

SAND MOVEMENT IN THE IN- AND OFFSHORE TIDAL AREA OF THE S.W. PART OF THE NETHERLANDS

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ABSTRACT

This paper deals with the resultant sand movement over the offshore underwater delta along the tidal inlets of the S.W. part of the Dutch coast and with the sediment exchange between the North Sea and the underwater delta.

It appears that a complicated circulation of sediments occurs in the whole channel system in the area, mostly directed perpendicular to the general coastline. On the shoals the sand transports by currents are almost negligible.

The picture of sand movement by waves suggests a net north-eastern sand transport over the shoals.

Also the data derived from sediment balances and grain-size differences point to a net northeastern movement of fine sand over the underwater delta.

The direction of the sand transport by currents and grain-size data reveal that there is an appreciable sediment exchange between the underwater delta and the North Sea in the Haringvliet area and apparently also along the southwestern part of the underwater delta.

1. INTRODUCTION

The closing of several tidal inlets in the S.W. part of the Netherlands will change the sediment transport regime seaward of the dams and on the underwater delta. The pattern of the tidal currents will change and also the influence of the waves on the bottom morphology. A review of the methods used and some results of investigations into these problems were treated by *Dronkers* (1970).

An over-all picture of the sediment transport patterns before the works started is essential in evaluating the changes in the future hydraulic situation.

The movement of mud ($d < 50 \mu$) was treated by *de Groot* (1963), and *Terwindt* (1967).

This article deals with the sand movement prior to the closure of the Haringvliet estuary (1970) and the Brouwershavense Gat tidal inlet (1971).

Figure 1 shows the bottom topography of the investigated area. It may be seen that the patterns of channels and shoals in the inlets is extended offshore, making up the underwater delta. This delta is arbitrarily bounded at the seaward side by the 15 m depth contour.

The following problems will be discussed:

- is there a resultant sand transport over the underwater delta;
- is there an appreciable exchange of sand between the North Sea and the underwater delta.

A definite solution of these problems requires quantitative data of the sand transport by the combined effect of currents and waves in the course of time. There is a clear distinction between the interrelation of current and wave effects on the sediment movement in the channels and on the shoals. The currents have a dominant effect in the channels. The wave influence here is relatively small because of the greater water depth. The sand movement by currents can be evaluated quantitatively, with a reasonable degree of accuracy. The channels play an important role in the whole system of the sand movement on the underwater delta, especially in the Oosterschelde and Brouwershavense Gat area. Here the channels run almost perpendicular to the underwater delta front and really dissects this delta. Sediments moving over the shoals may be supplied laterally to the channels, but will follow further the transport pattern which is determined by the tidal currents in these channels.

Outside the channels, on the shoals and along the underwater delta front both currents and waves influence the sand transport.

Up till now the combined effect of currents and waves on the sand movement in such area cannot be evaluated quantitatively although several computational models have been proposed by different authors. The model proposed by *Byker* (1968) attempts to combine the shear stresses exerted by currents and waves. Promising results are obtained with this model along more or less straight sandy beaches. (*Byker*, 1971). However, it is difficult to apply

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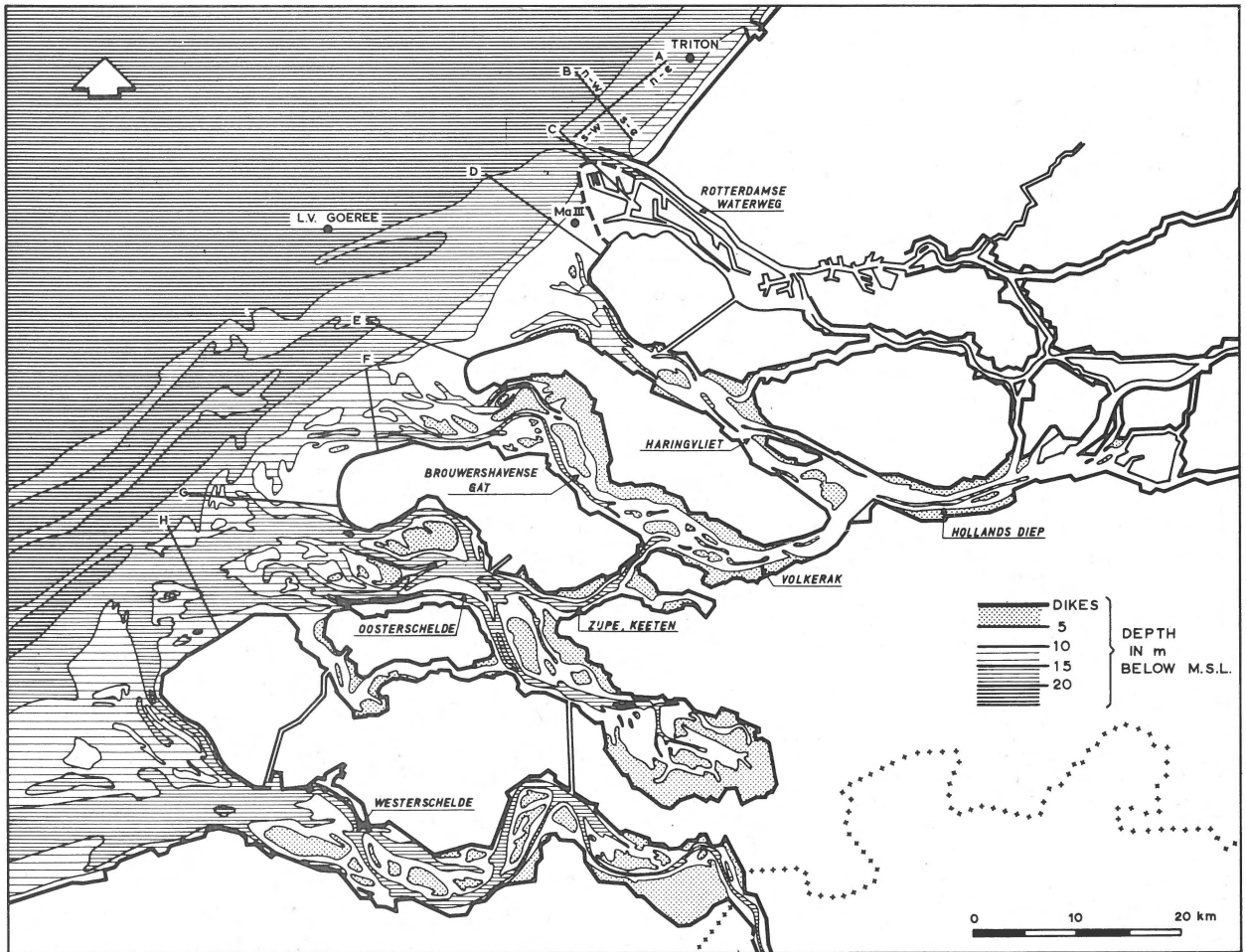


Fig. 1
Bottom topography of the area of investigation. Location of sampling lanes and wave measurement points (Triton, L.V. Goeree, Pole Ha III).

this model to areas with a complicated bottom morphology. Detailed information is required on the magnitude and direction of waves and currents on the places of interest in the area, which are not available at this moment. Furthermore the stochastic character of the waves is not considered in this model. Therefore great difficulties arise when using the model over longer periods. Finally checks of the model with measurements in areas with an irregular bottom morphology like the underwater delta are still too limited to get a general idea of the accuracy.

Another model is based on an empirical relationship between the longshore sand transport rate and the longshore component of the wave energy flux (Caldwell, 1965; Inman et al, 1969; Byker and Svasek, 1968; Komar and Inman, 1970; Komar, 1971). The magnitude of the energy fluxes per unit of crest length of waves over the underwater delta is influenced by the wave refraction pattern. The accuracy of the determination of the longshore component of the energy flux therefore de-

pends a.o. on the accuracy of the wave refraction patterns. These patterns are very complicated on the underwater delta due to the great bottom relief. Investigations into the accuracy of the refraction computations in such areas are now in progress by several researchers of Rijkswaterstaat. Meanwhile only qualitative data can be obtained by excluding the wave refraction and considering the total wave energy over a long period which is transferred to the underwater delta from different directions as indicated in par. 2.

A general picture of the sediment transport over the underwater delta can be obtained from the sediment balance. This balance is derived from comparison of sounding charts over a certain time. Amounts and areas of erosion and sedimentation can be established and from these data also indications on the sediment exchange can be derived. These indications can be supported by the grain-size data (par. 2). As is well known, finer particles can be transported over longer distances than coarser ones under equal hydraulic conditions. If the resultant sand-transport conditions remain

the same over longer periods we can expect a gradual coarsening in the erosion (source) area due to the removal of the finer sand in the receiving area a fining of the bottom material because of the incoming fine material.

The exchange of sand between the North Sea and the underwater delta is determined by the magnitude of the sand-transport component, perpendicular to the underwater delta front. This component is also influenced by the combined effect of currents and waves. The magnitude of this component can hardly be estimated in a quantitative sense. However qualitative indications of this exchange may be gained from current and wave data solely and from the grain-size variations over the underwater delta front (par. 3).

2. THE RESULTANT SAND TRANSPORT ON THE UNDERWATER DELTA

2.1. *The sand movement by currents*

As stated in the Introduction the combined effect of currents and waves on the sediment movement on the underwater delta is still unknown in a quantitative sense. However some qualitative data are discussed below.

First the sediment movement by the currents under absence of waves is considered.

Figure 2 a/d shows that the magnitude and direction of the tidal currents in the channels differ from those on the shoals. In the channels the currents run almost parallel to the channel axis. Only towards the edge of the underwater delta the current pattern becomes more elliptical. Furthermore in some channels there is a predominance of the currents either in flood or in ebb direction (see f.i. point 14 and 32 on figure 2).

On the shoals, however, more or less circular current patterns are observed. The directions of the currents change in an anti-clockwise manner.

This complicated pattern of the currents results from the interrelation between the currents in the tidal inlets, which are directed almost perpendicular to the coastline and the currents in the North Sea, almost parallel to the coast.

The magnitude and direction of the tidal currents will be influenced by neap tide-spring tide variations and by wind drift effects. Reliable information can only be obtained by continuous measurements over a longer period. In the last few years several continuous records of the currents were made on the underwater delta by means of the "Flachseestrommesser". Waves hardly influence the registrations of the "Flachseestrommesser" because the output consists of the mean value over a period of 5 minutes. Also separate current observations were made during one tidal cycle at different points on the underwater delta. The latter results only apply to the tide and winddrift conditions on the day of measurement.

Comparison of these results with those obtained from the

continuous records reveal that the measurements made during mean tidal conditions, are a good approximation of the mean values obtained from long term current data. Therefore the data of incidental measured current velocities, presented in figure 2 are reduced to mean tidal conditions.

In order to get an overall picture of the sediment transport capacity of the currents, computations were made of the suspended sand transport. These computations are based on the method described by Lane and Kalinske (1939, 1941) and modified by Morra (1948). A description is given in appendix I. Rather crude approximations must be applied in these computations. Therefore no great accuracy of the results can be expected. Morra (1950), however, found that the order of magnitude of the suspended sand load can be estimated with this method.

The various directions of the sand movement were also taken into account. Therefore successive intervals of directions are considered, each interval is 60° . For the continuous current measurement with the "Flachseestrommesser" the total sand transport over the total registration time (normally 1 month) has been computed and divided by the number of tides of this period. Then the mean sand load per tide is obtained. Figure 2a t/m d show the results. It demonstrates the complexity of the sand transport pattern on the underwater delta. The greatest sand transports occur in the large tidal channels of the Oosterschelde (point 34), the Brouwershavense Gat (point 26) and the Haringvliet (point 10, 11 and 14). The overall sand movement in the mouth of the Haringvliet appears to be much more intense than in the other inlets. This is due to the finer sediments in the Haringvliet area (fig. 4). The sand transport is relatively low on the shoals and along the underwater delta front because of the relative low velocities.

The direction of the resultant sand transport is mainly determined by the hydraulic character of the channels. Obviously in flood channels a net transport is observed in the direction of the flood currents (f.i. point 13 and 14) and the same holds for the ebb channels (f.i. point 10 and 12).

A complicated circulation of sand occurs in the whole channel system of the tidal inlets. All channels unite somewhere with other channels, as may be seen in figure 1 and 2. So sand f.i. in a flood channel with a net landward movement can be transferred to an ebb-channel and transported back seawards.

On the shoals of the underwater delta the net sand transport is directed northward in some places (point 7) and southward in others (point 15 and 16). A general trend cannot be found because the direction of the relative low sand movement in these areas is influenced by variations in the current characteristics (f.i. by wind-drift). This holds especially for the data obtained from one tidal cycle. More reliable results are obtained from the "Flachseestrommesser" data, which give the mean net sand transport over 1 month (point 6, 15, 20, 35, 36, 37, 38). They indicate that during this time a net southward sand transport took place at some

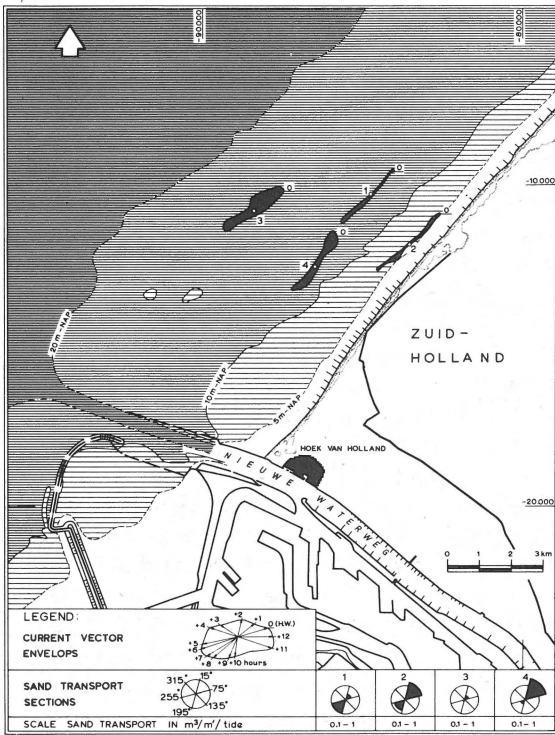


FIG 2a

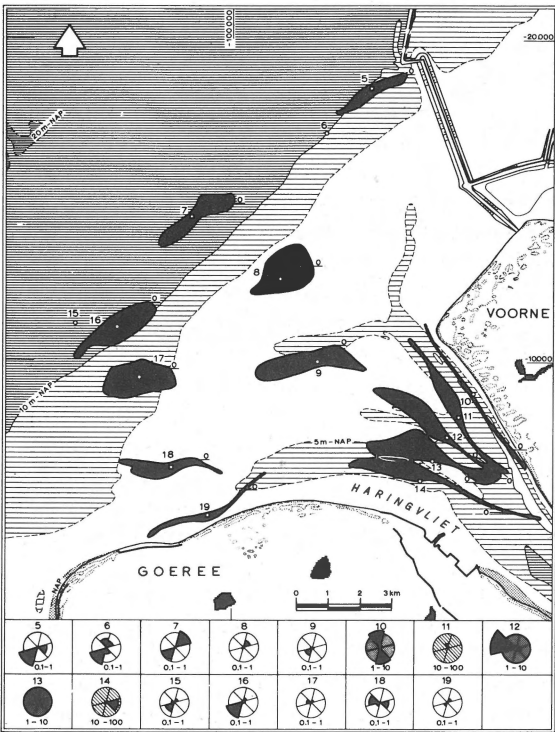


FIG. 2b

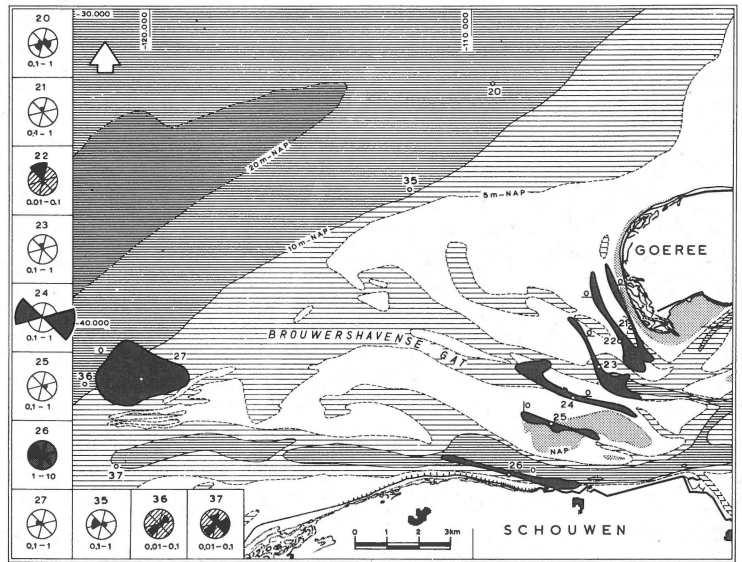


FIG 2c

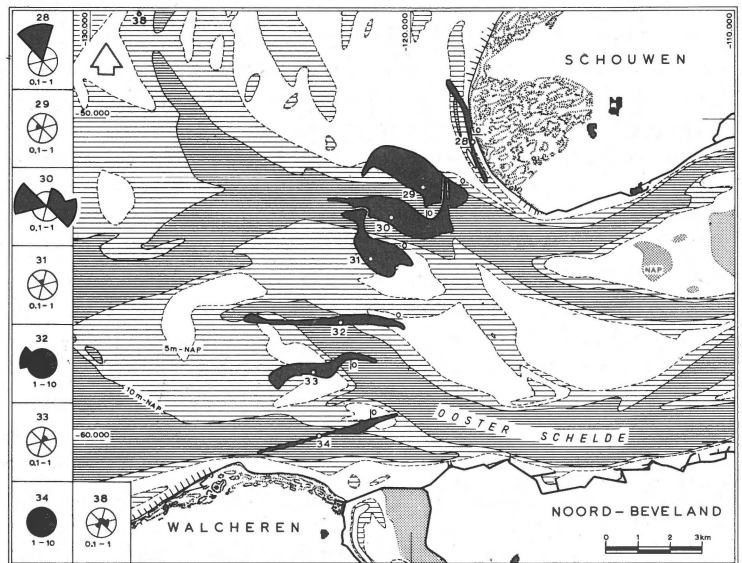


FIG 2d

Fig. 2

Current vector envelopes and suspended sand transport capacity by currents on several measurement points on the underwater delta and tidal inlets. o = H.W. reference on station Burghsluis. NAP = Dutch ordnance level.

locations on the outer delta of the Haringvliet (point 6, 15 and 20).

So the following tentative conclusions can be made: The sand-transport pattern by currents on the underwater delta is

largely determined by the hydraulic conditions in the tidal channels. In some channels where the flood flow is predominant, a net sand movement occurs from the underwater delta to the inlets. In channels where the ebb flow dominates sand is carried from the interior to the underwater delta. Exchange of sand from one channel to the other results in a complicated circulation pattern of the sediments.

The sand movement by currents over the shoals is of minor importance as compared with that in the channels.

2.2. The sand movement by waves

The sand movement by waves is especially important on the shoals and along the front of the underwater delta;

The directional effects of the waves on the resultant sand movement on the underwater delta is still obscure. As stated in the Introduction the wave energy flux can be indicative for the sand transport. The wave energy is transferred in the direction of the wave propagation. Refraction influences the direction and magnitude of the wave energy flux per unit of crest length. Accurate data cannot be obtained because of the complex refraction pattern on the underwater delta. However some general information can be presented.

Waves coming from the NW meet the underwater delta almost at right angles (fig. 1). Refraction may give longshore components of the wave energy flux, but in general the resultant of these longshore components can be in northern as well as in southern directions.

Waves reaching the underwater delta, however, from the W or SW will have a resultant longshore component of the energy flux which is directed to the northeast. In the same way waves from the N will have a resultant southward component of the energy flux.

In general the magnitude of these longshore components depend on the magnitude of the energy flux from a certain direction and the angle between this direction and the depth contours of the front of the underwater delta.

The wave energy fluxes from different directions over a certain period were roughly estimated by the following method:

Use was made of the wave data of the Lightvessel Goeree (Dorrestein, 1967). The data consists of the relative frequency of occurrence for waves classified according to the wave height (i), the wave period (j) for several strokes of the compass (k). The visually estimated wave heights may be transferred to the significant wave heights by means of a correlation diagram.

The wave energy flux for each class i, j is

$$N = 1/16 \rho g H_{si}^2 c_j \quad (1)$$

A parameter N_k for the wave energy flux for a certain direction k was obtained from

$$N_k = \sum_{ij} f_{ij} H_{si}^2 c_j \quad (2)$$

where N_k is a parameter for the wave energy flux per unit crest length in direction k; f_{ij} is the relative frequency of occurrence of waves in class i, j, H_{si} is the significant wave height in class i and c_j is the group celerity of waves in class j.

Figure 3 shows the values of N_k for various directions. This figure suggests that indeed more wave energy is transferred to the underwater delta from the SW-W sector than from the N sector. Thus a resultant northeastern component of the wave energy flux can be expected in the course of time.

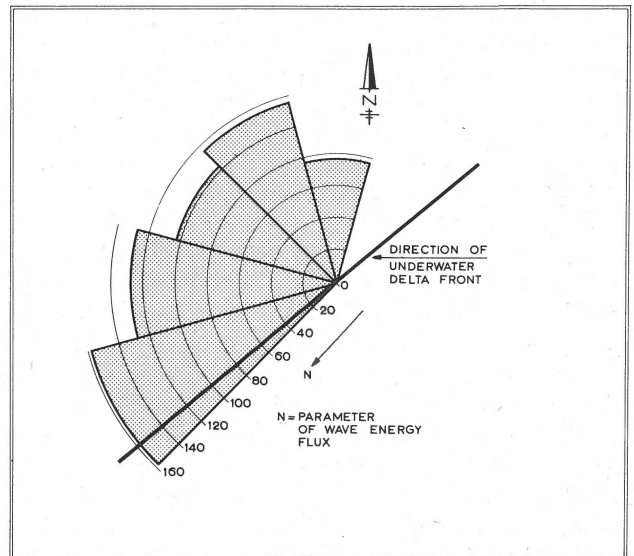


Fig. 3
Parameter of wave energy flux for the L.V. Goeree for several directions (explanation see text).

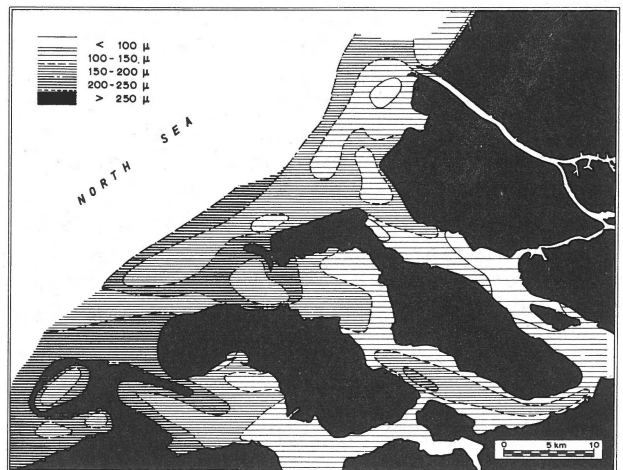


Fig. 4
Schematized picture of the mean grain-size of the sand fraction ($d > 50 \mu$) based on 2500 bottom samples, taken in 1959-1960.

2.3. The sediment balance

The net sedimentation and erosion in the estuaries, tidal inlets and underwater delta over different periods was studied by Haring (1955) who analysed sounding charts. Haring's data were summarized by M o r r a et al (1961).

It consists of the net sedimentation and erosion below M.S.L. covering the 1872-1952 period. These data are only indicative. The accuracy of the older sounding charts is certainly not high. This holds especially for the underwater delta area.

The data suggest however that some $3.5 \times 10^8 \text{ m}^3$ sediment was eroded in the Keeten-Oosterschelde and Westerschelde in the period 1872-1952. In addition to this an erosion of some 10^8 m^3 was estimated in the mouth of the Oosterschelde and Westerschelde. The underwater delta was extended seaward in this period, although the amount of sediment involved is uncertain, because of the lack of reliable sounding charts.

On the other hand in the Brouwershavense Gat and Haringvliet some 10^8 m^3 sediment were deposited. Also considerable deposition took place on the underwater delta in this area (rough estimate $1.5 \times 10^8 \text{ m}^3$).

The sediment contribution carried by the Rhine, Waal and Maas rivers into the Haringvliet is relatively small.

Most of the supplied sand is deposited and dredged in the transition zone between the rivers and the estuary. The total amount of sand from Waal and Maas which finally reaches the estuary, was estimated by Haring (1965) to be in the order of $0.15 \times 10^6 \text{ m}^3$. From this data the sand supply from the rivers to the Haringvliet in the period 1872-1952 may be roughly estimated as $0.1 \times 10^8 \text{ m}^3$.

This indicates that the net sedimentation in the Haringvliet in this period can only be attributed to the rivers for a small part and consequently comes mainly from the sea.

It is not likely that the large amounts of sediment which were eroded in the Oosterschelde-Westerschelde area in the period 1872-1952 were supplied to the south. The Dutch part of the Flandrian coast was almost stable in this period but along the southern Belgian coast rather severe erosion took place (Ver sch a v e, 1960).

Therefore there seems to be no other logic possibility than that these sediments were partly trapped on the seaward extension of the underwater delta and partly transported to the Brouwershavense Gat and Haringvliet areas to the north.

2.4. The grain-size data

If the resultant sand-transport conditions remains the same over longer periods in the erosion (source) area a gradual coarsening of the bottom material may be expected due to the removal of the fines and in the sedimentation area a fining because of the incoming fine material. Trends in the grain-size variations therefore may indicate a transport pattern.

Figure 4 gives a schematized picture of the mean grain-size of the bottom sand based on about 2500 samples, taken in 1959-1960.

From this figure a gradual fining of the bottom sand over the underwater delta from the mouth of the Oosterschelde (erosion area) towards Haringvliet (sedimentation area) can be observed, suggesting a resultant northward sediment transport.

The same figure 4 shows another interesting fact viz. that the fine type of sediments occurring in the mouth of the Haringvliet is also encountered in the mouth of the Rotter-

dam Waterway and along the adjacent coast. It is possible that these fine sediments are also connected with the suggested northgoing net sediment movement over the underwater delta. The river Rhine, as should be borne in mind, hardly discharges any sand into the North Sea (Terwindt, de Jong & van der Wilk, 1963). So this fine material cannot be supplied by this river in the observed quantities.

2.5. The sedimentation along the harbour moles of the Rotterdam Waterway during and after construction (1868-1876)

In the northern part of the underwater delta in the mouth of the Haringvliet and Rotterdam Waterway another indication of a net northward sediment movement can be obtained.

During 1868-1876 the new shipping channel, the Rotterdam Waterway, was dredged and two harbour moles were build.

Table 1 gives the net sedimentation along the North and South breakwater for different periods, derived from sounding charts analysis.

TABLE 1
Net sedimentation in 10^6 m^3 along the North and South breakwaters of the Rotterdam Waterway.

Period	Along North breakwater		Along South breakwater	
	Total	Annual mean	Total	Annual mean
1868-1873	2.2	0.4	1.3	0.21
1874-1881	1.6	0.2	1.8	0.22
1882-1888	0.6	0.1	0.6	0.09
1889-1958	-0.5	0.0	3.5	0.05

These data show that in the period 1868-1888 almost a like amount of sand was deposited along the North and South mole. The gradual decrease in the annual mean sedimentation reveals that in these 20 years a new dynamic equilibrium of the coastal form was reached. Along the South pier, however, a continuous sedimentation took place in the period 1888-1958 with a mean annual rate of 50.000 m^3 . It is reasonable to assume that these $3.5 \times 10^6 \text{ m}^3$ sand deposited during this period were supplied from the south and not from the north. Although the coastal zone in the north was eroding, these sediments have been added to the waters in the Waterway channel and have become a part of the sediment movement of this channel, which is directed perpendicular to the coast. Furthermore the amount of erosion along this coastal zone was too small as compared to the sedimentation along the South pier.

2.6. Behaviour of dumped spoil in the North Sea

Since 1961 dredged spoil from the Rotterdam Waterway and harbours is dumped in the North Sea about 6 km NW of the entrance in an original water depth of 14 m below M.S.L. The spoil is much finer than the original bottom sediment in

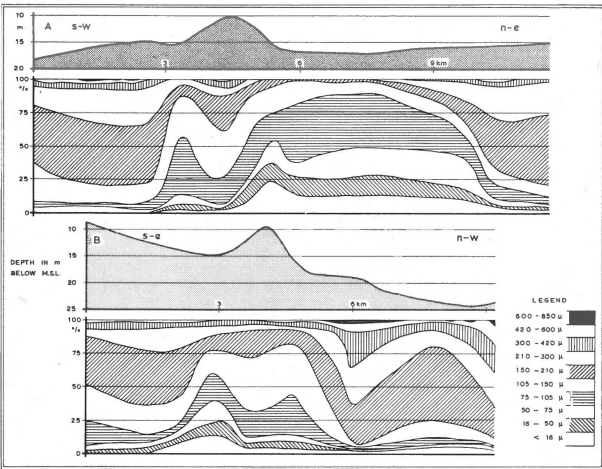


Fig. 5
Grain-size distribution in two lanes over the spoil dumping site in the North Sea (for location see fig. 1).

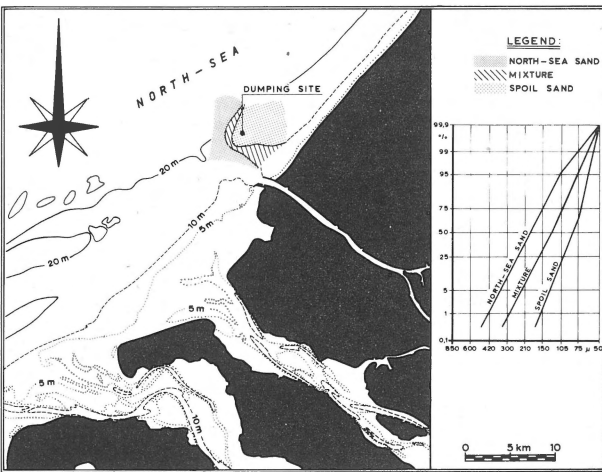


Fig. 6
Sediment types in the environment of the dumping site.

the dumping area. Therefore the spoil can be used as a tracer of resultant movement of *fine* sand in this area on a water-depth of 10-15 m below M.S.L.

Investigations of the spreading of this spoil were carried out in 1968. From 1961 until 1967 about $0.8 \times 10^8 \text{ m}^3$ spoil was dumped. The spoil consists for 30% of fine sand (material $> 50 \mu$) and for 70% of mud (material $< 50 \mu$). The d_{50} value of the sand fraction (mud excluded) range between 60 and 100μ .

The net sedimentation on the dumping site in the period 1961 until 1967 was $0.3 \times 10^8 \text{ m}^3$, or 40% of the total dumped spoil. In the dumping area the depth was reduced to 9 m below M.S.L. From numerous borings in the sedimentation area it appears that only 15% of the dumped mud can be traced. This means that the dumped sand principally remains

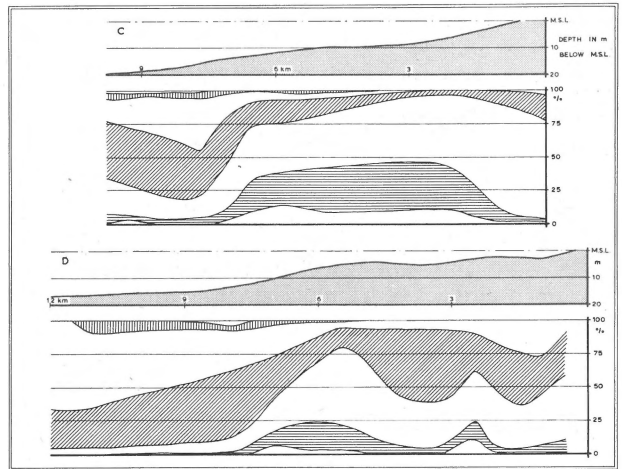


Fig 7a

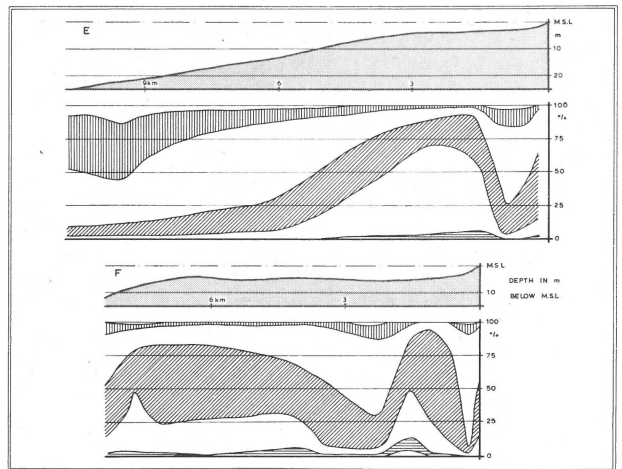


Fig 7b

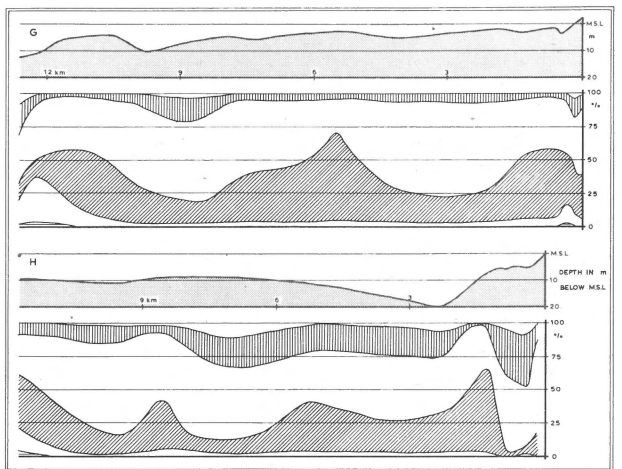


Fig 7c

Fig. 7
Schematised grain-size data in some lanes perpendicular to the coast (for location see figure 1). Number of sampling points lane C:30; D:42; E:32; F:19; G:26; H:25; Lane C, D, E mean of 8 observations.

in the vicinity of the dumping site but that the mud disappears almost entirely.

Figure 5 shows the grain-size data in two cross-sections over the dumping site. Based on these data three sediment-types can be distinguished (fig. 6) viz.: the original North Sea sand not influenced by the dumped material (d_{50} : 175-250 μ), the spoil sand ($d_{50} < 100 \mu$) and a mixture of both ($d_{50} \div 100$ -175 μ).

The sandy part of the spoil was transported in NE direction over a distance of 4 km outside the dumping area. The displacement to the SW is much smaller.

The data of the sediment balance, grain-size and the behavior of dumped spoil all seem to indicate an apparent net northward sand movement on the underwater delta in the course of time.

3. EXCHANGE OF SAND BETWEEN THE NORTH SEA AND THE UNDERWATER DELTA

3.1. Current data

If an exchange of sediments between the North Sea and the underwater delta takes place, it is active at the underwater delta front on water depths between 10 and 20 m (fig. 1). At these depths waves only occasionally during strong winds or storms influence the sediment movement. The waves may stir up sediments and this increases the sediment concentration of the water.

However the sediment exchange between the North Sea and the underwater delta is determined by the direction of the sand transports by currents. The data on figure 2 on point 5, 6, 20, 27, 36 and 38 shows that such an exchange is apparent.

3.2. Grain-size data

There is a clear distinction between the fine sands of the underwater delta of the Haringvliet and the much coarser sands on the bottom of the North Sea further offshore. If there is an important exchange of sediments between the two areas, a broad mixing zone is expected. This expectation is confirmed by findings illustrated in figure 7a, b and c. These figures show the schematized grain-size data in several lanes perpendicular to the coast. A mixing zone can be seen in lane C and D over a distance of about 3 km and in lane E of about 1 km.

Further southward (lane F and G) the difference between the grain-size data of the underwater delta and the North Sea becomes less distinct.

The current, wave and grain-size data all point to an appreciable exchange of sediments of the North Sea and underwater delta.

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APPENDIX I

COMPUTATION OF THE SUSPENDED SEDIMENT LOAD

The method of computation of the suspended sediment transport, used in this paper is based on work of Lane & Kalinske (1939, 1941), further elaborated by Morra (1950, 1958). Here only a brief description will be given of the formulae and of the assumptions.

Lane & Kalinske (1941) started from the well-known formula for the sand concentration gradient per unit depth under equilibrium conditions of no erosion nor sedimentation in a stationary flow.

$$cN = -\epsilon_h \frac{dN}{dh} \quad (1)$$

in which c = fall velocity of particles in a turbulent fluid;
 N = sand concentration;
 ϵ_h = momentum transfer coefficient;
 h = height above the bottom.

Assuming that the momentum transfer coefficient equals sediment transfer coefficient and further assuming that momentum transfer coefficient is constant over the water depth, Lane & Kalinske arrived at the following formula:

$$\frac{N_z}{N_a} = e^{-\frac{6}{k} t (z-a)} \quad (2)$$

in which N_z = sand concentration at height z ;
 N_a = sand concentration at reference height a ;
 k = Von Karmann's constant;
 t = $cC/qg\sqrt{RI}$;
 c = fall velocity;
 C = Chézy constant;
 q = degree of parabola of the vertical velocity distribution;
 R = hydraulic radius;
 I = slope of the water level;
 z = h/H ;
 H = water depth;
 h = height above the bottom.

if $a = 0$ then according to Lane & Kalinske (1939) and also Dronkers, (1970):

$$\frac{N_o}{\Delta F_c} = \frac{A}{2\pi^{1/2}} \left\{ \frac{1}{2t_c} e^{-t_c^2} - \frac{\pi^{1/2}}{2} \left(1 - \frac{2}{\pi^{1/2}}\right) \int_0^{t_c} e^{-t} dt \right\} \quad (3)$$

in which:

N_o = sand concentration near the bottom, ΔF_c = percentage material in a certain fall velocity class, $t_c = C/B\sqrt{2gRI}$, $t = v/B\sqrt{2gRI}$, A and B are empirical constants, which appeared to be $A = 39$ and $B = 0,75$, v = vertical velocity component.

Morra introduced (3) into (2) and obtained the following expression for the total suspended load integrated over the water depth per unit width:

$$M = \int_{z=0}^{z=1} N_o e^{-\frac{6}{k} z} \cdot V_z H dz \quad (4)$$

Morra further used a parabolic velocity distribution in the vertical

$$V_z = \frac{q+1}{q} Z^{1/q} V_m \quad (5)$$

With (5), (4) becomes:

$$M = N_o V_m H \cdot D \quad (6)$$

in which

$$D = \int_{z=0}^{z=1} e^{-\frac{6}{k} z} \cdot \frac{q+1}{q} \cdot Z^{1/q} dz \quad (7)$$

M may now be calculated.

Morra constructed graphs for the solution of (7) and (6). The following remarks may be made. In a tidal area the conditions of stationary flow and of equilibrium (no erosion or sedimentation) are not fulfilled. The assumption that the momentum transfer coefficient equals the sediment transfer coefficient has not been verified. The assumption that ϵ is constant over the water depth is physically unrealistic and a crude approximation. The constant k was taken as 0,4 but it is known that this value reduces with increasing sand concentration.

Because of these facts the accuracy of the results of the computation will not be very high. However Morra (1950) found that with this method the order of magnitude of the suspended load can be estimated.