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Massive Sedimentation Events at the Mouth of the Rotterdam Waterway

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ABSTRACT

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Under storm conditions, often more than 0.5 million tons of mud and fine sand are deposited in less than one week in the in-land part (Maasmond) of the access channels to the Europoort harbors at the mouth of the Rotterdam Waterway. The majority of this material comes from the sea. Transport of this material has previously escaped detection, and a satisfactory physical description of these massive-sedimentation events is lacking. A mechanism is proposed that can explain these sedimentation events. In the coastal zone, combined wave-current flows winnow muds and fine sands from the bottom, generate sediment-induced stratification in a layer a few decimeters thick, and transport these wave-induced near-bottom high-concentration suspension layers (WI-HCSLs) with the near-bottom water currents. In a large area residual flows in the lower portion of the water column are directed to the Maasmond, because of water-density differences from the relatively large Rhine fresh-water outflow. In a few days, sediments from a vast area are thus transported near the bottom to the Maasmond. Once in the Maasmond, they settle due to a considerable reduction of wave action and tidal current velocities there. Due to the high deposition rates, fluid-mud layers are formed that spread and consolidate slowly. A simple data-driven particle-deposition model simulates the transport and deposition of suspended sediment that enters the sedimentation area. The description of the sedimentation in the Maasmond with WI-HCSLs and with the particle-deposition model, is supported by a wide range of observations in this case study, such as sediment composition, and the positive correlation of sedimentation amounts with wave energy and fresh-water outflow. Further support is given by numerical examples based on transport processes and field data.

ADDITIONAL INDEX WORDS: *Harbor, waves, Rhine, high concentration suspension, fluid-mud.*

INTRODUCTION

Access channels to estuarine and open-sea harbors are often subject to considerable sedimentation, especially of silt and fine sand, resulting in costly maintenance dredging. Many sea harbors are located along the estuarine sections of large rivers where usually a turbidity maximum is observed near the most landward extent of salt penetration. Harbor sedimentation is largely governed by the position of the turbidity maximum and thus by the river run-off, *e.g.* near the harbor of Antwerp on the Scheldt (FETTWEIS, 1995), Hamburg on the Elbe (CHRISTIANSEN and KIRBY, 1991), and London on the Thames (INGLIS and ALLEN, 1957). Siltation in harbors with little or no estuarine effects is far less understood and appears to be largely controlled by weather conditions, *i.e.* by wave activity, such as occurs at Oostend and Zeebrugge in Belgium (WENS *et al.,* 1990). Sedimentation in the navigation channels to the port of Esbjerg (SW Denmark) was found to be governed by wave rather than tidal conditions (CLAUSEN *et al.,* 1981). Similarly, MADRELL and PEARSON (1991) observed that sedimentation in the approach channel to the Tees (E England) largely occurs under storm conditions, and PARKER (1994) noted that under high waves large sediment influxes may occur into otherwise low-turbidity areas.

Weather-controlled sedimentation is observed in the inland part (Maasmond) of the access channel to the Europoort harbor area at Hook of Holland (Figures 1 and 2). During storms, massive amounts of sedimentation (0.5×10^9 kg mud and fine sand) can occur here during periods of less than one week. Transport of these sediments has not been detected directly until now, largely because vessels cannot operate at the times they occur, and these events have not been explained adequately. During three hours around the end of the ebb, with near-bottom currents still being directed inland during that experiment, KIRBY and PARKER (1977) measured a landward-moving mobile fluid-mud layer in the Maasmond,

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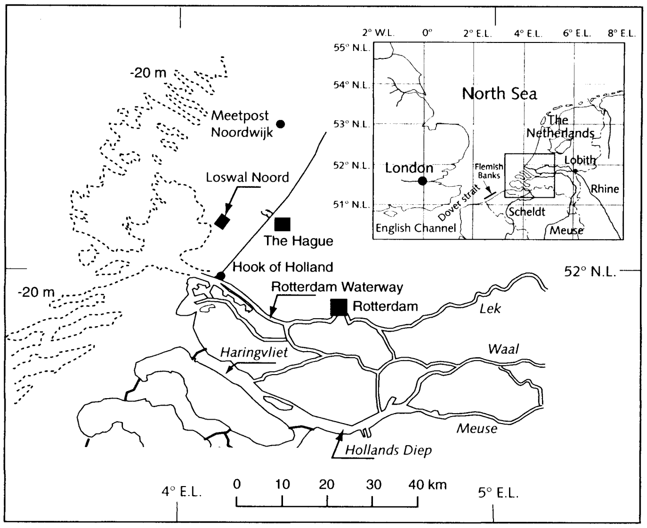

Figure 1. The Dutch Coastal zone and the fresh-water outlets. The annual mean discharge of the Rhine (2200 $m^3 s^{-1}$) is about 9 times higher than that of the Meuse (250 $m^3 s^{-1}$). Rhine water is divided over the Waal and Lek. The Rivers Waal, Lek, and Meuse discharge water to the North Sea through the Rotterdam Waterway and the sluices in the Haringvliet dam.

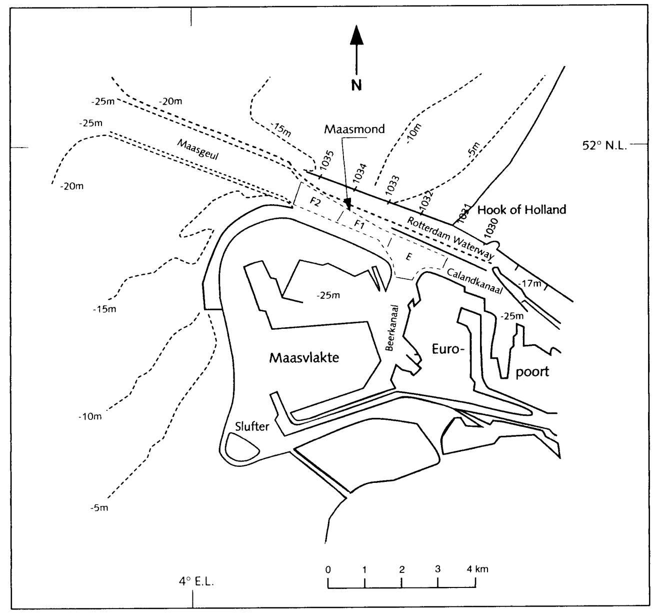

Figure 2. Mouth of the Rotterdam Waterway and the adjacent Europoort harbors. More than 80% of the annual sedimentation in the Europoort area occurs in compartments E, F_1, and F_2. Each year, 3.5×10^9 kg of mud and 1.5×10^9 kg of fine sand have to be dredged to maintain the navigation depth of these three compartments.

and discussed that the presence of such layers is related to periods of high wave activity in the Dutch coastal zone. On four separate days, VAN SCHEINDELEN (1985) measured, using an immersed instrumented float (dimensions about 0.2 m, with a density of 1,100 kg m^{-3} adjusted to that of the fluid-mud layer), landward movement during the flood flow with mean velocities up to 0.13 m s^{-1}. VAN LEUSSEN and VAN VELZEN (1989) argued that the sudden massive-sedimentation events involve the development of fluid-mud layers in the Maasmond area. In the Dutch coastal zone, fluid-mud layers have not been observed. Suspended-matter concentrations in and around the Maasgeul (the deepened navigation channel in the sea bottom, Figure 2) are generally low and vary from a few tens of mg l^{-1} in most of the water column to a few hundreds of mg l^{-1} near the sea bed, as measured for instance by VLEMMIX (1978).

The massive-sedimentation events in the Maasmond are responsible for significant dredging costs and need to be better understood before preventive counter measures are considered. We have made an inventory and analysis of available data and have collected additional data, from which a consistent description has emerged (VERLAAN and SPANHOFF, 1994). Most of the available data had been gathered by Rijkswaterstaat of the Dutch Ministry of Transport, Public Works and Water Management, partly on a routine basis, and partly in dedicated projects such as studies (*e.g.* SPANHOFF *et al.*, 1990a) into the possible return flow to the Maasmond of dredged material disposed at the Loswal Noord dumpsite (Figure 1). This paper presents the results of our study (VERLAAN and SPANHOFF, 1994), which has not previously been published in the literature.

In the following paragraphs, the study area is introduced, the sedimentation in the Maasmond is quantified from echo-sounding and density data, and the density structure of the deposited material is described. Next, the origin of the deposited material is discussed, and it is shown that the deposition rate correlates with wave conditions and to a lesser extent with river discharge. Then our sedimentation mechanism is presented that describes the massive-sedimentation events, while a simple data-driven model accounts for the sediment transport and settling in the Maasmond. In the discussion, observations and model results are integrated, and further arguments are given in support of the proposed sedimentation description.

AREA DESCRIPTION

The study area (Figure 2) is almost completely man made. The Rotterdam Waterway was constructed in the previous century to give the harbors in the city of Rotterdam a better connection with the North Sea. To accomodate the ever-growing vessels, in the 1960s the Maasvlakte land reclamation was constructed and the mouth of the Waterway was reshaped. An entrance channel in the North Sea (Maasgeul and Maasmond) and two dead-end inland channels (Caland- and Beerkanaal) were constructed and later deepened several times to the present depth of 25 m. The Europoort harbors were built on the inland channels which are separated from the Rotterdam Waterway by a dam; at the same time the northern pier was significantly extended.

Other estuarine areas of the Rhine-Meuse delta have been partly or completely shut-off from the North Sea, as was the case with the Haringvliet (Figure 1) that was closed in 1970 by a dam with sluices. Sea water enters the Rhine-Meuse estuary by the Rotterdam Waterway, and can reach several kilometers upstream of Rotterdam. The Rotterdam Waterway is considered to be a partially mixed estuary, with a tidal prism about the size of the fresh-water volume discharged during a tidal cycle.

The Rhine run-off, as measured at Lobith near the Dutch-German border, varies between 600 $m^3 s^{-1}$ and 13,000 $m^3 s^{-1}$ with an annual mean of 2,200 $m^3 s^{-1}$. Most of the Rhine water flows to the Rhine-Meuse estuary via the rivers Waal and Lek (Figure 1). The Meuse discharge is considerably smaller, ranging from 5 $m^3 s^{-1}$ to 3000 $m^3 s^{-1}$ with an annual mean of 250 $m^3 s^{-1}$. Thus the river Rhine supplies more than 80% of the fresh-water discharge to the Dutch coastal zone. Variation in fresh-water discharge through the open Rotterdam Waterway is small during most of the year. For a Rhine discharge below 1,500 $m^3 s^{-1}$, the sluices in the Haringvliet are closed and the fresh water passes the Rotterdam Waterway to the North Sea. Above 1,500 $m^3 s^{-1}$ the surplus is discharged during low tide through the Haringvliet as the sluices are more and more opened with increasing run-off. Above 6,000 $m^3 s^{-1}$, the extra fresh-water discharge divides itself over the Rotterdam Waterway and the Haringvliet. So for a Rhine discharge between 1,500 and 6,000 $m^3 s^{-1}$, the fresh-water discharge through the Rotterdam Waterway has a rather constant value of about 1,500 $m^3 s^{-1}$.

Water movement in the North Sea is dominated by a semi-diurnal M_2 tide. Near the mouth of the Rotterdam Waterway the tidal range varies between 1.5 m during neap tide and 1.9 m during spring tide. Vertically averaged tidal currents are about 1 m s^{-1}. They are directed parallel to the coastline, northeastward during flood and southwestward during ebb. Maximum flood almost coincides with high water. Residual flow is mostly north-eastward directed with a value of 0.04 m s^{-1} averaged over the water column. In the surface layer typical residual velocities are greater, between 0.07 m s^{-1} and 0.11 m s^{-1}, due to the prevailing southwesterly winds.

The relatively large fresh-water outflow from the Rhine and Meuse creates significant 3D density differences in the Dutch coastal zone that have a substantial impact on residual water movement. Up to 25 km offshore around and south of the Maasgeul, and as far as Meetpost Noordwijk (Figure 1) to the North, the residual near-bed currents are often directed on-shore or towards the mouth of the Waterway due to a density-driven circulation that is comparable with the better-known estuarine circulation. These near-bed residual currents have typical values of 0.03 m s^{-1}, increasing to 0.10 m s^{-1} under high-discharge conditions, as derived from current measurements (VAN ALPHEN *et al.,* 1988; VAN DER GIESSEN *et al.,* 1990; VERLAAN and SPANHOFF, 1992) and model simulations (DE KOK, 1992).

Waves in the Dutch coastal zone mainly have periods between 3 s and 9 s. Significant wave heights range from 0.5–1.0 m during calm weather periods to 3–5 m during storms. Waves from northerly and northwesterly directions on average have longer periods and larger heights than waves from southerly directions.

The water depth of the southern North Sea varies between 20 and 40 m. Pronounced banks occur at several places, notably the so-called Flemish Banks in front of the Belgian coast (Figure 1) that rise up to 25 m above the surrounding bed and have a water depth of 10 to 20 m.

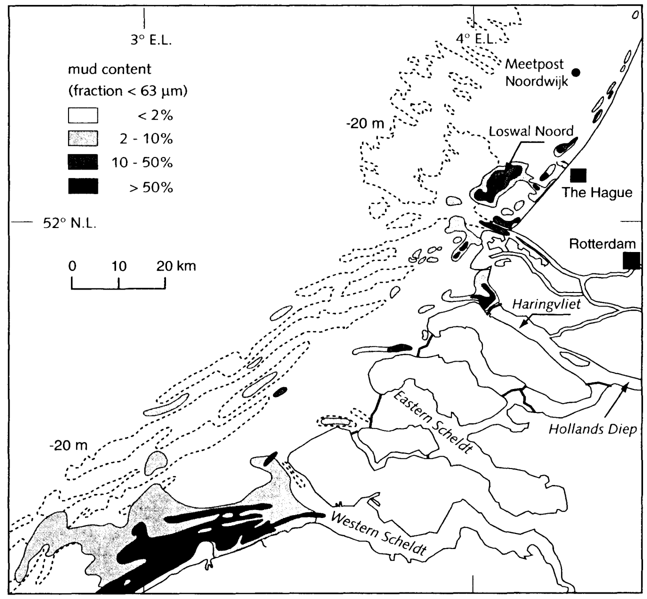

Figure 3. Mud deposits in the Dutch and Belgian coastal zone (after van Alphen, 1990). Major locations with a high mud content of the sea bed are the former mouth of the Haringvliet, the Loswal Noord dumpsite, and the Flemish Banks area.

Most of the southern North Sea bottom is covered with sandy sediments with grain sizes between 100 μm and 500 μm. An extensive area near the Flemish Banks in the Belgian coastal zone has bed deposits with up to 50% mud (Figure 3). A similar but more narrow zone of mud deposits is found along the entire Dutch coast (EISMA, 1968; VAN ALPHEN, 1990). There is less mud in this zone than off the Belgian coast; mud fractions vary between 2% and 10%.

Along the Belgian and Dutch coast mud is transported northeastward, its main source being the English Channel via the Dover Strait (EISMA and KALF, 1979; VAN ALPHEN, 1990). Local mud sources are relatively unimportant, although a possible major one is in the area of the Flemish Banks. These deposits are thought to erode during periods of strong winds (usually in winter) whereas during calm weather sedimentation occurs (GOSSÉ, 1977). The estimated annual mean net erosion from the Flemish banks is 1.0×10^9 kg of mud. The estimated total mud influx from the English Channel to the Belgian-Dutch coastal waters is 8.5×10^9 kg per year, averaged over several years (VAN ALPHEN, 1990).

On its way north the suspended sediment, which often has highest concentration values near the bottom, is concentrated towards the Dutch coastal zone, mainly by the above-mentioned near-bottom, on-shore residual-current components due to the river outflows. Yearly-averaged sediment concentrations at the surface are about 50 mg l^{-1} close to shore and decrease rapidly to background values of 3–5 mg l^{-1}, about 20 km offshore (VISSER *et al.,* 1991). Since the closure of the

Haringvliet, about 1.0 × 10^9 kg yr^{-1} of the transported marine mud has been deposited in front of the Haringvliet dam, and locally these deposits are 4 m thick with a mud content of 95% (VAN ALPHEN, 1990). This mud is prevented from entering the Haringvliet as the sluices are closed during the flood. A second major sink of NE-transported marine mud is sedimentation in the Maasmond and Europoort area (Figure 2), the subject of this paper. According to the mass balance of VAN DREUMEL (1995), this amounts to an annual 3.5 × 10^9 kg of marine mud.

At the entrance of the Maasmond, about 100 × 10^6 m^3 of water enters from the North Sea with each tide, which is about equally divided over the Rotterdam Waterway (water depth 16–18 m) and the Calandkanaal (water depth 23–25 m). Averaged over a year, each tidal cycle discharges about 65 × 10^6 m^3 of river water from the Rotterdam Waterway. Resulting depth-averaged tidal current velocities in the northern branch of the Maasmond are 1.0–1.2 m s^{-1} seaward during the ebb and 0.35–0.45 m s^{-1} landward during the flood. In the southern branch of the Maasmond, tidal currents are much smaller at about 0.5 m s^{-1} during both ebb and flood in compartment F_2, and rapidly decreasing landward to 0.2–0.4 m s^{-1} in compartment E (Figure 2). Both branches have a landward residual current in the lower part of the water column and a seaward one in the upper. Depth averaged it is almost zero in the southern branch but strongly seaward directed in the northern branch because of the freshwater discharge occurring there. Maximum ebb and flood currents in the southern branch precede those in the northern branch by 1.5–2.0 hours, by which some water is exchanged between the Rotterdam Waterway and the Calandkanaal. However, the amounts involved are small compared with the tidal volume, and there is relatively little interaction between the flows in the southern and northern branches.

The low current velocities in the southern branch of the Maasmond promote deposition of a substantial amount of incoming suspended matter, whereas deposition in the Rotterdam Waterway is minor. Consequently, large amounts of sediment are dredged to maintain the required water depth in the Maasmond and the Europoort harbor basins. Mud content of the bottom (defined as the fraction < 63 μm), varies between 50% and 100% in this area. More than 80% of the imported sediments, *i.e.* 3.5 × 10^9 kg yr^{-1} mud and 1.5 × 10^9 kg yr^{-1} fine sand (VERLAAN and SPANHOFF, 1994), are deposited and dredged in the Maasmond and in the seaward parts of the Caland-Beerkanaal (compartments E and $F_{1,2}$ in Figure 2). The present study concerns this material which, until summer 1996, was dumped at the Loswal Noord dumpsite, 5 km north of the mouth of the Rotterdam Waterway (SPANHOFF *et al.,* 1990a). In the area bordering the Maasmond, mainly because of this dumping, the generally sandy North Sea bottom (D_{50}: 100–500 μm) locally contains appreciable mud fractions (typical values 5–10%) as can be seen in Figure 3.

The Rhine and Meuse carry high loads of fluvial material to the Rhine-Meuse estuary (approximately 3.4 × 10^9 kg mud and 1.5 × 10^9 kg sand, annually; VAN DREUMEL, 1995). Of this, 75% is retained in the estuary, particularly in the Hollandsdiep-Haringvliet basin, and in the upstream harbor basins near the city of Rotterdam, around the turbidity maximum. The latter area is dredged and today the mud is stored on land, *e.g.* in the Slufter basin (Figure 2), because of its high contamination. Some contaminant values, together with historical ones, are discussed by SALOMONS and EYSINK (1981), who amongst other things deduce a tentative metal and mud balance for the estuary and its harbours. Additional information on the present study area is also given by these authors. Notably, since the closure of the Haringvliet in 1970, only small amounts of fluvial mud can escape to the sea. VAN DREUMEL (1995) constructed a mud balance for the entire Rhine-Meuse estuary and calculated that annually 0.2 × 10^9 kg and 0.7 × 10^9 kg of fluvial mud reach the North Sea by the Haringvliet and the Rotterdam Waterway respectively. This constitutes the finest fraction of the fluvial mud which, especially for the Rotterdam Waterway, enters the North Sea in a fresh-water surface layer that is usually quickly carried away in the previously-discussed top-layer residual current. This material is thus unlikely to settle near the mouth of the Rotterdam Waterway, and is in the order of 10–15% of the total mud supplied to the region (8 × 10^9 kg yr^{-1}, mentioned above).

SEDIMENTATION IN THE MAASMOND

To warrant access to the harbors for large ships, water depth and sedimentation in the study area is routinely monitored. For instance, weekly, or more frequently after storms, the depth of the Maasgeul and the deep part of the Maasmond is echo-sounded (210 and 15 kHz) along 3 lines parallel with the main axis of the channel. Furthermore, every two to five weeks, and after the detection by the above soundings of a possible significant sedimentation, full surveys of the Maasmond-Calandkanaal region (compartments E, $F_{1,2}$) are carried out. The latter consist of continuous 210-kHz echo soundings throughout the whole area, along 50-m spaced transects that are directed normal to the length axes of the compartments. Each survey, using a gamma-ray back-scatter probe (VAN OOSTRUM *et al.,* 1981), measures density profiles at 20–50 stations, which are evenly distributed over the compartments.

From the full surveys we derived sedimentation rates (mass per unit time). The echo soundings detect the water-mud interface and provide us with bottom volumes (with respect to a sub-bottom reference plane). From the density profiles of the full surveys, we deduced average densities for two sections of each profile; between the 210-kHz depth and the 1,200 kg m^{-3} density layer (= 1.2-density layer), and between the 1.2-density layer and a fixed reference depth, chosen here as 26 m. Vertical elevations are related to the Dutch ordnance level, NAP, which is close to mean sea level. Total sediment masses above the reference plane were determined from the thickness of the two sections and their average densities. For each compartment, sedimentation rates were obtained by dividing the mass differences (corrected for the known amounts removed by dredging) between consecutive surveys by their time difference.

Calculation of the derived weekly sedimentation rates (compartments E + F_1 + F_2; total area 2.2 × 10^6 m^2) in the period

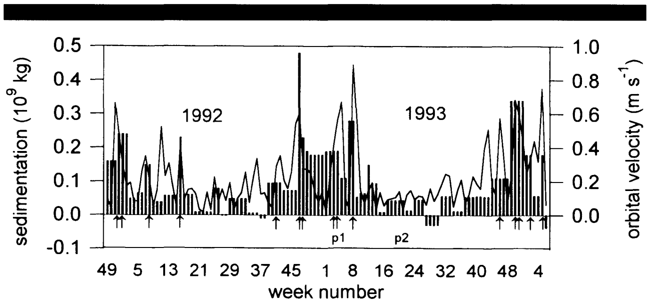

Figure 4. Weekly sedimentation amounts in compartments E, F_1, and F_2 and the weekly-average wave orbital velocity (at 20 m depth) of the one-third highest waves between December 1991 and February 1994. Most of the year, the weekly sedimentation is low (1–5 × 10^7 kg). During a few weeks (arrows on the horizontal axis) sedimentation is 10 to 20 times higher (0.2–0.5 × 10^9 kg). The actual sedimentation amounts of such events may be two to three times higher than the weekly values presented here, due to the averaging over several weeks. It is seen that massive-sedimentation events mostly coincide with periods of high waves.

December 1991 until February 1994 shows that rates vary considerably over a year (Figure 4). Throughout most of the year the rates are relatively low and can be explained by a net import of suspended material (see DISCUSSION). However, massive sedimentation of more than 0.5 × 10^9 kg between two full surveys has been observed several times. In those cases the above-mentioned main-axis parallel soundings show sudden reductions by an order of 2 m in the reflection depth of the 210-kHz acoustic signal. This demonstrates that the massive-sedimentation events occur in only one week or less. More than half of the annual sedimentation mass is imported during such events in a few weeks that mainly lie in the period from late autumn until early spring (see the arrows in Figure 4). Since the plotted sedimentation rates are estimates of several weeks, peak sedimentation values are partly levelled out.

In two typical sets of density profiles, measured one week and three months after a massive-sedimentation event, a transition layer is seen where the density increases from 1,025 kg m^{-3} (at the water-mud interface) to 1,200 kg m^{-3} (Figure 5). This upper layer, with concentrations between 10 g l^{-1} and 300 g l^{-1}, can be considered fluid mud (KIRBY and PARKER, 1977). Shortly after a massive-sedimentation event, the thickness of the fluid-mud layer can amount to 1–2 m, while a few months after an event it is less than a few decimeters (Figure 5). Further down, a second layer exists in the profile in which the density increases only slightly with depth. This layer can be several meters thick. In the Maasmond the density of this layer has a characteristic value between 1,200 kg m^{-3} and 1,240 kg m^{-3}. Below this layer the density rapidly increases to 1,400 kg m^{-3}, approaching the more sandy original bottom (depths > 25 m).

Reflection depths of the 210-kHz and 15-kHz signals, and the depth of the 1.2-density level along the longitudinal axis of the Maasmond-Calandkanaal between km 1031.5 and km 1035.0 are depicted in Figure 6. Here, the depth of the 1.2-density level was measured by monitoring the position of a towed fish called NAVITRACKER that adjusts its vertical position while sailing, to a predetermined density (here 1.2) in the mud layer with a continuously registrating density gauge (DE VLIEGER and DE CLOEDT, 1987). As often observed, the 210-kHz reflection depth has a minimum at km 1033.0, just seaward of the point where the Maasmond splits into the Rotterdam Waterway and the Calandkanaal. The thickness of the layer between the 210-kHz depth and the 1.2-density level varies between 0.4 m and 1.0 m, with a maximum value at km 1033.0 (Figure 6). The 15-kHz signal is reflected at a considerably higher depth, between 25 m and 27 m below the water surface.

The bed of the Maasgeul and Rotterdam Waterway consists mainly of sand and that of the Maasmond-Calandkanaal almost entirely of mud (Figure 7). A high gradient is observed between km 1033.0 and km 1036.0 in the Maasmond, from mainly fine sand seaward of km 1035.0 to mainly mud landward of km 1034.0.

Origin of Deposited Material

In the Rotterdam Waterway area fluvial and marine sediments mix. Mixing ratios in samples of suspended and bot-

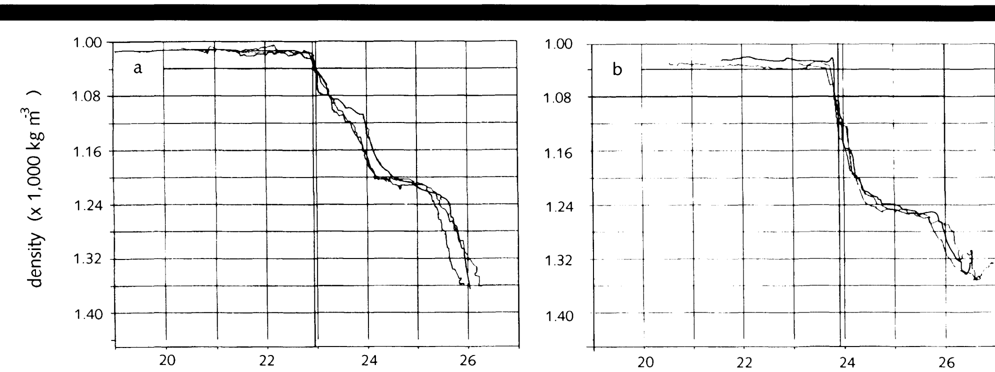

Figure 5. Density profiles of deposited material near km 1032.5 (Figure 2), (a) on January 27, 1993 (p1 in Figure 4), shortly after a massive-sedimentation event and (b) on May 15, 1993 (p2 in Figure 4), three months after a next one. Densities were measured with the gamma-ray densitometer of the Navitracker that was deployed here in a static mode by lowering it at a fixed location. Results are well reproduced at three different winch speeds.

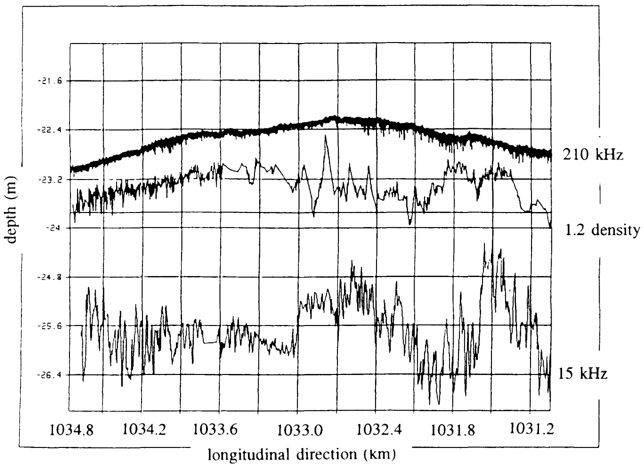

Figure 6. Reflection depths of the 210-kHz (upper line) and 15-kHz (lower line) echo sounding signals and the depth of the 1.2-density layer (middle line) along the length-axis of compartments F_2, F_1 and E between km 1035.0 and km 1031.3. The 210-kHz signal is reflected on the well-defined mud-water interface while the 15-kHz signal is reflected on density gradients at higher density levels. The 1.2-density layer was simultaneously determined with a towed Navitracker.

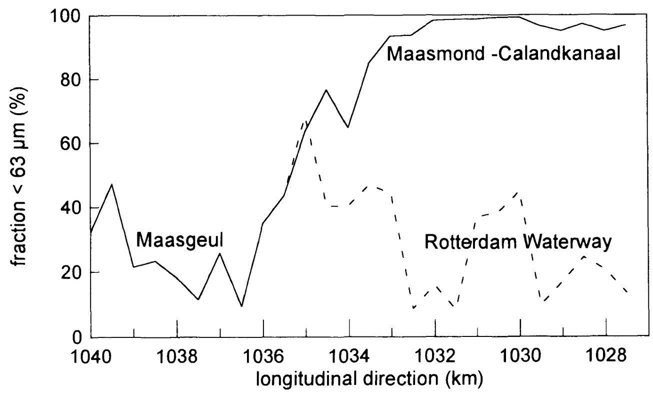

Figure 7. Measured fraction < 63 μm in bottom sediment. Landward of km 1035.5, the solid line reflects the bed composition along the length-axis of compartments F_1, F_2 and E, and the dashed line that along the length-axis of the Rotterdam Waterway (Figure 2). The samples were collected from the upper few centimeters of the bed at June 22–23, 1992.

tom sediments have been derived in several studies using natural-isotope ratios (carbon and oxygen) and elemental composition as tracers. Metal content of suspended sediments decreases rapidly with increasing salinity in a seaward direction in the Rotterdam Waterway. This is attributed to a strong decrease of the fluvial fraction, with desorption being negligible in this case (NOLTING *et al.*, 1989; PAALMAN and VAN DER WEIJDEN, 1992). Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope ratios of carbonates in the suspended sediments showed a similar behavior (SALOMONS and MOOK, 1987). Thus, relatively little fluvial sediment is assumed to reach the North Sea and Europoort harbors. For bottom muds, SALOMONS and EYSINK (1981) in their analysis of metal contents, adopted marine fractions of 90 ± 5% for Europoort, and circa 25% for the easterly and 60% for the westerly harbors near the city of Rotterdam. With carbon ($\delta^{13}C$) ratios of the carbonates contained in bottom muds, TURKSTRA (1988) found a gradual increase in the marine fraction between km 1001 (5%) and km 1032 (80%), with locally relatively high values (50–60%) in and around the westerly Rotterdam harbors (km 1014). The deposited material in the Maasmond area is believed to be mainly imported from the sea, as most of the fluvial sediment is trapped further upstream in the estuary. Particularly during massive-sedimentation events, the sea is the only source that can supply so much material. Moreover, the latter must be largely of marine origin since the fluvial fractions in the Dutch coastal waters are low (less than 20%; AREA DESCRIPTION; VAN ALPHEN, 1990; TURKSTRA, 1988).

For this study we confirmed the mainly marine origin of the deposited material, using Maasmond bottom samples taken in January 1994, just after a massive-sedimentation event that occurred at the end of December 1993. This event also coincided with an exceptionally high discharge of the rivers Rhine and Meuse. Carbon isotope data ($\delta^{13}C$) of the carbonates and organic fraction, and metal contents (Cd, Cu, Ni, Pb and Zn) all indicated that at least ⅔ of the mud was of marine origin. The remainder may quite well consist of riverine mud that had entered the North Sea through the Haringvliet, either at this event or earlier. A part may also have come from the Rotterdam Waterway, entering compartments E, $F_{1,2}$ directly, or via a detour in the North Sea.

Correlation of Sedimentation with Wave Activity and River Discharge

To help explain the massive-sedimentation events, we have attempted to correlate the observed Maasmond sedimentation rates with the wave orbital velocity, u_b, at the seabed. Using linear wave theory, u_b values at a water depth of 20 m were calculated from significant wave heights H⅓ and significant wave periods TH⅓ (averages of the ⅓-highest waves) that are routinely measured every 3 hours at the platform Meetpost Noordwijk, about 35 km north-east of the Rotterdam Waterway mouth and 10 km offshore (Figure 1). No wave data were collected at locations nearer to the mouth of the Rotterdam Waterway. In comparing several wave parameters at five locations in the southern North Sea with a water depth of 20–25 m, ROSKAM (1988) found that they differ less than 20% during storms. Since the water depth at the mouth of the Rotterdam Waterway (25 m) is the same as in most of the southern North Sea and high-wave periods occur predominantly during periods with onshore (westerly) winds, the wave heights and periods at the mouth of the Rotterdam Waterway and at the relatively nearby Meetpost Noordwijk can be considered essentially equal. They would differ at most by 5% (ROSKAM, 1997). Weekly u_b values were obtained by averaging the ⅓-highest 3-hourly values. Four-week moving averages were then taken of the weekly u_b and sedimentation values, and they were plotted against each other (Figure 8a). Fluctuations in weekly sedimentation amounts were thus fil-

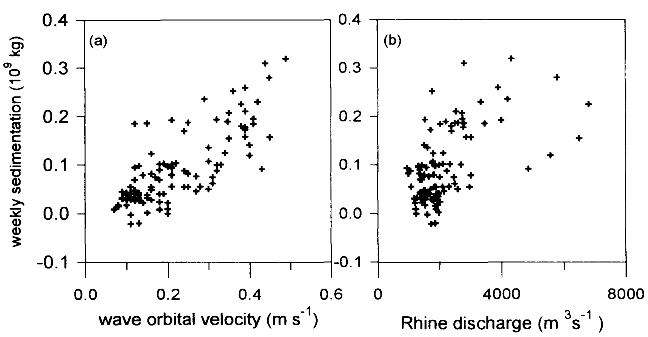

Figure 8. Weekly sedimentation in compartment E, F_1, and F_2 versus (a) the wave orbital velocity calculated at 20 m depth from wave data collected at meetpost Noordwijk (see Figure 1) and versus (b) the Rhine discharge at the Dutch-German border. Plotted values are moving averages over 4 weeks.

tered out and a clear correlation ($r^2 = 0.76$) is observed. Furthermore, we divided the data of Figure 8a into three subsets of average wind directions (WSW-WNW; WNW-NNE; NNE-WSW) of the one-third highest wind speeds during a week. The plots of these subsets of Figure 8a (not shown here) did not show an effect of the wind direction on the sedimentation rate (*i.e.,* winds with a northerly component lead to about the same sedimentation rates as winds with a southerly component, provided that the wave orbital velocities are the same).

Weekly sedimentation amounts were also correlated with the Rhine discharge at Lobith (Figure 1). The time lag between the gauge data at Lobith and the outfow at the Rotterdam Waterway is about 2 days (VAN ALPHEN *et al.,* 1988) and can here be neglected. Figure 8b shows the sedimentation rates to increase with fresh-water discharge; however, the correlation is lower ($r^2 = 0.59$) than with the wave orbital velocity.

PROPOSED SEDIMENTATION MECHANISM

Two mechanisms generally reported in the literature can in principle explain sedimentation in the Maasmond: (1) net import and settling of suspended sediment by tidal flow and (2) transport of fluid-mud layers that flow into the Maasmond from the sea. To explain the rapid sedimentation in the Maasmond of 0.5×10^9 kg in one week by the tidal-flow alone, a depth-averaged concentration of at least 700 mg l^{-1} would be required to enter the Maasmond with the flood and settle completely during slack water. Concentrations of this magnitude have never been observed in the water either in the Maasmond or elsewhere in the Dutch coastal zone, even during storms (VLEMMIX, 1978). Fluidization of mud layers at the sea bed under high-wave conditions can lead to fluid-mud layers (ROSS, 1988; ROSS and MEHTA, 1989; WOLANSKI *et al.,* 1992; MATHEW and BABA, 1995), which then are transported under the influence of the residual flow above them, and by gravitational effects (ROBERTS, 1993). This mechanism is virtually ruled out since it requires much higher mud contents at the bed than observed in most of the coastal zone that consists mainly of fine sand with a mud percentage below 10%.

Therefore, we propose an alternative description for the rapid sedimentation, based on the sediment-induced stratification in combined wave-current flows (GRANT and MADSEN, 1979; GLENN and GRANT, 1987). Under high-wave conditions, a wave boundary layer (WBL) develops. Its thickness, mostly smaller than 0.1 m in the Dutch coastal zone, depends on the dominant wave period, which usually is below 8 s. Under high-wave conditions, shear rates in the WBL are extremely high, leading to an almost homogeneous vertical distribution in the WBL of intensely resuspended fine sand and mud. Above the WBL, the shear production of turbulence is substantially lower and a sediment-induced stratification results, with a high concentration gradient in the lowest half meter or so of the water column. Coarse sand particles are poorly suspended and stay trapped within the WBL, with a strong gradient over the vertical therein. Thus, stratification mainly affects the vertical distribution of the silt-sized and fine-sand particles (GRANT and MADSEN, 1986) which are largely transported in a layer of a few decimeters thick: the wave-induced high-concentration suspension layer (WI-HCSL), analogous to the HCSL in the classification of PARKER (1994). The smaller clay-sized particles are approximately homogeneously distributed over the water column. Concentrations in the WI-HCSL are limited to a maximum that is controlled by the turbulence produced in combined wave-current flow and/or the amount of erodible sediment in the bed. The presence of these WI-HCSLs in the Dutch coastal zone is supported by model simulations and observations treated in the DISCUSSION.

The movement of the WI-HCSL follows the tidal flow in the lower water layers, with net sediment transports being determined by the near-bed residual flow which, in the study area, is strongly density-driven. Appreciable sediment quantities can thus be transported rapidly over several kilometers. They will enter the Maasmond through the Maasgeul, the deepest part of the area, and will largely stay trapped at this depth, once inside the Maasmond. There, wave intensity is much lower than at sea, as is the bottom roughness because of the presence of mud deposits. Turbulence, therefore, is far too low to maintain the HCSL (DISCUSSION), which ultimately settles over a relatively small area, while forming fluid-mud layers that subsequently spread over a larger area. The imported material is trapped, as shown by the following data-driven model.

PARTICLE-DEPOSITION MODEL

To calculate transport paths and the fate of mud and fine sand that enter the Maasmond from the sea, we constructed a simple (horizontal) one-dimensional particle model. The particles represent either suspended sand or mud, and are released every half hour at the entrance of the Maasmond (km 1035.4). Their velocities are assumed equal to the current velocity (u) in the lowest one meter of the water column. A particle settles when $u < u_{dep}$, where for each fine-sand particle u_{dep} is chosen randomly between 0.2 m s^{-1} and 0.4 m s^{-1}, and for each mud particle between 0 m s^{-1} and 0.2 m s^{-1}.

The velocities u_{dep} are based on the critical bottom shear stress τ_{cd} under which deposition can occur. KUYPER *et al.* (1991) found with laboratory experiments that τ_{cd} is 0.08 N m^{-2} for mud from the Maasmond. Under the assumption of a logaritmic velocity profile near the bottom, this corresponds to a u_{cd} of about 0.2 m s^{-1} at 1 m above the bottom. OCKENDEN (1993) found from laboratory experiments that τ_{cd} increases with settling velocity and that hardly any deposition occurs if the bottom shear stress is greater than 0.2 N m^{-2}. Consequently, for fine-sand particles a τ_{cd} of 0.2 N m^{-2} is adopted, corresponding to $u_{cd} = 0.4$ m s^{-1}. Particles that upon release move seaward are omitted from the calculation. For each particle the place of deposition is calculated. Once a particle settles, it is not resuspended.

A simulation was done with a velocity field measured with a Rhine discharge of 1895 m^3 s^{-1} and a tidal range of 1.8 m, a common situation (AREA DESCRIPTION). The original data set consisted of 13-hour quasi-synoptic current profiles at 18 stations in the Maasmond-Calandkanaal (SPANHOFF *et al.*, 1990b). The calculation uses data for the lowest one meter. The 1-D model has grid points every 300 m along the length axis of the Maasmond-Calandkanaal, and time steps every 30 minutes. For each time step and grid point velocities were interpolated from the data set. In the model, every half hour each particle adopts the velocity interpolated from its neighbouring grid points. When its velocity exceeds its u_{dep} the particle will be transported with that velocity during the next 30 minutes, otherwise it settles. The simulations involved 10,000 mud and 5,000 fine-sand particles. Twice as many mud particles were used since approximately ⅔ of the deposited material consists of mud and ⅓ of fine sand. In the calculation, about 25% of the particles moved seaward upon release and were thus omitted from the model computations. Results for the remaining 75%, deposited landward of km 1035.4, are shown in Figure 9. Fine-sand ends up seaward of km 1033 and mud mainly between km 1031.8 and km 1033.5. The high deposition values seaward of km 1035.0 near the release point, notably those of mud, are deemed an artefact of the model that neglects the remaining wave influence there. No deposition is computed landward of km 1031.5. The model results are in general agreement with the observed mud fractions of the Maasmond bed (Figure 7), notably with their increase in a landward direction.

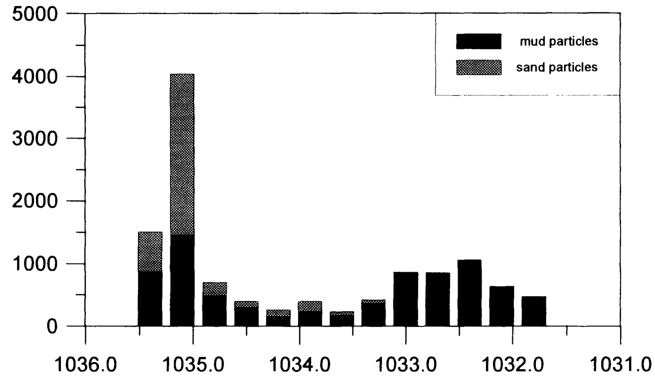

Figure 9. Number of (sand and mud) particles deposited in compartments E, F_1 and F_2, computed with a 1-D model for the length axis of the Maasmond-Calandkanaal. Particles are released at km 1035.4. The model was driven with a measured quasi-synoptic current field. Sand particles (0.2 m s^{-1} < u_{dep} < 0.4 m s^{-1}) are deposited seaward of km 1033, mud particles (u_{dep} < 0.2 m s^{-1}) mainly between km 1031.8 and km 1033.5. The high deposition values near the release point (seaward of km 1035), notably those of mud, are deemed an artefact of the model.

DISCUSSION

During most of the year, sedimentation in the Maasmond-Calandkanaal (compartments E, $F_{1,2}$; Figure 2) is moderate, on the order of 2×10^7 kg per week (Figure 4), or 1×10^9 kg yr^{-1}. This amount is attributed to the tidal volume of about 50×10^6 m^3 passing this area, assuming that from the suspension imported with the north-going flood 30 mg l^{-1} settles permanently, averaged over depth. This value can actually be smaller given that the deposition of riverine material may be relatively important under these conditions. Long-term observations of near-surface suspended-matter concentrations in the Dutch coastal zone confirm that they usually are some tens of mg l^{-1} higher south than north of the Maasmond (VISSER *et al.*, 1991). Since the suspended mud is transported northeastward (circa 8×10^9 kg yr^{-1}; VAN ALPHEN, 1990), the Maasmond obviously traps part of it (annually about 1×10^9 kg of mainly mud). This is realistic since the above-mentioned tidal volume of the Maasmond has about the same value as the alongshore residual water-mass transport (70×10^6 m^3 for an average depth of 10 m, and a residual current of circa 0.04 m s^{-1}) per tidal cycle in the first 4 km from the shore, where suspended mud concentrations are highest.

The majority of the annual deposits of circa 3.5×10^9 kg mud and 1.5×10^9 kg fine sand is imported during only 4 to 6 massive-sedimentation events that each involve about 0.5 $\times 10^9$ kg material in a few days. In our description, the massive amounts that enter the Maasmond under storm conditions are transported landward with the near-bed residual flow in a high-concentration suspension layer following the classification given by PARKER (1994). First, predominantly fine sand settles followed by mud that forms a fluid-mud layer as expected under these high deposition rates. This depositional pattern of fine sand and mud is consistent with the data (Figures 6 and 7) and with the computed deposition locations (Figure 9) of incoming suspended particles that are transported with the near-bed current velocities. For instance, in the analysis of the full surveys made shortly after an event, we found the mud deposition to be greatest near km 1033. This is illustrated in Figure 6 by the maximum thickness of the fluid-mud layer near km 1033 coinciding with the computed *locus* of mud deposition (Figure 9).

Up to the 1.2-density level, mud layers in the Maasmond are mobile, as *e.g.* discussed in the rheological study of Zeebrugge and Maasmond muds by MALHERBE *et al.* (1986). At higher densities mud flocs form an immobile framework which partially self-supports the soil medium, as reflected by the almost-constant density layers (1,200 kg m^{-3} to 1,240 kg m^{-3}) illustrated in Figure 5. With time, this almost-constant density layer becomes thicker as a result of the fluid mud settling. During consolidation, its density increases from

1,200 kg m^{-3} to 1,240 kg m^{-3}. Once formed, *e.g.* around km 1033, the fluid-mud layers (density < 1.2) will slowly spread under the influence of gravity, amongst other things. KIRBY and PARKER (1977) and VAN SCHEINDELEN (1985) observed fluid-mud movements in the Maasmond that were directed inland.

The observed massive-sedimentation events require appreciable amounts of sediment to be transported from the coastal zone to the Maasmond in a short time, probably a few days to a week. This is possible because of the proposed wave-induced HCSLs, in which relatively thin layers (order decimeters) of suspended sediment with intermediate concentrations (order 1–15 g l^{-1}) are transported over large distances by the near-bed residual currents. These range from 0.02 m s^{-1} to 0.10 m s^{-1}, are landward directed towards the Maasmond, increase with increasing river discharge, and occur over several tens to hundreds of km^2 (AREA DESCRIPTION). As river discharge increases, the area from which sediments can reach the Maasmond, and thus the sedimentation therein, will also increase (Figure 8b). In three days of a storm event, the above-mentioned near-bed residual currents transport near-bottom suspended material from an area of order 100 km^2 around the Maasmond to the latter. Then, a massive sedimentation of 4×10^8 kg mud can, for instance, be attributed to the import of mud that is entirely winnowed out of a 0.05-m thick bed layer containing 5% mud. Such mud contents, and higher ones, with a total area as assumed, are locally found in the sea bed of the Dutch coastal zone, *e.g.* in the former mouth of the Haringvliet and at the Loswal Noord dumpsite (Figure 3), which are within the zone where the residual near-bottom currents are directed towards the Maasmond (northerly and southerly respectively). After a storm event, the mud that has been carried away from these places, will be gradually replaced by new material from the south and from dredging activities. Furthermore, it is quite possible, as also suggested by EISMA and KALF (1979), that during calm-wheather periods, small amounts of mud settle in the Dutch coastal zone, yielding mud fractions of 1–5% in the surface sediments, that will again be transported during storms. Such admixtures within a 10–20 km radius from the Maasmond may also contribute to massive-sedimentation events. Thus, for the latter, sufficient material is in principle available, at least as long as the potential sources have been recharged after previous events.

In the foregoing example, typical suspended-mud concentrations of 7.5 g l^{-1} result if one assumes a 50-cm thick WI-HCSL. We have observed such values under high-wave conditions, in long periods without dumping, at a station four km northeast of the Loswal Noord dumpsite. Here we measured concentrations at 15 cm and 90 cm above the sea bed during a few months (VERLAAN and SPANHOFF, 1992). Under calm-weather conditions we found values of 50–100 mg l^{-1} at both levels. During storms, the sediment concentrations at 15 cm were almost two orders of magnitude larger, opposed to the values at 90 cm that increased less than a factor 10. These observations give strong support to the present explanation for massive-sedimentation events.

To obtain further support for the existence of WI-HCSLs in the Dutch coastal zone, we did some numerical calculations with the model (GN87) of GLENN and GRANT (1987). This model describes the near-bottom combined wave and current flow field over a movable bed on a continental shelf. It predicts vertical profiles for water velocity and suspended-matter concentrations, given minimal data for waves, currents and the grain-size distribution of the bed. The GN87 model accounts for the non-linear wave-current interaction, for ripple formation and degradation and near-bed sediment transport, and for suspended-sediment induced stratification. We included the effect of bed armoring in the GN87 model following the formulations given by WIBERG *et al.* (1994). We schematized the bed composition as observed in the coastal zone around the mouth of the Rotterdam Waterway, with three discrete grain-size fractions, 200 μm (45%), 100 μm (45%), and mud (10%). Following Stokes law, settling velocities of the 100-μm and 200-μm fraction are 5.6 and 21.0 mm s^{-1} respectively. For the mud fraction we take 2.5 mm s^{-1}, the Stokes velocity for 63-μm particles. Thus we account in a simple manner for the formation of flocs and aggregates of suspended-mud particles, as observed *e.g.* by KINEKE and STERNBERG (1989) in San Pablo Bay (California) and by VAN LEUSSEN (1994) about 10 km northeast of the Loswal Noord dumpsite (Figure 1). These authors concluded that *in-situ* settling velocities of flocs and aggregates are one to two orders of magnitude larger than the Stokes velocities of the primary mud particles (≪ 63 μm). Simulations with the GN87 model were done for a water depth of 15 m and a tidal-current velocity of 0.25 m s^{-1} at 0.15 m above the bed (about the average value over a full tidal cycle). The resuspension coefficient γ_0 had the value 0.002, following GLENN and GRANT (1987). Suspended-matter concentration profiles were calculated for the three different wave conditions indicated in Table 1 that are typical for the Dutch coastal zone. The table presents the following calculated values: suspended-sediment concentrations C_{10} at 10 cm and c_{100} at 100 cm above the bed, shear velocities u_{*cw} in and u_{*c} just above the wave boundary layer (=WBL), physical bottom roughness k_b, thickness δ_w of the WBL, and the stability parameter z/L at the top of the WBL, where L is the Monin-Obukhov length ($L = \rho u_*^3/\kappa g \langle\rho' w'\rangle$, with κ = Von Karman constant, g = acceleration of gravity, and ρ is density of seawater). Within the WBL, the Monin-Obukhov length L ($=L_{cw}$; $u_* = u_{*cw}$) is substantially higher than above it ($L = L_c$; $u_* = u_{*c}$), since L is proportional to the third power of u_* and $u_{*cw} > u_{*c}$. Stratification of the water column occurs if the stability parameter z/L is O(1), and can be neglected if z/L is $O(10^{-2} - 10^{-3})$.

Calculated concentration profiles (Figure 10) demonstrate the existence of a high-concentration suspension layer with a thickness of a few decimeters. The 100-μm and the mud fraction are seen to contribute most to the total suspended sediment concentration. The contribution of the 200-μm fraction is only significant within the WBL. This fraction is hardly transported since the residual current in the WBL is relatively small. Table 1 shows that the stability parameter z/L increases rapidly with increasing wave activity, and that stratification is particularly apparent just above the WBL, where the vertical concentration gradient is highest, whereas stratification is almost absent within the WBL. From the ta-

Table 1. *Results of GN87 model simulations for 3 wave conditions. Calculated values of: suspended-matter concentrations c_{10} at 10 cm and c_{100} at 100 cm above the sea bed, shear velocities u_{*cw} in and u_{*c} just above the WBL, thickness δ_w of the WBL, physical bottom roughness k_b, and stability parameters $z/L|z = \delta_w$ just above ($L = L_c$) and just under ($L = L_{cw}$) the top of the WBL.*

	c_{10} mgl^{-1}	c_{100} mgl^{-1}	u_{*cw} ms^{-1}	u_{*c} ms^{-1}	k_b cm	δ_w cm	z/L_c	z/L_{cw}
H1/3 = 2.0 m TH1/3 = 5.8 s	1865	329	0.051	0.025	5.0	3.9	0.15	0.018
H1/3 = 2.75 m TH1/3 = 6.8 s	4504	419	0.064	0.022	3.7	5.8	1.22	0.046
H1/3 = 3.5 m TH1/3 = 7.9 s	37,607	930	0.097	0.024	6.5	10.0	2.64	0.065

ble (3.5-m *versus* 2.0-m and 2.75-m waves) it is clear that material from a WI-HCSL will rapidly settle when the wave energy decreases, as, for example, upon entering the Maasmond.

The averaged mud concentration in the lowest 50 cm of the water column increases with wave activity from 0.3 g l^{-1} (Figure 10A) to 5.3 g l^{-1} (Figure 10C). The latter value is of the same order as the suspended-mud concentration of 7.5 g l^{-1} mentioned previously to explain rapid sedimentation in the Maasmond. The figure shows that some mud is also transported above the lowest 50 cm of the water column, e.g. in the lowest 2.5 m. By multiplying the computed concentration profiles of the three individual fractions (Figure 10) with the current velocity profile, an estimate is obtained for the mud fraction of the transported suspended sediment. Averaged over the lowest 2.5 m of the water column, we calculate transported mud fractions of 40% for the 2-m and 80–85% for the higher waves of Table 1. Such mud fractions are indeed observed in compartment $F_{1,2}$ (Figure 7).

Observations and model simulations demonstrate that in the Dutch coastal zone high waves do produce WI-HCSLs. Furthermore, the turbulence produced by current shear alone is too small to maintain a HCSL here. In other coastal seas such as the Amazone delta (CACCHIONE *et al.,* 1995) and estuaries such as the Severn (KIRBY and PARKER, 1983) and Gironde estuary (ALLEN *et al.,* 1977), the tidal current velocities are considerably higher than in the Dutch coastal zone and are able to produce a HCSL without the presence of waves.

The present description of the massive-sedimentation events provides an explanation for the long-existing puzzle on their nature. A crucial element is the existence in the coastal zone of WI-HCSLs which, as yet, have not been observed directly near the mouth of the Rotterdam Waterway. Probably they are also responsible for the sedimentation in several other sea harbors, as mentioned in the INTRODUCTION. They are hard to observe; vessels cannot operate under storm conditions, and they occur only close to the bed. Moreover, echo sounders are much less suited to detect HCSLs than fluid-mud layers because of the much lower concentration gradients in the former (PARKER, 1994).

Parts of the above description are specific to the Rotterdam area, and parts will be widely applicable to other regions and harbors with significant sedimentation during storms. For massive-sedimentation events to occur, a first prerequisite is a source of mud and fine sands. Near the mouth of the Rotterdam Waterway sources have been created, *e.g.* through the dumping at Loswal Noord, and through closing of the former Haringvliet estuary. It will be important to monitor future sedimentation, now that the dumpsite has been shifted 5 km northwest (summer 1996), and especially in the case of reopening the Haringvliet (almost permanently open sluices, except during storm surges). A second prerequisite are near-bed residual currents that transport WI-HCSLs from large areas towards the region of concern. Here the high fresh-water Rhine outflow is the agent that brings the WI-HCSLs

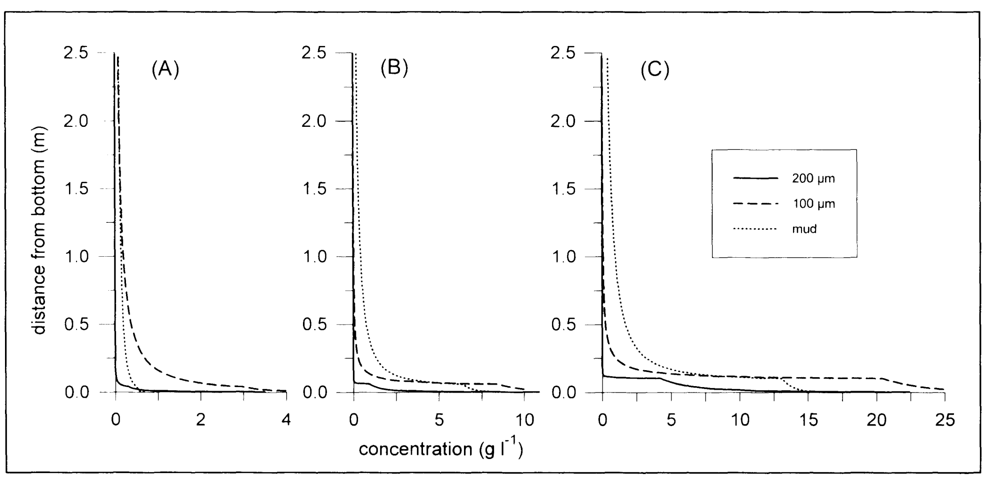

Figure 10. Concentration profiles in the lowest 2.5 meter of the water column for three sediment fractions: 200 μm (45%), 100 μm (45%), and mud (10%), that mimic the composition of the sea bottom, computed with the GN87 model for three wave conditions: (A) H⅓=2.0 m, TH⅓=5.8 s; (B) H⅓=2.75 m, TH⅓=6.8 s; (C) H⅓=3.5 m, TH⅓=7.9 s. The calculated total suspended-matter concentrations at 10 cm and 100 cm above the seabed of these profiles and the thickness of the WBL are given in Table 1. Sediment-induced stratification is highest just above the WBL (see 100-μm and mud fraction).

close to their sedimentation area. Thirdly, the HCSLs must be able to enter that area and to settle there. This has been achieved by the artificially deep entrance channels and harbors in the Europoort area.

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