A MUD BALANCE FOR BELGIAN-DUTCH COASTAL WATERS BETWEEN 1969 AND 1986

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ABSTRACT

Mud transport and mud-balances are usually calculated from multiplication of suspended matter concentrations and depth-averaged residual water transport. The results are assumed to underestimate the actual mud transport because the suspended matter concentrations are measured at the sea surface, mostly during calm weather. In addition, these kinds of budgets are sensitive to small variations in the estimated residual current velocity. These problems can be overcome by comparing the calculated transports with the fluxes that result from balancing amounts of erosion and deposition. The last figures integrate spatial differences in transport over time to a large extent. Following this approach it is shown that between 1969 and 1986 variations in the mud budget occurred as a result of large-scale human interference (deepening the approach channel to Zeebrugge, closure of Dutch Delta estuaries). The variations were small compared with the annual longshore mud transport, which is dominated by the amount of mud that passes from Dover Strait to Belgian-Dutch waters (c. 8.5 x 10^6 tons per year), but were relatively large when compared with the mud transport in the 20 km wide coastal zone. It is demonstrated that fluctuations in the annual frequency and duration of gales can cause the annual flux of mud to double in some years.

1. INTRODUCTION

Mud is defined as organic (dead or living) and inorganic matter with a particle size smaller than 63 microns; by its way of transport, mud is suspended matter. However, suspended matter also comprises fine sand, microorganisms (algae) and flocs with a particle size larger than 63 microns. Mud is brought into the ecosystem by input from rivers, adjacent seas and oceans, erosion of the seabed and the shore, and by primary production. Because of the way of transport, mud particles follow more or less the general residual water circulation. When turbulence generated by currents and/or waves falls below a certain level, mud particles settle out. Areas where net deposition of mud occurs within and along the North Sea include the Oystergrounds, Outer Silver Pit, German Bight, Skagerrak, Wadden Sea and The Wash (EISMA, 1981). Mud particles may also be deposited temporarily, e.g. during summer, when storm activity is low, to be re-suspended in winter.

Mud plays an important role within the marine ecosystem of the North Sea: the transport of the organic part can be considered as a large flow of nutrients and microorganisms which also serves as a transport medium for organic contaminants and heavy metals. Secondly, its presence reduces the amount of daylight available for the marine life in the water column and on the seabed. Budgets are important for validating the results of ecosystem modeling. Apart from its ecological importance, the mud transport in the Belgian and Dutch coastal waters also has major economic consequences: maintenance dredging almost continuously removes the mud that settles in the approaches to harbors such as Zeebrugge and Rotterdam.

Tentative mud balances have been derived for the Dutch Delta area (TERWINDT, 1967, 1977) and for the North Sea as a whole (EISMA, 1980). Recently, the computed residual water movement and surface suspended matter concentrations were combined so that a mud balance could be calculated for the Dutch coastal waters (ANONYMOUS, 1985). However, none of these balances took time-dependent fluctuations in the residual current and vertical gradients in concentration and current pattern into account. Studies along the Dutch coast show that concentrations and residual currents may vary significantly in space and time. For example, a clear residual landward bottom flow is observed near Noordwijk (VAN DER GIESSEN et al., this volume).

This paper describes an approach in which calculated fluxes of mud are compared with the amounts of mud deposited or eroded that can be deduced from literature and unpublished data. Data on the amounts of mud removed by maintenance are used to evaluate whether the estimated budgets are realistic (it is unlikely that
the amounts of mud dredged exceed the mud transport at that location). Within the area considered, large civil engineering works, such as the closure of the Delta estuaries (1970-1985) and the deepening of the approach channels to Zeebrugge and Rotterdam (1980-1985) may have influenced the mud transport. Therefore, averaged budgets will be derived for these two periods and for a few years before and after. The resulting fluxes can be considered as potential yearly fluxes, because they are integrated values. Actual mud transport may be larger or smaller than the potential transport, depending on the actual degree of turbulence every year, which in turn is largely determined by the frequency and duration of gales. This will be discussed. The approach used to calculate the mud balance assumes that the variations in the actual fluxes from year to year can be illustrated qualitatively by the year-averaged values of suspended matter concentration at certain locations and the amount of maintenance dredging in the seaward part of the Rotterdam harbours.

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Fig. 1. Location of the area. Dashed line indicates boundary of budget area. A<sub>20</sub>, G<sub>6</sub> and N<sub>2</sub> are locations of the time series of suspended matter concentrations (see Fig. 9).
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2. PREMISES

For the purposes of this paper, suspended matter is considered to be equivalent to mud. Strictly speaking, this is not correct, as suspended matter may comprise particles with a grain size larger than 63 micron. The contribution of organic matter to 'mud' will be discussed in section 6. To convert volume to weight it is assumed, unless indicated otherwise, that dredged material has a wet specific weight of 1300 kg/m³ and that it contains 500 kg of solid matter with a dry specific weight of 2500 kg/m³. For eroded sediments or material dredged for channel deepening a wet specific weight of 1600 kg/m³ and a solid matter content of 1000 kg/m³ are assumed.

Sedimentation and erosion rates can be measured accurately only if they are considered as an integrated value for several years. On the other hand, suspended matter concentrations fluctuate on a time scale of a week in response to wind conditions (Gosse, 1976). As a compromise, the results have been expressed as year-integrated values; time steps are one year. On this time scale the residual water transport is northeastward. The fluxes hold for imaginary cross-sections that run NWSE from the Belgian-Dutch coastline to the median line of the Southern Bight (Fig. 1), which is about 70 km offshore at Noordwijk.

3. SUPPLY

3.1. DOVER STRAIT

The values for year-averaged suspended matter concentrations in the surface waters of Dover Strait, which are 10.6 mg/l for the coastal area and 3.4 mg/l for the offshore area, are based on 65 measurements, performed between March 1977 and June 1980 (CNEXO, 1981; Table 1). Depending on the season, reported values from the coastal area vary from 1.8 to 22.8 mg/l, whereas offshore they range from 1.1 to 8.3 mg/l. Highest values are observed during winter and autumn. Eisma & Kalf (1987) and Van Alphen (1989) found comparable concentrations. Various authors have estimated the input of mud through Dover Strait (e.g. Van Veen, 1936; Postma, 1957; McCave, 1973; Eisma & Kalf, 1979). However, the residual water flux through Dover Strait varies between seasons because of wind influences (Prandle, 1978) - and so do suspended matter concentrations (CNEXO, 1981). In addition, net residual water fluxes and mud concentrations are distributed unevenly over the cross-section (Van Veen, 1936; Eisma & Kalf, 1979), although recent measurements show that the vertical gradient of mud is negligible most of the time (Van Alphen, 1988; Fig. 2). In all these approaches to estimating the input of mud, concentrations are multiplied by the annual residual water flux. Based on a very limited set of observations, but a detailed set of tidal current data (however, measured in conditions with low wind speeds) Van Veen (1936) assumed a net mud transport of about 1.5·10⁶ m³ per year, equivalent to about 4·10⁶ tons (dry weight). Eisma & Kalf (1979) multiplied a more reliable estimate of water flux (calculated by Prandle, 1978) by an averaged mud concentration of 1.9 mg/l for water masses with salinities above 35‰ and added a coastal mud transport of about 3.5·10⁶ tons per year to this result. In this way they arrived at a mud transport of 11.5 to 15·10⁶ tons per year through Dover Strait. The net supply of mud can be estimated more accurately if suspended matter concentrations and residual water fluxes are differentiated according to seasons and locations in the cross section. Using data from Van Veen (1936) on the residual current distribution, from Prandle (1984) on the residual water flux over the year and from CNEXO and my own observations on mud con-
concentrations, I deduced a net supply of mud of $17 \times 10^6$ tons per year (VAN ALPHEN, 1989). It should be stressed, however, that the actual mud supply may differ substantially from this value, because of slight differences in mud concentrations, in combination with uncertainties about residual water flux (Postma, pers. comm.). Nevertheless, I consider that $17 \times 10^6$ tons per year is currently the most reliable estimate for the long-term year-averaged suspended matter transport through Dover Strait. EiSMA (1981) assumed that about 50% of the transport through the Dover Strait reaches the Belgian and Dutch part of the Southern Bight. In this paper it will be shown that the mud transport along the Belgian-Dutch coasts probably is in the order of 7 to $10 \times 10^6$ tons per year, thus supporting a mud transport of about $17 \times 10^6$ tons per year through Dover Strait. Annual fluctuations in residual water flux through Dover Strait (PRANDLE, 1984) may impose a variation of about 17% on this figure. In combination with variations in year-averaged suspended matter concentrations this means, that year to year variations in the mud supply through Dover Strait can be in the order of at least 50%.

3.2. EROSION OF THE FLEMISH BANKS

Along the northeastern part of the Belgian coast, suspended matter concentrations attain values of up to several hundreds milligrams per litre (BASTIN, 1974; GULLENTOPS et al., 1977). This is partly because of the erosion of the clayey deposits that form the seabed in this area (BASTIN, 1974). By comparing successive depth charts of this area a net mud input of 0 to $2.4 \times 10^6$ tons per year is estimated, with 1.0 as the most realistic value (GOSSE, 1977).

3.3. DEEPENING THE APPROACH CHANNEL TO ZEEBRUGGE

Fig. 3 shows the amounts of material dredged for maintenance and deepening in the Zeebrugge area between 1969 and 1984 (TECHNISCHE SCELDE COMMISSIE, 1984).

Fig. 3. Amount of material dredged from the Zeebrugge area and approach channel per annum ($10^6$ tons per year with dry weight of 1.6 tons per m$^3$).
Note that in this area 1 m$^3$ of dredged material contains 1000 kg of solid matter. The approach channel was deepened between 1979 and 1984, resulting in an extra 75·10$^6$ tons of dredged material (see Fig. 3). The mud content of the solid matter was about 10% (Malherbe, pers. comm.). So, for this period the average input into Belgian-Dutch coastal waters was about 1.5·10$^8$ tons mud annually.

3.4. OOSTERSCHELDE

Prior to the completion of the storm surge barrier in the Oosterschelde in 1986 it was estimated that the estuary supplied 0.1·10$^8$ tons of mud annually (DRONKERS, 1985). Now, however, it is expected that there will be a net flux from sea into the estuary (see 4.2.).

3.5. RIVERS

The relevant rivers that supply mud to the area under consideration are the Scheldt, Meuse and Rhine. A negligible amount of the mud supplied by the river Scheldt escapes to sea (STeyaert & VAN Maldegem, 1987).

The amount of mud supplied by the rivers Rhine and Meuse by direct outflow or dumping of dredged material is estimated at an average of 1.5·10$^8$ tons per year (TERWINDT, 1977; ANONYMOUS, 1979). Since 1985, contaminated dredged material from the Rotterdam harbours has been stored in an artificial basin on land. Consequently, the supply has fallen down to a level of about 0.8·10$^8$ tons per year (Blokland, personal communication). Before the completion (in 1971) of the Haringvliet sluices, a net supply of 4·10$^6$ tons of mud per year was assumed, as a very rough estimate (TERWINDT, 1967). However, isotope analysis has suggested that marine mud was imported into the former estuary (Salomons & Moek, 1977). Probably, supply of river mud and loss of marine mud both occurred, as a consequence of the typical estuarine circulation, i.e. net outflow along the surface and net inflow along the seabed. Therefore, as an approximation, net supply is considered to be zero in this situation. Since 1971, river mud has not been able to escape to sea, as it settles in the Hollands Diep-Haringvliet basin (TERWINDT, 1977). Furthermore marine mud is prevented from fluxing into this estuary as the sluices are closed during flood.

3.6. MORPHOLOGICAL CHANGES IN THE AREA IN FRONT OF THE DUTCH ESTUARIES

The closure of the Grevelingen estuary and the construction of sluices in the Haringvliet and a storm surge barrier in the Oosterschelde estuaries has resulted in adaptation of the morphology (Van Den Berg, 1987) and lithology (Van Der Weiden, 1986) in the area in front of these estuaries to the new hydrodynamic situation. As a result, 0.4·10$^8$ m$^3$ of mud is eroded annually from the Haringvliet-Grevelingen deltas (KohsieK, 1988), which is equivalent to about 0.4·10$^6$ tons per year.

4. DEPOSITION

4.1. WESTERSCHELDE

Based on empirical research and mathematical modelling a net deposition of marine mud of 0.57·10$^6$ tons per year is assumed (STeyaert & Van Maldegem, 1987).

4.2. MORPHOLOGICAL CHANGES IN THE AREA IN FRONT OF THE DUTCH ESTUARIES

Apart from erosion of the outer delta (see 3.6), the morphological adaptation of this area to the new situation also comprises the infilling of former tidal channels by mud deposition. Cores (PieKaar & Kort, 1983) reveal that between 1970 and 1980 8.4·10$^6$ tons of mud was deposited in front of the Haringvliet sluices. Locally the deposits are 4 meters thick and have a mud content of 95%. In the Brouwershavens Gat channel 1.5·10$^8$ tons were deposited in the same period; so, on average 1.0·10$^8$ of mud is lost in this area annually (see also KohsieK, 1988). Erosion of the delta rim contributes 0.4·10$^8$ tons per year (see 3.6).

Now that the storm surge barrier in the Oosterschelde is operational it is expected that the resulting changes in hydrodynamics will lead to a net flux of marine mud into the Oosterschelde basin (THEGROEP UITGANGSSITUATIE, 1986). A net flux in the order of 1·10$^8$ tons per year has been estimated from unpublished data.

4.3. LOSWAL NOORD DUMPING SITE

The material that has been dredged in the Rotterdam harbour area and approach channel is dumped at sea at the 'Loswal Noord' site (Fig. 1). In 1980, 1981 and 1982 the amount dumped varied from 4.6 to 6.4·10$^6$ tons per year, and about 20% of the dumped mud remains on the seabed at the dumping site (Louisse, 1986).

Figures for other years can be obtained by assuming that the proportion of mud in the dumped material is constant over the years. Thus can be inferred that between 1974 and 1986 the amount of mud dumped at Loswal Noord varied from 3.5 to 7.2·10$^6$ tons per year and that permanent storage in the seabed ranges from 0.7 to 1.4·10$^8$ tons per year. Values of a comparable order of magnitude can be obtained from Van Heuvel (1988).
4.4. STORAGE IN SLUFTER ARTIFICIAL BASIN

Since 1985 only the least contaminated dredged material is permitted to be dumped at sea. The remainder, a mixture of river and marine mud (Salomons & Eysink, 1981), is stored in the 'Slufter' basin situated south of the entrance channel to the Rotterdam-Europoort harbours. So about $0.7 \times 10^6$ tons of marine mud and $0.7 \times 10^6$ tons of river mud is withdrawn from transport every year (Bloklund, pers. comm.).

5. MUD BALANCE

For the description of the mud transport 4 different periods are distinguished: before 1970, 1970-1980, 1980-1985 and 1985-1988. As an approximation, the mud supply through Dover Strait in the direction of the Belgian-Dutch coastal waters is kept constant throughout the years ($8.5 \times 10^6$ tons per year). The budgets for the four periods are presented schematically in Fig. 4.

Before 1970.

Supply through Dover Strait and erosion of the Flemish Banks gives a net input of $9.5 \times 10^6$ tons per year into the Dutch sector. About $0.6 \times 10^6$ tons is deposited in the Westerschelde, $1.5 \times 10^6$ tons of river mud is delivered by the river Rhine, and $0.7 \times 10^6$ tons is stored in the Loswal Noord dumping site. Approximately $9.7 \times 10^6$ tons may be transported north of this site annually.

1970-1980

Morphological changes in the area in front of the Delta estuaries result in a supply of $0.4 \times 10^6$ tons and deposition of $1.0 \times 10^6$ tons i.e. a net deposition of $0.6 \times 10^6$ tons of mud per year. Intensified dredging results in about $1.0 \times 10^6$ tons of mud being stored on the Loswal Noord seabed. Transport north of this dumping site remains at about the same level ($8.8 \times 10^6$ tons per year).

1980-1985

At Zeebrugge, an average of $1.5 \times 10^6$ tons of mud is added to the mud transport per annum. This gives a net input of $11.0 \times 10^6$ tons per year across the Belgian-Dutch boundary (a comparable value is given in Anonymous, 1985). Net deposition in front of the estuaries and in the Westerschelde still proceeds at the former level, but because of intense dredging campaigns, storage in the Loswal Noord is assumed to reach a maximum value of $1.2 \times 10^6$ tons per year. Transport north of the Loswal Noord is $10.1 \times 10^6$ tons per year.

The supply of mud produced by to the deepening work at Zeebrugge is terminated, but deposition in the Oosterschelde basin ($1 \times 10^6$ tons per year) has begun. In addition, contaminated dredged material from the Rotterdam area is stored on land, decreasing the annual supply of river mud from $1.5$ to $0.8 \times 10^6$ tons, while also $0.7 \times 10^6$ tons of marine mud is withdrawn from transport. Because of this, dumping at sea is reduced and storage at Loswal Noord falls to about $0.6 \times 10^6$ tons per year. Consequently, the potential transport north of the Loswal Noord drops to $6.8 \times 10^6$ tons per year; this is a decrease of about 30%.

From the above, it can be concluded that:
- the supply through Dover Strait is the dominant factor in the mud transport through the Belgian and Dutch waters of the Southern Bight
- except for the post-1985 period, the potential transport north of the Loswal Noord does not vary significantly in time; all fluctuations fall within the range due to fluctuations in the supply through Dover Strait (c. 2 to $5 \times 10^6$ tons per year).

6. DISCUSSION

So far we have considered potential amounts of erosion, sedimentation and transport as averaged figures for cross-sections of 50 to 70 km long for the periods distinguished. The question is however, how actual transport does take place, and what quantities of mud are involved.

Along the Belgian-Dutch coastline the residual water transport is north-eastward (Nihoul & Rinfola, 1981; Anonymous, 1985; Van Der Giessen et al., this volume). North of Dover Strait, suspended matter concentrations along the central axis of the Southern Bight remain fairly stable (less than 5 mg/l, Eisma & Kalf, 1987) but towards the coast they increase gradually to 50 mg/l off the Belgian coast. Erosion and concentration of mud in a gyre-like water movement off Zeebrugge is thought to be responsible for this maximum (Nihoul, 1975). This could explain why the amount of mud involved in maintenance dredging in the approach channel of Zeebrugge (7 to $10 \times 10^6$ tons per year, Malherbe, pers. comm.) is of the same order of magnitude as the longshore mud transport through the entire cross-section.

An important consequence of this gyre is that the effective transport across the Belgian-Dutch boundary is reduced significantly, as is proposed in Anonymous (1985), from 21.6 to $12.7 \times 10^6$ tons per year. These figures are based on surface measurements of suspended matter and residual current estimates. Remarkably the figure of $12.7 \times 10^6$ tons per year, which is corrected for the gyre-like waters movements, agrees relatively well
Fig. 4. Mud balance for the Belgian-Dutch waters of the Southern Bight averaged for the period before 1970(a), 1970-1980(b) 1980-1985(c) and after 1985(d) (×10^6 tons per year). The width of the arrows is proportional to the amount of mud transport. From the discussion it follows that mud transport is progressively confined in a narrowing strip along the coast in a northeastern direction.
with the transport inferred in this paper for the same period, viz. 11.0-10^6 tons per year.

Along the Dutch coast, concentrations decrease gradually, both alongshore and seawards (see Fig. 5). Thus, between the Belgian-Dutch boundary and Hook of Holland the isopleth of 10 mg/l shifts from 35 km offshore to 5 km offshore. Such a pattern could indicate settling of suspended matter in the water column, or deposition on the seabed. However, neither large vertical gradients in concentration (Eisma & Kalf, 1987) nor deposition in the seabed (Fig. 6) are observed. Obviously, after settling, the mud is transported in the lower layer of the water column. Eisma & Kalf (1979) hypothesized that there is a residual mud transport with a landward component within this layer. Recently Van Der Giessen et al., published data on currents, collected during one year in a 30 km long cross-section near Noordwijk (Fig. 1), and showed a persistent onshore residual bottom current, with a typical magnitude of 2.5 to 3.5 cm/sec. The mechanism that drives this onshore bottom current is probably a combination of density difference between nearshore less saline water and offshore more saline water, enhanced by wind effects and tidal asymmetry. The ratio between the magnitude of the residual current at the surface (alongshore) and bottom (onshore) is about 10 to 3 (Van Der Giessen et al., this volume), which is similar to that of the displacement of the 10 mg/l isopleth (30 km. offshore within 100 km alongshore). So, this net landward bottom transport explains the observed concentration pattern in the water column and seabed qualitatively relatively well. In addition tidal
asymmetry effects, caused by distortion of the tidal wave along the Dutch coast, may lead to mud transport being retarded south of Hook of Holland, resulting in higher concentrations there (DRONKERS et al., in press). Moreover, it can be concluded that further northeasterwards the mud transport is confined in an increasingly narrowing strip. For example through a cross-section of 70 km near Noordwijk, 12% of the suspended matter transport occurs within 3 km offshore and 45% within 20 km offshore (Fig. 7). This explains why large amounts of mud are deposited in areas near the coastline, such as former tidal channels, navigation channels and temporarily between breaker bars (VAN ALPHEN, 1987a) and in the nearshore area (EISMA & KALF, 1979).

By comparing the amount of mud involved in maintenance dredging in the Rotterdam Europoort area with the amount of mud involved in longshore transport in a 20 km wide strip along the coast, it can be concluded that both are of a comparable order of magnitude (about 5-10^6 tons per year). In addition it can be seen that the amount of mud supplied by the river Rhine to this strip (0.7 to 1.5-10^6 tons per year) contributes 14 to 30% of the longshore transport within this zone. This ratio is confirmed by isotope analysis of sediments in the Wadden Sea (EISMA et al., 1982) and of mud deposits in the nearshore area (TURKSTRA, 1989). It can also be concluded that within this 20 km wide nearshore zone, human activities periodically result in substantial sources and sinks and hence in substantial variations in the longshore mud transport over time. The cumulative effect may have led to a decrease in the mud transport within this 20 km zone, of about 50% at Noordwijk, especially since 1985. However, at present no adequate data exist to support this hypothesis.

It is remarkable that the fluxes through a 70 kilometre long cross-section at Noordwijk as deduced in this paper (6.8 - 10.1-10^6 tons per year), are comparable with those estimated by EISMA et al. (1982) and ANONYMOUS (1985) (8.9-10^6 tons per year). Earlier, a similar correspondence was observed at the Belgian-Dutch boundary. This is strange, because mud balances of the latter kind are based on measurements of suspended matter in the surface layer, performed during relatively calm weather conditions. In this way any vertical gradient in suspended matter concentration is neglected. This means that transports can be seriously underestimated, especially those taking place in storm conditions. The mud budget that resulted from the ap-
proach presented in this paper is based on a flux through Dover Strait plus or minus the amounts eroded, dumped and deposited, as estimated from integrated values over 5 to 10 years, taking the effects of gales and a vertical gradient in suspended matter implicitly into account. To explain why the results tally one has to note that the budgets of Eisma et al. (1982) and Anonymous (1985) were based on suspended matter. It may be that the organic contribution in suspended matter, which is practically absent in eroded or deposited mud, compensates for neglecting the vertical gradient in suspended matter and the increased concentrations during gales. Based on Ministry of Public Works measurements of water quality, the organic contribution into the yearly amount of suspended matter transport can be roughly estimated as at least 30%.

During gales the seabed is agitated by waves, and mud is resuspended. This results in higher concentrations of suspended matter (see e.g. Gosse, 1976) and temporarily larger transports. For the period 1976-1986 a strong correlation could be found between the yearly total of hours that the wind speed exceeded 14 m/s (Beaufort 7) from the 220-360° sector and the amount of mud removed in maintenance dredging in the Rotterdam-Europoort area (Fig. 8, see also Louisse, 1987).

The correlation between wind speed and suspended matter concentration averaged from the first and last quarter of every year for three locations was less clear (Fig. 9), but all stations behaved similarly between 1978 and 1984 (Fig 9c).

Interestingly, as time proceeds, concentrations at G6 gradually decrease vis-à-vis those at A20. This might indi-

Fig. 8. Relation between the annual amount of mud dredged in Rotterdam-Europoort area (M, in 10^6 tons dry weight per year) and the number of hours that the wind speed from the 220-360° sector exceeded 14 m/s. Period considered: 1974-1986.

cate mud deposition in the area situated between A20 and G6, hypothesized earlier to be in the order of 0.5 to 1.5·10^6 tons per year.

As can be deduced from Fig. 9, in years with a high incidence of gales the amounts of mud transported can be about twice as high as during years with few gales. This means that actual annual transports may double the potential fluxes derived earlier.

7. CONCLUSIONS

The mud balance presented in this paper is based on balancing amounts of erosion and sedimentation derived from the literature, and comparing these figures with the fluxes computed by others and with data on maintenance dredging. This approach seems to be successful; at least, it produces a consistent picture. With respect to this mud balance the following conclusions are important:

- the flux of mud through Dover Strait is the dominant feature for the mud transport in the Belgian-Dutch waters of the Southern Bight. The long-term average is that about 8.5·10^6 tons of mud passes to the Belgian and Dutch waters annually.
- large-scale human interference has resulted in local disturbances of the fluxes. These disturbances have been comparatively small as compared with the longshore mud transport through a 70 km long cross-section, but may have been substantial compared with the mud transport in a nearshore zone of about 20 km wide. For a 70 km cross-section at Noordwijk the net result of these human activities since 1985 has been a reduction of the annual flux by 30%. For the landward part of this cross-section (20 km), the reduction is 50%. However, it is questionable whether this can be distinguished already in the `noise' of the year to year fluctuations in transport that arise because of differences in the duration of gales (differences can be up to 100%).

- the proportion of river Rhine mud in the longshore transport of mud is in the order of 14% to 30%.
- the amount of mud involved in maintenance dredging in the Europoort area is comparable in magnitude to the estimated amount of mud transported through a 20 km long cross-section nearby.

8. REFERENCES

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Fig. 9. Time series of (a); number of hours with a wind speed greater than 14 m/s (Beaufort 7), (b) amount of mud dredged in Rotterdam-Europort area ($10^6$ tons dry weight per year) and (c); average suspended matter concentration in winter at $A_{20}$, $G_6$ and $N_2$ (mg/l) (see Fig. 1).


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