SAND-MUD DISTRIBUTION IN THE AMELANDER INLET

Sand and mud transport computations for a tidal inlet

April 2001

TuDelft

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Faculty of civil engineering and geosciences
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M.Sc. Thesis

TU Delft

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Preface

This report describes the study that has been carried out as Masters Thesis, within the framework of the study Civil Engineering at Delft University of Technology.

The goal of this study is to obtain more knowledge about sand-mud distribution in tidal inlets. Sand-mud distribution in one tidal inlet in the Dutch Wadden Sea, the Amelander Inlet, has been thoroughly studied. This study was split into two parts. The first part is the analysis of the available data. In the second part numerical models are used for explaining the observed sand-mud distribution in the Amelander Inlet.

I would like to thank my supervisors, prof.dr.ir. M.J.F. Stive, ir. M. van Ledden, dr.ir. Z.B. Wang, dr.ir. J.C. Winterwerp, dr.ir. J.A. Roelvink for sharing their knowledge and supporting me.

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Summary

In the tidal inlets in the Dutch Wadden Sea, the most important sediment types are sand, silt and clay. A distinction between the sediment types is made, because clay particles have cohesive properties. Consequently, the clay particles do not behave as individual particles but tend to stick together. Flocs are formed whose size and settling velocity are larger than those of the individual particles. The bed is mostly composed of a mixture of different sediment types. The bed has cohesive properties (and is called a mud bed) if the clay percentage is higher than 5-10%.

Understanding and predicting the sand-mud distribution in a tidal inlet can be of importance for different reasons. First, the sand-mud distribution can influence the morphological development of the inlet. Second, the mud content in the bed is of influence for the ecological system. Mud particles are a carrier of nutrients and thereby a source of food for several species. However, mud particles can also be attached to heavy metals and other polluting materials and can thereby cause heavy pollution.

At present, computer-models are not able to simulate the sand-mud distribution in tidal inlets. The bed composition variation cannot be taken into account in the computations. This is caused by a lack of knowledge about the processes and mechanisms that take place during mud transport and sand-mud interaction. Therefore, the goal of this study is to gain more knowledge about sand-mud distribution in tidal inlets. In this study the tidal basin of the Amelander Inlet has been chosen as area of interest.

The first part of the study consists of a data-analysis. The data is taken from the Sediment Atlas (Rijkswaterstaat, 1998) and consists of the grain size distribution at sample points in the tidal basin of the Amelander Inlet. To obtain these grain size distributions, samples were taken every kilometre or every five hundred meters. The samples were taken in the period April-July 1995. The grain size distribution was determined with the Malvern method. It is known that the Malvern method underestimates the finer fractions in a sample.

From the available grain size distributions, parameters representing the distribution are calculated. The calculated and analysed parameters are the mud content, the median diameter, the sorting of the sample and the skewness of the sample. The distribution parameters are calculated for the sand fraction only, because the finer fractions are unreliable. The parameters are plotted against position. After that, the parameters are plotted against each other to look for a correlation. The main results from the data-analysis are:

- The mud content is higher in the eastern area of the tidal basin than in the western area.
- For water depths smaller than two meters the mud content ranges from high to low values. This implies that a small water depth is a precondition for high mud contents but not the only one. Other factors determine whether the mud content is high at small water depths.
- If the distance from the gorge is greater than ten kilometres the mud content can be high. For smaller distances, practically no high mud contents are found in the tidal basin of the Amelander Inlet.

The second part of the study consists of using numerical models to try to simulate the observed sand-mud distribution in the Amelander Inlet. In the data-analysis, research questions were raised which can be answered with the models in this part. These questions concern the wave penetration, the tidal penetration, the water depth at high water and the level of the sand and mud flats. The computations are made within the Delft3D modelling system. First, hydrodynamic computations are made in Delft3D-FLOW. After that, sediment transport computations are made separately for the sand bed and the mud bed.
Sand mud distribution in the Amelander Inlet

Summary

The hydrodynamic computations are run for the situation without waves, and for eight situations with different wave/wind directions. The waves consist of waves penetrating from outer sea and locally generated wind waves. The main results from the hydrodynamic computations are:

- The maximum bed shear stress during a tidal cycle is higher in the western area than in the eastern area.
- The penetrating waves can be neglected compared to the locally generated wind waves, the height of these waves depend on the local geometry and the wind direction.

The sand transport computations are also run for the situation without waves, and for eight situations with different wave/wind directions. These computations are used to see where the sand bed is morphologically active.

With the mud transport computations, three situations are simulated in this sequence:
1. The first deposition phase during calm weather, initial situation: empty bed
2. The erosion phase during rough weather, initial situation: results first deposition phase
3. The second deposition phase during calm weather, initial situation: results erosion phase

During the first deposition phase, deposition areas are formed. In the net deposition areas the bed shear stresses are low, causing more mud to be deposited than eroded during a tidal period. After the calm weather period, the deposited mud layers are eroded by wave attack during the erosion phase. After the erosion phase, the second deposition phase takes place. During the erosion phase a lot of mud particles were suspended. However, part of these mud particles was not transported of the flat by the tidal current. In the second deposition phase, these mud particles will be deposited again. From this phase it can be seen how much of the mud particles are transported away from or towards an area.

The main results from the sand and mud transport computations are:

- The computed deposition is high in the coastal areas, the watersheds and in the eastern area of the tidal basin. The deposition rate is highest in the western area of the tidal basin. The second deposition phase shows much higher initial depositions due to the higher initial concentrations, especially in the eastern area.
- The erosion goes fastest in the western area of the tidal basin. In the eastern area it takes the waves a long time to erode the entire mud layer.

The main conclusions from this study are:

- The areas where deposition takes place are mainly determined by the occurring tidal action. The influence of waves is large at small water depths, and determines how much and how fast the mud particles are suspended. Whether the mud particles are transported after being stirred-up, is determined by the actual tidal action.
- Waves also are of influence for the deposition of mud layers. Waves in the tidal basin spread the mud particles from areas with high wave attack (high concentration) towards areas with low wave attack (low concentration). Due to this redistribution of mud, the mud particles, on a large scale, are transported from west to east in the tidal basin.
- Qualitatively, the computed mud deposition agrees with the measured mud contents on a large scale. With the help of the second deposition computation and the erosion computation, part of the differences can be explained and the measured mud contents are understood better.

Further experimenting with the wind speed, computing different phases in a certain sequence and the computation times for the different phases can improve the results and help understand and predict the measured mud contents on a more accurate level.
1 Problem description

1.1 Introduction

The Amelander Inlet, interest area of this study, is located in the Dutch Wadden Sea (see Figure 1-1). In the tidal inlets in the Dutch Wadden Sea, different sediment types are found. The spatial distribution of these sediment types is called sand-mud distribution. Understanding and predicting the sand-mud distribution in a tidal inlet can be of importance for different reasons. First of all, the sand-mud distribution can influence the morphological development of the inlet. Second, the mud content in the bed influences the ecological system. Mud particles are a carrier of nutrients and thereby a source of food for several species. However, mud particles can also cause heavy pollution by attaching themselves to heavy metals and other polluting materials.

In a tidal inlet, especially on the flats close to the watersheds and close to the coast, high mud contents are present. The Wadden Sea area has high ecological values, therefore it is important to be able to make reliable ecological predictions. The mud content is an important parameter for these predictions.

At present, computer models are often used to predict the consequences of either human interference or natural changes in tidal inlets. Examples of human interference are the closure of a channel and dredging. Natural changes include mean sea level rise and an increasing number of storms. However, it is not yet possible to make computations in which bed composition variations are taken into account. Therefore, it is not possible to predict the sand-mud distribution in a tidal inlet with a model. To be able to develop models, which do take the bed composition variation into account (sand-mud models) and can predict the sand-mud distribution in a tidal inlet, more knowledge is needed about the development of bed composition variations. At present, there is still a lack of knowledge on this subject. Especially about the processes and mechanisms that take place during the erosion and deposition of mud and about the interaction that takes place between sand and mud particles, not enough is known.

Figure 1-1: The Wadden Sea in the Netherlands
1.2 Description of the area

The Wadden Sea is located north of the Netherlands and Germany and proceeds northwards towards the west coast of Denmark. The system consists of barrier islands with tidal inlets in between. The Wadden Sea area of the tidal inlet, trapped between the barrier islands and the coast, is called the tidal basin. The tidal basin consists of channels and flats. The flats fall dry during low water. Distinctive attributes of this morphological system are the tidal flows via passes, the exclusion of waves by the barriers and little freshwater run-off. The net longshore current along the Dutch Wadden Sea propagates from west to east. The fine sediment in the Dutch Wadden Sea originates from different sources: rivers in the south of the Netherlands, the river the Ems in Germany, the Channel and cliff erosion.

In this study the sand-mud distribution in one tidal inlet is studied thoroughly. The Amelander Inlet was chosen for this purpose, for several reasons. First, the Amelander Inlet is one of the least complex tidal inlets in the Dutch Wadden Sea, because no major human interference has taken place. This makes it easier to unravel the underlying physical processes. Second, there is a lot of data available for the Amelander Inlet. Finally, a computer model is available for the Amelander Inlet. This can serve as good aid for studying the tidal inlet.

![Amelander Inlet between Ameland and Terschelling](image)

In this study the area of interest is only the tidal basin of the Amelander Inlet. The outer ebb delta is not taken into account. The main channels and flats in the tidal basin of the Amelander Inlet are shown in Figure 1-2. In this figure the Dutch names are used. Flats are called "...plaat/bult/riem", channels are called "...gat/diep/balg", the adjacent barrier islands are Ameland and Terschelling and the watersheds are called "...wad".
1.3 Goal of the study

The goal of this study is gaining more knowledge about sand-mud distribution in tidal inlets. To obtain this knowledge, the sand-mud distribution in the tidal basin of the Amelander Inlet is studied. First a data-analysis is carried out. The available data points in the Amelander Inlet are visualised in different ways, and analysed. The available data consist of grain size distributions at several locations, from which the mud content and some statistical parameters can be calculated. Because the available data set has a relatively low resolution (data points every five hundred meters), this study will focus on the sand-mud distribution on a large scale. After the data-analysis, numerical models are applied to try to answer the questions that followed from the data-analysis. With the hydrodynamic model the influence of certain hydrodynamic parameters on the sand-mud distribution is studied. With the sediment transport model an attempt is done to reproduce the observed mud contents qualitatively. Furthermore, the differences between sand transport and mud transport are studied with the sediment transport model.

General questions, which should be answered at the end of this study, are:

- Can the observed mud contents be reproduced qualitatively by a sediment transport model?
- Can the observed sand-mud distribution in the Amelander Inlet be understood and explained with the help of the models?
- What are the restrictions of the sediment transport model for the goal of this study?
- Can a relationship be found between certain hydrodynamic parameters and the presence of high mud contents?

In this study, when speaking of sand-mud distribution, only the horizontal bed composition variation is implied. The vertical bed composition variation is not taken into account.

1.4 Outline of the report

In chapter 2, the underlying theory for the contents of this study is described. After that, the data-analysis is carried out and described in chapter 3. From chapter 2 and 3, certain questions follow concerning the sand-mud distribution. The goal of using numerical models is to answer these questions. In chapter 4, the relevant theory for the models Delft3D-MOR and Delft3D-WAQ is described first. After that, the set-up for the computations carried out in this study is described and explained. In chapter 5, the hydrodynamic results are described and analysed. In chapter 6, the results of the sand transport and mud transport computations are described and analysed. Finally, in chapter 7 the conclusions and recommendations are found.
Sand mud distribution in the Amelander Inlet

Problem description
2 Sand-mud distribution in a tidal inlet

2.1 Sediment properties

In this study, the sediment types of interest are sand, silt and clay. The division between these sediment types is as follows (Dyer, 1986):

- 0.063 mm < Sand < 2 mm
- 0.002 mm < Silt < 0.063 mm
- Clay < 2 μm

The difference between the sediment types is made, because clay particles have cohesive properties. Electro-static forces, comparable to or higher than the gravity forces acting between the particles, cause these cohesive properties (Van Rijn, 1993). Consequently, the sediment particles do not behave as individual particles but tend to stick together. Aggregates are formed known as flocs, whose size and settling velocity is larger than those of the individual particles are. The silt particles are often also flocculated with and thereby bound to the clay particles. A mixture of the different sediment types mostly forms the bed. The behaviour of this mixed bed depends on the percentages of the different sediment types. A mud bed has cohesive properties and is usually defined as a fluid-sediment mixture consisting of water, sands, silts, clays and organic materials. In a sand bed the silt and clay percentages are so low that no cohesive properties are present. In this study, the mud content of a sample is considered as the percentage of the sample that consists of silt and clay (% <63 μm). If the clay content is higher than 5-10 % the sediment mixture has cohesive properties.

2.2 Processes in a tidal inlet

2.2.1 Tidal basin

The tidal basin, the area of interest in this study, is a waterbody entrapped behind coastal barriers. The Wadden Sea is almost a semi-enclosed bay with hardly any freshwater run-off in the basin. The basin mainly exists of meandering channels, sometimes braided but mostly branched, and flats, consisting of mud or sand.

![Diagram of tidal currents and water bodies](image)

*Figure 2-1: The tidal dynamics in the Wadden Sea: types of tidal passes and currents*
The Wadden Sea tidal inlets have distinct catchment areas, separated by watersheds where a lot of fine sediment can be deposited. Figure 2-1 shows the currents in the tidal basin for different situations, which can apply for a tidal inlet in the Wadden Sea.

2.2.2 Forcing in a tidal inlet

Tide

The tide is a set of long waves that propagate in the oceans. These long waves come into being due to the attraction forces of the moon, the sun and a small part of other stars. The variation in tide is therefore caused by astronomical variations.

The tidal waves cause relatively strong currents in and around a tidal inlet. The tidal current is characterised by the ebb current and the flood current. These strong currents may cause large sediment transports and subsequently significant changes in the bathymetry of the tidal basin. The flood currents will choose the way of the least resistance, which is along the coasts of the adjacent barrier islands. The main ebb channel usually has a central location in the tidal inlet.

In short tidal basins, such as the Amelander Inlet, the tidal wave is reflected and it has a standing character. When these tidal basins are long enough, the tidal wave resonates. When they are even longer, the tidal wave is dampened by friction and the reflected wave is weak, so that the tidal wave has a propagating character. In most tidal basins, the tidal discharges are largest in the inlet gorge, and decreasing in landward direction. Within the basin, the tide is deformed by bottom friction and other non-linear effects associated with the basin geometry. This tidal distortion causes asymmetries between high- and low-water flow change. These asymmetries cause a net movement of sediment, both sand and mud.

A quadratic friction law gives the shear stress at the bottom induced by the tidal current only:

\[ \tau_c = \frac{\rho g V^2}{C^2} \]  

Equation 2-1

with:
- \( \tau_c \) bed shear stress induced by current [N/m²]
- \( \rho \) mass density of water [kg/m³]
- \( g \) acceleration due to gravity [m/s²]
- \( V \) depth averaged velocity [m/s]
- \( C \) Chezy coefficient [m¹²/s]

Waves and wind

Wind creates water level changes (wind set-up), waves and currents. The wind-driven current can be of significant influence on the tide-driven currents. The most important waves at the coast are wind-generated waves. For a tidal inlet, two kinds of wind-generated waves can be distinguished. The first kind, are waves that were generated in the outer sea, at high water depths and large fetch lengths. These waves approach from sea and can possibly penetrate into the tidal basin. The second kind, are waves that are generated in the tidal basin, locally generated wind waves. These are generated at smaller water depths and fetch lengths.

If waves are symmetrical there will hardly be any net transport, because the sediment is moved back and forth over the same distance. In nature however, waves are not symmetrical (sinusoidal) so the sediment is moved further in one direction than in the opposite direction. This results in a small net sediment transport in one direction. However, this is not the most important effect of waves. The most important effect is the stirring effect. The waves can stir the sediment from the bed, the tidal currents will transport the stirred-up sediment and cause a
net sediment transport. By stirring up sediment, the waves can increase the sediment transport significantly.

The wave effect is dependent on the wavelength and the water depth. The influence of waves on the bed level depends on the combination of these two parameters. In general, the influence is higher in relatively shallow water. In relatively deep water the waves hardly have any influence. In Figure 2-2 the water particle movement in waves can be seen. The maximum orbital velocity is a measure for the amount of stirring up sediment that takes place.

\[ \tau_w = \frac{1}{2} \rho f_w u_0^2 \]

*Figure 2-2: Water particle movement in waves*

The shear stress at the bottom induced by waves is given by:

\[ \tau_w = \frac{1}{2} \rho f_w u_0^2 \]

*Equation 2-2*

with:

- \( \tau_w \) bed shear stress induced by waves [N/m²]
- \( \rho \) mass density of water [kg/m³]
- \( f_w \) friction factor [-]
- \( u_0 \) maximum horizontal orbital velocity [m/s]

The friction factor under waves depends on the relative roughness of the bed. The relation for \( f_w \) in terms of the relative roughness (Jonsson, 1966 rewritten by Swart, 1976) is:

\[ f_w = \exp\left[-5.977 + 5.213\left(\frac{a_0}{r}\right)^{0.194}\right] \quad \text{if} \quad \frac{a_0}{r} > 1.59 \]

*Equation 2-3*

\[ f_w = 0.30 \quad \text{if} \quad \frac{a_0}{r} < 1.59 \]

*Equation 2-4*

with:

- \( f_w \) friction factor [-]
- \( r \) bottom roughness [m]
- \( a_0 \) maximum horizontal displacement of water particles [m]

The tidal current velocity determines the transport part. The time-average value of the total bottom shear stress is used for the stirring up of material, thus independent of the direction. The time-average value consists of a combination of \( \tau_c \) and \( \tau_w \). The following formula gives this time-average value (van der Velden, 1995):
\[ \tau_{cw} = \tau_c + \frac{1}{2} \tau_w \]  

Equation 2-5

with:

- \( \tau_{cw} \): time-averaged total bed shear stress [N/m²]
- \( \tau_w \): bed shear stress induced by waves [N/m²]
- \( \tau_c \): bed shear stress induced by current [N/m²]

2.3 Bed behaviour

2.3.1 Sand bed

For a sandy bed an important process is the initiation of motion. Particle movement will occur when the instantaneous fluid force on a particle is just larger than the instantaneous resisting force related to the submerged particle weight and the friction coefficient. Shields (1936) gave a relation between the critical bed shear stress (\( \tau_{cr} \)) and the initiation of motion for sand particles. The initiation of motion can be described in several different ways. Is motion initiated when only one particle is moving or when all particles are moving? For the sand particles it is assumed that the bed load transport starts when all particles are rolling and moving. Meyer-Peter-Muller (1948), Kalinske-Frijlink (1952) and Van Rijn (1984) have derived important formulas for the bed load transport. The bed load transport immediately adjusts to the hydrodynamic situation. Once the bed shear stress falls under the critical bed shear stress, no transport takes place anymore.

![Diagram](image)

Figure 2-3: Particle movement for a sand bed

When the bed shear stress increases even more, particles will also be taken into suspension. This happens when the shear velocity near the bed (\( u^* \)) exceeds the settling velocity (\( w_s \)). In contrast to bed load transport, suspended sediment transport does not immediately adjust to the local hydraulic conditions. Therefore, advection and diffusion have to be taken into account for suspended sediment. When the deposition of sand is equal to the erosion of sand an equilibrium concentration is reached in the water column. Once the shear velocity falls under the settling velocity, the sand particles cannot be kept suspended and will be deposited. Depending on the hydraulic conditions ripples and dunes can be formed, influencing the bed friction. Therefore bed forms have to be taken into account in computations with a sandy bed.

An important formula for sand transport including waves is the Bijker transport formula. The Bijker transport formula combines the Kalinske-Frijlink formula for the bed load transport and the Einstein formula for the suspended sediment transport. The formula consists of a transport part and a stirring up part, for the transport part the bed shear stress due to currents (\( \tau_c \)) is used, for the stirring up part the time-averaged total bed shear stress (\( \tau_{cw} \)) is used.
2.3.2 Mud bed

As was said before, the presence of clay particles causes mud to have cohesive properties. These cohesive properties cause the possibility of floc formation, called flocculation. The dominant attractive electro-statical forces between the particles cause this flocculation (Van Rijn, 1993). The intensity of flocculation depends on the concentration in the water column and turbulence. According to Krone (1962) the effect of flocculation is negligible if the concentration is smaller than 300 mg/l. In the tidal inlets in the Wadden Sea, the concentration is about 50 mg/l, so the flocculation process can be neglected.

Consolidation is an important process in mud beds. Consolidation is the process of floc compaction under the influence of gravity forces with a simultaneous expulsion of pore water and a gain in strength of the bed material. Generally, three consolidation stages are distinguished (Van Rijn, 1993).

- initial stage (days): The flocs in a freshly deposited layer are grouped in an open structure with a large pore volume. The weakest bonds are broken down first and the network gradually collapses.
- secondary stage (weeks): The pore volume between the flocs is further reduced. Small thin vertical pipes (drains) are formed allowing the pore water to escape.
- final stage (years): The pore volume inside the flocs is further reduced and the flocs are broken down.

The consolidation process is strongly affected by the initial thickness of the layer, the initial concentration of the layer and the permeability of the layer (van Rijn, 1999). The critical erosion shear stress for a mud bed increases during the available consolidation time. The exact value for this parameter is difficult to predict because of insufficient understanding of the consolidation processes. Usually 0.2 N/m² is assumed for a small consolidation time of about a day. For increasing consolidation times this value can increase up to much higher values.

When the bed shear stress ($\tau_b$) exceeds the critical value for erosion ($\tau_e$), erosion will take place (see Figure 2-4). The erosion flux is not constant in time. This parameter ranges from $1.10^3$ to $1.10^5$ kg/(m²s). The strength and the density of the bed also varies with the depth, because of the above-mentioned consolidation (Parchura and Metha, 1985). An important formula for the erosion process for mud is derived by Partheniades (1963):

$$E = m_e \left( \frac{\tau_b}{\tau_e} - 1 \right)$$

Equation 2-6

with:

- $E$ = erosion [g/(m²s)]
- $m_e$ = erosion flux [g/(m²s)]
- $\tau_e$ = critical erosion shear stress [N/m²]
- $\tau_b$ = bed shear stress [N/m²]

In this formula the bed density is assumed to be constant over the depth, thereby the erosion rate is assumed to be constant over the depth. The erosion rate is also assumed to be constant in time. This formula is used in most mud models. When the critical erosion shear stress is exceeded, the particles immediately are taken into suspension. So the transport of mud particles is suspended transport only. Advection and diffusion therefore must always be taken into account for the transport of mud particles.
Sand mud distribution in the Amelander Inlet
Sand mud distribution in a tidal inlet

![Diagram](image)

**Figure 2-4: Erosion and deposition for mud**

Once Suspended, the mud particles are not deposited until the bed shear stress ($\tau_b$) falls below the critical deposition shear stress ($\tau_d$). This will take place around slack period (see Figure 2-4). Krone (1962) derived an important formula for the deposition of mud:

$$D = \left(1 - \frac{\tau_b}{\tau_d}\right)w_mc_m$$  \hspace{2cm} Equation 2-7

with:

- $D$: deposition term [g/(m²s)]
- $\tau_b$: bed shear stress [N/m²]
- $\tau_d$: critical deposition shear stress [N/m²]
- $w_m$: settling velocity mud [m/s]
- $c_m$: mud concentration [g/m³]

The critical deposition stress $\tau_d$ ranges from 0.03 N/m² to 0.15 N/m². The settling velocity $w_m$ normally lies between 0.1 - 1 mm/s.

The critical erosion shear stress of mud is usually higher than the critical deposition shear stress of mud. Therefore, there is no situation possible where erosion and deposition of mud occurs at the same time. This implies that there is no equilibrium concentration, as there is for sand transport. However, there is a period when no erosion and no deposition of mud takes place (when $\tau_d < \tau_b < \tau_e$, see Figure 2-4). In this situation the mud bed is stable. The roughness of a mud bed is usually smaller than that of a sand bed because bed forms are not formed on a large scale on mud beds.

### 2.3.3 Mixed sand and mud bed

When mud is added to a sand bed the strength of the bed increases. This can be caused by the cohesive material working like some sort of glue between the bigger sand particles. Another explanation can be that the fine sediment fills the pores of the sand bed and thereby decreases the roughness of the bed (Torfs, 1995). As was said before, the entire bed will have cohesive properties when the clay content exceeds about ten percent. When the mud content exceeds about thirty percent, the consolidation process is determined by the finer fractions only. The presence of sand has no influence anymore (Van Kesteren, 1994).

In the Amelander Inlet, the mud concentration is low (10-50 mg/l). Therefore, hindered settling can be neglected (Van Rijn, 1998) in this study. Because sand has a higher settling velocity, the sand particles reach the bottom before the mud particles. Because hindered settling can be neglected, the deposition of mud and sand particles can be regarded separately. Under these circumstances distinct layers are being formed in the Amelander Inlet.
Though the deposition process of mud and sand can be regarded separately, the interaction between sand and mud in the bed is definitely not negligible and should be taken into account. However, usable quantitative relations are not available (yet) for the consolidation and erosion processes.

2.4 Lag effects

2.4.1 Characteristic length and time scales

As was said before, advection and diffusion have to be taken into account for suspended sediment transport. This means that the transport has a non-local character in space and time: the concentration in a given point depends on its history further upstream. The characteristic length and time scales involved in these lag effects can be estimated by (De Vriend et al, 1998):

\[ L_c = O\left( \frac{|u|h}{w_s} \right) \]
\[ T_c = O\left( \frac{h}{w_s} \right) \]

with:
- \( L_c \) characteristic decay-length (spatial lag) [m]
- \( T_c \) characteristic decay-time (time lag) [s]
- \( h \) water depth [m]
- \( w_s \) settling velocity [m/s]
- \( |u| \) representative measure of current velocity [m/s]

water level

\[ \text{track of a suspended particle when depositing} \]

bottom

\( u \)

Figure 2.5: Lag effects with suspended sediment

The characteristic time scale for a sand particle, with a settling velocity in the order of \( 10^{-2} \) m/s and with a depth of ten meters, is about fifteen minutes. This is much smaller than the tidal period, and therefore the time lag for sand is relatively small. The corresponding length scale is in the order of a kilometre (for \( u = 1 \text{m/s} \)), which is not small compared to the dimensions of the channels and shoals. The lag effect for sand therefore can have considerable effects in a tidal inlet on a spatial level.

For mud, the settling velocity is much smaller than for sand. For a settling velocity of \( 10^{-4} \) m/s, even with a small depth of one meter the minimum characteristic time scale is more than 150 minutes. Hence, the characteristic time scale for mud is relatively high, and so is the characteristic length scale. As a consequence of these large characteristic scales, the residual transport for mud is determined by other processes than the residual transport for sand. For example, the tidal asymmetry has a different effect for mud as for sand transport (see Paragraph 2.4.: “Tidal asymmetry”).
2.4.2 Tidal asymmetry

Due to tidal asymmetry, net import or export of sediment to or from a tidal inlet exists. Tidal asymmetry can take place in two ways, both depending on the geometry of the tidal basin. The first way is of main importance for the net transport of sand and the second way is of main importance for the net transport of mud.

1. Tidal asymmetry for sand transport: difference in duration flood and ebb

The difference in the duration of flood and the duration of ebb is caused by the geometry of the tidal basin. The rate between the storage area and the flow area ($A_d/A_r$) determines the asymmetry. If the channels are relatively deep and the flat area is large, the flood period is longer than the ebb period (De Vriend et al, 1998). This implies larger tidal currents and therefore, a larger sand transport during ebb. The net sand flux is seaward. If the channels are shallow and the flat area is small, the net sand flux is landward. All suspended sand particles are deposited practically immediately during slack water, so the duration of the slack period is not of importance. The geometry of a tidal inlet will develop towards an equilibrium situation, in which the ebb sand transport equals the flood sand transport.

2. Tidal asymmetry for mud transport: difference in duration slack high water period and slack low water period

In contrast to sand, mud has a large time lag. Therefore, the duration of the slack period becomes dominant over the current velocity, and determines the net transport direction. The difference in the duration of the slack periods is determined by the geometry of the tidal basin. If the channels are relatively deep and the flat area is large, the duration of slack high water period is shorter than the duration of slack low water period (De Vriend et al, 1998). This implies that during slack low water, the suspended mud particles have more time to reach the bed level and be deposited. More sediment is deposited at the end of the ebb period and the net fine mud flux is seaward. If the channels are shallow and the flat area is small, for the same reasons the net mud flux is landward.

For sand and mud the following human interference has caused a net landward transport in the past:

- When the Zuiderzee (1932) and the Lauwerszee (1967) were closed off this caused sedimentation (sand and mud) in the Wadden Sea, due to tidal asymmetry. This sedimentation has now been completed for over ninety percent and has reached the equilibrium situation (Wadatlas, 1989).

A factor that keeps changing constantly and causes a net landward transport for sand and mud is:

- The land subsidence and relative sea level rise cause a slow vertical sedimentation (sand and mud) in the Wadden Sea (Eisma, 1997). The sedimentation takes place due to tidal asymmetry for sand and for mud transport.

However, for mud transport not only the tidal asymmetry determines the net transport. In the next sub-paragraph some other processes and their influences for mud transport are explained.

2.4.3 Scour lag and settling lag

In the previous section, tidal asymmetry was described. Tidal asymmetry causes a higher mud deposition during flood slack period than during ebb slack period. In this section, two processes are described that, in combination with tidal asymmetry, cause a net import of mud into the tidal basin.

Once the mud particles are brought into motion, they can be kept moving at velocities below the threshold of initial motion (the critical erosion shear stress is usually higher than the critical deposition shear stress). Consequently, between the threshold of erosion and the threshold of deposition, material is kept in motion. During this period no new erosion takes
place. This process is called scour lag. Combined with a higher mud deposition during flood slack period than during ebb slack period, the scour lag causes a net import of mud into the tidal inlet.

Due to the lag effect during the deposition of mud particles, a settling lag occurs. On the falling tide, the mud particles will start to settle once the turbulence in the flow is incapable of maintaining them in suspension. As the particles settle they move along on the (small) current velocity. The particles eventually reach the bed some distance from the point where settling begun (characteristic length-scale). Combined with a higher mud deposition during flood slack period than during ebb slack period, the settling lag causes a net import of mud into the tidal inlet.

Concluding, the combination of the settling lag effect, the scour lag effect, the tidal asymmetry for mud transport (see Paragraph 2.4.2: “Tidal asymmetry”) causes a net landward mud transport. At present, sedimentation rates for mud in the tidal basin are in the order of 1 to 2 mm/year (Eisma, 1997).

2.5 Tidal flats

Tidal flats are generally subdivided into salt marshes (at high tide level), mud flats (near high tide level), sand flats (near low tide level) and mixed flats in a broad transition zone between mud flats and sand flats. On the flats, the extent to which waves are present is very important for the morphological development. Mud flats mainly occur in areas that are well sheltered from waves. In areas that are exposed to high wave action, the flats are sandy.

The lag-effect (see Paragraph 2.4: "Lag effects") can explain how the tide can build up a shoal. When the flats are flooded, sediment-laden water from the channel moves up the shoals, where the velocity drops and the sediment tends to settle. Due to the lag-effect, the sediment is brought further up the flats. When the tide turns and the flats are drying, the water that comes from the flats contains little sediment when it reaches the channels. Due to the lag effect, less sediment is brought back into the channels than has been carried up the flats during flood. When waves are present, the picture reverses. Waves are much more effective in stirring sediment on the flooded flats than in the deep channels. The ebb flow from the flats contains more sediment than the flood flow towards the flat. The flats are broken down by the waves (de Vriend et al, 1998).

An important feature on flats is the flora and fauna. Benthic flora and fauna can actively trap sediment and enhance deposition. Generally there is a zonation, from neap tide to spring tide high water marks, of flora that are tolerant to decreasing frequency of immersion. During the summer, benthic flora and fauna are traps for settling suspended sediment. The presence of the flora and fauna thereby increase the amount of settled mud particles on a flat (Eisma, 1997).

2.6 Sand-mud distribution in a tidal inlet

In this section, the sand-mud distribution, which is roughly expected in a tidal inlet, is described. The described expectations are based on the theory in this chapter. Generally the mud content becomes higher, further away from the actual inlet and closer towards the watersheds and coast. The tidal water velocity, the wave action and the water depth usually decrease in this direction, implying a decrease in the total energy. Therefore more fine sediment can be deposited and less big grain diameters can be suspended again and transported closer to the coast and the watershed. Only the finest sediment can reach the...
watersheds and the coast, the coarser grains remain somewhere between the actual inlet and the coast / watersheds.

Higher mud contents are found on the flats than in the deeper channels. The main reason is the difference in water depth and hence the difference in time lags (paragraph 2.4: "Lag effects"). The time needed for a grain to be deposited is smaller on a flat than in a channel. In the same slack period, more grains can be deposited on a flat than in a deeper channel. Obviously, this only matters for suspended sediment and most of all for mud particles, which have a much larger time lag than sand particles.

For the erosion rate of the mud layers, waves play an important role on the flats. Therefore, wave penetration in a tidal inlet can be very important. In the shadow of the barrier islands the wave action is much smaller than right behind the gorge. Therefore the mud content can be higher. However, locally generated wind waves can play an important role in a tidal basin if the waves from outer sea do not penetrate into the tidal basin. These locally generated wind waves are much smaller than the waves from outer sea because of the smaller fetch length and depth in a tidal basin. On the flats with small water depths however, these small waves can still have a great influence.

The mud content in a tidal inlet is also very dependent on the season. During the summer the weather is usually calm. In this period the mud can be deposited and the mud layers are being growing. During the winter the weather is rough, and wind and waves have a greater influence. The mud deposits will be eroded by wave attack, the question is how much of the mud deposits remain intact after the wave attack. Part of the mud layers are seasonal and only present during the summer, while another part is more permanent and present to some extent during the entire year.
3 Data-analysis Amelander Inlet

3.1 Introduction

The available data for the Amelander Inlet is taken from the Sediment Atlas (Rijkswaterstaat, 1998). It contains data and maps concerning the measured median grain size diameter, mud content, grain size distribution and flow velocities in the entire Dutch Wadden Sea. The measurements have been taken every five hundred metres (in morphologically active areas) or every thousand metres and have been interpolated for the points in between. Because the resolution of the measurement points is relatively low, the interpolated maps locally are not representative for the actual situation.

In this chapter the data from the Sediment Atlas is analysed and discussed. When using the data from the Sediment Atlas some aspects have to be taken into account. Therefore first some information concerning the sampling, the sample processing and the producing of the maps is given.

3.2 Measurements

3.2.1 Sampling area and period

In the period of 1989-1997, seven thousand samples have been taken from the bottom of the Wadden Sea and the Eems-Dollard. The samples for the Amelander Inlet have been taken in the period April - July of 1995. These samples have been taken with a Van Veen happer (see figure 3-1). From the Van Veen happer a mixed sample has been taken from the upper ten centimetres of the bottom. Therefore, the vertical distribution of the different sediment types is not known. The samples were taken in a steady grid. Local morphology has not been taken into account when determining this grid.

![Figure 3-1: The Van Veen happer used to take samples](image)

3.2.2 Determination of grain size distribution

After the mixing of the samples, three sub-samples are taken and analysed for the grain size distribution. From these results the average was taken. To obtain the grain size distribution, the samples are sieved to remove the grains bigger than two millimetres (gravel). These grains are weighed separately. After that, the grain size distribution is determined with the Malvern
2600L Laser Particle Sizer. Two lenses measure the grain diameters within a certain range. An alternative for the Malvern method is the traditional sieve- and pipette method. In relation to this method the Malvern method has the advantage that in a short time a lot of samples can be analysed. The results however show some differences. The main reason is that for the sieve- and pipette method, in contradiction to the Malvern method, the samples are treated to remove lime parts, organic substances and split aggregates into mineral parts. This treatment makes sure that the finer grains are all deflocculated. For the finer fraction (%<63 μm), this causes different results. In general the Malvern Laser Particle Sizer underestimates the finest fractions within the mud fraction, because the flocculation is not taken into account.

In the maps in the Sediment Atlas, the heights of the sample locations are not taken into account. The locations in the channels are directly compared to the locations on the flats. In the areas where the morphology is strongly varying between the sample points, the exact location of the sample points is of great influence. It is of great influence whether the sample points are mainly in the channels or on the flats. For example, if the sample points are mainly in the channels the map will give much coarser grain diameters than if the sample points in the same area would have been mainly on the flats.

3.2.3 Distribution parameters

The data from the Sediment Atlas contains the distribution of the grains (in mass percentage) on all sample locations. The Φ-values are ranging from -2 to 10.5. The data are treated in Excel. To convert the Φ-values into grain diameters (see Table 3-1) the following formula is used:

\[ d = 2^{-\Phi} \]

*Equation 3-1*

with:

- \( d \)  grain size diameter [mm]
- \( \Phi \)  phi-value representing grain diameter [-]

<table>
<thead>
<tr>
<th>Mud</th>
<th>Sand</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>μm</td>
<td>μm</td>
<td>mm</td>
</tr>
<tr>
<td>40</td>
<td>4000</td>
<td>Boulder</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>Cobble</td>
</tr>
<tr>
<td>60</td>
<td>500</td>
<td>Pebble</td>
</tr>
<tr>
<td>Coarse silt</td>
<td>Coarse sand</td>
<td>Granule</td>
</tr>
<tr>
<td>70</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Medium silt</td>
<td>Medium sand</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Fine silt</td>
<td>Very fine sand</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Very fine silt</td>
<td>Very coarse sand</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Coarse clay</td>
<td>Coarse sand</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Medium clay</td>
<td>Medium sand</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Fine clay</td>
<td>Fine sand</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3-1: Conversion table grain diameter to Φ-value*
The grain size distribution of the particle sizes usually follows the log-normal Gaussian distribution (see Figure 3-2). On normal probability paper the characteristics of the cumulative distribution function (CDF) are such that between the ordinates 84 % and 16 % a straight line can approximate the log-normal distribution. The grain diameter, located midway between the 84% and 16%-ordinate, is called the geometric mean size \( d_{g} \). The \( d_{84} \) and \( d_{16} \) sizes are equidistant from \( d_{g} \). This distance is called the standard deviation \( \sigma_{g} \) and is a measure for the sorting of the sample.

![Figure 3-2: Log-normal Gaussian grain size distribution](image)

The samples, taken from the Amelander Inlet can be approximated by the log-normal distribution but do not exactly follow it. The \( d_{50} \) is the diameter at which fifty percent by weight of the sediment is finer. When the size distribution follows the log-normal distribution and is symmetrical, \( d_{g} = d_{50} \). However, when this is not the case the degree of asymmetry (that means the degree in which the \( d_{50} \) deviates from the \( d_{g} \) and therefore the degree in which the distribution deviates from the log-normal distribution) can be expressed in the skewness parameter. Examples of grain size distributions, present in the Amelander Inlet, are shown in Figures FB.3-1 to FB.3-6 (Appendix A). It can be seen that the distributions with higher mud contents do not have one clear peak but two peaks (bimodal grain distribution). Often one sand-peak and one mud-peak can clearly be distinguished. If the mud content becomes very high the sand peak disappears and one mud peak is present with a tail with coarser sediment.

The following distribution parameters have been calculated in Excel:

- **Mud content:** All percentages for the grains < 63 \( \mu \)m are accumulated, giving the mud content for each sample point.
- **Clay percentage:** All percentages for the grains < 4 \( \mu \)m are accumulated, giving the clay percentage for each sample point.
- **Median diameter \( d_{50} \):** Starting from \( d = 4 \) mm (coarsest) the percentages are accumulated until 50 percent is exceeded. Between the accompanying diameter and one diameter before an interpolation takes place to determine the \( d_{50} \), the diameter at which 50 percent of the entire sample is finer.
- **Grain diameter \( d_{84} \):** As for \( d_{50} \), but now accumulation until 16 percent is exceeded, this means 16 percent of the sample is coarser and therefore 84 percent of the sample is finer (\( d_{84} \)).
- **Grain diameter \( d_{16} \):** As for \( d_{50} \), but now accumulation until 84 percent is exceeded, this means 16 percent is coarser and therefore 16 percent of the sample is finer (\( d_{16} \)).
- **Standard deviation \( \sigma_{g} \):** The standard deviation \( \sigma_{g} \), which is a measure for the sorting of the sample, is calculated with the following formula:

\[
\sigma_{g} = \sqrt{\frac{d_{84}}{d_{16}}}
\]

\textit{Equation 3-2}
Sand mud distribution in the Amelander Inlet
Data-analysis Amelander Inlet

- **Mean diameter \(d_g\):** The geometric main diameter \(d_g\) can be calculated with the following formula:
  \[
  d_g = \sqrt[3]{d_{84}d_{16}}
  \]
  \(Equation\ 3-\ 3\)

- **Skewness \(sk\):** The skewness, which is a measure for the symmetry of the sample, is calculated with the following formula:
  \[
  sk = \frac{\log \left( \frac{d_g}{d_{50}} \right)}{\log \sigma_g}
  \]
  \(Equation\ 3-\ 4\)

As was mentioned before, the Malvern method underestimates the fines within the mud fraction. Therefore, the \(d_{50}, \sigma_g\) and \(sk\) for the entire fraction are not representative values. All grain diameters < 63 \(\mu m\) have been taken out of the data selection, before these distribution parameters are calculated. So the \(d_{50}, \sigma_g\) and \(sk\) are calculated for the sand fraction only.

### 3.3 Analysis of measurements

#### 3.3.1 Introduction

The calculated distribution parameters are visualised by interpolation of the sample points in Quickin. This is only done for the parameters that are of interest to analyse: the median diameter \(d_{50-sands}\) standard deviation \(\sigma_{g-sand}\), skewness \(sk_{sands}\), the mud content and a sediment classification according to the Folk scheme (explained later on). In this section, the spatial distribution of the calculated parameters is shown and analysed.

![Figure 3-3: Depth Amelander Inlet 1993 (m)](image)

In Appendix A, the sample points from which the contour plots have been interpolated can be seen. From the sample points it can be seen whether a spot in the contour plot is caused by
just one sample point or more sample points. Furthermore, you can see whether the sample points are taken from a flat or in a channel. In this paragraph the contour plot results will be analysed. For the analysis a depth contour plot, dating from 1993, has been used too (see Figure 3-3).

In figure FB.3-7 in Appendix A, the depth is also shown, but at a finer scale to obtain a more accurate view of the flat and channel system. The depth points have been measured in 1993, while the other samples were taken in 1995. Some areas may give unexpected combinations of depth and for example mud content. This can be caused by the development of the channel and flat system in the two years between the depth measuring and sample taking. Finally, the maps with the residual sediment transport and flow velocity are taken directly from the Sediment Atlas. These will be discussed roughly and compared with the above-mentioned data.

3.3.2 Mud content

The mud content has been visualised in two different ways, ranging from 0-100 percent (see Figure 3-4) to see the sand-mud distribution on a large scale, and ranging from 0-30 percent (see Figure FB.3-10 in Appendix A) to see the same on a smaller scale. In the sand-mud distribution on a large scale some areas can be seen with a high mud content. These areas have been studied and the locations of the samples have been looked into. The mud contents are high along the entire coast of the Amelander Inlet. The high mud content in this area is caused by small water depths, small tidal velocities and a large distance from the gorge of the tidal inlet, as was explained in Paragraph 2.6 ("sand-mud distribution in a tidal inlet"). These high mud contents confirm the expectation.

Furthermore high mud contents are seen in the eastern area of the tidal basin. It looks like the drumstick shape of this island protects the area behind it from incoming waves. To compare, in the western area of the tidal basin the mud contents are much lower, while the water depths are small there too. The difference can be caused by a difference in wave- or tidal penetration. The southern coastline of Ameland in the Wadden Sea is smooth while tidal inlets interrupt the southern Terschelling coastline in the Wadden Sea. This implicates greater tidal action south of Terschelling.

From this analysis the question follows, what the tidal penetration and wave penetration in the Amelander Inlet look like. Is there a great difference between the western and eastern area of the tidal basin for these two factors? Furthermore the distance from the gorge of the tidal inlet (the source of the sediment) might play an important role. The areas with low mud contents are very close to the gorge. This distance is probably correlated in some way to the before mentioned wave and tidal penetration. The question follows, where the mud comes from; what is the source of the sediment? These questions can be answered with the help of Delft3D-FLOW for the tidal and wave penetration and Delft3D-MOR for the sediment transport (the source of the sediment).

On a smaller scale, an area with higher mud contents can be seen at the southwestern tip of Ameland (area 1). From the sample figure (Figure FB.3-8 in Appendix A), it can be seen that the sample points in this area are taken close to the coastline. It is possible, that groins have been built here to protect the coast from erosion. The high mud contents are found in the sheltered areas between the groins. At the south coast of Ameland a pier has been built for incoming ships, this might also have created a sheltered area where a lot of mud is deposited.
Figure 3-4: Mud content in Amelander Inlet (%)

Figure 3-5: Sediment classification according to Folk scheme in Amelander Inlet (-)
Also on a smaller scale, high mud contents are seen in the area in the Dantziggat channel (area 2). About six sample points in a row give high mud contents in this area. This can be caused by the time difference between the depth measuring and the sample taking (respectively 1993 and 1995). During these two years, the channels and flats might have changed position a bit. Another explanation can be the presence of old mud layers, which are reached by erosion of the channel. Because old layers have consolidated for a long time the critical erosion velocity has become very high and the mud layer is not easily eroded.

In Figure FB.3-8 (Appendix A), some points can be seen that have a significant deviating value from the values of the surrounding points. Interpolated these points are spread out and produce an area in the contour plot indicating a higher mud content. The deviating values can be caused by a mistake in the sample taking. Therefore these small spots are neglected. Because it concerns only a few points, they do not really disturb the overall visualisation of the situation, and are not removed.

With the mud content another sediment classification of the samples can be made according to the Folk scheme (Soulsby, 1997). The classification is shown in Figure 3-6. This classification has been visualised, and can be seen in Figure 3-5. Assuming that no gravel is present in the Amelander Inlet the next classification is made:

![Figure 3-6: Sediment classification according to the Folk scheme](image)

In the western area of the tidal basin the bed is sandy close to the gorge, towards the watershed and coastal area sandy mud is found. In the eastern area the bed consists of sandy mud close to the channels, closer to the watershed and coastal area sandy mud is found. It is assumed that the sand flats are located near low-tide level, while mud flats are located near high tide level (Eisma, 1997). Whether this applies for the Amelander Inlet, can be shown by plotting the water depth against the measured mud content (see Paragraph 3.4.2: "Correlation mud content-depth").

### 3.3.3 Median diameter

The median diameter $d_{50\text{-sand}}$ is a representative grain diameter for the sand fraction of the sample. This distribution parameter can be seen in Figure 3-6 for the Amelander Inlet. Average sand has a $d_{50}$ of about 0.2 mm.

The $d_{50\text{-sand}}$ in the tidal basin shows a refinement in the direction of the watershed and the coast. This refinement is also seen in the western area of tidal basin, though less than in the eastern area of tidal basin. It appears, that the western area of the tidal basin is under influence of higher tidal velocities and wave attack. The western area is closer to the gorge and therefore more influenced by tidal currents and waves. In the western area a bit further away from the gorge, the $d_{50}$ does refine, while the mud content does not increase. The refinement of the $d_{50\text{-sand}}$ is caused by a decrease of tidal and wave energy.
Figure 3-7: Median diameter sand fraction in Amelander Inlet (mm)

Figure 3-8: Standard deviation sand fraction in Amelander Inlet (―)
The mud content does not increase because of this decrease in energy. This is probably caused by the water depth; the water depth determines the time lag which is relatively high (and therefore of influence) for mud transport and relatively small for sand. It can be concluded that for the refinement of sand, the tidal and wave energy are most important. For the mud content, the water depth and thus the time lag also has great influence.

The time lag can be calculated with the results of Delft3D-FLOW. The water depth at high slack water, combined with the settling velocity of mud particles (Equation 2-8b) gives the time lag. When the time lag exceeds the available slack period, not all mud particles can be deposited.

3.3.4 Standard deviation

The standard deviation is a measure for the sorting of the sample. If the standard deviation $\sigma_s \leq 1.4$, the sediment sample is said to be well sorted. A well sorted sample contains a narrow range of grain sizes. If the standard deviation $\sigma_{g-sand} > 4$, then the sediment sample is said to be well mixed, this means that the sediment sample contains a wide range of grain sizes. In between these values the sorting is intermediate. The standard deviation has been calculated for the sand fraction of the sample, excluding the mud part. In Figure 3-7 the contour plot of the standard deviation in the Amelander Inlet can be seen.

For the sand fraction almost all sample points have a standard deviation between 1.2 and 1.5. This implies very narrow grain distributions, and little spreading around the median diameter that was seen in Figure 3-6. The median diameter does not have any correlation with the standard deviation. All sample points, whether it concerns fine or course sand, are well sorted.

3.3.5 Skewness

The skewness is a measure for the asymmetry of the grain size distribution of a sample. If the skewness is negative, that means that $d_{50}/\text{median} > d_p/\text{mean}$ (see Equation 3-4), the grain size distribution on a $\Phi$-scale has a tale in the fines. This indicates distributions, which are dominated by the finer grades; this is associated with protected calm areas where the fine grades can be deposited. If the skewness is positive, that means that $d_p > d_{50}$ and the grain size distribution on a $\Phi$-scale is skewed towards the coarser. These positive skewnesses indicate areas with sediments deposited in environments dominated by wave activity or strong current action. The skewness has been calculated for the sand fraction of the sample, excluding the mud part. Only the asymmetry of the sand peak is taken into account. For sample points with high mud contents, this value makes no sense because no sand peak is present. At these points positive skewnesses are calculated for the sand peak, that is not even present.

The skewness values range around zero, there are no areas with values higher or smaller than respectively +0.2 or -0.2. These are small values, especially for the very well sorted samples we have here. A small deviation of the perfectly symmetric distribution already gives a considerable skewness because of the small standard deviation. In the outer delta clearly a lot of points with a positive skewness can be seen where sand peaks are indeed present, indicating great wave action and tidal currents. In the tidal basin the values are around zero, negative here and there and positive mainly at the points with great mud contents (as was explained before). Overall, the protected and attacked areas cannot be recognised, because the fine fraction was not included. The only conclusions can be that the skewness for the sand fraction always remains between +0.2 and -0.2. The sand peaks in the Amelander Inlet are symmetrical.
3.3.6 Residual sediment transport and flow velocities

In Figure 3-9, the residual sand transport directions are shown. This figure has been taken from the Sediment Atlas and has been derived from the "Sediment Trend Analysis", also known as the McLaren method. From the differences in the grain diameters from location to location, the direction where the sediment has come from is derived. For this method, the median grain diameter and the accompanying grading and skewness have been used. This method however is under a lot of discussion and should therefore be used with care, for example next to other knowledge on water movement and sediment transport.

The residual inflow of sand mainly occurs along the sides of the ebb tidal delta. The residual outflow of sand in the ebb channel is dominant in the centre of the ebb tidal delta. In the channels themselves, the Borndiep as well as the Boschgat, the net sand transport is landward. Furthermore, from the channels the sand is transported towards the flats. Circulation of the sand transport takes place around the muddy flats. Figure 3-9 gives a general overview of the sediment transport directions in the Amelander Inlet, but as was said should be used with care. In Delft3D the residual sand transport directions are studied further.

In Figure 3-10, the flow velocity can be seen at four different times in a tidal period. The flow velocity is maximal at mid tide level and is around zero at high water and low water. This implies that the tidal wave in the basin has a standing character. Furthermore, it can be seen that during low water, the flats fall dry. The expected $u_{\text{max}}$ is around 1.5 m/s. Detailed knowledge about the tidal currents at different times in a tidal cycle and places in the Amelander Inlet will be gained from Delft3D-FLOW.
Figure 3-10: Residual sand transport based McLaren method (Rijkswaterstaat, 1998)

Flow velocities in tidal cycle in Amelander Inlet
- from left to right:
  picture 1: mid tide
  picture 2: low water
  picture 3: mid tide
  picture 4: high water
in cm/s

Figure 3-11: Variation flow velocities over a tidal cycle (Rijkswaterstaat, 1998)
3.4 Correlation distribution parameters

3.4.1 Introduction

In the previous section, the spatial distribution of the calculated parameters was discussed. It was noted that the mud content depends, first of all, on the water depth. Therefore, the possible correlation between the mud content and the depth is studied further. Second, the mud content seems to depend on the distance from the gorge (because of decreasing tidal and wave action further away from the gorge). The possible correlation between the mud content and the distance from the gorge is also studied in this section. Finally, the distribution parameters ($d_{50,\text{sand}}$, $\sigma_{B,\text{sand}}$ and $s_{k,\text{sand}}$) have been plotted against the mud content.

The available data points are located in the tidal basin (Wadden Sea) and the outer sea (North Sea). Because the area of interest is the tidal basin only, the data points from this area are used for the correlation figures. The data points located in the outer sea have been eliminated from the data set.

3.4.2 Correlation mud content-depth

In Figure 3-12, the mud content has been plotted against depth. Because the data from the Sediment Atlas and therefore the calculated parameters are on a grid of 500x500m, and the depth data are on a 200x200m grid, the parameters have to be linked to the depth points. This is done in Excel; the nearest-by depth point has been assigned to the mud content.

![Figure 3-12: Mud content against depth below NAP](image)

The reference depth level in Figure 3-12 is NAP. High tide level is at about -1m and low tide level is at about +1 m. There is a distinctive peak in the mud contents for depths smaller than two meters. Apparently, for these small depths the mud content can range from very small to very high values. For depths larger than two meters, the mud contents decrease towards zero. For water depths up to 2 meters the flats can be muddy or sandy. For water depths larger than 2 meter, the flats are mainly sandy.
However, there are a few scattered points. There are a few possible explanations for these deviating points. The first reason can be the presence of an old mud layer that is reached by erosion in a channel (as was explained for the Dantziggat). The second reason can be the different dates for the sample taking (April 1995) and the depth measurements (1993). A point located at a border of a channel in 1993, might have become a flat in 1995. The third reason can be mistakes, made when the two different grids are linked. The maximum mistake that can be made is a hundred meters. If a sample point is at the border of a channel it could be assigned to a depth point a hundred meters further on a flat. About the points located higher than one meter nothing can be said because there are only a few points available at this height.

The main conclusion from this figure is that high mud contents are possible but do not always occur for depths smaller than two meters. So, one precondition for high mud contents is a small water depth. Apparently, this is not the only precondition for the presence of mud layers. Other factors determine whether or not at these small water depths mud actually is being deposited or not. The main other factors are wave action, tidal penetration and the presence of benthic flora and fauna on tidal flats with the capability to trap sediment and enhance deposition. These factors influence each other too.

3.4.3 Correlation mud content-distance from the gorge

In the previous section, some factors were mentioned that have an influence on the deposition of mud in the higher located areas. Two of those factors, the tidal penetration and the wave penetration, are closely connected to the distance from the gorge of the tidal inlet. Furthermore, the mud particles come into the tidal inlet through the tidal gorge.

![Graph showing mud content against distance from the gorge](image)

*Figure 3-13: Mud content against distance from the gorge*

Therefore, the distance from the gorge is likely to have a correlation with the mud content. In Paragraph 2.6 ("sand-mud distribution in a tidal inlet") it has already been explained that in theory, a refinement takes place in a tidal inlet further away from the gorge and closer towards the water sheds and coast.
For every available data point, the absolute distance from the gorge has been calculated in Excel and plotted against the occurring mud content. Only the higher located sample points (depth < 2 meters) are shown in Figure 3-13. A few sample points, located close to the gorge but with high mud contents, have been eliminated from the data set. These points are located in between jetties or high on the island. Ten sample points like this have been eliminated from the data set.

In Figure 3-13 it can be seen that the mud contents increase when the distances from the gorge increase. For distances smaller than 5.000 m practically no high mud contents occur. For distances between 5.000 and 10.000 m the mud content increases but stays under thirty percent. For distances greater than 10.000 metres the mud content can have any value ranging from zero to a hundred percent. High mud contents can occur at these places but not necessarily do.

3.4.4 Correlation distribution parameters-mud content

The median diameter of sand is plotted against the mud content in Figure 3-14. For low mud contents between three and ten percent, the $d_{50}$-sand is ranging from 0.15 to 0.3 mm. For some samples the sand fraction is finer, while the mud content is still low. The water depth has a different influence on the median diameter than on the mud content. This explains, how a smaller median diameter for sand, does not necessarily mean that the mud content is higher too. This was also noticed in the contour plots.

![Figure 3-14: Median diameter sand fraction against mud content](image)

For higher mud contents, the median diameter for the sand fraction decreases with the increasing high mud content. The sand fraction is finer if the mud content becomes higher. This was expected, because in the areas where the mud content is higher, the tidal and wave energy is lower. The lower tidal and wave energy also cause a smaller median diameter for sand.
Figure 3-15: Sorting sand fraction against mud content

The standard deviation of the sand fraction is around 1.4 everywhere (see Figure 3-15). A value of 1.4 for the standard deviation indicates a very narrow sand peak. The few points with a little bit wider distributions probably contain coarser sediments. Conclusion from this figure, is that the sand fractions in the Amelander Inlet are well sorted everywhere and independent of the mud content.

Figure 3-16: Skewness sand fraction against mud content

The skewness value ranges around zero between +0.2 and -0.2. As was said before, these are small values. The sample points with high mud contents and accompanying higher positive skewness values should not be taken into account. At these points, the sand peak is not distinctively recognizable and therefore, the skewness value says something about the tail of
the mud peak ($\phi>4$) and not about the sand peak. From Figure 3-16, no correlation between the mud content and the skewness for the sand fraction is seen. The skewness of the sand fraction is within the same range for the entire range of mud contents.

![Graph showing clay percentage against mud content](image)

*Figure 3-17: Clay percentage against mud content*

The next parameter is the clay percentage. The clay percentage is plotted against the mud content to see the rate between the mud and clay percentage. Figure 3-17 shows a good linear relation between the clay percentage and the mud content. A line representing a clay/mud rate of 1:7 represents the data set. The scatter around this line is acceptable. However, if you take into account that the Malvern Laser Particle Sizer method is known to underestimate the finer fractions within the mud fraction, the actual clay/mud rate is probably lower than the measured clay/mud rate of 1:7.

### 3.5 Research questions

With the knowledge from the previous theoretical chapter, interesting questions follow from the data-analysis carried out in this chapter. These questions can be studied with the help of Delft3D-FLOW, Delft3D-MOR and Delft3D-WAQ. The questions are summarised in this paragraph.

- What does the tidal penetration look like?
  *Delft3D-FLOW*: look at the residual currents and the course of the tidal velocities during a tidal period, check influence of drumstick shape of the island.
- What does the wave penetration look like?
  *Delft3D-FLOW*: look at the occurring wave-heights, check influence of drumstick shape of island.
- What is the characteristic time scale for mud particles at certain water depths, and is this time available during occurring slack periods?
  *Delft3D-FLOW*: manual calculations with available slack periods and water depths.
- What is the influence of waves on the sediment transport?
  *Delft3D-MOR and Delft3D-WAQ*: compare the computations with wind and waves with the computations without wind and waves for sand as well as mud.
• Where does the deposited sediment come from, what does the transport path of the sediment particles look like?
  *Delft3D-MOR and Delft3D-WAQ*: averaged sediment transport over a tidal cycle.

• Which factors influence the difference between sand transport and mud transport?
  *Delft3D-MOR and Delft3D-WAQ*: compare the sand and the mud computations.

• Where do the mud particles transported into the tidal inlet deposit during calm weather, and which deposition areas are attacked the most by wind and waves during rough weather?
  *Delft3D-WAQ*: look at the deposition of mud with tidal action only and the erosion rate of the deposited mud layers when waves are included.

These are just the questions that raised from the data-analysis. With the results of Delft3D these questions should be answered. However during the modelling in Delft3D it can turn out that Delft3D can not really answer certain questions or other interesting questions can rise. Eventually, the conclusions and interpretations of the results will generally be based on these questions. They can be changed somewhat during the process, some aspects can be supplemented and other aspects may turn out to be less interesting.
4 Theoretical background and set-up of model

4.1 Introduction

The hydrodynamic model and sand transport model used in this study (Wilkens, 1999) have been set-up in Delft3D-MOR. The so-called Bornrifmodel was originally applied, with the goal to reproduce the development of the spit on the western tip of Ameland. Interesting conclusions from the study by Wilkens, about the Bornrifmodel are:

- The model overestimates the influence of waves, compared to the influence of tidal currents.
- In the areas that are protected from waves, the morphological activity is too small.
- The transport on the flats is probably too high in comparison to the transport in the channels.

The set-up of the Delft3D-MOR Bornrifmodel by Wilkens has largely been copied. In this chapter, the set-up and the underlying theory is described. Furthermore the changes to the original model set-up are justified. The input for Delft3D-WAQ has been set-up in this study and is explained in this chapter too.

First, the general theoretical background for the used modules in Delft3D is described. After that, the set-up of the models, applied in this study, is described. The information in this chapter is taken from the user manual of Delft2D-MOR (1996), the user manual of Delft3D-FLOW (1997), the user manual of Delft3D-MOR (2000), Wilkens (1999) and the user manual of Delft3D-WAQ (1999).

4.2 Theoretical background

4.2.1 Delft3D-MOR

Introduction

Delft3D-MOR fully integrates the effects of waves, currents and sediment transport on morphological developments. It has been designed to simulate the morphodynamic behaviour of rivers, estuaries and coasts on time scales of days to years due the complex interactions between waves, currents, sediment transport and bathymetry. Although the name suggests otherwise, Delft3D-MOR has so far only been run 2D depth-averaged. The 2DH model is coupled to a 1DV-vertical model forming a quasi-3D model. The Bornrifmodel has been set up this way too.

The modelling system consists of four modules, which are being linked, controlled and executed by the steering main module (see Figure 4-1). The four modules are:

- Delft3D-FLOW
- Delft3D-WAVES
- Delft3D-TRSSUS/TRSTOT
- Delft3D-BOTTOM

The main module controls the execution of the process simulation. Depending on the simulation, different modules are executed. The main module controls the order in which the processes are activated, and how data communication is organised. Furthermore, it has a number of options to stop a process. The simulated process is organised by the main module.
according to a user-defined process tree. The flow, wave and transport modules have a hydrodynamic time frame (one or two tidal periods). A cyclic writing mode with a user specified cycle length is applied in these modules. The bottom module has a morphological time frame, which is longer than the hydrodynamic time frame.

![Diagram of Sand distribution in the Amelander Inlet](image)

*Figure 4-1: General structure of Delft3D-MOR*

The communication file is a special file; it is used by the system to facilitate inter-module data exchange. It is created by the system, and can be used as a basis for future runs. In the Bornrifmodel, all the above mentioned modules are used.

**Flow module**

Delft3D-FLOW provides the hydrodynamic basis for the transport computations made in Delft3D-MOR and Delft3D-WAQ. The module calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing. In the Bornrifmodel the two-dimensional depth-averaged version is used to simulate flow by solving the unsteady shallow water equations in two dimensions.

The main physical phenomena, taken into account in Delft3D-FLOW (and in the applied hydrodynamic model) are:

- Tidal forcing
- Coriolis forcing
- Wind-driven flow velocity
- Wave-driven flow velocity
- Drying and flooding of tidal flats
- Bed shear stress on the bottom
- Turbulence induced mass and momentum fluxes
- Influence of waves on the bed shear stress (2D only)
- Wave induced stresses and mass fluxes (2D only)

Delft3D-FLOW solves the flow equations for an incompressible fluid, under the shallow water assumption. The system of equations consists of the horizontal momentum equations and the continuity equation.
1. Conservation of momentum in x-direction (depth and density averaged):

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{g \partial \eta}{\partial x} - f v + \frac{guU}{C^2(h + \eta)} - \frac{F_x}{\rho_w(h + \eta)} - v \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) = 0 \quad \text{Equation 4-1}
\]

2. Conservation of momentum in y-direction (depth and density averaged):

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{g \partial \eta}{\partial y} + f u + \frac{gvU}{C^2(h + \eta)} - \frac{F_y}{\rho_w(h + \eta)} - v \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) = 0 \quad \text{Equation 4-2}
\]

The following terms are present in these formulas:
(1) velocity gradient
(2),(3) advective terms
(4) pressure gradient
(5) coriolis force
(6) friction
(7) external forces (wind, waves)
(8) viscosity

3. Continuity equation (depth and density averaged)

\[
\frac{\partial \eta}{\partial t} + \frac{\partial (h + \eta)u}{\partial x} + \frac{\partial (h + \eta)v}{\partial y} \quad \text{Equation 4-3}
\]

with (for the three formula's):
- C Chezy coefficient [m^3/s]
- h bottom depth [m]
- f Coriolis parameter [m]
- F_{xy} x- en y-component of external forces [kgm/s^2]
- u,v depth averaged velocities [m/s]
- U absolute magnitude of total velocity [m/s]
- \rho_w mass density of water [kg/m^3]
- v diffusion coefficient [m^1]
- \eta water level variation [m]

Wave module

The wave module is based on HISWA. HISWA is a numerical model that obtains realistic estimates of wave parameters from given wind, bottom and current conditions. The module begins at the wave boundary where the wave characteristics are defined. From there on, the energy balance approach is applied. For each spectral wave component the rate of energy change is equal to the net effect of wave growth by wind and dissipation due to bottom friction, wave breaking and currents. The energy propagates across a grid covering the area.

Sand transport module

There are two different types of transport modules in Delft3D:
1. TRSTOT Computes the total sediment transport rate for a given flow field development, using the time dependent flow and wave fields and a fixed bed level available on the communication file.
2. TRSSUS Computes the sediment transport rates, with a separate approach for the bed load and suspended sediment transport for a given time dependent flow field.

In this study TRSSUS has been used with the Bijker formula (including waves). The Bijker formula is an equilibrium suspended sediment transport formula. The stirring effect of waves is accounted for via a wave-induced enhancement of the bed shear stress. An applied option in TRSSUS is the continuity step. In stead of using the velocity components from the flow field group CURTIM, the discharge components are used. TRSSUS, using these discharge components, the water level from the flow field group CURTIM and the actual bed level, computes the velocity components. In this way, the velocity can be updated without a re-computation of the flow field by the flow module. In the original Bornrifmodel a re-computation of the flow field is made after five continuity steps. In this study the computational time is never longer than twenty days, so a re-computation of the flow field is never necessary. Only continuity steps are made.

The depth-averaged advection-diffusion equation to be solved for suspended sand reads:

\[
\frac{\partial c_s}{\partial t} + \alpha_u \left( u \frac{\partial c_s}{\partial x} + v \frac{\partial c_s}{\partial y} \right) - \frac{\partial}{\partial x} \left( \varepsilon_x \frac{\partial c_s}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_y \frac{\partial c_s}{\partial y} \right) = \frac{(c_{se} - c_s)}{T_c} \tag{4-4}
\]

with:
- \( T_c \) adaptation time for vertical sediment concentration profile [s] (see Equation 2-8b)
- \( \alpha_u \) coefficient [-]
- \( u, v \) depth-averaged velocity [m/s]
- \( \varepsilon_x, \varepsilon_y \) dispersion coefficient [m²/s]
- \( c_s \) concentration of suspended sediment [kg/m³]
- \( c_{se} \) equilibrium concentration of suspended sediment [kg/m³]

\[
c_{se} = \frac{S_{sus}}{uh} \tag{4-5}
\]

with:
- \( S_{sus} \) suspended sand transport with Bijker formula including waves [kg/(m²s)]
- \( u \) depth-averaged velocity [m/s]
- \( h \) water depth [m]

**Bottom module**

In the module BOTTOM, the bed level variation due to gradients in the sediment transport is computed. The module reads the averaged sediment transport rates from the communication file. The determination of the bottom level changes is based on the bed level continuity equation:

\[
\left( 1 - \varepsilon_{por} \right) \frac{\partial z_b}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = 0 \tag{4-6}
\]

with:
- \( S_x, S_y \) sediment transport components [m³/s]
- \( z_b \) bed level [m]
- \( \varepsilon_{por} \) bed porosity [-]

The bottom module updates the running time, in total the running time is ten tidal periods. The time step defined for the bottom module in the main module, is overruled by an optimal time step determined in the bottom module.
The maximum value for the Courant number is set at 0.9 so that a stable computation is ensured. The optimal time step will be computed as the minimum of $\Delta t$ determined according to:

$$
\sigma_{\text{max}} = \frac{c_{\text{bed}} \Delta t}{\Delta l} \tag{4-7}
$$

with:
- $\sigma_{\text{max}}$ maximum courant number [-]
- $c_{\text{bed}}$ bed celerity [m/s]
- $\Delta t$ optimal time step [s]
- $\Delta l$ local cell width [m]

The used bed level celerity is the time-averaged celerity:

$$
c_{\text{bed}} = \frac{b_e S_{\text{ave}}}{(1 - \varepsilon_{\text{por}}) h_{\text{ave}}} \tag{4-8}
$$

with:
- $c_{\text{bed}}$ bed celerity [m/s]
- $b_e$ constant depending on the chosen sediment transport relation [-]
- $\varepsilon_{\text{por}}$ bed porosity [-]
- $S_{\text{ave}}$ time-averaged transport [m$^2$/s]
- $h_{\text{ave}}$ time-averaged water depth [m]

4.2.2 Delft3D-WAQ

Delft3D-WAQ is a 3-dimensional water quality model framework. It solves the advection-diffusion sediment equation for a predefined computational grid and for a wide range of model substances. Delft3D-WAQ allows great flexibility in the substances to be modelled, as well as in the processes to be considered. Delft3D-WAQ is not a hydrodynamic model, so information on flow fields is supplied by Delft3D-FLOW.

Before water quality computations can be made the hydrodynamic results from Delft3D-FLOW have to be converted. Conversion is required for coupling the hydrodynamic database of Delft3D-FLOW to the Delft3D-WAQ framework. The coupling module provides the computational water quality model DELWAQ with hydrodynamics in the required format.

The depth-averaged advection-diffusion equation to be solved in Delft3D-WAQ reads:

$$
\frac{\partial h c_s}{\partial t} + \frac{\partial u h c_s}{\partial x} + \frac{\partial v h c_s}{\partial y} - \frac{\partial}{\partial x} \left( D_x h \frac{\partial c_s}{\partial x} \right) - \frac{\partial}{\partial y} \left( D_y h \frac{\partial c_s}{\partial y} \right) = E - D \tag{4-9}
$$

with:
- $E$ erosion term [kg/(m$^2$s)]
- $D$ deposition term [kg/(m$^2$s)]
- $h$ water depth [m]
- $u, v$ depth-averaged velocity [m/s]
- $c_s$ suspended concentration [kg/m$^3$]
- $D_x, D_y$ dispersion coefficients [m$^2$/s]

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The erosion and deposition term are determined by the Partheniades and Krone formula's:

\[ \begin{align*}
    E &= 0 \quad \text{if } \tau_b < \tau_e \\
    E &= m_e \left( \frac{\tau_b}{\tau_e} - 1 \right) \quad \text{if } \tau_b \geq \tau_e \quad \text{Equation 4-10} \\
    D &= 0 \quad \text{if } \tau_b \geq \tau_d \\
    D &= w_m c_m \left( 1 - \frac{\tau_b}{\tau_d} \right) \quad \text{if } \tau_b < \tau_d \quad \text{Equation 4-11}
\end{align*} \]

with:
- \( \tau_b \) bottom shear stress \([\text{N/m}^2]\)
- \( \tau_e \) critical shear stress for deposition \([\text{N/m}^2]\)
- \( \tau_d \) critical shear stress for erosion \([\text{N/m}^2]\)
- \( m_e \) erosion flux \([\text{kg/(m}^3\text{s})]\)
- \( w_m \) settling velocity mud \([\text{m/s}]\)
- \( c_m \) suspended mud concentration \([\text{kg/m}^3]\)

### 4.3 Set-up of model

#### 4.3.1 Delft3D-MOR

**Structure of computations**

The flow module uses ninety percent of the entire computation time. Because a lot of computations are made over a small time span, a simplification of the original process tree is made. Only one initial flow computation (tidal action), including a spin-up time, is made. The communication file from this initial flow computation is used as a restart file for the other flow computations. Furthermore, if waves are taken into account, they are included in the flow computation. A communication file is created, including all hydrodynamic information concerning a certain wave/wind direction. The communication file can be used as a restart file for the transport computations. So the computations are split in an initial flow computation, hydrodynamic computations for different wave/wind directions (flow and waves) and transport computations (transport and bottom). The process trees are shown in Figure 4-2.

![Figure 4-2: Structure of applied computations in this study](image-url)
Grids

A curvilinear orthogonal grid (see Figure FB.4-1 in Appendix B) is used, which provides high resolution in the area around the gorge. In this area the minimum gridsize is 100 m, while in the other areas the maximum gridsize is 600 m. In this study, the main area of interest is the tidal basin. The resolution has shown to be high enough. In this study, a 1993 bathymetry with gridcells of 200x200 m was used (see Figure FB.4-2 in Appendix B), this was the closest available time to 1995 (when the bed composition data was taken). In Figure FB.4-2, the applied observation points can be seen too.

The wave module in Delft-3D is only able to handle rectangular grids. Therefore, separate grids have to be created for the computation of the wave fields. Furthermore, the angle between the orientation of the wave crests and the up-wave boundary of the grid should not exceed approximately fifteen degrees, so separate grids have to be created for each wave/wind direction. The wave grids are linked to one overall bottom grid. In this study every wave and wind direction could be of importance. Therefore eight wind and wave directions around the clock have been computed with a step of forty-five degrees in between. For these eight cases, eight different wave grids have been created with the up-wave boundary perpendicular to the wave and wind direction. The size of the gridcells is 100x200 m. This is accurate enough comparing to the available data (500x500 m), so nested grids are not necessary. In Figure FB.4-4 (Appendix B), the wave grids for wind and waves from the North and Northwest are shown as an example.

Boundaries and boundary conditions

The computational grid for the Bornrifmodel contains six boundaries. Three of them are closed boundaries located at the Wadden Sea side and the other three are open boundaries located at the North Sea side. The closed boundaries coincide with the watersheds and the coastline. The location for the western boundary at the Wadden Sea side has been adjusted in this study. In the original study this boundary was not placed on the western watershed. Therefore it has been moved towards the east, and placed exactly over the western watershed. The assumption of a closed boundary becomes more accurate. At the open boundaries boundary conditions are applied. In the study by Wilkens, the boundary types were chosen by simulating different combinations. The following combination of boundary types gave the most accurate results: West- velocity, North- current and East- velocity. The tidal information from the morphologically representative cycle is represented by harmonic conditions, which are imposed on the open boundaries in the Bornrifmodel. A tidal cycle is morphologically representative, if the tide-averaged transports approximate the transports averaged over a spring tide-neap tide cycle.

Wave conditions have to be imposed at one end of the wave grid. The wave conditions This is the up-wave boundary. The wave grid has to be large enough to keep disturbances caused by the wave boundaries out of the area of interest.

Time steps

In the original Bornrifmodel the time step for flow computations is two minutes. In this study it turned out that the drying and flooding procedures are not so accurate with this time step. Therefore, the time step in the flow module has been reduced to half a minute. This time step seems to be high enough for a small computation time and small enough to ensure accurate results. To obtain smooth computations, the time step in the transport formula is taken smaller than the time lag for a suspended sand particle. In Paragraph 2.5 ("Lag effects") it is calculated that the time lag is approximately fifteen minutes. In this study six minutes has been chosen as time step in the transport module.
Input parameters

The input of physical and numerical parameters have been kept at default values taken from the study done by Wilkens (1999). The Coriolis force has been taken into account, spiral flow has not been taken into account. The bottom roughness is set as a Manning roughness of 0.026. In Table 4-1, the default input parameters, for the flow module, are shown.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial water level</td>
<td>1.00 m</td>
</tr>
<tr>
<td>gravity</td>
<td>9.813 m/s²</td>
</tr>
<tr>
<td>water density</td>
<td>1023 kg/m³</td>
</tr>
<tr>
<td>air density</td>
<td>1.0 kg/m³</td>
</tr>
<tr>
<td>temperature</td>
<td>0 °C</td>
</tr>
<tr>
<td>salinity</td>
<td>0 p.p.m.</td>
</tr>
<tr>
<td>wind stress coefficient</td>
<td>0.025</td>
</tr>
<tr>
<td>bottom stress formulation due to waves</td>
<td>Fredsoe</td>
</tr>
<tr>
<td>horizontal eddy viscosity</td>
<td>1.0 m²/s</td>
</tr>
<tr>
<td>time step</td>
<td>0.5 min.</td>
</tr>
<tr>
<td>bottom roughness according to</td>
<td>Manning</td>
</tr>
<tr>
<td>roughness U</td>
<td>0.026</td>
</tr>
<tr>
<td>roughness V</td>
<td>0.026</td>
</tr>
<tr>
<td>extra drying/flooding procedure</td>
<td>max</td>
</tr>
<tr>
<td>threshold depth</td>
<td>0.100 m.</td>
</tr>
<tr>
<td>marginal depth</td>
<td>2 m.</td>
</tr>
<tr>
<td>smoothing time</td>
<td>60 min.</td>
</tr>
</tbody>
</table>

Table 4-1: Default input parameters flow module

The input of the physical and numerical parameters for the wave module have also been kept at default values taken from the study done by Wilkens (1999). The input parameters for the wave module are shown in Table 4-2.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectral peak enhancement factor</td>
<td>3.30</td>
</tr>
<tr>
<td>width energy distribution</td>
<td>4.00</td>
</tr>
<tr>
<td>gravity</td>
<td>9.813 m/s²</td>
</tr>
<tr>
<td>water density</td>
<td>1023 kg/m³</td>
</tr>
<tr>
<td>gams</td>
<td>0.8</td>
</tr>
<tr>
<td>gamd</td>
<td>0.88</td>
</tr>
<tr>
<td>alfa</td>
<td>1.0</td>
</tr>
<tr>
<td>wave friction</td>
<td>0.01</td>
</tr>
<tr>
<td>current friction</td>
<td>0.005</td>
</tr>
<tr>
<td>shape factor frequency spectrum</td>
<td>5.00</td>
</tr>
<tr>
<td>critical mean frequency limit</td>
<td>1.10</td>
</tr>
<tr>
<td>dissipation coefficient</td>
<td>3.00</td>
</tr>
<tr>
<td>diffusion Y</td>
<td>0.10</td>
</tr>
<tr>
<td>diffusion theta</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 4-2: Default input parameters wave module
The input of the physical and numerical parameters for the transport module have also been kept at default values taken from the study done by Wilkens (1999). The input parameters for the transport module are shown in Table 4-3.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>transport option</td>
<td>TRSSUS</td>
</tr>
<tr>
<td>time step</td>
<td>6 min.</td>
</tr>
<tr>
<td>cycle length flow</td>
<td>744 min.</td>
</tr>
<tr>
<td>cycle length waves</td>
<td>744 min.</td>
</tr>
<tr>
<td>spiral flow</td>
<td>not included</td>
</tr>
<tr>
<td>correction coeff. shields number (FYTA)</td>
<td>1.0</td>
</tr>
<tr>
<td>coefficients for slope effect</td>
<td>1000000</td>
</tr>
<tr>
<td>initial concentration of suspended sediment</td>
<td>0.00001</td>
</tr>
<tr>
<td>inflow boundary condition</td>
<td>equal to equilibrium conc.</td>
</tr>
<tr>
<td>outflow boundary condition</td>
<td>equal to upstream conc.</td>
</tr>
<tr>
<td>dispersion coefficient</td>
<td>1.0</td>
</tr>
<tr>
<td>settling velocity of suspended sediment</td>
<td>0.017 m/s</td>
</tr>
<tr>
<td>density of sediment</td>
<td>2650 kg/m³</td>
</tr>
<tr>
<td>grain size D50</td>
<td>200 µm</td>
</tr>
<tr>
<td>porosity</td>
<td>0.4</td>
</tr>
<tr>
<td>kinematic viscosity of water</td>
<td>1.0 E^6</td>
</tr>
</tbody>
</table>

Table 4-3: Default input parameters sand transport module

4.3.2 *Delft3D-WAQ*

**Structure of computations**

Suspended sediment was used as model substance and the processes simulated are deposition and resuspension. The active substances are:
- The suspended mud concentration \([g/m^3]\)
- The deposited mud on the bed \([g/m^3]\)

Three different situations for mud transport are computed in this sequence in Delft3D-WAQ:
1. First mud deposition phase during calm weather
2. Mud erosion phase during rough weather, after calm weather.
3. Second mud deposition phase during calm weather, after rough weather.

**Initial and boundary conditions**

For the two substances, initial and boundary conditions have to be defined. The initial conditions are different for the three different situations. For the first deposition phase, the initial conditions are a constant concentration of 50 mg/l and an empty bed. If the initial condition is a bed consisting entirely of mud (like in the sand computations) the transport of mud is unrealistically high. A lot of mud will be stirred up from places where mud will never be deposited. The erosion and deposition will give very extreme values that can never occur. Therefore, the initial condition has to be an "empty" bed. The rough weather attacks the deposition areas formed during the first deposition phase. Therefore, the results (concentration and mud deposition) from the last computed time step for the first deposition phase are used as initial condition for the rough weather computations. For the second deposition phase, the initial conditions (concentration and mud deposition) are the results from the last computed time step for rough weather (wave/wind direction Southwest).
The boundary conditions are similar for the three different situations. For all situations, the boundary condition on the open boundaries is a concentration of 50 mg/l and a mud deposition of 0 g/m².

**Input parameters**

For the active processes, the following process parameters have to be defined: the deposition shear stress, the erosion shear stress, the settling velocity and the erosion flux. In Paragraph 2.3 ("Bed behaviour") these parameters were mentioned and some occurring values were mentioned. These four parameters are very important but still very difficult to predict because of a lack of knowledge. For the settling velocity, a high value (1 mm/s) has been chosen, because in this way the maximum possible depositions are computed. For the same reason a low value was chosen for the erosion flux (1.10⁻⁵ kg/(m²s)). For the critical deposition shear stress an average value has been chosen in this model (0.1 N/m²). For the critical erosion shear stress the value depends on the computed situation.

During calm weather the deposits are recent so the critical erosion stress can not be taken too high (τₑ = 0.5 N/m²). During the rough weather period, the wind and waves attack the deposits after a certain period of calm weather. In this calm period the deposits have had the chance to consolidate and strengthen and therefore a higher critical erosion shear stress can be chosen in this situation (τₑ = 1.5 N/m²). During the second deposition phase, the critical erosion shear stress is also low (τₑ = 0.5 N/m²).

The default values for the process parameters and the other input parameters can be seen in Table 4-4. Some observation points are added compared to the Delft3D-FLOW computations. In Figure FB.4-5 these observation points, mainly located in possible deposition areas, are shown.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>aggregation</td>
<td>no aggregation</td>
</tr>
<tr>
<td>dispersion first direction</td>
<td>1 m²/s</td>
</tr>
<tr>
<td>dispersion second direction</td>
<td>1 m²/s</td>
</tr>
<tr>
<td>time step</td>
<td>12 min.</td>
</tr>
<tr>
<td>boundary condition concentration</td>
<td>50 g/m³</td>
</tr>
<tr>
<td>deposition shear stress</td>
<td>0.1 N/m²</td>
</tr>
<tr>
<td>minimum waterdepth for deposition</td>
<td>0.1 m</td>
</tr>
<tr>
<td>sedimentation velocity</td>
<td>80 m/d</td>
</tr>
<tr>
<td>resuspension flux</td>
<td>1000 g/(m²d)</td>
</tr>
<tr>
<td>numeric schema</td>
<td>scheme 15: iterative solver</td>
</tr>
<tr>
<td>no dispersion if flow rate is zero</td>
<td>True</td>
</tr>
<tr>
<td>no dispersion over open boundaries</td>
<td>True</td>
</tr>
<tr>
<td>use first order schema</td>
<td>True</td>
</tr>
</tbody>
</table>

*Table 4-4: Default input parameters mud transport module*
5 Hydrodynamic computations

5.1 Introduction

The Delft3D-FLOW hydrodynamic computations have been carried out for a situation with tidal action only and for different situations with tidal action and waves. Every wave/wind direction can be of importance and therefore eight directions have been computed (see Figure 5-1 for these directions). In all computations, the wind direction is similar to the wave direction at the boundaries of the model.

![Diagram of wave/wind directions]

*Figure 5-1: Computed wave/wind directions*

The computed waves can be split in two kinds:

- Wind waves generated in the outer sea penetrating into the tidal basin (called penetrating waves in the continuation of this study).
- Wind waves generated in the tidal basin (called local wind waves in the continuation of this study).

Penetrating waves only occur if the wave/wind direction is directed towards the tidal inlet. Therefore, penetrating waves are only taken into account for the directions West, Northwest, North and Northeast. For the other wave/wind directions, only local wind waves are taken into account. The standard wave parameters for the penetrating waves, and wind conditions, have been taken over from the Bornrif study (Wilkins, 1999). The values are $H_s = 2$ m and $T_p = 7$ s for the penetrating waves at the boundaries of the model, and the wind speed is 10 m/s over the entire grid. This resembles a Beaufort number of five to six. No further study has been done into the values of these wave/wind parameters.

<table>
<thead>
<tr>
<th>Flow computation</th>
<th>Tidal action</th>
<th>Wave/wind direction</th>
<th>Wave parameters</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal action</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Waves N</td>
<td>yes</td>
<td>North</td>
<td>$H_s=2$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves NWa</td>
<td>yes</td>
<td>Northwest</td>
<td>$H_s=2$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves NWb</td>
<td>yes</td>
<td>Northwest</td>
<td>$H_s=2$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves NWc</td>
<td>yes</td>
<td>Northwest</td>
<td>$H_s=4$ m, $T_p=7$ s</td>
<td>0 m/s</td>
</tr>
<tr>
<td>Waves W</td>
<td>yes</td>
<td>West</td>
<td>$H_s=2$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves SW</td>
<td>yes</td>
<td>Southwest</td>
<td>$H_s=0$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves S</td>
<td>yes</td>
<td>South</td>
<td>$H_s=0$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves SE</td>
<td>yes</td>
<td>Southeast</td>
<td>$H_s=0$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves E</td>
<td>yes</td>
<td>East</td>
<td>$H_s=0$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves N</td>
<td>yes</td>
<td>Northeast</td>
<td>$H_s=2$ m, $T_p=7$ s</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>

*Table 5-1: Overview hydrodynamic computations*
In Table 5-1 an overview is given of the hydrodynamic computations. The results for these computations are discussed and analysed in this chapter. In the last section, some of the research questions from the data-analysis are discussed with the help of the discussed results from Delft3D-FLOW.

5.2 Results hydrodynamic computations

5.2.1 Introduction

The results for the hydrodynamic computations are represented by a number of figures. The figures can be found in Appendix C. An overview of these figures is shown in Table 5-2.

| Visualisation       | $|u|/\tau$ | $d$ | $u$ | $H_{rms}$ | $\tau_{max}$ | $\tau$ |
|---------------------|-----------|-----|-----|-----------|---------------|--------|
| Borndiep            | FB.5-1a   | FB.5-1b |
| End Borndiep        | FB.5-1c   | FB.5-1d |
| Piet Scheve flat    | FB.5-2a   | FB.5-2b |
| Kromme Balg         | FB.5-2c   | FB.5-2d |
| Friesche Wad        | FB.5-3a   | FB.5-3b |
| Koffiebonen flat    | FB.5-3c   | FB.5-3d |
| Tidal variation over last tidal period | FB.5-4 - FB.5-7 | FB.5-16 - FB.5-17 |
| At high water       |           | FB.5-8 - FB.5-10 |
| Maximum during tidal period |           | FB.5-11 - FB.5-15 |

Table 5-2: Resulting figures hydrodynamic computations

with:

- $|u|/\tau$: Time variation of magnitude of respectively flow velocity and bed shear stress (for situation with tidal action) over three computed tidal periods [m/s and N/m²]
- $d$: Time variation of total water depth over three computed tidal periods [m]
- $u$: Tidal variation of flow velocity over last tidal period [m/s]
- $H_{rms}$: Root mean square wave height [m]
- $\tau_{max}$: Maximal bed shear stress during last tidal period [N/m²]
- $\tau$: Tidal variation of bed shear stress over last tidal period [N/m²]

The current magnitude, bed shear stress magnitude and the total water depth are plotted for some observation points in Figures FB.5-1 to FB.5-3 (see figure FB.4-2 in Appendix B for the locations of the observation points). After that, the flow velocity is plotted for eight different time steps in the last tidal period in Figures FB.5-4 to FB.5-7. The total water depth is plotted behind the flow velocity, so that the variation of drying and flooding of the flats can be seen too. The root mean square wave heights are plotted during high water (maximum wave heights) for every wave/wind direction, in Figures FB.5-8 to FB.5-10. Finally, the bed shear stress is shown. First, the maximum values of the bed shear stress during the last tidal period are shown for the situation with tidal action in Figure FB.5-11. Second, the maximum bed shear stress during the last tidal period is shown for every wave/wind direction in Figures FB.5-12 to FB.5-15. After that, the tidal variation of the bed shear stress over the last tidal period is shown for the situation with tidal action in Figure FB.5-16 and for the situation with wave/wind direction Southwest in Figure FB.5-17.
5.2.2 Hydrodynamics at observation points

From Figures FB.5-1 to FB.5-3 it can be seen that all computations become stable after one tidal period. The second and third tidal period give identical results. Therefore it is said that the computation has adjusted after one tidal period. During the first tidal period obvious spin-up effects are seen.

The first three observation points are located in channels. In Figures FB.5-1a and FB.5-1b, the hydrodynamics for Borndiep are shown. The tidal range is two meters. The current magnitude is zero, one hour after high tide/low tide, indicating a very small phase lag. The maximum current magnitude and bed stress magnitude occurs during mid tide ebb current, indicating that the Borndiep is an ebb-dominated channel. In Figures FB.5-1c and FB.5-1d, the hydrodynamics for the end of the Borndiep channel are shown. The tidal range is still two meters. The current magnitude has decreased some at the end of the channel, while the bed shear stress has increased. This is probably caused by the higher relative roughness because of the smaller water depth. Furthermore, the tidal wave at the end of the Borndiep channel has a phase lag compared to the Borndiep of two hours. Friction in the Borndiep channel causes this phase lag. Apparently, the tidal wave gets a propagating character in stead of a standing character. In figures FB.5-2c and FB.5-2d, the hydrodynamics for the Kromme Balg channel are shown. The current magnitude and bed stress magnitude is maximal during mid tide flood current. Therefore the Kromme Balg is a flood-dominated channel. The values for the bed stress magnitude and current magnitude are smaller than in the Borndiep channel, less transport takes place. No phase lag is seen at the Kromme Balg.

The other three observation points are located on flats. In Figures FB.5-2a and FB.5-2b, the hydrodynamics for the Piet Scheve flat can be seen. This flat is only flooded near high water. The current and bed stress magnitude are very small. In Figures FB.5-3a and FB.5-3b, the hydrodynamics for the Friesche Wad are shown. This flat is flooded a bit sooner. Therefore the bed stress magnitude and current magnitude are a bit higher, but still small. In Figures FB.5-3c and FB.5-3d, the hydrodynamics for the Koffiebonen flat are shown. The flat only falls dry very close to low water. The maximum waterdepth is almost two meters and the current and bed stress magnitude are considerably higher. On all three flats, the flooding period is shorter than the drying period. Therefore, the current and bed stress magnitudes are higher during flooding than during drying.

In the discussed hydrodynamics, waves and wind were not included. Especially at small water depths (the flats), this can make a big difference for the bed shear stress.

5.2.3 Variation of flow velocity over the last tidal period

In Figures FB.5-4 to FB.5-7, the variation of the flow velocity and the total water depth is shown over the last tidal period. Different time points in the tidal period are shown. The figures start just after low water (Figure FB.5-4a). The flow velocities are small and all flats are dry. The water is flowing into the tidal basin through the two main channels, but has not reached the flats yet. During mid tide flood current (Figure FB.5-4b), the water is reaching the flats and the lower located flats are flooded. The flow velocity is high in the channels. The first flooded flats are mainly the flats in the area around the Westgat channel and the Kromme Balg (the western area of the tidal basin). In the eastern area of the tidal basin and near the coast the flats remain dry (Figure FB.5-5a). These flats are located higher and it takes longer for the water to reach these flats. During high water (Figure FB.5-5b), all flats have been flooded. The flow velocity is small, especially on the flats. During this high water slack period, suspended sediment can be deposited on the flats (because the flow velocity and the mean water depth are small).
After high water (Figure FB.5-6a), the water starts flowing off the flats into the channels and from the channels into the outer sea. The falling dry process starts at the flats located close to the gorge. The flats located further away, notice the influence of low water in the outer sea later. The slack period lasts longer on these flats (near the coast and in the eastern area of the tidal basin). During mid tide ebb current (Figure FB.5-6b), water is flowing off all flats. On the flats in the eastern area and the coastal area the flow velocities are smaller (less water flows off). After mid tide ebb current (Figure FB.5-7a) the flats start falling dry, in the western area as well as the eastern area. At low water (Figure FB.5-7b), all flats have fallen dry. The flow velocity is small. In the areas that have not fallen dry but do have small water depths suspended sediment can be deposited during this ebb slack period.

**General conclusions:** From the above-described tidal cycle, it can be concluded that in the eastern area and coastal area of the tidal basin the tidal flow velocities are smaller than in the western area of the tidal basin. Furthermore, the tidal changes reach the flats in the western area sooner than the eastern area. The western area has to do with greater tidal action than the eastern area of the tidal basin. First of all, the western area is closer to the gorge of the tidal inlet. Second, the Boschgat and Kromme Balg are shorter channels than the Borndiep. Therefore, in the channels in the western area the tidal wave has a standing character while in the channel in the eastern area some friction takes place and the tidal wave gets a propagating character. This was also seen from the hydrodynamics for the observation point at the end of the Borndiep, where a small phase lag was present.

### 5.2.4 Root mean square wave heights

In Figures FB.5-8 (wave/wind directions North, Northeast, East and Southeast) and FB.5-9 (wave/wind directions South, Southwest, West and Northwest), the root mean square wave heights at high water are shown. The maximum wave heights (<0.3 m in almost the entire tidal basin) occur at the wave/wind directions South and Southeast. The wave heights are minimum (<0.2 m in almost the entire tidal basin) at wave/wind direction Southwest. The difference between the wave heights is not great for the different wave/wind directions, and is not great for the different locations in the tidal inlet. However, on the flats these small differences can still make a big difference. Furthermore, the eventual wave effect is very dependent on the water depth.

In Figure FB.5-10 the influence of local wind waves and penetrating waves are compared. Three computations are carried out, with the following parameters:

- Figure FB.5-10a: $H_s = 2 \text{ m}, \ \text{Wind} = 10 \text{ m/s} \ (\text{reference})$
- Figure FB.5-10b: $H_s = 2 \text{ m}, \ \text{Wind} = 0 \text{ m/s} \ (\text{no local wind waves})$
- Figure FB.5-10c: $H_s = 4 \text{ m}, \ \text{Wind} = 10 \text{ m/s} \ (\text{influence wave height})$

Without local wind waves, practically no waves are present in the tidal basin compared to the reference situation. The penetrating waves hardly penetrate into the tidal basin. From the computation with a higher significant wave height, it is seen that this parameter does not influence the wave pattern in the tidal basin. The influence of penetrating waves is only noticeable in the gorge of the tidal inlet. The waves in the tidal basin are mainly local wind waves. The wave heights in the tidal basin are dependent on the wind direction and speed, and independent of the penetrating wave height and length. Because of the negligible influence of the penetrating waves, only the wind direction is assumed to influence the wave heights in the tidal basin in the continuation of this study. Furthermore, when speaking of waves, local wind waves are meant in the continuation of this study.

### 5.2.5 Maximum bed shear stress during the last tidal period

In Figure FB.5-11, the maximum bed shear stress during the last tidal period is shown for the situation with tidal action. Only tidal currents cause the bed shear stress. The bed shear stress
is maximal in the channels. Especially in the eastern area and the coastal areas of the tidal basin, the bed shear stresses are low on the flats. In the western area of the tidal basin, the bed shear stress is relatively higher.

For the situation with waves, two different kinds of bed shear stresses can be read from the model. For sediment transport modelling it is important to predict the maximum bed shear stress during a wave cycle, $\tau_{\text{max}}$, while the current velocity and the turbulent diffusion are determined by time-mean bed shear stress, $\tau_{\text{mean}}$. In this study, sediment transport modelling and thus the $\tau_{\text{max}}$ is of interest. The maximum value of $\tau_{\text{max}}$ during the last tidal period, is shown for the situations with tidal action and waves, in Figures FB.5-12 (North and Northeast), FB.5-13 (East and Southeast), FB.5-14 (South and Southwest) and FB.5-15 (West and Northwest).

The bed shear stresses for the situations with waves are much higher than for the situation without waves. For the situation without waves, the maximum bed shear stress is lower than 2 N/m$^2$ in the largest part of the tidal basin. For the situation with waves, the bed shear stress ranges up to 12 N/m$^2$ in the tidal basin.

The maximum bed shear stresses occur for the wind directions Southeast and South. Especially in the western area of the tidal basin the bed shear stresses are high for these wind directions. In the eastern area the bed shear stresses are relatively low. The minimum bed shear stresses occur for the wind directions West, Northwest and North. For all wave/wind directions the bed shear stresses are relatively low in the eastern area. In the western area and the coastal areas the bed shear stresses can be very high, this depends on the wave/wind direction. The small differences in wave heights between the different wave/wind directions, make great differences in the bed shear stresses on the flats. The bed shear stresses are maximal in the areas with great tidal action, small water depths and high waves.

![Figure 5-2: Correlation tidal action - bed shear stress including waves](image)

For the higher located areas, the maximum bed shear stresses due to tidal action are lower than 1 N/m$^2$. In Figure 5-2 it can be seen that for these flats, the maximum bed shear stress due to waves (wind direction Southwest) increases with increasing tidal action. So great tidal action goes together with a higher bed shear stress. For the channels with higher water depths, the bed shear stress due to tidal action is higher than 1 N/m$^2$. For these channels, the bed shear stress due to waves decreases with increasing tidal action. The effect of waves becomes smaller at higher water depths.
General conclusions: For the situation without waves, the bed shear stresses are significantly lower in the eastern area than in the western area of the tidal basin. Including waves, increases the bed shear stress a lot. The combination of wave heights, tidal action and the water depth determines the actual bed shear stress for the situation with waves. For all wave/wind directions, the bed shear stresses are relatively low in the eastern area of the tidal basin. In the western area, the tidal action is great, and depending on the wind direction (and the occurring wave heights at this direction), the bed shear stresses can be very high.

5.2.6 Variation of bed shear stress over the last tidal cycle

The variation of the bed shear stress over the last tidal cycle for the situation without waves is shown in Figure FB.5-17. The variation of the bed shear stress for this situation follows the variation of the flow velocity during a tidal cycle. The bed shear stress is maximum during mid tide current, and minimum during high and low water.

The variation of the bed shear stress over the last tidal period for wave/wind direction Southwest is shown in Figure FB.5-18. The bed shear stresses are maximal during high water, because the wave heights are maximal at this time. During low water, the bed shear stresses are minimal. This is because the wave heights are smaller during low water. Furthermore, most flats have fallen dry so the total area with small water depths has decreased compared to high water.

5.3 Research questions

In this section, the results from Delft3D are coupled to the data-analysis in chapter 3. First, the research questions that were mentioned in the data-analysis and can be solved in Delft3D are repeated, after that they are discussed.

- What does the tidal penetration look like?
  Delft3D-FLOW: look at the residual currents and the course of the tidal velocities during a tidal period, check influence of drumstick shape of the island.

The tidal velocities in the tidal basin are of course the highest in the tidal channels. Other than that, the higher-located areas close to the gorge are subjected to the highest tidal velocities. The tidal influence is noticeable sooner and longer as in higher-located areas further away from the gorge. The tidal action is higher south of Terschelling (western barrier-island), where small tidal bays can be seen, than south of Ameland (eastern barrier-island), where the coast is very smooth. The cause for the smaller tidal velocities in the eastern area of the tidal basin, is the propagating character of the tidal wave in the Borndiep channel. The Borndiep is a longer channel than the ones in the western area, and the friction decreases the tidal action at the end of the Borndiep (where the eastern area of the tidal basin is located). This was also seen from a phase lag, present at the end of the Borndiep.

- What does the wave penetration look like?
  Delft3D-FLOW: look at the occurring waves, check influence of drumstick shape of island.

From Delft3D, it turns out that the penetration of waves into the tidal inlet is very small, no matter how high the significant wave height is. The waves in the tidal basin are mainly local wind waves. Therefore, no areas are really protected from waves. The local wind waves can be generated anywhere in the tidal basin, depending on the wind direction and the tidal basin's geometry. In some areas the waves are small at a certain wave/wind direction but it is very probable that for another wave/wind direction the waves are higher. The assumption that the
wave height is higher and therefore the mud content is lower close to the gorge of the tidal inlet turns out not to be true. The areas with the highest mud contents also have relatively high wave action, compared to the areas with low mud contents. Apparently, the tidal velocity has a greater influence. The sediment can be stirred up by waves, but if the velocity is very low, it will not be transported very far before it is deposited again. This way, the net transport can be very low, even for relatively high waves.

The eastern area of the tidal basin, especially close to the coast, has low values for the bed shear stress for every wave/wind direction. The waves are slightly lower than in the rest of the tidal basin. Apparently, the lower tidal velocity makes the difference in this area. This can also be seen from Figure 5-3 and Figure 5-4. The tidal action has an obvious relation with the measured mud content. For low tidal action, the mud content can be high. For greater tidal action, the mud content decreases (accept for some scatter points). For the wave heights, the mud content ranges from high to low for every value.
Sand mud distribution in the Amelander Inlet
Hydrodynamic computations

- What is the characteristic time scale for mud particles at certain water depths, and is this time available during occurring slack periods? *Delft3D-FLOW*: manual calculations with available slack periods and water depths.

The minimal time that is needed for the upper suspended mud particles to reach the bed level is calculated. This is the characteristic settling time-scale that was discussed in Paragraph 2.4 ("Time lags"). This time can be calculated with Equation 2-8a from this paragraph. This is not equivalent to the time needed to deposit all mud particles that are in suspension at a certain time. It is equivalent to the minimum time required to deposit all mud particles.

In Table 5-3, the characteristic settling time-scales can be seen for different combinations of settling velocities and water depths. The available time is very dependent on the hydrodynamic situation. Mostly about half an hour is available during slack water.

<table>
<thead>
<tr>
<th>h (m)</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>1</th>
<th>1.25</th>
<th>1.5</th>
<th>1.75</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>41</td>
<td>83</td>
<td>125</td>
<td>166</td>
<td>208</td>
<td>250</td>
<td>290</td>
<td>333</td>
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<tr>
<td>0.5</td>
<td>8</td>
<td>16</td>
<td>25</td>
<td>33</td>
<td>41</td>
<td>50</td>
<td>58</td>
<td>66</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>8</td>
<td>12.5</td>
<td>16</td>
<td>21</td>
<td>25</td>
<td>29</td>
<td>33</td>
</tr>
</tbody>
</table>

*Table 5-3: Characteristic settling time-scale mud particles (minutes)*

For the settling velocity of 1 mm/s for all higher located areas (<2 m water depth) the characteristic settling time-scale is within this half hour. For the settling velocity of 0.5 mm/s the areas with water depths smaller than 1 meter have a small enough time-decay. And for the settling velocity of 0.1 mm/s the water depth has to be smaller than 0.25 m. The time needed to deposit the mud particles is very dependent of the settling velocity and the water depth.
6 Sediment transport computations

6.1 Introduction

The set-up of the sand- and mud transport models was already described in chapter 4. The results for both computations are described in 6.2 and 6.3, respectively. In the last section of this chapter, the results for the transport computations are compared with the bed composition measurements. The research questions from the data-analysis are discussed in the last section too.

6.2 Sand transport computations

6.2.1 Overview

The sand transport computations simulate two different situations:
- Situation with tidal action only
- Situation with tidal action and waves; this situation is computed for eight different wave/wind directions

An overview of the sand transport computations is shown in Table 6-1. The computation time for all sand transport computations is ten tidal periods.

<table>
<thead>
<tr>
<th>Sand transport Computation</th>
<th>Tidal action</th>
<th>Wave/wind direction</th>
<th>Wave parameters</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal action</td>
<td>yes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Waves N</td>
<td>yes</td>
<td>North</td>
<td>$H_s=2$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves NW</td>
<td>yes</td>
<td>Northwest</td>
<td>$H_s=2$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves W</td>
<td>yes</td>
<td>West</td>
<td>$H_s=2$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves SW</td>
<td>yes</td>
<td>Southwest</td>
<td>$H_s=0$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves S</td>
<td>yes</td>
<td>South</td>
<td>$H_s=0$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves SE</td>
<td>yes</td>
<td>Southeast</td>
<td>$H_s=0$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves E</td>
<td>yes</td>
<td>East</td>
<td>$H_s=0$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Waves N</td>
<td>yes</td>
<td>Northeast</td>
<td>$H_s=2$ m, $T_s=7$ s</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>

Table 6-1: Overview sand transport computations

The results for the sand transport computations are represented by Figures FB.6-1 to FB.6-5. These are shown in Appendix D. In Table 6-2, it can be seen which parameters are shown in which figure. For the sand transport computations, three parameters are shown: the averaged sand transport, the bed level change and the tidal variation of the sand concentration. In Table 6-2, it can be seen that these three parameters are shown for different situations. First of all, the parameters are shown for the situation with tidal action only (Figure FB.6-1 and FB.6-2). Second, the parameters are shown for the situation with the reference wave/wind direction Southwest (Figure FB.6-3 and FB.6-4). Local wind waves are most important in the tidal basin. The wind direction Southwest occurs most frequently (see compass rose in figure E-1, appendix E) and therefore, this is the reference wave/wind direction.

Finally, the parameter bed level change is shown, representing all computed wave/wind directions (Figure FB.6-5). To obtain this figure, weighting factors have been applied. The weighing factors represent the frequency of occurrence for a wind direction. In appendix E,
it is explained how the weighting factors are defined. For every wave/wind direction, the computed bed level change is multiplied with the relevant weighting factor. The results for all wave/wind directions are added up. In this way, one figure with a bed level change representing all wave/wind directions is obtained.

<table>
<thead>
<tr>
<th>Computation</th>
<th>$\Delta z$</th>
<th>$S_{tot}$</th>
<th>$c_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal action</td>
<td>FB.6-1a</td>
<td>FB.6-1b</td>
<td>FB.6-2</td>
</tr>
<tr>
<td>Waves Southwest</td>
<td>FB.6-3a</td>
<td>FB.6-3b</td>
<td>FB.6-4</td>
</tr>
<tr>
<td>Waves all directions</td>
<td></td>
<td>FB.6-5</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6-2: Resulting figures sand transport computations*

with:

- $S_{tot}$ Tidally averaged suspended and bed load transport [kg/(m$^3$)]
- $\Delta z$ Bed level change after ten tidal periods [m]
- $c_s$ Tidal variation suspended sand concentration at four time points: mid tide flood and ebb current and high and low water [kg/m$^3$]

### 6.2.2 Results sand transport computations

First, the results for the situation with tidal action only are shown. In Figure FB.6-1a, the averaged bed- and suspended load is shown for this situation. Virtually no transport is induced by tidal action on the higher located areas. In the main channels and the branches some sand transport is induced. The averaged transport is mainly directed seaward, which implies ebb-dominated channels (Borndiep and Westgat). At the sides of the main channels the averaged direction is landward (flood-dominated). Furthermore, the transport is higher through the Borndiep than through the Westgat. From the bed level change in Figure 6-1b, the same pattern is seen. The morphologically active areas are located in the channels. The erosion and deposition areas are located close to each other. Close to every erosion-area, an area is located where the eroded sand is deposited again. In Figure FB.6-2, the tidal variation of the sand concentration is shown. The initial concentration is $1.10^{-5}$ kg/m$^3$. The concentration immediately drops to lower values in almost the entire tidal basin. Only in the channels, some of the sand particles can be kept in suspension. During high slack water, the concentration is extremely low everywhere, because the tidal currents are very small. The concentration values are compared to the bed shear stresses at the same time (Figure FB.5-17 in Appendix C). The patterns for the suspended concentration follow the patterns for the bed shear stress.

Second, the results for the situation with tidal action and wave/wind direction Southwest are shown. In figure FB.6-3a, the averaged bed- and suspended load is shown for this situation. The net sand transport has increased compared to the situation without waves (Figure FB.6-1a). In the side branches with smaller water depths but also a considerable tidal action, the net sand transport has increased a lot. The transport on higher located areas, increases dramatically due to the wave effect, too. On higher located areas the suspended load/bed load rate is smaller than in the areas with larger water depths. In Figure 6-3b (the bed level change for this situation), it can be seen that the morphologically active areas are still located mainly around the main channels and side branches. Due to waves, the morphological active areas are extended around the channels. However, the morphological activity is still small for the higher located areas. In Figure FB.6-4, the tidal variation of the sand concentration is shown. The initial concentration is also $1.10^{-5}$ kg/m$^3$. The concentration values in the channels are relatively low. Due to the large stirring effect of waves, the sand concentration is high on the flats. For this situation, the sand concentration values are also compared to the actual bed
shear stresses (Figure FB.5-18 in appendix D). Again, the patterns for the suspended concentration follow the patterns for the bed shear stress in the entire tidal basin. Finally, the bed level change representing all wave/wind directions is shown in Figure FB.6-5. Practically the same erosion and deposition patterns are seen as for the situation with waves from the Southwest. Only small differences are seen, and only locally.

6.2.3 Discussion sand transport computations

Close to every erosion-area, an area is located where the eroded sand is deposited again. This pattern is typical for sediment transport computations without morphological bottom updates. The initial sediment transport is computed and not the morphological development for a long period of time. Though these computations do not represent the actual morphological development, it can be concluded that the suspended sand particles adapt almost instantaneously to the local hydrodynamic conditions. The quick adjustment of the sand concentration to the actual hydrodynamic conditions indicates that the time and space lags for suspended sand transport are small. For the situation with tidal action only, the concentrations are maximal in the channels. For the situations with tidal action and waves, the concentrations are maximal on the flats.

For the situation with tidal action only, the main channels are morphologically active. Due to the wave effect, the morphological activity is increased in these areas and extended towards the side channels with smaller water depths. Despite the large stirring effect of waves, the higher located flats are not morphologically active. The tidal current is too weak to induce high net sand transports. If the stirring effect due to waves is large, but the tidal current is weak, the net sand transport is small. If the tidal current is strong, the large stirring effect due to waves can increase the morphological activity drastically.

Finally, from the comparison of the bed level change due to wave/wind direction Southwest with the bed level change due to all wave/wind directions, it can be concluded that the wave/wind direction does not influence the main directions and intensity of the net sand transport.

6.3 Mud transport computations

6.3.1 Overview

The mud transport computations also simulate the situation with tidal action only and the situation with tidal action and waves. The situation with tidal action only, simulates a period with calm weather. During this period, it is expected that mud deposits in areas with small tidal currents. The situation with tidal action only is called the deposition phase (1). The deposition phase is computed for six months. It is assumed that the calm weather takes place for a long period in a row. The situation with tidal action and waves simulates a period with rough weather. During this period, it is expected that the mud deposits from the previous phase are eroded by wave attack. The situation with tidal action and waves is called the erosion phase (2). The erosion phase is computed for twenty tidal periods. It is assumed that the rough weather period does not take place for a long period in a row. During the erosion phase, a lot of mud particles are taken into suspension. To see what happens with these mud particles, once the weather calms down after rough weather, a second deposition phase (3) is computed. It is expected that part of the eroded mud deposits return during this phase, because the suspended mud particles are deposited again. The second deposition phase is computed for twenty days, using the results from reference wave/wind direction Southwest as initial conditions.
Mud transport Computation | Wave/wind direction | Initial conditions | Computation time | $\tau_c$ (N/m²)
--- | --- | --- | --- | ---
1a. First dep. phase short | - | Empty bed, $c_m=50$ mg/l | 20 days | 0.5
1b. First dep. phase long | - | Empty bed, $c_m=50$ mg/l | 6 months | 0.5
2a. Erosion phase N | North | results 1b | 20 T | 1.5
2b. Erosion phase NW | Northwest | results 1b | 20 T | 1.5
2c. Erosion phase W | West | results 1b | 20 T | 1.5
2d. Erosion phase SW | Southwest | results 1b | 20 T | 1.5
2e. Erosion phase S | South | results 1b | 20 T | 1.5
2f. Erosion phase SE | Southeast | results 1b | 20 T | 1.5
2g. Erosion phase E | East | results 1b | 20 T | 1.5
2h. Erosion phase NE | Northeast | results 1b | 20 T | 1.5
3. Second dep. phase | - | results 2d | 20 days | 0.5

Table 6-3: Overview mud transport computations

In Table 6-3, an overview of the computed mud transport computations is shown for the different phases. The results for the mud transport computations are discussed in the following subparagraphs (6.3.2 to 6.3.4).

6.3.2 Mud transport computations first deposition phase

Overview figures

The results for the first deposition phase are represented by the Figures FB.6-6 to FB.6-12. An overview of these figures representing is given in Table 6-4. Two observation points are used for the results: Piet Scheve (see Figure FB.4-2 in Appendix B) and Vrijheidsflat (see Figure FB.4-4 in Appendix B: point 5). For these observation points, the bed shear stress, the mud concentration and the mud deposition during the first twenty days are shown in respectively Figures FB.6-6 and FB.6-8. The same parameters are shown for the same observation points in Figures FB.6-7 and FB.6-9, but now for the last tidal periods (equilibrium situation). In Figures FB.6-10 and FB.6-11, the mud concentration and deposition for four time points in a tidal period are shown for the equilibrium situation. These time points are: mid tide flood, high water, mid tide ebb and low water. Finally, in Figure FB.6-12 the total mud deposition after six months is shown.

| Visualisation | $\tau_{\text{max}}$ | $c_m$ | D | $D_{\text{total}}$
--- | --- | --- | --- | ---
Piet Scheve adjustment time | FB.6-6a | FB.6-6b | FB.6-6c |
Piet Scheve equilibrium situation | FB.6-7a | FB.6-7b | FB.6-7c |
Vrijheidsflat adjustment time | FB.6-8a | FB.6-8b | FB.6-8c |
Vrijheidsflat equilibrium situation | FB.6-9a | FB.6-9b | FB.6-9c |
Tidal variation equilibrium situation | | FB.6-10 | FB.6-11 |
One time point | | | | FB.6-12 |

Table 6-4: Resulting figures mud transport computations for first deposition phase

with:

$\tau_{\text{max}}$ Bed shear stress for tidal action only [N/m²]
$c_m$ Suspended mud concentration [g/m³]
D Mud deposition first deposition phase [g/m²]
$D_{\text{total}}$ Total mud deposition after six months [g/m²]
Observation points Piet Scheve and Vrijheidsflat

The results for observation point Piet Scheve are shown first. In Figure FB.6-6, the bed shear stress (FB.6-6a), the mud concentration (FB.6-6b) and the mud deposition (FB.6-6c) are shown for the first twenty days at Piet Scheve. It can be seen that during the first few tidal periods, the mud concentration adjusts to the hydrodynamic conditions by decreasing (see Figure FB.6-6b). After about seven days, an equilibrium situation is reached. Because the mud concentration decreases during the first tidal periods, the net mud deposition per tidal period decreases too. When the equilibrium situation is reached, the net mud deposition per tidal period becomes constant (see Figure FB.6-6c).

In Figure FB.6-7, the same parameters are shown in detail for the equilibrium situation. In Figure 6-7a, the bed shear stress is plotted. In Figures FB.6-7b and FB.6-7c, the mud concentration and deposition are shown respectively. When the point is flooded, the bed stress exceeds the critical erosion shear stress of 0.5 N/m². Some mud particles are eroded and the suspended mud concentration increases. At slack water, the bed shear stress drops under 0.1 N/m². Suspended mud particles are being deposited and the suspended mud concentration decreases. Because the deposition during a tidal period is higher than the erosion, the mud layer is growing at the Piet Scheve point. During the equilibrium situation, the maximum mud concentration is about 10 g/m³ and the constant growing rate of the mud layer is about 5 g/m² per tidal period. After six months, about 1900 g/m² has been deposited at Piet Scheve, to give a quantitative idea of this number, the layer thickness is calculated:

\[ d = \frac{1900 \text{g/m}^2}{3.10^3 \text{g/m}^3} = 0.0063 \text{m} = 6.3 \text{mm} \]

Second, the results for the observation point Vrijheidsflat are shown. In Figure FB.6-8, the bed shear stress (FB.6-8a), the mud concentration (FB.6-8b) and the mud deposition (FB.6-8c) are shown for the first twenty days at Vrijheidsflat. The adjustment period of the mud concentration can be seen at the Vrijheidsflat too. The mud concentration and net deposition per tidal period decrease in the first few tidal periods. After about 4 days, the equilibrium situation is reached.

In Figure FB.6-9, the same parameters are shown in detail for the equilibrium situation. In Figure 6-9a, the bed shear stress is plotted. In Figures FB.6-9b and FB.6-9c, the mud concentration and deposition are shown respectively. The critical erosion shear stress is never exceeded at this point. At slack water, the bed shear stress drops under 0.1 N/m², mud is deposited and the mud concentration decreases. During the equilibrium situation, the maximum mud concentration is about 5 g/m³ and the constant growing rate of the mud layer during is about 2.5 g/m². After six months, about 550 g/m² has been deposited at Piet Scheve. The net deposition rate during a tidal period is lower than for the Piet Scheve flat.

Tidal variation mud concentration and deposition

In Figure FB.6-10, the tidal variation of the mud concentration is shown for the equilibrium situation of the first deposition phase. During rising water, the tidal currents increase and mud is suspended in the areas where the bed shear stress exceeds 0.5 N/m². The mud concentration increases. At high slack water, the mud concentration decreases again. On the flats, all mud particles are being deposited, while for the areas with higher water depths a part of the mud particles are kept in suspension. After high water, the mud concentration stays about constant in the entire tidal inlet until low slack water is reached. At low slack water, the mud concentration decreases again because mud particles are being deposited.

The tidal variation of the mud deposition for the equilibrium situation of the first tidal period is shown in Figure FB.6-11. During high slack water, the first deposits are seen in the western area of the tidal basin. Later, slack water reaches the eastern area and mud is deposited there.
too. During mid tide ebb current, mud is being eroded. Most erosion takes place in the western area of the tidal basin. The largest part of the mud that was deposited in the eastern area of the tidal basin remains behind. The largest part of the deposited mud particles in the western area, are eroded during mid tide ebb current. During low slack water, only a small amount of mud particles is deposited.

The tidal variation of the mud concentration and deposition during the first deposition phase is compared with the tidal variation of the bed shear stress for tidal action (Figure FB.5-17). The mud concentration adjusts to the bed shear stress fast at the higher located areas. In the other areas (water depth $> \pm 1.5$ m), the mud concentration cannot follow the bed shear stresses immediately. During high slack water, not all mud particles are deposited in these areas while the bed shear stresses are very low.

**Total mud deposition after six months**

In Figure FB.6-12, the total mud deposition after six months is shown for the first deposition phase. The deposition areas are mainly located in the coastal areas, and close to the watersheds. In the western area, the amount of deposition in the deposition areas is larger than in the eastern area of the tidal basin. However, in the eastern area the deposition areas are relatively larger in size. In the western area, the deposition areas are only located very close to the coast and watershed. In the eastern area, the deposition areas are further extended towards the centre of this area.

In Figure 6-1, the total mud deposition after six months for the situation with tidal action only has been plotted against the water depth below NAP. A water depth of -1 m is located at high tide level, and a water depth of +1 m is located at low tide level.

![Figure 6-1: Correlation water depth-total mud deposition after six months](image)

The water depth shows a peak in the mud deposition for water depths smaller than $+1.5$ m and larger than $-1$ m (high tide level). The highest mud depositions are present at water depths between 0 m (NAP) and $+1$ m (low tide level).

In Figure FB.6-2, the correlation between the total mud deposition after six months and the maximum bed shear stress during a tidal period for the situation with tidal action is shown.
The mud deposition first increases with an increasing bed shear stress until the maximum bed shear stress has reached a value of about 0.5 N/m². After that, the mud deposition decreases with an increasing bed shear stress. For areas with a maximum bed shear stress higher than 1.5 N/m², practically no net deposition takes place.

Discussion results

If more mud particles are deposited than suspended during a tidal period a net deposition area is observed in the results. Once the equilibrium situation is reached, the deposition rate becomes constant. To obtain a high deposition rate, two contrary demands apply:

- On the one hand, the bed shear stress must be low, at least during some part of the tidal period, to obtain a deposition area.
- On the other hand, the bed shear stress must be high to supply mud from the surrounding area.

For areas with higher water depths, the time lag is considerable for mud deposition. During high slack water most mud is deposited in the western area of the tidal basin, where the concentration is highest. However, these high concentrations also imply greater tidal action. Therefore, at these areas most deposited mud particles are taken into suspension again during mid tide ebb current. The main deposition areas are the areas, where the deposition is low during high slack water. These low depositions will not be suspended during the rest of the tidal period, because the tidal action is small.

The main deposition areas are seen in the coastal areas and at the watersheds. In the eastern area the deposition areas are relatively larger. At the watersheds, a closed boundary has been applied in the model, which is not a correct assumption. Especially at the western watershed, a lot of water (and sediment) is transported over the watershed, and the closed boundary therefore does not represent the real situation. At this watershed, the computed deposition is probably too high.
6.3.3 Mud transport computations erosion phase

Overview figures

The results for the erosion phase are represented by the Figures FB.6-13 to FB.6-21. An overview of these figures is given in Table 6-5. For two observation points (Piet Scheve and Vrijheidsflat), the bed shear stress, the mud concentration and the mud erosion are shown for the first six tidal periods in Figures FB.6-13 and FB.6-14 respectively. After that, in Figure FB.6-15, the mud concentration for four time points in the second tidal period is shown. These four time points are: mid tide flood, high water, mid tide ebb and low water. During the first tidal period, small depositions (in areas that are not net deposition areas) are eroded, and spin-up effects can take place. Therefore, the results for the second tidal period are shown. In Figures FB.6-16 to FB.6-19, the net erosion during the second tidal period is shown, for every wave/wind direction. In Figure FB.6-20a, the net erosion during the second tidal period is shown, representing all wave/wind directions together (including weighting factors, see Appendix E). In Figure FB.6-20b, the number of tidal periods it takes to erode the entire mud deposition after six months (during first deposition phase) is shown. The net erosion during the second tidal period representing all wave/wind directions is taken as erosion rate per tidal period. Finally, in Figure FB.6-21 the change in concentration during the erosion phase is shown. In Figure FB.6-21a, the concentration is shown at the beginning of the erosion phase and in Figure FB.6-21b, the concentration is shown at the end of the erosion phase.

<table>
<thead>
<tr>
<th>Visualisation</th>
<th>( \tau_{\text{max}} )</th>
<th>( c_{\text{m}} )</th>
<th>E</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piet Scheve first six tidal periods</td>
<td>FB.6-13a</td>
<td>FB.6-13b</td>
<td>FB.6-13c</td>
<td></td>
</tr>
<tr>
<td>Vrijheidsflat first six tidal periods</td>
<td>FB.6-14a</td>
<td>FB.6-14b</td>
<td>FB.6-14c</td>
<td></td>
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<tr>
<td>Variation over second tidal period</td>
<td></td>
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<td>FB.6-15</td>
<td></td>
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<tr>
<td>Net erosion for second tidal period, for every wave/wind direction</td>
<td></td>
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<td>FB.6-16 to 6-19</td>
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<tr>
<td>Net erosion for second tidal period, representing all wave/wind direct.</td>
<td></td>
<td></td>
<td>FB.6-20a</td>
<td></td>
</tr>
<tr>
<td>Number of tidal periods needed to erode the deposited mud layer</td>
<td></td>
<td></td>
<td>FB.6-20b</td>
<td></td>
</tr>
<tr>
<td>Time point beginning erosion phase</td>
<td>FB.6-21a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time point end erosion phase</td>
<td>FB.6-21b</td>
<td></td>
<td></td>
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</tbody>
</table>

Table 6-5: Resulting figures mud transport computations for erosion phase

with:

- \( \tau_{\text{max}} \) Bed shear stress including wave/wind direction Southwest [N/m²]
- \( c_{\text{m}} \) Suspended mud concentration [g/m³]
- E Mud erosion [g/m²]
- T Number of tidal periods needed to erode the entire mud layer that was deposited during first deposition phase [-]

Observation points Piet Scheve and Vrijheidsflat

In Figures FB.6-13a, FB.6-13b and FB.6-13c respectively the bed shear stress, the mud concentration and the mud erosion are shown for the observation point Piet Scheve, for the situation with tidal action and wave/wind direction Southwest. In Figure FB.6-13a, it can be seen that the bed shear stress exceeds the critical erosion shear stress (1.5 N/m² in the erosion phase) amply. Furthermore, it can be seen that erosion \((\tau_{\text{c}} > \tau_{\text{s}})\) takes place during almost the entire period that the flat is flooded. In Figure FB.6-13b, the mud concentration is seen. Due to the inclusion of waves, the mud concentration has increased from 10 g/m³ (Figure FB.6-7b) to 400 g/m³. During the erosion phase, the mud concentration is increasing linearly in time. In
Figure FB.6-13c, it can be seen that the erosion rate for the mud layer is much larger than the deposition rate during the previous phase (Figure FB.6-7c). The erosion rate is about 300 g/m² per tidal period. The mud layer that was deposited in six months is eroded in approximately three days. The influence of the τc/τx rate on the erosion rate can be seen combining Figures FB.6-12a and FB.6-12c. During falling water, the bed shear stress decreases and the erosion rate decreases too.

In Figures FB.6-14a, FB.6-14b and FB.6-14c respectively the bed shear stress, the mud concentration and the mud erosion are shown for the observation point Vrijkheideflat, for the situation with tidal action and wave/wind direction Southwest. In Figure FB.6-14a, it can be seen that the bed shear stress including is much lower than for the Piet Scheve flat. The critical erosion shear stress is exceeded, but not amply. In Figure FB.6-14b, it is shown that the mud concentration increases from 5 g/m³ (Figure FB.6-8b) to 175 g/m³ due to the inclusion of waves. During the erosion phase, the mud concentration is decreasing linearly in time at the Vrijkheideflat. In Figure FB.6-14c, the erosion rate is shown. The erosion rate is about 35 g/m² per tidal period (much smaller than at Piet Scheve!). Though less mud was deposited, a longer period of rough weather is needed to erode the entire mud layer. So, the deposition rate is smaller at the Vrijkheideflat, but the erosion rate is also smaller.

**Tidal variation mud concentration**

In Figure FB.6-15, the variation of the mud concentration for the situation with wave/wind direction Southwest is shown. The mud concentration is high during low water. During rising water, the mud concentration decreases. During high water the mud concentration is minimal. After that the mud concentration increases again until low water is reached. At low water, the mud concentration is maximal. Furthermore, it can be seen that the areas with the largest depositions during the previous phase have high mud concentrations during the period with waves. In the eastern area the mud concentration is relatively low, especially in the coastal area.

**Net mud erosion for second tidal period**

From the history plots (Figure FB.6-13 and FB.6-14), it was seen that the mud erosion rate is higher than the mud deposition rate. At the end of the computation time (ten days) a lot of the deposited mud particles will have been taken into suspension. Therefore, the net mud erosion is shown for the second tidal period. In this way a qualitative idea is given of the extent to which a flat is attacked by waves. The net mud erosion is only studied for the points where net deposition occurred during the first deposition phase.

In Figures FB.6-16 (a. North- b. Northwest), FB.6-17 (a. West- b. Southwest), FB.6-18 (a. South- b. Southeast) and FB.6-19 (a. East- b. Northeast), the net mud erosion for the second tidal period is shown. In general, there is not a lot of difference between the different wind directions. The only distinct differences occur at the barrier islands' coasts and at the western coastal area. The first area is well protected during wind from the Northeast, North and Northwest (FB.6-19b, FB.6-16a and FB.6-16b). Especially during the wind directions Southeast, South, Southwest (FB.6-18b, FB.6-18a and FB.6-17b) this area is heavily attacked. The second area is well protected during almost all wind directions, but for the directions Northeast, North and Northwest (FB.6-19b, FB.6-16a and FB.6-16b) the area is attacked a bit more. The erosion rate in the eastern coastal area of the tidal basin is small for every wave/wind direction. The erosion rate is higher in the western area of the tidal basin.
In Figure 6-3, the erosion and deposition during the second tidal period for wave/wind direction Southwest has been plotted against the mud deposition after six months for the first deposition phase. The sharp increasing line for the erosion with an increasing deposition represents the lack of mud particles to be eroded. When all mud particles present are eroded, the erosion cannot increase more. For areas with small mud depositions during the previous phase, the erosion ranges from very small towards the limiting factor of the present mud deposition. For areas with a larger deposition, the present mud deposition is not a limiting factor anymore. In some areas, even during the erosion phase, net deposition takes place.

In Figure 6-4, the correlation between water depth below NAP and the computed erosion rate is shown. The scatter plot indicates a clear trend, with higher erosion rates associated with shallower water depths.
The erosion rate for wave/wind direction Southwest is plotted against two influencing factors, the water depth and the bed shear stress including waves. In Figure 6-4, the influence of the water depth is shown. For very small water depths, the erosion rate is small. When the water depth increases, the erosion rate increases too. This continues until the water depth is about 0.5 m, after that the erosion rate decreases again. The described pattern is the same as for the total mud deposition in the previous phase, shown in Figure 6-2. In Figure 6-2, a peak in the net mud deposition is observed also at a water depth of about 0.5 m.

![Bed shear stress including waves (N/m²)](image)

**Figure 6-5 : Correlation bed shear stress (incl. waves) - computed erosion rate**

In Figure 6-5, the correlation between the bed shear stress and the erosion rate is shown for wave/wind direction Southwest. For small bed shear stresses, the deposition areas are not eroded at all. The depositions are even growing for a few points. For maximum bed shear stresses during a tidal period higher than 2 N/m², the erosion rate starts increasing with the increasing bed shear stress.

In Figure FB.6-20a, the net erosion rate during the second tidal period, representing all wave/wind direction is shown. In the eastern coastal area and at the borders of the tidal basin the erosion rate is not high. An exception is the area at the western watershed, where the erosion rate is very high. At the deposition areas in the centre of the tidal basin, the erosion rate is also very high. In Figure FB.6-20b, the number of tidal periods it takes to erode the deposited mud layers during the first deposition phase, is shown. The net erosion rate representing all wave/wind directions was taken to obtain this figure. In the eastern coastal area the erosion goes slowly. In the western area the erosion rate is high. However, large mud layers were deposited during the deposition phase. Therefore, the number of tidal periods it takes to erode these mud layers is not as low as would be expected from the high erosion rate. In the western area at the coast of Terschelling, the erosion of the mud layers goes very slowly.

**Change in concentration during erosion phase**

In the history plots (Figures FB.6-13 and FB.6-14), it was seen that at Piet Scheve the concentration increases during the erosion phase, while at Vrijheidsflat the concentration decreases during the erosion phase. To see this change in concentration during the erosion phase, the concentration is shown for the first tidal period and for the last tidal period in
Figure FB.6-20. During the first tidal period (Figure FB.6-20a), the concentration follows the hydrodynamic conditions (see bed shear stress wave/wind direction Southwest in Figure FB.5-15). The concentration is high in areas with high bed shear stresses, and low in areas with low bed shear stresses. During the last tidal period, the concentration has diffused in the tidal basin. The concentration in areas with high bed shear stresses have decreased, while the concentration in areas with low bed shear stresses have increased. The concentration is still higher in the areas with high bed shear stresses, but the difference with the areas with low bed shear stresses has become smaller.

Discussion results

The erosion rate during the erosion phase is much higher than the deposition rate during the first deposition phase. The parameters $m_e$ (erosion flux) and $w_m c_m$ (deposition flux) are of the same order of magnitude. The difference in the erosion and deposition rate must be caused by the difference in $\tau_b/\tau_d$ rate and $\tau_e/\tau_d$ rate. Furthermore, it was also seen that more time is available for erosion to take place, than there was for deposition to take place. This depends on the period of time during a tidal period that respectively $\tau_b > \tau_e$ and $\tau_e < \tau_d$.

From the computations for the erosion phase, it can be concluded that the wave/wind direction influences the erosion pattern only for a few areas. In general, for all wave/wind directions, the net erosion rate for the second tidal period is small in the eastern area of the tidal basin and in the coastal area. At the western watershed and in the centre of the tidal basin, the erosion rate is much higher. However, because the deposition was large at the western watershed it still takes the waves quite some tidal periods to erode the entire deposited mud layer.

The erosion rate is small for very small water depths. First of all, this is caused by the small deposition in the previous phase in these areas (see Figure 6-2). Second, for small water depths and therefore low tidal action, the bed shear stress including waves is also low (see Figure 5-2). With increasing water depth (and thus tidal action), the mud deposition and the bed shear stress including waves, increase. Therefore, the net erosion rate during a tidal period increases too. At a water depth of about 0.5 m the maximum erosion rate is reached. For water depths higher than 0.5 m the wave stirring-effect at bed level decreases (see also Figure 5-2). As was mentioned, the bed shear stress including waves is very important for the erosion rate. When the maximum bed shear stress during a tidal period exceeds 2 N/m², erosion starts taking place. From that point, the net erosion rate increases linearly with an increasing bed shear stress.

Finally, an important conclusion can be drawn from the time variation of the mud concentration during the erosion phase. During the period with rough weather, the mud particles are transported from areas with high concentrations (high wave attack) towards areas with low concentrations (low wave attack). In this way the mud particles are redistributed over the tidal basin due to the wave effect. On a large scale, in the Amelander Inlet the mud particles are transported from the western area towards the eastern area.

6.3.4 Mud transport computations second deposition phase

Overview figures

The figures representing the results for the second deposition phase are shown in Table 6-6. The two shown observation points are located in net deposition areas in the tidal basin (see figures FB.4-2 and FB.4-4 for the exact location of the observation points). The results for the second deposition phase, can be seen in Figures FB.6-22 to FB.6-25.
### Table 6-6: Resulting figures mud transport computations second deposition phase

<table>
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<th>Visualisation</th>
<th>$c_m$</th>
<th>$D$</th>
<th>$D_{1,\text{short}}$</th>
<th>$D_{\text{ero}}$</th>
<th>$D_{\text{total}}$</th>
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<tr>
<td>Piet Scheve for twenty days</td>
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<td></td>
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<tr>
<td>Vrijheidsflat for twenty days</td>
<td>FB.6-23a</td>
<td>FB.6-23b</td>
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<tr>
<td>One time point</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Difference with total mud deposition after 6 months</td>
<td>FB.6-25a</td>
<td>FB.6-25b</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

with:

- $c_m$: Suspended mud concentration [g/m²]
- $D$: Mud deposition second deposition phase [g/m²]
- $D_{1,\text{short}}$: Total mud deposition after twenty days for first deposition phase [g/m²]
- $D_{\text{ero}}$: Total mud deposition after ten days with wave/wind direction Southwest [g/m²]
- $D_{\text{total}}$: Total mud deposition after twenty days for second deposition phase [g/m²]

The second deposition phase is computed to simulate the situation when the weather calms down after the erosion phase. From the results, it can be seen how many of the suspended mud particles are deposited again, and how many have been transported away. The actual effect of ten days of rough weather can be studied in this way. What exactly is shown in the figures, is explained in the following subsections.

### Observation points Piet Scheve and Vrijheidsflat

In Figure FB.6-22a and FB.6-22b, respectively the mud concentration and the mud deposition during the second deposition phase (during twenty days) is shown for the point Piet Scheve. In Figure FB.6-22a, it can be seen that the initial concentration is higher than for the first deposition deposition phase (Figure FB.6-6). After about nine days, the same equilibrium situation is reached as during the first deposition phase. From Figure FB.6-23b, it can be seen that more mud is deposited during the adjustment time of the second deposition phase than during the adjustment time of the first deposition phase. When the equilibrium situation is reached, the deposition rate becomes the same as for the first deposition phase.

In Figure FB.6-23a and FB.6-23b, respectively the mud concentration and the mud deposition during the second deposition phase (during twenty days) is shown for the point Vrijheidsflat. In Figure FB.6-23a, the high initial concentration is seen. After about nine days, the equilibrium situation is reached. From Figure FB.6-23b, the high mud depositions during the adjustment time are seen (compared to the first deposition phase in Figure FB.6-8).

For Piet Scheve and Vrijheidsflat, the differences between the first and second deposition phases are seen in the adjustment time. During this period mud particles that were suspended during the erosion phase, are deposited. Once the equilibrium situation is reached, no differences can be seen between the first and second deposition phase.

### Total mud deposition after twenty days

In figure FB.6-24a, the total mud deposition after twenty days is shown for the first deposition phase. In Figure FB.6-24b, the total mud deposition after twenty days is shown for the second deposition phase. Figure FB.6-24a is compared with Figure FB.6-24b. For the second deposition phase, the deposition is a lot higher than for the first deposition phase. Especially in the eastern area of the tidal basin and at the borders of the tidal basin, the deposition is a lot higher. Furthermore, the deposition areas have also increased in size. During the second deposition phase, deposition areas are seen that were not seen during the first deposition phase.
In Figure 6-6, the total mud deposition during the second deposition phase is plotted against the total mud deposition during the first deposition phase. The mud deposition during the second deposition phase is obviously higher than during the first deposition phase. The points, where no deposition took place during the first deposition phase but deposition did take place during the second deposition phase, can be seen too (on the x-axis). The sharp line in this figure represents the fact that the deposition during the second deposition phase can never be smaller than the deposition during the first deposition phase.

**Difference with total mud deposition after six months**

The difference with the total mud deposition after six months shows the changes in mud deposition that takes place. The difference is shown for two situations. First, the difference is shown with the mud deposition at the end of the erosion phase (and the beginning of the second deposition phase). The total mud deposition after ten days for the erosion phase is subtracted from the total mud deposition after six months for the first deposition phase. The result is shown in Figure FB.6-25a, positive values indicate net erosion during the erosion phase and negative values indicate net deposition during the erosion phase.

Second, the difference is shown with the mud deposition at the end of the second deposition phase. The total mud deposition after twenty days for the second deposition phase is subtracted from the total mud deposition after six months for the first deposition phase. The suspended mud particles have had a chance to deposit and certain mud layers are rebuilt in this way. The difference shows the effect of ten days of rough weather on the mud depositions in the tidal basin. The result is shown in Figure FB.6-25b, positive values indicate that a net loss of mud particles has taken place due to the erosion phase and negative values indicate that a net gain of mud particles has taken place due to the erosion phase.

In Figure FB.6-25a, it can be seen that deposition (negative values) during the erosion phase took place in only a few very small areas. Most of the mud depositions formed during six months of calm weather are being eroded (positive values) during the rough weather period of ten days. After the erosion phase, almost no mud depositions are present anymore. In Figure FB.6-25b, it can be seen that a net loss of mud particles (positive values) takes place mostly in the areas in the western and middle area of the tidal basin and in some areas with small water
depths in the eastern area. These areas are attacked by waves most heavily. Mud particles are transported away and are thereby lost. A net gain of mud particles (negative values) takes place mostly in the areas with a bit larger water depths in the eastern area. The wave attack is lower at these areas. The gain of mud particles takes place in two different ways. First, there are areas where no net deposition took place during the first deposition phase, while during the second deposition phase net deposition does take place. The size of the deposition areas is extended at a few locations due to the preceding erosion phase. Second, there are areas where net deposition takes place during the first deposition phase, but due to the preceding erosion phase the deposition increases. Especially in the eastern coastal area the deposition has increased in this way.

![Graph showing loss or gain of mud particles due to erosion phase](image)

**Maximum bed shear stress for wave/wind direction Southwest (N/m²)**

*Figure 6-7: Correlation bed shear stress waves - loss or gain of mud particles*

In Figure 6-7, the maximum bed shear stress during a tidal period for wave/wind direction Southwest is plotted against the loss and gain of mud particles due to the erosion phase with the same wave/wind direction. It can be seen that for low bed shear stresses, a gain of mud particles takes place due to the erosion phase. For high bed shear stresses a loss of mud particles takes place due to the erosion phase. This figure shows that mud particles are transported away (loss of mud particles) from the areas with high wave attack, and towards (gain of mud particles) the areas with low wave attack.

**Discussion results**

The deposition after twenty days for the second deposition phase is higher than the deposition after twenty days for the first deposition phase. Two effects cause a higher deposition. First, the deposition during the first tidal periods in the second deposition phase is higher because of the higher initial concentration due to the stirring effect of the preceding erosion phase. Second, the second deposition phase starts with the results from the erosion phase (wave/wind direction Southwest) as initial condition. The first deposition phase starts with an empty bed. However, it was shown that only in a few small areas some deposition is present after the erosion phase. Therefore, the first effect is dominant.
The redistribution of mud particles during the erosion phase has the following consequences for the deposition areas:

- Mud depositions in areas with high wave attack are eroded fast, and the mud particles are transported away from these areas. When the weather calms down, the mud layer will partly, but not entirely, return when the suspended mud particles are deposited again in these areas.
- Mud deposition in areas well protected from local wind waves are eroded slowly, and mud particles are transported towards these areas. When the weather calms down after wave attack, more mud will be deposited than was present before the rough weather period in these areas.

On a large scale, mud particles are transported from the western area of the tidal basin towards the eastern area of the tidal basin during the erosion phase. Furthermore, the net deposition areas are extended in size, due to the redistribution of mud particles. Because of the higher initial concentration in certain areas, more deposition than erosion can take place during a tidal period in the second deposition phase, while in the first deposition phase more erosion than deposition took place during a tidal period. Finally, it can be concluded that the interaction of rough weather and calm weather influences the distribution of the mud layers strongly. For higher wind speeds the redistribution effect might be increased, and more deposition areas might be formed.

6.4 Link to data-analysis

6.4.1 Introduction

The research questions that were raised in the data-analysis are recalled and for as far as possible answered in the first paragraph of this chapter. After that, the results of the mud computations are compared to the measured data. This comparison is difficult because the measured data are mud contents of the upper ten centimetres of the bottom and the computed data are the depositions of mud during a period of six months. Quantitatively, the computations and measured data are not comparable; a qualitative comparison can be made.

When comparing sand transport to mud transport, it should be kept in mind that the computations have a different structure. The sand computations were made with a sandy bed as initial situation while the mud computations were made with an empty bed as initial condition.

6.4.2 Research questions

- Where does the deposited sediment come from, what does the transport path of the sediment particles look like?
  
  Delft3D-MOR and Delft3D-WAQ: averaged sediment transport over a tidal cycle.

For the sand computations, close to an erosion-area there is a deposition-area. This indicates the short transport path of a sand particle. Within a tidal period, the sand is deposited immediately once the sand particles cannot be kept suspended. For mud, the transport path is usually longer. Sand particles are available in the entire tidal basin, and can be transported into the tidal basin due to tidal asymmetry for sand. When sand deposition takes place, the sand particles are usually eroded from another area in the tidal basin. Mud is available only in restricted areas of the tidal basin, and is transported into the tidal basin from outer sea. When mud deposition takes place during calm weather, the deposited mud particles usually directly originate from the North Sea. During the erosion phase, the suspended mud particles are partly transported towards areas with low wave attack within the tidal basin.
• Which factors influence the difference between sand transport and mud transport?  
*Delft3D-MOR and Delft3D-WAQ:* compare the sand and the mud computations.

A mud particle has a longer transport path than a sand particle, and can be kept suspended much easier. Mud particles have smaller settling velocities, causing part of this difference. Furthermore, it was shown that for mud transport the time lag can be relatively high while for sand transport the time lag is relatively low. The suspended mud concentration does not instantaneously adjust to the hydrodynamic conditions, while the suspended sand concentration does instantaneously adjust to the hydrodynamic conditions. The time lag is determined by the settling velocity and the water depth. At small water depths, the time lag is small and the suspended mud concentration does adjust to the hydrodynamic circumstances instantaneously.

In the beginning of this chapter it was said that comparing sand computations to mud computations is difficult because of the different initial conditions and the different structure of the computations. The sand computations are used to see in which areas sand-mud interaction can occur. These are the areas where mud is being deposited and the sand bed is also morphologically active. However, from the computations it is seen that the morphologically active sand areas practically exclude the mud deposition areas. This implies that no interaction between sand and mud is present in the tidal inlet. It is probable however, that this not a correct conclusion. The used condition was a wind speed of 10 m/s (Beaufort number 5-6). When a real storm (Beaufort number 10-12) occurs the morphological sand activity can possible also reach the mud deposition areas.

• What is the influence of waves on the sediment transport?  
*Delft3D-MOR and Delft3D-WAQ:* compare the computations with wind and waves with the computations without wind and waves for sand as well as mud.

Obviously, the waves increase the sediment transport for sand as well as mud transport. For the situation without waves, the bed shear stresses are highest in the channels during mid tide current and lowest during high and low water. For the situation with waves, the bed shear stresses are highest on the higher located areas during high water (highest waves) and lowest during low water.

For sand transport, the difference between the transport with and the transport without waves is mainly the extent of the transport. Erosion and deposition occurs for a sandy bed because the hydrodynamic situation changes from place to place, and the sand bed immediately adjusts to these changes. The erosion and deposition areas are increased by the wave effect, and spread out to a greater area. When erosion or deposition was present at a certain place, the erosion or deposition will increase when waves are present. During the situation with waves a larger area of the tidal basin is morphologically active. On the flats, the morphological activity is increased by waves the most. Relatively, the activity on the flats is still low also for the situation with waves.

For mud transport, the difference between the transport with and the transport without waves is not the extent of the transport or the morphological active areas as it was for sand. The difference is that during the situation without waves, deposition occurs in certain areas, while in these same areas erosion occurs during the situation with waves. Deposition areas during the situation without waves are the areas where more mud particles are deposited than eroded, because of low tidal action. When waves are included the bed shear stresses increase, and the balance turns. More mud particles are now being eroded than deposited. Therefore the mud layers that were deposited during the situation without waves, are eroded during the situation with waves.
Sand mud distribution in the Amelander Inlet
Sediment transport computations

- Where do the mud particles transported into the tidal inlet deposit during calm weather, and which deposition areas are attacked the most by wind and waves during rough weather?

*Delphi3D-WAQ*: look at the deposition of mud under tidal forces only and the breaking down rate of this deposited layer when waves are included.

The mud particles that are transported into the tidal inlet, according to the computations, mostly deposit in areas with small water depths far away from the gorge. The highest depositions occur in the areas where the tidal action is small enough to allow the deposition of all mud particles, but large enough to increase the supply of mud particles. However, the areas with maximum depositions are also the areas that are attacked by waves the most (erosion rate increases with increasing deposition rate). Especially in the eastern area and coastal areas of the tidal basin, the deposition and erosion rates are very small. In these areas, the tidal action is low. Even though the wave heights are practically the same as in the rest of the tidal basin, the low tidal action induce relatively small transport rates during the erosion phase.

6.4.3 **Comparison computed mud depositions with measured mud contents**

In this paragraph, the computed mud depositions are compared to the measured mud contents in the tidal basin of the Amelander Inlet. The mud depositions are computed for the situation with tidal action only. However, the measured mud contents are formed by a combination of tidal and wave action. It is tried to explain the differences with the help of the erosion rate and the redistribution of mud particles due to waves. Besides these explanations, there are also some other explanations for deficiencies in the computed results.

In Figure FB.6-26, the measured mud contents and the computed mud depositions are shown in one figure. In this way, they can be compared. Iso-lines, representing the measured mud contents, are plotted over the computed deposition areas. The iso-lines represent measured mud contents of 10% and 40%. The differences between the computed mud depositions and measured mud contents are described.

In the area at the western watershed, the assumption of a closed boundary causes high depositions that are not confirmed by the measurements. It was already expected that the assumption of a closed boundary at this watershed would cause this deficiency. The area at the southern coast of Terschelling, connected to the watershed area, also shows high depositions in the computations. These high depositions are not confirmed by the measurements. The closed boundary assumption probably causes this partly. Furthermore, the tidal action might be larger in this area than was computed (the interrupted coastline implies large tidal action). It is computed that the erosion rate at the western watershed is very high. Waves causes large erosion in this area. Furthermore, due to the redistribution of mud particles during the erosion phase, a large part of the eroded mud particles are transported away from this area.

The area, close to the gorge, also shows higher computed mud depositions than are seen in the measurements. Only a small wave (for example a swell that is almost always present) would already increase the bed shear stresses in the area close to the gorge to such an extent that these depositions are eroded. In the erosion computations, it was seen that the erosion rate when waves are present is high at these flats.

Along the coastal area, there are a few areas where the measurements show high mud contents while the computations do not show deposition areas. These are areas with a bit larger water depths. According to the computations, no mud is deposited in these areas. However, during the second deposition phase, the mud deposition increases in these kinds of areas with low wave attack. Through further experimenting with wind direction and speed, the computations might be able to simulate these high mud contents. Another possible explanation for the high
mud contents in these areas is the presence of old mud layers formed hundreds of years ago. The old mud layers can not be simulated with these computations, because they were formed under completely different hydrodynamic conditions. With these computations, only the freshly deposited mud layers can be simulated. Some research could be done into which mud layers are freshly deposited and which are old mud layers. This can be seen from the extent, to which the mud has consolidated. The critical erosion shear stress is a measure for the consolidation. For old mud layers the critical erosion shear stress can be very high because of the long consolidation time.

On a large scale, the computations and measurements agree on higher mud contents in the eastern and coastal areas than in the western area of the tidal basin. The agreement increases when it is taken into account that the computed deposition at the western watershed is caused by a wrongly assumed closed boundary. Furthermore, the erosion rate of the mud deposition in the western area of the tidal basin is very high. The redistribution of the mud particles during the erosion phase, on a large scale, causes a transport of mud particles from the western area of the tidal basin towards the eastern area of the tidal basin.

The measured mud content as well as the computed mud deposition was plotted against the water depth in respectively Figure 3-12 and Figure 6-2. The figures show the same pattern. In both figures a peak is seen for the mud content or mud deposition. The main difference between the two figures, is that the computed mud depositions are small for depths higher than 1.5 meter while the measured mud contents are small for depths smaller than 2.5 meters. The peak is wider for the measured mud contents than for the computed mud contents. In some areas with a bit higher water depths, indeed high measured mud contents were seen while no mud deposition was computed. As was said before, the redistribution of mud particles, due to rough weather periods, can possibly influence the computed mud deposition so that mud deposition also takes place at these areas with a bit higher water depths.
7 Conclusions and recommendations

7.1 Conclusions

7.1.1 Data-analysis

The most important conclusions that were drawn from the results of the data-analysis are:

- The sand-mud distribution in the Amelander Inlet, at a large scale, is as was expected from theory. So, the mud content is higher in the coastal areas and close to the watersheds. The fact that the eastern area has higher mud contents than the western area of the tidal basin is striking.

- It was seen that refinement of the grain diameter for the sand fraction does not necessarily imply a higher mud content. This indicates that influencing factors such as tide, waves and water depth play different roles in sand as in mud transport.

- In this study, a clay/mud rate of 1:7 was found for the Amelander Inlet. However the Malvern method is known to underestimate the finest fractions within mud.

- High mud contents occur for water depths smaller than two meters (below NAP). For these small water depths, the mud content can be high but not necessarily is high. Concluding, a small water depth is one precondition for the presence of high mud contents. Whether at these small water depths, high mud contents are actually present, depends on other factors.

7.1.2 Hydrodynamic computations

From the hydrodynamic computations some of the research questions, which were raised in the data-analysis, can already be answered:

- The tidal action is higher in the western area of the tidal basin than in the eastern area. The western area is closer to the gorge and has a bit higher water depths.

- From the wave computations, it can be concluded that the penetrating waves can be neglected compared to the local wind waves. For the different wind directions, the wave patterns show some small differences. Generally, the wave heights are a bit higher in the western area than in the eastern area of the tidal basin. The water depths are a bit higher in the western area, this causes a bit higher local wind waves in this area.

- The bed shear stresses follow the tidal and wave action, and therefore are higher in the western area of the tidal basin than in the eastern area of the tidal basin. The bed shear stress including waves is low for areas with very small tidal currents. In areas with high enough tidal currents, the inclusion of waves severely increases the bed shear stresses especially in the areas with small water depths. At these small water depths, small differences in wave height cause large differences in the bed shear stress.

7.1.3 Sediment transport computations

When comparing sand computations to mud computations, as far as possible, a few observations can be made:

- First of all the morphologically active sand areas exclude the deposition areas for mud, so no sand-mud interaction areas can be found from these computations.

- The influence of waves on sand and mud transport is different. For sand transport, waves increase the occurring erosion and deposition during the situation without waves. For mud transport, waves cause erosion at locations where during the situation without waves deposition was taking place. Mud layers that were deposited during calm weather are eroded during rough weather. The higher bed shear stresses due to waves increase the
erosion velocity and turn the balance from net deposition towards net erosion during a tidal period.

- For sand it was seen that the concentration immediately adjusts to the equilibrium concentration, while for mud the adjustment time is noticeable at high water depths. The time lag for mud is larger than for sand. The time lag depends on the water depth and the settling velocity and is very important for mud transport.

From the three different phases in the mud computations, the following can be concluded:

- For the calm weather situation, the deposition velocity depends on the bed shear stress due to tidal action and the deposition flux \( (w_mC_m) \). The deposition flux depends on the mud concentration, which also depends on the bed shear stress due to tidal action. To obtain a high deposition rate, conflicting demands apply. On the one hand, the bed shear stress must be low enough to obtain a deposition area \( (\tau_b < \tau_d) \). On the other hand, the deposition rate increases with increasing bed shear stress (because of a larger supply of mud particles).

- In general, the mud layers deposited during the deposition phase are eroded faster than they were deposited. The difference between the erosion and deposition rate is caused by the difference in \( \tau_b/\tau_d \) rate and \( \tau_e/\tau_d \) rate. The erosion rate is highest in the areas where the water depth is small and the tidal action is not too small. In the Amelander Inlet, the erosion rate is high in the western and middle area of the tidal basin and low in the eastern area of the tidal basin where the water depths are a bit larger.

- During the rough weather period a lot of mud particles are eroded. However, the wave attack is different within the tidal basin. In areas with high wave attack the concentration becomes very high, while in protected areas not a lot of mud is suspended. Due to diffusion, mud particles are transported from the areas with high wave attack (high concentrations) towards areas with low wave attack (low concentrations). During the rough weather period, a redistribution of the suspended mud particles takes place.

- When the weather calms down after rough weather, the influence of the redistribution can be seen. In areas with high wave attack, the mud layer will partly but not entirely return when the weather calms down. In these areas, the net effect due to the rough weather period is a loss of mud particles. In areas with low wave attack, more mud is deposited when the weather calms down, than was present before the rough weather period. In these areas, the net effect due to the rough weather period is a gain of mud particles.

### 7.1.4 Comparison computed results to measured data

From the comparison of the hydrodynamic results with the measured mud content, it was seen that the tidal action has a larger influence than the wave action. For maximum bed shear stresses lower than 1.5 N/m² a peak in the measured mud contents is seen. The sediment can be stirred up by waves, but if the tidal current is very low, it will not be transported very far before it is deposited again. In this way the net transport can be very low, even for relatively high waves.

On a large scale, the computations and measurements qualitatively agree on higher mud contents in the eastern and coastal areas than in the western area of the tidal basin. The agreement increases when it is taken into account that the computed high depositions at the western watershed are caused by a wrongly assumed closed boundary. Furthermore, taking into account the erosion rate and the redistribution of the mud particles during the erosion phase helps understanding and predicting the measured mud contents.
7.2 Recommendations

The computations can be adjusted in some ways to improve the results. Furthermore, these computations can also be extended and certain parameters can be changed to gain further knowledge.

- The closed boundary that was assumed in the model grid, causes an accumulation of mud at the western watershed that is not seen in the measurements. This closed boundary could be adjusted to improve the results of the mud computations.
- The depth that was used in the model was not measured at the same time as the data points that were compared to the results of the model. The depth was measured in 1993 while the samples were taken in 1995. It should be checked whether the depth has changed a lot in these two years and thereby influences the results.
- In the Delft3D-WAQ model, no digging and burying of mud particles was taken into account. Maybe including these effects can improve the results.
- Local wind waves have proven to be very important for the Delft3D-WAQ model. Therefore computations should be done with other wind speeds to see the sensitivity of the mud model for this factor.
- The calm weather period following a rough weather period, was computed with results from wind direction Southwest only. This should be done with all other wind directions. Furthermore, the computation times for the calm weather situation in combination with these rough weather situations can be changed, to see if the duration of the preceding wave period has great influence.
- The mud layers are formed by the interaction of calm weather periods and rough weather periods. In this study one wave period was computed, and one following calm weather period. It would be interesting to try to simulate one entire year. The data for one year should be collected and split in a certain amount of periods (depending on the accuracy that is wanted). For every period a representing wind speed/direction, based on the available data, and the duration of this period are defined. These periods should be computed in the right sequence. The initial conditions are taken from the computed results of the preceding period.

Furthermore, the present models have some restrictions causing the computations to be less accurate.

- First of all the influence of benthic flora and fauna, that can actively trap sediment and enhance deposition, can not be taken into account in the Delft3D-WAQ.
- Some simple output options are missed in Delft3D-WAQ. Defining a cross section, like is possible in Delft3D-MOR, is not possible in Delft3D-WAQ. This would allow to see the net transport of mud particles into and out of certain areas. Also the time-averaged transport cannot be quantified in Delft3D-WAQ. If the same output options are available, comparing sand and mud computations is easier too.
- The critical erosion parameter is assumed to be constant in time and depth. This is not a very accurate assumption. The time and depth dependence of the erosion parameter has a large influence on the mud transport. Some kind of formulation for the erosion parameter should be found to be able to take this into account.
- The bed shear stress that is taken into account for the sediment transport is the maximum bed shear stress during a wave cycle. However, this is not the actual occurring bed shear stress all the time. This causes an overestimation of the wave-effect. This is probably one of the reasons why such high values had to be taken for the erosion parameter for the situation with waves. It should be studied whether another value for the bed shear stress (maybe the mean value) can be taken and would give better results.
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Sand mud patterns in the Amelander Inlet
References

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Sample 7471: Depth = 0 m.

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Current magnitude, bed stress magnitude and total water depth

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Sand–mud distribution in Amelander inlet

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Delft3D–FLOW FIGURE FB.5–1
Hydrodynamics for Piet Scheve and Kromme Balg

Current magnitude, bed stress magnitude and total water depth

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Hydrodynamics for Friesche Wad and Koffiebonen flat
Current magnitude, bed stress magnitude and total water depth

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Variation of tidal velocity over last tidal period
Tidal action only

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Variation of tidal velocity over last tidal period
Tidal action only

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Waves and wind from North

Waves and wind from Northeast

Waves and wind from East

Waves and wind from Southeast

Root mean square wave heights in Amelander Inlet
Including local wind waves and/or penetrating waves
At high water, $H_s=2$ m, $T_p=7$s, windspeed=$10$m/s

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Sand-mud distribution in Amelander Inlet

Delft3D-FLOW FIGURE FB.5-8
Root mean square wave heights in Amelander Inlet
Including local wind waves and/or penetrating waves
At high water, Hs=2 m, Tp=7s, windspeed=10m/s

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Delft3D-FLOW  FIGURE F8.5-9
Comparison local wind waves with penetrating waves
Wave/wind direction Northwest
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Maximum bed shear stress in a tidal cycle
Waves and wind from East and Southeast

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Waves and wind from West

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Variation sand concentration over first tidal period

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Sand-mud distribution in Amelwijk inlet

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Variation sand concentration over first tidal period

Wind/wind direction: Southwest

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Sand-mud distribution in Amelodee Basin

Delft3D-MAR FIGURE FR.1-1
Bed level change representing all wave/wind directions
Weighting factors applied

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Piet Scheve adjustment time

Bed shear stress, mud concentration and mud deposition

First deposition phase

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Piet Scheve equilibrium situation (last tidal periods)
Bed shear stress, mud concentration and mud deposition
First deposition phase

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Vrijheidsflat adjustment time
Bed shear stress, mud concentration and mud deposition
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Sand-mud distribution in Amelander Inlet

Delft3D-WAQ FIGURE FB.6-8
Vrijheidsflat equilibrium situation (last tidal periods)
Bed shear stress, mud concentration and mud deposition
First deposition phase

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Variation of mud deposition over last tidal period
Tidal action only

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Sand-mud distribution in Amelander Inlet
Total mud deposition after six months
First deposition phase
Iso-lines: depth = 0.7m, 5m and 10m

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Sand-mud distribution in Armelander Inlet
Delft3D-WAQ  FIGURE FB.6-12
Piet Scheve first six tidal periods
Bed shear stress, mud concentration and mud erosion
Erosion phase, wave/wind direction Southwest

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Vrijheidsflat first six tidal periods
Bed shear stress, mud concentration and mud erosion
Erosion phase, wave/wind direction Southwest

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Delft3D-WAQ FIGURE FB.6-14
Variation of mud concentration over second tidal period
Wave/wind direction Southwest

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Net erosion mud deposition for second tidal period
Wave/wind directions North and Northwest
Within iso-lines: net deposition areas

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Net erosion mud deposition for second tidal period
Wave/wind directions West and Southwest
Within iso-lines: net deposition areas

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15-3-2001
Sand-mud distribution in Amelander Inlet
Delft3D-WAQ
FIGURE FB.6-17
Net erosion mud deposition for second tidal period
Wave/wind directions South and Southeast
Within iso-lines: net deposition areas

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Net erosion mud deposition for second tidal period
Wave/wind directions East and Northeast
Within iso-lines: net deposition areas

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FB.6-19

15-3-2001
Figure FB.6-19
Net erosion mud deposition for second tidal period
Representing all wave/wind directions (incl. weighting factors)
Within iso-lines: net deposition areas

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Concentration during first tidal period

Concentration during last tidal period

Change of concentration during erosion phase
Wave/wind direction Southwest
Iso-lines: depth = 0.7m, 5m and 10 m

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Piet Scheve for twenty days
Bed shear stress, mud concentration and mud deposition
Second deposition phase

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Sand-mud distribution in Amelander Inlet

Delft3D-WAQ FIGURE FB.6-22
Vrijheidsflat for twenty days
Bed shear stress, mud concentration and mud deposition
Second deposition phase

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FB.6–24a
First deposition phase

FB.6–24b
Second deposition phase

Total mud deposition after twenty days
Comparison first and second deposition phase
Iso-lines: depth = 0.7m, 5m and 10m

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Sand–mud distribution in Amelander inlet

Delft3D–WAQ
FIGURE FB.6–24
Deposition after six months—deposition erosion phase

Deposition after six months—deposition second deposition phase

Difference with total mud deposition after six months
a. Mud deposition end erosion period (wind direction Southwest)
b. Mud deposition end second deposition phase (wind direction Southwest)

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Sand–mud distribution in Amelander IJssel
Total mud deposition after six months
First deposition phase
Iso-lines: measured mud content = 10% and 40%

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Sand-mud distribution in Amelander Inlet

Delft3D-WAQ FIGURE FB.6-28
Appendix E: Frequency of occurrence wind directions

In this appendix the wave/wind directions that have been used in the computations are looked into. From the analysis (Paragraph 6.2.3: "Root mean square wave heights") it turned out that all the waves in the area of interest, the tidal basin, are local wind waves. Therefore only the chance of occurrence for the wind directions has to be studied. With this knowledge the probability of the above-described situations can be described. The compass rose for Den Helder is shown in Figure E-1. This is the place nearest- by to the Ameland Inlet for which a compass rose was found. The compass rose for the study-area is assumed to be about the same as for Den Helder.

The compass rose contains two different parts:
- The black part, giving the percentage of occurrence of certain wind velocities for a certain wind direction. Starting from the inside of the compass rose the four different kinds of lines has the following meaning:
  1. 0,0-3,0 m/s
  2. 3,0-7,9 m/s
  3. 8,0-13,9 m/s
  4. >14,0 m/s
- The grey part, giving the mean wind velocity for this wind direction.

![Figure E-1: Compass rose at Den Helder](image)

In Tables E-1 and E-2, the data that follows from the compass rose is shown in numbers.

<table>
<thead>
<tr>
<th>wind direct.</th>
<th>averaged flow velocity (m/s)</th>
<th>percent. total</th>
<th>percent. 0-3 m/s</th>
<th>percent. 3-8 m/s</th>
<th>percent. 8-14 m/s</th>
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<td>0.52</td>
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<td>51.18 %</td>
<td>30.58 %</td>
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Table E-1: Absolute percentages wind data
<table>
<thead>
<tr>
<th>wind direct.</th>
<th>averaged flow velocity (m/s)</th>
<th>percent. total</th>
<th>percent. 0-3 m/s</th>
<th>percent. 3-8 m/s</th>
<th>percent. 8-14 m/s</th>
<th>percent. &gt;14 m/s</th>
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<td>100 %</td>
<td>11.73 %</td>
<td>51.18 %</td>
<td>30.58 %</td>
<td>6.51 %</td>
</tr>
</tbody>
</table>

Table E-2: Relative percentages wind data

To describe the wind climate the wind directions are first roughly discussed in four "corners":
1. The North to West corner
2. The West to South corner
3. The South to East corner
4. The East to North corner

For the wind directions it can be seen that the directions ranging from West to South occur the most. The directions ranging from East to North and North to West occur a bit less than the West to South corner while the directions from the corner South to East take place the least.

The North to West corner has reasonably high percentages for the higher wind speeds (8-14 and >14 m/s). About forty percent of the time the wind speed is higher than 8 m/s, so within this sector the wind speeds can be reasonably high. For the West to South corner the same goes but in greater extent. The wind speeds are higher than 8 m/s also about fifty percent of the time. The South to East corner has the highest percentages for the smaller wind speeds (0-3 and 3-8 m/s). Within this sector the wind speeds are usually very low. In the East to North corner higher wind speeds can occur reasonably regularly, just like in the North to West corner.

During the time of occurrence the averaged wind speed is very small (<3 m/s) for the South to East corner, as was expected. For the East to North corner the wind speed is somewhat higher (around 4 m/s) and for the North to West and West to South corners the averaged flow velocities are the highest (around 5 m/s)

It can be concluded in general that the wind directions SSW, SW, WSW and W should be looked at as the directions that have the most influence. These directions occur most often and if they occur the chance for high wind speeds is reasonably high. The direction S has an average influence just like the directions N, NNE, NE, ENE, E, ESE, SE and SSE. These
directions occur somewhat less than the before-mentioned directions but there is a reasonably chance for higher wind speeds. The directions SSE, SE, ESE have a very low percentage of occurrence and when they occur the wind speed almost always stays low. Therefore these directions' influence on the morphological development in the tidal basin is minimal.

To be able to make one total picture for a certain parameter including the effect of all wind directions, this parameter can be added up and the average value can be calculated. However that way the frequency of occurrence for each wind direction is not included. To include the chance of occurrence for every wind direction that was described in this appendix, weighting factors are defined. Added up these weighing factors must be one. The weighting factors have been defined from the chance that the wind velocity for a certain wind direction is higher than 8 m/s. The results can be seen in Table E-3.

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<th>Wind direction</th>
<th>Weighing factor</th>
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</thead>
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<tr>
<td>Northeast</td>
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<td>East</td>
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<tr>
<td>West</td>
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</tr>
<tr>
<td>Northwest</td>
<td>0.16</td>
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</tbody>
</table>

*Table E-3: Weighting factors for wind directions*

The wanted parameter can be multiplied with the weighting factor for every wind direction. After that the results of these multiplications are added up and the total "averaged" picture of the parameter is obtained.