Fluxes of fine sediment along the Dutch coast and the impact of Maasvlakte 2

A system description

Report of work package 1 & 2
Baseline Silt PMR

October, 2006
Fluxes of fine sediment along the Dutch coast and the impact of Maasvlakte 2

A system description

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October, 2006
CLIENT: Rijkswaterstaat RIKZ

TITLE: Fluxes of fine sediment along the Dutch coast and the impact of Maasvlakte 2
A system description

ABSTRACT:
There is concern that land reclamation for the proposed Maasvlakte 2 development (referred to as MV2) will lead to changes in the transport of suspended particulate matter (SPM) along the Dutch coast and into the Wadden Sea. This in turn could potentially affect the ecological conditions in the Wadden Sea.

This report describes the existing knowledge of the transport of SPM in the southern North Sea in general, and in the Dutch coastal zone in particular. A qualitative description is proposed on the effects of an extension of MV2 on the SPM-fluxes and fate along the Dutch coastal zone (the 'hypotheses').

From the analysis it can be concluded that the major part of marine SPM stems from the South, partly through erosion of the cliff coasts, partly front import from the Atlantic Ocean, and possibly partly from erosion of the Flemish Banks. However, no consensus exists on the latter source. Although it seems relatively small in comparison to the other sources, erosion of the Flemish Banks and hence sediment import to the Dutch coastal system, must be closely related to storm events in the southern North Sea, more directly than the other sources.

The fresh water plume of the River Rhine in particular (the 'coastal river') plays an important role in the transport of SPM along the Dutch coast. Because of the interaction of earth rotation, tide, fresh-saline water-induced density gradients and bed friction, SPM is transported in a narrow band mainly in northern direction. Temporarily some southward transport may occur as well. Because of bed friction, a near-bed net current towards the coast is generated on top of the net northern flow, which brings sediment to the coast. The accumulation of SPM in this zone can be observed from in situ and satellite measurements.

It is expected that MV2 will not affect the input of SPM into the Dutch coastal system, nor will it affect the total amount of fresh water delivered to the system, the overall tidal motion, or the meteorology in the system. The effects of MV2 are expected to occur at a relatively small scale, as the land reclamation itself is fairly small in comparison to the coastal system.

In summary, the following impact of MV2 on the flux of SPM along the Dutch coast towards the Wadden Sea is expected:
- A decrease in SPM close to the coast, compensated by larger SPM-concentrations further offshore,
- An increase in temporal variations of SPM because of buffering of SPM in the Haringvliet mouth and larger residence times of Haringvliet fresh water south of MV2.

REFERENCES: project ref. RKZ-1661

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I  Introduction

1.1  Background

There is concern that land reclamation for the proposed Rotterdam Mainport (PMR) or “Maasvlakte 2” development will lead to changes in the transport of suspended particulate matter (SPM) along the Dutch coast and into the Wadden Sea. This in turn could potentially affect the ecological conditions in the Wadden Sea. This concern is supported by earlier studies (related to Maasvlakte 2 and the study of an airport island in the North Sea (Flyland), e.g. van Kessel 2001, Boon 1999a and Boon 1999b) that have already indicated that such large land reclamation projects may influence the flow pattern and the magnitude of the SPM transport, not only locally near the reclamation, but also at a larger scale, affecting SPM transport along the coast and the water and sediment exchanges with the Wadden Sea. Although recent model studies indicate only a minor effect for the most recent design of the future land reclamation, it is still desirable to have the possibility to verify this prognosis in the future by means of direct monitoring.

In order to determine the effects of land reclamation, it is essential to establish the baseline (reference) situation of the flux of SPM along the Dutch coastal zone towards the Wadden Sea. Which extra measurements (if any) are needed to establish its baseline? The transport in question is the north-eastern directed residual fluxes of SPM along the northern and southern coasts of Holland and towards the Wadden Sea.

In determining the annual average marine SPM flux, the high level of variability for the water flow rates and the SPM concentrations, in both time and space, must be taken into account. This is especially important, since it is not sufficiently known if the Maasvlakte 2 extension will give rise to measurable effects in SPM fluxes along the Dutch coast and towards the Wadden Sea; will the effects be lost in the ‘noise’ of the current SPM flux variability? And, if large changes in future SPM concentrations are observed after the construction of Maasvlakte 2, is this caused by the land reclamation? Which monitoring is needed to answer these questions in the future?

In order to answer these questions, RIKZ Den Haag requested WL | Delft Hydraulics to carry out the project “Baseline silt study for the Rotterdam Mainport Development Project (Baseline monitoring PMR, T₀)”, project reference RKZ-1661.

1.2  Overall aim of the project

The overall aim of the project Baseline silt PMR is to make an inventory of the presently available data related to the SPM flux, and its variability, along the Dutch coast and into the Wadden Sea, and to elaborate on measurement and data analysis methods in order to be able to determine changes that may occur to the SPM fluxes after the Maasvlakte 2 extension has been effected. Any changes to the SPM fluxes may be determined by means of carrying out an effect-monitoring program (T₁), similar to the baseline monitoring (T₀). The problems of
the large variability in SPM fluxes, the large spatial scales and the inherent difficulty (or unreliability) of measuring SPM will be taken into consideration in the approach of the proposed study.

The primary objective of the study is specified into two sub-objectives:

1. Define (measuring) methods to identify possible changes in the flux of fine suspended matter (SPM) in the Dutch coastal zone towards the Wadden Sea,

2. Define a method to assess whether such changes, if they occur, are induced by the extension of the Maasvlakte.

Any measurement campaign for the baseline study will need to address how to identify and measure any potential changes in the SPM fluxes and to determine whether future changes in the SPM fluxes can be attributed to the presence of the Maasvlakte 2 extension. See Figure 1-1 for the project work flow description.

### Figure 1-1: Flow diagram Baseline silt PMR project approach

1.3 Definition SPM

This study focuses on the possible effects of an extension of the Maasvlakte on the transport and fate of SPM in the Dutch coastal zone and Wadden Sea. We define Suspended Particulate Matter (SPM) as all particulate matter that is not classified as bed material. This implies that SPM contains mainly cohesive sediment, which consists of mineral and organic components.
SPM is likely to contain also a non-cohesive fraction in the form of silt or fine sand, as SPM is transported in the form of flocs. On purpose, we do not characterize SPM through its diameter, as the SPM diameter depends on whether or not the material is in a flocculated or dispersed state. This implies that information on the measuring techniques should be given, when data from the literature are used in this study. The same holds for the fraction of organic material – some SPM data will contain only the inorganic fraction, whereas other data will contain all sediment components. This information will be given, where relevant.

1.4 This report

This document contains a system description of the Dutch coastal zone and Wadden Sea relevant to assessing possible effects of the construction of Maasvlakte 2, and constitutes:
1. A qualitative description of the processes responsible for SPM transport and fate in the Dutch coastal zone and Wadden Sea;
2. Quantitative chronological summary of measures in the past and future in Dutch coastal zone.

This report describes an overview of existing knowledge and general understanding of the transport of fine suspended sediment (referred to as SPM in this report) in the southern North Sea in general, and in the Dutch coastal zone in particular. This is done in quantitative terms as far as possible by relying on data published earlier in various sources. On the basis of this general understanding a qualitative description is proposed on the effects of an extension of the Maasvlakte (referred to as MV2) on the transport sand fate of SPM along the Dutch coastal zone. Also the effects of autonomous developments foreseen for the near future are qualitatively discussed, as far a possible.

It is noted that the current understanding of the transport and fate of SPM in the Dutch coastal zone is largely based on the extensive, so-called, DONAR data-base, which contains SPM-values obtained from two-weekly boat surveys, starting in 1975, during which water samples were taken from near the water surface at a large number of fixed stations. However, care should be taken when using these data, as discussed by Dronkers (2005). The 1975-program was changed in 1984, reducing the number of transects along the Dutch coast. After 1995 a new vessel was deployed, which could survey only at wind speeds below 6 Bft, i.e. at more gentle weather conditions than the old survey vessel. Moreover, before 1990, water samples were taken with a bucket 2 m below the water surface, whereas after 1990, samples were pumped from 1 m below the water surface. This implies that in time, SPM-values have a bias towards lower concentrations, estimated by Dronkers (2005) at a decrease in SPM-values by 25% after 1991. Hence, the SPM-concentrations measured after 1991 may have to be increased by 35% to obtain a consistent data set from 1975 till present.
2 General description of the North Sea and summary of developments

The entire North Sea, from the English Channel up to the 61° latitude, has a surface of about 550,000 km² and a mean depth of about 75 m. The area up to the 57° latitude (north Denmark), generally referred to as southern North Sea, has about half that surface area and a mean of depth of about 50 m, while its southern part is much shallower with mean depths of about 20 – 30 m; the 20 m isobath, for instance, is found at about 10 – 30 km off the Dutch coast.

The seabed is mainly sandy, with pronounced linear sand ridges off the coasts of Belgium and the UK. At some locations, glacial clay deposits come to the surface, and there are some mud accumulation areas, as discussed elsewhere in this report.

The climate in this area is temperate, and the weather is characterised by the occurrence of frequent depressions, in particular during autumn and winter; the annual mean wind in the Dutch coastal zone is from SW with a mean velocity of about 9 m/s. Fresh water inflow is relatively small and does not affect the hydrodynamics in the North Sea, except in the coastal zones; here the so-called ROFI’s are of major importance in controlling the local hydrodynamics and transport patterns (e.g. De Kok, 1996; Souza and Simpson, 1997).

More details information on the North Sea physical system can be found for instance in Becker (1981) and Otto et al. (1990).

In this report, the focus is on the Dutch coastal zone.

Dronkers (2005) gave an overview of the historical developments in the Dutch coastal zone. His text is integrally given below, extended with information on the locations for the dumping of dredging material from the Port of Rotterdam. Figure 2-1 gives an overview of the various developments in the Dutch coastal zone.
Closure Zuyderzee 1931–1932. The former Zuyderzee (ca. $4 \times 10^8 \text{ m}^2$) was, some 1000 years ago, connected to the North Sea by Texel Inlet (main connection) and Vlie Inlet (secondary connection). With time, the Texel Inlet widened and deepened; scouring continued till the closure of the Zuyderzee. In this very shallow sea (average depth of a few meters) the tidal wave was strongly damped; almost no reflected tidal wave existed at Texel Inlet. The closure of the Zuyderzee did not strongly alter the tidal prism at Texel Inlet, because of an increase of the tidal amplitude (both at Texel Inlet and Vlie Inlet). However, the nature of the tidal wave changed; it became more a standing tidal wave than a progressive damped wave (Ligtenberg, 1998). The current velocities in the channels near the closure dam (Afsluitdijk) strongly decreased after the closure, especially in the landward part of the remaining Texel Inlet basin.

Construction Europoort (1957-1960). Extension of the Rotterdam harbour that affected the geometry of the coastline as the Islands of Rozenburg and De Beer south of the Nieuw Waterweg were made part of a new dock and channel network. Seaward entrance of the Rotterdam harbour about doubled in size after the construction of the Calandkanaal. There
are no indications of significant effects on the currents offshore, beyond the direct vicinity of the docks and channels.

*Extension harbour moles IJmuiden (1965-1967).* Enlargement and improvement of the entrance channel offshore the locks of IJmuiden was carried out together with a seaward extension of the harbour moles from 1 km to about 2.5 km. This extension had a significant influence on longshore sand transport, as witnessed by strong beach accretion at both sides of the moles – especially at the southern side. Beach erosion occurred at greater distance (up to about 10 km) from the moles. The tide curves were not affected by the harbour mole extension. There are no measurements indicating an influence on tidal currents at some distance from the moles.

*Closure Lauwerszee 1969.* The Lauwerszee was connected to the North Sea by the Frisian Inlet, which lost almost half of its flood storage area due to the closure of the Lauwerszee. The tidal currents in the remaining Frisian Inlet basin were strongly reduced, especially near the closure dam, resulting in heavy sedimentation. There was no evidence of an important influence of its closure on neighbouring Wadden basins.

*Closure Haringvliet 1965-1970.* Before closure, the Haringvliet was the main Rhine outlet channel. Discharge of Rhine water is still possible through sluices in the closure dam. These sluices are open during ebb tide, in periods of high Rhine runoff. Otherwise the Rhine outflow is directed through Rotterdam Waterway. The flood storage area of the Haringvliet Inlet extended some 50 km inland. Tidal currents seaward of the closure dam were strongly reduced, especially in the channels of the former ebb tidal delta. Heavy mud (and sand) deposition occurred in these channels, estimated at 25 Mton in the period 1970-1974 (Stam et al., 2002; Dam, 2004); this estimate is several times higher than the findings of an earlier study (Pickhaar and Kort, 1983). The location and orientation of the ebb delta shoals experienced significant change: landward displacement and more longshore orientation. A new dune area and a sand spit developed at the headland south of the former inlet.

*Closure Grevelingen Inlet 1970-1972.* The Grevelingen tidal basin was connected to the North Sea by inlet channels with a depth of several tenths of meters. After closure, siltation occurred in the former tidal channels at the seaward side of the closure dam. The former ebb tidal delta was modified in a way similar to the Haringvliet ebb tidal delta. The new current and wave conditions changed the cross-shore profile of the Grevelingen ebb delta shoals in such a way that they became partly emergent at low water.

*Rotterdam harbour extension Maasvlakte I 1970-1974.* The harbour extension consisted of several elements: (1) a 5 km seaward extension of the former island De Beer, south of the Rotterdam Waterway; (2) dredging of deep harbour basins and a deep entrance channel (Eurogeul, Maasgeul) up to some 20 km offshore; (3) extension of the northern harbour mole to a length of 4 km; (4) sand nourishment of the triangle north of the harbour mole. The new configuration is maintained through regular dredging and sand nourishments. Part of the Maasgeul (landward part of the Eurogeul) acts as a sediment trap, in particular for fine marine sediments. This sediment (on average 3-4 dry Mton/year sand and 3-4 dry Mton/year mud) is dumped at the disposal site Loswal, some 5 km northwest of Hook of Holland. Most of this sediment is resuspended from the disposal site and taken away by currents. Siltation in the Maasgeul has decreased by about 40% after displacement (1996) of
part of the sediment at the disposal site “Verdiepte Loswal” 5 km further west (Stutterheim, 2002).

*Extension Scheveningen harbour moles (1968-1971).* By the end of the 1960s the existing harbour moles of Scheveningen have been extended. There are no indications that this has affected the currents and transports outside the direct vicinity.

*Zeebrugge harbour 1972-1985.* Zeebrugge harbour is built seaward of the former harbour entrance; it is located within two large harbour moles extending some 4 km offshore. A deep harbour basin and entrance channel have been dredged; the dredged material, which contained a high percentage of clay, has been disposed offshore. Intensive maintenance dredging is required (annual dry weight in the order of 20 Mton), due to the high mud content of the seabed and the turbidity of the coastal waters.

*Slufter storage basin for contaminated mud 1984.* The Slufter storage basin is a southward extension of Maasvlakte I, providing additional wave and current shelter for the former outer delta of the Haringvliet. In the period 1985-1990 an increased deposition of 10-15 Mton of fine sediment has been reported in the outer Haringvliet delta (Dam, 2004) and there are no indications yet that this rate decreases.

*Partial closure Eastern Scheldt 1982-1986.* In the Eastern Scheldt inlet a storm surge barrier was constructed, which is closed only under extreme storm conditions. The barrier constriction and the closure of several landward parts of the original flood storage area have caused a 30% reduction of the tidal prism. The reduction of tidal currents has caused channel sedimentation, due to import of fine marine sediment and due to erosion of tidal flats. The adaptation of the Eastern Scheldt to a new equilibrium morphology is expected to take several centuries, during which the Eastern Scheldt will act as a fine sediment sink. A bottom survey carried out a few years after the partial closure revealed a modest mud accumulation of 0.2 Mton/year in the tidal basin (Ten Brinke and Dronkers, 1993). The same study reports a substantial difference in mean fine suspended sediment concentrations of about 10 mg/l between the seaward and landward sides of the inlet barrier. If this difference is indicative of flood water and ebb water concentrations, the mud accumulation in the Eastern Scheldt would amount to 6 Mton/year. As this discrepancy has not yet been resolved, the mud import is estimated at 3 ± 3 Mton/year.

*Maintenance of the Dutch coastline through sand nourishment 1980-present.* In 1979 a coastal policy was adopted to stop coastal retreat. Coastal nourishment with sand taken offshore (below the 20 m depth contour) was designated as the preferred method to implement this policy. Till 2000 the annual nourishment volumes were around 6 Mm$^3$. This was disposed on the beaches; afterwards also sand nourishments were effectuated on the shoreface at depths less than 5 m. After 2000, the annual nourishment volumes have increased up to around 12 Mm$^3$. There is evidence that coastal erosion near the Wadden Inlets is related to sand import into the Wadden Sea, needed for morphological adaptation to sea-level rise.

Figure 2-1 also gives an overview of the locations where sediments dredged in the basins and navigational channels of the Port of Rotterdam are, c.q. have been dumped. Basically, there are three dumping locations:
• *Loswal Noord*, in use from 1964 till mid 1996; before 1985 also sediment from capital dredging has been disposed at this site.
• *Loswal Noord-West*, in use from mid 1996 till present.

Further to these historic developments, a large number of new developments are foreseen. The following summary will be further detailed in a next phase of the study when the data-analysis methods will be evaluated. In an arbitrary order:
1. Continuation of maintenance dredging of harbour basins and navigational channels,
2. Extension of the Maasvlakte (MV2),
3. Changes in sluicing regime Haringvlietsluizen (“Kierbesluit”),
4. Changes in sluicing regime Afsluitdijk, including the construction of a third sluice,
5. Construction of offshore wind farms,
6. Large scale sand mining for beach suppletions,
7. Large scale sand mining for construction MV2,
8. Large scale sand mining for general construction sand (a.o. WCT, Vlissingen),
9. Large scale sand mining activities in Belgium part of North Sea coastal zone,
10. Establishment of natural sea reserves banning human activities,
11. Moving of Norfolk line from Scheveningen to Vlaardingen (less dredging at Scheveningen),
12. Changes in commercial fishing (in particular seabed disturbing beam trawling),
13. Land reclamation along Zuid-Holland coast (Plan New-Holland, c.q. Plan Waterman),
14. Industrial North Sea Island (airport at sea, etc.),
15. Sea level rise and other climate changes (river flows, wind and wave climate).
3 Sediment properties

Irian and Zöllmer (1999) have analysed the mineralogy of about 500 surface samples from the North Sea bed. Their results are shown in Figure 3-1 and Figure 3-2.

![Figure 3-1: Smectite (left panel) and illite (right panel) percentage of the clay mineral content in the North Sea. (Irian and Zöllmer, 1999)](image)

From this analysis it appears that illite is the dominant clay mineral with a mean content of 51%, followed by smectite (27%), chlorite (12%) and kaolinite (10%). These minerals, however, are not distributed homogeneously, as can be seen in Figure 3-1. According to Irion and Zöllmer, the illite and chlorite minerals stem from erosion of the Fennoscandian Shield during the Pleistocene period. This explains why their content is higher in the North. The Skagerak and Norwegian Trench are characterised by large depths, and they form well-known accumulation areas for fine sediments in the North Sea. The relative large amounts of smectite and kaolinite originate from transports from the Baltic and the southern North Sea. The East Anglia coast consists of Tertiary soils with a high kaolinite content. As these soils are subject to serious erosion, they form a source of kaolinite rich sediments. The relative high smectite content in the Strait of Dover and along the Belgium and Dutch coast are believed to originate from erosion of the smectite-rich Cretaceous formations in the Strait of Dover (French and English cliff coasts).
Figure 3-2: Kaolinite (left panel) and chlorite (right panel) percentage of the clay mineral content in the North Sea.

Further detailed information, in particular on the sediment properties from a few bore holes in the Belgium coastal zone, can be found in the MOCHA-report (2005) and in Fontaine (2004). These data corroborate the results presented in Figure 3-1 and Figure 3-2.

Few data are available on the grain size and settling velocities of the suspended sediment. Table 1 presents an overview of data published by Van Leussen (1994), Chen and Eisma (1995), Jago and Jones (1998) and Puls et al. (1995 and 1999). Note that both Jago and Jones and Puls et al. distinguish between an “active fraction” that exchanges with the bed, and a very fine “background” fraction with settling velocities of about 1 - 4 \times 10^{-3} \text{ mm/s}. Also Jones et al. (1998) found an organic background fraction with a modal settling velocity of $5 \times 10^{-4} \text{ mm/s}$ from settling tube measurements; however, also large organic aggregates were observed with settling velocities up to 0.2 mm/s. These data, together with the observations on the sediment input from the Atlantic Ocean, as described in Section 4, suggest that at least an organic and a mineral fraction have to be accounted for in the sediment budgets in the North Sea.

Table 1: Summary of settling velocities of North Sea sediment.

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<td>Jago and Jones (1998)</td>
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<td>0.1 - 0.3</td>
</tr>
<tr>
<td>Puls et al. (1995)</td>
<td>2 - 50</td>
<td></td>
<td></td>
<td>0.002 - 0.08</td>
<td></td>
</tr>
<tr>
<td>Jones et al. (1998)</td>
<td></td>
<td></td>
<td></td>
<td>5 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>Jones et al. (1998)</td>
<td></td>
<td>mainly organic aggregates</td>
<td></td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>
Note that the data by Van Leussen in Table 1 are based on his measurements with the Video In Situ system. Measurements with a field settling tube are known to yield substantially smaller settling velocities, and Van Leussen found values with such an instrument of about 0.05 mm/s.

An important aspect that affects the sediment dynamics in general, and the water-bed exchange processes in detail, is the contribution of biological activity. Biological activity can increase the settling velocity of the sediment through flocculation effects, especially in deeper water, and through pelletization by filter feeders in shallow water. Within the bed, bioturbation is important, mixing freshly deposited sediments through the upper cm’s of the bed. Moreover, sediments may become immobilised by algae growth, and/or erosion resistance may increase by bacterial substrates. In shallow water, these effects are further enhanced by wave activity, bed forms and sorting of sediments, as a result of which armoring may occur. It is believed that these effects are especially important in shallow, more or less sheltered areas, such as the Wadden Sea and the mouth of the Haringvliet. Though quite some information is available on the individual biological processes, e.g. Van Leussen (1994) and Paterson et al. (1997), their quantitative description is poor at present.

Recently, a number of numerical modelling studies on the North Sea have been finalised. From calibration of the transport and fate of SPM against the DONAR data base, a settling velocity of 0.25 mm/s was found to yield the best results (WL | Delft Hydraulics et al., 2005). Note that these data are based on analysis of water samples taken close to the water surface, at relative quiet weather conditions. These data are therefore biased to lower SPM-values and the finer fraction of the sediment. From an analysis of data collected at three locations near Noordwijk through smart buoy measurements (the so-called CEFAS-data, e.g. Hartog and van de Kreeke, 2003; Royal Haskoning, 2006), it is concluded that the coarser fraction of the SPM should have a settling velocity of about 0.5 mm/s (e.g. Van Kessel, 2006).
4 Sediment sources

Fine-grained sediment in the North Sea is supplied from a variety of sources:

- Through the open sea boundaries (Dover Strait and Atlantic Ocean).
- Coastal erosion, especially from the French and English cliff coasts along Dover Strait. An impression of these sources can be obtained from Figure 4-1 (Recherches Géologiques, 1955), showing the extend of erodable clay deposits from the Jurassic period (light green) and erodable chalk deposits from the Cretaceous period (green-blue). The coast of Boulogne sur Mer, for instance is renowned for an erosion rate of many km’s per century, supplying large amounts of chalk-rich sediments.
- Sediment supply by bed erosion:
  ⇒ From geotechnical analyses some researchers concluded that the Flemish Banks themselves are not eroding and thus do not form a net source of sediment. However, behind these banks large accumulation areas exist with a considerable net sedimentation, e.g. Figure 4-2 (TNO-NITG, 1984). It is likely that a part of these sediments will be resuspended during rough weather conditions and transported north by the tidal flow. Note that under such weather conditions also the residual eddy at this location collapses (see Section 6). On the other hand, Fontaine (2004) concludes from an analysis of literature, historical surveys and clay mineralogy that the Flemish Banks supply about 1 Mton/year of SPM to the Dutch coastal zone, whereas MOCHA (2005) comes to the same conclusion, without giving any hard figures.
  ⇒ Fine sediments can deposit during calm weather conditions and be re-entrained during rough weather periods. This would imply that the sea bed would not be a net source of sediment, but merely affects the phasing of sediment availability (see also Section 8). This buffer mechanism probably is especially important in sheltered areas like the mouth of the Haringvliet, the Wadden Sea, and the area behind the Flemish Banks, as discussed above.
Figure 4-1: Overview of erodable coasts: Cretaceous deposits are marked with blue and Jurassic deposits are marked by light green.
Figure 4-2: Overview of mud deposits in the Belgium coastal zone. (Source TNO-NITG, 1984.)
• At a number of locations old clay deposits are exposed. For instance off the coast of Walcheren clay deposits from Roman and Medieval times are found which are eroding at present; their contribution to the overall mud balance is small however.

• Input of fluviatile sediment through riverine inputs and dumping of dredged materials.

Available information from literature of the mean annual supply is collected in Table 2, including information from De Kok (2004).

Table 2: Mean annual supply of fine sediment to the North Sea.

<table>
<thead>
<tr>
<th>Process</th>
<th>Location</th>
<th>Reference</th>
<th>load (10^9 \text{ kg/yr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net inflow through open sea boundaries</td>
<td>Dover Strait</td>
<td>Eisma and Kalf (1979)</td>
<td>11.5 to 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eisma and Irion (1988)</td>
<td>20 to 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lafitte et al. (1993)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pohlmann and Puls (1994)</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velegrakis et al. (1997)</td>
<td>2.5 to 30.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>McManus and Prandle (1997)</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velegrakis et al. (1999)</td>
<td>2 to 71</td>
</tr>
<tr>
<td>Atlantic Ocean and Baltic</td>
<td>Eisma and Irion (1988)</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pohlmann and Puls (1994)</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>Total inflow</td>
<td>Eisma and Irion (1988)</td>
<td>30 to 40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pohlmann and Puls (1994)</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>McManus and Prandle (1997)</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Coastal erosion</td>
<td>Holderness</td>
<td>Odd and Murphy (1992)</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>McCave (1987)</td>
<td>1.4</td>
</tr>
<tr>
<td>Norfolk+Suffolk</td>
<td>Odd and Murphy (1992)</td>
<td>6.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>McCave (1987)</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>McManus and Prandle (1997)</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Eisma and Irion (1988);</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odd and Murphy (1992)</td>
<td>8.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>McCave (1987)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Bed erosion</td>
<td>Flemish Banks</td>
<td>Van Alphen (1990)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eisma (1981)</td>
<td>&lt; 2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fontaine</td>
<td>1</td>
</tr>
<tr>
<td>Total bed and coastal erosion</td>
<td>Eisma and Irion (1988)</td>
<td>9 to 13.5</td>
<td></td>
</tr>
<tr>
<td>Rivers</td>
<td>Total</td>
<td>Eisma and Irion (1988)</td>
<td>4.8</td>
</tr>
<tr>
<td>Primary production</td>
<td>Total</td>
<td>Eisma (1981)</td>
<td>1</td>
</tr>
<tr>
<td>Atmospheric deposition</td>
<td>Total</td>
<td>Eisma (1981)</td>
<td>1</td>
</tr>
<tr>
<td>All processes</td>
<td>Total</td>
<td>This Table</td>
<td>47 to 118</td>
</tr>
</tbody>
</table>

It is concluded that no consensus exists on the sources of sediment and their yield. However, the higher values for coastal erosion are advocated by Dyer and Moffat (1998). The smaller input would not explain the total amount of suspended matter in the southern North Sea (excluding the Belgium and Dutch coastal zone), estimated at about 100 to 400 Mton from their measuring campaign. Moreover, no agreement exists on whether the Flemish Banks form a net source of SPM. However, this is important as the flux along the Dutch coast responds much more quickly to erosion due to storm events of these banks than to input from, e.q. through Dover Strait. Hence, one can expect a more direct correlation between this source and waves occurring in the Dutch coastal zone.
From Table 2 it can be concluded that the annual input of riverine sediments into the North Sea amounts to about 4 – 10% of the input through the open boundaries and through coastal and bed erosion. However, riverine import is important in relation to nutrients and organic material (and contaminants).

The annual input of fine sediments into the North Sea shows a significant seasonal variation: for instance, most of the coastal erosion input will occur during rough weather conditions. As a result, values of the suspended sediment concentration also show a seasonal variation with mean winter values that may be five times higher than mean summer values (e.g. Section 6).

Open boundaries

The English Channel and Atlantic Ocean apply for the largest input of sediment (more than 60% of the total input). Despite their low concentrations, extensive amounts of suspended matter enter the North Sea system due to large inflows of water involved (it is noted that the net flux of water through Dover Strait is estimated at about 100,000 m³/s, e.g. Table 7). Variations of this input may have an important impact on the seasonal behavior of suspended matter in the North Sea. Field measurements in the Channel were carried out within the MAST project Fluxmanche II. In Table 3 the results of the Car-ferry monitoring on the Cherbourg-Southampton transect are given (derived from Boxall et al., 1995).

Suspended sediment concentrations at the Atlantic boundary are considered to be low, approximately 1-2 mg/l (Eisma and Kalf, 1987) and very fine. From an analysis of the hydrodynamic conditions in the northern part of the North Sea and from sediment transport simulations, it is concluded that all sediments entering from the Atlantic settle near the Atlantic - North Sea boundary, except for the finest fractions. Hence it can be concluded (see also Section 3) that the sediments entering the North Sea from the Atlantic consist of organic material and/or very fine dispersed clay minerals.

Table 3: Suspended Matter data (mg/l) form car ferry monitoring Cherbourg-Southampton transect.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>n.a.</td>
<td>38</td>
<td>n.a.</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>36</td>
<td>n.a.</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>28</td>
<td>n.a.</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>8</td>
<td>3</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>10</td>
<td>4</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>30</td>
<td>4</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

**Dumped sediments**

Most of the countries bordering the North Sea, including the United Kingdom, the Netherlands, Belgium and France have offshore dumping sites, primarily for dredged sediments form navigational channels and harbour basins. In Table 4 and 5 the data sources of suspended matter from dredged material are listed. These tables are obtained from Boon et al. (1997).

The major part of these sediments is of marine origin. These dumping activities do therefore hardly contribute to the net amount of sediment in the North Sea. However, they may affect the phasing of sediment availability (as the above-mentioned bed-erosion processes) as some
time elapses between sedimentation of the fine sediment and its dredging and dumping. Data on the Western Scheldt are from WL | Delft Hydraulics (2006).

Table 4: Data sources of dredged sediments.

<table>
<thead>
<tr>
<th>Country</th>
<th>Origin</th>
<th>Time-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>PARCOM inventories 1990</td>
<td>annual averaged 1990</td>
</tr>
<tr>
<td>France</td>
<td>PARCOM inventories 1990</td>
<td>annual averaged 1990</td>
</tr>
<tr>
<td>Belgium</td>
<td>MUMM</td>
<td>weekly averaged 1994</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Ministry of Public Works and Transport</td>
<td>weekly averaged 1994</td>
</tr>
<tr>
<td>Germany</td>
<td>(no information)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Annual amount of dredged materials dumped into the North Sea, UK and France data are from 1990, the other data from 1994 (PARCOM codes are given between brackets).

<table>
<thead>
<tr>
<th>Country</th>
<th>Total wet weight [kton/yr]</th>
<th>Total dumping dry weight SPM [10^9 kg/yr]^1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>United Kingdom</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thames</td>
<td>1,070</td>
<td>0.294</td>
</tr>
<tr>
<td>Humber</td>
<td>12,400</td>
<td>3.410</td>
</tr>
<tr>
<td>Forth</td>
<td>1,064</td>
<td>0.293</td>
</tr>
<tr>
<td>Tees</td>
<td>443</td>
<td>0.122</td>
</tr>
<tr>
<td>Wash</td>
<td>113</td>
<td>0.031</td>
</tr>
<tr>
<td>Wight</td>
<td>485</td>
<td>0.133</td>
</tr>
<tr>
<td>Dover</td>
<td>711</td>
<td>0.196</td>
</tr>
<tr>
<td><strong>Belgium</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coastal area</td>
<td>16,320</td>
<td>4.488</td>
</tr>
<tr>
<td><strong>Netherlands</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loswal Noord</td>
<td>19,091</td>
<td>5.250</td>
</tr>
<tr>
<td>Ijmuiden</td>
<td>4,648</td>
<td>1.278</td>
</tr>
<tr>
<td>Western Scheldt</td>
<td>10,200</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>France</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duinkerken</td>
<td>3,887</td>
<td>1.069</td>
</tr>
<tr>
<td>Calais</td>
<td>1113</td>
<td>3.06</td>
</tr>
<tr>
<td>Le Havre</td>
<td>1604</td>
<td>0.441</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>18,000</td>
<td></td>
</tr>
</tbody>
</table>

^1 Conversion from wet weight to dry weight of suspended matter (mud):

\[
SPM_{dry} = L_{wet} \cdot (1 - \phi_{poros}) \cdot \rho_{sed} \cdot (1 - \phi_{sand})
\]

where:

- \( SPM_{dry} \): Suspended matter dry weight (ton)
- \( L_{wet} \): Wet volume (m³)
- \( \phi_{poros} \): Porosity on volume basis (~0.75) (-)
- \( \rho_{sed} \): Density of sediment (~2.5) (ton/m³)
- \( \phi_{sand} \): Fraction of sand (~0.45) (-)

^2 Large fresh water flows from the Rhine/Meuse estuary cause density stratification leading to vertical distribution of suspended matter with relatively high near bottom concentrations. Due to this vertical circulation, a substantial (at least about 10%) part of the amount dumped at Loswal Noord and Ijmuiden will re-enter the estuaries to become once more part of the dredging and dumping activities.
Note that Fettweis and Van der Eynde (2003) estimate the current total amount of dumping at about $10 \times 10^9$ kg/yr dry weight. Figure 4-3 shows the amount of dumped dredging material in the Dutch coastal zone between Terheide and Kijkduin, as given by De Kok (2004).

![Figure 4-3: Dry weight mass of sediment dredged in Europoort and the Port of Rotterdam (Maasgeul, Maasmond, entrance Caland-Beerkanaal en Rotterdam Waterway), dumped in Dutch coastal zone; during some years, the dumped material includes also capital dredging works. Red: dumped by Port Authorities Rotterdam; Blue: dumped by Rijkswaterstaat; Cyan: total.](image)

**Riverine inputs**

Routine monitoring surveys have yielded large data sets for the water quality of the major rivers flowing into the North Sea (reviewed by Wullfraat et al., 1993). However, even if sufficient and reliable data on river composition are available, it is doubtful if these data can be used to estimate the net sediment input towards North Sea. Physical and geological processes will regulate the retention of suspended matter in estuaries. Accurate estimates of the net supply of fluvial loads of sediment are therefore difficult to assess without knowing the filtering capacity of the estuary. In Table 6 the riverine loads of some estuaries are presented (Zwolsman, 1994).

<table>
<thead>
<tr>
<th>Estuary</th>
<th>Input fluvial SPM [$10^9$ kg/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forth</td>
<td>0.095-0.099</td>
</tr>
<tr>
<td>Humber</td>
<td>0.172-0.225</td>
</tr>
<tr>
<td>Thames</td>
<td>0.078</td>
</tr>
<tr>
<td>Scheldt</td>
<td>0.315-0.970</td>
</tr>
<tr>
<td>Rhine/Meuse</td>
<td>1.420-1.500</td>
</tr>
<tr>
<td>Weser</td>
<td>0.310-0.500</td>
</tr>
<tr>
<td>Elbe</td>
<td>0.800-0.860</td>
</tr>
<tr>
<td>Ems</td>
<td>0.070-0.100</td>
</tr>
</tbody>
</table>
It is noted that the figure for the Rhine/Meuse estuary comprises the load that is directly released into the North Sea. The total load supplied by the rivers is a factor 2 – 3 larger, but a major part is trapped in the various harbour basins and other accumulation areas (such as riverine flood planes) (e.g. Zwolsman, 1994).

**Coastal erosion**

A significant source of fine suspended matter is erosion of the Holderness cliffs, located north of the Humber estuary and the Norfolk/Suffolk cliffs located at the coast of East Anglia. These cliffs, which reach some 25 meters, have been formed by unconsolidated Quaternary sediments consisting of chalk. Under natural conditions these cliffs are eroding with an average rate of retreat of approximately 1 m/yr (Clayton, 1989). Estimates of the annual supply of eroded fine sediments are given by Dyer and Moffat as 2.6 Mton/yr for the Holderness cliffs and 6.3 Mton/yr for the cliffs along the East Anglian coast (Dyer and Moffat, 1994).

Fontaine (2004) refers to studies by Lahousse (2000) who reports a coastal retreat by 2 – 25 cm per year of the illite rich cliff coasts near Cap-Blanc-Nez in the English Channel. Though it is not clear how much fine sediment input this would imply, Velegrakis et al. (1999) estimate this amount at at least 1.1 Mton/year.
5 Hydrodynamic forcing

The water movement in the North Sea greatly determines the pathways of sediment. Tides, density differences (due to river inflow), wind stress and waves determine the transport of SPM on a wide range of time scales. Below these forcing agents are discussed separately, although eventually it is the (nonlinear) combination of all that determines the residual transport that is of interest for the present study. (‘Residual’ refers to time scales at least longer than the tidal period, in practice also long enough to average out varying weather conditions, hence a few days at least.)

5.1 Tides

The tide in the southern North Sea is characterized as predominantly semi-diurnal. The amplitude of the M2-component is at least three times larger than other components such as S2 and N2. Through their interaction, these components generate a significant spring-neap effect. The diurnal components are small, their amplitude amounting to about 10% of the semi-diurnal tide.

In the southern part of the North Sea resonance effects occur with the tidal flow through Dover Strait, generating higher components by non-linear interactions. Also some shallow water effects occur in the coastal zones, and especially in the sea arms of the North Sea. For more details, the reader is referred to Becker (1981) and Otto et al. (1990).

Residual flows in the entire North Sea are counter clockwise. In the Dutch coastal zone the depth-averaged (Eulerian) residual flow velocities amount to a few (5 – 10) cm/s. However, the residual flow in the upper part of the water column is greatly affected by wind, baroclinic and geostrophic effects, especially under stratified conditions (coastal river), and the residual flow velocities near the water surface can increase up to a few dm/s. Note that patches of fresh water may have substantial larger northward velocities.

Figure 5-1 shows a map of the amphidromic systems for the depth-averaged current of the M2 tide in the southern North Sea, as obtained from a 2Dh simulation of the tidal movements in the North Sea. Iso-phase lines are defined as the set of points where the current reaches its maximum value at the same time. Qualitatively, Figure 5-1 is similar to the pictures presented by Becker (1981) and Xia et al. (1995).

It is noted that the amphidromic systems for the horizontal and vertical tide do not coincide. At the amphidromic points for the horizontal tide, the tidal velocities are not zero. Around these amphidromic points, the tidal ellipses reduce to a circle (Xia et al., 1995), as a result of which the residual flow becomes converging (De Swart, 2001). It is indeed remarkable that the deposition areas 2, 3 and northern part of area 15 of Figure 8-1 coincide with the current amphidromic systems (Figure 5-1) in the southern North Sea; siltation in area 18 is caused by the large depth (Norwegian Trench).
Figure 5-1: Amphidromic systems for M_2 tidal velocities; computed with DELFT3D.
Figure 5-2 shows the phasing of the horizontal and vertical tide along the Dutch coast in the form of circular diagrams, as obtained from a 2Dh simulation of the tidal movement in the North Sea. These diagrams represent the relative time of High Water with respect to High Water off Zeeuws Vlaanderen, and the time difference between High Water Slack and High Water. For the major part of the Dutch coast this time difference appears to be 2 to 2.5 hrs, indicating that the flow direction remains more or less northern for the first 2 – 2.5 hrs of
falling water, and, vice versa, the flow direction remains more or less southern for the first 2–2.5 hrs of rising tide. The latter implies that sediments (and fresh Rhine water) traveling south with the tide will enter the sea arms of the Holland delta (and sometimes, when the wind is favorable even the Zeeuwse delta), thus dispersing in southern direction.

Note that further north around the tidal inlets of the Wadden Islands, the vertical and horizontal tide are almost 90° out of phase, i.e. HW and HWS coincide. This is of course induced by the large tidal basin formed by the Wadden Sea. Further off the coast this tidal filling effect diminishes.

### 5.2 Rivers

The Dutch coastal zone is largely affected by riverine waters. Because of salinity-induced density gradients and Coriolis effects, a relative narrow band of a width of 20 to 30 km, depending on the river flow and wind conditions, of fresh/brackish water is formed along the Dutch coast. This band of fresh/brackish water is known as the Coastal River. The interaction between density gradients and Coriolis effects within the Coastal River generates a net flow in northern direction, a geostrophic coastal jet (in meteorology known as the thermal wind). Because of bed friction, a near-bed net current towards the coast is generated on top of said net northern flow. Moreover, the overall streamlines converge because of the bathymetry of the southern North Sea (e.g. Thoolen et al., 2000), a pronounced net coastward transport is generated, keeping the river plume close to the coast together with the fine sediment suspended in this flow. This is illustrated in Figure 5-3, which shows the SPM distribution on a clear winter day. The cross-shore SPM concentration gradient is enhanced by the near-bed currents which bring sediment close to the bed efficiently towards the coast. Only wind can bring the Coastal River away from the coast, e.g. by upwelling during northern winds and wind-induced shear stresses at its surface during north–north eastern wind.
It is important to appreciate that the Coastal River has a highly irregular appearance, with a wavy edge, often attached to the coast, but sometimes not, as said, and sometimes in the form of patches of fresh/brackish water because of a pulsed inflow from the Rotterdam Waterway and/or the Haringvliet Sluices, or due to hydrodynamic instabilities, e.g. Figure 5-4 (see also De Kok, 1994, 1996). These patches may merge or split up in smaller patches during their journey along the Dutch coast (e.g. De Boer et al., 2005; De Ruyter et al., 1992; Souza and Simpson, 1997; Visser et al., 1997).
Figure 5-4: Left: Standard deviation of NOAA SST remote sensing imagery in May 1998 in the Southern North Sea, based on 38 images. There are three regions of high SST variation: the central North Sea, the shallow tidal flats and the Rhine ROFI. On the central North Sea thermal stratification is dominant, while in the Rhine ROFI salinity stratification is dominant. Right: Example of an SST image of the Rhine ROFI in May 1995. The white spots are plume edges mistaken for clouds by the atmospheric correction procedure.

The vertical structure of the Coastal River is largely determined by tide and the amount of fresh water (river run-off). During neap tide, the Coastal River is normally fairly stratified over the water depth because of tidal straining, whereas during spring tide conditions, the Coastal River is well mixed because of the mixing energy by the large tidal velocities. Of course, also wind can be a significant generator of turbulence, mixing the water masses over the vertical.

5.3 Winds

The predominant wind in this part of the world is West-South-West at a mean speed of approximately 7 – 9 m/s (Beaufort 4). However, winds at much higher speeds and from other directions occur frequently. In particular NNW winds are renowned for the waves and set-up they can generate.

These winds also affect the net flow through Dover Strait, and the set-up in the Strait. However no general agreement exists on the amount of water entering the North Sea through Dover Strait, as can be seen in Table 7. However, the large effect of wind is predicted by all authors. For conditions with tide and mean wind, the net flux through Dover Strait is estimated at 100,000 to 150,000 m³/s.
**Table 7: Long term net fluxes through Dover Strait [in 10^3 m^3/s], from Gerritsen et al. (2000).**

<table>
<thead>
<tr>
<th>source</th>
<th>tide only</th>
<th>tide + mean wind</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prandle (1978)</td>
<td>115</td>
<td>155</td>
<td>M2, SW wind based on ^137^Cs data; SW-(\tau)(_{wind}) = 0.07 Pa</td>
</tr>
<tr>
<td>Prandle (1984)</td>
<td>50</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Salomon &amp; Breton (1993)</td>
<td>37</td>
<td>149</td>
<td>wind SW, 8 m/s</td>
</tr>
<tr>
<td>Prandle et al. (1996)</td>
<td>36</td>
<td>94</td>
<td>based on HF-radar and ADCP data</td>
</tr>
</tbody>
</table>

Van der Molen (2000) studied the influence of the meteorology and its schematization on the residual current patterns and large scale sand transport in the North Sea, using a depth-averaged hydrodynamic and sand transport model, including the effects of an augmented M2-tide, wind driven flow and waves. Simulations were carried out for tide only, tide + wind-driven currents, tide + waves, and tide + wind-driven currents + waves for a constant SW-wind at 0.7 m/s, for a full 10-year period of meteorology (1981-1992) and a schematization of the latter. This schematization consisted of 109 individual simulations, each for one specific wind field (speed and direction), which were continued for 100 days after which a dynamic equilibrium was attained.

Van de Molen concluded that only the combined case tide + wind-driven currents + waves yielded fair results. Moreover, the time-averaged results for the full 10-year period and the weighted averaged schematised meteo-condition were almost identical. This implies that the meteorology can be schematised in a number of weighted individual wind conditions.

### 5.4 Waves

The waves within the North Sea can be classified as short waves \((T_s < 10 \text{ s})\) and long waves, or swell \((T_s > 10 \text{ s})\). Holthuijsen et al. (1996) show on the basis of wave computations, that for extreme conditions, short waves are depth-limited in the southern part of the North Sea (till about 55° latitude), with maximum wave heights of about \(H_{s,max} \approx 0.4 \ h\), where \(h\) is the local water depth.

Short shallow water waves are characterised by \(kh < 1\), where \(k\) is the wave number; these waves are affected by the sea bed. Only very short waves with wave periods of at most a few seconds will not be affected by the sea bed. Vice versa, this implies that some short shallow water waves can disturb the sea bed. The long waves or swell do all disturb the sea bed.

Computations of the suspended sediment transport with tidal flow only show that fine sediments, imported from the Atlantic Ocean, settle rapidly in the northern part of the North Sea. Also computations of the wave-induced bed shear stresses suggest that sedimentation is likely to occur, and that the deposits will not be eroded by waves (or currents). This is an indication that these sediments are much finer than those elsewhere in the North Sea, as was noted earlier in this report.

However, Van der Molen (2001) shows in his study on sand transport that it is the combination of tidal currents, wind-induced currents and wave-induced stirring that governs the sediment transport, in particular in the northern part of the North Sea. At present it can
be hypothesised that fine-grained sediment imported during summer time (quiet weather conditions) will settle for the larger part in the northern part of the North Sea. During autumn and winter, when rough weather prevails, fine-grained material in these deposits is re-suspended and becomes available for transport in the North Sea system. Such a hypothesis is necessary to close the mass balance of sediment in the North Sea system.

Torenga (2002) reported a preliminary study on the transport of fine sediment by wave-induced effects in the breaker zone, a zone of 400 – 600 m wide along the uninterrupted Holland coast. From this study two important conclusions can be drawn:

- During storm conditions, the residual, wave-induced (northern) flow velocities are an order of magnitude larger than the tide-induced residual flow velocity (e.g. MARE, 2001 and Torenga, 2002). It is estimated that the weighted yearly wave-induced sediment transport in this breaker zone is about two to three times larger than the tide-induced transport,
- The large wave-induced residual flow velocities also imply a travel time in the breaker zone along the uninterrupted Holland coast from Hoek van Holland to Den Helder during storm conditions of about one week only (if not weighted for occurrence and frequency of the storms).
6 Transport patterns and paths

The patterns and paths of the suspended sediment transport are governed by the water movement. Zimmerman (1981) explains the generation of residual circulation cells as a result of the interaction between gradients in bed topography, Coriolis effects and the tidal flow. He argues that this process is responsible for the formation and preservation of linear tidal sand ridges. Nihoul et al. (1975) focus on the effects of the tidal stresses, obtained by integration of the momentum equation over the tidal period, on the residual circulation patterns. They argue that the residual flow velocities, obtained from averaging the computational results of a dynamic (intra-tidal) simulation may be in error by 100%. The error in the residual currents, as obtained by solving the tidally averaged equations would be much smaller. Nihoul et al. (1975) introduce the stream function in the tidally averaged equations, and add values for the tidal stresses, as assessed from intra-tidal computations; the resulting stream function equation is solved numerically. The resulting streamlines are presented in Figure 6-1. The closed streamlines off the Flemish coast are very remarkable. As they coincide more or less with the local turbidity maximum, it is tempting to conclude that sediment is trapped in this residual circulating cell.

Heaps (1978) shows that Nihoul’s approach fails when wind-induced velocities become too large, which would imply that the picture of Figure 6-1 is only correct for quiet-weather conditions. It can be discussed however, whether such residual flow patterns are representative for residual transport patterns: closed streamlines in a Eulerian residual flow field do not necessarily imply closed transport paths, e.g. Abraham et al. (1987) and Gerritsen (1985). The best method to obtain such residual transport fields is by tracing particles released at every grid point of a computational model: the residual transport field is then defined by the net path of the particles. Note that the resulting residual transport field may be a function of the time of release with respect of the phase of the tide, especially in the vicinity of the coast and/or tidal inlets.

The riverine water masses from the European continent remain relatively close to the coast, as a result of the interaction between the fresh water induced density currents and Coriolis
effects, to form a 20 – 30 km wide band of fresh to brackish water along the coast, referred as the Coastal River. Within the Coastal River gravitational circulations perpendicular to the coast are generated, which result in an accumulation of fine-grained suspended sediments in the coastal zone with significant higher sediment concentrations near the coast than further offshore. As an example, a picture by Visser (1993) is presented in Figure 6-2 (long term averaged over 1975-1983); a more recent analysis is presented by Suijlen and Duijn (2001) - see also Figure 9-3.

The accumulation of suspended sediment in the coastal zone has been observed during numerous measurements, from satellite recordings and from three-dimensional numerical simulations (De Kok, 1994; Salden, 1998). Upon close inspection of the coastal river, a meandering-like pattern is observed, most probably as a result of baroclinic instabilities (see also Fig. 10). De Kok (1994, 1996) refers to these instabilities as internal Rossby waves. It is noted that large scale constructions in the coastal zone, such as an airport on an artificial island, may affect these instabilities, for instance their amplitude, wave length, and/or phasing.

A fresh water plume also emerges from the English coast and crosses the southern North Sea in north-eastern direction. Recent measurements (Van Raaphorst et al., 1998; Van Raaphorst et al., 2001) show that the continental and English river plumes do not mix: a cross section more or less perpendicular to the Dutch coast shows first a region of lower salinity (along the Dutch coast) induced by the Dutch Coastal River, then a region with higher salinity at almost undisturbed values, then a region again with lower salinity induced by the English rivers, finally followed by higher salinities again. These results suggest that fresh water and sediments from East Anglia do not reach the Dutch coastal zone.

It is well-known that a major, deeper part of the North Sea can become thermally stratified in the summer period as a result of solar heating (De Goede, 2000). This will reduce the vertical turbulent mixing significantly. It is not known in detail how this will affect suspended sediment concentration distributions, but the effects on the ecology in the North Sea have been studied (Peeters et al., 1995). However, it can be argued that the stratification
effects off the coastal zone do not affect the transport and fate of SPM within the Dutch coastal zone, or, vice versa, that the measures foreseen in the Dutch coastal zone will not affect these stratification effects.

An important hydrodynamic phenomenon consists of the converging stream lines along the Dutch coast. Because of the geometry of the southern North Sea, a considerable contraction of streamlines is generated (Thoolen and Van Kessel, 2001). As a result, a net transverse sediment flux towards the coast is obtained from numerical model experiments. Thoolen and Van Kessel found that the transverse sediment flux through the boundary aligned with the coast of a stretch from Scheveningen to Callantsoog of 50 km wide is of the same order of magnitude as the longitudinal flux through the 50 km cross section at Scheveningen. However, the existence of this transverse flux has not yet been verified with observations.

Dronkers (2005) analyzed the travel time of SPM in the Dutch coastal zone. He reasoned that peaks in SPM should ultimately have the same (marine) origin, and that delay times in the occurrence of these peaks are a measure of the effective travel times of SPM. Figure 6-3 shows the biennial running averages of SPM measured at Flushing in the mouth of the Western Scheldt and at Texel tidal inlet (Den Helder). The peaks in SPM apparently have a time delay of 3 – 6 years. As the travel time by passive advection from the Western Scheldt to Texel tidal inlet amounts to about 1 – 2 months, this implies that SPM should be stored temporarily somewhere during their travel along the Dutch coastal zone.

Figure 6-4 shows the correlation between the amount of sediment dumped at sea (various Loswal locations – e.g. Figure 1-1) and the biennial running average concentration at Texel tidal inlet. In this case, a time shift of about one year (two at most) is observed (Loswal data leading Texel data). Dronkers reasons that this good correlation most likely is merely a result of high SPM-values in the natural system, than that it reflects the transport of dumped material towards Texel tidal inlet, as the amount of dredging required is governed by the siltation rates in the Maasmond area, which in turn is (mainly) governed by high values of SPM in the natural system. Again, the fine sediment should be stored temporarily to explain this time shift.
It is noted, however, that the data in b are contaminated with volumes of capital dredging; hence the variation in actual sedimentation in the harbour basins and navigational channels is less pronounced than Figure 6-4 suggests.

Along the closed Dutch coast (Loswal – Texel), the only location where fines can be stored is the sandy seabed. Indeed, there are strong indications that this is the case and that the residence time of fines in the seabed amounts to about 2 years (e.g. Section 8). The longer time shifts between the SPM-peaks at Flushing and Texel tidal inlet can than possibly be explained by temporal storage in the Zeeland tidal inlets and ebb tidal deltas.
7 Transport fluxes

Eisma (1981) presented an overall balance of the residual transport fluxes of fine grained sediments in the North Sea. His results are presented in Figure 7-1, which stems from a compilation by Salden (1998), who combined the results by Eisma (1981) and Van Alphen (1990). Note that the various sources in Figure 7-1 are (considerably) smaller than those given in Table 2.
Starting from Eisma’s work, Van Alphen (1990) constructed a flux diagram for the Dutch coastal zone, which has been considered as the most accurate picture for almost a decade. A diagram of transport fluxes, as assessed by Van Alphen, is presented in Figure 7-2, yielding a longshore flux of about 7 - 9 Mton/year. Van Alphen based his balance on an estimate of the sediment input through Dover Strait three times smaller than current insights (e.g. McManus and Prandle and Table 2). These new insights were recently incorporated by Salden (1998), who concluded that the longshore fluxes might be larger by a factor of three, or possibly even more, as little information is available on the sediment loads and fluxes during storm conditions. Salden’s modified values have been added to Van Alphen’s diagram between brackets.

The instantaneous sediment flux shows a considerable variation over the year: winter fluxes may be at least five times larger than summer fluxes, as can be deduced from the monitoring data on suspended sediment concentrations throughout the year (e.g. Suijlen and Duin, 2001). On top of this seasonal effect, short time variations have been observed during and directly after storm events, which however are not too important for water quality and ecological effects.

As mentioned before, Torenga (2002) estimated that the weighted yearly sediment transport in this breaker zone is about two to three times larger than the tide-induced transport.

Note that very little data are available under storm conditions, whereas the above mentioned fluxes have been assessed on the basis of quiet weather conditions, and an extrapolation beyond. However, it is known that under storm conditions suspended sediment concentrations in the Dutch coastal zone may become very high (during the SILTMAN-project mid-depth concentrations of about 600 mg/l have been measured at four anchor stations a few km off shore, De Kok, 2000; Winterwerp et al., 2001). As a result, the total annual fluxes of fine sediment may even exceed the values predicted by Salden (1998).

The coastal river, described in the Sections 5 and 6, is responsible for a pronounced gradient in suspended sediment concentration perpendicular to the coast. Typical summer values for suspended sediment concentration 20 km off the coast measure about 5 mg/l, whereas close to the coast values up to 100 mg/l have been recorded. This is depicted in Figure 7-3 from Suylen and Duin (2001) showing that the major part of the SPM-flux (near the water surface!) occurs in a narrow band of 6 km along the coast, whereas the fresh water content in the Rhine River plume decreases more gradually over a band of 40 to 50 km. As
the near-bed current in the coastal zone is directed towards the coast, it is inferred that the near-bed SPM will not extend said 6 km band. The reader is also referred to Section 9 (Figure 9-3) and to De Kok (2004) and WL | Delft Hydraulics et al. (2005) for a cross-sectional distributions of the SPM-flux as obtained from numerical computations.

As mentioned before, the streamlines along the Dutch coast converge (Thoolen et al., 2001), as a result of which a considerable transverse sediment transport component is expected. In fact numerical model simulations predict that this transverse component is of the same magnitude as the longitudinal component (Thoolen et al., 2001). This implies that the cross-shore concentration gradients increase, which affects the exchange processes with the Wadden Sea.
8 (Temporal) Accumulation areas

Figure 8-1 shows the net sedimentation areas as established by Eisma (1981). Deposits of mainly mud are found at and around the Oyster Grounds (Site 3), which includes very deep pits, formed in glacial times, filled with many tens of meters of mud, such as the Outer Silver Pit, Markham’s Hole, Botney Cut and Western Mud Hole. Eisma also identifies mud deposits off the Belgium coast. The reader is also referred to Fig. 4-2 (courtesy TNO-NITG), showing net deposition areas in the Belgium coastal zone. This area can probably supply mud to the North Sea system during storm conditions, i.e. it serves as a temporary buffer, catching sediment during quiet to moderate weather conditions, part of which is released during rough weather. The ebb tidal delta of the Haringvliet (mouth of Haringvliet) most probably has a similar buffer function, where this is possibly also true for the ebb tidal delta of the other sea arms (Grevelingen, Western and Eastern Scheldt).

Figure 8-1: Areas of net sedimentation in the North Sea, according to Eisma (1981).
De Haas and Wieringa (1997) recently found that the annual siltation in the Skagerak and Norwegian Trench amounts to about 74 Mton, considerably larger than the value reported by Eisma (1990), amounting to 17 Mton/yr.

De Kok (2004) summarizes SPM-accumulation in the Dutch delta:

**Western Scheldt**
According to Van Alphen (1990), about 0.5 Mton of marine fine sediment is yearly deposited in the Western Scheldt, whereas Van Maldegem and Vroom (1995) estimate this accumulation at 0.3 Mton/yr, which however would be compensated by 0.2 Mton/yr of riverine sediment into the North Sea.

**Easter Scheldt**
Van Alphen (1990) estimates the net accumulation of fine marine sediment in the Easter Scheldt at 1 Mton/yr, whereas Ten Brinke (1993) estimates the gross import at 1.5 Mton/yr, and the net accumulation at 1.2 Mton/yr. Note that Ten Brinke concludes that the Easter Scheldt was exporting fine sediment prior to the construction of the storm surge barrier.

**Mouth of Grevelingen and Haringvliet**
In the first years after the closure of the Grevelingen and Haringvliet, large amounts of fine marine sediment have been deposited in the mouth of these sea arms. De large tidal channel Rak van Scheelhoek in the Haringvliet mouth, for instance, has been filled with sediment, consisting of 90% mud. Dronkers (2005) estimates that about 25 Mton of marine mud accumulated in the Haringvliet mouth in the period 1970 – 1974, based on information by Stam et al. (2002) and Dam (2004). De Kok (1999, 2000) estimates an accumulation rate in the mouth of the Haringvliet much smaller than the initial 1 Mton/yr. Probably, the mouth of the Haringvliet now serves as a temporal storage of fine sediment during calm weather periods, to be released during periods of (severe) wave action. The yearly gross exchange of fine sediment between the mouth of the Haringvliet and the North Sea would amount to 0.5 – 1 Mton/yr.

**Maasmond**
Large amounts of sediment are deposited in the basins and navigational channels of the Port of Rotterdam (referred to as the Maasmond). To safeguard navigation, large amounts of sediment have to be dredged, as shown in Fig. 4-3. The annual variation is large as a result of contributions from capital work and variations in hydro-meteo conditions. It is estimated that about 37% of all sediments deposited on the Loswal locations consists of marine mud, and 10% of riverine mud. This would imply that lately about 2.4 Mton of marine mud is dredged and dumped yearly. Only part of the deposited material remains at its dumping location, estimated by De Kok (2004) at 0.5 Mton/yr. About 0.3 Mton/yr is recirculated back to the Maasmond, and the remaining 1.6 Mton/yr is transported North along the Dutch coast with the Coastal River. Note that said 0.5 Mton/yr does not stay in/on the seabed forever, as discussed below.

**IJmuiden**
In the harbour of IJmuiden about 1 – 2 Mton/yr of marine mud is deposited and dredged. The dredged material is dumped North of the IJgeul, the navigational channel towards the harbour. As no accumulation of mud is allowed in the harbour basin, the Port of IJmuiden
(nor those of Scheveningen and Rotterdam) contribute to the net flux of SPM in the Dutch coastal zone.

**Wadden Sea**

Based on a number of sources, De Kok (2004) estimates that the net yearly accumulation of fine marine sediment in the Dutch Wadden Sea amounts to about 3 Mton. Dronkers (2005) notes that there are no indications that this amount, or its composition, did vary considerably during the last 50 years. The current picture is that during calm weather periods a net import of sediment from the North Sea into the Wadden Sea occurs, whereas during storm periods, the sediment concentration in the Wadden Sea may become quite high, and sediment is exported. However, the Wadden Sea is considered as a net sink for fine-grained sediments.

**Slufter**

In the years 1985 – 1994, about 20 Mton of mud has been stored in the Slufter mud storage basin – this sediment was contaminated in general. According to De Kok (2000), the majority of this sediment is from the more upstream harbour basins, and about 50% of this mud is of marine origin.

The seabed can serve as a sediment buffer by storing sediment during calm weather periods and releases this sediment during storm. Winterwerp (1998) estimated that during storm conditions with \( H_s = 4.5 \) m, sediment layers with a thickness of 5 – 10 cm are stirred from the seabed. It can be assumed that all fine-grained sediments within that layer are then mobilised and mixed over (a part of) the water column.

How are these fine sediments entrained into the seabed, and how much is entrained? This, unfortunately, is not known at present. From a few observations (e.g. FLYLAND-report on the impact of sand mining) the concentration of fines in the upper part of the seabed is estimated at a few percent, which is in agreement with Sandeh’s (2002) findings. The buffer capacity in a coastal area of \( 10 \times 200 \) km\(^2\) would amount to about 9 Mton. The following conceptual picture can be drawn:

- Fine-grained sediment settles throughout the tide with a flux \( W_s \times c \), where \( W_s \) is the settling velocity of the sediment and \( c \) the suspended (near-bed) sediment concentration. Most of these deposits are re-eroded immediately throughout the major part of the tidal cycle by tide-induced currents and/or wave effects.
- Only around slack water during calm weather conditions, the deposited sediments remain on the bed for some longer time period. It is estimated that these conditions prevail during 20% of the time.
- Our basic hypothesis is that during these calm weather conditions, fine-grained sediment can be entrained (buried) into the bed by physical and/or biological processes, as discussed below.
- During storm conditions, waves stir up the upper few cm to few dm of the seabed, mobilizing the fine-grained sediment. After the storm period, the mobilized sediments settle again. However, segregation will take place, as no or little fine sediment is trapped by the settling sand particles and the seabed will contain little fine material. Hence, the process of entraining fines into the sand bed can start again.

Data summarised by Sandeh (2002) reveal that the natural fraction of fines in the upper few dm of the seabed around Loswal Noord and Loswal Noordwest are small and do not exceed 3%, and generally amount to a few 0.1% up to 1.7%. From this observation it can be
deduced that the natural fraction will be smaller. Sandeh (2002) also summarizes studies on
the sediment composition at and around Loswal Noord and Loswal Noordwest, based on
surveys by RIKZ, NIOZ, AquaSense, TNO-NITG and Medusa. The natural mud fraction (< 63
μm) around Loswal Noord amounted to about 0.3 – 1.4%. The mud content at and directly
around the dumping locations amounted to many tens percent (up to 37%) in 1996, the last
year that Loswal Noord was used. Within two to three years, the natural mud content was re-
established at most sample locations, but one, where the mud content remained high. It is
noted, however, that TNO-NITG concludes that this is (partly) due to sedimentation of “clean”
sand on top of the mud-containing bed, i.e. the fines would not necessarily have been
washed out of the bed.

The picture around Loswal Noordwest is similar, in the sense that the low natural mud
content increased up to several tens percent when dumping at this site commenced in 1996.
This time, also surveys further away from the actual dumping locations have been carried
out, showing that up to a few km around Loswal Noordwest the mud content has increased
up to a few percent (with a maximum up to 6.7%).

Langeveld (2005) analyzed the observations that the volume of sediments retrieved in the
“Verdiepte Loswal” is much smaller than is to be expected from the amount of dumped
dredging material. He concluded on the basis of additional surveys, literature survey and
physical reasoning that large amounts of (fine) sediment have been washed away rapidly
from this site.

From this brief survey we conclude that a part of the fine sediment released (at the dumping
locations) in the North Sea is retained in the seabed. However, it is not clear whether these
fines are actually entrained into the seabed, or that the dumped dredging material only
covers the existing seabed, or partly displaces it by the physical impact of dumping. Data
suggest that these sediments are washed out of the bed relatively fast (within 2 – 3 years),
though it has also been suggested that the coarsening of the upper part of the seabed is
caused by sedimentation of sand containing few fines, i.e. by segregation during dumping.

This period of 2 – 3 years is consistent with observations by Laane et al. (1999), who
present data on the residence times of contaminants in the North Sea bed from which they
conclude that the residence time of fine sediment in the bed amounts to about 2 year on
average.

In a recent study, an analysis was made on the amount of fines that can be stored in the
North Sea bed during calm weather conditions and how these fines are being remobilised
during storm. On the basis of an incomplete physical understanding, a heuristic model was
developed to simulate the buffering of fines in the seabed (Van Kessel, 2006). This model
was calibrated and validated on the basis of the CEFAS data referred to in Section 9. It was
concluded that:

- The new model describes the buffering of fines in the North Sea seabed satisfactory
  from a qualitative point of view, bearing in mind that little is known about the actual
  processes and few data are available.
- The effect of buffering of fines in the North Sea seabed is an important mechanism,
  responsible for important seasonal variations in SPM-concentrations along the Dutch
  coast through (temporal) withdrawal of fines form the Coastal River.
9 Spatial and temporal variation of SPM

9.1 Spatial distribution

The suspended sediment concentrations in the southern North Sea are small in general, ranging from a few mg/l in the northern part to a few 10 mg/l further south. In the coastal zones larger concentrations are measured up to 50 to 100 mg/l under mild weather conditions, and up to 20 g/l near the bed under storm conditions (De Kok, 2000). Closer to the shore, concentrations increase rapidly, as shown in Figure 5-4 and Figure 9-1 and Figure 9-2. In the breaker zone, concentrations can reach well over 100 mg/l and even more than 500 mg/l, as reported in Torenga (2002).

An idea of the concentrations near the water surface, and its spatial distribution can be obtained from remote sensing pictures, such as the image shown in Figure 5-4.

Also in vertical direction significant gradients in SPM are observed, e.g. Figure 9-3, showing the vertical structure of salinity and SPM at a transect at Callantsoog (Groenendijk, 1990).

Figure 9-1: Summer mean values of suspended sediment concentration (after Suijlen and Duijn, 2001).

Figure 9-2: Winter mean values of suspended sediment concentration (after Suijlen and Duijn, 2001).
9.2 Temporal variation

A mean picture of representative values of the suspended sediment concentration is given by Visser (1993). Note that Suijlen and Duijn (2001) have established pictures of the concentration field in the form of a climatological sediment atlas, more representative for various hydro-meteo conditions (seasonal effects, rough weather conditions, etc.). Based on long term field observations the summer and winter mean values are obtained (see Figure 9-1 and Figure 9-2). Note that the surface concentrations upon which these figures are based (DONAR-data) are considerably smaller than the depth-mean values, as noted elsewhere in this report.

An impression of the seasonal variations can also be observed by plotting the long-term averaged monthly means of SPM at location in the Dutch coastal region. An example for the Appelzak transect is given in Figure 9-4.
Further work on the relation between hydro-meteo conditions and SPM values in the Dutch coastal zone was carried out by Merckelbach (1996). He made a correlation between the amount of sedimentation in the so-called dredging basins (silt traps) E and F over the period 1990 – 1995 in the Caland/Beerkanaal in the Maasmond area and various hydro-meteo parameters. He found a significant correlation between said sedimentation rates and the wave energy, with a time shift of 6 weeks. No satisfactory physical explanation could be found for this time shift. Correlation with other hydro-meteo parameters was not found. It is noted that said 6 weeks are not in agreement with travel times from the Flemish Banks to the Maasmond area, as derived by Dronkers (2005), and discussed elsewhere in this report.

Finally, an impression of the day-to-day variation in SPM can be obtained from the CEFAS data. Data for the period March 2000 till March 2002 measured near the water surface are shown in Figure 9-5. These data have been obtained at Noordwijk 10, i.e. an anchor station at 16 m water depth, about 10 km offshore. It is observed that the SPM-values show large variations, with high values in particular in winter 2001/2002, and between 2000 and 2001. A closer inspection of the data would reveal a spring-neap cycle as well.
An impression of the seasonal variation in suspended matter in the southern North Sea, outside the Dutch coastal zone, can be obtained from Van Raaphorst et al. (1998), Vos et al. (2000) and Dyer and Moffat (1998) - see Figure 9-6 by the latter authors. The data are obtained from the NERC North Sea Project during 1988/1990. Large amount of data were gathered during 15 monthly cruises on the North Sea on the distribution of salinity, temperature, nutrients and beam transmission. Vertical profiles of the concentrations were measured with an optical sensor, calibrated locally against the sediment concentration of water samples. The concentration of sediment is influenced by seasonal and short-term variations in water movements. During periods of storm, mostly during winter, concentrations are several times higher than during periods with calm meteorological conditions.
The variability of SPM forms one of the steering mechanisms for the seasonal variation in primary production in light limiting areas.

Based on the various information the driving mechanisms for the seasonal variation in the SPM concentrations are the temporal fluctuations in:

- wind and wave induced stresses;
- seasonal buffering of fines in the seabeck and/or ebb tidal deltas, c.q. sea arms;
- erosion of cliff coasts and/or Flemish Banks;
- fluctuations of SPM-flux through the British Channel;
- consolidation/stabilization of sea bed by biological activity,
- and possibly, variations in flocculation properties by biological activity.
10 Exchange mechanisms with Wadden Sea

The tide in the Wadden Sea co-oscillates with the North Sea. Buijsman and Ridderinkhof (2006) analysed ADCP measurements in the Marsdiep during six years between 1998 and 2003. They could explain 98% of the observations from a harmonic analysis, based on 144 tidal constituents, of which the semi-diurnal, with their overtides and the diurnal constituents are the most important. They found a gross flow rate fluctuating between 50,000 and 90,000 m$^3$/s. The residual flow amounts to about 2900 m$^3$/s, from the Wadden Sea towards the North Sea. This is considerably larger than the mean outflow of fresh water sluiced through the Afsluitdijk, amounting to about 500 m$^3$/s. The remainder originates from import through the Vlie (Ridderinkhof, 1988). From numerical simulations it is concluded that the residual flow through the Marsdiep is largely governed by the prevailing wind (speed and direction), e.g. Van Kessel et al. (2006).

The flow is characterized by large horizontal circulation cells. During flood, the larger velocity is found in the centre of the inlet, whereas during ebb the strongest currents are found in the north of the channel. This induces a clockwise circulation during flood, and during ebb a small clockwise circulation cell in the north and a large counter-clockwise circulation cell in the south of the inlet.

Vertical profiles of the flow velocity are almost logarithmic of shape (but can be described with a power-law profile as well). This would suggest that the effects of gravitational circulation in the Marsdiep tidal inlet are small. However, numerical studies (Delft Hydraulics et al., 2005) showed considerable shearing over the vertical in the net water flow rate. In fact, net inflow near the bed was found in almost all simulations. This discrepancy can be explained from the small net effects of gravitational circulation in the Marsdiep in relation to the large gross flow rates, as a result of which the reverse flow components are difficult to measure accurately.

Though the Marsdiep is characterized by a net outflow of water, studies on the Wadden Sea sediment balance suggest that there is a net import of fine sediment (Postma, 1961; Eisma, 1981; De Kok, 2004; Dronkers, 2005). Gerritsen et al. (1990) estimate the yearly accumulation of fine sediment in the Wadden Sea at 2 – 3 Mton/yr. Figures on the net import of fine sediment vary from about 1 Mton/yr to as high as 10 Mton/yr. However, no definite data on actual measurements of the net sediment flux have yet been published.

A number of processes may be responsible for this net import:
1. Gravitational circulation: If most of the SPM is found near the bed, a significant net import of SPM can be generated by gravitational circulation.
2. Lag effects; generally two effects are distinguished (e.g. Postma, 1961):
   - Settling lag: As settling takes time, sediment will settle beyond the point where it falls below its transport capacity. As this time during HWS is often larger than during LWS, a net flood directed transport may result,
   - Scour lag: Following slack water, the flow accelerates and will re-erode sediment deposited during slack water. However, the flow velocities to re-erode the sediment are generally larger than the velocity to keep the sediment in suspension, and again a net transport can be generated. As the flow velocity towards the head of a tidal basin decreases, scour lag often generates flood directed transport as well.
3. Deposition (on intertidal areas): if part of the sediment entering through the Marsdiep accumulates in the Wadden Sea, a net import through the Marsdiep is the result, as the ebbing water contains less sediment than the flooding water.

4. Water level effects: The mean water depth in the Wadden Sea, with its pronounced intertidal areas, is smaller during HWS than during LWS, as a result of which a larger fraction of the sediment will settle during HWS than during LWS. Moreover, during HWS, the shallow, mildly exposed parts at the head of Wadden Sea, are flooded.

5. Tidal asymmetry: For the Wadden Sea asymmetry in the slack water period is important. If the temporal velocity gradients during HWS are larger than during LWS, flood dominant transport prevails (see also Settling Lag).

6. Other processes: A series of other processes may determine the net flux of sediment as well. Biological (and flocculation) processes affect the net sedimentation rate in the Wadden Sea and are responsible for significant seasonal variations. This is also the case for wave effects, as the stronger winds during winter time erode the sediment from the intertidal areas, which may become available for export by the ebb current.


11 Conclusions

11.1 General conclusions

From the analyses in the previous sections it can be concluded that the major part of the marine fine suspended sediment stems from the South, partly through erosion of the cliff coasts, partly from import from the Atlantic Ocean, and possibly partly from erosion of the Flemish Banks. Note that no consensus exists on the latter source, but, though it seems relatively small in comparison to the other sources, erosion of the Flemish Banks and hence sediment import to the Dutch coastal system, must be closely related to storm events in the Southern Bight of the North Sea, more directly than the other sources.

The fresh water plume of the River Rhine in particular (ROFI = Region Of Fresh water Influence) plays an important role in the transport of the fines along the Dutch coast. Because of the interaction of earth rotation, tide, fresh-saline water induced density gradients and bed friction, fine sediment is transported in a narrow band mainly in northern direction. Temporarily, some southward transport may occur as well.

11.2 Qualitative description of MV2-effects

Between 2008 and 2012 the authorities of the Port of Rotterdam will construct an extension of the present land reclamation (Maasvlakte) of over 10 square kilometers. An impression of the lay-out of the extension of the Maasvlakte, referred to as MV2 for brevity, is shown in Figure 11-1.

Figure 11-1: Indicative lay-out of MV2 (so-called Doorsteekvariant).
It is expected that MV2 will not affect the input of sediment into the Dutch coastal system, nor will it affect the total amount of fresh water delivered to the system, the overall tidal motion, or the meteorology in the system. The effects of MV2 are expected to occur at a much smaller scale, as the land reclamation itself is fairly small in comparison to the coastal system.

It is anticipated that MV2 may have the following effects:

1. The hydrodynamics in the vicinity of MV2 may change. The (tidal) flow will be reflected away from the coast, increasing the curvature of the streamlines locally, inducing changes in circulation patterns (both Eulerian and Lagrangean). The reflected flow will be accompanied by a reflection of the SPM flux. The effect of changes in circulation patterns on the SPM flux cannot be understood without modelling.

2. The wave climate may be altered by MV2, both because of sheltering and refraction owing to changes in bathymetry. The changes in wave climate may change the (temporary) sedimentation of SPM in the Haringvliet mouth, decreasing either the total amount of SPM in the coastal zone north of the Haringvliet through permanent accumulation, or affecting the phasing of SPM availability through temporary buffering of SPM, released during storm.

3. Changes may occur in the amount of fine sediment depositing in the fairways and harbour basins of the Port of Rotterdam, as their configuration will change. Because this material will have to be dredged and dumped offshore, this does not affect the overall sediment balance, but may effect the phasing of SPM transport in time, and the SPM concentration distribution perpendicular to the coast.

4. Because of the changes in circulation patterns and the protruding MV2, fresh water released through the Haringvliet may reside longer south of MV2, as a result of which the salinity south of MV2 may decrease and the behavior of the Coastal River may be affected.

5. Because the mouth of MV2 will be located further offshore than in the current situation, fresh water enters the coastal zone further offshore, and (small) changes in the distribution of fresh water input from the Rotterdam Waterway and Haringvliet may occur, on top of the changes in residence time of fresh Haringvliet water south of MV2. In combination with changes in the local hydrodynamics, the initial mixing and pulsed input of the fresh water plume (Coastal River) is affected. Most likely, the Coastal River will widen, and with that the band in which SPM is transported northward. This would imply lower SPM-concentrations near the coast, though the total flux will not alter.

6. A widening of the Coastal River and the accompanied smaller SPM concentrations near the coast will decrease the amount of sediment that will be transported through the Marsdiep. The water flow rate and its distribution through the Marsdiep itself will not be altered.

7. It is noted that even if less fine sediment would be transported through the Marsdiep into the Wadden Sea, this deficit in fine sediment may enter the Wadden Sea through other tidal inlets, as fine sediment is not lost by the construction of MV2, but merely redistributed in the (possibly wider) Coastal River.

In summary, one may expect the following impact of MV2 on the flux of SPM along the Dutch coast towards the Wadden Sea:

1. A decrease in SPM close to the coast, compensated by larger SPM-concentrations further offshore,
II. An increase in temporal variations of SPM because of buffering of SPM in the Haringvliet mouth and larger residence times of Haringvliet fresh water south of MV2.

11.3 Considerations

The effects of MV2 on the SPM flux are expected to decrease in northern direction, with the larger effects near the land reclamation, and the smaller near the Marsdiep. However, near the land reclamation, the flow is very complicated. Therefore, monitoring stations further north, say near Noordwijk, are more suited to assess the effects of MV2 on the SPM fluxes.

The effects of MV2 on the exposure to waves within the Haringvliet ebb tidal delta is most pronounced during storm conditions. Possible changes in SPM flux as a result of this wave sheltering are therefore expected to be maximal during winter time.

It is not understood how the amount of fresh water (river flow) or wind speed and direction affect possible changes in SPM flux as a result of the MV2 land reclamation. This implies that it is not known whether the effects of MV2 by flow rate and wind on the SPM fluxes vary over the year (i.e. with the seasons). Therefore it should be recommended to establish these possible effects throughout the year. However, it is noted, that the Coastal River is more pronounced during high river flow, hence the measurements themselves are likely to be more accurate during high river flow.

From a theoretical point of view, the effect of MV2 on the SPM fluxes in the Dutch coastal zone and through the Marsdiep can be measured as follows:

- It seems impossible to measure changes in the water movement, c.q. flow rate of the Coastal River,
- However, the location, width and transport rate of the Coastal River and their possible changes can be established from measurements of water temperature and salinity,
- (Changes in) SPM fluxes can be measured from SPM concentration measurements in the Coastal River along the Holland coast and from (changes in) sediment flux through the Marsdiep,
- (Changes in) SPM fluxes can be also be established from (changes in) the siltation rates of harbour basins and navigational channels located along the Coastal River, such as Scheveningen and IJmuiden.

Note that it can be expected that the correlation between SPM-values in the Zeeland delta and those north of the Maasvlakte are expected to be small, as the former are affected largely by (temporal) buffering in the ebb tidal deltas and sea arms. This can be concluded from the much longer net travel time of SPM along the different parts of the coast.

11.4 Autonomous developments

In future the SPM-flux along the Dutch coast may also be affected by other measures and some other new developments, described in Chapter 2. These are repeated here for convenience, together with their possible impact in italic font.

1. Continuation of maintenance of harbour basins and navigational channels (Changes in cross-shore SPM-distribution because of changes in dump location, and changes in phasing of the SPM-flux with time because of a time lag between sedimentation and dredging. The total flux will not alter),
2. Changes in sluicing regime Haringvliet sluizen (“Kierbesluit”) (Changes in the distribution of fresh water input from the Rotterdam Waterway and Haringvliet may occur, affecting the cross-shore SPM-distribution and the phasing of the SPM-flux. The total flux may alter as well, because of changes in accumulation in the Haringvliet mouth),

3. Changes in sluicing regime Afsluitdijk (Changes in the sluicing regime will cause changes in the salinity distribution in the Wadden Sea, which may result in changes in the SPM-flux through the Marsdiep, and possibly other tidal inlets),

4. Construction of offshore wind farms (Offshore wind farms may affect the mixing within the Coastal Plume, affecting the cross-shore SPM-distribution),

5. Large scale sand mining for beach supplentions (The fines mobilized during sand mining operations may increase the total flux of SPM along the Dutch coastal zone),

6. Large scale sand mining for construction MV2 (The fines mobilized during sand mining operations may increase the total flux of SPM along the Dutch coastal zone),

7. Large scale sand mining for general construction sand (a.o. WCT, Vlissingen) (The fines mobilized during sand mining operations may increase the total flux of SPM along the Dutch coastal zone),

8. Large scale sand mining activities in Belgium part of North Sea coastal zone (The fines mobilized during sand mining operations may increase the total flux of SPM along the Dutch coastal zone),

9. Establishment of natural sea reserves banning human activities (Less sediment will be mobilized from the seabed by anthropogenic activities, which may affect the cross-shore SPM-distribution and the phasing of the SPM-flux; most likely the total flux will not alter),

10. Moving of Norfolk line from Scheveningen to Vlaardingen (less dredging at Scheveningen) (Less dredging implies less dumping, which may affect the cross-shore SPM-distribution and the phasing of the SPM-flux),

11. Changes in commercial fishing (in particular seabed disturbing beam trawling) (Less sediment will be mobilized from the seabed by anthropogenic activities, which may affect the cross-shore SPM-distribution and the phasing of the SPM-flux; most likely the total flux will not alter),

12. Land reclamation along Zuid-Holland coast (Plan New-Holland, c.q. Plan Waterman) (Land reclamation may alter the hydrodynamics of the coastal plume, affecting the cross-shore SPM-distribution),

13. Industrial North Sea Island (airport at sea, etc.) (An island at sea may affect the mixing within the Coastal Plume, affecting the cross-shore SPM-distribution),

14. Sea level rise and other climate changes (river flows, wind and wave climate) (Climate changes may affect the total amount of fine sediment available for transport along the Dutch coast, as well as the entire transport patterns of SPM as a result of changes in fresh water input, wind climate, etc. Climate changes are expected to yield a major impact on the SPM-flux along the Dutch coast).

These effects may contaminate measurements on the impact of MV2 on the SPM-flux along the Dutch coastal zone to a greater or lesser extent.
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