remains in the upper water layer. On its way seaward it becomes progressively mixed with the underlying seawater and the difference in salinity between surface and lower layers, which is at first considerable, decreases. The decrease in stratification depends on the intensity of mixing, which in its turn mostly depends on tidal movement. Sometimes wind plays an important rôle.

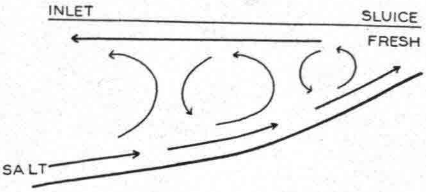

Fig. 12. Scheme of water circulation in a well stratified estuary.

Salinity always increases seaward in the upper as well as in the lower water layers. The quantity of fresh water transported to the sea in unit time must on an average be the same as through every transverse section of the estuary, and also equal to the quantity flowing from the river in unit time. The total quantity of water moving seaward in the upper water layer must increase, since the admixed sea water must be taken along. The seaward movement of salt water in the upper layer is compensated by transport of salt water within the lower layers in an opposite direction (fig. 12). The transport of fresh water to the sea in the upper layer therefore causes a seawater circulation from the open sea into the area along the bottom and from the area back to the open sea along the surface. The energy for the transport of the river water itself is provided by the field of density. Energy is also required for the seawater circulation, described above, since bottom water of high density must be transferred to the surface layer of lower density. This energy is provided by the forces bringing about vertical mixing, viz. the tides, sometimes the wind.

It will be clear that in the system described, transport of fresh water quickens the rate of water exchange between estuary and sea and renewal of the subsurface layers. Nevertheless, part of the bottom water can be stagnant, especially if there is a bottom elevation in the inlet, as is often the case.

In order to study the question of the transport of fresh water through the Wadden Sea, a representative section was chosen, running from one of the IJsselmeer sluices through a tidal channel to the North Sea. Here, salinity measurements were carried out regularly, especially around high tide (fig. 13). The marked variations in salinity called for a long series of observations. These were continued at intervals of about one month for three years (1949, 1950 and 1951). From these data the average curve of salinity given in fig. 14 A was derived. In order to obtain the average horizontal distribution of salinity of the area investigated, this curve has been combined with data from salinity surveys such as the one of fig. 9 (fig. 14 B). The distribution of fig. 14 B applies to cases when fresh water is only discharged at Den Oever. The original data used for the construction of figs. 14 A and B are not given here in detail, but are on file at the Zoological Station.

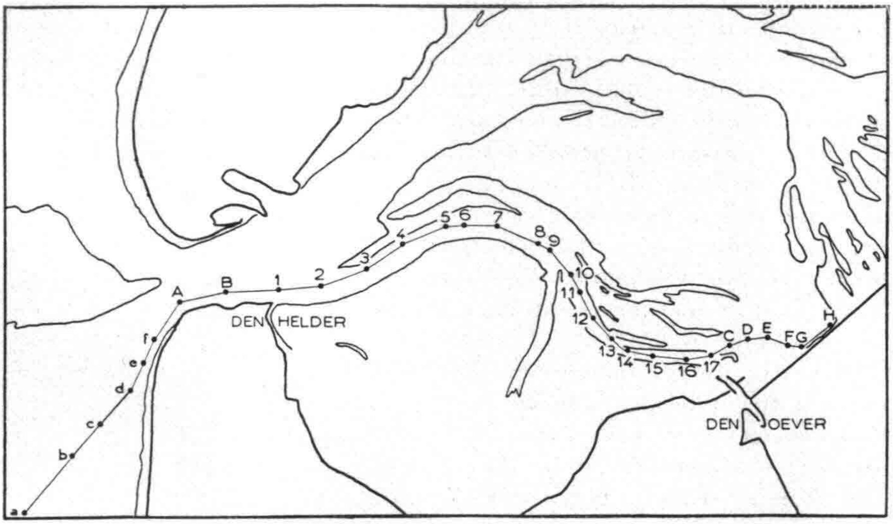

Fig. 13. Main section of investigation; location of the stations, where measurements were carried out monthly during 1949, 1950 and 1951.

Usually large quantities of water are also discharged at Kornwerderzand (table 1). Probably about one half of the supply from this sluice (3.3×10^6 m^3/ tide) moves seaward through the area investigated, the other half leaving the area through the Vlie area (Postma, 1950). Therefore, about 25 % of all fresh water present in the area studied originates from Kornwerderzand and 25 % from Den Oever. However, along the section from Den Helder to Den Oever the influence of Kornwerderzand will be much smaller, probably less than 5 %. Another interfering factor is the

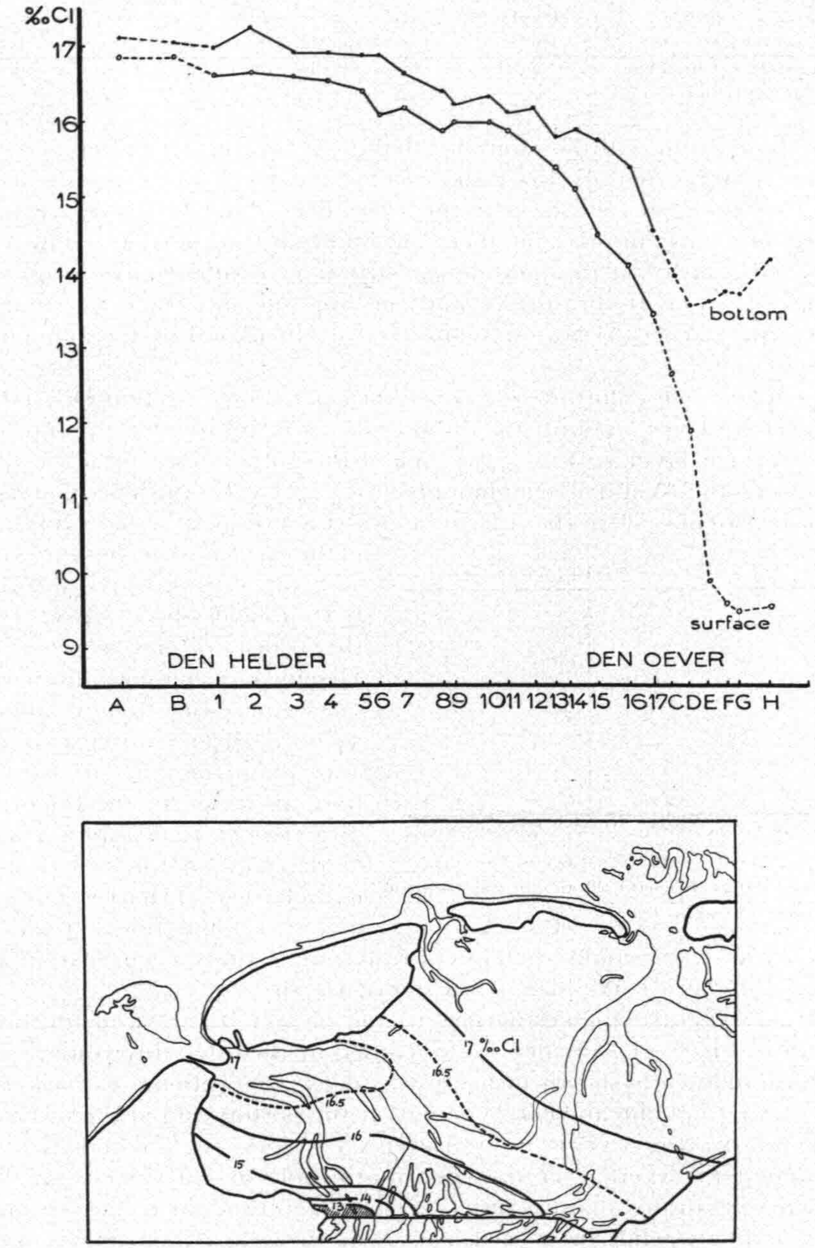

Fig. 14. A: average distribution of salinity along the section of fig. 13. B: average horizontal distribution of salinity of the area investigated, when fresh water is only discharged at Den Oever.

supply of fresh water at Den Helder (table 1) and south of this town. All things considered, about 10% of the fresh water along the section studied may not have originated from Den Oever. As the calculations to be carried out are comparatively rough, this percentage will be left out of account.

In comparison with horizontal differences, the vertical differences in salinity are generally low (about 0.5 ‰ Cl). A more pronounced stratification only exists near the IJsselmeer sluice. If we leave this area out of account for a moment, we find that transport of fresh water can only take place through the seaward movement of enormous quantities of water at the surface and the opposite movement of similar quantities along the bottom. This may be elucidated by the following calculation.

The average chlorinity of the western part of the section Den Helder–Den Oever amounts for the bottom layer to about 16.5, and for the surface layer to 16 ‰; the chlorinity of the North Sea water entering the Wadden sea amounts to 17 ‰ Cl. From these figures it can be calculated (in the way to be described on p. 27) that every m^3 of the surface layer contains only 1/17 m^3 of fresh water and the bottom layer only 1/34 m^3. For the transport of 1 m^3 of fresh IJsselmeer water it would therefore be necessary to move about 34 m^3 of surface water seaward and about the same amount of bottom water in the opposite direction. Actually, an average of 10 × 10^6 m^3 of fresh water is discharged at Den Oever during every low tide (table 1). This transport would therefore involve an estuarine circulation of 0.34 × 10^9 m^3 of Wadden Sea water of 16–16.5 ‰ Cl.

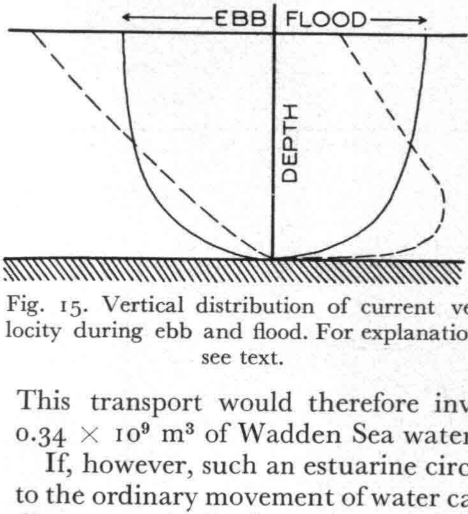

Fig. 15. Vertical distribution of current velocity during ebb and flood. For explanation see text.

If, however, such an estuarine circulation were to go on in addition to the ordinary movement of water caused by the tides, this would, as is diagrammatically shown in fig. 15, lead to great differences between the strength of ebb and flood currents at the bottom and at the surface. The full-drawn curves in fig. 15 (after VAN VEEN, 1937) schematically represent the average vertical distribution of current velocity in the absence of salinity (density) differences (with ebb and flood curves about symmetrical), while the dotted lines show the approximate deflections that would be caused by the estuarine circulation (with ebb and flood curves quite asymmetrical). The estuarine circulation would increase the ebb current at the surface and the flood current near the bottom, whereas the flood current at the surface and the ebb current near the bottom would show a decrease. In our case the velocity of the surface currents would be about three times greater during the ebb-tide than during the flood.

Such a difference between the velocities of ebb and flood currents, though far greater than the possible error of observation, has never actually been measured. All measurements, on the contrary, indicate that ebb and flood currents are of about the same strength, for which fig. 11 may serve as an example. The average flood current at the surface in this instance amounts to about 60 cm/sec., the average ebb current to 70. Although the former is indeed somewhat smaller than the latter, the difference between the two is small, and other measurements, particulars of which need not be given here, show the same results or even a smaller difference. This means that this combination of estuarine and tidal circulation fails to give an adequate explanation of the transport of fresh water seaward. It must be assumed that the strong tidal circulation causes such an intense mixing that the fresh water is divided more or less equally over both surface and bottom water, so that no estuarine circulation is developed. It will at best play a rôle in the vicinity of the IJsselmeer sluices, where fresh stratification of water masses goes on all the time.

Generally speaking, the fresh water is therefore not transported as a surface layer, but as part of a mixture which is of about the same composition near surface and bottom. Exchange of water between Wadden Sea and North Sea will take place at about the same rate for both fresh and salt water. Since differences in density may be assumed not to play an important rôle in water movement, the only remaining forces that can bring about an exchange are tidal movement and wind, which cause horizontal and vertical mixing of water masses. The mutual shifting of water masses of channels and tidal flats, described on p. 19, may have a special bearing in this respect.

The fact that the influence of fresh water on water movement in the Wadden Sea is of secondary importance becomes especially clear, if we compare tidal forces with the forces caused by the field of density.

The force exerted by the tide is proportional to the slope of the water surface. The degree and direction of the slope change in the course of the tide. On an average however, the slope along the special section studied (compare fig. 13), derived from tidal gauge observations at Den Helder and Den Oever, is about 3 cm per km (measured along the tidal channel), directed inward during the flood and seaward during the ebb. The field of density can be derived from the distribution of salinity and temperature. The average horizontal distribution of salinity at high tide, already given in fig. 14, has been combined with details of the vertical distribution obtained from observations like those of fig. 11. The temperature is considered to be the same all over the section and equal to the yearly average of 11° C. In that case the lines of equal density coincide with the isohalines (fig. 16).

From the field of density the slope of isobaric surfaces can be determined, if the position of zero level can be indicated. This position is approximately estimated on the following grounds. Above level surface isobaric surfaces slope in the direction of the sea and forces are exerted in that direction. Below zero level the reverse is the case and forces are exerted in the direction of the land. The sum of all horizontal forces must be about equal, since the ultimate horizontal transport of water is practically nil. The small quantity of fresh water discharged is of no importance in this respect. As bottom friction also exerts a horizontal force, it is difficult to estimate the exact position of level surface, but it must be situated somewhere between the bottom and the water surface. Assuming its position to be about 3 meters below the water surface (compare fig. 16) it can easily be computed from the field of density that the relative slope of the upper isobaric surface, which coincides with the water surface, must be about 0.2 cm per km, near the sluice about 0.5 cm/km. The slope of all other isobaric surfaces is smaller.

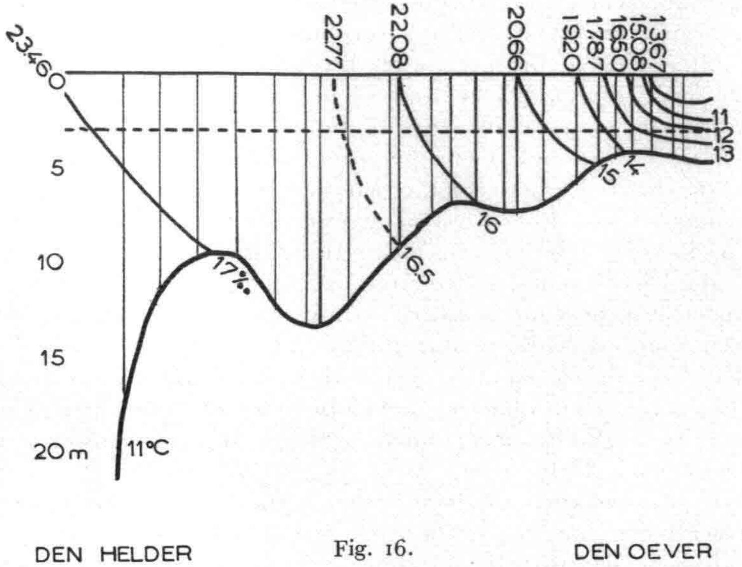

Fig. 16.

The forces exerted by the field of density are proportional to the slope of the isobaric surfaces. The number of 0.2 cm/km may therefore be compared with the 3 cm/km calculated for the slope caused by the tide. The conclusion can be drawn that the influence of the field of density on water movement must be smaller than the influence of the tide.

3. THE TRANSPORT OF FRESH WATER

It may be concluded from the preceding discussion that in the Wadden Sea vertical mixing prevents the development of marked stratification. This means that the velocity of transport of fresh water through the estuary to the sea mainly depends on the rate of water exchange between Wadden Sea and North Sea. Conversely, it must be possible to calculate the water exchange from the rate of transport of fresh water. The calculation of the latter will be based on the following line of thought.

From water volumes and salinity one should be able to estimate the total amount of fresh water present in the part of the Wadden Sea through which the fresh water from the IJsselmeer is transported to the North Sea. The relation between this amount and the quantity discharged per tide would then be known. If the former amount were three times as large as the latter, this would mean that in the course of every tide one third of the fresh water present in the Wadden Sea would be carried to the North Sea. One could also say that the fresh water requires three tides for passing through the Wadden Sea; this period has been termed flushing time by Ketchum (1951).

The main difficulty is to estimate the amount of fresh water present. The calculation will be restricted to water originating from Den Oever and therefore be based on figs. 14 A and B.

The volume of fresh water, V_f, present within a certain volume V of estuarine water, can be computed from the salinity, S_n, of the volume in question and the salinity, S, of the sea water outside the estuarine region, according to this formula:

$$V_f = \frac{S - S_n}{S} \times V \quad (1).$$

The amount of fresh water present within the Wadden Sea can therefore be calculated, if the chlorinity of the incoming North Sea water, and the salinity and water volume of the area concerned are known. The average chlorinity of $17\,^0/_{00}$, measured in the (tidal) inlet, will be held to be the chlorinity of the sea water entering the Wadden Sea. The average salinity distribution of the area is given in fig. 17 A, which is based on the following method.

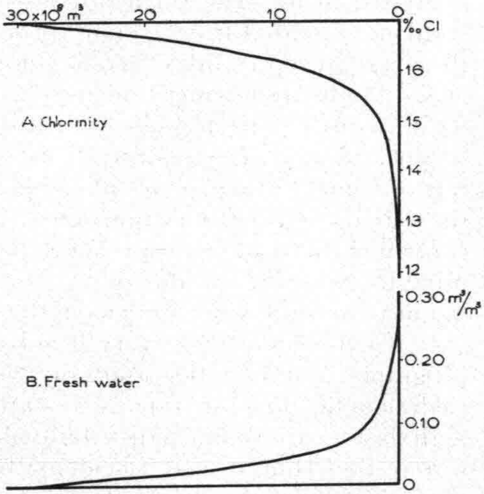

Fig. 17. Increase of salinity (A) and fall of the concentration of fresh water (B, computed from A) with increasing volumetric distance to Den Oever; for explanation see text.

The diagram represents the average chlorinity along the vertical (average for three years; see table 23) for the section Den Helder-Den Oever, obtained from figures 14 and 16. Besides the average chlorinities, however, we should also know the corresponding water volumes. The horizontal axis of fig. 17 therefore does not represent the geographical distances between the stations of observation, as is the case in the above figures, but gives their volumetric distances. The latter have been obtained as follows.

Viewed from the sluice of Den Oever every isohaline of fig. 14 B compasses at high tide a certain volume of water, which volume increases with each isohaline. The enclosed volumes can be determined by means of the bottom topography of the area, which is known from observations by the Dutch Hydrographic Office. It is convenient to use these volumetric instead of the geographical distances, since thus the influence of the geographical character of the estuary is to some extent eliminated.

The distribution of fresh water within the area can now be estimated from the salinity distribution of fig. 17A according to formula (1); the result is given in fig. 17 B. As stated, the horizontal axis of this diagram gives the volumetric distance to the sluice, which has been expressed in m^3. The vertical axis of fig. 17 B gives the fresh water content, expressed in m^3 per m^3 of seawater. Hence, every square of the diagram represents a certain volume of fresh water. The area enclosed by the fresh water line and the two axes represents the average total quantity of fresh water, which is $132 \times 10^6 m^3$.

Since the average quantity of fresh water discharged during one tide amounts to 10.3×10^6 m^3 (table 1), the total quantity present in the estuary is 12.8 times this figure. Because the average fresh water content of the Wadden Sea remains the same, the quantity flowing out into the North Sea is also 10.3×10^6 m^3 per tide or 8% of the total quantity of fresh water present in the Wadden Sea.

It is self-evident that every dissolved substance that has the same geographical distribution and gradient as the fresh water will be carried along at the same rate as the latter. This will mostly be the case with dissolved substances distributed homogeneously in the IJsselmeer water itself, but it may accidentally also hold for substances not originating from this source. Examples of this kind will be given in the following chapters. The rate of transport of such a compound can easily be determined by estimating the total quantity of the material present in the Wadden Sea and taking 8% of this figure. If a small percentage of the substance is also present in the North Sea, its concentration in the latter must first be subtracted from the values found in the Wadden Sea. It goes without saying that there is no point in such estimations, if the rate of transport can be determined directly from the quantity of the compound supplied to the area in unit time.

An improvement on the above procedure can be obtained, if we regard the transport of fresh water to the North Sea as being caused by a process similar to diffusion. The "coefficient of diffusion" C at a particular place will then be defined by

$$R = C \frac{d\,V_f}{dx} \quad \ldots\ldots\ldots\ (2),$$

where R indicates the quantity of fresh water transported per unit of time, V_f the concentration of fresh water, and x the volumetric distance from the place in question to the IJsselmeer sluices. The term $\frac{dV_f}{dx}$ is represented by the degree of slope of the fresh water curve of fig. 17 B. Its value decreases according as the distance from the sluice increases. R, which represents the quantity of fresh water discharged in unit time, e.g. the tidal period, has the same value along the whole line. Therefore, the coefficient of diffusion increases according as the distance from the sluice increases, whereas in an ordinary process of diffusion this coefficient is considered to be constant.

After C has been determined, the equation (2) could be used to calculate the rate of transport of a foreign substance which has the same geographical distribution as the fresh water (isographs of the substance running parallel to the isohalines), but which has a different gradient. This might for example be the case with an unstable compound discharged with the fresh water from the IJsselmeer, and disintegrating gradually during its transport through the Wadden Sea. In the equation (2), V_f should then be replaced by the concentration of the substance actually observed. C being known, the rate of transport, represented by R, could be estimated and would in our example turn out to decrease according as the distance from the sluice increases.

The problem would become more complicated if the substance considered were to show a geographical distribution different from the distribution of the fresh water. This will in general be the case with substances not discharged into the Wadden Sea with the fresh water itself, but brought into the area at another point. If no direct measurement of the discharged quantities were possible, the order of magnitude of the transport could nevertheless be roughly estimated from the distribution of the substance in the Wadden Sea, if we take the coefficients of diffusion to be about the same as those calculated from the fresh water distribution.

4. SEGMENTATION AS AN EMPIRICAL APPROACH TO THE PROBLEM OF WATER EXCHANGE

The conclusions arrived at in the previous section would become more valuable if it were possible to develop a method which would allow us to confirm the results obtained along another way.

An attempt will therefore be made to estimate the relation between the distribution of salinity observed at a certain moment, and the quantities of IJsselmeer water discharged in a particular period preceding that moment. This relation can only be estimated if the fate of every single volume discharged is known. The total volume of fresh water present in the Wadden Sea at a certain moment is the sum of fractions of all volumes discharged within a certain period preceding the moment in question, the fractions being smaller as the discharge from which they originate is farther back in time. At first, the whole of a volume will contribute to the fall in salinity; after a few tides, however, its influence will gradually decrease, since part of it has gone to the North Sea; after a number of tides it will practically have disappeared into the latter.

An empirical segmentation method to determine the transport of a particular volume of fresh water was first developed by Ketchum (1951). Here, his concept has undergone an important modification, however. It starts from the idea that the IJsselmeer water on its way through the Wadden Sea can be followed from tide to tide. It is assumed that the quantity of fresh water discharged in the course of one tide will within the next tidal period reach the part of the Wadden Sea immediately adjoining the sluice, which will here be called the first segment. During the next tide the water of the first segment – which by then is supposed to have completely mixed with the fresh water – is assumed to mix completely with that of a second, and during the third tide the contents of the second are supposed to mix completely with those of a third segment, and so on.

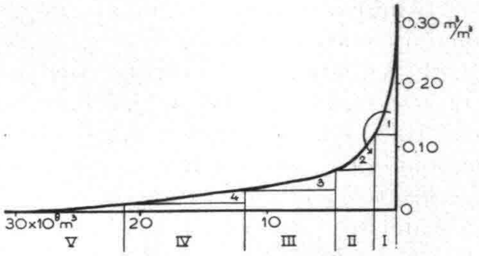

Fig. 18. Division of the Marsdiep area into segments; for explanation see text.

The volumes of the segments may conceivably be determined in the following way. We have seen that the distribution of fresh water within the area studied can be represented by the diagram of fig. 17 B. The area enclosed between the lower horizontal axis, the vertical and the fresh water curve itself represents the total volume of fresh water present. The amount of fresh water displaced from segment I to segment II by complete mixing of the two segments is represented by triangle 1 (fig. 18). The volume of segment I is chosen in such a way that triangle 1 is just able to take up the amount of fresh water discharged per tide (10.3×10^6 m^3, see table 1). The volume of the first segment can be read off from the horizontal axis, while the total amount of fresh water within this segment is represented by the triangle plus the rectangle below it.

The dimensions of the second and following segments are determined in the same way as the size of the first, all triangles being as large as nr. 1. If during the second tide segments II and III become completely mixed, this will cause a displacement of an amount of fresh water of the size of triangle 2 from the inner to the outer segment. If this process is applied to every pair of segments the result will be a shifting of all triangles over the distance of one segment. As all triangles have the same area, the amount of fresh water in every segment will remain unchanged, the first segment receiving fresh water from the IJsselmeer, the last segment supplying fresh water to the North Sea.

The dimensions of the segments depend on the slope of the fresh water line: the steeper this slope, the smaller the range of the segment. The segments grow larger in the direction of the North Sea; this is comprehensible since current velocity increases in the same direction and therefore also intensity of mixing and water exchange. The area studied is found to contain four complete segments and part of a fifth. If segment V has about the same range as segment IV, about three quarters of the former fall within the circumference of the Wadden Sea.

The above representation of discontinuous water exchange from segment to segment is only intended to be a useful means for calculations; it is self-evident that it does not represent the actual process of exchange. The very supposition that mixing will be complete over a certain distance within a certain time, in our case one tide, cannot, of course, be true. On the other hand, water exchange is not a continuous process comparable with diffusion, as supposed earlier, but it is connected with the tidal cycle. One particular volume of fresh water can often be followed for a few tides, becoming progressively mixed with the seawater, but still clearly distinct from the environment. This characteristic is brought out better by the segmentation method. During the first high tide after its discharge the volume of fresh water will find itself within the limits of the first segment, in the next tidal period its boundaries will have reached the end of the next one, etc.

As stated, the concept of segmentation set forth above has been derived from an empirical method to investigate water exchange in estuaries, developed by KETCHUM (1950, 1951). His method of segmentation is, however, quite different from the one followed above. The limits of his segments are defined by the distance over which a particle of water moves on the flooding tide. The percentage of water, placed within a segment during one tide, is determined by the ratio in which the intertidal volume stands to the high tide volume, the intertidal volume being the volume difference of the segment between high tide and low tide. A great advantage of the method is therefore that calculations of the rate of exchange are only based on easily available data as volume of river flow, geographical shape of the estuary and the range of the tide. Computations carried out by Ketchum on a number of different estuaries showed that the calculated distribution of salinity agrees with the distribution actually observed.

Although Ketchum did not express himself in this way, his method essentially implies that after low tide pure sea water enters the estuary with the flood, covering the area with a layer of undiluted sea water, which in the first instance does not mix with the estuarine water. The thickness of this layer, which is assumed to penetrate as far as the head of the estuary, would be equal to the tidal amplitude. At high tide complete mixing with the estuarine water would take place. Next, the mixture is supposed to be transported seaward by the ebb movement.

According to this method every segment is supposed to be in direct contact with the open sea. Our own method supposes that every segment exchanges water only with its neighbours. For this reason, mutual comparison of the two procedures is difficult.

The segmentation of the Wadden Sea, as determined above, will be used to estimate the transport of a particular volume of fresh water

TABLE 6

The movement through the Marsdiep area of a separate volume of fresh water sluiced at Den Oever; for explanation see text.

Segment volumes: × *10^8 m^3:*	*I* *1.6*	*II* *3.2*	*III* *7.2*	*IV* *9.7*		*I* *1.6*	*II* *3.2*	*III* *7.2*	*IV* *9.7*	*V* *10.0*	
Tide					*Total loss to North Sea, %*						*Total loss to North Sea, %*
1	100	—	—	—	0	100	—	—	—	—	—
2	33	67	—	—	0	33	67	—	—	—	—
3	33	22.5	44.5	—	0	33	22.5	44.5	—	—	—
4	18.5	37	19	25.5	0	18.5	37	19	25.5	—	—
5	18.5	17	39	0	25.5	18.5	17	39	12.5	13.0	—
6	12.0	23.5	16.5	22.5	25.5	12.0	23.5	21.5	30.0	0	13.0
7	12.0	12.5	27.5	0	48.0	12.0	14.0	31.0	15.0	15.0	13.0
8	8.0	16.5	11.5	16.0	48.0	9.0	17.0	19.5	26.5	0	28.0
9	8.0	8.5	19.5	0	64.0	9.0	11.0	25.5	13	13.5	28.0
10	5.5	11.0	8.5	11.0	64.0	7.0	13.0	16.5	22.0	0	41.5
11	5.5	6.0	13.5	0	75.0	7.0	9.0	20.5	11.0	11.0	41.5
12	4.0	7.5	5.5	8.0	75.0	5.0	11.0	13.5	18.0	0	52.5
13	4.0	4.0	9.0	0	83.0	5.0	7.5	17.0	9.0	9.0	52.5
14	2.5	5.5	4.0	5.0	83.0	4.5	8.0	11.0	15.0	0	61.5
15	2.5	3.0	6.5	0	88.0	4.5	6.0	13.0	7.5	7.5	61.5
16	2.0	3.5	3.0	3.5	88.0	3.5	7.0	8.5	12.0	0	69.0
17	2.0	1.5	5.0	0	91.5	3.5	5.5	11.0	6.0	6.0	69.0
18	1.0	2.5	2.0	3.0	91.5	3.0	6.0	7.0	10.0	0	75.0
19	—	—	—	—	94.5	3.0	4.0	9.0	5.0	5.0	75.0
20	—	—	—	—	—	2.5	4.5	6.0	8.0	0	80.0
21	—	—	—	—	—	2.5	3.0	7.5	4.0	4.0	80.0
22	—	—	—	—	—	2.0	3.5	5.0	6.5	0	84.0
23	—	—	—	—	—	—	—	—	—	—	84.0

discharged at Den Oever. During the first high tide after the discharge this volume is supposed to be divided evenly over the first segment. The distribution of the volume at the following tides is determined on the supposition that mixing of neighbouring segments is completed in one tidal cycle. The distribution calculated for successive tides after the discharge is given in table 6, where the initial volume is put at 100. As can be seen in fig. 18 the Wadden Sea appears to contain between four and five segments and calculations are therefore given for both cases.

During the first tide the volume of 100 is supposed to be introduced into segment I. During the second tide complete mixing of the segments I and II will distribute this volume homogeneously over these segments. As segment II has a larger volume than I (3.2 against 1.6×10^8 m^3), the former will then contain most of the fresh water (67 against 33). During the third tide mixing of the segments I and II causes no redistribution of the fresh water over these segments, since they have been mixed completely already during the preceding tide. Mixing of II and III, however, will introduce fresh water into III at the expense of II. During the fourth tide mixing of II and III will have no effect, but mixing of I and II will carry fresh water from I to II until the ratio 1.6:3.2 has again been attained. During this tide mixing of III and IV will cause transport of fresh water to segment IV, etc.

Segment V is incomplete and it has therefore been assumed that its volume is equal to that of segment IV. Exchange between the last segment and the North Sea has been supposed to deprive this segment of all fresh water supplied to it during the preceding tidal cycle.

During the first four to five tides there is no loss of fresh water to the North Sea; after that period the fresh water gradually disappears. The decline is more rapid with four than with five segments, see also fig. 19, curves A and B. However, neither curve A, nor curve B indicates the

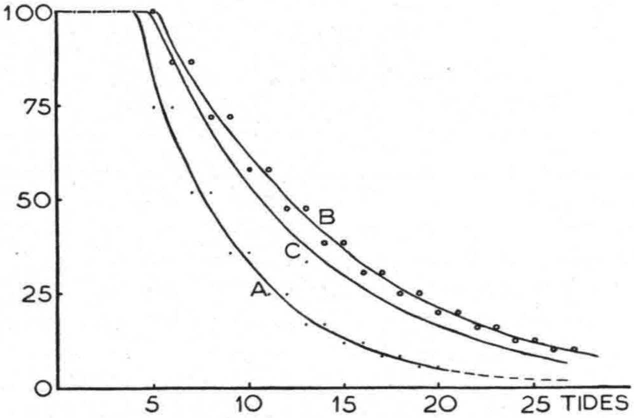

Fig. 19. The percentage present in the Wadden Sea of one particular discharge of fresh water after a number of tides.

actual decrease. The position of the intermediate curve C, which is more exact, has been approximately determined by assuming that the ratio of the difference in volume between the values indicated by A and C to that between the values of A and B is equal to the ratio of the volume of the incomplete segment V present in fig. 18 to the volume of the complete segment V.

Curve C allows us to estimate how much has remained of a particular volume of fresh water a certain number of tides after the discharge. After 23 tides about 10% of the original volume is left. If the same amount of fresh water was discharged at every tide, the quantity of fresh water remaining from tide 23 and earlier tides would amount to about 5% of all fresh water present. For the determination (from discharge data) of the total amount of fresh water present in the Wadden Sea at a given time, it is mostly considered sufficient to take into account 22 tides previous to that moment.

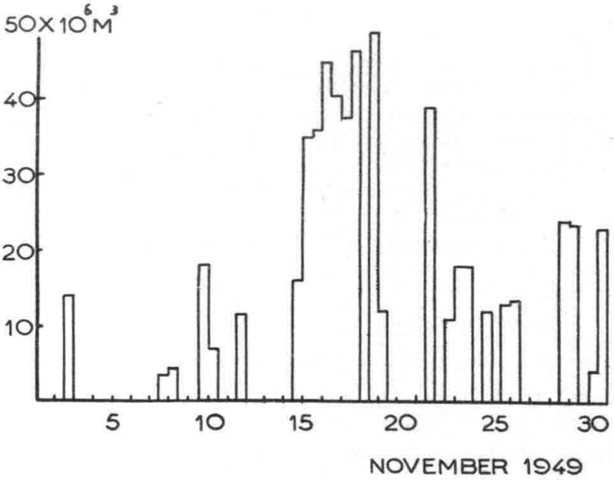

Fig. 20. Example of the discharge of fresh water at Den Oever.

We shall for a moment assume that at every low tide the same amount of fresh water is discharged at Den Oever. In that case, and provided a steady state has been attained, the area below the curve C of fig. 19 represents the total quantity of fresh water present in the Wadden Sea. This area is found to be equal to about 13 discharge units. On p. 28 this quantity has been estimated to amount to 12.8 units. The agreement between the two estimates supports the empirical segmentation method followed.

After having estimated the rate of transport of one particular volume of fresh water, we may in conclusion return to our starting-point, which was: how to determine the relation between the distribution of salinity observed at a certain moment and the quantities of fresh water discharged in a particular period preceding that moment.

As has been said before, the salinity figures have been found by monthly observations around high tide from Den Helder to Den Oever (table 23); the volumes of IJsselmeer water discharged at Den Oever are known from measurements by the "Dienst van de Zuiderzeewerken". Fig. 20 gives an example of this discharge for the month of November, 1949.

For every monthly set of salinity observations a diagram similar to that of fig. 17 A, representing the rise of salinity along with increasing volumetric distance to Den Oever, has been drawn and the corresponding volume of fresh water has been derived from it in the way described for the average distribution on p. 28. The values found are given in column 3 of table 7.

The amount of fresh water present within the Wadden Sea as the remainder of the water discharged during the 22 previous tides is given in column 4 of this table.

TABLE 7

Comparison of the accumulation of fresh water determined from the salinity surveys with the accumulation calculated from discharge data; Marsdiep area.

Nr.	*Date*	*Calculated from salinity*	*Calculated from discharge*	*Nr.*	*Date*	*Calculated from salinity*	*Calculated from discharge*
		× 10⁶ m³	× 10⁶ m³			× 10⁶ m³	× 10⁶ m³
–	13- 7-48	237	257	19	10- 5-50	354	332
1	26- 1-49	349	213	20	3- 6-50	217	147
2	16- 2-49	95	133	21	3- 7-50	131	131
3	24- 2-49	77	6	22	1- 8-50	234	74
4	6- 5-49	94	16	23	31- 8-50	98	163
5	14- 7-49	0	0	24	19- 9-50	20	96
6	27- 7-49	0	0	25	19-10-50	190	181
7	13- 9-49	0	0	26	15-11-50	48	158
8	20-10-49	0	0	27	18-12-50	293	351
9	22-10-49	62	76	28	10- 1-51	113	168
10	25-10-49	45	150	29	13- 2-51	133	224
11	1-11-49	359	245	30	28- 2-51	221	231
12	9-11-49	82	33	31	13- 3-51	213	173
13	12-12-49	180	219	32	17- 4-51	51	236
14	9- 1-50	237	200	33	5- 6-51	118	42
15	7- 1-50	135	69	34	13- 7-51	28	200
16	22- 2-50	205	268	35	29- 8-51	170	198
17	13- 4-50	0	0	36	5-11-51	345	272
18	24- 4-50	54	6				

The relation between the total quantities of fresh water determined from salinity and discharge figures is given in the diagram of fig. 21. The swarm of points is represented by the dotted line, which is drawn in such a way that the sum of squares of the perpendiculars from the points to this line is the smallest possible; the coefficient of correlation, being 0.722, indicates a significant correlation between the two sets of data. The deviation of the line from the ideal relation, represented by the line of equality, is only small.

It must be pointed out here that the two sets of data, correlated above, have not been obtained independently of each other. The positions along the horizontal axis have been found from the discharge data by means of segments. The latter, however, have in their turn been determined from average salinity figures. The positions along the vertical axis are based on the same salinity figures. Nevertheless, the reliability of the segmentation method followed is demonstrated by the fact that the dotted line nearly coincides with the ideal line. Also the significance of the correlation between the two sets of data is not lessened by the above mentioned interdependence. This correlation shows again that the method followed gives reliable results, especially since for many individual data the cause of the deviation from the ideal line can be shown to be independent of this method. In some cases the value plotted along the horizontal is too high, because the salinity values were measured at low instead of high tide. Some other vertical values are too low, since the salinities were measured on days with strong wind, which caused an accelerated exchange of water.

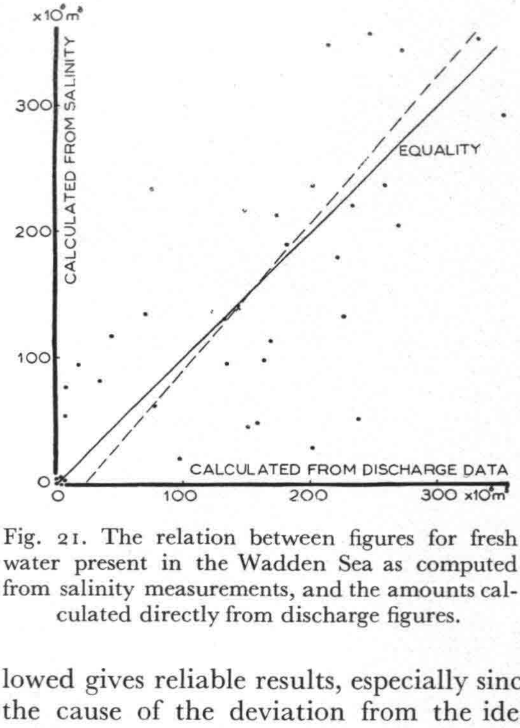

Fig. 21. The relation between figures for fresh water present in the Wadden Sea as computed from salinity measurements, and the amounts calculated directly from discharge figures.

It is further interesting to note that the two series of data can best be represented statistically by a straight line. This indicates that the rate of transport of fresh water is not influenced considerably by the amount of fresh water present; otherwise, a curved line would have been observed. The straight line correlation fits in with the conclusion set down on p. 19 and 25.

III. DISTRIBUTION AND TRANSPORT OF SUSPENDED MATTER

In this chapter an attempt will be made to account for the presence of large quantities of suspended matter in the Wadden Sea and the quantitative variations occurring from place to place. Stress will be laid on the study of the light fraction (silt), since the latter comprises among other things organic matter and clay, which were considered to be of special interest.

A picture of the distribution of suspended matter throughout the area of investigation was formed by studying thousands of water samples. The local variations of suspended matter have been studied by measurements from anchored ships. Besides, observations have been carried out on particular distinct masses of water marked by floats.

The most interesting feature of the distribution of silt within the Wadden Sea is the existence of a gradient in silt concentration from the inlets to the interior part. In order to explain this it was necessary to give attention to details concerning the transport of the silt and to the composition of the bottom material. These subjects will therefore be treated in some detail. All this work would not have been possible without the valuable cooperation of the "*Studiedienst van de Rijkswaterstaat*".

1. TIDAL VARIATIONS OF SUSPENDED MATTER AT FIXED STATIONS

The variations in suspended matter in the Danish Wadden Sea have been studied in detail by Gry (1942). Most of his conclusions are in agreement with our own observations and therefore seem to hold for the Wadden Sea as a whole.

The quantity of material in suspension at a certain place depends in the first place on current velocity. As the current velocity varies periodically with the tide, observations had to be continued during at least one tidal cycle. The stations of observation were spread all over the southernmost part of the Wadden Sea. Their positions are indicated by numbered bold points in fig. 22. As a rule, samples were taken every half hour at three points along the vertical: just below the surface, about 1 meter above the bottom and at one third of the distance from bottom to surface. Simultaneously, the current velocity was measured with an Ott current meter suspended halfway down the water. It is assumed that in this way the approximate average current velocity along the vertical was found.

In addition to the main stations, fig. 22 shows the positions of a number of secondary stations, where samples for the determination of suspended matter were collected just as at the main stations, but here no current measurements were carried out. These stations were situated along sections running across the most important tidal channels of the area. The stations of a cross-section are marked alphabetically in addition to the number which they take from the main station situated in the same section. At the secondary stations samples were taken at intervals of 1–1.5 hours, only at the surface and near the bottom. The average quantities of silt and sand at all stations are given in table 8. Only at the main stations was sampling of sufficient frequency to allow of separation of data for flood and ebb. At most stations salinity and temperature have also been measured, but these figures will only be given if they are of importance for the problems under discussion.

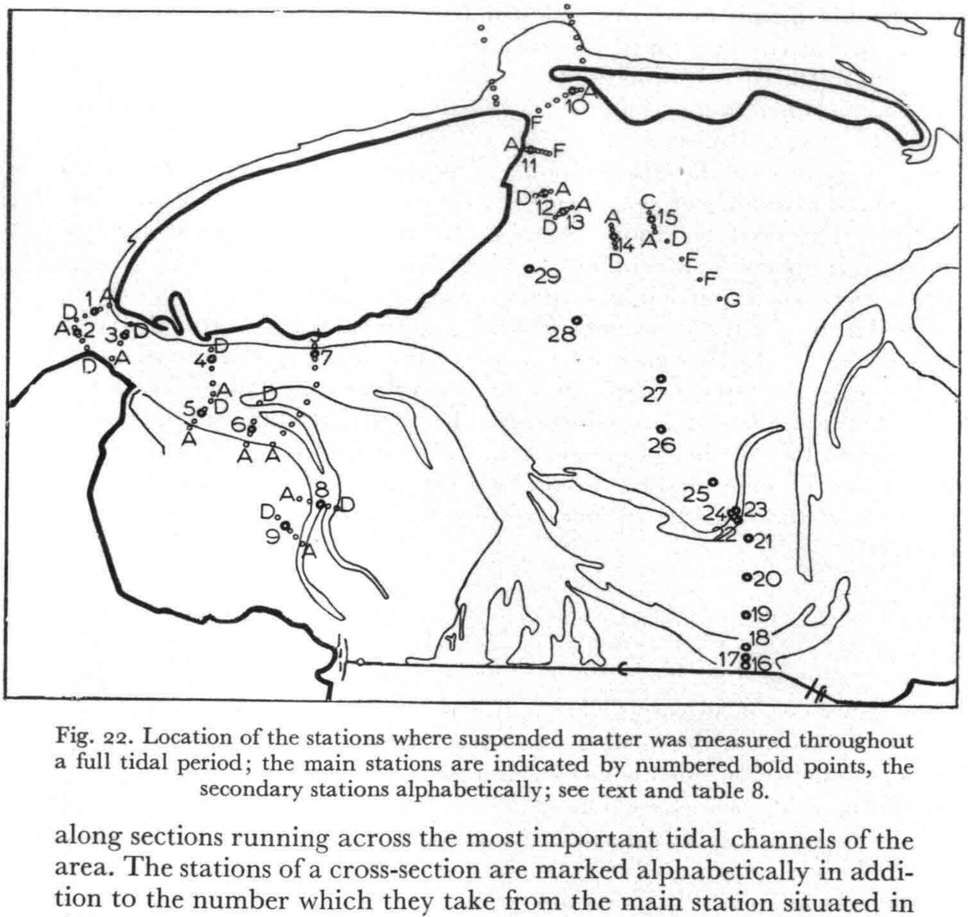

Fig. 22. Location of the stations where suspended matter was measured throughout a full tidal period; the main stations are indicated by numbered bold points, the secondary stations alphabetically; see text and table 8.

TABLE 8

Average quantities of suspended matter in the Wadden Sea; for positions of stations compare fig. 22.

Nr. Station	*Date*	*Depth, HW, m*	*Silt, mg/l*			*Sand, mg/l*		
			Flood	*Ebb*	*Full tide*	*Flood*	*Ebb*	*Full tide*
1	31-5-49	0	4.9	7.7	6.3	3.6	7.5	5.6
		6	7.6	10.3	9.0	27.6	17.4	22.5
		B, 9.5	8.5	10.0	9.3	35.8	25.9	30.4
1 A	31-5-49	0	—	—	5.4	—	—	3.5
		B, 5	—	—	13.5	—	—	9.0
1 B	31-5-49	0	—	—	5.6	—	—	2.8
		B, 11	—	—	13.0	—	—	7.7
1 C	31-5-49	0	—	—	6.0	—	—	3.6
		B, 9	—	—	7.5	—	—	7.9
1 D	31-5-49	0	—	—	5.9	—	—	4.4
		B, 6	—	—	5.7	—	—	14.0
2	1-6-49	0	4.0	3.5	3.8	3.1	2.3	2.7
		20	10.6	5.1	7.9	7.7	7.6	7.7
		B, 32	6.9	12.6	9.8	10.9	8.1	9.5
2 A	1-6-49	0	—	—	6.1	—	—	9.4
		B, 12	—	—	10.2	—	—	8.5
2 B	1-6-49	0	—	—	5.3	—	—	6.3
		B, 32	—	—	15.6	—	—	14.9
2 C	1-6-49	0	—	—	6.0	—	—	4.3
		B, 30	—	—	9.0	—	—	6.0
2 D	1-6-49	0	—	—	22.4	—	—	7.4
		B, 22	—	—	34.6	—	—	14.2
3	2-6-49	0	4.7	5.8	5.3	8.1	10.9	9.5
		22	9.2	8.6	8.9	48.2	31.6	39.9
		B, 33	9.0	11.1	10.1	70.7	110.9	90.8
3 A	2-6-49	0	—	—	6.9	—	—	5.1
		B, 28	—	—	15.3	—	—	32.0
3 B	2-6-49	0	—	—	5.1	—	—	4.1
		B, 39	—	—	7.8	—	—	13.0
3 C	2-6-49	0	—	—	7.0	—	—	6.5
		B, 11	—	—	9.8	—	—	100.1
3 D	2-6-49	0	—	—	5.7	—	—	6.0
		B, 6	—	—	11.4	—	—	20.0
4	3-6-49	0	6.8	3.5	5.2	6.6	3.9	5.3
		18	6.7	5.1	5.9	17.1	6.5	11.8
		B, 28	9.5	6.1	7.7	42.6	21.1	31.9
4 A	3-6-49	0	—	—	4.0	—	—	2.9
		B, 10	—	—	9.6	—	—	19.8
4 B	3-6-49	0	—	—	4.4	—	—	3.7
		B, 12	—	—	10.4	—	—	13.2
4 C	3-6-49	0	—	—	3.9	—	—	3.0
		B, 18	—	—	5.9	—	—	12.1
4 D	3-6-49	0	—	—	3.8	—	—	4.5
		B, 22	—	—	11.1	—	—	15.0

Nr. Station	*Date*	*Depth, HW, m*	Silt, mg/l *Flood*	 *Ebb*	 *Full tide*	Sand, mg/l *Flood*	 *Ebb*	 *Full tide*
5	9- 6-49	0	9.3	11.8	10.6	4.7	8.5	6.6
		8	17.3	19.0	18.2	9.7	7.4	8.7
		12	41.5	29.8	35.7	13.4	11.9	12.7
5 A	9- 6-49	0	—	—	12.9	—	—	3.9
		B, 2	—	—	17.3	—	—	17.4
5 B	9- 6-49	0	—	—	10.2	—	—	3.0
		B, 6.5	—	—	23.9	—	—	5.2
5 C	9- 6-49	0	—	—	13.0	—	—	6.9
		B, 12.5	—	—	22.7	—	—	9.4
5 D	9- 6-49	0	—	—	14.3	—	—	25.6
		B, 6.5	—	—	17.9	—	—	58.2
6	10- 6-49	0	22.3	13.1	17.7	2.9	3.2	3.1
		10	14.9	21.8	18.4	2.6	3.3	3.0
		B, 16	31.3	30.5	30.9	11.1	7.8	9.5
6 A	10- 6-49	0	—	—	14.5	—	—	3.2
		B, 5	—	—	36.9	—	—	46.3
6 B	10- 6-49	0	—	—	11.7	—	—	2.6
		B, 12.5	—	—	30.8	—	—	16.6
6 C	10- 6-49	0	—	—	11.8	—	—	2.9
		B, 13.5	—	—	25.4	—	—	6.0
6 D	10- 6-49	0	—	—	14.6	—	—	7.9
		B, 3	—	—	23.8	—	—	65.0
7	11- 6-49	0	4.9	7.1	6.0	0.9	0.5	1.7
		16	7.4	10.7	9.1	2.5	1.3	1.9
		B, 24	13.0	19.1	16.1	5.8	2.9	4.4
7A	11- 6-49	0	—	—	11.7	—	—	1.1
		B, 8	—	—	21.7	—	—	10.6
7 B	11- 6-49	0	—	—	12.5	—	—	1.8
		B, 12	—	—	25.8	—	—	11.6
7 C	11- 6-49	0	—	—	15.1	—	—	1.6
		B, 7	—	—	26.9	—	—	2.3
7 D	11- 6-49	0	—	—	17.4	—	—	3.1
		B, 9	—	—	16.0	—	—	4.9
7 E	11- 6-49	0	—	—	7.5	—	—	1.6
		B, 3	—	—	6.2	—	—	1.5
7 F	11- 6-49	0	—	—	7.3	—	—	1.6
		B, 7	—	—	18.0	—	—	3.7
7 G	11- 6-49	0	—	—	7.8	—	—	0.7
		B, 20	—	—	14.2	—	—	5.2
7 H	11- 6-49	0	—	—	12.3	—	—	1.2
		B, 27	—	—	15.1	—	—	3.7
7 J	11- 6-49	0	—	—	10.2	—	—	1.4
		B, 9	—	—	15.9	—	—	4.3
8	13- 6-49	0	22.7	14.7	18.7	3.2	2.9	3.1
		9	28.6	25.8	27.2	9.3	4.7	7.0
		B, 14	36.1	31.3	33.7	24.0	4.1	14.1
8 A	13- 6-49	0	—	—	20.1	—	—	3.4
		B, 7.5	—	—	28.2	—	—	20.8
8 B	13- 6-49	0	—	—	15.1	—	—	4.0
		B, 6.5	—	—	29.1	—	—	5.2

Nr. Station	*Date*	*Depth, HW, m*	*Silt, mg/l*			*Sand, mg/l*		
			Flood	*Ebb*	*Full tide*	*Flood*	*Ebb*	*Full tide*
8 C	13- 6-49	0	—	—	12.1	—	—	1.7
		B, 7	—	—	30.0	—	—	4.4
8 D	13- 6-49	0	—	—	9.6	—	—	1.3
		B, 2.5	—	—	15.7	—	—	1.5
9	14- 6-49	0–7	± 25	—	± 25	± 2	± 2	± 2
9 A	13/14-6-49	0	—	—	19.0	—	—	3.7
		B, 7	—	—	23.0	—	—	17.6
9 B	13/14-6-49	0	—	—	21.0	—	—	6.0
		B, 6.5	—	—	24.1	—	—	5.1
9 C	13/14-6-49	0	—	—	11.3	—	—	1.9
		B, 2	—	—	20.9	—	—	6.3
9 D	13/14-6-49	0	—	—	16.0	—	—	3.3
		B, 2	—	—	38.2	—	—	7.7
10	19- 8-49	0	12.7	12.7	12.7	7.7	12.7	10.2
		10	14.9	12.9	13.9	11.6	12.9	12.3
		B, 15	17.4	15.4	16.4	17.6	15.4	16.5
10	22- 8-49	0	16.9	10.7	13.8	3.0	5.1	4.1
		10	16.6	13.3	14.9	7.4	4.0	5.7
		B, 16	14.2	12.8	13.5	16.5	5.6	—
10 A	19- 8-49	0	—	—	11.8	—	—	2.6
		B, 2	—	—	14.7	—	—	11.8
10 B	19- 8-49	0	—	—	20.0	—	—	5.8
		B, 15	—	—	12.2	—	—	9.8
10 C	19- 8-49	0	—	—	13.2	—	—	4.0
		B, 2	—	—	22.3	—	—	9.3
10 D	19- 8-49	0	—	—	12.1	—	—	4.6
		B, 2	—	—	16.5	—	—	6.5
10 E	19- 8-49	0	—	—	16.7	—	—	11.9
		B, 4.5	—	—	16.9	—	—	6.0
10 F	19- 8-49	0	—	—	16.0	—	—	6.9
		B, 2.5	—	—	18.5	—	—	10.0
11	18- 8-49	0	11.8	10.4	11.1	4.5	5.4	5.0
		6	13.0	16.7	14.9	6.9	6.4	6.7
		10	17.2	16.3	16.8	7.6	20.8	14.2
11 A	18- 8-49	0	—	—	12.5	—	—	6.6
		B, 6	—	—	15.5	—	—	7.9
11 B	18- 8-49	0	—	—	13.8	—	—	23
		B, 6	—	—	15.1	—	—	30.7
11 C	18- 8-49	0	—	—	11.1	—	—	9.3
		B, 14	—	—	14.8	—	—	5.1
11 D	18- 8-49	0	—	—	13.3	—	—	6.3
		B, 2.5	—	—	15.2	—	—	7.9
11 E	18- 8-49	0	—	—	13.3	—	—	3.4
		B, 2.5	—	—	14.3	—	—	6.8
11 F	18- 8-49	0	—	—	15.1	—	—	5.3
		B, 4	—	—	13.9	—	—	16.1
12	20- 8-49	0	15.7	10.8	13.2	2.8	4.3	3.1
		5	12.4	13.9	13.2	7.6	5.8	6.7
		B, 8	20.4	13.4	16.9	10.8	9.5	10.2

Nr. Station	Date	Depth, HW, m	Silt, mg/l			Sand, mg/l		
			Flood	*Ebb*	*Full tide*	*Flood*	*Ebb*	*Full tide*
12 A	20- 8-49	0	—	—	11.0	—	—	6.0
		B, 3.5	—	—	14.6	—	—	9.2
12 B	20- 8-49	0	—	—	12.0	—	—	3.9
		B, 6	—	—	14.4	—	—	8.6
12 C	20- 8-49	0	—	—	10.8	—	—	4.9
		B, 6.5	—	—	13.9	—	—	8.5
12 D	20- 8-49	0	—	—	9.8	—	—	5.0
		B, 3	—	—	13.8	—	—	5.3
13	23- 8-49	0	14.0	9.0	11.5	12.5	4.0	8.3
		4	12.0	13.5	12.8	7.0	9.0	8.0
		B, 7	17.0	19.5	18.3	7.5	12.0	9.8
13 A	23- 8-49	0	—	—	9.6	—	—	3.7
		B, 5	—	—	18.6	—	—	21.8
13 B	23- 8-49	0	—	—	9.3	—	—	3.8
		B, 6	—	—	14.2	—	—	18.4
13 C	23- 8-49	0	—	—	10.1	—	—	2.8
		B, 6.5	—	—	13.4	—	—	10.3
13 D	23- 8-49	0	—	—	10.5	—	—	3.3
		B, 5.5	—	—	11.0	—	—	15.6
14	24- 8-49	0	49.5	61.5	55.5	7.8	21.5	14.7
		3	46.5	58.0	52.3	50.7	118.1	84.4
		B, 6	66.5	59.5	63.0	81.0	—	—
14 A	24- 8-49	0	—	—	36.3	—	—	12.0
		B, 3	—	—	36.8	—	—	45.2
14 B	24- 8-49	0	—	—	38.7	—	—	10.8
		B, 5	—	—	41.2	—	—	31.2
14 C	24- 8-49	0	—	—	32.0	—	—	8.0
		B, 5	—	—	37.9	—	—	24.6
14 D	24- 8-49	0	—	—	31.9	—	—	6.6
		B, 4	—	—	46.9	—	—	57.6
15	25- 8-49	0(B, 9.5)	24.8	13.0	18.9	5.0	4.3	4.7
15 A	25- 8-49	0	—	—	19.9	—	—	3.2
		B, 4	—	—	35.5	—	—	53.2
15 B	25- 8-49	0	—	—	30.0	—	—	10.4
		B, 10	—	—	47.1	—	—	13.7
15 C	25- 8-49	0	—	—	36.2	—	—	31.4
		B, 2.5	—	—	42.6	—	—	45.9
15 D	25- 8-49	0	—	—	16.8	—	—	6.5
15 E	25- 8-49	0	—	—	16.8	—	—	4.3
15 F	25- 8-49	0	—	—	12.1	—	—	2.9
15 G	25- 8-49	0	—	—	11.9	—	—	3.1
16	22- 5-51	0	24.7	21.0	45.7	6.3	4.8	11.1
		B, 4.5	23.8	27.2	51.0	11.8	6.0	17.8
17	22- 5-51	0	14.0	14.3	28.3	6.6	5.8	12.4
		B, 8	35.5	30.1	65.6	7.9	7.6	15.5
18	22- 5-51	0	7.6	7.1	14.7	5.5	4.1	9.6
		8	11.6	11.0	22.6	8.5	8.8	17.3
		B, 14	13.9	11.9	25.8	17.1	6.6	23.7
19	5- 6-51	0	19.3	12.0	31.3	7.1	4.1	11.2
		B, 2	19.5	12.6	32.1	4.4	4.3	8.7

Nr. Station	Date	Depth, HW, m	Silt, mg/l Flood	Ebb	Full tide	Sand, mg/l Flood	Ebb	Full tide
20	5- 6-51	0	13.9	8.1	22.0	7.8	3.3	11.1
		B, 2	20.5	9.4	29.9	10.2	5.6	15.8
21	5- 6-51	0	12.7	7.7	20.4	4.9	4.9	9.8
		B, 2	13.5	8.2	21.7	9.7	4.9	14.6
22	25- 5-51	0	11.7	9.2	20.9	5.0	4.9	9.9
		B, 11	20.1	11.6	31.7	19.2	9.5	28.7
23	24- 5-51	0	13.3	11.0	24.3	6.3	4.7	11.0
		7	18.3	16.1	34.4	6.3	5.9	12.2
		B, 11	19.8	15.8	35.6	7.4	6.3	13.7
23	25- 5-51	0	13.9	12.3	26.2	3.0	5.4	8.4
		8	18.8	15.5	34.3	6.6	4.7	11.3
		B, 12	18.2	17.3	35.5	10.4	6.1	17.5
24	24- 5-51	0	15.1	12.0	27.1	5.2	5.1	10.3
		B, 3	40.2	24.1	64.3	12.1	17.8	29.9
25	6- 6-51	0	13.7	11.4	25.1	5.4	3.8	9.2
		B, 1	—	13.8	—	—	9.7	—
26	6- 6-51	0	10.7	11.4	22.1	4.3	3.7	8.0
		B, 4.5	14.8	18.0	32.8	10.1	8.8	18.9
27	6- 6-51	0	8.2	11.8	20.0	4.6	3.6	8.2
		B, 2	13.8	15.1	28.9	3.8	5.1	8.9
28	3- 7-51	0(B, 1)	13.6	9.0	22.6	6.3	8.0	14.3
29	3- 7-51	0	13.4	16.6	30.0	9.1	9.0	18.1
		B, 1	23.3	—	—	9.9	—	—

Observations were carried out at so many points in order to gain an insight into the geographical distribution of suspended matter in the area studied. However, the variations in the quantity of suspended matter at any particular point in the course of the tide will be examined first. Three stations, numbered 3, 8 and 13, will be taken as examples. The variables measured are plotted in figs. 23, 24 and 25 respectively. The diagrams show water level, current velocity and suspended material. The rate of transport of water along the main stations, expressed in kilometers, is given in table 10 A.

The quantity of particulate matter goes up and down with the current velocity, although changes are sometimes very irregular. A strong current brings more material into suspension than a weak one. Evidently, there is constant competition between the turbulent action of the current which causes an upward movement of suspended matter, and the force of gravity which causes the particles to settle. It is understandable that the concentration of sand and silt decreases upward along the vertical, and also that this is more the case with the heavier sand grains than with the lighter silt particles (see table 8).

The suspended matter reacts with a certain inertia to changes of current velocity. Mostly, there is a lag of time between the turn of the tide, when current velocity is zero, and the moment at which the

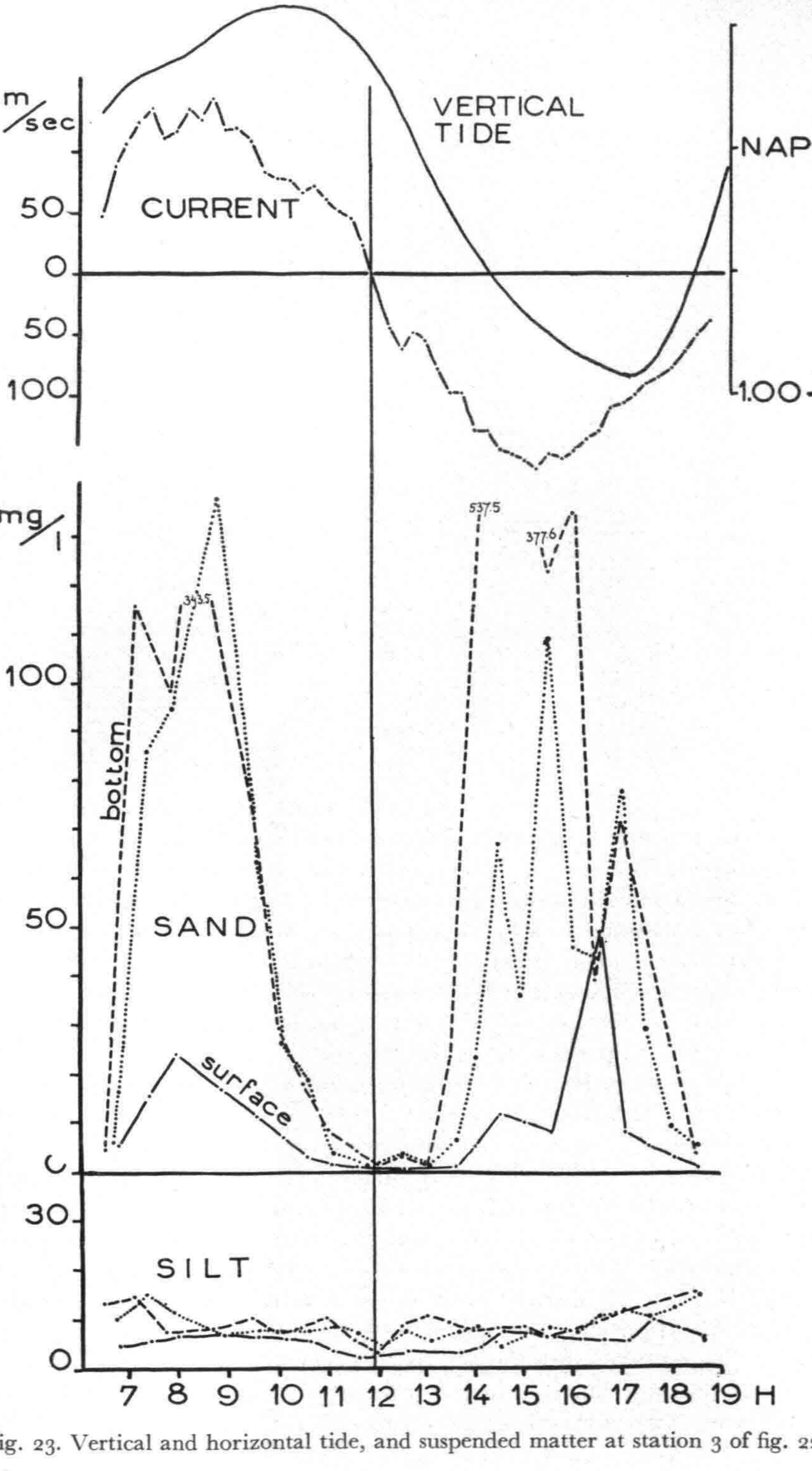

Fig. 23. Vertical and horizontal tide, and suspended matter at station 3 of fig. 22.

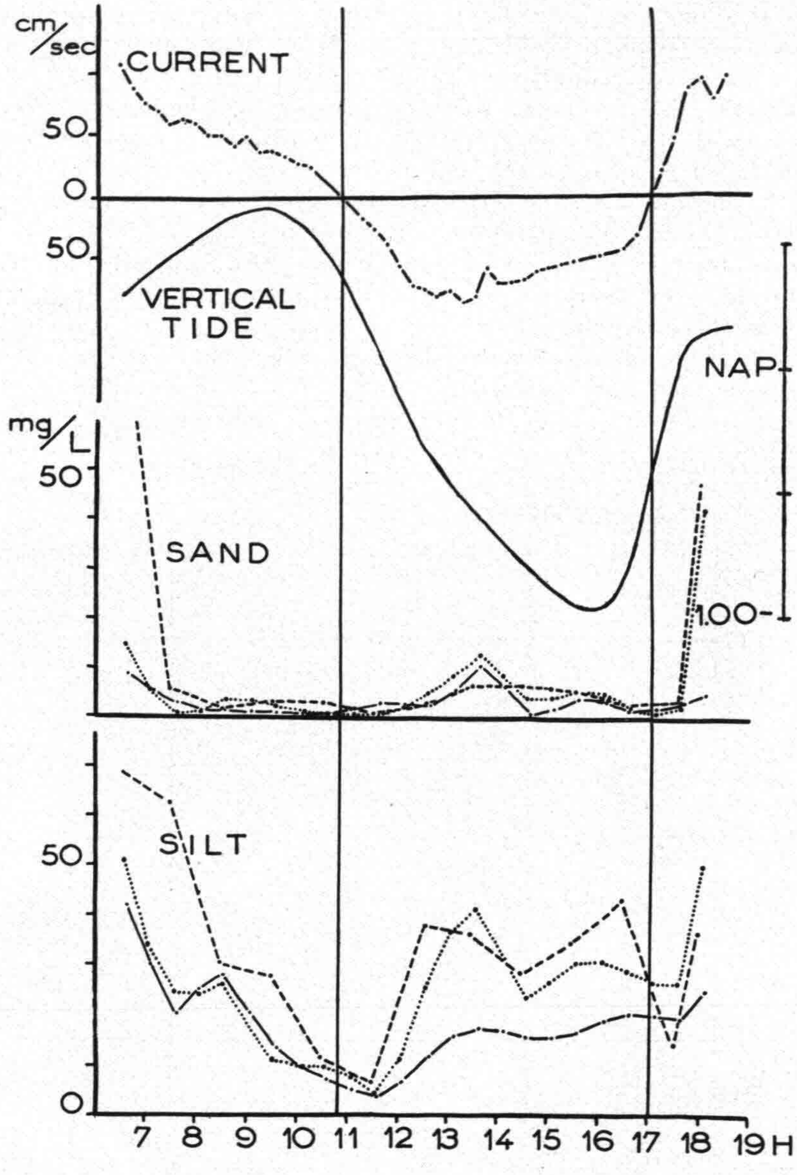

Fig. 24. Vertical and horizontal tide, and suspended matter at station 8 of fig. 22.

lowest figures for suspended material, especially suspended silt, are found. Of the three figures 23, 24 and 25, only fig. 24 shows the effect clearly; the minimum of suspended silt is in this case found from half an hour to one hour after the turn of the tide. Table 9 gives all other observations available, which point to the same phenomenon; GRY (1942) also gives a number of examples.

The effect has not been observed at station 3 of fig. 22 and other stations with low silt concentrations, probably because the rise and fall of the curve for suspended matter in the course of the tide is slight and the minimum therefore hardly distinct. At station 13 (fig. 25) and a number of similar stations the effect is probably indiscernible because of the irregular variations in the quantity of suspended matter.

The time lag observed can easily be explained from the fact that in a period of increasing current velocity some time is needed to bring material into suspension. On the other hand, when the current decreases, it takes time before the material has settled. In an area with alternating currents an equilibrium is therefore never attained.

In this connection it is of importance to consider the rate at which

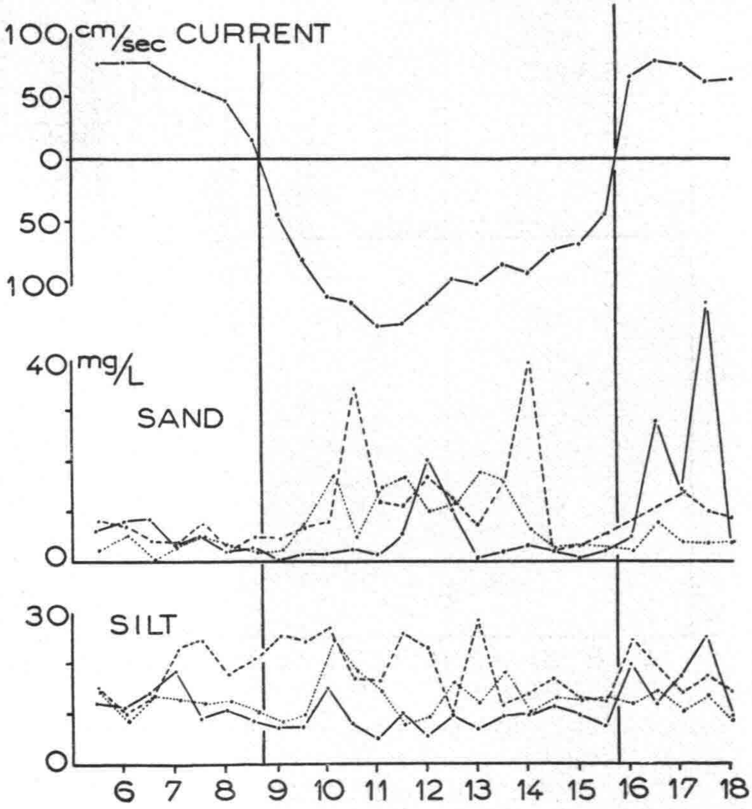

Fig 25. Current velocity and suspended matter at station 13 of fig. 22.

TABLE 9

The time interval separating the moment of minimum concentration of suspended matter from the turn of the tide. S D: turbidity measurement with Secchi disc.; S: concentration of suspended matter near surface. At the stations of fig. 22, not mentioned in this table, the time interval was indistinct.

Date	*Position of Station*	*Depth, m*	*Tide*	*Method of observation*	*Time interval, minutes*
26-6-36	Texelstroom	31	H W	S D	15
23-9-36	Marsdiep	39	H W	S D	20
23-6-39	Den Helder, harbour	10	H W	S D	20
5-6-40	Den Helder, harbour	10	H W	SD, S	25.15
20-5-47	Texelstroom	35	H W	S D	40
20-5-47	Texelstroom	35	L W	S D	indistinct
21-5-47	Texelstroom	35	H W	S D	45
21-5-47	Texelstroom	35	L W	S D	indistinct
30-6-47	Den Helder, harbour	10	H W	S D	25
21-7-47	Den Helder, harbour	10	H W	S D	35
26-6-48	Mal Zwin	12	H W	S D	more than 40
14-7-48	Den Helder, harbour	10	H W	S D	35
6-8-48	Mal Zwin	12	H W	S D	20
6-8-48	Mal Zwin	12	L W	S D	15
23-9-48	Oude Vlie	8	H W	S D	30
21-3-49	Den Helder, harbour	10	H W	S	45
10-6-49	Mal Zwin, station 6, fig. 22	16	L W	S	30
11-6-49	Texelstroom, station 7	24	H W	S	15
13-6-49	Mal Zwin, station 8	14	H W	S	45
13-6-49	Mal Zwin, station 8	14	L W	S	30
14-6-49	Amsteldiep, station 9	7	H W	S	30
28-6-49	Mal Zwin	12	H W	S D	45
6-7-49	Den Helder, harbour	10	H W	S D	25
7-7-49	Den Helder, harbour	10	H W	S D	10
19-8-49	Engelsmangat, station 10, fig. 22	15	L W	S	30
19-8-49	Engelsmangat, station 10, fig. 22	15	H W	S	45
18-8-49	Vogelzwin, station 11	10	H W	S	± 40
19-8-49	Vogelzwin, station 11	10	L W	S	± 30
20-8-49	Vogelzwin, station 12	8	L W	S	30
20-8-49	Vogelzwin, station 12	8	H W	S	indistinct
23-8-49	Vogelzwin, station 13	7	H W	S	35
23-8-49	Vogelzwin, station 13	7	L W	S	0
25-8-49	Jack IJst, station 15	9.5	H W	S	30
25-8-49	Jack IJst, station 15	9.5	L W	S	0
17-7-50	Den Helder, harbour	10	H W	SD,S	25,15
22-5-51	Dove Balg, station 16, fig. 22	4.5	H W	S	40
22-5-51	Dove Balg, station 16, fig. 22	4.5	L W	S	0
22-5-51	Dove Balg, station 18, fig. 22	14	H W	S	60?
24-5-51	Omdraai, station 23	11	H W	S	50
25-5-51	Omdraai, station 23	12	H W	S	30
6-6-51	Binnen Breesem, station 26	4.5	H W	S	20
6-6-51	Binnen Breesem, station 27	4.5	L W	S	indistinct
28-6-51	Texelstroom	35	L W	S D	30

the suspended particles settle. Though sand grains up to 200 μ have been observed under the microscope in small numbers, the average grain size of the sand will probably not have surpassed 100 μ. According to Stokes' law sand grains of 100 μ diameter sink about 0.5 m/min.; sand grains of 50 μ about 0.1 m/min. On an average, the silt fraction, consisting of particles smaller than 50 μ, may sink some 1–10 cm/min. During slack water the sand fraction will therefore settle out of the upper part of the water column within a few minutes. The silt fraction will need much more time. Hence it is primarily silt which causes the interval in time between the turn of the tide and the moment of minimum concentration of suspended matter.

Figs 23 and 24 show that the silt concentration is higher at low

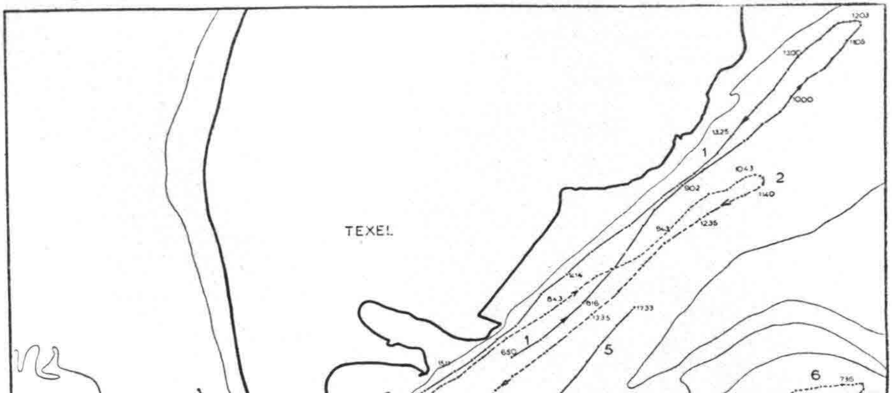

Fig. 26, A and B. Distances covered by floats during one tidal cycle; Marsdiep Area, June 1949.

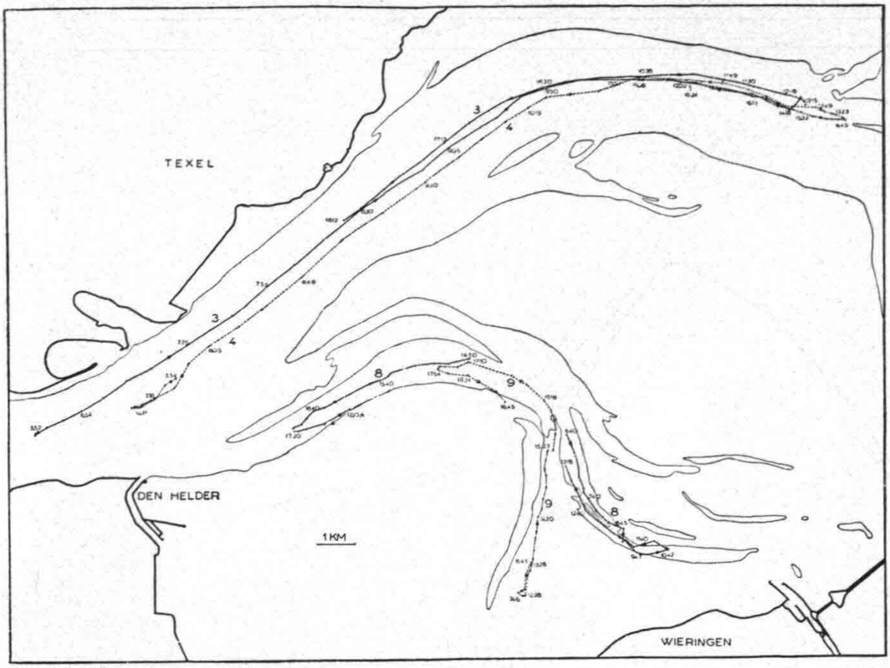

Fig. 26 B

tide than at high tide. As will be shown, this difference is caused by the geographical distribution of the suspended matter, which will be discussed below.

2. OBSERVATIONS NEAR MOVING FLOATS

In the case of a fixed station, as discussed in the previous paragraph, one is concerned with samples from different water masses, since during the observations the water passes by the place of observation. Useful additional information has been obtained by taking samples from a special mass of water marked by a float. The float consists of two iron planes fastened perpendicularly to each other and hanging vertically from a wire attached to a small buoy. If the planes are large enough, the movements of the buoy depend on the velocity of the water layer in which the planes are suspended and not on the current velocity at the surface. In most experiments the planes hung in the bottom water.

The distances travelled by the floats during approximately one tidal cycle are given in figs. 26 and 27, and table 10. On the Texelstroom, the largest channel of the Marsdiep area, distances of more than 20 kilometres were covered; in the smaller channels distances were pro-

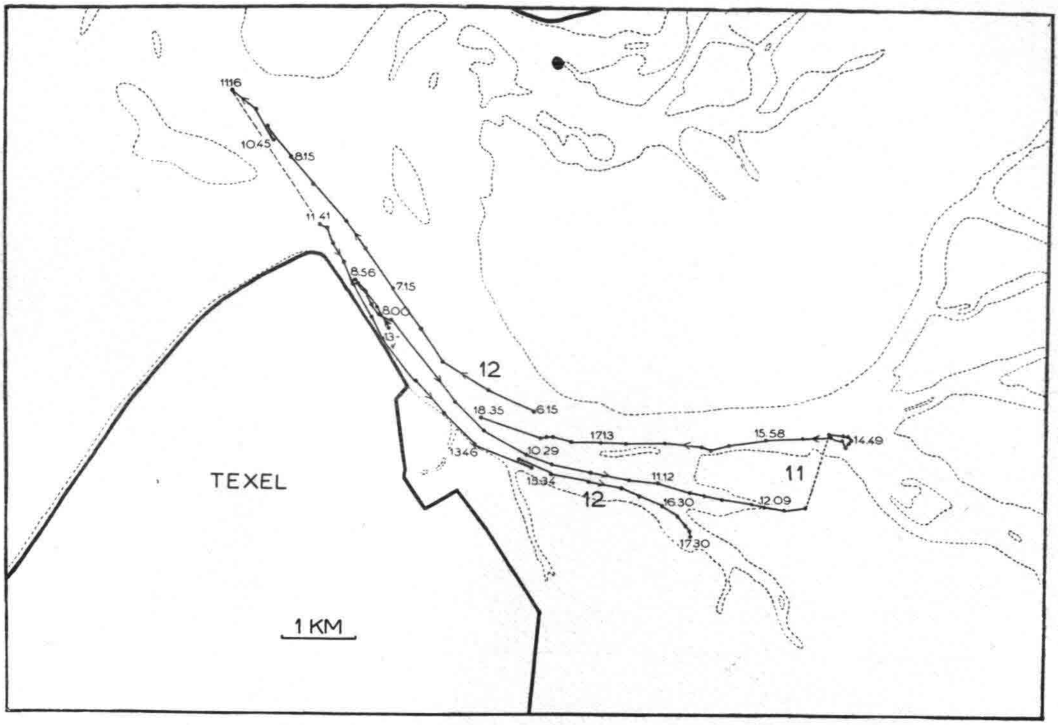

Fig. 27. Distances covered by floats during one tidal cycle; Eyerlandse Gat, August 1949.

TABLE 10

Distances covered by floats; compare figs. 26 and 27.

Nr. Experiment	*Date 1949*	*Tidal channel*	*Depth Float, m*	*Flood, km*	*Ebb, km*
1	31-5	Molengat-Texelstroom	10	—	19
2	1-6	Schulpegat-Texelstroom	10	—	18
3	2-6	Texelstroom	10	24	—
4	3-6	Texelstroom	10	22	—
5	9-6	Texelstroom-Schulpegat-Mal Zwin	10	—	21.5
6	10-6	Mal Zwin	6	—	—
7	11-6	Texelstroom	10	—	16.5
8	13-6	Mal Zwin	4	—	12.5
9	14-6	Mal Zwin-Amsteldiep	3	—	8.5
10	19-8	Engelsmangat-Vogelzwin	6	11	—
11	18-8	Engelsmangat-Vogelzwin	6	8	—
12	20-8	Engelsmangat	0.8–10	9	—
13	23-8	Vogelzwin	2–10	±10	±10

portionally shorter. The floats generally followed the same traverse forth and back; an interesting exception is the experiment of 9-6-1949. At the turn of the tide the floats turned clockwise as well as counterclockwise.

The variations in silt content in a particular mass of water during the course of a tide are the same as the changes observed at the fixed stations (figs. 28 and 29). Much silt is brought into suspension when the force of tide is at its height, whereas shortly after slack water the concentration drops to a minimum.

3. GEOGRAPHICAL DISTRIBUTION OF THE SUSPENDED MATTER

The fixed stations were situated all over the Marsdiep area and the adjoining area of the Eyerland tidal inlet between Texel and Vlieland.

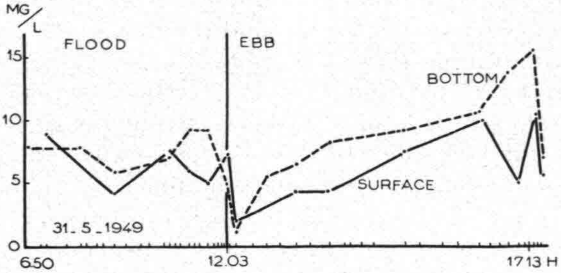

Fig. 28. Variations of suspended silt during float experiments I, fig. 26 A.

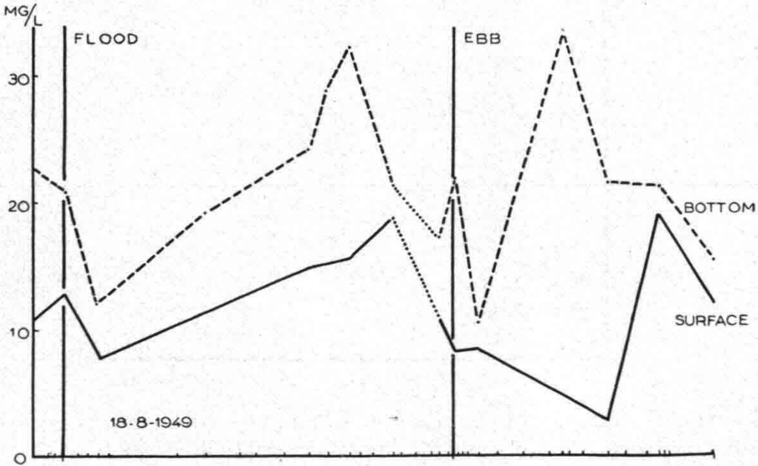

Fig. 29. Variations of suspended matter during float experiment II, fig. 27.

The observations at these stations can therefore be used to estimate differences from place to place in the amounts of suspended silt and sand. However, if comparisons between the various stations are to be valid, it must be certain that the differences observed are not caused by changes in wind force from day to day during the days of observation.

Since no special study of wind influence was made, such data are hardly available. Long-range observations, also on stormy days, would be required to gain an insight into the quantitative influence of wind. It is difficult, however, to continue measurements under bad weather conditions.

Some information about the influence of wind on the concentration of suspended matter was obtained from observations in the harbour of Den Helder. Here, measurements were made at high tide about one metre below the water surface. It must be realized, however, that the point of observation is sheltered by the coast from strong winds and therefore not representative of conditions on the open sea. Moreover, measurements were made only around the turn of the tide and therefore the concentrations measured are below the average. On the other hand, the harbour, shaped like a canal and open at both ends, formed a passage to the flats behind it and therefore fully possessed the characteristics of a tidal channel. In this respect, at any rate, it provided a good opportunity for representative sampling.

The monthly averages of the observations for the years 1949 and 1950 are given in fig. 30. The quantity of suspended material is higher in

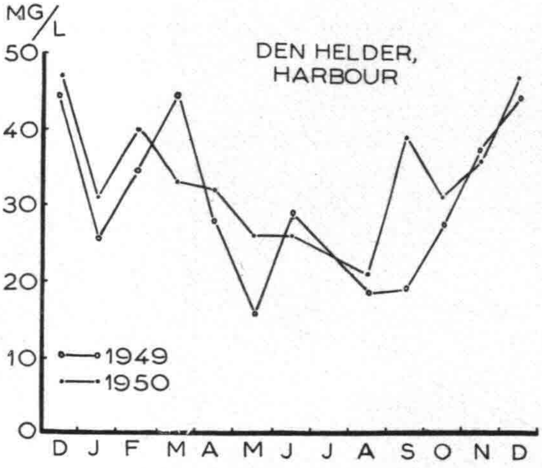

Fig. 30. Monthly averages of suspended matter in the harbour of Den Helder for the years 1949 and 1950. The samples have been taken from sea water pumped daily into the aquarium of the Zoological Station around high tide; depth about 1 m below the surface.

TABLE II

Concentration of suspended matter in the harbour of Den Helder around H W during October 1949; compare fig. 30.

Date, October	*Total susp. matter mg/l*	*Date, October*	*Total susp. matter mg/l*	*Date, October*	*Total susp. matter mg/l*
1	6.4	13	27.0	23	39.8
2	9.2	16	12.8	24	89.5
4	7.2	17	26.0	25	25.1
5	8.7	18	10.4	26	27.0
8	8.0	20	54.4	28	25.8
9	6.0	21	58.2	average	25.9

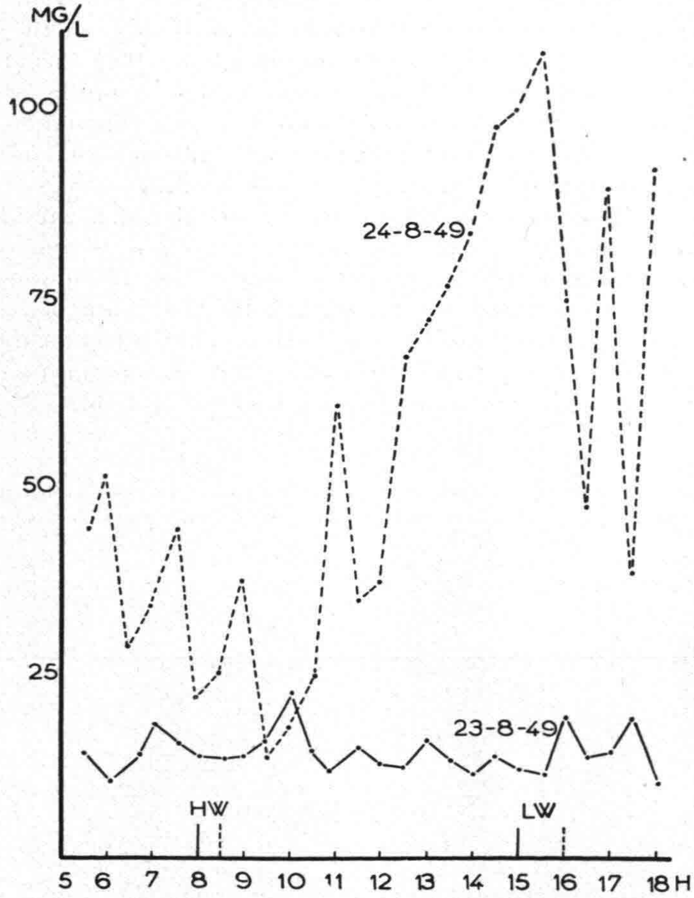

Fig. 31. Comparison of the concentration of total suspended matter at the stations 13 and 14 of fig. 22, to demonstrate wind influence; average of measurements along the vertical. Wind force resp. 7 and 12 m/sec., depth 7 and 4 m.

winter than in summer, with a maximum of about 45 mg/l in December and a minimum of 20 mg/l in August. The individual observations, however, show much larger differences; an example is given in table 11. During a heavy storm in March 1949 an exceptional quantity of no less than 447 mg/l was measured. The next day already this amount had been reduced to 20 mg/l. Obviously the higher average values in winter are not caused by a constant higher level of concentration, but by extra high values on days with strong wind. Such days occur more frequently in winter than in summer.

The observations at the main stations of fig. 22 were carried out on calm days, with the exception of those at station 14. It is interesting to compare this station with the nearby station 13, where measurements were made under normal wind conditions; in both cases the depth of the water was about the same. On the rough day the concentration of suspended matter was from 4 to 5 times as high as on the calm day (table 8; fig. 31). It is clearly to be seen that sand contributes more to this increase of concentration than the finer material does, probably because the bottom near the stations is poor in silt.

From the above observations it may be concluded that wind has an appreciable influence on the amount of material in suspension. Since most observations were carried out on calm days in summer, the average silt values found are lower than the true annual average; judging from figures obtained for the harbour of Den Helder they are perhaps even twice as low. On the other hand, the constant weather conditions during the observations increased the probability that the

TABLE 12

The average surface concentration of suspended matter in a section compared with the concentration in the same section a day or a few days later; for positions of sections compare fig. 22.

Section	*First observation*	*mg/l*	*Second observation*	*mg/l*	*Difference, mg/l*
2, A–D	1949, 31 May	17.3	1949, 1 June	15.3	— 2.0
3, A–D	1 June	13.3	2 June	10.7	— 2.6
4, A–D	2 June	8.4	3 June	7.4	— 1.0
5, A–D	3 June	16.3	9 June	21.7	+ 5.4
6, A–D	9 June	15.7	10 June	17.3	+ 1.6
7, A–J	10 June	15.1	11 June	12.9	— 2.2
7, A–J	11 June	12.9	13 June	14.0	+ 1.1
8, A–D	13 June	16.0	14 June	14.3	— 1.7
11, A–F	18 August	21.7	19 August	26.3	+ 4.7
12, A–D	18 August	22.6	20 August	17.2	— 5.4
13, A–D	20 August	17.6	23 August	13.5	— 4.1
14, A–D	23 August	20.5	24 August	68.4	+47.9
15, A–C	24 August	60.9	25 August	43.9	—17.0

measurements are mutually comparable. This was checked by carrying out measurements twice at the same station. The differences from one day of observation to the other are low, when compared with the differences from station to station (table 12).

A comparison of figs. 23 and 24 makes it quite clear already that sand must have a geographical distribution different from that of silt. Station 3 of fig. 23, situated in the tidal inlet, shows high values for sand and low ones for silt. The reverse is the case at station 8 (fig. 24), situated farther inward. Full particulars about average concentrations of sand and silt are given in table 8. They show that high sand concentrations occur only in the tidal inlet. The quantities of sand in suspension are found to decrease as one moves from the Marsdiep either to the Wadden Sea or to the North Sea. Obviously, only the strong currents prevailing in the Marsdiep are able to bring large amounts of sand into suspension.

The geographical distribution of silt will be discussed in more detail. Figs. 32, 33 and 34 give the minimum values, the average and the maximum values respectively. By minimum values are meant the

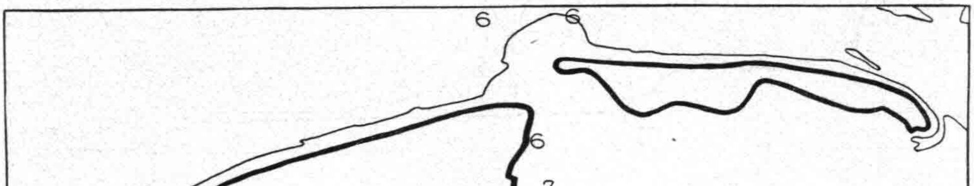

Fig. 32. Geographical distribution of silt; minimum concentrations.

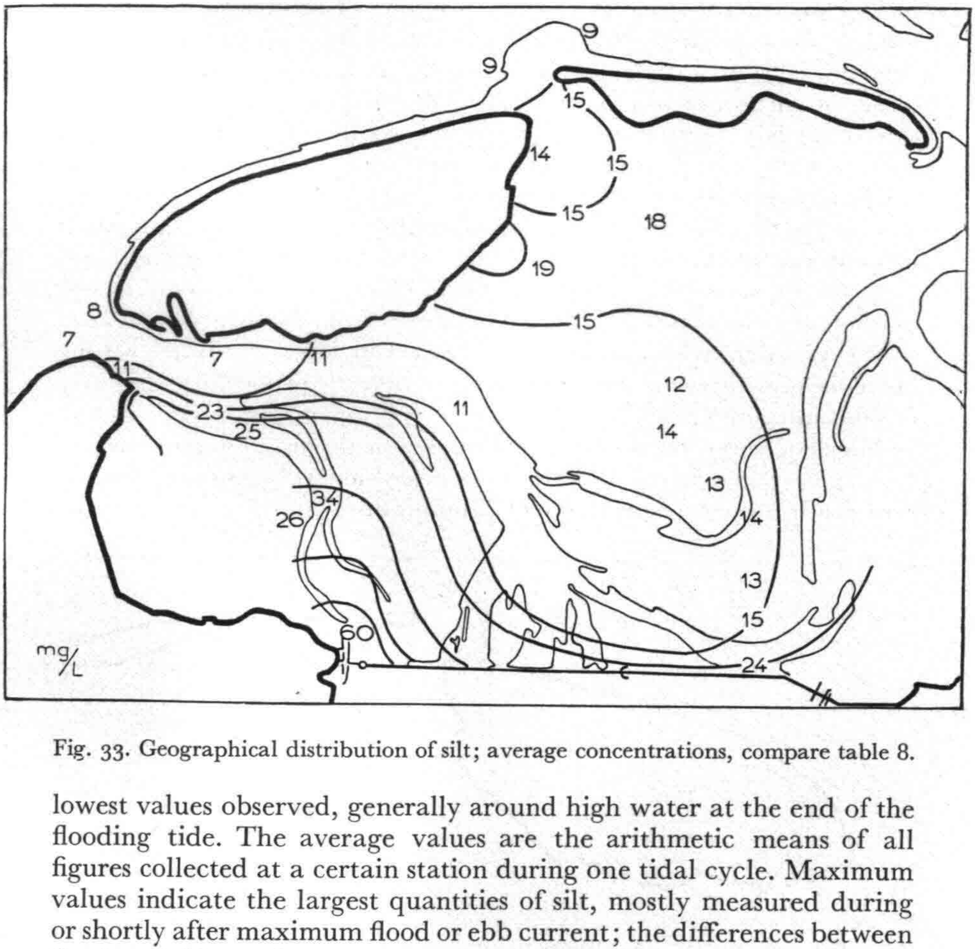

Fig. 33. Geographical distribution of silt; average concentrations, compare table 8.

lowest values observed, generally around high water at the end of the flooding tide. The average values are the arithmetic means of all figures collected at a certain station during one tidal cycle. Maximum values indicate the largest quantities of silt, mostly measured during or shortly after maximum flood or ebb current; the differences between flood and ebb maxima are mostly small. Both maximum and minimum values refer to the average concentrations along the vertical.

The geographical distribution of the average silt values shows a gradual increase of suspended silt from the North Sea inward (fig. 33). The increase is most pronounced in the direction of the coast and the Afsluitdijk. At the western end of the dike values up to 60 mg/l are found. Along the Texelstroom suspended silt increases only slowly. To give a clear picture of the distribution some isographs are drawn, but no special importance should be attached to their course.

Roughly the same pattern is found for the geographical distribution of maximum and minimum values; in the latter case the differences from station to station are very small. It may therefore be concluded

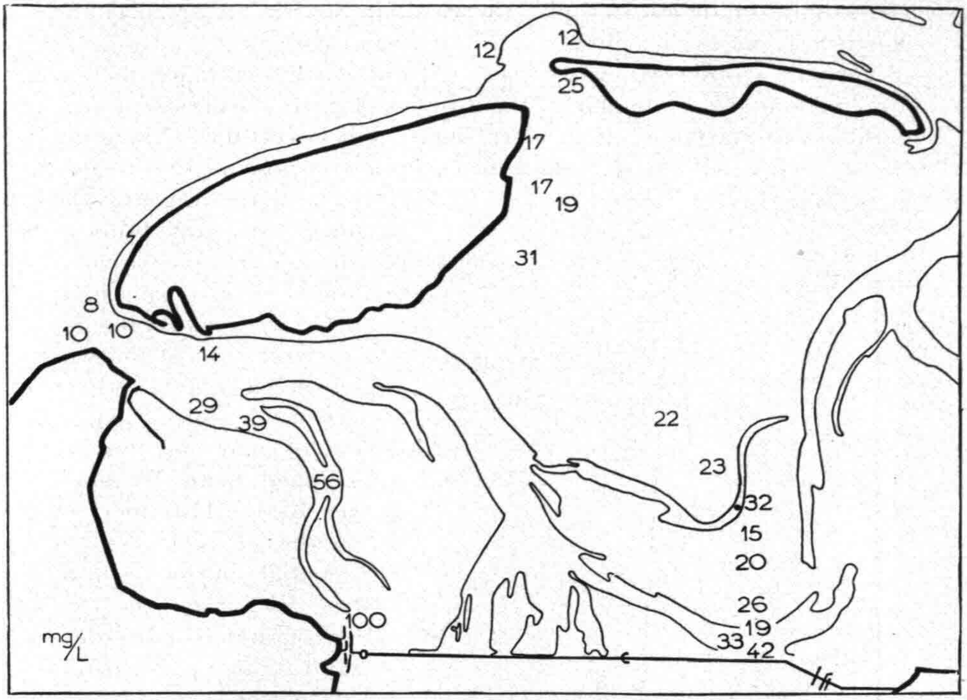

Fig. 34. Geographical distribution of silt; maximum concentrations.

that throughout the whole tide the silt concentration within the Wadden Sea is on a higher level than in the North Sea and that this concentration increases gradually in the direction of the coast.

From fig. 33 and table 8 the average concentration of suspended silt of the part of the Wadden Sea here studied has been estimated at 18 mg/l. The average concentration of sand is about 5 mg/l (see table 8), so that the total average amounts to 23 mg/l. The adjoining part of the North Sea contains only 6 mg/l of suspended silt or one third of the Wadden Sea value (see below). It has been remarked already that these values only hold for calm weather conditions.

Not only in the area dealt with in this investigation, but also in other parts of the Wadden Sea, is the silt content of the water relatively high, as appears from observations by GRY (1943) in areas near Esbjerg (Denmark) and by HAGEN (1856; compare KALLE, 1945) and LÜNEBURG (1951) for the Jade Bay. Also KAMPS (personal communication) found the same for the eastern part of the Dutch Wadden Sea.

Before we can discuss the cause of these high concentrations, it is necessary to know the quantities of suspended silt of the surrounding areas that exchange water with the Wadden Sea. In this respect the North Sea and the IJsselmeer are of importance.

North Sea observations were carried out during calm weather in four sections perpendicular to the Dutch coast, in a section running parallel with the coast, and from the lightvessel Texel off the Marsdiep (fig. 1, table 13 and fig. 35). With the exception of those measured close by land, the values for the total of suspended matter are low. The above mentioned value of 6 mg/l has been accepted as the silt concentration of the water entering the Marsdiep.

Considerable quantities of water are further supplied to the Wadden Sea by the IJsselmeer. A number of data were collected about the fresh water discharged at Den Oever and Kornwerderzand (table 14). Suspended matter was found to vary between 10 and 30 mg/l, with an average concentration of about 15 mg/l. It will be observed that this amount lies below the average silt concentration of the adjoining part of the Wadden Sea itself and even below the over-all average of 18 mg/l. No quantities of sand of any importance were found in the IJsselmeer water.

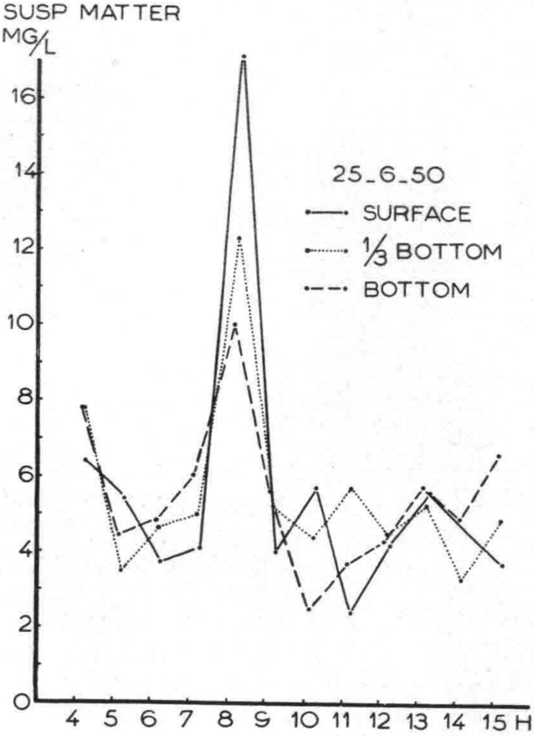

Fig. 35. Variation of total suspended matter near the Dutch lightvessel Texel; for location compare fig. 1.

4. TRANSPORT OF SUSPENDED SILT

For a discussion of the causes of the geographical distribution of silt observed it will be of importance to know the quantities of silt transported by the tidal currents and to determine whether there is a significant difference between the figures for ebb and flood.

TABLE 13

Total suspended matter in the North Sea near the Dutch coast; compare fig. 1.

Nr. Station	*Date*	*Latitude*	*Distance from coast in km*	*Depth, HW, m*	*Total suspended matter, mg/l Surface*	*Bottom*	*Remarks*
1	23-6-49	52° 54′	2.2	8.5	7.5	16.4	Section off Callantsoog; average of one tide
2			4.8	11.5	7.9	18.0	
3			7.6	18.0	7.9	8.2	
4			10.5	19.0	5.3	7.5	
5			13.5	22.0	5.9	3.6	
6			16.2	24.5	5.5	6.6	
7	28-6-49	52° 9′	3.6	11.5	6.5	19.0	Section off Wassenaar; average of one tide
8			5.1	16.0	6.8	8.4	
9			6.5	18.5	5.1	6.8	
10			7.9	18.5	6.6	6.9	
11			9.6	19.0	4.8	5.9	
12			11.2	20.0	6.0	7.0	
13	24-6-49		8.–	—	3.8	—	11 Surface samples from Den Helder to Hook of Holland
14	22-8-48	53° 22′	0.8	3.5	9.5 (2.2)	12.8 (1.3).	Section off Vlieland; average of one tide; data on sand in parentheses
15			1.6	3.5	10.8 (3.1)	12.0 (2.7)	
16			2.2	3.0	12.7 (4.1)	12.3 (2.0)	
17			2.9	8.5	11.6 (3.1)	14.2 (2.3)	
18			3.3	15.0	10.2 (2.5)	14.7 (4.2)	
19			2.8	15.5	9.4 (2.9)	9.7 (1.9)	
20	22-8-49	53° 18′	0.4	2.0	19.9 (10.9)	26.1 (11.4)	Section off Texel; average of one tide; data on sand in parentheses
21			0.8	2.0	15.4 (5.5)	20.5 (6.2)	
22			1.3	5.0	17.3 (9.4)	14.4 (4.2)	
23			1.7	6.5	11.0 (2.9)	19.8 (5.8)	
24			3.8	11.5	6.9 (1.6)	12.1 (1.7)	
25			4.6	14.5	7.2 (3.9)	8.1 (1.8)	
26	22-9-49		8.–	—	5.0	—	9 Surface samples from Terschelling to Den Helder
27	22-6-50		13.–	22.0	8.5	16.8	Lightvessel Texel, H.W., wind force 7
27	25-6-50		13.–	22.0	5.7	6.0	Light vessel Texel, tidal average
28	26-6-50		13.–	22.0	4.5	6.0	Lightvessel Texel, H.W., wind force 1–3.

The amounts of silt passing the stations of observation during ebb and flood tide respectively can be found by multiplying the figure for silt by that for the current velocity measured simultaneously. If silt concentration is given in mg/l and current velocity in dm/sec the result can be expressed in milligrams of silt passing every second through a vertical area of one dm^2 perpendicular to the current.

TABLE 14

Total suspended matter in fresh water discharged from the IJsselmeer at Den Oever and Kornwerderzand around low water.

Date 1950	*Den Oever, mg/l*	*Date*	*Den Oever, mg/l*	*Kornwerderzand, mg/l*
1-8	17.9	4-9	—	9.9
2-8	11.7	5-9	9.7	10.1
3-8	12.6	5-9	12.9	13.3
4-8	11.7	8-9	14.3	16.5
4-8	21.0	8-9	8.0	—
5-8	15.8	9-9	9.7	21.4
5-8	11.4	11-9	10.6	29.0
7-8	9.2	12-9	8.4	22.8
8-8	10.7	12-9	—	10.0
14-8	14.3	13-9	10.4	22.9
15-8	12.8	13-9	12.2	16.5
17-8	11.9	14-9	11.3	14.5
18-8	12.2	14-9	17.0	15.7
19-8	15.2	15-9	10.5	18.6
25-8	13.1	15-9	14.6	—
26-8	14.8	18-9	18.2	24.5
28-8	14.7	19-9	—	45.0
29-8	11.1	19-9	11.6	23.5
30-8	13.3	20-9	—	17.5
30-8	12.0	20-9	15.9	32.0
31-8	11.3	21-9	17.9	22.5
31-8	17.8	22-9	18.4	17.6
1-9	12.6	23-9	13.8	14.5
		24-9	—	15.4
		24-9	18.1	13.3
		25-9	13.3	21.7
		25-9	11.1	17.1
		26-9	24.0	22.7
		26-9	14.7	18.2
		27-9	—	11.1
		27-9	12.6	14.7
		28-9	14.1	23.3
		28-9	13.6	22.6
		29-9	11.5	12.5
		29-9	16.3	17.5
		30-9	—	15.6
		30-9	12.9	13.6
		1-10	13.1	—
Average	13.5		13.5	18.8

The example given in fig. 36 is based on data regarding silt and current found in fig. 23; the vertical mean of silt concentration had to be used, because only the vertical mean of current velocity was measured. In the graph the areas enclosed by the horizontal axis and the curve therefore represent the total quantities of silt transported

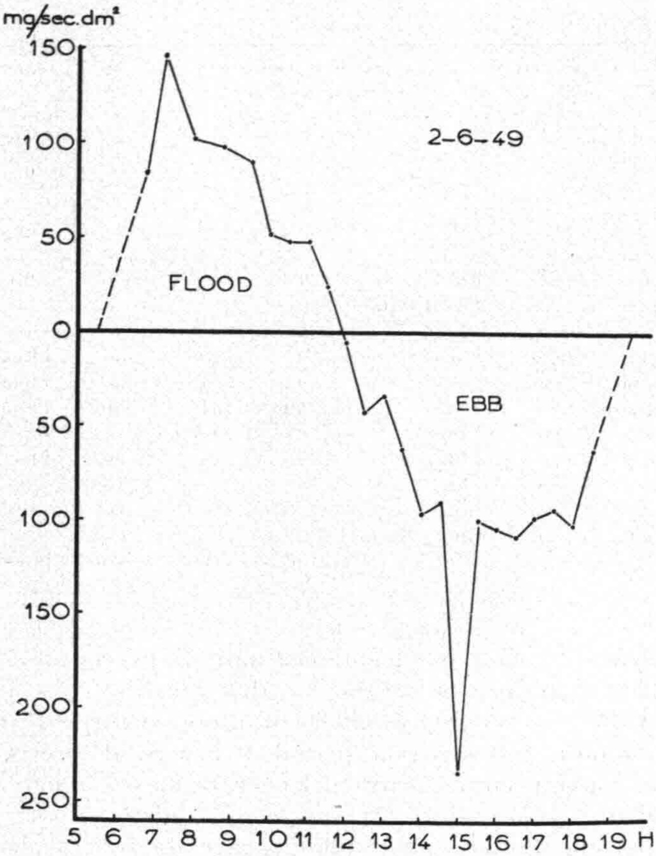

Fig. 36. Transport of silt at station 3 of fig. 22, compare also fig. 23.

through one dm² in flood and ebb direction respectively. The difference between the two areas represents the residual transport of silt, which in this particular case is found to be in ebb direction.

In this way the transport of silt has been calculated for most of the main stations of observation (table 15). In some cases flood transport is found to be larger than ebb transport, sometimes the reverse is the case, and a few times there is no appreciable difference. The results thus provide no general evidence for the existence of a one-sided transport of silt. Perhaps an exception must be made for some areas, for example the tidal channel Omdraai, where all observations indicate a residual transport in flood direction (stations 22, 23 and 24). This channel forms the connection between the Marsdiep tidal area and the area of the Vlie tidal inlet and a surplus of silt may therefore be transported from the former to the latter area. A cross-section of the

TABLE 15

Transport of suspended silt at the main stations; compare figs. 22 and 37, and table 8.

Nr. Station	*Flood, g/dm²*	*Ebb, g/dm²*	*Residual transport, g/dm²*	*Nr. Station*	*Flood, g/dm²*	*Ebb, g/dm²*	*Residual transport, g/dm²*
3	1620	2270	Ebb 650	16	2190	1510	Flood 680
4	1620	—	—	17	—	2450	—
5	2920	3580	Ebb 660	18	1590	1680	Ebb 90
6	4210	3720	Flood 490	19	770	1020	Ebb 250
7	—	1620	—	20	550	270	Flood 280
8	3120	3010	Flood 110	21	300	290	Flood 10
9	1060	450	Flood 610	22	2130	900	Flood 1230
10	2920	2290	Flood 630	23	1910	1690	Flood 220
11	2870	3240	Ebb 370	23	2400	1650	Flood 750
11	1730	2540	Ebb 810	24	1230	790	Flood 440
12	1220	2000	Ebb 780	25	—	410	—
13	2170	3210	Ebb 1040	26	1720	970	Ebb 750
14	5010	13220	Ebb 8210	27	—	700	—
15	—	2230	—	28	360	130	Flood 230
				29	170	240	Ebb 70

channel formed by the above-mentioned stations covers at mean water level (N.A.P.) an area of 10^6 dm², so that roughly 0.7×10^6 kg of suspended silt (dry weight) would be transported through the Omdraai to the north in every tidal period. It is possible, however, that part of this amount is transported back over the flats; compare stations 18, 19 and 26.

A comparison of table 15 with table 10 (see also fig. 37) shows that residual transport of silt is mainly caused by residual transport of water and not by a larger concentration of silt during one of the two tidal phases. This shifts the problem mainly to the question of residual water movement in the Wadden Sea. So far there is no conclusive evidence of the existence of such residual transport. On the contrary, current measurements by Rijkswaterstaat (unpublished reports of Van Veen, 1934, and Ferguson, 1939) show that ebb and flood transport through the Marsdiep and Vlie tidal inlets do not differ to a significant degree. According to these observations the total transport of water through the Marsdiep by the flood tide is 0.875×10^9 m³ and by the ebb tide 0.99×10^9 m³, but the possible error of observation is considered to be too large to attach value to this difference. In the Vlie tidal inlet these values amount to 0.88×10^9 m³ for the flood and 0.85×10^9 m³ for the ebb. Our own observations on the distribution of salinity and temperature do not point to a net transport of water in one direction or the other either (compare

Postma, 1950). Therefore, residual transport of water, if actually existing, is considered to be of minor importance. Consequently, the same applies to the transport of silt.

The transport of silt through the Marsdiep can be roughly estimated by combining the above figures found by Rijkswaterstaat with the total average silt concentration in the transverse section of the tidal inlet (table 8, stations 3 and 3A–3D, and fig. 38). This average amounts to 8.5 mg/l; the total quantity of silt transported in ebb or flood direction may therefore amount to 8 × 10^6 kg.

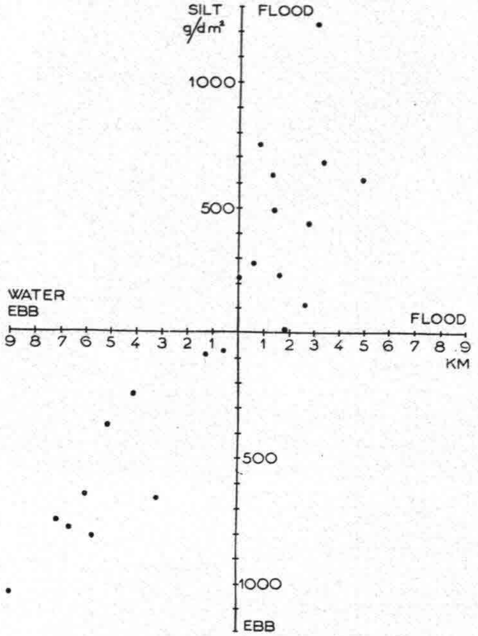

Fig. 37. Relation between the residual transport of water, expressed in km, and residual transport of silt, expressed in g/dm², at the main stations of fig. 22.

Attention may once more be drawn here to the fact that the observations were carried out under normal wind conditions. However, especially on days with strong winds or storm, much more particulate matter is brought into suspension and transported than is normally the case. Since most strong winds blow from the south-west it is possible that this causes an over-all transport of water and silt to the north-east, that is from the North Sea to the Wadden Sea and from one part of the Wadden Sea to the other. This residual transport may quantitatively be of much importance. One might ask whether it means a gain of silt for the Wadden Sea area. The answer must remain doubtful. The Marsdiep area will probably lose silt in this way, since North Sea water, relatively poor in suspended silt, will enter the area through the Marsdiep and water rich in silt is moved to the east.

Another effect of strong winds may be of even more importance. Although these matters are to be discussed in later chapters it may be mentioned here already that the quantity of suspended silt present in the Wadden Sea depends among other things on the rate of water exchange between the Wadden Sea and North Sea. The rate of exchange is certainly accelerated by strong winds and this will cause an extra transport of suspended silt back to the North Sea, especially since it is combined with higher concentrations of silt in suspension.

The quantity of silt supplied to the Wadden Sea by the IJsselmeer can easily be calculated since both water discharge (16.8 × 10^6 m^3) and silt concentration (15 mg/l) are known (tables 1 and 14). It

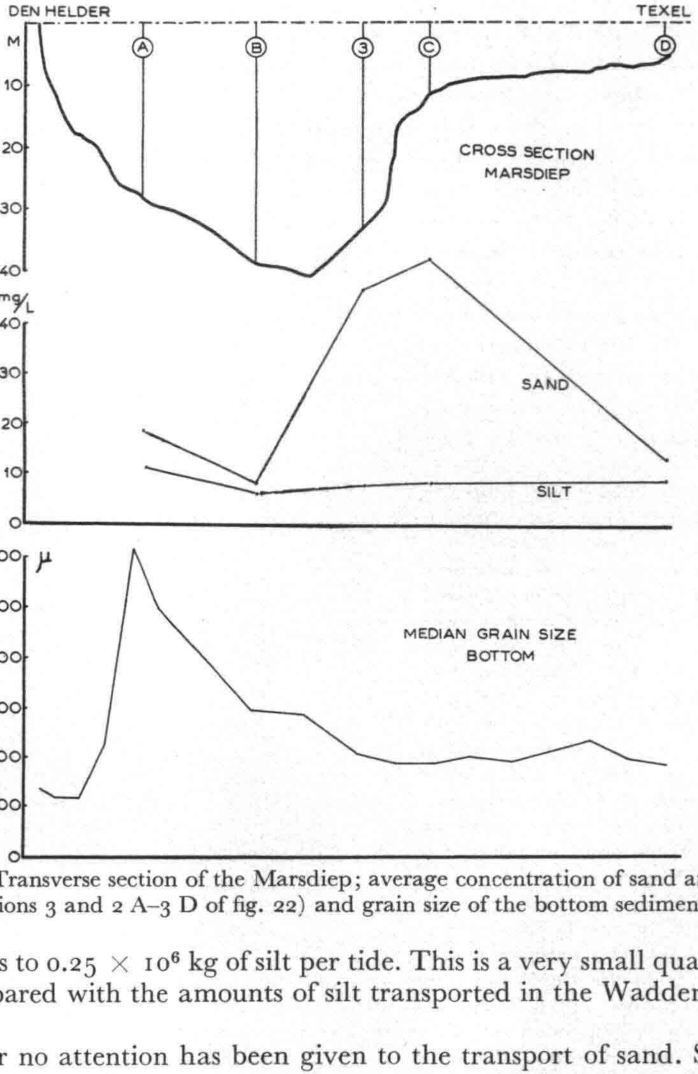

Fig. 38. Transverse section of the Marsdiep; average concentration of sand and silt (stations 3 and 2 A–3 D of fig. 22) and grain size of the bottom sediment.

amounts to 0.25 × 10^6 kg of silt per tide. This is a very small quantity as compared with the amounts of silt transported in the Wadden Sea itself.

So far no attention has been given to the transport of sand. Some information on this point can be obtained from the data of tables 8 and 13. The differences between individual stations as regards the concentration of sand are much larger than in the case of silt; the measurements along the cross-section of the Marsdiep may serve as an illustration (fig. 38). Obviously changes in the disposition of bottom material are greater in one place than in another; probably channels and flats become deeper at certain points and are more or less filled up at others. For example, FERGUSON (unpublished report of the „Rijkswaterstaat", 1943) has observed that the tidal channel Molengat, west of the Marsdiep, grew deeper during the period 1935–'38, while at the same time the Texelstroom, east of the Marsdiep, became shallower. This may partly be due to transport of sand from one channel to the other.

The transport of sand into the Wadden Sea has been discussed in greater detail by VAN BENDEGOM (1950), who supposes that the Wadden Sea bottom follows the rise in mean sea level, which would involve a transportation of sand from the North Sea to the flats. This sand is provided by the Dutch North Sea coast. From the rate of coastal recession during the last 100 years VAN BENDEGOM calculated that every year about 3.5×10^6 m^3 of sand would be available for the western Wadden Sea. Of this amount about 1.75×10^6 m^3 of sand/year or about 2.5×10^6 kg (dry weight) per tide may enter the area through the Marsdiep. The amount of water transported through this tidal inlet by ebb and flood being about 10^9 m^3, a surplus concentration of 2.5 mg/l during the flooding tide would be sufficient to bring about such a movement of sand. Actually, the average concentration of sand in the water passing through the Marsdiep amounts to about 30 mg/l (table 8, stations 3 and 3A–3D, and fig. 38), so that a difference of 2.5 mg/l might easily escape observation, especially because much sand may be transported along the bottom, and therefore not be observed in sampling. Therefore the data for sand, in contrast to those for silt, have little value for transport calculations.

5. THE ACCUMULATION OF SUSPENDED SILT

It has been shown on p. 57 (figs. 32, 33 and 34) that the concentration of suspended silt in the Wadden Sea is considerably higher than in the North Sea. As the exchange of water between the two areas is intensive (see chapter II), this ought to cause a residual transport of silt along the gradient from the former area to the latter. In trying to evaluate the extent of such a residual transport we may assume that the distribution of suspended silt agrees with that of the fresh water (compare figs. 33 and 14 B). In that case during every tide about 8% of the excess of suspended silt in the Wadden Sea must be transported to the North Sea. If the surplus concentration of silt is taken to be $18 - 6 = 12$ mg/l (pp. 57 and 58), and the high tide volume of the Marsdiep area is put at 3.1×10^9 m^3 (table 1), the surplus transport by the ebb movement should amount to 3×10^6 kg per tide.

It may be assumed for a moment that this amount of silt is actually transported in the course of every tide to the North Sea. In that case this loss should be neutralized by a gain from some source or other.

Since high silt concentrations are related with low salinity values, it may be asked whether the supply of silt from the IJsselmeer yields sufficient quantities. As a matter of fact, the amount of 0.25 × 10^6 kg per tide found on p. 64 is almost negligible if compared with the quantity of 3 × 10^6 kg to be accounted for. Besides, no considerable quantities of fresh water are discharged into the eastern part of the Dutch Wadden Sea, where the silt concentrations are also high.

The suggestion might be made that fresh amounts of silt are constantly brought into suspension by abrasion from the bottom of the Wadden Sea or certain sections of the coast. This appears to be the case in the Danish Wadden Sea, according to GRY (1943). However, neither extensive changes in bottom configuration nor coastal erosion take place in the Marsdiep area.

As no other sources for the supply of silt than the above-mentioned ones are available, one is led to the conclusion that eventual losses to the North Sea must be balanced by a gain from the same area. This conclusion is also supported by the observations on p. 63, which show that the amounts of silt transported through the tidal inlet by the ebb tide and the flood tide are approximately equal. As the total transport of silt during ebb or flood is 8 × 10^6 kg, an ebb surplus of 3 × 10^6 kg would most probably not have escaped observation.

If, however, no excess transport of silt to the North Sea should exist, this would mean that silt is accumulated within the Wadden Sea against its own gradient. In others words, the levelling effect of the water exchange between Wadden Sea and North Sea would be opposed by a force causing accumulation of silt, especially in the interior part of the Wadden Sea. A state of equilibrium would be reached if the two forces neutralized each other.

In this connection the following argument may be enlightening. We may for a moment assume that some dissolved, non-suspended substance is present in a higher concentration in the Wadden Sea itself than in the North Sea, for example because a surplus of the substance is temporarily introduced into the area together with the fresh water. In fact, fresh water itself may be regarded as a "negative" dissolved substance. It is self-evident that some time after the supply has been cut off, the higher concentration of the Wadden Sea will have dropped again to the concentration of the North Sea. If, therefore, such a levelling effect is not found in the case of silt, one may well ask whether this can be due to the fact that silt is not a dissolved, but a suspended substance. Contrary to the concentration of most dissolved substances, the concentration of suspended substances increases downwards from the surface to the bottom. Moreover, the concentration of the latter is subject to tidal variations (see figs. 23, 24 and 25). The accumulation of silt may therefore either be caused by the gradient of silt along the vertical or by tidal differences in silt concentration. Both possibilities will be discussed here.

1. An increase in silt concentration from the water surface to the bottom could result in an accumulation of silt, if the bottom water were to show an over-all transport in the direction of the interior of the Wadden Sea and the surface water a similar transport in the opposite direction. This would cause a surplus transport and an accumulation of suspended silt inward. In a state of equilibrium the loss in one direction would neutralize the surplus transport in the other.

The above-mentioned circulation of water frequently occurs in estuaries, but is not found in the Wadden Sea, with the exception of the areas quite near the IJsselmeer sluices. Therefore, the explanation offered certainly does not hold for the Wadden Sea as a whole. A second objection is the existence of high silt concentrations near the Frisian coast, where no large quantities of fresh water are discharged and, consequently, no circulation of the type discussed above exists. It must therefore be concluded that the explanation suggested is not capable of general application.

Attention may be drawn here to another effect of fresh water on suspended silt. It is generally assumed that mixing of fresh and salt water causes colloidal and finely divided suspended matter to combine to particles of larger size. Such particles will settle more easily. The same accumulation of silt results from the activity of molluscs, which with their filtering mechanisms produce faecal pellets (VERWEY, 1952). These processes probably support the accumulation of silt both at the bottom and in the water, but they do not provide an explanation for the mechanism of this accumulation.

2. It may also be suggested that the transport of silt into the Wadden Sea against the gradient is in some way or other caused by the variations in silt concentration during the tidal cycle. This transport may be supposed to neutralize an equally large loss of silt in an opposite direction, caused by the water exchange in the same direction as the silt gradient.

The tidal variations of silt must then be supposed to act in such a way that the pattern of behaviour exhibited by ebb and flood in relation to silt is asymmetric, the ebb tide not being able to carry back all the silt carried inward by the flood.

In this connection attention may be drawn to fig. 39, which shows the percentages of silt in bottom samples taken by the Zoological Station for biological purposes (see also HANSEN, 1952). Unfortunately the samples are not divided equally over the area, data relating to flats being scarce. Nevertheless, the difference between the distribution of sand and that of silt is clearly brought out. This divergence is in the first place caused by the progressive decrease of water movement from

Fig. 39. Mud content of bottom samples collected with a Van Veen bottom sampler, primarily for biological research. Large circles indicate mud to half sand–half mud, smaller circles half sand–half mud to sand with little mud, smallest circles sand with very little or no mud, points coarse sand, often with gravel and shell remains.

the North Sea to the Wadden Sea interior. A soft bottom can never exist in places frequently exposed to the impact of waves or places where strong currents prevail. Silty areas are therefore restricted to flats protected against strong winds by the coast and some places near the coast too deep for the impact of waves to have any effect, and without strong currents (for example Vlieter and Amsteldiep, fig. 2).

If fig. 39 is compared with fig. 33, we are struck by the fact that the distribution of bottom silt corresponds to a notable degree with the distribution of suspended silt. The effect that creates the silt gradient may therefore also be connected with decreasing water movement from the outer to the inner part of the Wadden Sea. This point of view is also supported by the fact that the tidal flats in the eastern Dutch Wadden Sea, better sheltered from strong winds than those of the western Wadden Sea, besides being more silty, are also marked by very high quantities of suspended silt (KAMPS, personal communication).

In view of these considerations we may try to base an explanation on what we know about the inertia exhibited by suspended silt in reacting to changes of currents, discussed on p. 43–48. It has been shown that the amount of silt in suspension at each phase of a period of increasing current velocity is constantly lower than the amount found for the corresponding velocity after the steady state has been attained; during decreasing current velocity the reverse was found to be the case.

If we follow up this line of thought, the behaviour of a certain mass of water during its displacement by the flood may be studied. As long as the mass of water is travelling in the large channels, its flow is much faster than it becomes farther inward, and it contains the amount of silt appropriate to the turbulence caused by this rate of flow. More or less gradually, however, the mean current velocity decreases. The silt content being too high in relation to this slower rate of flow, part of it will slowly settle to the bottom. Because silt reacts so slowly to velocity changes, however, it will be transported farther in flood direction than would have happened if sinking took no time.

After the turn of the tide the mass of water will move in an opposite direction. However, the inert reaction of the silt to the decrease of current velocity during the transport inward has caused the silt to settle in places, where the current is actually too weak to carry it away. Therefore, if ebb and flood have about the same current velocity, a certain fraction of silt is left behind on the bottom. The latter therefore receives a second enrichment of silt above the one caused in the first instance by the decrease in water movement towards the Wadden Sea interior. The process repeats itself during every tidal period, until the bottom has become so silty, and the concentration of silt in the water overhead has become so high, that the gradient of silt thus generated neutralizes the residual transport inward.

The explanation of silt accumulation as developed above, if true, will hold for the whole of the Wadden Sea, since it is based on the progressive decrease of water movement towards the coast. In different localities, however, other forces may also play a rôle or be of even more importance. Near the mouths of the rivers Ems, Weser and Elbe, the supply of fresh water may exert a much greater influence than in the Dutch Wadden Sea and the explanation given on p. 67 may be valid. As said before, GRY (1943) has shown that in the northern part of the Danish Wadden Sea high concentrations of suspended silt are caused by erosion of coastal marshes. The same may be the case in other areas.

It may further be remarked that according to the above theory the silt gradient depends not only on the decrease in current velocity or, to put it more generally, on the decrease in water movement inward, but also on the concentration of suspended silt in the North Sea.

It may finally be observed that accumulation of silt in either the first or the second way discussed above may also occur in other estuaries than those of the Wadden Sea region. Especially the accumulation of suspended matter caused by estuarine water circulation (p. 24) may be of more widespread importance. The Nieuwe Waterweg near Rotterdam may serve as a fine example, compare CANTER CREMERS (1921). Many coastal harbours where fresh water is discharged may provide other instances.

IV. THE CYCLE OF ORGANIC MATTER

From a biological point of view organic matter constitutes the most important part of the suspended material. Sessile plants being practically absent, the production of particulate organic material by phytoplankton organisms forms the basis of animal life and determines its density. The main purpose of this chapter will be to gain an insight into this organic production.

Particulate organic matter, from a non-biological point of view, behaves as part of the suspended matter. This point will be treated in detail. Moreover, a study will be made of the seasonal variations of organic matter caused by varying rates of decomposition and production in the course of the year. Further, the exchange of organic matter between Wadden Sea and North Sea will be discussed. It will be shown that there is a residual transport of organic matter from the North Sea into the Wadden Sea. An attempt will be made to evaluate the quantitative importance of this transport and, further, to determine total phytoplankton production and mineralization of organic matter in the Marsdiep area. In this connection a study was made of the cycle of phosphorus and of chlorophyll, the former being a factor regulating production, the latter being a measure for the amount of phytoplankton.

Observations on organic matter, phosphorus components and chlorophyll were mostly carried out along the same section where also salinity data were collected (fig. 13). To supplement these observations a number of measurements were carried out in other parts of the Marsdiep area, especially in the harbour of Den Helder, which provided a convenient opportunity for daily observations. The complete data are on file at the Zoological Station.

I. QUANTITY AND COMPOSITION OF PARTICULATE ORGANIC MATTER

If suspended matter is examined under the microscope, sand grains, pieces of shells and living plankton are easily discerned. Besides these, a relatively large amount of dead organic matter is found to be present. It will be referred to hereafter as detritus, which consists of dead organisms and all kinds of organic debris. The quantitative relation between dead and living organic matter is difficult to determine, but in the Wadden Sea the dead material certainly forms the major part, possibly up to more than 90% of the total (p. 98). For the North Sea VAN GOOR (1923, p. 173) estimated that the aggregate of organic detritus is 50–100 times as large as the amount of plankton organisms; this value, however, may be rather inaccurate. In the Bay of Kiel more than 95% of the particulate organic matter consists of detritus (GILLBRICHT, 1951), whereas in the English Channel this percentage amounts to only 15–30% (ARMSTRONG and HARVEY, 1950, p. 151).

VERWEY (1952) assumes that the high percentage of dead organic matter present in estuarine areas is caused by the mixing of different water masses. He supposes that part of the plankton organisms are killed by sudden changes of temperature and salinity (see also BROCKMANN, 1908, 1929 and KÜHL and MANN, 1953). In addition, however, the percentage of detritus may be influenced by water movement. In deep or quiet water plankton debris may disappear from the water column because it sinks down to the bottom, whereas in shallow areas settling of detritus may to a large degree be prevented by the influence of wind and currents.

In the particular case of the Wadden Sea it is further possible that here much suspended matter, containing living as well as dead organic material, is filtered from the water through the activity of molluscs, while only dead organic matter in the form of faecal pellets is returned (VERWEY, 1952). In this way the quantity of detritus may be augmented at the expense of living organic matter, although faecal pellets are perhaps not brought into suspension easily. We shall return to these points on p. 91–93

The chemical analyses of suspended matter have been discussed already on p. 9. Attention may be drawn here especially to the last column of table 4, giving the relation of C, N and P for the organic material. There are considerable differences in chemical composition from one sample to another, but the average of all determinations, 40: 7.4: 1, does not differ significantly from the relation 41 : 7.2 : 1 for living plankton (COOPER, 1934; FLEMING, 1940; KETCHUM and REDFIELD, 1949; for a summary see SVERDRUP, JOHNSON and FLEMING, 1946, p. 236; for North Sea samples compare also BRANDT and RABEN, 1920). Since it has been assumed that a large part of the organic matter consists of detritus, the relation apparently also holds for the latter, although, according to SEIWELL and SEIWELL (1938), phosphorus may be mineralized more easily than the other elements.

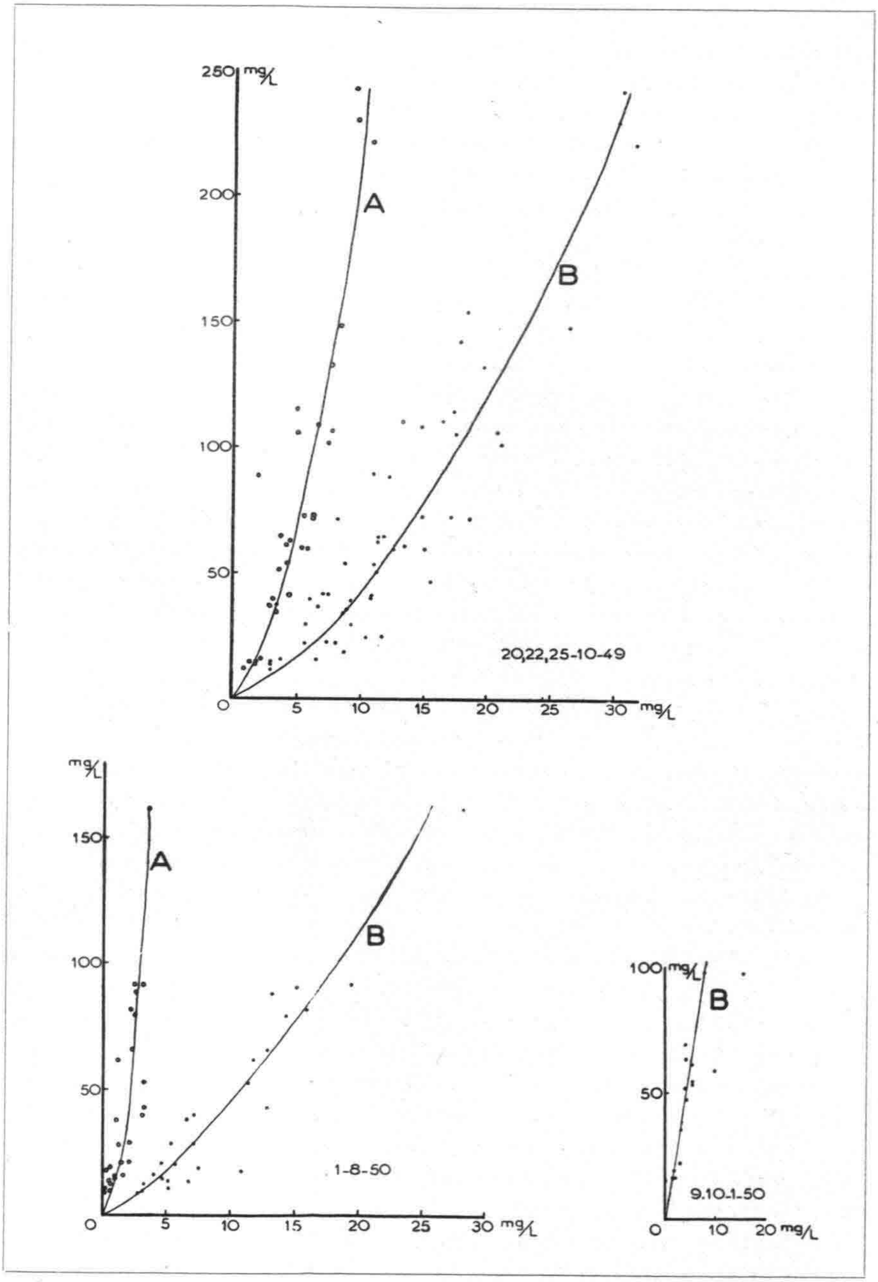

Fig. 40. Relation between total suspended matter and carbon dioxide content (A), resp. loss on ignition (B) for samples taken simultaneously along the section of fig. 13.

The amounts of organic matter present have been determined, first, by loss through ignition and, secondly, by ascertaining the quantity of particulate phosphorus. According to table 4, the phosphorus percentage amounts to about 1 % if the ratio of carbon to organic matter is put at 1 : 2.3. Other analyses, to be discussed below, give the somewhat lower value of 0.7 %.

2. THE RELATION BETWEEN SUSPENDED ORGANIC MATTER AND THE TOTAL AMOUNT OF SUSPENDED MATERIAL

It may be expected that particulate organic matter follows more or less closely the quantitative variations of total suspended matter. This

TABLE 16 A

Organic matter, estimated from loss on ignition minus CO_2, at the Wadden Sea stations of table 8; compare also fig. 22.

31-5-49	1	27.8	2.5	8.9	much sand
1-6-49	2	13.8	1.3	9.4	
2-6-49	3	32.2	2.6	7.8	much sand
3-6-49	4	22.6	2.0	8.9	much sand
9-6-49	5	30.8	4.1	13.3	
10-6-49	6	27.5	4.4	15.6	
11-6-49	7	13.1	2.7	20.7	
13-6-49	8	34.6	4.3	12.4	
14-6-49	9	27	3.9	14.4	only surface

TABLE 16 B

Organic matter, estimated from loss on ignition minus CO_2, at the North Sea stations of table 13; compare also fig. 1.

23-6-49	1	Surface	7.5	1.2	
		Bottom	16.4	1.4	
		Total	*12.0*	*1.3*	*10.8*
23-6-49	2	Surface	7.9	1.9	
		Bottom	18.0	3.5	
		Total	*13.0*	*2.7*	*20.8*
23-6-49	3	Surface	7.9	1.6	
		Bottom	8.2	1.5	
		Total	*8.1*	*1.6*	*19.8*
23-6-49	4	Surface	5.3	0.8	
		Bottom	7.5	0.8	
		Total	*6.4*	*0.8*	*12.5*
23-6-49	5	Surface	5.9	0.9	
		Bottom	3.6	0.9	
		Total	*4.8*	*0.9*	*18.8*
23-6-49	6	Surface	5.5	1.2	
		Bottom	6.6	0.8	
		Total	*6.1*	*1.0*	*16.4*

supposition is confirmed by observations along the section of fig. 13. The increase in total suspended matter causes an increase of its organic component, the relation between the two being best represented in most cases by a curved line, indicating that on the whole organic matter is more easily kept in suspension than the inorganic material (figs. 40 and 41).

Since it may be assumed that there is a direct correlation between the quantity of organic matter and the quantity of silt (suspended matter minus the sand fraction) the geographical distribution of organic matter will roughly correspond with the distribution of silt. If that

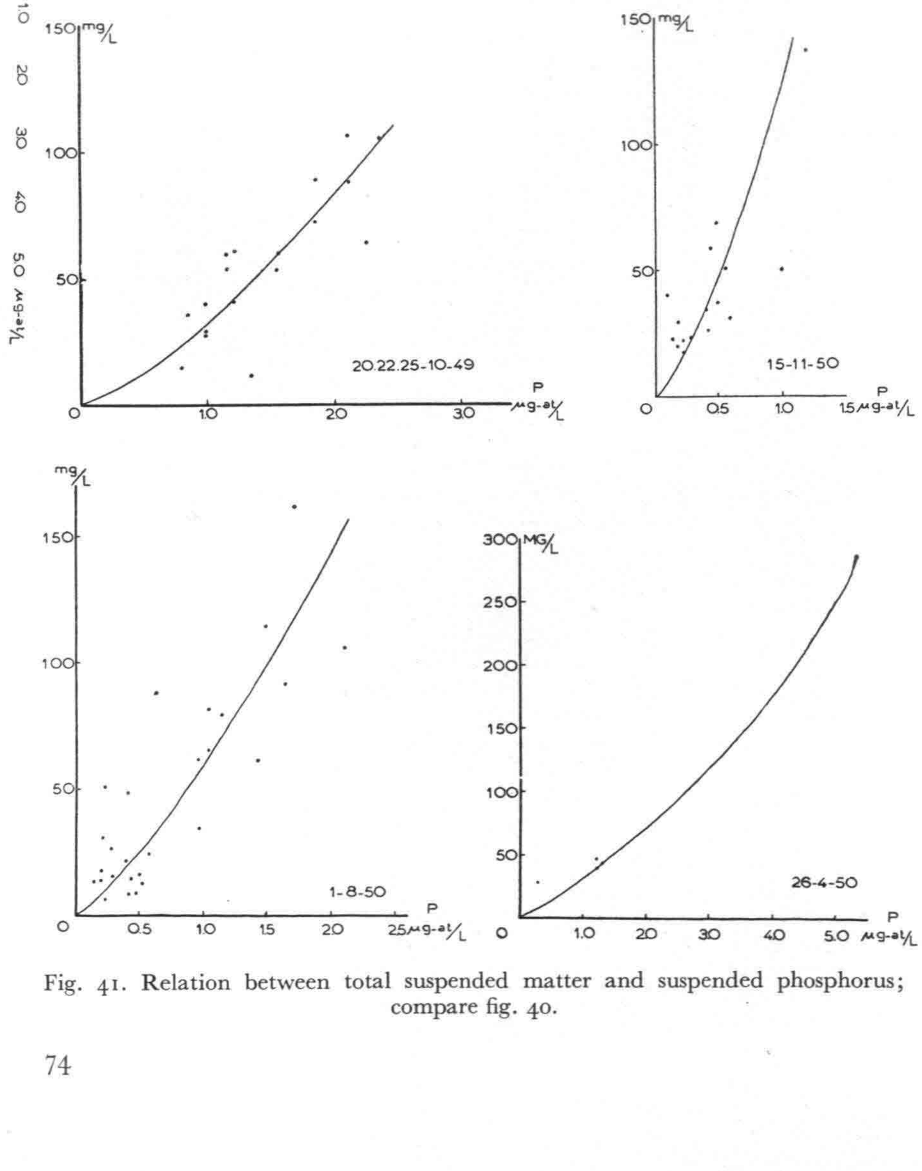

Fig. 41. Relation between total suspended matter and suspended phosphorus; compare fig. 40.

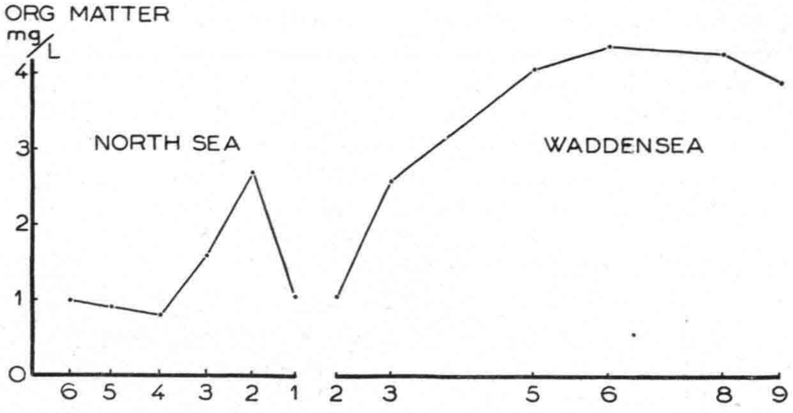

Fig. 42. The progressive increase of suspended organic matter from the North Sea to the Wadden Sea, June 1949; based on table 16.

is actually the case, the concentration of suspended organic matter of the Wadden Sea will be from two to three times higher than that of the North Sea. This is confirmed by measurements of organic matter at stations in both areas during a complete tidal period (table 16, fig. 42).

The conclusion seems justified that the concentration of suspended organic matter in the Wadden Sea is maintained at its high level in the same way as described for suspended silt in chapter III. However, in contrast to silt, organic matter is constantly in process of decomposition and synthetization. Therefore, a larger production of organic matter in the Wadden Sea itself than in the North Sea may perhaps also account for this gradient. We shall revert to this point on p 99.

A comparison of the graphs of figs. 40 and 41 makes it seem quite probable that the amount of organic matter present changes in the course of the year. The concentration of suspended organic matter is relatively high in summer and low in winter. A more complete insight into seasonal changes is obtained by considering all the different types of observations available. Most of these observations were carried out along the section of fig. 13; a number of others refer to measurements carried out at other points of the Marsdiep area, especially in the harbour of Den Helder.

For every set of simultaneous observations the average quantities of both organic and suspended matter were determined. As the average quantity of suspended matter of the Marsdiep area is 23 mg/l (p 57), all observations have been reduced to this mean value by means of graphs like those of figs. 40 and 41. In this way the influence of quantitative variations of suspended matter has been eliminated, and the figures for organic matter thus will roughly represent the average amounts present. The results of the calculations are given in fig. 43, one curve showing the seasonal changes of particulate P, the other the quantitative variations of organic matter as derived from the difference between ignition loss and carbon dioxide content. The latter is assumed to be constant all the year round and therefore represented by a horizontal line, indicating the mean of the CO_2-analyses, which is 1.8 mg/l or 8% of the total of suspended matter. In summer organic matter is found to amount to about 4 mg/l or 17% of all suspended material, in winter it decreases to about 1 mg/l or 4%. Suspended phosphorus shows roughly the same variations. The phosphorus percentage of organic matter appears to amount to about 0.7%, which is somewhat lower than the figure derived from the analyses of table 4.

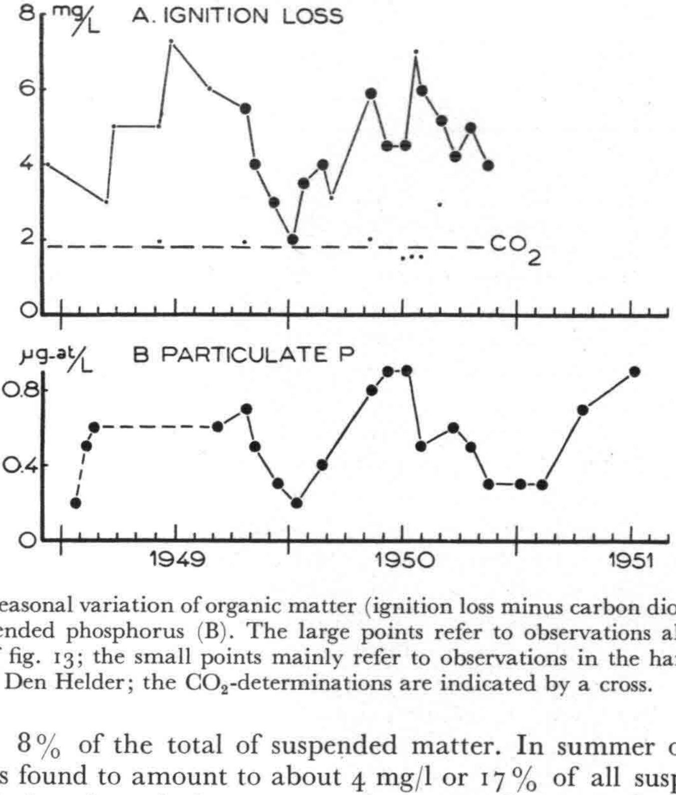

Fig. 43. Seasonal variation of organic matter (ignition loss minus carbon dioxide, A) and suspended phosphorus (B). The large points refer to observations along the section of fig. 13; the small points mainly refer to observations in the harbour of Den Helder; the CO_2-determinations are indicated by a cross.

Although every single point of fig. 43 is based on a set of observations, the resulting curves derived are believed to indicate only the general trend of quantitative changes of organic matter and no special value must be attached to the position of summer maxima and winter minima.

Doubt may arise, moreover, if it is permissible to assume that the average quantity of suspended matter amounts to the same value of 23 mg/l the whole year round, because the winter averages proved to be greater than those of the summer months

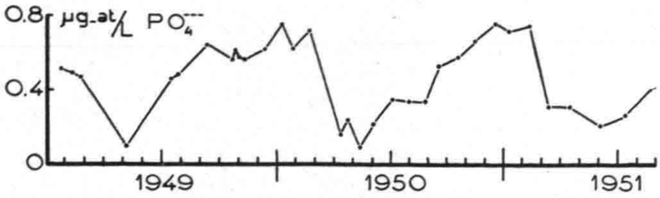

Fig. 44. Seasonal variation of phosphate in the Wadden Sea; average of the observations along the section of fig. 13.

(p. 54). However, this difference is caused by a more frequent occurrence of days with much wind during the winter months. If these days are excluded, the winter values for suspended matter are probably not very different from the summer values. Since observations were nearly always carried out under quiet weather conditions, also in winter, the summer figures are probably directly comparable with the winter figures.

So far the following conclusions can be drawn. Generally speaking, the quantity of suspended organic matter in the Wadden Sea is roughly proportional to that of suspended silt. Therefore, the distribution of organic matter is probably about the same as that of silt as shown in fig. 33 and the concentration within the Wadden Sea is high as compared with that in the North Sea. Further, suspended organic matter is subject to seasonal variations, the quantities being higher in summer than in winter.

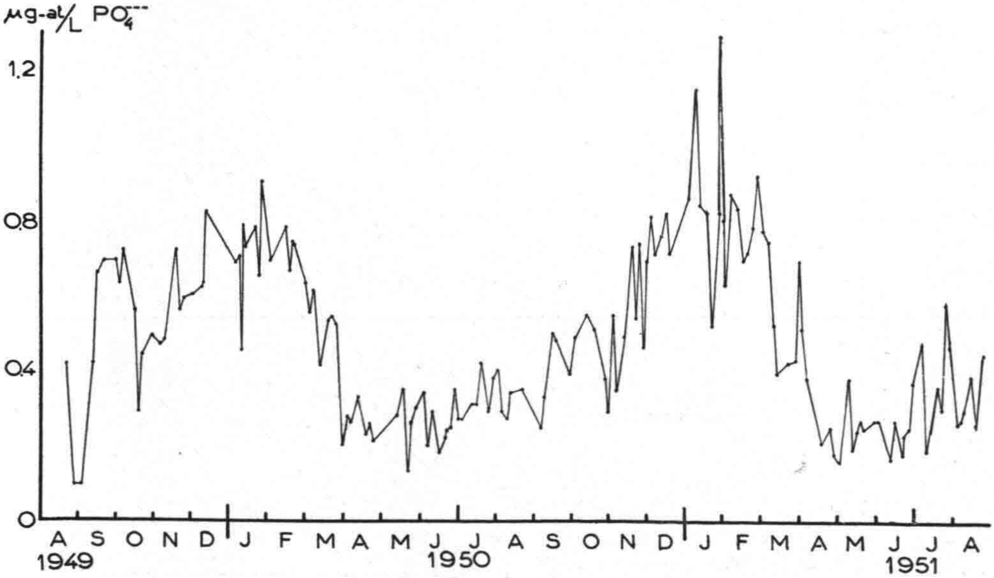

Fig. 45. Seasonal variation of phosphate in the harbour of Den Helder; observations from the water pumped daily at high tide from about 1 m below the surface into the aquarium of the Zoological Station.

3. THE CYCLE OF PHOSPHORUS

Since phosphorus is essential to the production of organic matter, more information on the cycle of organic matter may be obtained by studying the variations in the components of this element. It is present in an organic as well as an inorganic form and, besides, in a dissolved and a particulate condition. Probably, inorganic particulate P is quantitatively of minor importance, compare p. 13; thus three forms of P remain

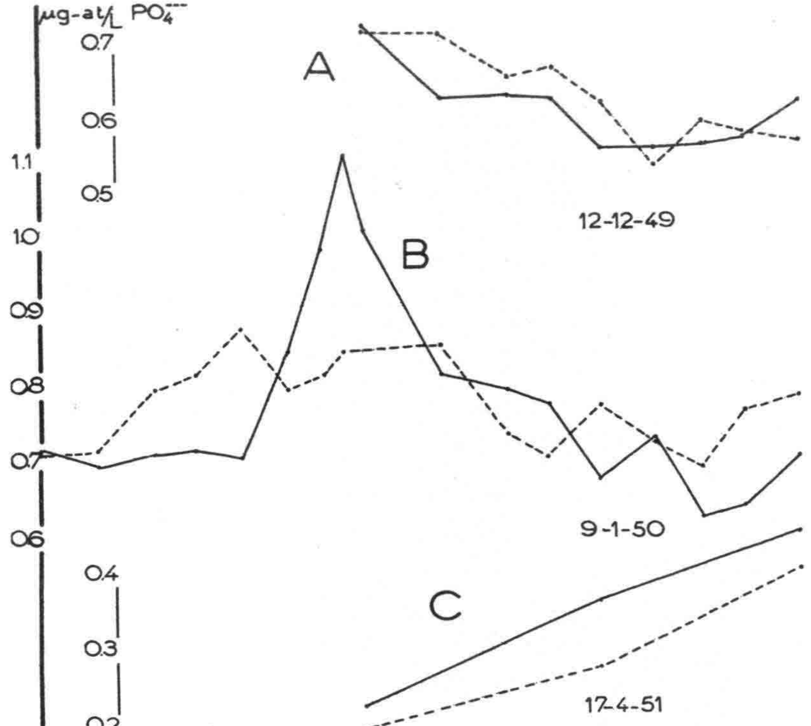

Fig. 46. Examples of the phosphate observations along the section of fig. 13.

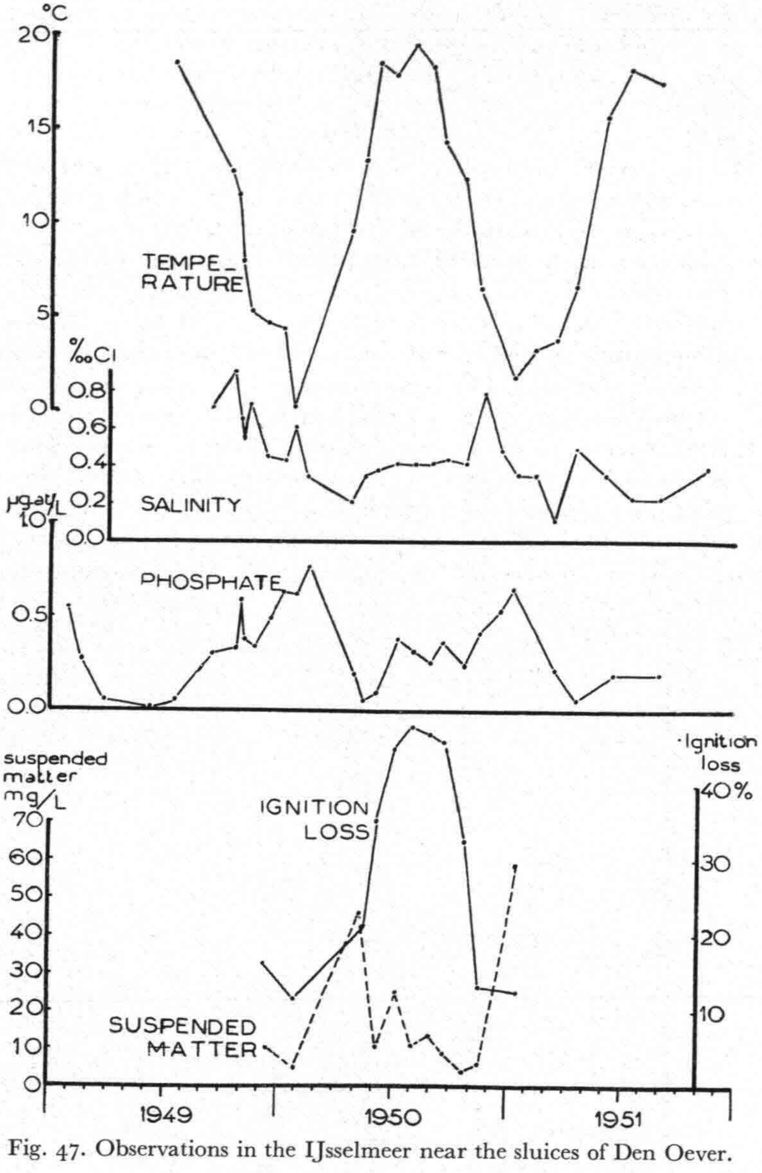

Fig. 47. Observations in the IJsselmeer near the sluices of Den Oever.

to be discussed: phosphate, dissolved organic phosphorus and particulate organic phosphorus. These three components will first be discussed separately; after that their mutual relation will be examined.

A. Phosphate

The seasonal cycle of phosphate was studied by SCHEELE and VERWEY (unpublished) from 1936 to 1940 in the harbour of Den Helder. This study was continued in 1948 and extended, moreover, over the whole of the Marsdiep area. As mentioned before, regular observations were carried out in the section of fig. 13.

Phosphate is subject to seasonal changes and shows a marked geographical distribution. The seasonal cycle of phosphate is represented in figs. 44 and 45. The annual variation corresponds with the results of similar observations carried out in other places, for example the English Channel, compare for example ARMSTRONG and HARVEY, 1950. In winter decomposition of organic matter prevails over assimilation and organic phosphorus is mineralized to phosphate; in spring and summer Wadden Sea phosphate is consumed by phytoplankton. The maximum occurs in January, the minimum in May. Evidently, phos-

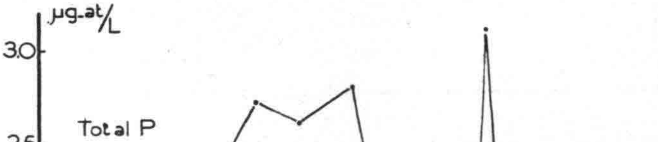

Fig. 48. Observations in the IJsselmeer near the sluices of Den Oever; phosphorus compounds.

phorus is a limiting factor for phytoplankton growth, since in spring phosphate is completely or nearly used up.

The data of stations 1–17 of fig. 13 may be used to form an idea of the quantitative distribution of phosphate. Some series of observations are given in fig. 46. The differences in phosphate-concentration from station to station are small, although salinity differences are often considerable. Apparently, the phosphate-concentration of the IJsselmeer, contrary to what might be expected, is about as high as that of the Wadden Sea itself. This conclusion is borne out by measurements in the IJsselmeer, which show that the concentration is even somewhat lower there (fig. 47). – Further, phosphate in the North Sea will be expected to be about as high as in the Wadden Sea. Observations, however, carried out some fifteen kilometers outside the tidal inlet, show that PO_4-values are somewhat lower here too (fig. 49, table 17).

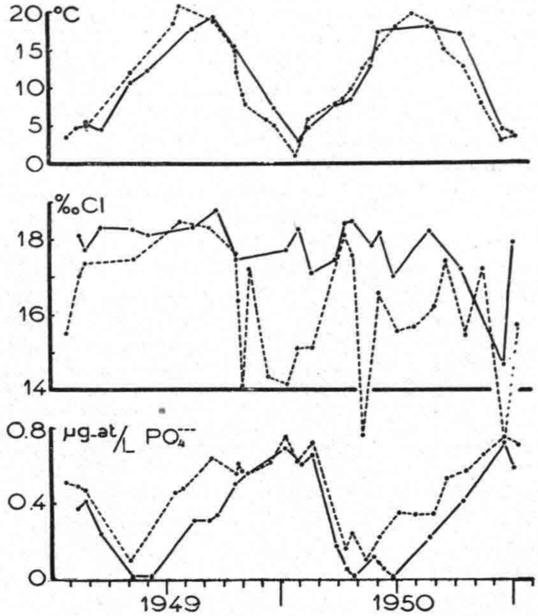

Fig. 49. Temperature, chlorinity and phosphate concentration of the North Sea (full-drawn line) compared with the Wadden Sea (dotted line). The North Sea values refer to observations about 15 km outside the Marsdiep; the Wadden Sea figures are averages of observations along the section of fig. 13; compare table 17.

In view of the difference in phosphate content between the North Sea and the Wadden Sea and the exchange of water between the two areas, phosphate concentrations would be expected to increase slowly inward into the Wadden Sea. However, an examination of fig. 46 and all other data available shows that this is the case in only a few sets of observations. In about as many cases the reverse is true and often there is no significant difference. Consequently, the fall from the standard of concentration of the Wadden Sea to that of the North Sea must take place in the relatively short stretch of about 15 km outside the tidal inlet. The following two reasons may probably account for this abrupt gradient. First, near the sluice of Den Oever the phosphate concentration is reduced in periods of a large supply of fresh water, because the IJsselmeer has a lower phosphate concentration than the Wadden Sea (fig. 47). Secondly, the fresh water discharged in relatively small amounts into the harbour of Den Helder contains very large amounts of phosphate, on an average about 20 µg-at/l (table 18). Therefore, the admixture of even small amounts of this kind of water already causes an appreciable rise of phosphate. In this way a phosphate gradient inside the tidal inlet is probably levelled out and the fall to the North Sea value must take place just outside the tidal inlet.

The fresh water discharged into the harbour of Den Helder originates from the Noordhollandsch Kanaal. The high phosphate content of the canal is partly caused by sewage from the town of Den Helder, partly supplied by a large area south of this town. That large quantities of phosphate may here be involved will appear from the following computation. The phosphate concentration being 20 µg-at/l and the water discharge per tide 0.8×10^6 m^3, the quantity of phosphate supplied to the Wadden Sea amounts to 16.0×10^9 µg-at, or 480 kg per tide. For the IJsselmeer these figures are 0.3–0.4 µg-at/l, 16.9×10^6 m^3 per tide and 6.8×10^9 µg-at phosphate or 204 kg of P per tide respectively. The canal therefore supplies more

TABLE 17

Phosphate and dissolved organic phosphorus in the North Sea; compare also fig. 47.

Date	*Temp., °C.*	*Cl, $^0/_{00}$*	*PO_4, µg-at/l*	*Diss. org. P, µg-at/l*	*Total diss. P, µg-at/l*	*Station*
1- 2-50	2.90	18.24	0.60	0.30	0.90	Outer buoy Molengat
1- 2-50	3.15	18.85	0.47	0.21	0.68	Lightvessel Texel
21- 2-50	5.03	17.12	0.60	0.23	0.89	Outer buoy Schulpengat
29- 3-50	7.56	17.43	0.17	0.46	0.63	Outer buoy Schulpengat
12- 4-50	7.88	18.37	0.05	0.63	0.68	Outer buoy Schulpengat
25- 4-50	8.51	18.44	trace	0.59	0.59	Outer buoy Schulpengat
25- 5-50	12.84	17.83	0.12	0.62	0.77	Outer buoy Schulpengat
7- 6-50	17.21	18.13	0.05	0.41	0.46	Outer buoy Schulpengat
27- 6-50	—	18.10	0.05	—	—	Lightvessel Texel
27- 6-50	—	17.04	—	0.58	0.58	Outer bouy Molengat
24- 8-50	18.11	18.18	0.22	0.56	0.78	Outer bouy Schulpengat
11-10-50	17.13	17.22	0.41	0.24	0.66	Outer buoy Schulpengat
20-12-50	4.47	14.64	0.72	—	—	Outer buoy Molengat, surface
20-12-50	4.42	16.68	0.50	0.17	0.67	Outer buoy Molengat, bottom
20-12-50	6.56	19.19	0.40	0.14	0.44	Lightvessel Texel, surface
20-12-50	6.71	19.16	0.36	0.14	0.50	Lightvessel Texel, bottom
3- 1-51	4.18	17.94	0.59	—	—	Outer buoy Schulpengat
6- 6-51	12.38	18.05	0.00	0.48	0.48	Lightvessel Texel
24- 8-51	18.00	17.27	0.18	0.65	0.83	Outer buoy Molengat
24- 8-51	18.01	17.82	0.21	0.54	0.75	Outer buoy Schulpengat

phosphate than the IJsselmeer. However, for total phosphorus the quantities are 650 and 1050 kg respectively, because the canal water contains only relatively little organic P, the IJsselmeer on the contrary considerable amounts (fig. 48).

Inside the harbour of Den Helder the large amounts of phosphate discharged with the fresh water cause an inverse relation of chlorinity and phosphate (fig 50). Outside the harbour this relation soon becomes imperceptible.

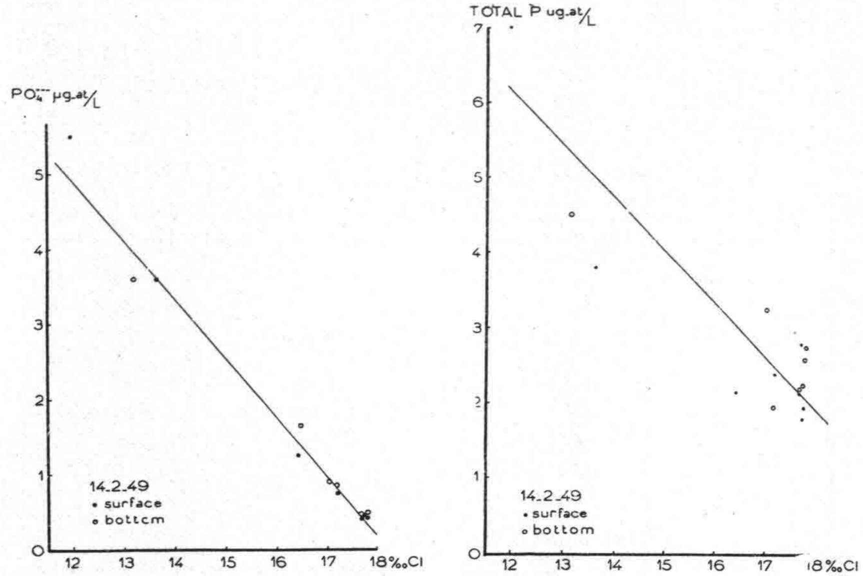

Fig. 50. Relation between phosphate, resp. total phosphorus, and chlorinity in the harbour of Den Helder.

Some sets of observations along traverses, running from Den Helder in a north-easterly direction, show that phosphate is evenly distributed through the whole Marsdiep area and adjoining areas (table 19). Higher values near Den Helder may again be explained from the influence of fresh water from the harbour.

B. Dissolved organic phosphorus

Measurements carried out along the section indicated in fig. 13 tend to show more pronounced differences in dissolved organic P from one station to another than in the case of phosphate (fig. 51).

In part these variations certainly represent actual differences, but they may to some extent, at any rate, also be due to less accurate analyses, although all determinations were run in duplicate; compare table 5.

Just as in the case of phosphate, the individual observations do not show a consecutive gradient of dissolved organic P in the direction of the North Sea or in the opposite direction. Nevertheless, as was shown

TABLE 18

Phosphorus content of fresh water discharged in the harbour of Den Helder; surface samples.

Date 1951	*PO_4, μg-at/l*	*Diss. org. P, μg-at/l*	*Part. P, μg-at/l*	*Total P, μg-at/l*
14-2	18.6	5.1	0.4	24.3
4-4	8.8	4.2	1.6	14.6
21-6	24.3	6.1	0.7	31.1
4-8	21.5	7.2	4.1	32.8
13-10	20.3	9.1	1.4	30.8
15-12	26.1	1.6	3.3	30.9
average	*19.9*	*5.5*	*1.9*	*27.4*

TABLE 19

Phosphate concentrations along a traverse from Den Helder to Terschelling and back through the North Sea; 21 and 22 September 1949.

Time	*Temp., °C.*	*Cl, $^0/_{00}$*	*PO_4^{---}, μg-at/l*	
21 Sept.				
14.45	18.35	17.50	0.88	Marsdiep
15.00	18.44	18.28	0.65	
15.10	18.32	18.28	0.69	
15.30	18.09	18.33	0.56	Texelstroom-Omdraai-Oude Vlie
15.45	18.07	18.33	0.52	
16.00	17.73	18.33	0.42	
16.15	17.64	18.41	0.46	
16.30	17.83	18.41	0.41	
16.45	18.08	18.43	0.43	
17.00	18.19	18.48	0.50	Watershed Marsdiep-Vlie area
17.06	17.85	18.43	0.43	Inschot-Vliestroom-Schuitengat
17.20	17.90	18.51	0.41	
17.35	17.73	18.49	0.41	
17.50	17.84	18.50	0.39	
18.05	17.84	18.44	0.45	
18.20	17.86	18.42	0.38	
18.35	17.82	18.43	0.36	
18 50	17.79	18.43	0.57	
22 Sept.				
6.30	17.40	18.43	0.50	
6.50	17.32	18.44	0.39	
7.05	17.64	18.46	0.41	
7.20	17.88	18.51	0.33	North Sea
7.35	18.09	18.51	0.31	
7.50	18.25	18.54	0.19	
8.05	18.29	18.51	0.35	
8.37	18.46	18.53	—	
9.07	18.52	18.65	0.26	
10.05	18.42	18.63	0.31	
10.35	18.40	18.34	0.32	
11.20	18.37	18.12	0.44	Marsdiep
11.35	18.29	18.12	0.44	
11.50	17.98	18.07	0.55	

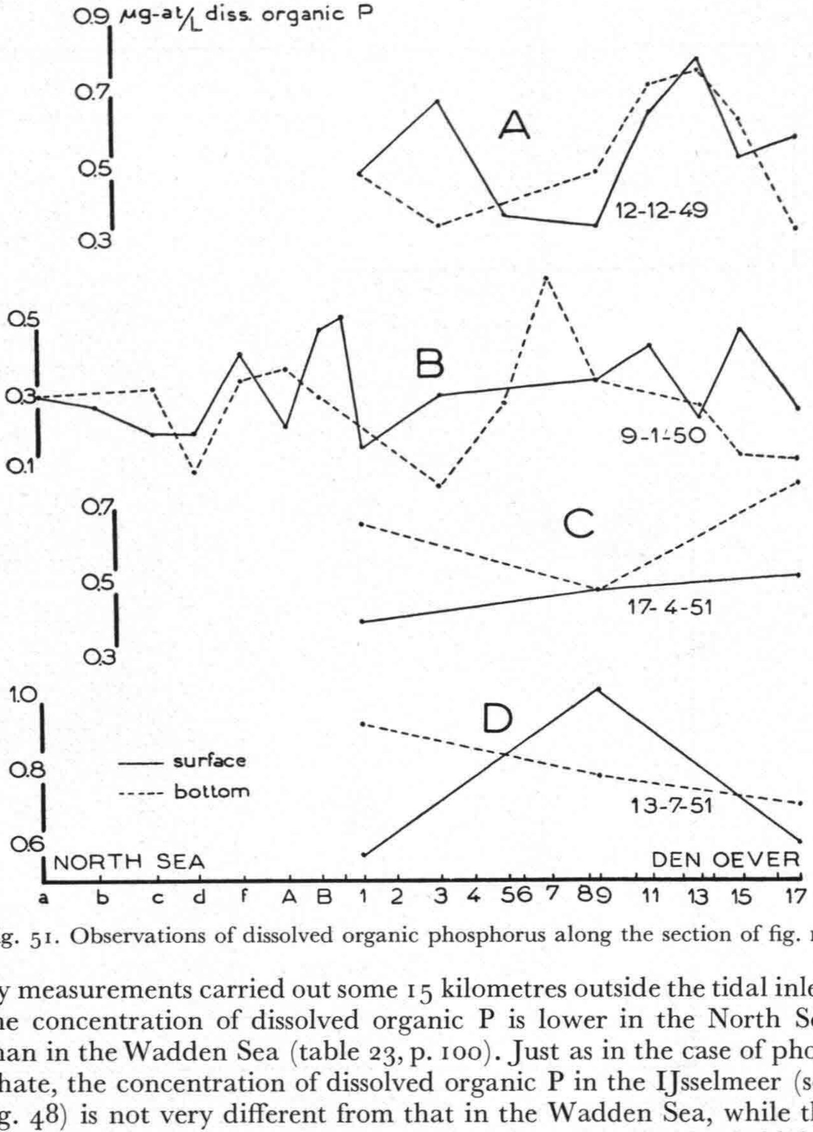

Fig. 51. Observations of dissolved organic phosphorus along the section of fig. 12.

by measurements carried out some 15 kilometres outside the tidal inlet, the concentration of dissolved organic P is lower in the North Sea than in the Wadden Sea (table 23, p. 100). Just as in the case of phosphate, the concentration of dissolved organic P in the IJsselmeer (see fig. 48) is not very different from that in the Wadden Sea, while the concentration in the fresh water discharged at Den Helder is higher (table 18). Thus the absence of a gradient of dissolved organic P may be explained in about the same way as in the case of phosphate.

The seasonal variation of dissolved organic P is roughly the reverse of that of phosphate, but runs parallel with that of particulate P (fig. 52). Apparently, the rise in organic suspended matter in spring on account of increased phytoplankton production is accompanied by a rise in soluble decomposition products containing phosphorus. The maximum of approximately 0.8 µg-at/l is about as high as the winter value for phosphate. In winter the concentration decreases to about 0.3 µg-at/l. Thus complete mineralization of all dissolved organic P is never attained. Because the seasonal variation in phosphate content runs counter to that of dissolved organic phosphorus, the seasonal changes in total dissolved phosphorus (phosphate plus dissolved organic P) are small (fig. 53). An inconspicuous minimum may occur in spring (1950: May–June, 1951: March).

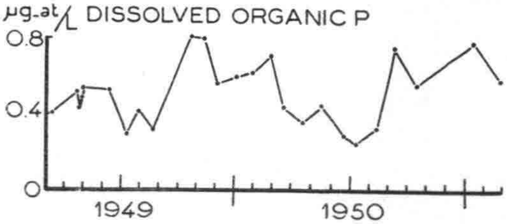

Fig. 52. Seasonal variation of dissolved organic phosphorus; averages of observations along the section of fig. 13.

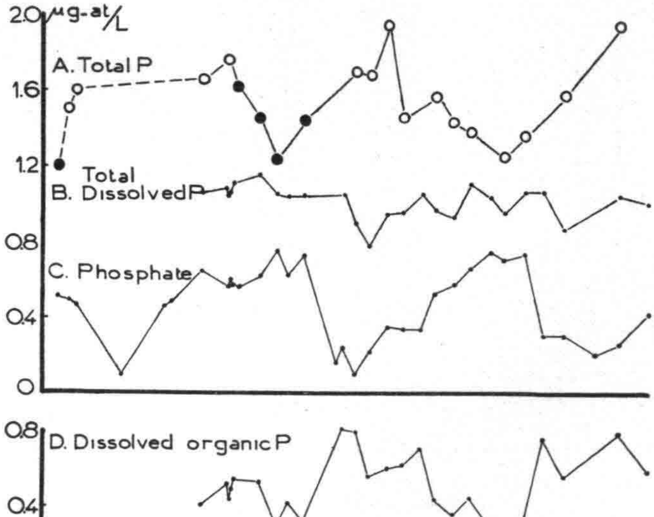

Fig. 53. Combination of figs. 43 B, 44 and 52, to show the seasonal variation of total phosphorus and total dissolved phosphorus; for explanation see text.

C. Suspended organic phosphorus

As has been said before, suspended phosphorus may contain a small quantity of inorganically combined P, but it is believed to consist mainly of organic phosphorus. Since this component has been discussed already on p. 13, a single remark may suffice here.

Maximum concentrations of particulate P occur in spring and summer when conditions for phytoplankton growth are most favourable (0.8 μg-at/l, fig. 53); the concentration is at a minimum in winter (0.2 μg-at/l). Even in summer, however, only a small part of all the phosphorus present is actually contained in living matter: the particulate P itself will partly be present in detritus, while about one half of the total P will be present as dissolved organic phosphorus.

4. THE EXCHANGE OF PHOSPHORUS BETWEEN WADDEN SEA AND NORTH SEA

It has been shown in chapter III that the concentration of suspended matter is higher inside the Wadden Sea than outside. This gradient has been explained as resulting from the balance of two opposing influences. One influence, the exchange of water between Wadden Sea and North Sea, tends to level the gradient. The other, probably connected with the progressive decrease of current velocities from the tidal inlet to the coast, tends to accumulate suspended matter against the gradient. This accumulating mechanism only affects suspended material.

Not only suspended matter, however, but also its organic component (including particulate P) and also the dissolved P (phosphate and dissolved organic P) were found to be present in higher concentrations inside the Wadden Sea than outside. Though it must be admitted that the gradient of dissolved P, as compared with that of particulate P, is only small (no more than about 0.2–0.3 μg-at/l from the inner part of the Wadden Sea to the outer), even this small gradient must cause a net transport of dissolved P from the Wadden Sea to the North Sea.

Although the above value of 0.3 μg-at/l is only a very rough estimate, it will here be used in an attempt to calculate the loss of dissolved P to the North Sea. This will be done by means of the rate of the exchange of fresh water, which is 8%, as we found in chapter II. The result of a computation based on these data will give us some idea of the quantity involved in spite of the fact that the geographical distribution of dissolved P is different from the distribution of fresh water. As a matter of fact, the actual distribution of dissolved P even seems to point to a greater transport to the North Sea than the above 8%, because comparatively high concentrations of this substance are even found quite near the tidal inlet.

Since the high tide volume of the Marsdiep area is 3.1 × 10^9 m^3, the total excess of dissolved P must be about 0.93 × 10^{12} μg-at/l or 30,000 kg dissolved P. On the strength of the above percentage of 8%, we find that about 2400 kg of dissolved P would be transported to the North Sea in every tidal period.

The question may be asked how this loss is compensated. First of all it seems natural to suppose that dissolved P is brought into the area together with the fresh water. Water rich in phosphorus from the harbour of Den Helder, however, contributes only about 500 kg per tide (p. 82). The supply from the IJsselmeer cannot increase the amount of dissolved P in the Marsdiep area, as the concentration in the IJsselmeer is too low. The supply of dissolved P by the fresh water is therefore insufficient to cover the loss.

It might further be supposed that the loss is neutralized at the expense of the store of phosphorus in the bottom. There is indeed an extensive exchange of P between the bottom and the water overhead, but it seems improbable that this exchange should, on the whole, show a balance in favour of the water rather than the reverse. It is more reasonable to suppose that on an average the total amount of P in the bottom remains the same.

The improbability of a sufficiently large and continuous supply of P by the bottom to compensate for a continuous loss of about 1900 kg P per tide can be shown as follows. Determinations on a rather silty tidal flat near Den Helder enable us to make a rough calculation of the quantities of P present in the bottom. The total P content of 10 samples, from a traverse 250 meters in length, was found to vary between 10.8 and 4.9 μg-at/per gram of material – dried and free of salt – with an average of 7.3 μg-at/g (table 20). Values of the same magnitude (about 10 μg-at/g) have been found by HÄNTZSCHEL (1939); compare also MOORE (1930, 1931). A bottom layer 1 cm in thickness may therefore contain about 73 mg-at or about 2 g P m^2. The P-content of bottom animals, which is about 0.2 g P m^2, can be left out of account[1]. The Mardiep area, covering 0.69 × 10^9 m^3 (table 1), may thus contain about 1.4 × 10^6 kg P in a layer of 1 cm. Therefore, if the bottom should have to supply 1900 kg P per tide or about 1.4 × 10^6 kg per year, every year a layer of about 1 cm would be deprived completely of phosphorus. Such a process could not possibly continue over many years.

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[1] VERWEY (1952) estimated the density of molluscs in this part of the Wadden Sea at some 10 individuals per m^2; a full-grown animal contains about 1 g of organic matter with a phosphorus content of about 1%. Hence these 10 animals contain about 0.1 g P. Other bottom animals may contribute the same amount.

TABLE 20

Phosphorus content of mud samples collected along a traverse over a tidal flat. Zuidwal, 11 September 1951.

Nr.	*Total P, μg-at/g dry material*	*Location*	*Nr.*	*Total P, μg-at/g dry material*	*Location*
1	10.8	Edge of bank	7	8.7	175 m
2	5.9	40 m from edge	8	7.6	190 m
3	4.9	70 m	9	6.6	205 m
4	5.8	100 m	10	7.8	220 m from edge
5	7.0	130 m			
6	8.2	160 m	average	*7.3*	

Since no sufficient quantities of P are supplied to the water of the Wadden Sea from the land-side or from the bottom of the Wadden Sea itself, it only remains possible to assume that the amount of dissolved P transported to the North Sea returns in some way or other from the same area.

In this connection the supposition developed in chapter III, that a balance of suspended matter is maintained between the North Sea and the Wadden Sea, might provide an explanation. As soon as the amount of particulate organic matter in the Wadden Sea decreases as a result of insufficient production, organic matter will be supplied from the North Sea, until a state of equilibrium is again attained. This means that the loss of dissolved P to the North Sea is neutralized by the transport of particulate organic P from the North Sea into the Wadden Sea.

The above assumption may also provide an explanation for the seasonal variation observed in total phosphorus (dissolved P + particulate P). Unless phosphorus is lost to other areas, the total phosphorus content of a certain mass of water will remain constant, whatever combinations may occur within the water mass itself. It appears from fig. 53 that in the Wadden Sea total P does not maintain a constant concentration all the year round, but is subject to seasonal changes. A minimum occurs in January and a maximum round about July. Apparently phosphorus is removed from the Wadden Sea water in autumn and supplied again in spring. We may ask how this is possible.

It might be suggested, that the seasonal variation in total phosphorus is caused by an exchange between the bottom and the water overhead, which would mean that phosphorus is released from the bottom in spring and taken up again in autumn. However, this is contrary to what might normally be expected. In spring and summer food is abundant and the bottom population increases and is more active, thus causing the fixation of organic matter, including phosphorus, at the expense of the water overhead. The reverse may take place in autumn and winter.

On the other hand the exchange of phosphorus between Wadden Sea and North Sea might also account for the seasonal changes. In the author's opinion it is indeed this phenomenon which is the real cause of the changes in total P content in the course of the year. On the strength of the argument set forth in preceding sections we may assume that part of the suspended organic matter in the Wadden Sea is provided by the North Sea; a decrease of suspended organic matter in the North Sea would therefore also cause a decrease in the Wadden Sea. Since the quantity of suspended organic matter, hence also of particulate P, in the North Sea is higher in summer than in winter, the Wadden Sea will follow these variations. In this connection it is of importance to note that the variation in total P content is in the first place caused by variations in suspended P. The concentration of dissolved P in the Wadden Sea exhibits only minor changes (fig. 53). Attention may yet be given to the quantitative relation between particulate P, dissolved organic P and phosphate (table 23). In the Wadden Sea these substances are found in the ratio of 1:0.9:0.8 (average of all data available), which figures are more in favour of particulate P than those for the North Sea near the coast, where the ratio is 1:1.6:1.2 (average of data of table 17). To find an explanation for this difference we may pursue a line of argument analogous to the one followed before. In the Wadden Sea particulate P is constantly maintained in a relatively high concentration, which is always about 2–3 times as high as in the North Sea. Dissolved P, on the contrary, is exchanged freely and therefore never attains values considerably higher in one area than in the other.

The question finally arises, why also the concentration of dissolved P is higher, though only to a small extent, inside the Wadden Sea than outside.

In this connection it must be realized that the presence of large quantities of suspended matter within this area may in itself be a sufficient reason for the occurrence of a high concentration of decomposition products. If two separate water masses, one containing more particulate organic matter than the other, are compared under the same conditions and in a state of equilibrium, it may be expected that also the quantity of dissolved P in the first volume will be higher than in the second.

We should not unduly simplify matters by assuming that, if the Wadden Sea were to be separated from the North Sea, the former would (after some time) contain particulate P and dissolved P in the same ratio as the North Sea. Still, if for a moment we allow this assumption, it may serve to illustrate the following point. The concentration figures of particulate P and dissolved P in the North Sea are 0.25 μg-at/l and 0.69 μg-at/l respectively (table 23). The Wadden Sea figure for particulate P is 0.5 μg-at/l; on the above assumption dissolved P ought to have a concentration of 1.38 μg-at/l. The difference between this theoretical figure and the concentration of 1.0 μg-at/l actually observed may be regarded as being due to the exchange of water between the two areas, which tends to reduce the value for dissolved P in the Wadden Sea to the North Sea concentration of 0.69 μg-at/l.

No importance must be attached to the above value of 1.38 μg-at/l. Nevertheless this hypothetical figure shows that an explanation of the higher concentration of dissolved P in the Wadden Sea simply as a result of the higher concentration of particulate organic matter is possible.

The amount of dissolved P may further be increased at the expense of particulate P through mineralization of the large amount of dead and living organic matter present on and in the bottom of the Wadden Sea. The quantity of organic matter that becomes decomposed will probably to a large extent be replaced by a supply of particulate P from the water overhead, although in some places bottom diatoms may also contribute to this amount (Gröntved, 1949). In this way the amount of dissolved P in the water may be increased at the expense of particulate P.

The part of the exchange due to the activity of molluscs allows of quantitative determination. The cockle (*Cardium edule* L.) and mussel (*Mytilus edulis* L.), which form the greater part of the animal bottom population, feed on suspended organic matter by filtering particulate material from the water. VERWEY (1952; see also LINKE, 1940) estimates that the quantities of suspended matter withdrawn in this way from the water by their combined filtering activities must be put at no less than 330 × 10^6 kg (dry weight) per year or 0.45 × 10^6 kg per tide; 11 % or 50.000 kg of this material per tide is considered by him as consisting of organic matter. However, his calculations refer to the whole area south of the watershed of Terschelling; if we consider only the Marsdiep area, this leaves $69/156 \times 50{,}000 = 22{,}000$ kg (compare table 1). This amount is partly used for the metabolism of the animals, partly converted into living tissue and for the rest rejected with the faeces. The metabolic products are directly returned to the water, the other products indirectly after having been stored in the bottom for a shorter or longer period.

The amount of particulate P strained from the water in this way is about 1 % of the organic matter, or 220 kg P, per tide. The greater

TABLE 21

The excretion of phosphate by the Cockle (*Cardium edule* L.) and the Mussel (*Mytilus edulis* L.).

Experiment I, 11-7-49. 18 Cockles, 4 l sea water t = 16.9°C Cl = 17.96 $^0/_{00}$			Experiment II, 26-6-50. 20 Cockles, 4 l sea water t = 17.1°C Cl = 17.18 $^0/_{00}$			Experiment III 20 Cockles, 4 l sea water t = 17.2°C Cl = 17.18 $^0/_{00}$		
Time, min.	*PO_4, µg-at/l*	*PO_4-increase per cockle, µg-at/l/h*	*Time, min.*	*PO_4, µg-at/l*	*PO_4-increase per cockle, µg-at/l/h*	*Time, min.*	*PO_4, µg-at/l*	*PO_4-increase per cockle, µg-at/l/h*
0	0.78	—	0	0.87	—	0	0.70	—
6	0.96	0.49	30	1.36	0.20	30	1.05	0.14
20	1.54	0.55	60	1.95	0.24	60	1.40	0.14
35	1.93	0.35	90	1.95	0.00	90	1.50	0.04
50	2.35	0.37	120	1.95	0.00	120	1.55	0.02
80	2.60	0.11	150	2.40	0.18	150	1.80	0.10
145	2.80	0.04	180	2.90	0.20	180	2.25	0.18
Average		*0.32*	Average		*0.14*	Average		*0.10*

Experiment IV, 26-6-50 20 Cockles, 4 l sea water t = 17.1°C Cl = 17.17 $^0/_{00}$			Experiment V, 27-6-50 20 Cockles, 4 l sea water t = 17.1°C Cl = 17.19 $^0/_{00}$			Experiment VI, 27-6-50 20 Cockles, 4 l sea water t = 17.3°C Cl = 17.15 $^0/_{00}$		
Time, min.	*PO_4, µg-at/l*	*PO_4-increase per cockle, µg-at/l/h*	*Time, min.*	*PO_4, µg-at/l*	*PO_4-increase, µg-at/l/h*	*Time, min.*	*PO_4, µg-at/l*	*PO_4-increase, µg-at/l/h*
0	0.63	—	0	1.11	—	0	0.58	—
30	1.05	0.17	30	1.53	0.17	30	0.99	0.16
60	1.30	0.10	60	1.46	0.00	60	1.20	0.08
90	1.32	0.01	90	1.82	0.14	90	1.38	0.07
120	1.40	0.03	120	2.40	0.23	120	1.69	0.12
150	1.70	0.12	150	2.40	0.00	150	1.82	0.05
180	1.90	0.08	180	2.80	0.16	180	1.60	—
Average		*0.09*	Average		*0.12*	Average		*0.09*

Experiment VI, 27-6-50 20 Cockles, 4 l sea water t = 17.3°C Cl = 17.10 $^0/_{00}$			Experiment VII, 21-7-49 18 Mussels, 4 l sea water t = 16.5°C Cl = 18.51 $^0/_{00}$		
Time, min.	*PO_4, µg-at/l*	*PO_4-increase per cockle, µg-at/l/h*	*Time, min.*	*PO_4, µg-at/l*	*PO_4-increase per mussel, µg-at/l/h*
0	0.78	—	0	0.55	—
30	1.16	0.15	15	0.80	0.10
60	1.35	0.08	45	1.02	0.09
90	1.47	0.05	105	1.45	0.09
120	1.88	0.16			
150	1.98	0.04			
180	1.80	—			
Average		*0.09*	Average		*0.09*

part of it will only return to the water after mineralization to dissolved P. In a state of equilibrium this amount will also be 220 kg P/tide.

Some laboratory experiments have shown that the cockle and mussel excrete considerable quantities of phosphate (table 21). About 20 cockles, collected on a tidal flat the morning or the day before the experiment, with an average size of about 3.5 cm, a wet weight without shells of 2 g and a dry weight of 400 mg, were for about three hours kept in a small aquarium containing 4 l of sea water of 17° C. The water, poor in phosphate, but containing a normal quantity of suspended organic matter, was kept circulating through the aquarium until the animals had opened their shells and could be expected to have started pumping; the supply of water was then cut off.

Apart from the exceptionally high phosphate production in experiment I, it was found that one cockle produced between 0.14 and 0.08 μg-at/l/hour, with an average of 0.103 μg-at/l/hour, or 0.037 mg/l PO_4–P/tide. This is equivalent to the decomposition of about 3.7 mg (dry weight) or organic matter per tide if the phosphorus content of the organic matter is assumed to be 1 %. In this connection the experiments of MANN (1952), which indicate that cockles consume 180 mg of oxygen per kg (net weight) per hour are of interest. This figure is supported by observations on other molluscs (VAN DAM, 1935, 1938, HAZELHOFF, 1938; WHEDON and SOMMER, 1938; and KUENEN, 1942). It is equivalent to the decomposition of 4.1 mg (dry weight) of organic matter per tide per cockle of 2 g.

From the figures given by VERWEY (1952, p. 218–221) the number of cockles in the Marsdiep area can be computed at not less than 2.7×10^9 individuals. Assuming a consumption of 4 mg per cockle per tide, these animals appear to digest 11000 kg of organic matter/tide. It can also be calculated from VERWEY's figures, that these cockles retain on an average 18400 kg of suspended organic matter/tide if the organic percentage of suspended matter is supposed to be 11 %. Since VERWEY's calculations are minimum estimations, this quantity may actually be twice as high and then amount to about 36000 kg/tide.

It follows from the above calculation that only part of the suspended organic matter passing through cockles and probably also mussels is mineralized within a short period. The residue is retained for a longer time in faeces, pseudofaeces and animal flesh and will be decomposed only gradually. However, the total amount of this material present cannot be estimated, the resistance of the faeces against decomposition under Wadden Sea conditions being unknown.

The figures given by VERWEY, which we used above, are minimum estimations, so that the actual amount of dissolved P returning from the bottom to the water may be larger than 220 kg/tide. Other animals will also make a contribution, so that in all perhaps 500 to 1000 kg P/tide is supplied to the water through the activity of bottom animals. The latter value is equivalent to 50,000–100,000 kg of organic matter, or 0.03 mg/l.

The value of 1000 kg dissolved P/tide constitutes about half of the quantity of 1900 kg dissolved P/tide, supposed to escape to the North Sea. The activity of bottom animals may therefore form an important contribution to the maintenance of the gradient of dissolved P from the Wadden Sea to the North Sea.

Besides through animal activity, dissolved P will be formed in the bottom by bacterial decomposition of organic bottom material, originating from suspended matter which has settled to the bottom without being filtered by molluscs. The amount of this material is very difficult to estimate. Apart from this, it will be difficult to determine the rate of mineralization of this material.

Apart from high concentrations of organic matter, differences between Wadden Sea and North Sea of chemical and physical factors as salinity, temperature, and light penetration, might cause less favourable conditions for the growth of phytoplankton in the former area than in the latter, or a more rapid decomposition, and hence a higher concentration of dissolved P. Very little can be said about these possibilities, but it seems improbable that they will play an important rôle.

To sum up the points brought out in the foregoing discussion, we see that certain aspects of the phosphorus cycle find a natural explanation, if they are considered from a point of view that recognizes the close relation between suspended silt and particulate organic matter and takes into account the behaviour of suspended silt as described in chapter III.

The relations between North Sea and Wadden Sea appear to be rather complicated. There is probably a slow residual transport of organic matter from the former to the latter area during periods of rising concentrations of organic matter, while the reverse occurs when the concentrations of organic matter are falling. Of much greater quantitative importance, however, is the constant movement of organic matter from the North Sea to the Wadden Sea, which balances the transport of dissolved P in the opposite direction. The latter transport is caused by the fact that the concentration of dissolved phosphorus is higher in the Wadden Sea than in the North Sea.

The chief cause of the occurrence of this gradient of dissolved phosphorus is probably the activity of bottom animals, combined with the decomposition of large amounts of organic matter, accumulated both in the water and in the bottom of the Wadden Sea through the constant movement of suspended matter towards the interior. Chemical and physical differences between the Wadden Sea and the North Sea probably play only a minor rôle in this process.

Most important from a biological point of view is the conclusion that the production of organic matter within the Wadden Sea must be smaller than the rate of decomposition. The balance is restored by organic matter supplied by the North Sea.

5. THE PRODUCTION OF ORGANIC MATTER

From the previous discussion some insight has been gained into the quantitative difference between production and decomposition in the

Wadden Sea and its causes. However, this did not lead to a conclusion as regards the total quantities of organic matter produced or mineralized. An attempt will be made below to determine the approximate extent of organic production.

Because sessile plants are practically absent all organic matter originates from phytoplankton. To get an insight, therefore, into the productive capacity of the Wadden Sea, the quantity of phytoplankton present should, if possible, be determined. KREPS and VERJBINSKAJA (1933) and HARVEY (1934) introduced chlorophyll as a means of measuring this amount. The determination of chlorophyll has been discussed on p. 14.

In order to determine the amount of phytoplankton by means of chlorophyll it is of course necessary to know the chlorophyll percentage of phytoplankton.

Some confusion has been caused by the use of HARVEY's pigment units (HARVEY, 1934). One unit is equal to the green colour of 1 ml of a solution of 430 mg $NiSO_4 . 6 H_2O$ and 25 mg $K_2Cr_2O_7$ in 1000 ml of distilled water. DEUBER (according to RILEY, 1938) and GUTHRIE (according to HARVEY, 1950) both compared this solution with pure chlorophyll. DEUBER computed that one pigment unit amounts to 0.88×10^3 mg of chlorophyll; GUTHRIE found 3×10^3 mg.

RILEY (1941), who probably used DEUBER's value, found on Georges Bank that 17.44 mg of chlorophyll (for the greater part contained in diatoms) corresponds with 600 mg of dry organic matter, including the ash; this works out a chlorophyll content of 2.91 %. However, the ash content of diatoms may amount to more than 40 % (BRANDT and RABEN, 1920); for ash-free organic matter the chlorophyll percentage may therefore rise to about 5 %.

PACE (1941) found for cultures of Nitzschia closterium 2.32 %, also uncorrected for ash. He estimated the ash content at roughly 10 %, which means that for ash-free organic matter his percentage becomes only 2.59 %.

HARVEY (1950) determined the chlorophyll percentage in the sea off Plymouth indirectly by means of the relation between organic matter and phosphorus and between phosphorus and chlorophyll. One pigment unit was found to be equal to 0.0135–0.0175 mg of ash-free dry organic matter. If GUTHRIE's value were used, the chlorophyll percentage would amount to about 20 %, which is certainly too large. If DEUBER's value is used the chlorophyll percentage of ash-free organic matter decreases to 4.9–6.5 %. The value found by DEUBER is therefore certainly nearer the truth than the one given by GUTHRIE.

From determinations by GILLBRICHT (1951) in the Bay of Kiel it may further be concluded that the organic matter of diatoms contains 11.9 % chlorophyll and that of peridinians 4.0 %.

All things considered, a value of 6 % seems the best figure to use here as an approximation of the chlorophyll percentage of ash-free, dry phytoplankton.

Chlorophyll analyses in the Wadden Sea were started in April 1951; the observations are still continued. Complete data will be published in a separate paper, but table 22 and figs 54 and 55 may already give an idea of the average quantities and seasonal variations.

As can be seen from table 22, containing percentages found at the stations 1,9 and 17 between Den Helder and Den Oever (table 13), the chlorophyll concentration varies considerably from station to station with a decrease in the direction of the Wadden Sea interior. Nevertheless, the scarce data collected outside the tidal inlet indicate that the concentration of chlorophyll is considerably higher in the Wadden Sea than in the North Sea (fig. 55).

As appears from table 22 and fig. 54 the chlorophyll content of the Marsdiep area varies between about 30 mg/m^3 in summer and 3 mg/m^3 in winter, with an average of about 13 mg/m^3. Assuming that all chlorophyll is contained in living phytoplankton and constitutes 6% of its organic part, about 0.5 mg/l of ash-free phytoplankton would be present in summer and 0.05 mg/l in winter, with an annual average of 0.2 mg/l.

TABLE 22

Chlorophyll concentrations in the Wadden Sea between Den Helder and Den Oever; stations 1, 9 and 17 of fig. 13.

Date	*Depth*[1]	*Station 1*		*Station 2*		*Station 3*	
		Chlorophyll mg/m^3	*$^0/_{00}$ Cl*	*Chlorophyll mg/m^3*	*$^0/_{00}$ Cl*	*Chlorophyll mg/m^3*	*$^0/_{00}$ Cl*
13- 7-51	S	5	16.55	11	16.65	26	15.32
29- 8-51	S	(32)	12.48	15	15.84	14	15.65
5-11-51	S	15	16.03	14	14.38	(42)	1.79
12- 6-52	S	11	16.77	16	16.19	24	16.09
24- 7-52	S	20	17.14	17	16.54	6	16.51
	B	15	16.88	23	16.38	5	15.67
8- 9-52	S	22	17.68	10	16.91	12	15.41
	B	18	17.76	18	16.98	—	—
24-10-52	S	10	17.87	12	16.24	4	13.80
	B	6	17.87	13	16.62	7	14.39
12-12-52	S	4	14.31	5	14.78	7	11.93
19- 2-53	S	—	—	2	13.92	10	—
	B	12	13.15	—	—	2	15.27
24- 3-53	S	10	15.47	3	13.86	1	13.82
25- 3-53	S	11	16.27	12	14.22	2	14.08
	B	—	—	12	15.37	1	14.06
1- 5-53	S	19	17.43	—	—	8	14.16
	B	—	—	24	17.44	12	15.65
21- 5-53	S	5	17.73	7	17.32	3	16.84
	B	9	17.65	21	17.41	7	16.75
3- 7-53	S	20	16.86	21	15.97	7	14.86
	B	34	17.11	49	15.91	11	14.66
30- 7-53	S	15	16.13	23	15.75	11	14.28
	B	31	16.52	27	15.85	12	14.31
Average[2]	S	15	—	13	—	7	—
	B	18	—	23	—	7	—

[1] S = surface sample, B = bottom sample.

[2] Data with surface samples only have been omitted.

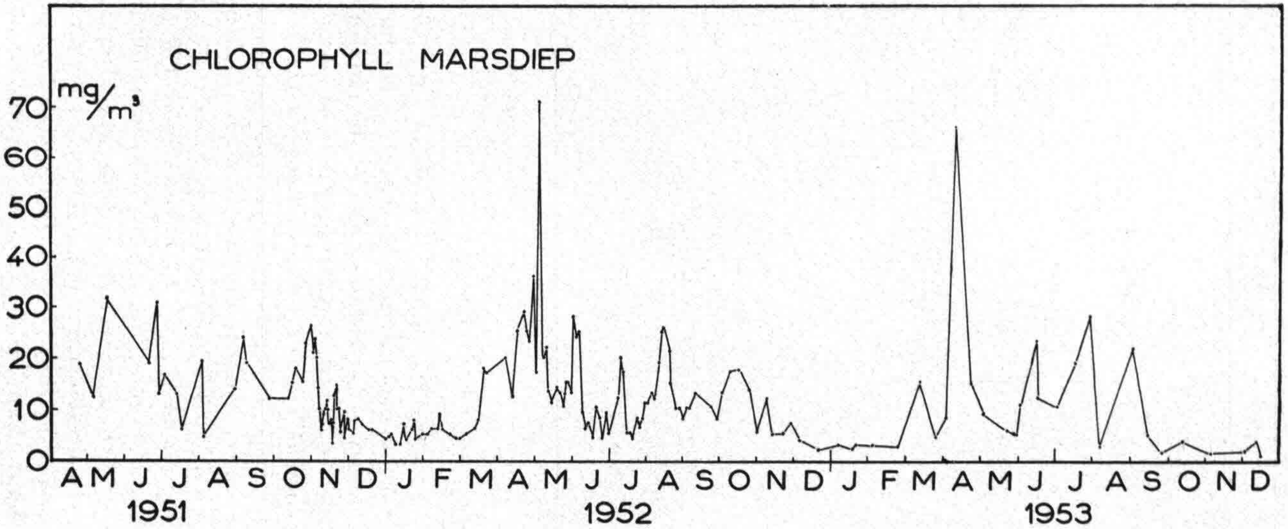

Fig. 54. Seasonal variation of chlorophyll; observations in the Marsdiep during high water.

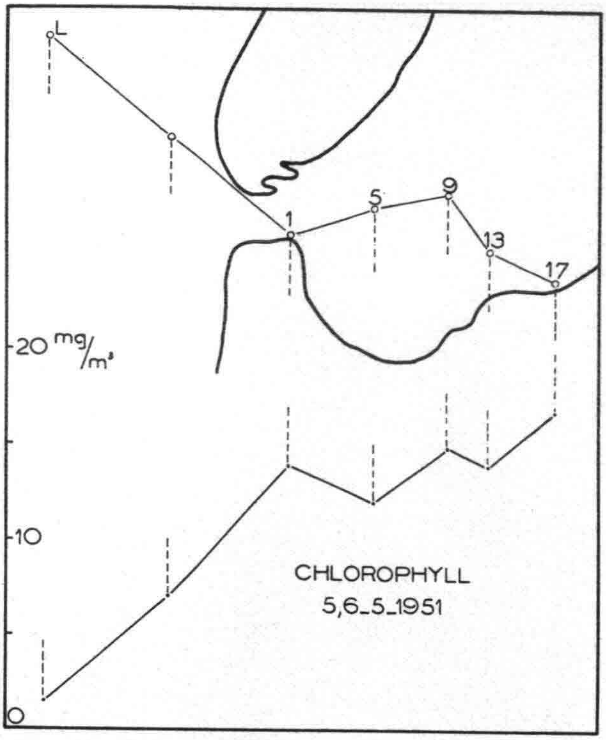

Fig. 55. Chlorophyll values of surface samples in a traverse through the Wadden Sea and into the North Sea.

However, part of the chlorophyll is probably not contained in living material, but incorporated in detritus. According to Krey (1951) and Gillbricht (1951) about 50% of the chlorophyll in the Bay of Kiel may be contained in detritus. Riley (1941) on the other hand puts this figure at 1% for Georges Bank. If the percentage of 50% is applied to the Wadden Sea, the average quantity of phytoplankton becomes only 0.1 mg/l; a value between 0.1 and 0.2 mg/l will be adopted for our further considerations. Since the average quantity of organic matter in the Wadden Sea is about 2.5 mg/l, only 4–8% of all suspended organic matter in this area would then consist of phytoplankton. As the entire volume of the Marsdiep area at high tide is 3.1×10^9 m^3, a total of about $0.3\text{–}0.6 \times 10^6$ kg of phytoplankton would then be present in this area. It goes without saying that this figure can be no more than a rough approximation.

Having approximately estimated the average amount of phytoplankton present, we may return to the question how much organic matter may be produced in the Marsdiep area per unit time. Strictly speaking, a distinction should be made between "Gross production" and "Phytoplankton production", in which case the quantitative difference between the two would be constituted by the consumption of organic matter by the phytoplankton itself (RILEY, 1940). It is phytoplankton production that will be discussed here. To determine this production the rate of growth of the phytoplankton population must be known. LOHMANN (1908) observed in the Bay of Kiel an average daily growth of 30%; also HARVEY (1950), from his own observations and those of others, assumes a daily production of 30%.

This percentage will be applied to the Wadden Sea. It works out at a daily increase of phytoplankton of 0.03–0.06 mg/l (ash-free, dry weight), or 100,000–200,000 kg for the whole of the Marsdiep area. If we translate this into terms of phosphorus, on the assumption that organic matter contains 1 % P, the consumption of phosphate–P for the daily production would amount to 0.0003–0.0006 mg/l/day, or 0.01–0.02 μg-at/l/day or 0.005–0.01 μg-at/l/tide, or 500–1000 kg P/tide, for the whole area.

Productivity estimates for other areas, comparable with the Wadden Sea, are scarce. Long Island Sound is probably a good example. RILEY (1941), from experiments with light and dark bottles, computes that the phytoplankton production there is 95–875 g of carbon/m^2/year. The mean depth of the Sound being 20 m, this would be equal to 0.014–0.12 mg/l/day. To find the corresponding figures for organic matter from these carbon values, the latter must be multiplied by 2.3; this would give a production of 0.035–0.30 mg/l/day, 3–15 times higher than the figure given above. However, conditions for phytoplankton growth are somewhat more favourable in the Sound than in the Wadden Sea. PRATT (1950), who carried out productivity experiments in concrete tanks, studied the relation between phosphate consumption and chlorophyll concentration; it can be derived from fig. 5 of his paper that phosphate is consumed at a rate of 0.07 μg-at/l/day if the chlorophyll content is 10 mg/l. This means a production 3–7 times higher than the figure given above. Here, especially light conditions were more favourable in his tanks than in the Wadden Sea.

Although the figures found should of course be regarded with considerable reserve, we seem to be justified in concluding that the North Sea makes a significant contribution to the productivity of the Wadden Sea. For if our figures are approximately right the supply of organic matter from the North Sea (assumed to be about 2000 kg P/tide; see p. 88–89) would be of the same magnitude as the production of organic matter within the Wadden Sea itself (computed at 500–1000 kg P/tide).

SUMMARY

In this paper an attempt has been made to describe for the Dutch Wadden Sea water movement, transport of suspended matter and the cycle of suspended organic matter. Stress has been laid on the fact that these are related subjects, which therefore ought to be studied in combination. The discussion was based on observations made in the years 1949–1951 in the southwestern part of the area. A summary of the figures found from these observations is given in table 23.

TABLE 23

Comparison of average data for the North Sea, about 15 km outside the tidal inlet, with data for the Wadden Sea (Marsdiep area).

	North Sea	*Wadden Sea*
Chlorinity, $^0/_{00}$	18	16 (9-17)
Salinity, $^0/_{00}$.	32	29 (16-31)
Suspended silt, mg/l	6	18
Suspended sand, mg/l	—	5
Total suspended matter, mg/l	—	23
Organic matter, summer, mg/l.	1.5	4
Organic matter, winter, mg/l	—	1
Organic matter, average, mg/l.	—	2.5
Phosphate, summer, μg-at/l	0.05-traces	0.10-traces
Phospate, winter, μg-at/l	0.60	0.75
Phosphate, average, μg-at/l	0.31	0.49
Dissolved organic P, summer, μg-at/l	0.60	0.80
Dissolved organic P, winter, μg-at/l.	0.20	0.30
Dissolved organic P, average, μg-at/l	0.38	0.53
Total dissolved P, average, μg-at/l	0.69	1.02
Particulate P, average, μg-at/l	0.25	0.60
Total P, average, μg-at/l	0.94	1.62
Chlorophyll, summer, mg/m^3	—	30
Chlorophyll, winter, mg/m^3	—	3
Chlorophyll, average, mg/m^3	—	13

For a good understanding of the results two facts appear to be of primary importance. First, there is a considerable exchange of water between Wadden Sea and North Sea, which is constantly at work to change Wadden Sea conditions, so that they approach those of the North Sea. Secondly, the concentration of light suspended material (silt) and of suspended organic matter is, notwithstanding this exchange, constantly higher in the Wadden Sea than in the North Sea.

1. *Water movement* (Chapter II).

In the southwestern Wadden Sea the vertical salinity gradient is only slight and the transport of fresh water is therefore mainly the result of tidal mixing, while transport as a result of differences in density plays only a minor part. The mixing processes are greatly stimulated by differences in water movement between channels and tidal flats.

The rate of the exchange of water between Wadden Sea and North Sea resulting from these mixing processes was determined from the distribution of fresh water, which in its turn could be found from salinity figures. The average quantity of fresh water present in the area studied is 13 times the average amount discharged from the IJsselmeer during one tide. Therefore in every tidal period 8% of the total quantity of fresh water present within the Wadden Sea is transported to the North Sea. This percentage can be applied to every dissolved substance that has the same distribution as the fresh water.

A simple empirical method was developed to calculate the water exchange in a well-mixed estuary by means of a segmentation method. The figures calculated by means of this method for the amounts of fresh water present in the area studied were found to exhibit a significant correlation with those calculated from the salinity distribution.

2. *Suspended matter* (Chapter III)

Observations throughout a full tidal period at fixed stations and in distinct water masses marked by floats provided the basis for the study of suspended matter. The material was divided into two fractions, called "sand" and "silt", separated at a grain size of about 50 μ.

The amount of material in suspension varies with current velocity. There is a time lag varying from a few minutes to one hour between the turn of the tide and the moment at which the minimum concentration of suspended matter is measured.

Large amounts of suspended matter are transported forth and back by the tidal streams; the total quantity of silt transported in every tidal phase through the Marsdiep amounts to 8×10^6 kg of dry weight. There is no conclusive evidence of a residual transport of silt in one direction or the other.

Although no substantial quantities of silt are supplied to the area by the IJsselmeer or by internal abrasion, the concentration of suspended silt is maintained at a higher level in the Wadden Sea than in the North Sea. The increase of the quantity of suspended silt inward is gradual and runs parallel with an increase in the silt content of the bottom.

The higher concentration of suspended silt in the Wadden Sea as compared with the North Sea is supposed to be caused by an accumulation mechanism resulting from a progressive decrease in water movement (especially a decrease in mean current velocity) from the outer to the inner part. The concentration actually observed is thought to be the result of the balance maintained between this accumulation and the loss of silt through water exchange. The mechanism does not prevent the loss of dissolved substances.

3. *Organic matter.*

The cycle of organic matter was studied by determining the quantities of organic matter present, and computing the phosphorus content of water and organic material. The phosphorus is partly present as particulate P, partly as dissolved P. The particulate P is for the greater part contained in organic matter, while the dissolved P consists partly of organic P, partly of phosphate.

The quantities of organic matter, as well as those of the phosphorus components, are subject to annual variations. The largest quantities of organic matter and organic P (particulate as well as dissolved) are found in summer, whereas phosphate attains its maximum in winter.

The concentration of suspended organic matter (as well as suspended P) parallels the concentration of suspended silt and is therefore higher in the Wadden Sea than in the North Sea. It is supposed that the reason for this high concentration is the same as for the high concentration of suspended silt.

The concentration of dissolved P is also, though only slightly, higher in the Wadden Sea than in the North Sea. Since dissolved substances are exchanged freely, this causes a residual transport of dissolved P to the latter area. In every tidal period a net amount of 2400 kg of dissolved P is supposed to be transported to the North Sea. Fresh water from the harbour of Den Helder contributes to this quantity to the extent of about 500 mg/tide; the IJsselmeer, however, does not contribute to this amount, since the phosphorus concentration of the fresh water from this source is too low. The loss of the remaining 1900 kg of dissolved phosphorus is probably neutralized by the transport of the same amount of particulate organic phosphorus, incorporated in organic matter, from the North Sea to the Wadden Sea.

It follows from the foregoing paragraphs that part of the organic matter present in the Wadden Sea is formed in the North Sea. Another part will be synthesized by phytoplankton assimilation in the area itself. A rough estimate of this phytoplankton production has been made by means of chlorophyll determinations, which show that probably only 4–8% of the suspended organic matter consists of living phytoplankton. The highest phytoplankton concentrations occur in summer, the lowest in winter. The production of organic matter has been estimated from these data by assuming a daily growth of phytoplankton of 30% of its own weight. The production then appears to amount to 50,000–100,000 kg of organic matter per tide or 110 g/m²/

year. This quantity is equal to 500–1000 kg P/tide. The supply of organic matter by the North Sea, which would amount to some 2000 kg P/tide, would therefore be of the same magnitude as the production of organic matter within the southwestern Wadden Sea itself.

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