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TU Delft
Delft University of Technology

Department of Civil Engineering
Hydraulic and Geotechnical Engineering Division
Hydromechanics Section

The Ems/Dollard estuary

A physical system description

R. van der Ham

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Hydraulic and Geotechnic Engineering Division
Department of Civil Engineering
Delft University of Technology
Delft, The Netherlands

Preface

In 1993 an interdisciplinary research programme on the behaviour of mud in tidal waters was initiated by the The Board of NWO-BOA. The programme aims at obtaining more detailed insight in the dominant processes that govern the transport behaviour of mud. These processes have strong time variability and therefore the general approach is to obtain long-term in situ measurements on a number of key parameters in a tidal channel and on a tidal flat. One of the surplus values of this research programme is that it contributes to an interdisciplinary perception of the behaviour of intertidal areas, in which the relevance of biological, physical and chemical processes and human activities is represented in a well-balanced way.

This report provides a physical system description of the Ems/Dollard estuary with emphasis on those processes and human activities that are dominant for the development of mud and sand beds in the estuary. It is addressed in the first place to participants of the BOA Theme project and in the second place to other researchers interested in the Ems/Dollard. Hopefully this report provides a basis for a fruitful discussion on the development of mud and sand beds in the Ems/Dollard estuary.

Acknowledgements

This work was supported by the Netherlands Geosciences Foundation (GOA) with financial aid from the Netherlands Organisation for Scientific Research.

Special thanks go to Arie den Toom for his assistance in the preparation of the Figures.

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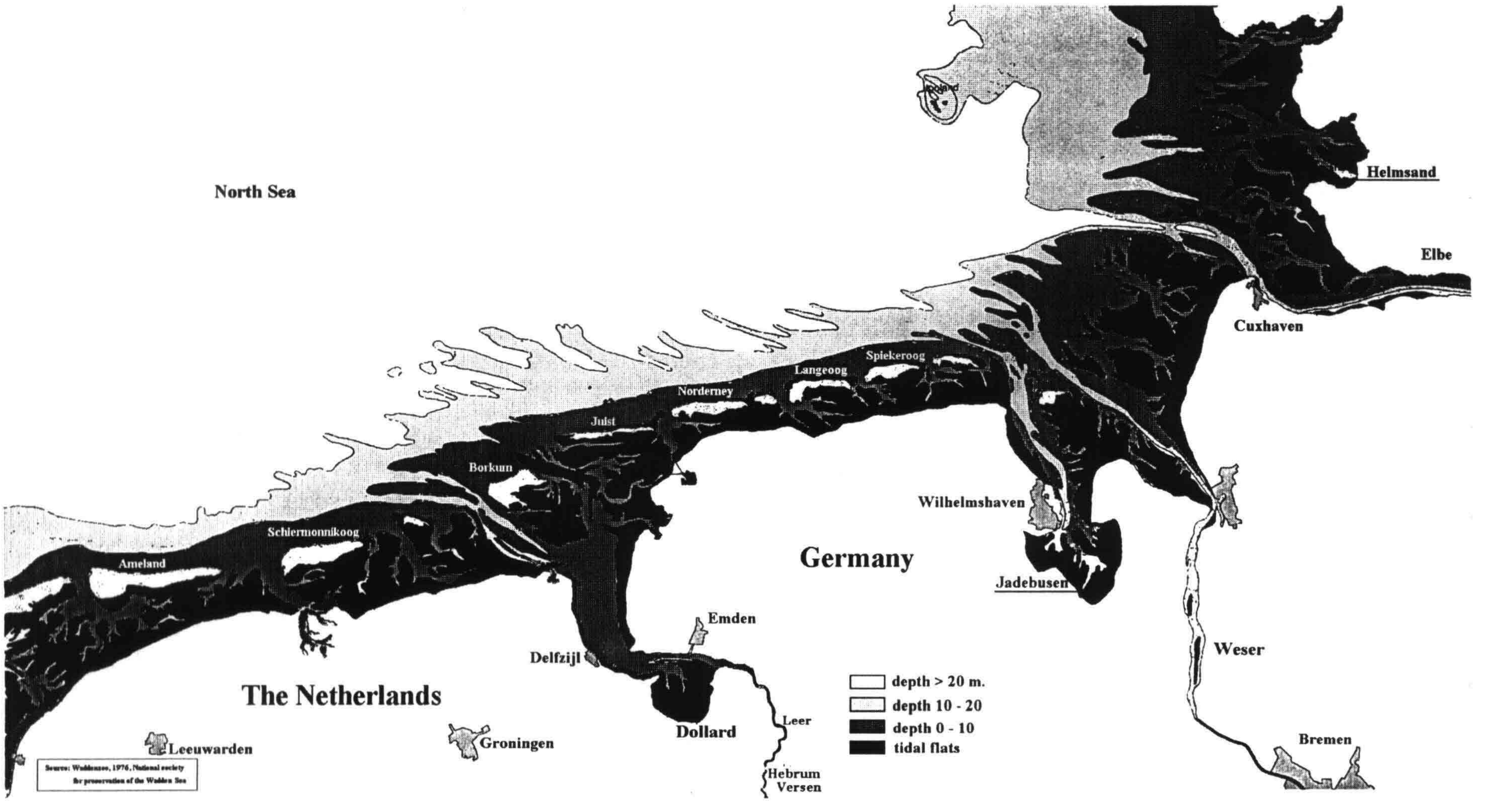
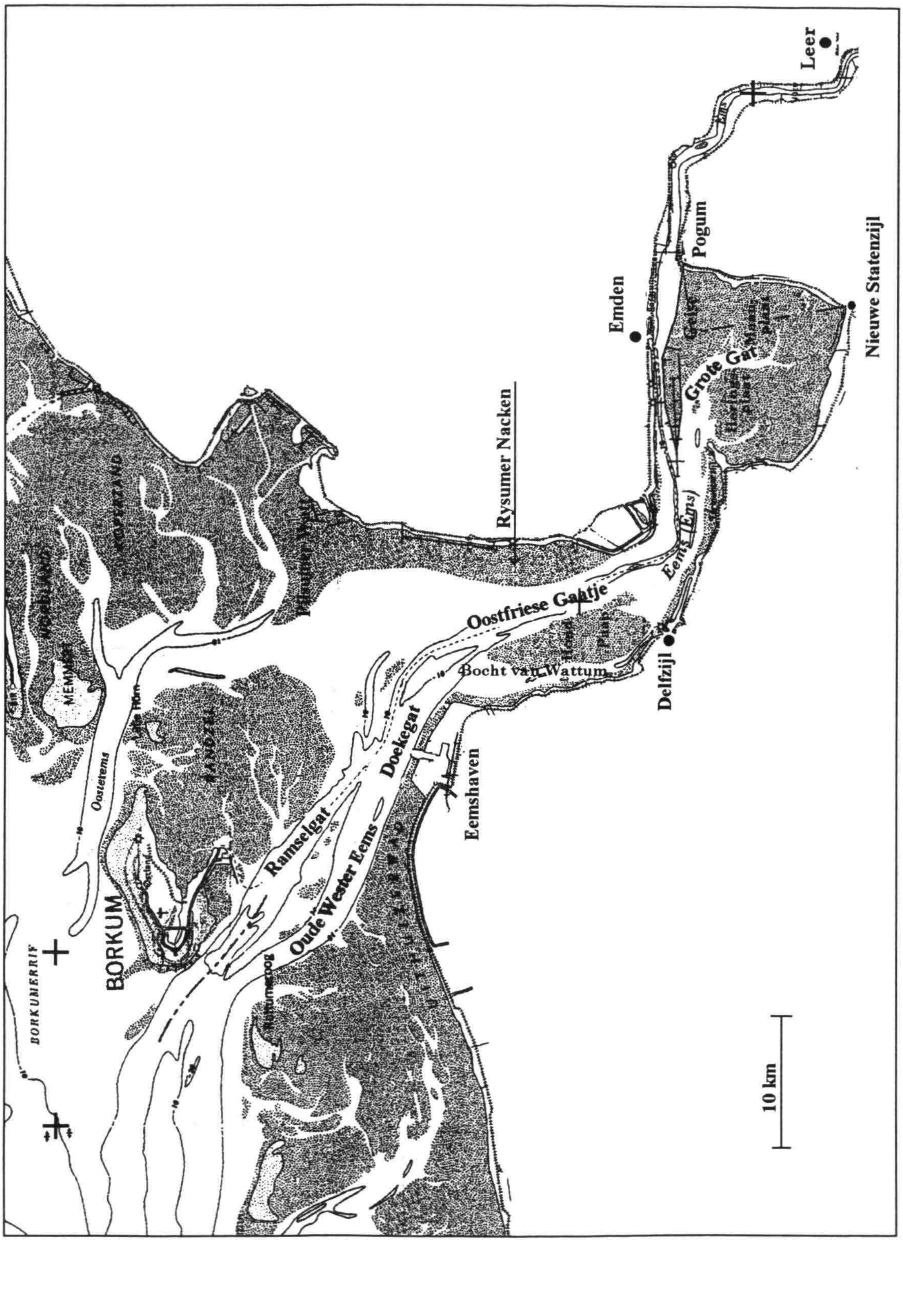

North Sea
Helmsand
Elbe
Cuxhaven
Spiekeroog
Langeoog
Norderney
Juist
Borkum
Schiermonnikoog
Ameland
Wilhelmshaven
Germany
Jadebusen
Emden
Delfzijl
Weser
The Netherlands
Dollard
Leer
Leeuwarden
Groningen
Hebrum
Versen
Bremen
depth > 20 m.
depth 10 - 20
depth 0 - 10
tidal flats
Source: Waddenzee, 1976, National society
for preservation of the Wadden Sea

Chapter 1 Introduction

The meso-tidal estuary of the river Ems is situated in the north-eastern part of The Netherlands between the tidal limit at the weir at Hebrum and the seaward boundary, which is formed by the islands Rottumeroog and Borkum, and the stagnant-waters behind these islands on the intertidal flats Ransel and Uithuizerwad. It has been chosen as the area for investigation because it is characteristic of tidal inlets in the Netherlands and because an extensive field survey has been carried out already in the area. The transport of mud in this estuary has been investigated by Eisma (1986), De Jonge (1992) and Van Leussen (1994), so that much is known of the physical behaviour of this estuarine system.

The field work will be carried out at two locations: in the middle of the Dollard on the Heringsplaat and the in the adjacent channel Grote Gat. That is because our study focuses mainly on the temporal variability and less on spatial variability. Nevertheless a good physical description of the estuary is required to be able to compare it with other estuaries and to get a thorough understanding of the scale and the impact of mud transport. Therefore the estuary is characterised by describing its topography, the tidal behaviour, and the distribution of typical estuarine properties comprising salinity, the composition of the sediment and the tidal averaged suspended sediment concentration. Special attention will be paid to the transport of fine sediments in the estuary. Appendix A presents a summary of the physical properties of the Ems/Dollard estuary.


Leer
Pogum
Nieuwe Statenzijl
Emden
Rysumer Nacken
Grote Gat
Oostfriese Gaatje
Eems (Ems)
Bocht van Wattum
Delfzijl
Doekegat
Eemshaven
Ramselgat
Oude Wester Eems
BORKUM
Oosterems
RANDZEL
MEMMERT
BORKUMERRIF
10 km

Chapter 2 Topography

In this chapter the topography and morphology of the Ems/Dollard estuary is described and a short historical overview is presented because much of the present day topography is the result of natural processes like flooding and siltation, and through human activities comprising land reclamation, dredging activities, diking and regulation works like the 'Geise dam'. The human involvement is most dominant in the Dollard reach and the Emder Fahrwasser, the area of interest for our research on accumulation and transport of fine sediments.

2.1 Present day morphology

The Ems/Dollard shows typical properties of both an estuary and an intertidal basin. It has more or less a funnel shaped river mouth, but unlike most estuaries it has a relatively large brackish water surface elevation area provided by the Dollard reach. The latter is more typical for intertidal reaches, despite of these deviations the Ems/Dollard will be referred to as an estuary.

The estuary is about 110 km long, measured along the main tidal channel, it covers 470 km^2 and comprises roughly 50% intertidal flats. It can be divided into three reaches (see Figure left). The most seaward reach is where the estuary intersects with the Wadden Sea. It has a total area of 215 km^2. The most notable aspect of the complex topography is the two-channel system devided by a series of shoals.

The middle and more narrow reach extends from Eemshaven to the mouth of the Dollard, near Reide. The total area is 155 km^2 and only 35% consists of tidal flats. The Hondpaap is the most important tidal flat; it divides this reach into two channels.

The most upper reach reaches from the mouth of the Dollard to the mouth of the Eems, near Pogum. The total area is about 100 km^2. The morphology of the Dollard reach is very characteristic for tidal reaches but relatively simple. It consists of one main tidal channel, the Grote Gat, surrounded by tidal flats and creeks. The bathymetry of the Ems/Dollard is presented in Appendix B.

The small scale morphology of the tidal flats is highly dynamic and complex. It can change locally on a typical time scale of a week from muddy to sandy, the presence of simultaneous accumulation and erosion at locations only a few hundred meter apart is often observed (Van der Lee, in prep). This process is affected by creeks and by bio-turbation through erosion and burrowing of the upper layer of sediment respectively; both give the tidal flats a battered sight, see Figure 2.2.

Figure 2.2 Salt pasture in the Dollard reach.

Appendix B presents GIS[1] data on the topography of the estuary, more information about the topography can be found in De Jonge (1992) and GRAN (1990).

2.2 A short overview of recent history

The estuary was formed during the Holocene with the river Ems more or less at the present position. Due to a number of floods in the 14th and 15th century the Dollard was formed, which obtained its maximum size of 350 km^2 in about 1500. Land reclamation by diking began pretty much at the same time and new polders succeeded each other over a relatively short period (see Figure 2.3). The accretion at the time was probably large because it was a custom to wait until the salt pasture was overgrown before dikes were built.

The Ems flowed initially like a meandering curve directly past the old town of Emden. However, the curve was broken in 1509 by a storm surge and despite great efforts in 1585 to restore its old route the Ems kept its new position: Emden became difficult to reach for larger vessels. In order to prevent further siltation of the Ems, and to fix its position, the 'Geise Leitwerk' was constructed between 1872 and 1900: the Ems, or 'Emder Fahrwasser', became separated form the Dollard. In the same period the southern part of the 'Oostfriesche Gaatje' was dredged through, which lead to a natural widening and deepening of this channel, but lead simultaneously to the siltation of the tidal channel 'Bocht van Wattum'.

In the fifties plans were made for opening Emden harbour for large ore-tankers. A 12 kilometre long Geisedam was constructed in 1962, 400 m north of the old 'Leitwerk', a 2.3 km long 'Leitwerkes Seedeich' was constructed on the north side of the Emder Fahrwasser in the same period. The original plan provided in a sediment trap, located upstream of Emden although it has never been constructed. A new plan had been developed: the Dollard harbour project, which hasn't been realised for reasons of economy and environmental care.

2.3 Accumulation of sediment in the Dollard reach

Recent research by means of different measuring techniques reveals various accumulation rates caused by either low accuracy of the measurements, or incorrect interpretation of the results.

Smit et al. (1960) reconstructed the accumulation from about 1500 when the Dollard reached its largest expansion. They found an annual accretion rate of 1.7 cm for the polders reclaimed in the 17th century and 1.3 cm for polders reclaimed in the

[1]Geographical Information System

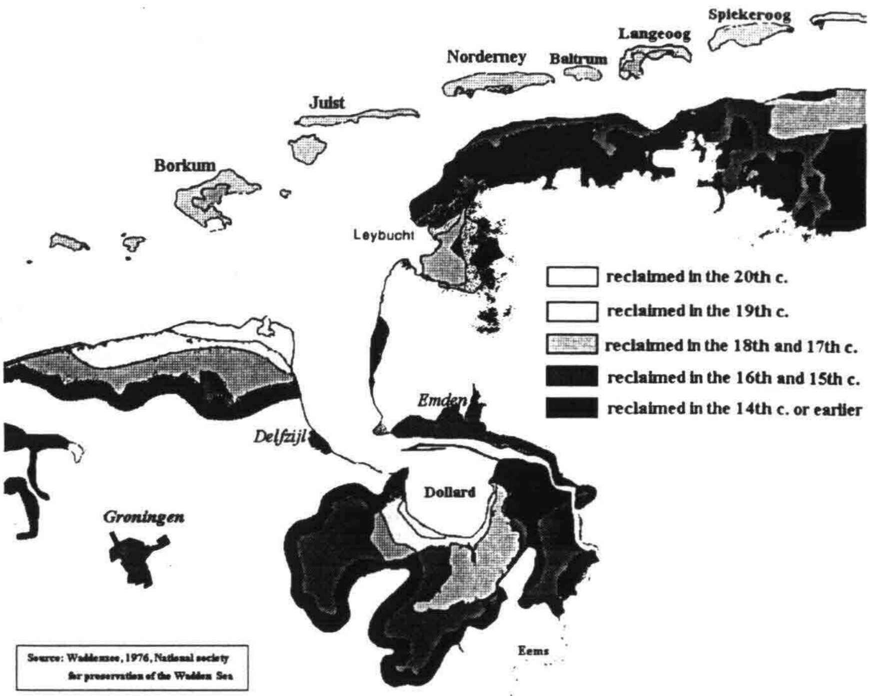


Figure 2.3 Land reclamation in the Ems/Dollard estuary during the last centuries

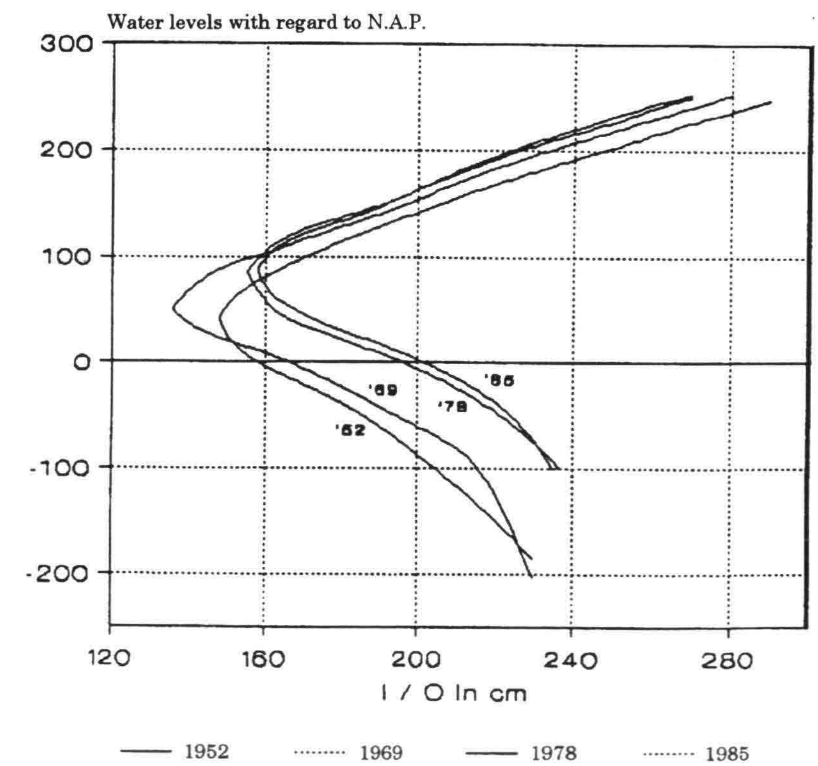


Figure 2.4 The mean water depth, that is the 'wet volume' (I) divided by the 'wet surface (O)' at various water levels (0 = N.A.P., Source: GRAN, 1990)

19th century. The decrease in accretion rate can be explained from the composition of the sediment bed, which shows that in the beginning of the accretion old clay layers contributed to the availability of mud besides the fine sediment from the adjacent North Sea (Wiggers, 1974).

An accretion of approximately 1-3 mm/year over the last century was found by means of a ^{210}Pb-method and a pollen method (Heijnis, 1987). For the ^{210}Pb-method only six samples were used and for the pollen method only one sample. The results of these measurements should therefore be interpreted with care. On the other hand it strenghtens the idea supported by some researchers, that the development of the morphology of the Dollard reach came to an end. They refer to the fact that sea maps from the last 50 years show hardly any changes in the morphology of channels and intertidal flats (Abrhamse 1976, Wiggers 1974).

Sounding measurements carried out over the last 40 years show a different insight in the development of the Dollard. In Figure 2.4 the development of the mean water depth is shown for various water levels over the period 1952 - 1985 (GRAN, 1990). The mean water depth is defined as the ratio of the wet volume (I) and the wet surface (O). The minimum mean water depth coincides with the flooding of the tidal flats, the water level at which this happens increased from N.A.P. +0.4 m in 1952 to N.A.P. +0.8 m in 1985. It can be concluded that the surface level increased 1 cm/year since the early fifties. The area-elevation volume provided by the Dollard reach shows a decrease of approximately 10% over the last 30 years (GRAN, 1990).

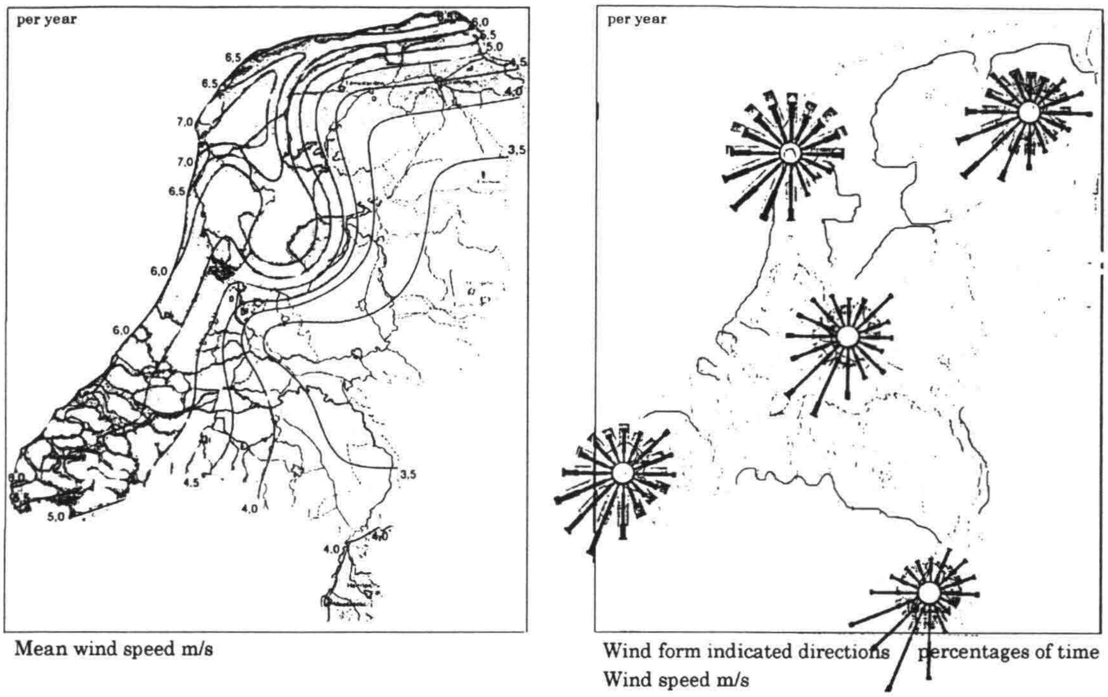


Figure 3.1 Annual wind speeds and wind directions (Source: Klimaatatlas, 1974)

Chapter 3 Meteorology

The annual air temperature is 9 °C, its fluctuations are regulated by the seasonal varying insolation and the moderating influence of the North Sea especially along the coastline: the air temperature along the coast is always a few degrees higher in winter and a few degrees lower in summer compared to the more inland situated reaches. The water temperature in the upper reach differs even more from the sea water temperature since the water depth is much smaller.

The annual precipitation is 675 mm near the barrier islands and 700 mm near Emden with a deviation of approximately 40 mm , its difference from the evaporation is approximately 150 mm .

The mean annual wind direction is predominantly from the south westerly directions. The mean annual wind speed is 6.5 m/s near the barrier islands and 4.5 m/s in the Dollard reach (see Figure 3.1). The strongest winds are mostly from south westerly direction in winter, and the weakest are North east to south east mostly during summer (Klimaatatlas, 1976).

Chapter 4 Hydrodynamics and fresh water input

As for most Dutch estuaries the tidal range and the tidal asymmetry increase in the landward direction. The latter phenomenon is an important property of an estuary for the direction of the sediment transport (Postma).

As stated in the previous chapter, the surface area in the upper reaches is relatively large, in combination with the relatively small fresh water input, the tidal induced currents in combination with the wave climate dominate the hydrology of the estuary. This is expressed amongst others by the strong tidal mixing. In this chapter the tidal behaviour, the fresh water input at various locations and the salinity distribution are presented, and the tidal mixing is discussed.

4.1 Tidal behaviour

The tidal range increases from 2.2 m near Borkum via 3.0 m at Delfzijl to 3.3 m in the Dollard reach. Very prominent for this estuary is the diurnal inequality which can reach 0.3 m at Delfzijl. The non-lineararity of the estuary is decribed by the ratio of the tidal contituents M_4 and M_2, which is about 0.05 in the outer reach and 0.1 near Emden. The tidal asymmetry is described by the phase angle of the tidal constituents M_2 and M_4, which is about 160° in the outer reach, 180° in the Emder Fahrwasser, and then decreases further upstream (Van Leussen, 1994). This implies that the duration of the flood is shorter than the duration of ebb which is illustrated in table 3.1.

The phase angle between M_2 and M_4 for the *water velocities* of approximately 90° for the Dollard reach (BOA Progress report 1993-1995), contrary to the phase angle in the river Ems upstream from Pogum which decreases towards 20°(Van Leussen, 1994).

Table 4.1
Tidal properties of the Ems/Dollard estuary in 1989 (GRAN, 1990)

	Mean tide (m)			Spring tide (m)			Duration (h:min)	
Location	HWS	LWS	Tidal range	HWS	LWS	Tidal range	Flood	Ebb
Delfzijl	1.3	-1.7	3.0	1.4	-1.8	3.3	5:50	6:35
Knock	1.3	-1.7	3.0	1.4	-1.8	3.3	6:02	6:23
Emden	1.4	-1.8	3.2	1.6	-2.0	3.5	6:07	6:18
Pogum	1.5	-1.8	3.3	1.6	-1.9	3.6	6:00	6:25
Nw.St.zijl	1.4	-1.9	3.3	1.5	(-2.0)	3.5	-	-

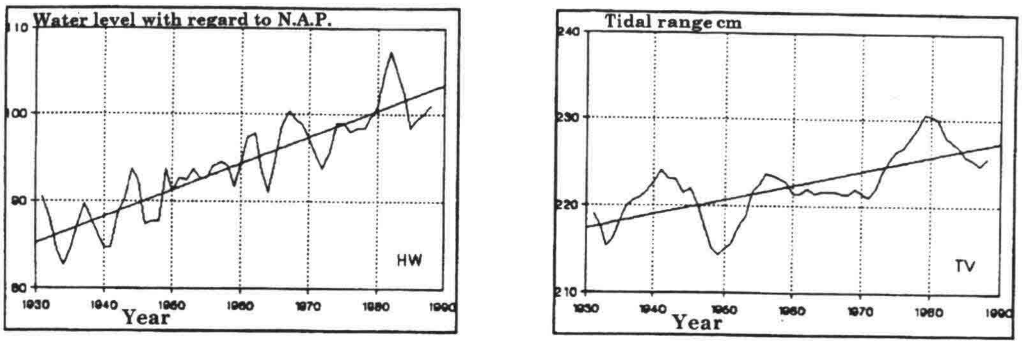


Figure 4.1 Moving average of the high water level and the tidal range over three years plus the trend lines at Borkum Südstrand (Source: GRAN, 1990)

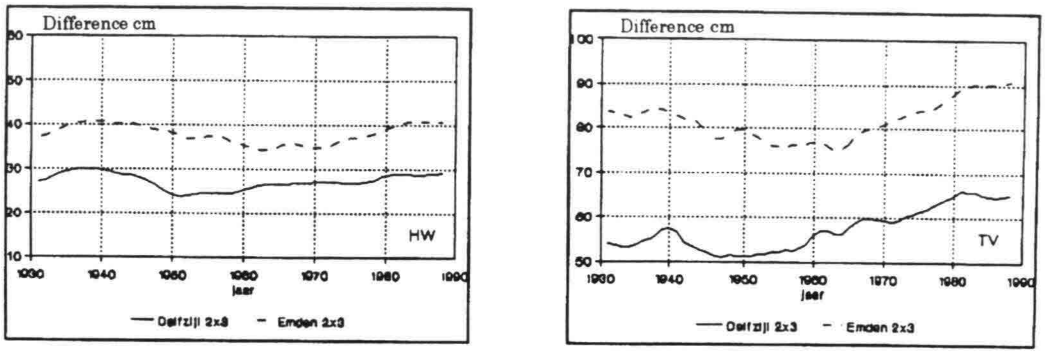


Figure 4.2 Moving average of the level of HWS and the tidal range at Delfzijl and Emden reduced with the water level at Borkum Südstrand (Source: GRAN, 1990)

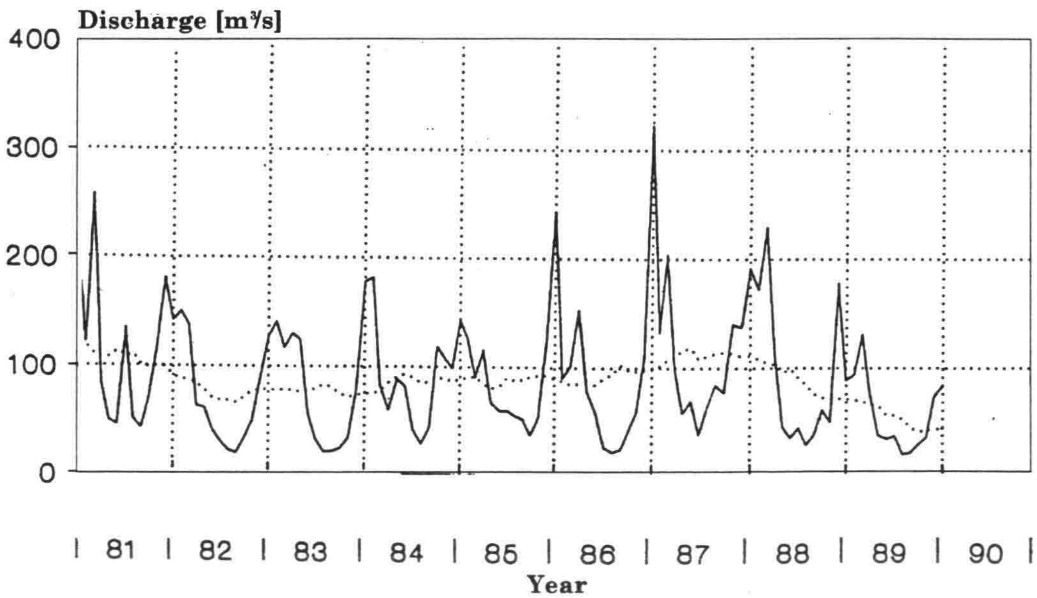


Figure 4.3 Discharche at Versen, monthly averaged 1981/1990
(Source: GRAN 1990)

It can be concluded that on the whole the duration of the flood tide is shorter than that of the ebb tide, and upstream from the Emder Fahrwasser the peak velocities during flood are much larger than the ebb velocities, therefore the Ems/Dollard estuary can be assumed flood dominated.

The annual mean water level and the annual mean tidal range on the seaward boundary increased 0.2 cm/year, averaged over the period 1931-1990, see Figure 4.1. This trend is in agreement with the increase in the annual mean high water level of 0.25 cm/year for the Wadden-sea over the same period. The strong variations shown in Figure 4.1 are largely explained by the difference in annual wind strength and wind direction (Bossinade et al., 1993).

In the inner part of the estuary the tidal range increased according to the increase at the seaward boundary, although it seems that since about 1960 the tidal range in the estuary increased even more (see Figure 4.2). Additional to this observation, the flood reaches Delfzijl 8 minutes earlier, and Nieuwe Statenzijl 15 minutes earlier, compared to the sixties (GRAN, 1990). These findings point towards a reduced drag on the tidal wave caused by either natural or artificial changes in the morphology of the estuary, they are in agreement with the increase in mean water depth over the last decades (Chapter 2, Fig.2.4).

4.2 Wave climate

The wave climate is dominated by locally generated wind waves, only in the outer reaches wave penetration from the adjacent North Sea is present. A fetch of a few kilometre in combination relative small mean water depth results in small wave heights in the range of 0.1 to 0.5 m. The impact of waves on the sediment beds, on the other hand, is substantial when compared to the tidal currents (Dronkers, 1986).

The wave growth is mainly limited through white capping, which is often observed for wind speeds exceeding 4 Beaufort. Surf zones on the borders of tidal flats are absent in the inner part of the estuary. This can be explained by the considerable reduction of the fetch when tidal flats become exposed.

4.3 Fresh water discharge

The main fresh water input is coming from the Ems river. The Ems is a rain fed river and has a yearly averaged discharge of 78 m^3/s at Versen over the period 1941-1986. Its discharge shows a significant variation in distribution over each season: a high peak in winter a relatively low discharge in summer (see Figure 4.3). More rivers and channels are entering the Ems/Dollard estuary which are altogether an important

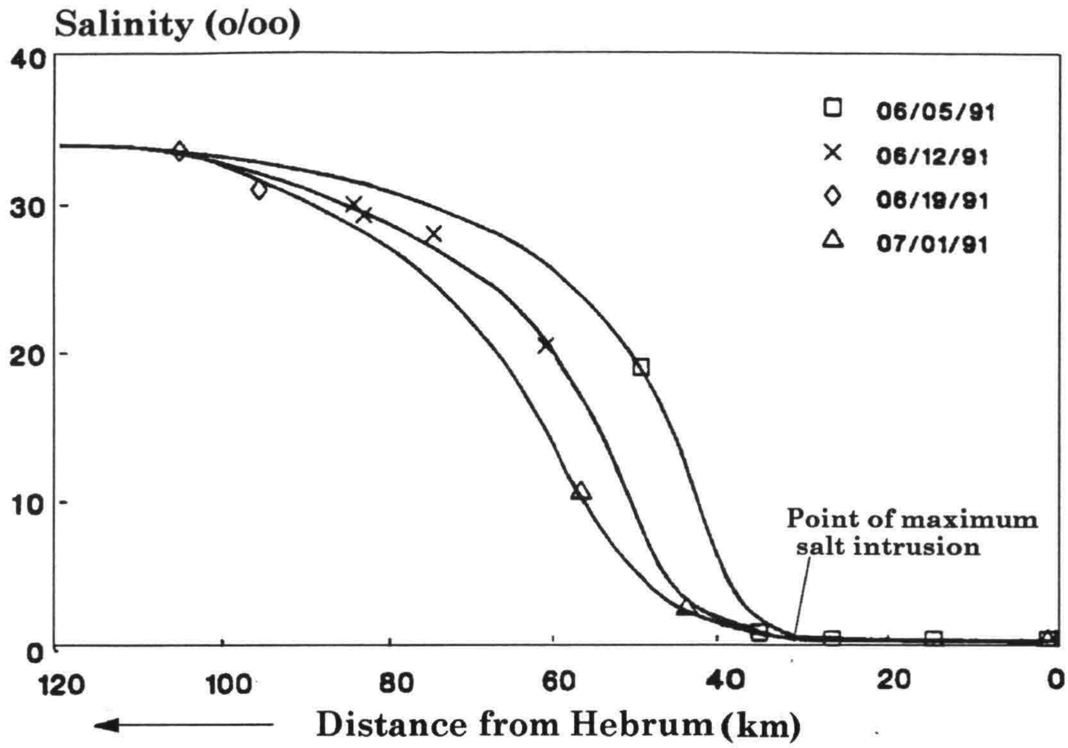


Figure 4.4 Longitudinal salinity distribution during June 1991. The river discharge increased from 25 m^3/s in the first half of June to about 60 m^3/s at June 19th and July 1st. (Source: Van Leussen, 1994)

contribution to the total fresh water input. Their drainage areas are listed in table 4.3:

Table 4.2 Drainage areas (GRAN, 1990)

Location	**area (km^2)**	**discharge (m^3/s)**
Ems (Versen)	8469	78 (1941-1986)
Leda (Leer)	2078	24 (1984-1986)
Ems (from Leer to Emden)	1987	unknown
Discharge at Emden harbour	190	<1 [1]
Discharge at Knock	453	unknown
Westerwoldsche Aa (Nieuwe Statenzijl)	793	unknown
Discharge at Termunterzijl	187	15 (1971-1986)
Discharge at Delfzijl Harbour (Eems channel, Duurswold and Fivelingo)	1099	10 (1981-1986)

[1] Hafenambt Emden

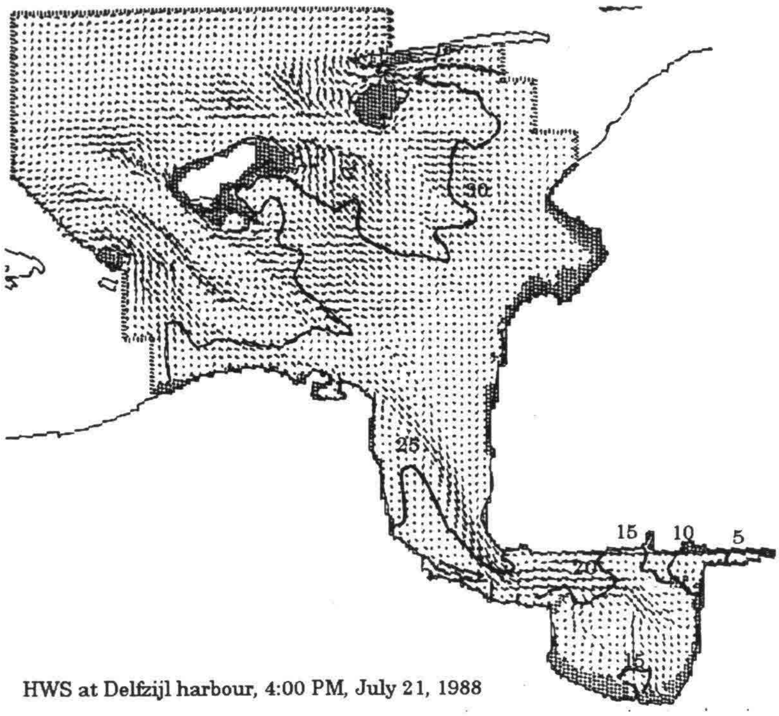
The measurement of the discharge of the Leda takes place only since 1983, from which it can be concluded that the contribution of the Leda is more important than its drainage area suggests (GRAN, 1990). The distribution of the total mean annual fresh water discharge, about 150 m^3/s, the can be estimated as follows: 50% at Versen, 30% between Versen and Pogum (e.g. Leda), 15% at Nieuwe Statenzijl and Delfzijl harbour, and 5% at other locations.

4.4 Longitudinal salinity distribution

The longitudinal salinity distribution for varying river discharges is presented in Figure 4.4 (Van Leussen, 1994). It shows that the salinity distribution moves seaward as a result of an increase of the river discharge, from 25 m^3/s in the first half of June to about 60 m^3/s during the second half of June. The slope of the salinity distribution is some what steeper for the low discharge compared to the period of higher discharge. The entire salinity distribution shifts under the influence of the tide which is illustrated very clearly in Figure 4.5 (RWS,1990).

4.5 Tidal mixing

An estuary can be classified as stratified, partly mixed or well mixed depending on the vertical differences in salinity. A measure for the mixing in a estuary is provided by the Estuary Richardson-number (Fisher, 1976):



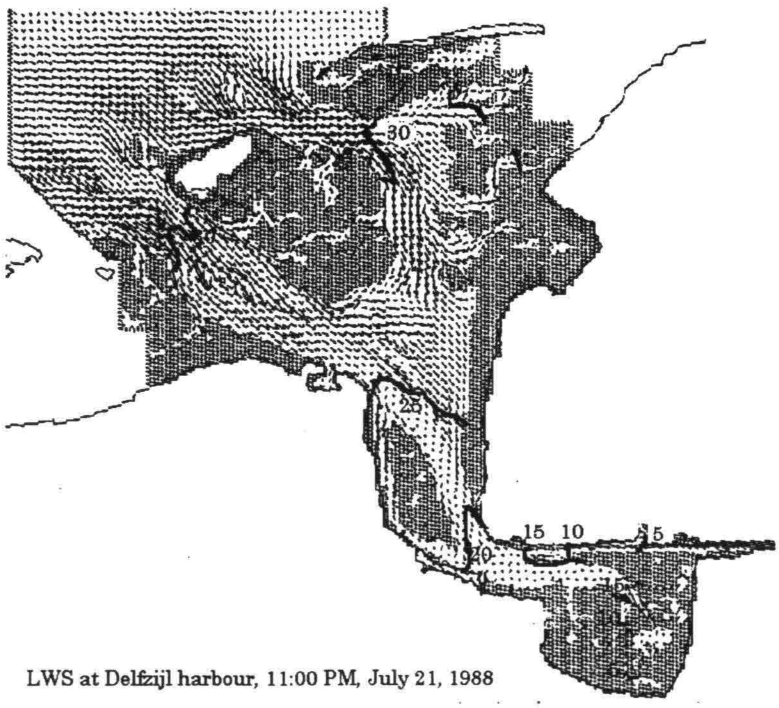


Figure 4.5 Salinity distribution in the Ems/Dollard, a numerical model simulation of the tide on 21 July 1988. The iso-lines represent the salinity every 5‰ Source: DGW-92010, Robaczewska K.B., 1992

$$Ri_E = \frac{\Delta\rho\, g\, a\, Q_f}{\rho\, A\, u_t^3}$$

$\Delta\rho$(kg/m^3) is the density difference between the fresh water and the sea water, g(m/s^2) is the gravitational number, a(m) is a typical water depth Q_f(m^3/s) is the fresh water discharge, ρ(kg/m^3) is the density of the sea water, A(m^2) the cross sectional area at the mouth and u_t(m/s) is the root mean square velocity in the mouth. The numerator is a measure for the power that is needed to mix the fresh discharge over the whole water column and the denominator is a measure for the available power. For partly mixed estuaries the range for Ri_E lies between 0.08 and 0.8.

Table 4.3 Estuary Richardson number

Location	a (m)	A (m^2)	u_t (m/s)	$Q_{f,low}$ (m^3/s)	$Q_{f,high}$ (m^3/s)	$\Delta\rho/\rho$ (-)	$Ri_{E,low}$ (-)	$Ri_{E,high}$ (-)
Mond Dollard	10	11000	1	30	300	0.02	0.05	0.005
Emder Fahrw.	10	5100	0.8	30	300	0.02	0.23	0.023
Turbidity max.	5	2900	0.8	30	300	0.02	0.10	0.010
Grote Gat	10	2700	0.6	5	40	0.01	0.07	0.008

The values for Ri_E for parts of the estuary, presented in Table 4.3, show that even at high river discharge only the Emder Fahrwasser and in the Turbidity Maximum near Pogum the estuary is partly stratified. These rough estimations are in agreement with various measurements of vertical salinity distributions showing only small variations in salinity except for the Emder Fahrwasser in the turbidity maximum (Van Leussen, 1994).

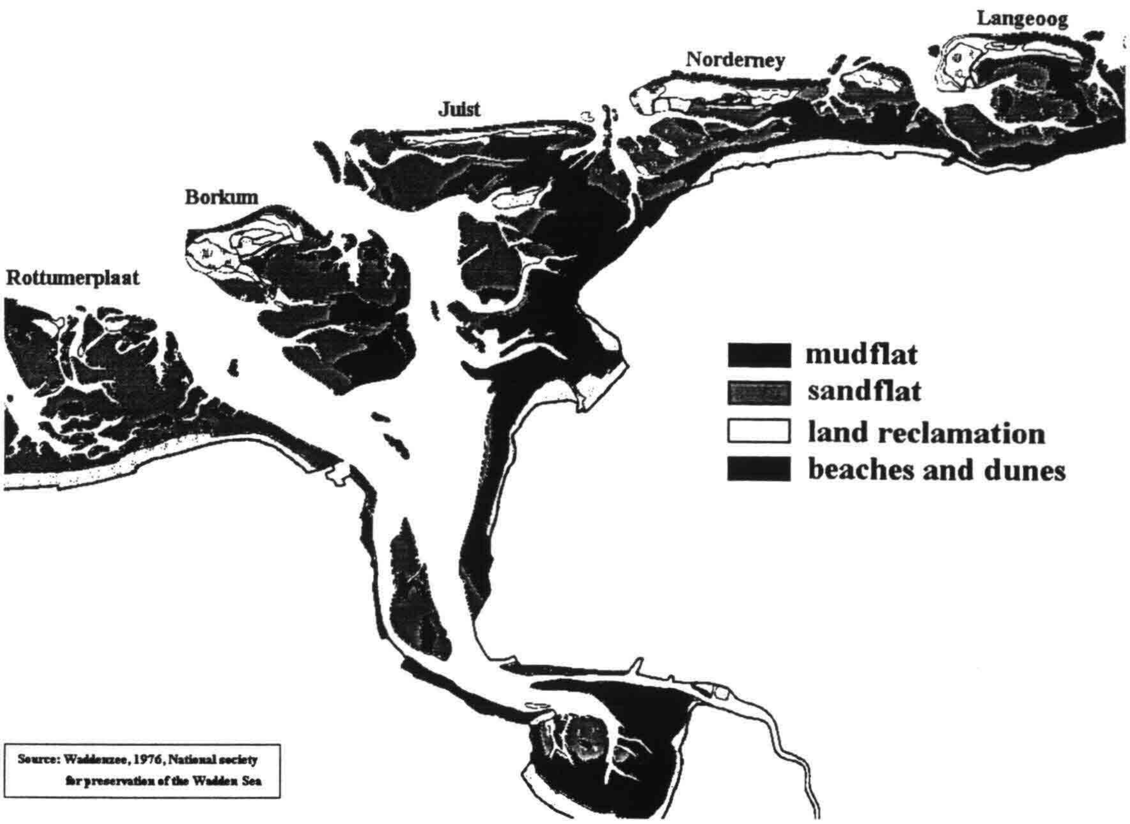


Figure 5.1 Sand and mud distribution in the Ems/Dollard

Chapter 5 Fine Sediment Characteristics

Sediment is characterised in the first place by its grain size: sand (>63 μm), silt (3 μm - 63 μm), and clay (<3 μm). The sand and silt consist of mainly quartz, feldspar and mica, the clay minerals are mainly illite, kaolinite and montmorillonite.

The cohesive properties, such as yield strength and bed stability of fine sediments are basically determined by the sediment composition and its surface properties, which are determined by the biological constituents and the percentage of clay. A summary of the most important physico-chemical properties related to the transport of cohesive sediment was determined in the framework of the EC Mast-I Research Programme, see Table 5.1 (MAST-1, 1993). It will be used here as a guideline for presenting the characteristics and the distribution of the sediments in the Ems/Dollard estuary.

<table>
<tr><td colspan="4">Table 5.1 LIST OF PHYSICO-CHEMICAL PROPERTIES
(As discussed in the EC MAST report on cohesive sediment properties)</td></tr>
<tr><td colspan="2"><u>1. Physico-chemical properties of the over flowing fluid</u>
Chlorinity
Oxygen content
pH
Sodium Adsorption Ratio (SAR)
Temperature
Redox Potential
Na-, K-, Mg-, Ca-, Fe-, Al-ions</td><td colspan="2"><u>3. Water-bed exchange processes</u>
Critical shear stress for deposition
Critical shear stress for erosion as a function of the sediment concentration (C)
Erosion rate as a function of sediment concentration
Equilibrium slope of immersed and emerged deposits as a function of C
Settling velocity distribution as a function of salinity (S)
Permeability as a function of C
Liquid limit</td></tr>
<tr><td colspan="4"><u>2. Physico-chemical properties of the mud</u></td></tr>
<tr><td>Sand content
Chlorinity
Oxygen content
pH</td><td>Temperature
Redox Potential
Na-, K-, Mg-, Ca-, Fe-, Al-ions</td><td>Grain size of deflocculated sediment
Specific surface area (SSA)</td><td>Cation Exchange Capacity (CEC)
Organic content
Bulk density</td></tr>
<tr><td colspan="4">Mineralogical composition, for instance:
smectite, chlorite, illite, koalinite, montmorillonite, quartz, feldspar, calcite, dolomite</td></tr>
</table>

5.1 Sand/mud distribution

The distribution of sand and mud is shown in Figure 5.1. In the upper reaches most flats contain large amounts of mud, except for the northern part of the Heringsplaat

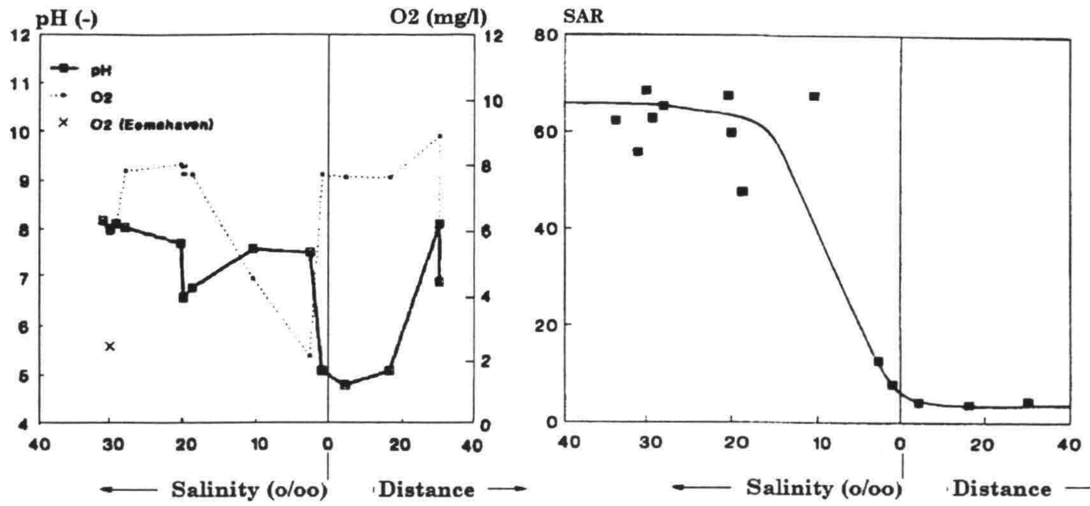


Figure 5.2 Longitudinal distribution of the pH, O_2, and SAR in the Ems/Dollard estuary during June 1991 (Source: Van Leussen, 1994)

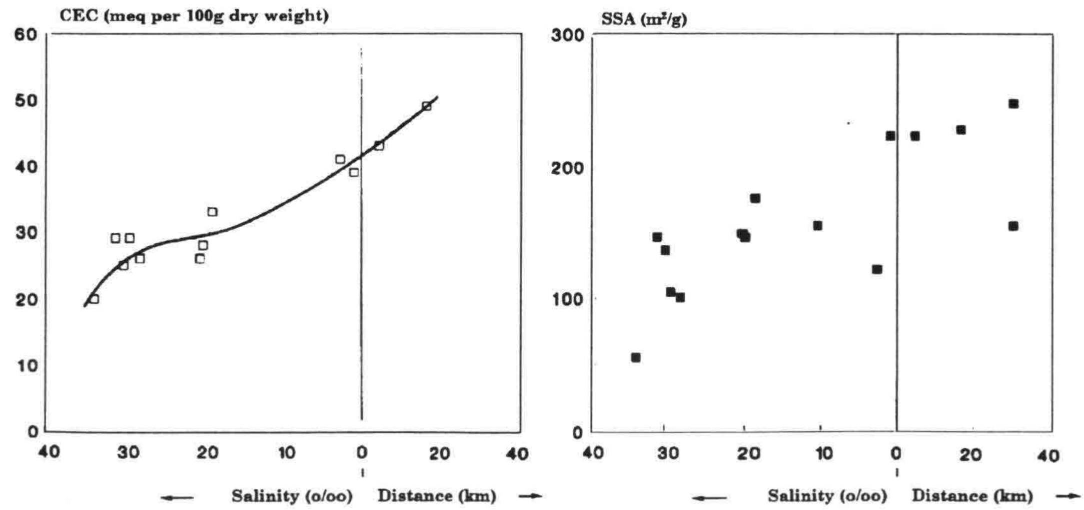


Figure 5.3 Longitudinal distribution of the CEC and SSA in the Ems/Dollard estuary during June 1991 (Source: Van Leussen, 1994)

and the Maanplaat. In the middle reaches the flats are partly covered with a mixture of sand and mud, and in the seaward reaches only small amounts of mud are found. Tidal channels with a muddy sediment bed are the Emder Fahrwasser, Groote Gat and the Bocht van Wattum (GWWS, 1991). On the flat Rysumer Nacken and in the tidal channel Bocht van Wattum the percentage mud is probably increased by the dumping of dredging material from the Emder Fahrwasser.

The sand/mud distribution is continuously changing during the year as a result of amongst others storm events, variable organic activity or dredging activities. The overall transport behaviour of the mud and thereby its distribution in the Ems/Dollard over the different seasons is not completely understood. Generally speaking, more mud is found on the tidal flats in summer than in winter. It is not known if the mud is actually leaving the estuary in winter.

5.2 Physico-chemical properties

Some of the physico-chemical properties of suspended sediment have been measured at various locations along the estuarine axis of the Ems/Dollard estuary. It has been shown that some of these properties, such as the organic content, pH, Redox Potential and the Oxygen content, are related to biological processes, which are typically season dependent (Van Leussen 1994, Eisma 1986). For a comprehensive description of the physical/chemical and biological processes related to these properties the reader is referred to Dronkers (1988).

The salinity distribution was discussed in Chapter 3, where it was stated that the salinity is a good indicator for the location of the typical estuarine processes related to mixing of salt/fresh water, and therefore salinity has been chosen here as the independent variable along the estuarine axis in the salt water part of the estuary, instead of the topographical distance. The location of zero salinity has been chosen off about Leer.

The oxygen and the pH distribution of the overflowing fluid measured in June 1991 is shown in Figure 5.2. The pH may be expected to have an important effect on the chemical reactions and equilibria. The minimum pH of about 5, just after the point of maximum salt intrusion, seems extremely low, and could not be explained. The oxygen content decreases with decreasing salinity, which is often observed in estuaries and is attributed to biological activity (Van Leussen, 1994).

The Sodium Adsorption Ratio (SAR) is proportional to the ratio of the exchangeable cations of low valency and high valancy, when equilibrium is assumed.

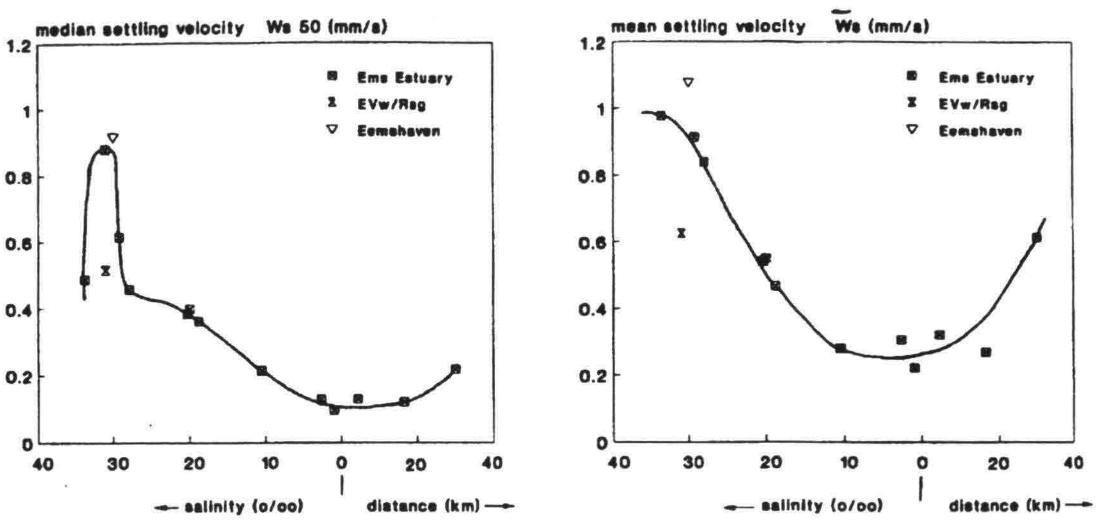


Figure 5.4 Longitudinal distribution of the median settling velocity and the mean settling velocities in the Ems Estuary. Values obtained from laboratory settling experiments for $C_0 = 1$ kg/m^3. (Source: Van Leussen, 1994)

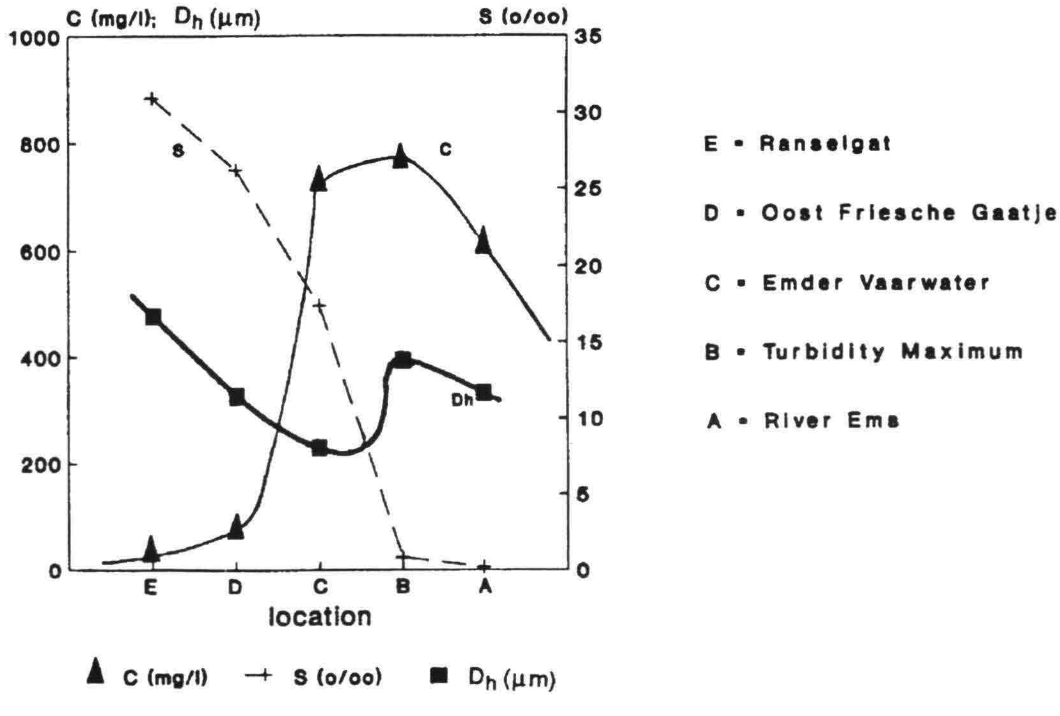


Figure 5.5 Sizes of macro flocs, measured at 2.8 m below the surface by means of an under water camera at normal current strength. The fine-grained sediment concentration (C) and the Salinity (S) were measured at the same level.

A high content of high valancy cations, a low SAR, reduces the width of the diffusive double layer surrounding the clay particles and thereby reduces the repulsive forces between them. The SAR distribution is also given in Figure 5.2, it confirms the general findings of high SAR values in the salinity region and low SAR values in the fresh water part of the estuary.

The cation exchange capacity (CEC (meq/100 g)) is a measure for the maximum number of cations that can be attracted, in general it corresponds to the shear strength of a sediment. Its distribution is given in Figure 5.3, it shows that there is an increasing trend in the landward direction. It could be possible that an increasing amount of clay is incorporated in the suspended sediment.

The specific surface area (SSA) is closely related to the CEC value and a clear indication for the particle surface available for adsorptive processes (Fig. 5.3). The increase in the SSA is in agreement with the increase in the CEC value.

The mineralogical composition of sediment samples taken at various positions in the Ems/Dollard is presented in Table 5.2. The compositions of the samples from Delfzijl harbour and from Eems harbour hold for the complete sediment sample whilst the remaining ones are composition analyses of the sediment fraction smaller than 0.5 μm.

Table 5.2 Composition of clay minerals and quartz
(percentage by weight)

	illite	kaolinite	montmor.	quartz	organic
Ems Estuary(< 0.5 μm)					
West Dollard	80	5-10	5-10	ca. 5	
Ems-mouth	80	5-10	5-10	ca. 5	
Ems low tide banks	80-90	ca. 5	ca. 5	ca. 5	
Fluviatile, Ems[1] (< 0.5 μm)	90-100	-	< 3	< 1	
Marine, Rottumeroog[1] (< 0.5 μm)	80	5-10	5-10	ca. 5	
Delfzijl[2] (complete sample)	10	<2	-	55	2
Eems Harbour[2] (complete sample)	20	<10	-	35	9

[1]Favejee, 1960
[2]Delft Hydraulics- RWS, 1990

The first samples from the upper reaches show that illite is the largest fraction of the clay minerals. In the fluviatile suspended sediment from the River Ems kaolinite is

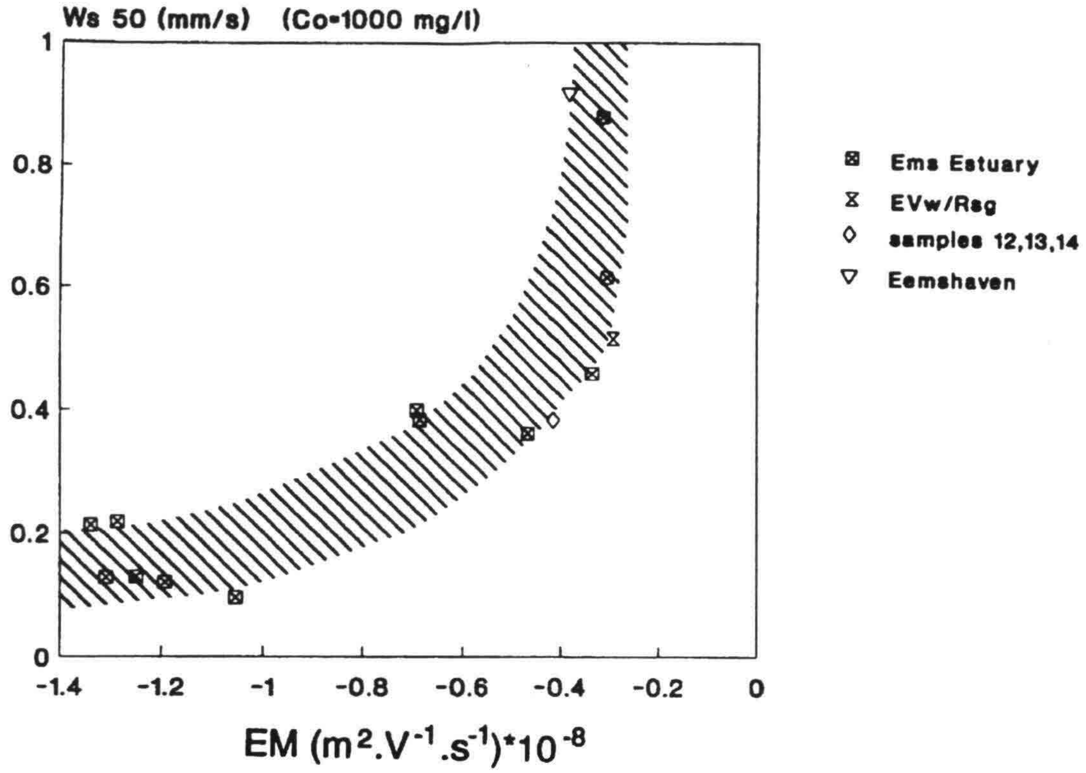


Figure 5.6 Corrolation between the Electrophoric Mobility and the mean settling velocity (w_S)

absent, this has implications for the origin of the Ems/Dollard mud (see section 6.4). The samples from Delfzijl and Eems Harbour show that no montmorillonite was found, for which no explanation is available. The relatively large fraction of illite in relation to the much smaller fraction of kaolinite is in agreement with the first five samples. The organic content is small compared to the organic content found in Emden harbour (Hafenambt Emden, 1960), but probably shows a strong seasonal variation.

5.3 Settling velocities

The distribution of the settling velocities is related to the sediment concentration, the turbulence structure of the flow, and the physico-chemical surface properties of the sediment, which are in turn influenced by salinity, dissolved organic substances and the origin of the water/sediment sample (Van Leussen, 1994).

The distributions of the median and mean settling velocities obtained from settling experiments are given in Figure 5.4. It is clear from this figure that the settling velocity increases in the seaward direction. The high value for the median settling velocities for a salinity of 30 ‰ seems to indicate that a relatively large part of the cohesive sediment is flocculated in this region. It is hypothysed that in the high salinity part of the estuary the sediment sub-fraction smaller than 25 μm could be flocculated forming micro flocs, these micro flocs linked together by for example polysaccharides form the macro flocs with large settling velocities (Van Leussen, 1994).

The general increase in mean settling velocity is in agreement with the increase in the macro floc size measured with an underwater video system 'VIS' (Figure 5.5) and with results reported by Eisma et al (1991). The drop in floc size in the low saline part of the estuary maximum can be explained by the solution muco polysaccharides at low salinity (Eisma, 1986),

The repulsive force between small particles/micro flocs is determined by the surface charge which is reflected by the Electrophoretic Mobility (EM). The EM seems to be a good indicator of the flocculation ability, it is determined by the coatings of the particles of organic material, and the availability of cations (divalent cations are favourable). The longitudinal distribution of EM corresponds well with results from other estuaries such as the Gironde and the Loire estuaries (Van Leussen, 1994). The relation between settling velocity and EM seems very good despite the varying hydrodynamic conditions and the availability of biological activity along the estuarine axis (see Figure 5.6).

Chapter 6 Sediment transport

The tide induced sediment transport in the Ems/Dollard is determined by the hydrodynamic conditions, comprising tidal asymmetry, current strength and wave climate, and the amount of sediment available for transport. Availability of sediment is determined amongst others by biological activity and the consolidation process of deposited sediment. The impact of the dredging activities on the total sediment transport is substantial as will be shown. In order to obtain more insight in the net transport direction of the sediment in the Ems/Dollard estuary, some results of the Mc Laren method and the source(s) of the Ems/Dollard sediments are discussed.

6.1 Siltation rates, dredging and dumping

The turbidity maximum is situated in the Emder Fahrwasser and is therefore the area of largest siltation rates. The major part of the sediment that is entering the Emder Fahrwasser, about 7000 ton dry material per tide, is deposited and has to be removed by dredging (Hafenambt Emden, 1995). The main part of the dredged material has been dumped in the polder of Larrelt-Wybelsum before 1950. After that, the Rysumer Nacken has been used as the main deposition area. From 1950 until 1965 the amount of dredged material was approximately 1.6×10^6 m^3. From 1965, when the Emder Fahrwasser was deepened by 1 m on average, the amount of dredged material became 5×10^6 m^3. An overview of the annual amount of dredged material form the Emder Fahrwasser is given in Figure 6.1 (GRAN, 1990).

From Emden harbour about 4×10^6 m^3 material with unknown density was dredged and pumped into upland disposal areas located in the lands of Emden-Riepe from 1954 until 1990. These large quantities were unacceptable for both economical as well as environmental reasons. The solution for this problem was to allow for a thick layer of fluid mud, with a density of about 1150 kg/m^3, in the outer harbour, thereby creating a natural barrier against new sedimentation, the quantities pumped ashore reduced to about 1.4×10^6 m^3 (Hafenambt Emden, 1995)

Other locations of dredging activities are Gaatje Bocht, the region between the Alte Ems and Doeke Gat, Delfzijl harbour and Eems harbour. The material is dumped in the Mond van de Dollard, the tidal channel Bocht van Wattum, the channel south of the Alte Reede and other locations. The amount of dredged material from Delfzijl harbour and dumped in the Mond van the Dollard between 1970 and 1987 is shown in Figure 6.2.

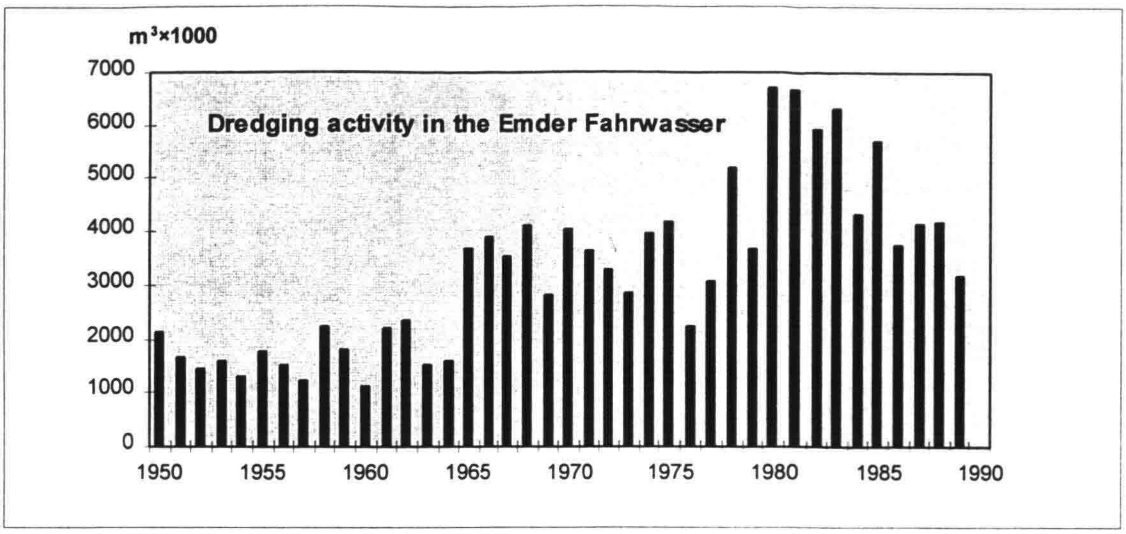


Figure 6.1 Amount of dredged material from the Emder Fahrwasser

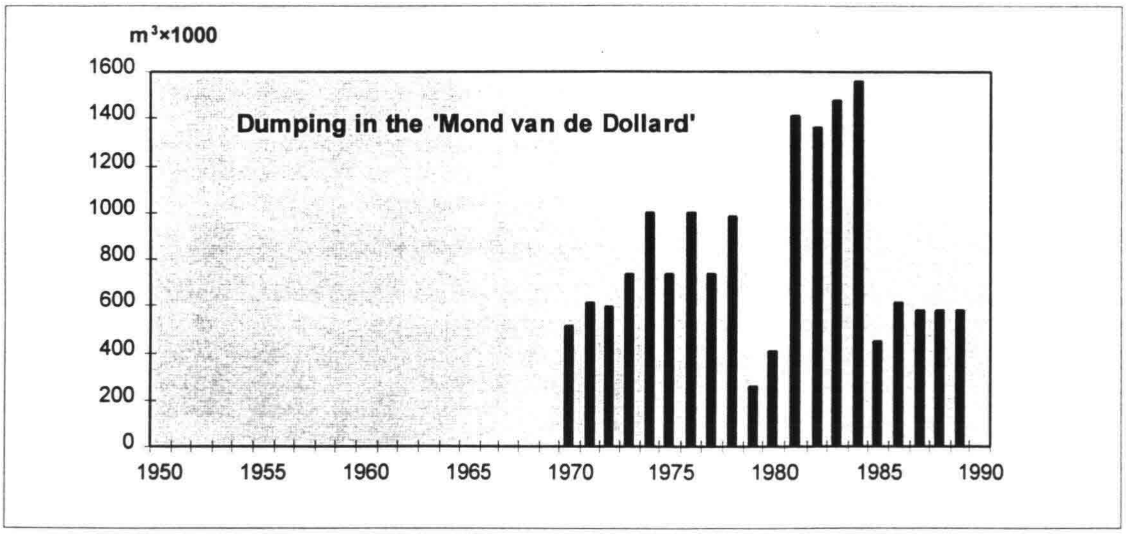


Figure 6.2 Amount of dredged material from Delfzijl harbour and dumped in the Mond van de Dollard

6.2 Suspended sediment concentration

The suspended sediment concentration increases towards the turbidity maximum near Pogum and then decreases further upstream, which is illustrated in Figure 6.3 showing the results of a floating experiment in June 1990 (Van Leussen, 1994). During HWS and LWS the suspended sediment concentrations are minimal, during flood the suspended sediment concentrations are on average somewhat higher compared to those during ebb. This difference is most pronounced for the River Ems.

The sharp density interface observed in the turbidity maximum points to the presence of a layer of fluid mud. The sediment fluxes are therefore relatively high in this region, tens of tons of dry material per metre channel width in both directions.

The resulting suspended sediment transport is mainly governed by the hysteresis between the suspended sediment concentration and the current velocities. The resulting transport as found by Van Leussen was in the landward direction for Ransel Gat and Oost Friesche Gaatje. In the turbidity maximum the transports were sometimes in the landward and sometimes in the seaward direction. These findings are in agreement with modelling results (BOA Progress Report, 1995) showing a maximum landward transport when the phase angle of the M2 and M4 of the current velocities is 90° (no tidal asymmetry), which can be assumed to be the case for the lower and middle part of the estuary, and the Dollard except for the Emder Fahrwasser and the river Ems.

6.3 Mc Laren Method

The Mc laren method is based on the sediment trend analyses of particle sizes. It is assumed that the strongest correlation between the sediment size histograms coincides with a transport path. The sediment transport directions are found from the skewness of the histograms.

The transport paths for sand are shown in Appendix C, all are net accretion which means that the estuary is filling up with sand (GWWS, 1991). The ebb dominated transport regime is located in the river Ems (fresh water flux), the tidal channels Oost Friesche Gaatje and the Alte Ems. The flood dominated regimes are located in the tidal channel Ranzel Gat and on the south side of the Alte Ems, and on the south side of the Oost Friesche Gaatje. The present-day navigation channel is not always following the ebb dominated transport regions, therefore higher average dredging are to be expected in the region between the Alte Ems and the Doeke Gat and in the narrows between the training wall and Oost Friesche Gaatje. This expectation is in accordance with the experience in practice.

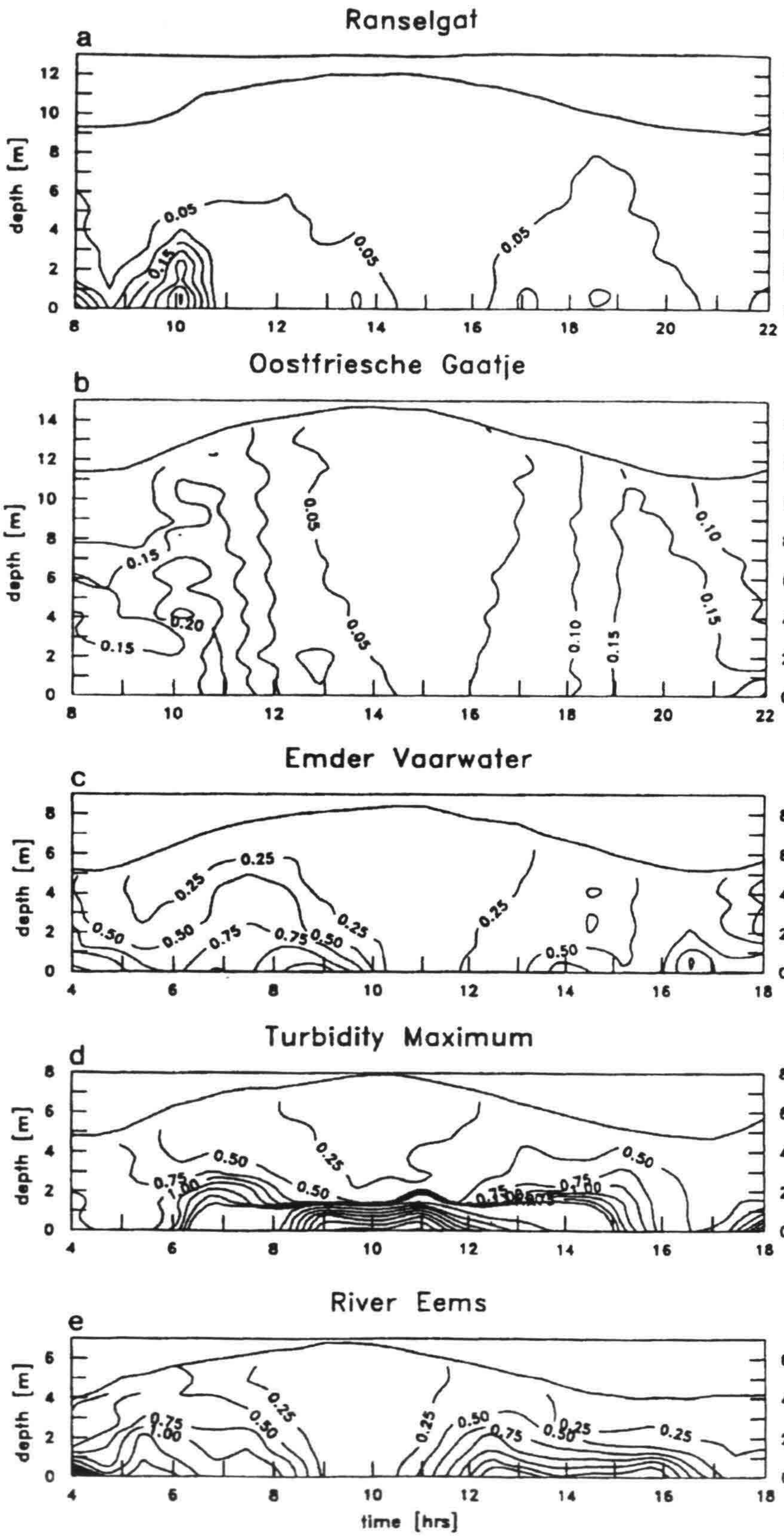


Figure 6.3 Distribution of suspended sediment (kg/m^3) for five locations in the Ems/Dollard estuary during a full tidal cycle (floating measurements). (Source: Van Leussen, 1994.)

For cohesive fine sediments the flocculation process is very important for particle sizes, in chapter 4 it was mentioned that the fine sediments (< 25 μm) stick together to form micro flocs with a constant composition (see also section 6.4). It is not likely that, when the major part of the cohesive sediment is flocculated, the size histograms of the sediment give information on the transport direction or net accretion. The Mc laren method is therefore more appropriate for determining transport of sediments of a granular nature.

6.4 Sediment Sources

Granulometric measurements have shown that marine sediments, contrary to river sediments, have constant ratios of the of the precentages of sub-fractions in the range up to 25 μm. An explanation for this phenomenon is that in the high salinity region the fine sediment particles are always knitted together forming micro flocs, and these micro flocs remain intact during sedimentation. Favejee (1960) showed that the granular composition of mud from the Dollard, the mouth and low-tide banks of the Ems are comparable with the marine sediments, and furthermore contain 5 to 10 % kaolinite, which is fully absent in the Ems mud. This points to a marine origin of the major part of the mud.

The large amount of 'marine' mud (> 70%) on the low tide banks could originate from fossil marine sediment layers eroded by the Ems (Favejee, 1960). The conclusion is therefore that the mud in the Ems/Dollard estuary originates either from recent marine deposits or eroded fossil marine sediment layers. It is therefore difficult to tell from the sediment orgin wether at present a net accretion of mud occurs, or not.

Literature

Abrahamse, J. et. al. (red.), **1976**, *'Wadden Sea'*, Landelijke Vereniging tot Behoud van de Waddenzee, Harlingen, The Netherlands (in Dutch)

Akkerman, et.al., **1987**, *'Joint German-Dutch research on sediment and salinity distribution in the Beneden Eems and the Dollard'*, Research Report GWWS 87.001, Tidal Waters Division, Dutch Department of Public Works, Groningen, The Netherlands (in Dutch)

Boede-group, **1983**, *'Biological Research Eems - Dollard Estuary', An overview of eco-sytems research between 1973 and 1982'*, BOEDE publ. 1983 no. 1, NIOZ, Texel, The Netherlands (in Dutch)

Bossinade, J.H., Bergs, van den, J., Dijkema, K.S., **1993**, *'De influence of wind on the annual flood along the Friese and Groninger Wadden coast'*, Research Report GRAN 1993 - 2009/IBN-rapport 049, Directie Groningen, Dutch Department of Public Works/ Institute for Forest and Nature Research Texel, The Netherlands (in Dutch)

Dronkers, J., **1986**, *Tidal assymetry amd estuarine morphology*, Neth.J. Sea Res. 20: 117-131

Dronkers, J. Van Leussen, W., **1988**, *'Physical Processes in Estuaries, Papers presented at an international symposium on physical processes in estuaries, held Sept. 9-12, 1986'*, ISBN 0-387-129266-(U.S.), Springer-Verlag, Heidelberg, Germany

Eisma, D., **1986**, *'Flocculation and de-flocculation of suspended matter in estuaries'*. Neth.J.Sea Res.20, 183-199

Eisma, D., et.al., **1991**, *Suspended-matter particle size in some West-European estuaries; Part I: Particle size distribution,* Neth. J. Sea Res. 28(3), 193-214

Favejee, J.CH.L., **1960**, *'On the origin of the mud deposits in the Ems-estuary'*, Verh. Kon. Geol. Mijnb.k. Gen. /Geol. Serie, Dl. XIX/Symposium Ems-Estuarium (Nordsee), p.147-151, 's-Gravenhage, The Netherlands

Fisher, H.B., **1976**, *'Mixing and dispersion in estuaries, Annual review of Fluid Mechanics'*, 8, p.107

Heijns, H., Berger, G.W., Eisma, D., **1987**, *Accumulation rates of estuarine sediment in the Dollard area: comparison of* ^{210}Pb *and pollen influx methods*, The Dutch Journal of Sea Research 21(4), p295-301, The Netherlands

Heuvel, van, TJ.,**1992**, *'Sediment transport in the Eems-Dollard estuary, according the Mc Laren method'*, Research Report DGW-92.027, Tidal Waters Division, Dutch Department of Public Works, 's-Gravenhage, The Netherlands (in Dutch)

Jonge, de, V., **1992**, *'The Ems Estuary'*, RWS-Report WH91.034, Tidal Waters Division, Dutch Department of Public Works, Haren, The Netherlands

Leussen, W.,**1994**, *'Estuarine macro flocs and their role in fine-grained sediment transport'*, Thesis Utrecht University, Department of Earth Science, ISBN 90-393-0410-6, Utrecht, The Netherlands

Robaczewska, K.B., **1992**, et.al., *' "EEMS" a water course and quality model of the Ems-Dollard estuary'*, Research Report DGW-92010, Tidal Waters Division, Dutch Department of Public Works, 's-Gravenhage, The Netherlands (in Dutch)

Wiggers, A.J., **1960**,*'The granular composition of Holocene Sediments in the Dollart-Ems estuary, in the Ems-Estuary (North Sea)'*,Verh.Kon.Ned.Geol.-Mijnb.k.Gen.,19, The Netherlands (In German)

Wiggers, **1974**, *'Sedimentation in the Dollard, in Dollard a portrait of a landscape'*, p. 16-18, Landelijke Vereniging tot Behoud van de Waddenzee, Letsch Groningen, The Netherlands (In Dutch)

Various authors, **1972**, *'Klimaatatlas van Nederland'* , The Netherlands

Various authors, **1988**, *'The development of the Dollard in the period 1969/70 -1985'*, Notanummer 1988-2001, Dutch Department of Public Works - Directie Groningen, Groningen, The Netherlands (in Dutch)

Various authors, **1990**, *'Report Hydrologic research Beneden Eems and Dollard 1952 - 1985, Part 3'*, Research Report GRAN 1990-2003, German-Dutch Eems committee, Wasser- und Shiffahrtsamt Emden/ - Directie Groningen, Groningen, The Netherlands(in Dutch)

Various authors, **1991**, 'Sediment transport in the Ems Dollard estuary, according to the Mc Laren method', Research report GWWS-91.002, Dutch Department of Public Works, Tidal water Division, The Netherlands (in Dutch)

Appendix A A summary of the physical properties of the Ems/Dollard estuary

Climate

- The water temperature is between 10 and 15 degrees Celsius (in summer the temperature gradient is positive in landward direction and in winter it is negative)
- The annular precipitation is 75 cm
- Winds from the west dominate, and are about 7(m/s) near the barrier islands and 4(m/s) in the Dollard reach on annual basis

	upper part (Dollard reach)	middle part	lower part
Topography			
Intertidal areas	85%	35%	45%
Total area (km^2)	100	160	220
Mean water volume (m^3)	$120\ 10^6$	$550\ 10^6$	$770\ 10^6$
Tide			
Prism (m^3)	$115\ 10^6$ (Dollard) / $75\ 10^6$ (Emd. F.W)		$1000\ 10^6$
Excursion (km)	12	-	17
Range (annual)(m)	3.3	2.8	2.3
Peak velocities (spring tide) (m/s)	1	1.3	1.5
diurnal inequality	can reach about 0.3 m		
Sediment size distribution			
sand (d > 55 μm)	50% (kg/kg)	67%	87%
silt (3 < d < 55 μm)	30%	28%	12%
clay[2] (d< 3 μm)	20%[1]	5%	1%

Fresh water discharge (m^3/s)	Summer	Winter
Ems	50	200
Westerwoldsche Aa	5	15

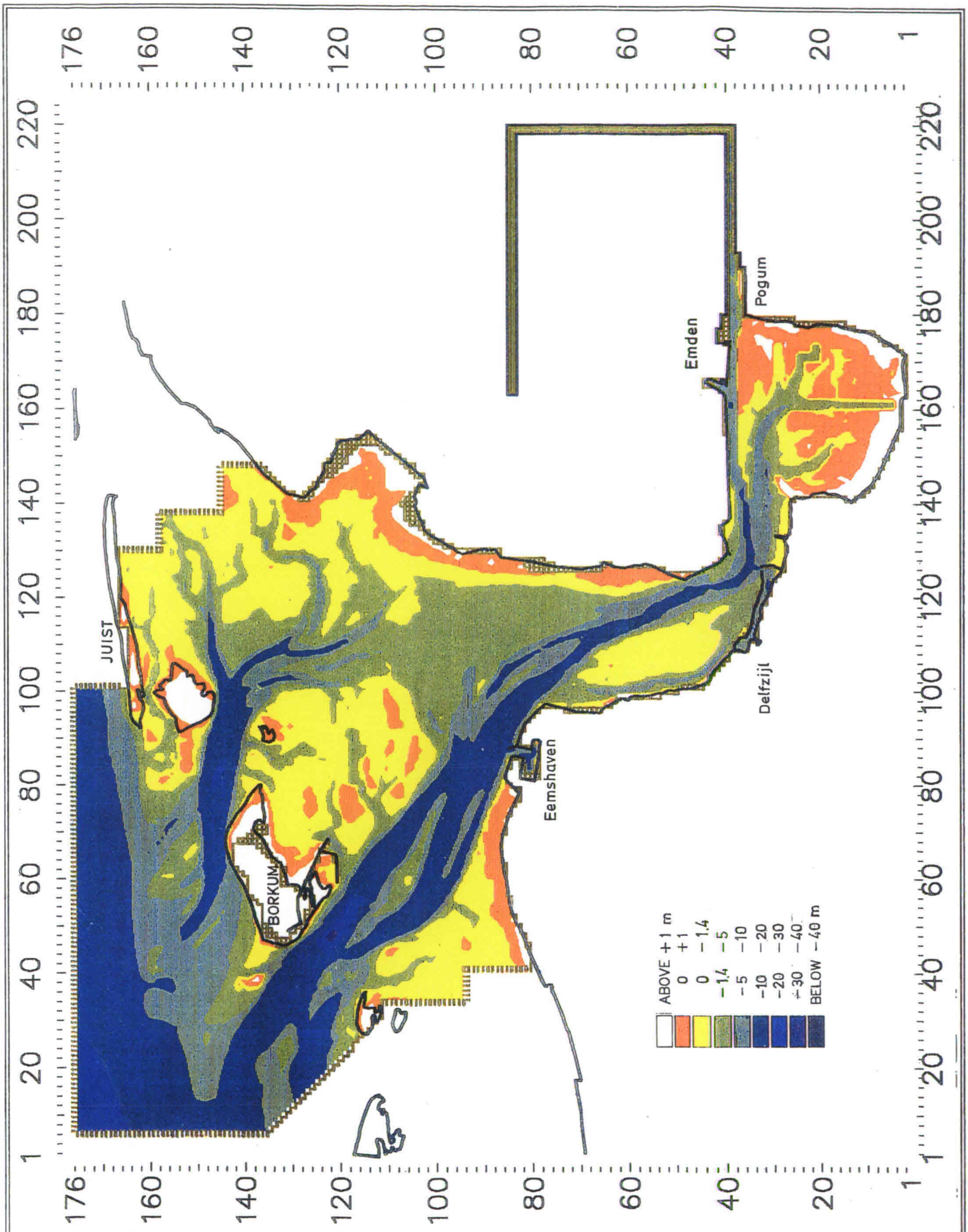
Mixing characteristics for dissolved matter (days)	High Discharge	Low discharge
Sea water mean age	14	36
Flushing time Ems water	12	72
Dillution dissolved matter e^{-1} times	18	36

[1] Clay content in the Dollard reach differs from 5% in the centre to 50% and higher near shore
[2] The organic content is about 7% of the clay content

Source: De Jonge, 1992

Appendix B Topography and Mud distibution (GIS data)

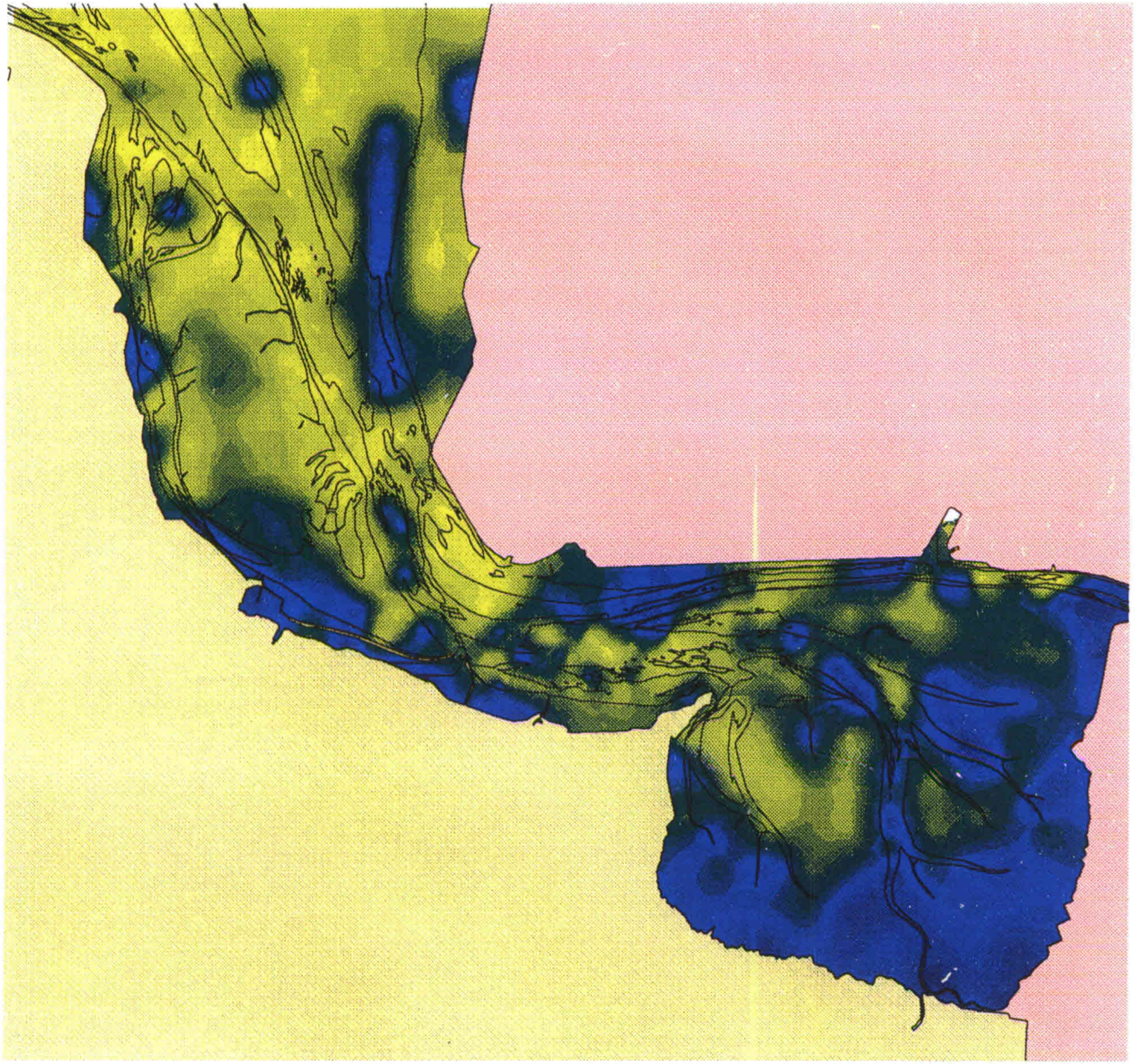
(The Dutch word 'slib' means mud)



Bodemschematisatie van het EEMS-model	bijlage: 3
	Rapport.DGW-92.010
DIENST GETIJDEWATEREN	

Isokleurenkaart afgeleide waarden.

Eems-Dollard met slibpercentages.



Legenda kleurenkaart.

Fraktie: Slib

Gewichtsperc. van de fraktie.

- *0 - 1 %*
- *1 - 2 %*
- *2 - 5 %*
- *5 - 10 %*
- *10 - 15 %*
- *15 - 20 %*
- *20 - 25 %*
- *25 - 30 %*
- *30 - 35 %*
- *35 - 40 %*
- *40 - 45 %*
- *45 - 50 %*
- *50 - 55 %*
- *55 - 60 %*
- *60 - 65 %*
- *65 - 70 %*
- *70 - 75 %*
- *75 - 80 %*
- *80 - 85 %*
- *85 - 90 %*
- *90 - 95 %*
- *95 - 100 %*

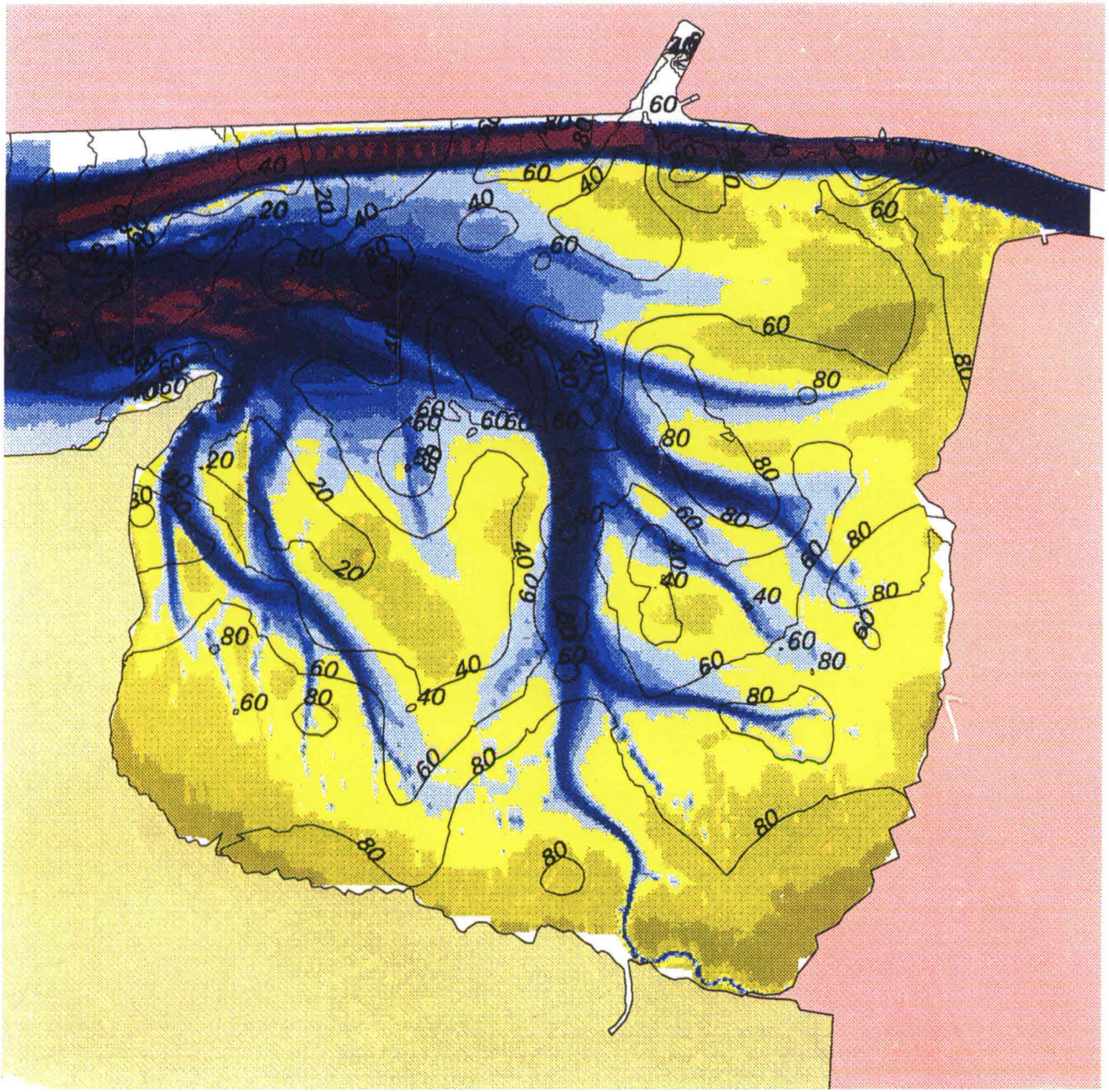
Gegevens dieptelijnen

Lijnen om de 5 meter

Rijkswaterstaat
Rijksinstituut voor Kust en Zee

Isolijnen afgeleide waarden.

Dollard met slibpercentages.



Legenda kleurenkaart.

Dieptegegevens

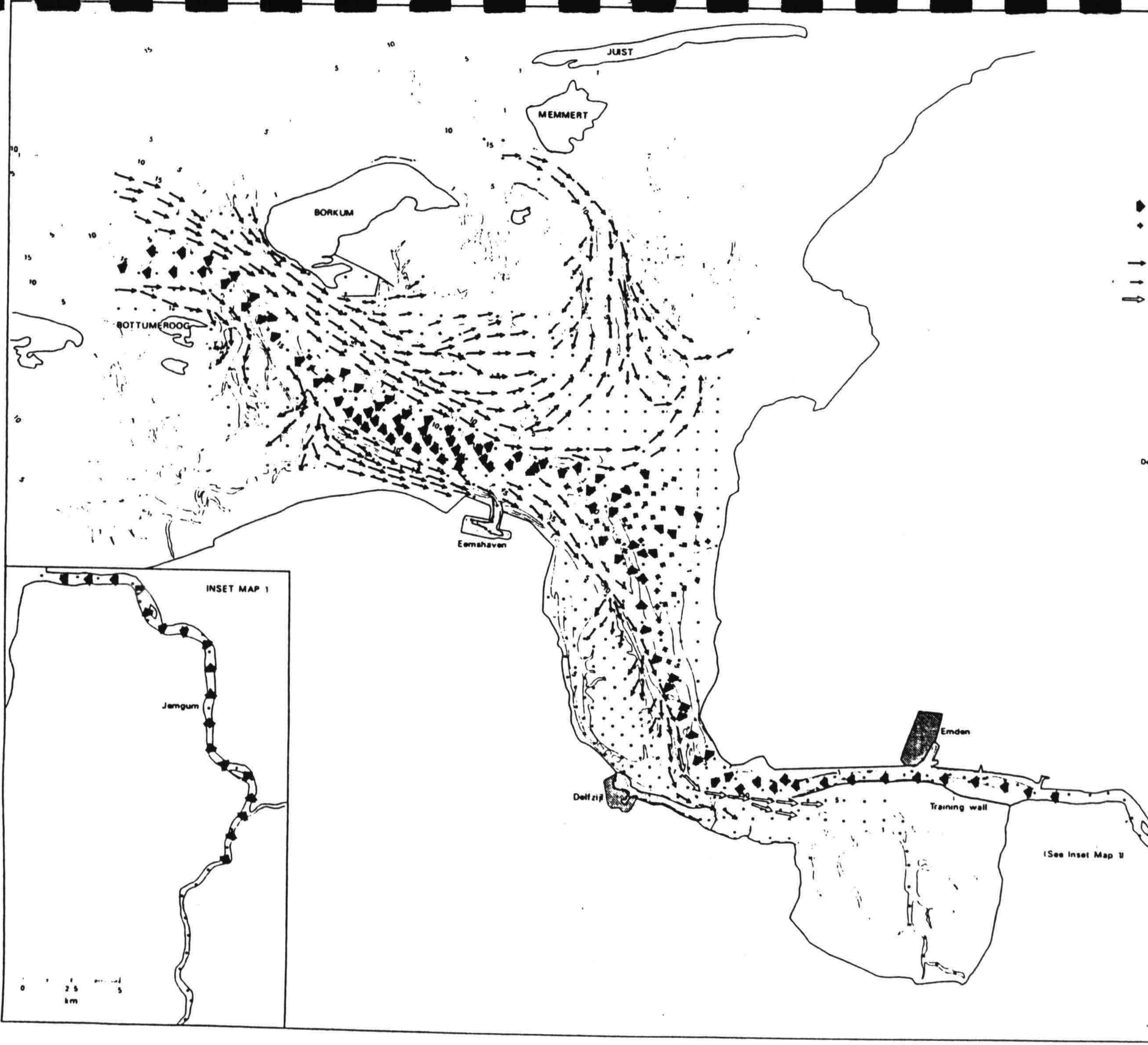
20 - 25 dm boven NAP	
15 - 20 dm ,,	,,
10 - 15 dm ,,	,,
5 - 10 dm ,,	,,
0 - 5 dm boven NAP	
0 - 5 dm onder NAP	
5 - 10 dm ,,	,,
10 - 15 dm ,,	,,
15 - 20 dm ,,	,,
20 - 30 dm ,,	,,
30 - 40 dm ,,	,,
40 - 50 dm ,,	,,
50 - 75 dm ,,	,,
75 - 100 dm ,,	,,
100 - 150 dm ,,	,,
150 - 200 dm ,,	,,
200 - 300 dm onder NAP	

Gegevens isolijnen.

Gewichtsperc. van de fraktie.
Fraktie: Slib
Eenheid: percentages

Rijkswaterstaat
Rijksinstituut voor Kust en Zee

Appendix C Sediment transport directions of sand according the Mc Laren method (GWWS, 1991)



SEDIMENT TRANSPORT
IN THE EEMS/DOLLARD ESTUARY

for: Rijkswaterstaat, Tidal Waters Division
Den Haag, The Netherlands.

by: GeoSea Consulting (U.K.) Ltd.
Cambridge.

Figure 4:
NET SEDIMENT TRANSPORT
PATHWAYS FOR SAND