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MUD IN THE DUTCH DELTA AREA

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ABSTRACT

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Mud is transported to the Dutch delta area from the Rhine, Waal, Maas and Scheldt rivers (resp. 0.6; 2.5; 0.7 and 0.7 million tons/year). Above, in the Rotterdam Waterway about 3.5 million tons of mud per year are brought in from the sea. The mud of the underwater delta comes from the Channel, the Haringvliet, from biological formation, from erosion of older clay and mud deposits and from mud that is dumped in this area from the Rotterdam harbours. In recent years the last mentioned quantities amount to approximately 4 million tons per year.

The mud content in the water varies greatly over the area, as illustrated in figure 2.

INTRODUCTION

In a previous publication (T e r w i n d t, 1967) a general picture was given of the existing knowledge of mud transport in the Dutch delta area. Since then new data have become available which enable us to amend former points of view. Moreover, as a result of the execution of many civil engineering works in recent years the mud transport and mud sedimentation have changed significantly. The canalisation of the Rhine causes temporary mud deposition in the canal reaches when the weirs are closed. The flow pattern and the movement of mud along the Dutch coastal zone has changed, due to the extension of the Europoort harbours, the dredging of the mouth and the shoaling of the upper reaches of the Rotterdam Waterway, the closing of the Haringvliet estuary and the Brouwershavense Gat. Finally, the quantity of mud dredged up from the Rotterdam harbours has increased considerably in recent years. This mud is dumped in the North Sea and can thus be considered as a significant mud source along our coast.

This paper deals with the quantity of mud that is being carried into the delta area; the transport of mud within the area; and the average mud content in the various basins.

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METHOD OF INVESTIGATION

Normal bottle-type samplers were used to obtain water samples. Sampling was performed mostly one meter below the water surface. Samples were filtered, dryed and weighed in the laboratory. In some cases, when sand admixtures were expected, the water sample was first poured through a 50 micron mesh sieve to exclude the sand particles. So the term "mud" is here understood to include all matter of which the fall velocity in still water is less than that of a quartz grain 50 μ in diameter. The mud content is expressed in milligrams of dry matter per litre and the quantity of mud in tons of dry matter. For the conversion of tons of dry matter into m^3 of dredged mud the watercontent of the mud must be known. This varies with the degree of consolidation of the mud. Fresh deposits of mud usually have a watercontent of 90% and higher and a specific gravity of about 1.15. Harbour mud with a watercontent of about 80% has a conversion factor of 1 m^3 of mud = 0.5 ton of dry matter.

MUD TRANSPORT

The mud transport in tidal waters is fairly complicated. At certain locations the mud content in the water can change sharply in a relatively short time: the mud passes in clouds. Generally, the mud content near the bottom is higher than that near the surface of the water, but the vertical distribution varies rapidly and the laws governing the processes are hardly understood. Differences in density complicate matters even more. The intruding sub-layers of saline water (salt wedge), with a high shear stress at the bottom, can stir up large quantities of mud and thus affect the horizontal and vertical distribution of the mud.

Another problem is the sedimentation of mud. River and marine mud can be flocculated in the rivers and the estuaries in the south-western part of The Netherlands as a result of the high concentration of ions in these waters. The extent of the flocculation also depends on the mud concentration and the turbulence of the water. During transport the particles of mud change their shape, composition and size and consequently their possibilities of sedimentation.

Waves can stir up already deposited mud, while also the size of the particles will be reduced by wave action.

Changes in river discharges and tidal movements affect the ebb and flood volumes in the estuaries and sea arms. As a result the mud contents and mud transport – although with some delay – will also be affected. This variability is the reason why there is no proper correlation between river discharge, tidal characteristics, wind (waves) and measured mud content distributions in the vertical in the lower reaches of our rivers. Readings of the mud content, however, can be used to estimate an average annual mud discharge.

An often used but inaccurate method to analyse the pattern of mud transport is based on the assumption that mud particles follow the same course as the water particles. This means that the diffusive transport is being neglected and that only advective transport is taken into account. Changes in the water movement are generally predictable with the aid of calculations and/or model research. The mud transport, however, will not behave in the same way as the water movement, because mud is heavier than water and thus settles down: once precipitated it is difficult to get it on the move again. Moreover, the mud is susceptible to dispersion as a result of the diffusion which in turn depends on the mud content gradient. However, due to the lack of anything better this method will be adopted in this paper.

MUD SOURCES

In recent years de Groot and his coworkers have given a fairly complete picture of the various mud sources based on the contents of heavy metals. They discovered that marine mud along the coast of the delta area, including the Easternscheldt, up to the Waddensea showed the same relatively low content of heavy metals, while river mud, as a result of pollution, contains high concentrations of these heavy metals. (de Groot, 1973, de Groot *et al.*, 1973, de Groot & Allersma, 1975).

In the estuaries of the Scheldt and the Rotterdam Waterway, where the river and sea water meet, a gradual diminishing in content of heavy metals is noticeable in a seaward direction. (de Groot & Allersma, 1975). It is not yet established whether this should be ascribed to mixing only or whether other processes also play a role. (Duinker & Nolting, 1976, Müller & Förstner, 1975).

THE INTRODUCTION OF MUD INTO THE SYSTEM OF THE DELTA WATERS

The boundaries of the area within which the mud transport in the delta area is being studied have been chosen (abitrarily) as follows: At the landward side the boundary of the area is drawn where the tidal influence ends (Hagestein, Tiel, St. Andries). At sea the area is defined by a line drawn parallel with the coast at a distance of 20 km from it and 2 lines perpendicular to the coast at the Belgium/Netherlands border and at Scheveningen. Into this confined area mud is being transported from various sources, viz. from the rivers Rhine, Waal, Meuse and Scheldt and from the North Sea (Fig. 1).

The average yearly mud supply from the Lower Rhine (Lek) was estimated at about 0.7 million tons (Terwindt, 1967). This figure was determined before the canalisation of the Rhine occurred. As a result of the Rhine canalisation the average discharge of the Lek decreased by about 20% because more water is discharged through the river IJssel. One may assume that as a result the average yearly mud supply has also been reduced by about the same percentage and therefore might be fixed at 0.6 million tons. With time the mud supply from the Lek, due to the Rhine canalisation, has changed considerably, because at low Rhine discharges with closed weirs the mud mostly settles in the weir reaches. The mud is then carried off again when the weirs are opened as soon as the Rhine discharges increase. The mud supply into the Rotterdam Waterway can therefore reach considerable quantities in a short period of time.

The average yearly mud supply from the Waal and Meuse rivers is still estimated to be 2.5 million tons and 0.7 million tons respectively.

Continuing readings by the Rijkswaterstaat show a provisional volume of mud supply from the Scheldt near the Belgium/Netherlands border of approximately 0.7 to 1 million tons/year (Kooiker, 1975, Bakker, 1975).

In total about 4.5 to 4.8 million tons of mud are being transported annually from the continent into the system of the delta waters. The mud supply from the North Sea towards the delta waters which comes from the south along the Belgian coast has been estimated at 1 million tons/year (Terwindt, 1967).

The balance of supply and discharge of mud from the West is still unknown. A mud content gradient appears to exist perpendicular to the coast line, however. This gradient is caused by waves, which carry much water and mud towards the coast. This water transport towards the coast will be compensated by water discharge due to counter currents off the coast, but further out the mud will be caught up again in currents flowing towards the coast. So currents and waves carry the mud to the coast. For that reason the

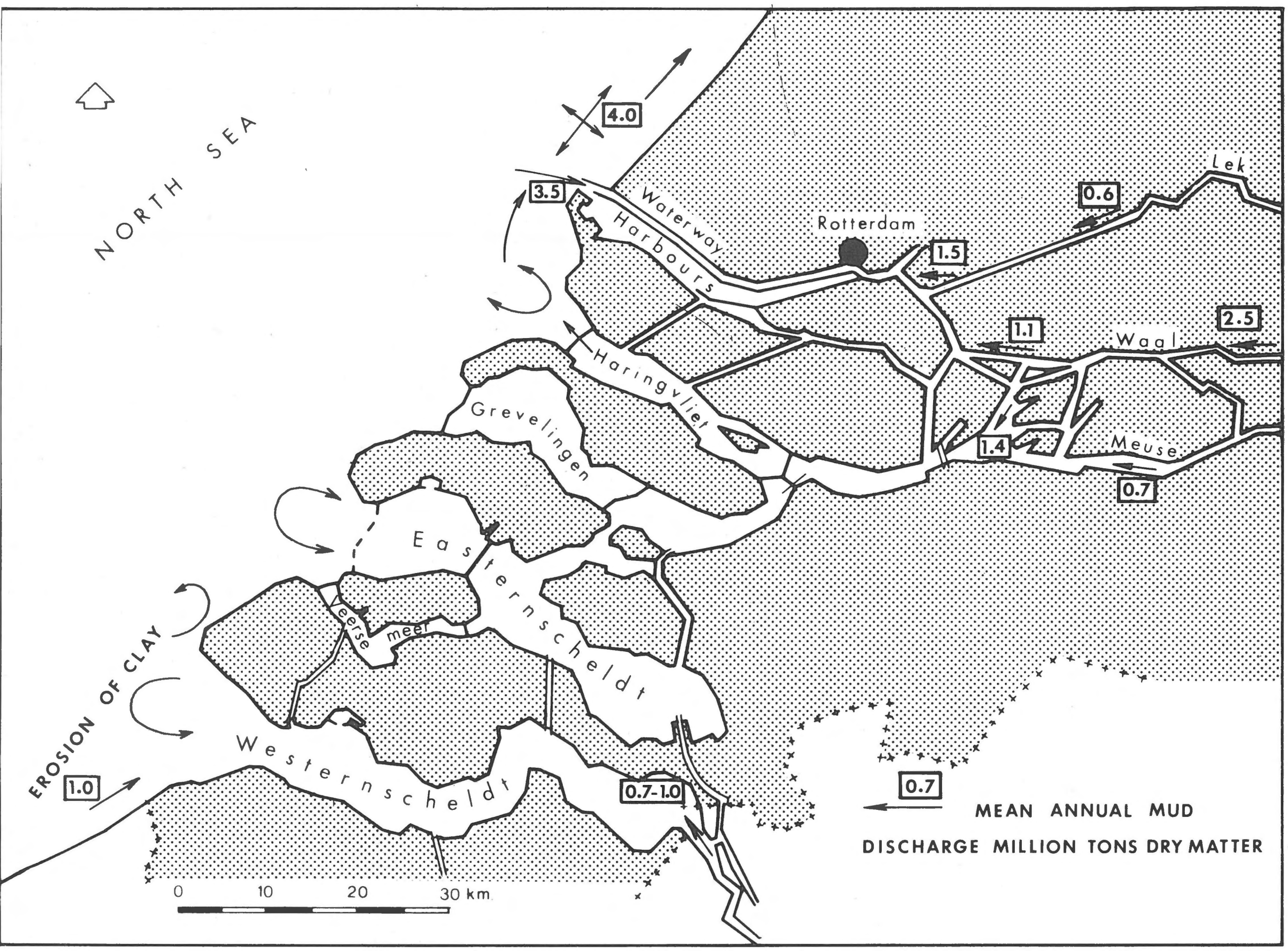

Fig. 1
Mean annual mud discharge in million tons of dry matter in the Dutch delta area.

mud transport mainly takes place in a zone near the coast. To the west of the delta area this zone is approximately 20 – 40 km wide and north of the Rotterdam Waterway 5 – 10 km wide.

MUD TRANSPORT WITHIN THE SYSTEM

Rotterdam Waterway-Europoort

The average mud supply from the Lower Rhine (Lek) is estimated at 0.6 million tons a year. The other Rhine branch, the Waal, yearly injects an average of 2.5 million tons. One may assume that this amount of mud is divided in proportion to the discharges of the Lower and Upper Merwede. This means that about 45% of the mud from the Waal is carried to the Rotterdam Waterway via the Lower Merwede, the Noord and the old Meuse, which is 1.1 million tons a year. Thus in total approximately 1.7 million tons of dry matter will flow yearly into the Rotterdam Waterway from the rivers.

It has been estimated that apart from the mud about 1.5 million tons of fine-grained sand is being supplied from the various river branches. The total supply of sediment into the Rotterdam Waterway therefore amounts to approximately 2.6 million tons per year.

According to the data of the Rijkswaterstaat and the City of Rotterdam the total volume of dredged material in the rivers and ports was 12 million m^3 in 1974 and 12.3 million m^3 in 1975. This means that every year approximately 6 million tons of sediment are being removed from the Waterway. From this quantity a maximum of 2.6 million tons is supplied by the rivers. So about 3.5 million tons per year is brought in from the sea. There are indications that for the greater part the supply of mud and sand occurs during periods of stormy weather.

Lake Brielle

The mud content of Lake Brielle is low. At the inlet near Spijkenisse the average content is about 25 mg/l, but at the

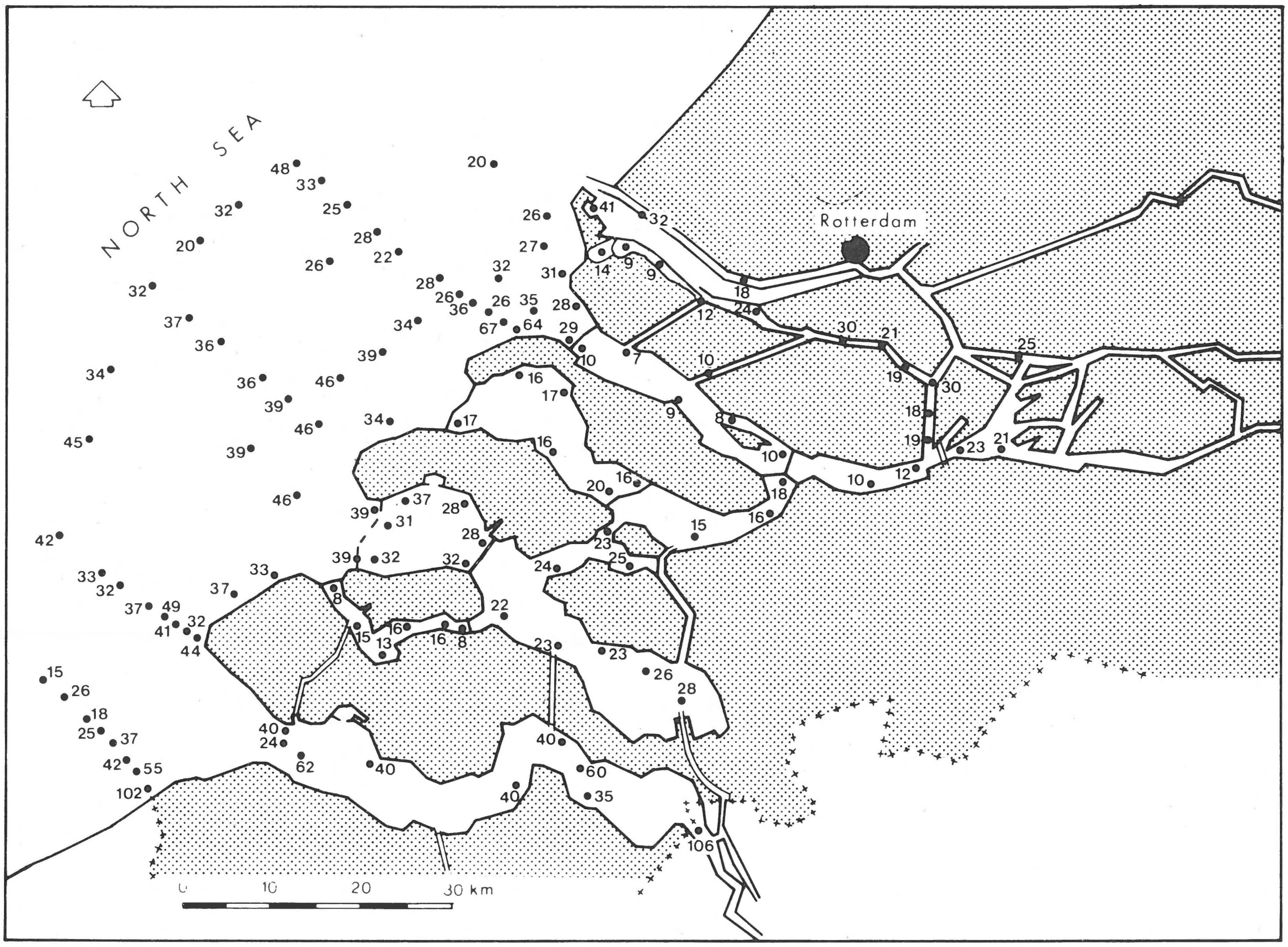

Fig. 2
Mean mud content in mg/l in the Dutch delta area, measured during calm – fairly calm sea over 1972 – 1975 (Number of observations: underwater delta 25; other areas > 75).

end of the entrance canal the content is already reduced to about 10 mg/l. (Fig. 2). In 1972 the supply of mud via the inlet sluice as well as from other sources amounted to about 1800 tons. The mud deposit amounts to about 75% of the supply, thus in the order of 1500 tons.

New Merwede – Haringvliet

The river Waal yearly discharges approximately 2.5 million tons of dry matter. As already mentioned above approximately 1.1 million tons of this amount is transported into the Rotterdam Waterway. That means that another 1.4 million tons find its way into the New Merwede – Haringvliet every year. The Meuse adds another 0.7 million tons. Thus in total 2.1 million tons of dry matter is being transported yearly into that area.

Total sedimentation in the New Merwede, Amer and Hollands Diep amounts to about 3 million tons a year. Of this a maximum of 2.1 million tons is mud and 0.9 million tons is fine-grained sand. The major part of this sedimentation (50%) takes place in the New Merwede while 30% settles in the Amer and 15% in the Hollands Diep. In the Upper Merwede only 5% of the total settles. As a result of this sedimentation the mud content in the above mentioned trajectory drops by about 50%.

It has been established that during periods of high Rhine discharges the sedimentation area will be found farther down the stream in the direction of the Haringvliet (Fig. 3). Due to higher current velocities, which occur under these circumstances, previously deposited mud layers can be eroded again. It is quite possible that in this way mud from the Haringvliet is transported into the sea. This is not necessarily caused by the erosion of the mud layers only, but might also be the result of the higher mud content in the river water which coincides with these high discharges. Until now, however, it has been established that with Rhine discharges up to about 6000 m^3/sec. the Haringvliet still functions fully as a mud trap and that quantities of mud transported to the sea are actually still very small. One should note that when the sluices are closed at high tide the water in the Haringvliet is

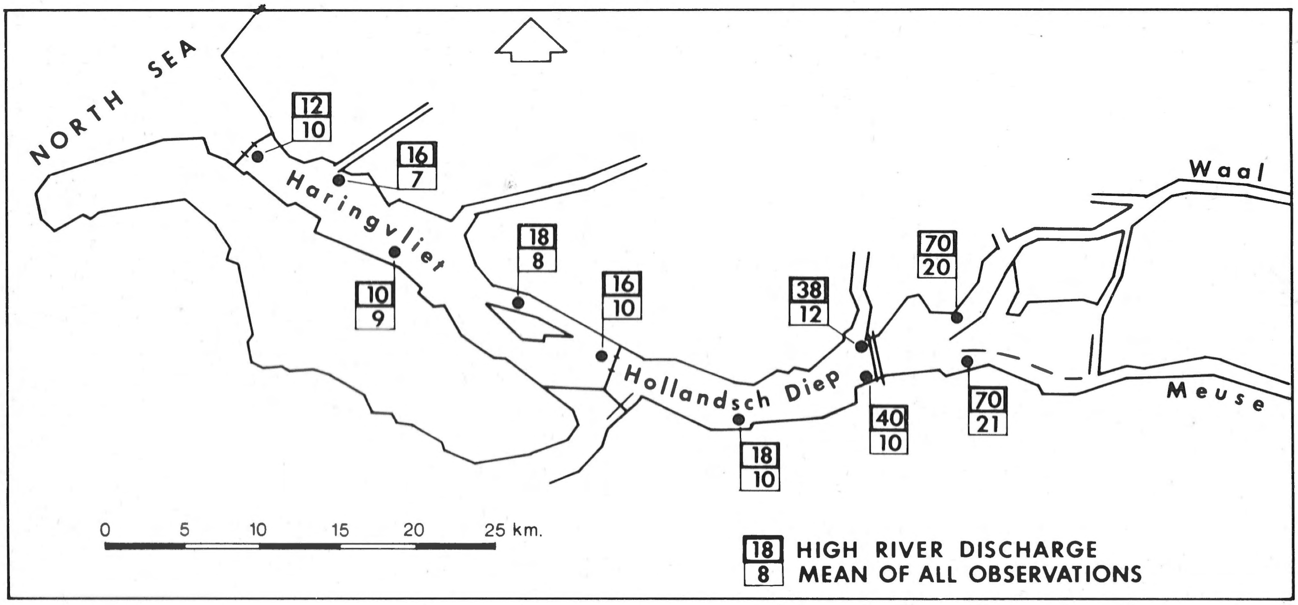

Fig. 3
Mud content in the Haringvliet during high river discharge and during normal conditions (Number of observations: total > 100; high Rhine discharge: 10-15).

brought to a standstill for at least 6 hours which gives the mud the time to settle.

The Easternscheldt

There is a gradual decline in the average mud content from the mouth to the central section of the Easternscheldt (Fig. 2). In the eastern section, however, there is another increase in the mud content.

The established reduction is probably caused by sedimentation. The increase in the eastern section could be the result of a residual transport of suspended matter in the direction of the coastal border (van Straaten & Kuenen, 1957; Postma, 1961; Groen, 1967).

The mud in the Easternscheldt comes from the North Sea or originated in the basin itself. The major part of the mud in the Easternscheldt is of organic origin (plankton). Certainly in spring time during the growth of algae 50 to 75% of the mud is of organic origin. During the remaining part of the year roughly 50% of the mud is made up of organic matter.

In the Keeten-Zijpe-Krammer-Volkerak we observe a gradual decline in the average mud contents from 25 mg/l in the Keeten to 15 to 20 mg/l in the Volkerak. This reduction can probably be attributed to sedimentation of mud due to the slowing down of the water currents in this area. To combat salinity an average of about 20 m^3/sec. of Holland Diep water is discharged to the south via the Volkerak locks. This water contains about 11 mg/l of mud. The mud flow through the Volkerak locks therefore amounts to approximately 7000 tons/year. South of the Volkerak locks a yearly sedimentation of approximately 3 million m^3 takes place. The percentage of mud is estimated at roughly 40%. This means a yearly settlement of mud of about 0.6 million tons. From these figures it follows that south of the Volkerak locks only 1% of the mud sedimentation is formed by matter that passed through the Volkerak locks and that 99% must be brought in from the Easternscheldt.

Lake Grevelingen

The mud content of the water of the Grevelingen is low: 15 to 20 mg/l. The mud loading is also small. The annual supply from adjacent sources via the lock at Bruinisse is roughly 1000 tons. The shoals in the Grevelingen are very sandy. The mud that precipitated after closure, or was brought in later, is concentrated in the deep channel sections. This concentration is the result of wave action which stirs up the deposited mud in shallow places and brings it into suspension again. This resuspended mud can then settle down permanently in the deeper sections.

Lake Veere

The mud content in lake Veere is extremely low (approximately 15 mg/l) (Fig. 2). This mud is mostly of organic origin. The mud supply to the lake comes from the polders and is also due to the yearly change in the waterlevel of the lake. In autumn the level is lowered by 0.70 m. In this case the water, with a relatively low mud content (15 to 20 mg/l), is discharged into the Easternscheldt. In spring water is brought back again to the lake from the Easternscheldt. This water has a higher mud content (approximately 30 – 40 mg/l).

Owing to these two actions the mud transport varies considerably from year to year. Over the years 1972 and 1973 this amounted to an average of approximately 1000 tons of dry matter. In the "wet" year of 1974 this reached even 7000 tons due to the high polder discharges.

The Westernscheldt

Extensive measuring by the Rijkswaterstaat in the Westernscheldt estuary provided the average mud contents which are shown in Fig. 2 (B a k k e r, 1975; K o o i k e r, 1975). There proved to be a sharp decline of the mud content from the Belgian/Dutch border in a seaward direction. This must be ascribed to the mixing of river- and seawater (with a much lower mud content) in the area and to mud sedimentation especially in the Land van Saaftinge (d e G r o o t, 1963).

There is a net inward supply of mud from the sea into the estuary. From observations it has been established that the mud content at flood tide is higher than at ebb tide while the volume of ebb and flood tide remains more or less equal.

The "underwater delta"

As we have already seen this area receives mud from the south along the Belgian coast and from the west. Another source of mud supply for this area is the mud transport through the Haringvliet locks. Before the closure of the estuary the Haringvliet contributed significantly to the mud movement in the coastal zone facing the Haringvliet – Rotterdam Waterway. A small part of the Haringvliet mud was carried to the Brouwershavense Gat.

After the closure the mud transport from the Haringvliet decreased sharply. The mud contents in the mouth dropped by a factor 5 – 10 (from 100 to 300 mg/l to 30 to 60 mg/l). Only during high flush-discharges is the mud-load still of some importance, although the mud content is low. It is true though that with high flush-discharges deposited mud in the discharge channels might be eroded and in this way be added to the coastal waters.

Mud can also be provided by erosion of mud containing sand layers and old clay deposits, which form a large part of the bottom especially in the mouth of the Western- and Easternscheldt (B a s t i n, 1971; H o u b o l t, 1968). During heavy gales in these areas relatively high mud contents are observed in the water as a result of this erosion.

One more source is the biological formation of mud in the form of plankton.

Another very important source of mud to the underwater delta is from the mud dumped after the dredging operations in the Rotterdam Waterway and harbours (Fig. 1) and in the entrance channel; the navigation channel for supertankers to the Europoort. A broad estimate of the size of this source is shown in Table I. This estimate is based on the data provided by the Rijkswaterstaat and the Public Works Department of the City of Rotterdam. Assumptions were made concerning the sand ratio in the mud, originating from various areas. The mud from the entrance channel dredged from depths of up to 65 feet consisted for about 25% of Holocene marine clays. The major part of this clay has been "broken down" to mud during the dredging, and was pumped overboard and added to the coastal waters. Only a small percentage of the mud together with the sand was actually dumped at the dumping site.

A number of strongly resistant mounts of clay have been removed with a dredger. The lumps of clay that were pried loose have been dumped in troughs in the vicinity of the channels.

The quantity of mud that came free with the deepening of the entrance channel is roughly estimated to be 20% of the total dredged quantity.

A study of the sea bottom at the dumping site showed that, in the long run, the major part of the dumped mud is washed out again from the bottom deposits and is added to the mud transport of the coastal waters (T e r w i n d t, 1968).

In a test with radio-active marked mud that was dumped at the dumping site it appeared that about 10% of the tracer was found again in the mouth of the Rotterdam Waterway. If one accepts this figure as the order of magnitude for the total contribution of dumping site mud to the mud transport in the mouth of the Waterway, then this means that annually about 0.8 million m^3 of mud flows back into the Waterway from the dumping site, i.e. 0.4 million tons. With a total mud supply of 3.5 million tons per year from the sea to the Waterway this means that approximately 10% of the marine mud would be coming from the dumping site. It should be

year	dumped quantities from maintenance and deepening in million m^3				dumped quantities of mud in million m^3	Holocene marine mud from the entrance channel in million m^3
	Rijkswaterstaat		the city of Rotterdam			
	maintenance	deepening	maintenance	deepening		
1959	1,2				0,6	
1960	2,6				1,3	
1961	5,4				2,7	
1962	3,4				1,7	
1963	1,7		-	2,7	1,3	
1964	2,0		0,3	3,6	2,0	
1965	1,9		1,3	3,8	2,8	
1966	6,2		1,0	4,2	3,9	
1967	3,5	10,8	4,7	5,2	8,7	1,7
1968	4,5	14,6	5,2	5,6	10,5	2,6
1969	3,8	12,2	1,5	2,9	6,1	2,0
1970	0,8	6,2	0,3	5,5	2,9	
1971	3,4	6,0	0,6	2,8	3,9	
1972	4,1	–	1,6	2,3	3,7	
1973	8,3	–	1,8	–	8,1	
1974	9,6	–	1,0	–	8,5	

Table I Mud-injection in coastal waters in the vicinity of the dumping site.

pointed out, however, that these figures are as yet broad estimates and will certainly need closer verification. That the recorded heavy silting in the Europoort during storms is mostly caused by mud stirred up from the dumping site has certainly not been ignored. It is quite possible that with a N.W. storm in the coastal area in the mouth of the Waterway a residual water movement is generated in SW direction. Mud stirred up from the dumping site can thus reach the mouth of the Waterway.

The underwater delta loses mud to the estuaries of the Rotterdam Waterway, the Westernscheldt and Easternscheldt, but also in a northerly direction along the coast. This is caused by the fact that along the coast of the central part of Holland an average residual water movement in a northeastern direction occurs in time. It is also quite possible that the underwater delta loses mud along the western border and may be even along a part of the southern border.

The mud transport over the underwater delta can be analysed on the basis of the water movement. The water movement in the mouths of the sea-arms before the closure of the estuary shows a circulation pattern. This means that the water masses in the mouths have a circular movement and that relatively little exchange takes place with the water masses of the various sea-arms. These circulation systems are clearly recognizable in the drift of the water particles. Also the mud transport, which will presumably follow the water movement, is affected by these circulation systems. These circulation patterns are closely connected with the currents on the underwater delta. Along the heads of the islands there are in general currents in NW-SW direction, but in the sea-arms the direction is W-E.

After closure of the estuaries, the circulation systems will undergo some changes due to a weakening of the currents in W-E direction and the patterns of the currents will run more parallel to the coast; however, these systems will certainly not disappear. That can be seen from tidal computations as well as from the measurements that have been made in these estuaries since the closure of the Brouwershavense Gat. The old channel system in the underwater delta proves to have a clear guiding effect on the circulation streams. At present it is not yet possible to establish whether the exchange between the newly created circulation systems is greater than it was before, or not. Of great importance in this case is the presence of residual flows over the underwater delta since the closure. Due to the fact that the tidal current velocities will decrease, the effects of wind- or wave-driven currents will become relatively greater. For these reasons one might expect a somewhat greater water exchange between the various systems. It is not impossible that after the completion of the delta works the coastal waters in front of the delta area will be more strongly influenced by the waters coming from the Westernscheldt, the Haringvliet and the Rotterdam Waterway than at present. Also, as far as the mud transport is concerned, one may then expect a greater exchange and transport along the coast. Mud coming from the Westernscheldt, the Haringvliet and the Rotterdam Waterway will then be transported further to the central part of the delta coast.

On a larger scale we can consider the area of the underwater delta as a huge mixing system, in which a large quantity of mud is contained which is supplied by a number of internal sources and from along the eastern border (Waterway, dumping site and to a less extent from the Haringvliet) and which loses mud along the northern, but possibly also along the western and southern, sea borders. The average mud content in this buffer zone can change sharply over a short period of time. With a storm mud is being stirred up and with a calm sea much mud can settle down. However, over longer periods of time the mud content will vary very little. For an estimate of the order of magnitude of the quantities of the mud over the underwater delta the following figures may be useful.

With an area of 2000 km^2, an average depth of 10 m and a mean mud content of 50 mg/l there is approximately 1 million tons of mud in suspension over the underwater delta. The greatest role, however, is played by the sea bottom. Suppose that from the top 5 cm of the sea bottom 5% weight of mud is removed or added, this then represents a quantity of mud of about 10 million tons.

If this trend of thought is followed up it becomes more easily explicable that with each enlargement of the harbour area increased silting in the ports is observed. With the increased tidal volume more mud will come in from the buffer zone. The system will not "suffer", however, because practically all the settled mud in the ports is dumped back into the sea and thus added to the system again. If the dumping of the dredged mud near the coast ceased or the mud were brought to dumping sites on land then, in the long run, this would lead to a decrease in the average mud content of the system and thus to a decrease in silting. This process would go very slowly because many million m^3 of mud are involved in the system and the silting in the harbours represents only a small portion of it.

The closure of the Haringvliet estuary has a special significance in this respect. The sharp decrease of the mud supply from the Haringvliet to this system will contribute to a reduction in the average mud content of the system.

CONCLUSIONS

The yearly average mud transport from the Rhine and Waal rivers to the Rotterdam Waterway is about 2.6 million tons of dry matter. Every year about 6 million tons of mud are being dredged. That means that approximately 3.5 million tons of mud per year are brought in from the sea.

After closure of the Haringvliet estuary the major part of the mud carried by the Waal and Meuse settles in the New Merwede, Amer and Hollands Diep. The mean annual deposit amounts to approximately 3 million tons of dry matter, of which at the most 2.1 million tons are mud and the rest fine grained sand. Due to these deposits the mud content in the trajectory of New Merwede – Hollands Diep drops to about half. The contents in the Haringvliet are about 5 to 10 times lower in comparison with the situation before the closure. That is also the reason why the contribution of the Haringvliet to the mud transport along the coast is very sharply reduced.

The mud in the Easternscheldt partly originates from the North Sea but for a large part is also formed in the basin itself. The lowest mud content is found in the central part. Towards the eastern border the content increases.

The mud content in lake Grevelingen and Lake Veere is low: an average of 15 to 20 mg/l. In lake Brielle even lower values are found.

The Westernscheldt receives yearly about 0,7 million tons of mud from the river Scheldt. There is also mud transport from the sea, but the quantity is as yet unknown. The average mud content of the Westernscheldt shows a sharp decline in the vicinity of the Netherlands-Belgian border. In the estuary itself the average mud content varies between 40 and 60 mg/l.

The mud of the underwater delta might come from the Channel carried along the Belgian coast, from the Haringvliet, from biological (plankton) formation, from the erosion of other clay and mud deposits and from mud that is dumped in this area from the Rotterdam harbours.

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