Influence of biological activity on morphology and bed composition in the Friesche Zeegat

M.Sc. Thesis

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Preface

This report forms the completion of my study Civil Engineering & Management at the Department for Water Engineering and Management, which is part of the Faculty of Engineering Technology at the University of Twente, The Netherlands. I would like to thank the members of my graduation committee dr. ir. Denie Augustijn and dr. ir. Michiel Knaapen from the University of Twente and drs. Mindert de Vries from WL|Delft Hydraulics for their support and supervision. I would also like to thank Gerben de Boer for his help with Delft3D.

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Marco, Jeffrey and Bartje, thanks for listening to me during those endless 'discussions' in the Vestingbar. Finally, I would like to thank my parents for supporting me (not only financially), my brothers Michiel and Sander and my sister Hilde. But most of all I would like to thank my girlfriend Annemiek, for supporting me especially in the last few weeks.

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Abstract

There is an increasing interest between abiotic and biotic environments of rivers, lakes, estuaries and seas. In the Wadden Sea, biological activity can have a considerable influence on changes in bed level and composition. For example, *Macoma balthica* redistributes and destabilises the bed by motion through the bottom. Diatoms stabilise the bed by forming a sticky substances which glues the sediment together. Mussel bed increase the roughness of the bed and by filtrating the water column, they increase the deposition of faeces between their shells. Apart from natural hazards to biology, like cold winters and storms, there is a huge scala of human interests, which can influence biology. There are industrial interests like gas and sand mining, and fishery, or recreational interests, like mud pounding (in Dutch: wadlopen), and water sports.

Especially, the industrial activities have the largest impact on biology. Sand mining has a large impact on local bed levels and may have an impact on species abundance, e.g. settlement of mussel larvae and existence of *Macoma balthica*. Gas mining results in a large-scale bed level decrease, which can influence the height of the mussel beds, or result in a decrease of the Chlorophyll-a concentration, because of the lack of light they need for photosynthesis. Fishery directly influences species abundance, but an unwanted side effect is the dragging of the fishing nets over the bottom. This also negatively influences biology living in, near or on the bottom.

In this report the influence of biological activity on morphology and composition in the Friesche Zeegat, a tidal inlet in the Dutch Wadden Sea, is discussed. Van Ledden (2003) developed an application to the Friesche Zeegat of the sand-mud model, based on the numerical model Delft3D. This sand-mud model is extended with the biological parameters proposed in Paarlberg et al. (2005), in order to simulate the influence of the bivalve *Macoma balthica*, diatoms and mussel beds. In Paarlberg et al. (2005), a description is given of the destabilising and stabilising effect of *Macoma balthica* and diatoms on the critical bed shear stress and erosion coefficient.

Macoma balthica (individuals/m^2) decreases the critical bed shear stress and increases the erosion coefficient, while diatoms (Chlorophyll-a content, μg/g) increase the critical bed shear stress and decrease the erosion coefficient. This is also applied to the stabilising effect that the mussel beds have on the bed surface. The mussel beds are parameterised as a constant Chlorophyll-a content with a maximum stabilising effect. A reference situation is developed in order to compare the influence of the different organisms on changes in bed level and composition. Both, the results from the reference situation and the results including biological activity, are compared with observed data from the morphological development of the Friesche Zeegat.

Comparing the reference situation with observed data indicate that the mud content in the top layer of the bottom and the bed level change show similarities and differences. The computed mud content is too high in the entire basin, but the mud distribution shows good agreement. The bed level change shows good agreement in the entrance of both tidal channels. In the tidal basin net erosion is observed, but the model predicts a slight sedimentation. The magnitude of erosion and sedimentation is not of the same order. The observed data is obtained from a period of 25 years, while the computed data is based on a period of 2 years.

The results including biological activity show better agreement with the observed mud content and bed level change. The destabilising effect by the bivalve *Macoma balthica* is dominant over the stabilising effect caused by the diatoms or mussel beds. However, because of an error in the model, the contribution of the stabilising effect by the mussel beds on the mud content and bed level change is not very reliable. In order to diminish the unwanted influence of the mussel beds, also a simulation without the mussel beds is performed. These results show that the stabilising effect by the mussel beds have a significant influence on the mud distribution but not on the total amount of mud. The influence of the mussel beds can not be neglected, but the destabilising effect is more significant than the stabilising. So, the total amount of mud decreases significant by the influence of biological activity.

For further research it is necessary to implement the biological parameters in the new version of the sand-mud model. In order to study the influence of the waves on the bed shear stress and to increase the simulation period to a greater time-scale. It is recommended to implement the seasonal influence on species abundance and existence and the interaction between organisms.

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Chapter 1

Introduction

1.1 Biogeomorphology

There is an increasing interest in the interaction between the abiotic and biotic environments of rivers, lakes, estuaries and seas. Biogeomorphology is the interaction between biology and morphology. Morphology is the interaction between water and sediment motion and bed topography. Biology is the study of the relationships between organisms and their environment. Biological activity affects the sediment structure and sediment dynamics and it may influence the hydrodynamics. For example, a juvenile mussel bed collects considerable amounts of fine sediments between August and November, and beds can rise up to 30-40 cm above the surrounding mudflats (Dankers et al., 2001).

Benthic organisms have an effect on their environment by stabilising or destabilising the surface of the bed. The term benthos refers to all organisms living in, on or near the bottom. Different types of benthos can be distinguished: zoobenthos, like clams, mussels and worms, and phytobenthos, like algae. Deposit feeders like the bivalve *Macoma batlhica* and the laver spire shell (*Hydrobia ulvae*) feed on organic matter in or on the sediment surface. By burrowing and motion through the bed these organisms redistribute the bed and cause resuspension of the sediment. This bioturbation results in a less consolidated bed and lower critical bed shear stress. In figure 1.1 a schematisation is given of the effects that the different benthos have on the morphological cycle.

The excretion of mucus or EPS (Extracellular Polymeric Substance) by algae glues the sediment together, this results in an increase of the critical bed shear stress. Algal-mats are formed when large biomasses of diatoms occur, e.g. during calm springs and summers. These diatoms populations strongly fluctuate as a result of changes in environmental conditions. Mussel bed also have a stabilising effect, they protect the bed surface from resuspension and erosion. They even enhance the flux of suspended sediment to the bed via suspension feeding and biodeposition. Suspension feeding means that the organisms filtrate water out of the water column to obtain food. During this process also fine-grained sediments are filtered out of the water. The faeces and pseudofeaces these mussels excrete, remain between the shells and their bysus threads, this causes biodeposition (Widdows and Brinsley, 2002).

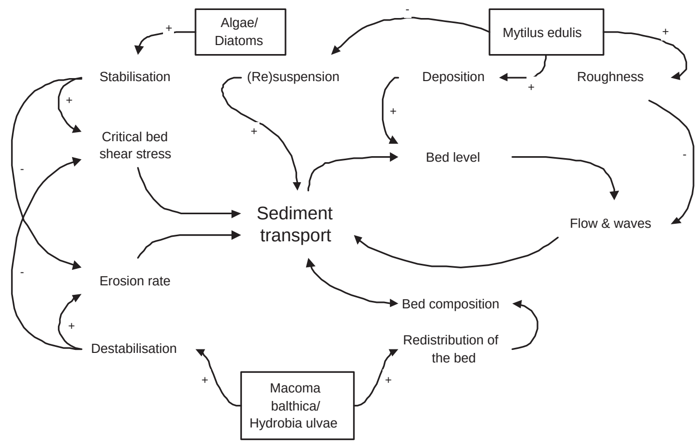


Figure 1.1: The influences of the biological processes on the morphological cycle (De Vries, 2005).

In the past few years several studies have been conducted on the before mentioned biological influences on the large-scale morphology. Oost (1995) examined the influence of biodeposition by Mytilus edulis (the blue mussel) in the Dutch Wadden Sea. He states that high amounts of faeces and pseudo-faeces, which are produced by mussels, influence the suspended sedimentation concentration in the water column and sedimentation of fine-grained sediments.

Knaapen et al. (2003) focussed on the effects of bioturbation and biostabilisation and the possibility to introduce these biological effects directly into long-term morphodynamic models. This idea has been applied to two cases. The results of the first case indicate that this approach can reproduce the influence of benthic organisms on the mud content of the bed. The second case shows that even low numbers of organisms can influence the characteristics of large bed forms. Paarlberg et al. (2005) studied the effects of biodestabilisers and biostabilisers on the erosion and mixing process of the sediment bed on an intertidal flat in the Western Scheldt, the Netherlands. The destabilising organisms always cause a significant decrease in mud content in the bed and an increase of erosion, while the stabilising organisms can increase the mud content in the bed and sedimentation.

Because the bivalve *Macoma balthica* and diatoms are representatives of organisms with a destabilising effect and a stabilising effect (Widdows et al., 1998; Widdows and Brinsley, 2002), these organisms are implemented in the sand-mud model by Van Ledden (2003). Furthermore in this research, a third organism is added which causes a stabilising effect on the sediment strength. Also, mussel beds can have a significant influence on sedimentation in the Friesche Zeegat (Oost, 1995).

1.2 Area description

The Dutch Wadden Sea is a shallow, semi-enclosed part of the North Sea, mainly consisting of tidal mud flats, sand flats, gullies and salt marshes. The area is bordered by a series of barrier islands, the Wadden Islands. The Wadden Sea stretches along the North Sea coast from Den

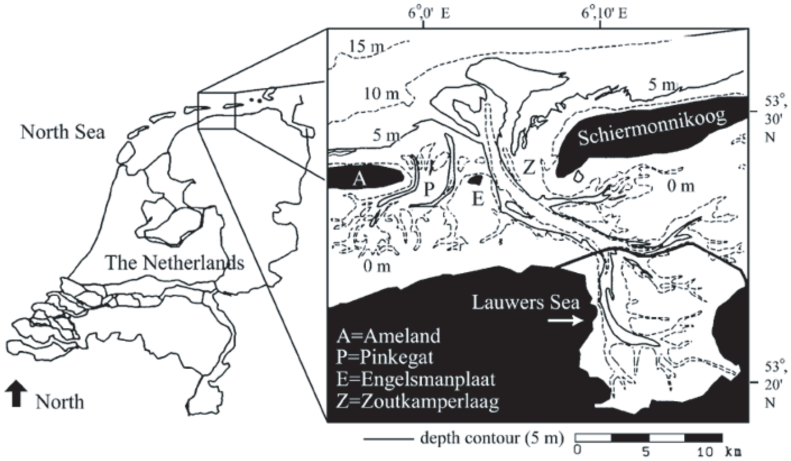


Figure 1.2: Location of the Friesche Zeegat (Van Leeuwen et al., 2003).

Helder (the Netherlands) up to Esbjerg (Denmark). The Friesche Zeegat is a tidal inlet in the eastern part of the Dutch Wadden Sea and is situated between the barrier islands Ameland and Schiermonnikoog (see Figure 1.2). In the inlet a supra-tidal shoal, the Engelsmansplaat, is located. It causes a seperation of two inlet systems called the Pinkegat (on the west) and the Zoutkamperlaag (on the east). Both systems have their own ebb-tidal delta: the Pinkegat delta is about half the size of the Zoutkamperlaag delta (Van Leeuwen et al., 2003).

Since 1969, the Friesche Zeegat, with an area of about 450 km2, has undergone significant morphological changes due to the reclamation of a large part of it, the Lauwerszee. As a consequence the tidal prism, which is defined as the total amount of water which moves in and out during a tidal cycle, has been reduced by about 34% (Wang et al., 1995). The Zoutkamperlaag was reduced from 305 $\cdot 10^6$ m^3 to 200 $\cdot 10^6$ m^3 (Oost, 1995). Due to this change the system was no longer in equilibrium with the morphological conditions and as a result a substantial amount of sand and mud has been deposited in order to change to a new morphodynamic equilibrium.

The Friesche Zeegat is characterised by channels, shallow tidal flats and salt marshes. Not only human activities take place, such as navigation, fishing and aquaculture, recreation and mining, there is also an abundance of biological activity. These two can interfere and both may influence the morphodynamics in the Friesche Zeegat. Together with the process-based sand-mud model by Van Ledden (2003), these features make the Friesche Zeegat a suitable model area for studying the influence of biological activity on bed level and bed composition changes.

1.3 Sand-mud model

Van Ledden (2003) applied the process-based sand-mud model to the Friesche Zeegat in order to investigate its predictive capabilities in a quantitative way. His research focussed on the long-term morphological simulations, studying the morphological behaviour of the tidal basin

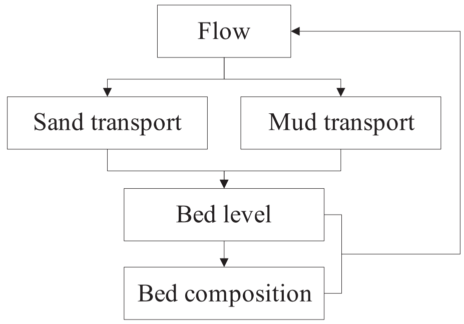


Figure 1.3: Setup of the original sand-mud model (Van Ledden, 2003).

after the closure of it in 1969.

The sand-mud model is 1DV (point) model which gives a prediction of the bed composition in a particular point. It is coupled with the numerical modelling system Delft3D (D3D) by applying it to the whole grid. This makes it possible to perform morphological calculations in order to predict the spatial distribution of sand and mud in the Friesche Zeegat. D3D is suited for hydrodynamic and morphodynamic computations for coastal, rivers and estuarine environments. It can carry out simulations of flow, sediment transport, morphological development and waves. WL|Delft Hydraulics is copyright owner of the Software.

The sand-mud model is chosen because it focusses not on sand transport only, but also on the fine-grained sediment transport. Most organisms are believed to influence the mud content in the bottom and mud concentration in the water column (Knaapen et al., 2003; Paarlberg et al., 2005).

1.4 Research objective

This research aims at contributing to the understanding and modelling of biological influences on large-scale morphological changes in estuaries and tidal basins. The objective is:

To determine the influence of biology on bed level and composition in the Friesche Zeegat, by implementing the stabilising and destabilising effect, that organisms have on the surface of the bed, in the existing sand-mud model by Van Ledden (2003).

The research objective implies the following research questions of which the answers will contribute to the fulfillment of this objective.

- Which organisms have affect on the morphology and bed composition in the Friesche Zeegat?
- How can these organisms be implemented in the sand-mud model by Van Ledden (2003)?
- What is the difference on morphology and bed composition between simulations with and without biological activity?

- Does the sand-mud-bio model show agreement with actual measurements in the Friesche Zeegat?

Biological activity has influence on the stability of the bed in the Friesche Zeegat by affecting the critical bed shear stress and erosion coefficient (Paarlberg et al., 2005). These parameters are included in the sand-mud model by Van Ledden (2003). The results of the simulations with and without biological activity are compared with each other and compared with the measurements of bed composition and computed mud contents in the Friesche Zeegat.

1.5 Outline of the report

Chapter 2 describes which organisms have influence on the sediment strength and their characteristics. First the background of the sand-mud model and second the parametrisation of the biological influence is studied in Chapter 3. In Chapter 4 the model set-up of the reference situation without biological activity is described and the results of this reference situation are given in Chapter 5. In Chapter 6 the results from the reference situation are compared with the results from three different scenarios with biological activity. Chapter 7 contains the discussion of the results of this research, and in Chapter 8 the main conclusions are given, together with recommendations for further research.

Chapter 2

Biological characteristics

In this research the main destabilising organism is the bivalve *Macoma balthica*. The stabilising effect is caused by diatoms and mussel beds. The biological characteristics of the three different organisms are described. *M. balthica* abundance is schematised in four different depth zones. The content of Chlorophyll-a is also depth dependent and the distribution of the mussel beds is based on actual data.

2.1 *Macoma Balthica*

The bivalve, *Macoma balthica*, is widely abundant throughout north-west Europe. It can be present at very high but variable densities and it is found from the upper part of the intertidal flat to the shallow subtidal zone. It is not recorded in parts of the North Sea deeper than 25 m. The main breeding period of the *M. balthica* is between February and May. A second spawning period occurs in August. Along the Dutch coast the highest biomasses are found in estuaries and tidal inlets. The bivalve prefers muddy sediments with relatively high silt-clay percentages (Holtmann et al., 1996). *M. balthica* has a long inhalant siphon that enables it to feed in two different ways; deposit and suspension feeding. The burying depth of the bivalve during autumn and winter is sufficient to protect it from most predators and against washing away and extreme low temperatures. The average depth during temperate spring and summer in the western Dutch Wadden Sea is between 2 to 3 cm and in the eastern Dutch

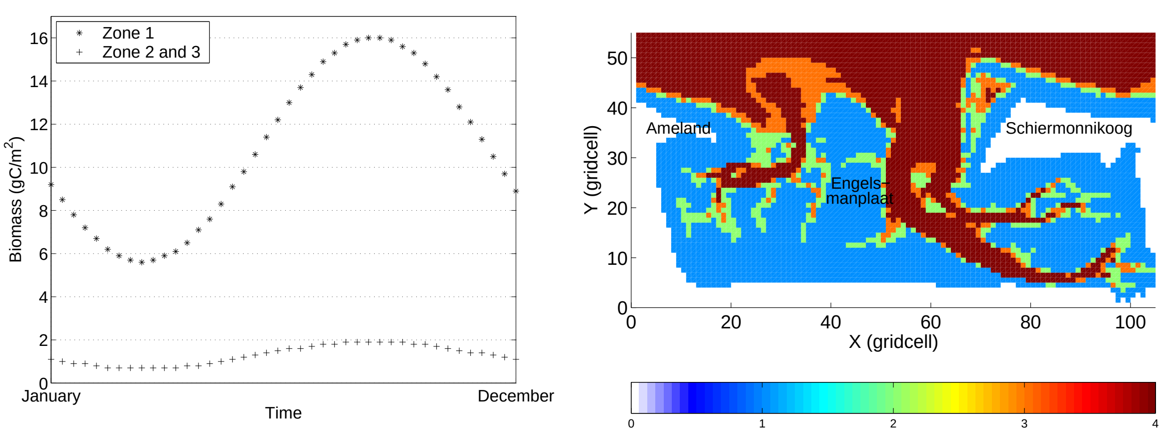
Figure 2.1: The bivalve *Macoma balthica*

Wadden Sea it is between 2.5 and 6.5 cm. This is well within reach of the predators (De Goeij and Honkoop, 2002).

Macoma balthica densities are generally higher following a cold winter, this is caused by an increase in food source and a reduction of predators . There is also a relationship between the *M. balthica* density, its grazing activity and the microphytobenthos biomass. At times of high *M. balthica* abundance the microphytobenthos will be grazed and the biomass lowered (Widdows and Brinsley, 2002). Studies in the Humber and the Westerschelde have recorded a correlation between sediment erodibility and the activity and density of *M. balthica*. As a result of the burrowing, deposit feeding and grazing activity of *M. balthica*, the bed surface had a lower critical shear stress and a higher erosion coefficient (Widdows et al., 1998).

2.1.1 *Macoma balthica* density and distribution

M. balthica can be found from the upper part of the intertidal flat to the shallow subtidal zone. For the Western Wadden Sea seasonal variations in biomass data of *M. balthica* is available related to different depth zones (Wijsman, 2004). The seasonal variations in biomass is presented in Figure 2.2(a). From this data set the annual average biomass is taken in order to apply it to the Friesche Zeegat. In ecology *M. balthica* biomass is an accepted indicator, however, according to Paarlberg et al. (2005) *M. balthica* density correlates better with critical bed shear stress and erosion coefficient. The average grazer weight is 0.01 gC/n, this means that a biomass of 1 gC/m^2 represents 100 individuals/m^2 (ind/m^2). The number of ind/m^2 is divided over four depth zones, which are given in Table 2.1. In zone 1 the average density is 1078 ind/m^2, zone 2 and 3 both have a density of 129 ind/m^2. In zone 4 there is no activity of the bivalve *M. balthica*. In Figure 2.2(b) the four depth zones in the Friesche Zeegat are presented.



(a) (b)

Figure 2.2: *Macoma balthica* (a) biomass (gC/m^2) (Wijsman, 2004) and (b) distribution (ind/m^2) according to the four depth zones in the Friesche Zeegat.

depth zone	h (m)	biomass (gC/m^2)	density (n/m^2)
1	$h \leq 1$	10.78	1078
2	$1 < h \leq 2$	1.29	129
3	$2 < h \leq 3$	1.29	129
4	$h > 3$	0	0

Table 2.1: Depth zones (Mean Sea Level) and yearly average biomass (gC/m^3 and density (ind/m^2) of *M. balthica*

2.2 Diatoms

Diatoms are restricted to the intertidal or shallow subtidal zone in turbid waters (e.g., estuaries and coastal lagoons) due to lack of light available for photosynthesis in deeper water. This implies that the stabilising effect brought about by diatoms will mainly be restricted to the intertidal zone (Andersen et al., 2004). Sutherland et al. (1998) demonstrated a strong relationship between critical erosion shear stress and microphytobenthos density. This study showed a significant increase in critical shear stress and a reduction in erosion rate with increasing Chlorophyll-a content.

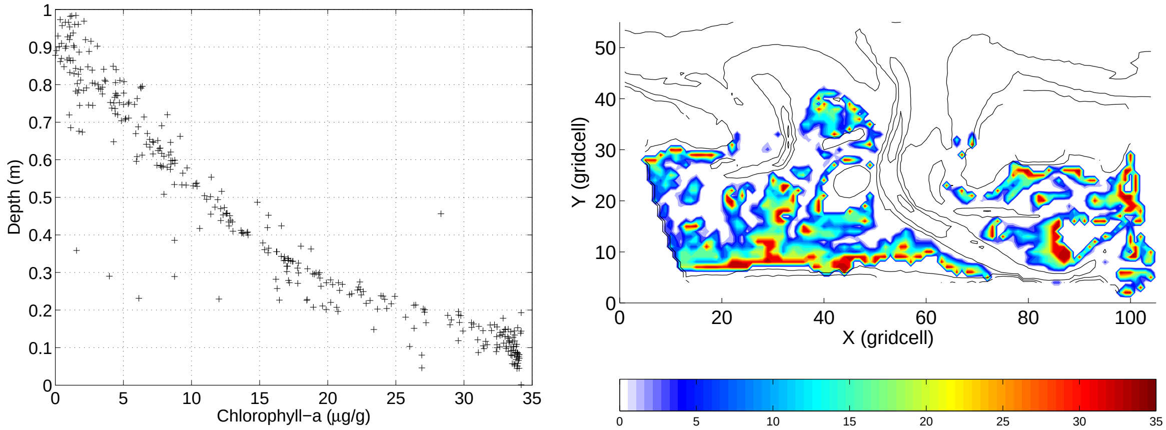
During a bloom period in spring algae mats are formed by large densities of diatoms which produce a sticky substance made of polysaccharides that glues the sediment together and prevents it from erosion. These communities include both motile algae (epipelic diatoms) as well as sessile algae attached to sand grains (epipsammic diatoms) (Wolfstein et al., 2000).

2.2.1 Chlorophyll-a content and distribution

Stabilisation by diatoms is represented by the Chlorophyll- a content [μg g^{-1}], which is an indicator of microphytobenthos biomass (Staats et al., 1998). Because Chlorophyll-a can be found in intertidal or shallow subtidal waters, ten depth zones are used within one meter depth (mean water level) to give a distribution of the Chlorophyll-a concentration (Blauw,

depth zone	h (m)	concentration (μgChl/g)
1	$0.0 \leq h < 0.1$	34.09
2	$0.1 \leq h < 0.2$	31.98
3	$0.2 \leq h < 0.3$	20.47
4	$0.3 \leq h < 0.4$	16.61
5	$0.4 \leq h < 0.5$	14.10
6	$0.5 \leq h < 0.6$	9.54
7	$0.6 \leq h < 0.7$	6.84
8	$0.7 \leq h < 0.8$	4.34
9	$0.8 \leq h < 0.9$	2.19
10	$0.9 \leq h \leq 1.0$	1.18

Table 2.2: Depth zones (Mean Sea Level) and yearly average biomass of diatoms.



(a) (b)

Figure 2.3: Chlorophyll-a (μgChl/g) (a) concentration in one meter water depth and (b) distribution in the Friesche Zeegat according to the depth zones.

2004). These zones are given in Table 2.2 and the relation between depth and Chlorophyll-a content is given in Figure 2.3(a).

2.3 Mussel beds

The blue mussel *Mytilus edulis* is a natural inhabitant of the Dutch Wadden Sea. It produces more than a million eggs per animal, of which only a few survive. This reproduction of pelagic larvae occurs in May and the beginning of June, but can extend over a longer period. The larvae are not capable of searching actively for suitable substratum, they are distributed by wind and tidal driven currents (Brinkman et al., 2002). The location of settlement is unpredictable. After settlement, the larvae move no more than a few decimeters. A small proportion of the larvae will find some substratum which in the Wadden Sea consists of dikes, chains, ropes, adult mussels or cockles and even bare sand or silt.

Mussels have considerable influence on the estuarine ecosystem. They can occur in such densities that they filter a water volume equal to a whole estuary in a couple of days (Dankers and Koelemaij, 1989). Also, the structure and stability of the bed in the Wadden Sea is enhanced because of the mussels beds. If the mussel population is destroyed, remnants are visible as elevations of clay banks or shell layers. The total area covered by mussel beds and the amount of sediment stored beneath them can be substantial. For example, in the years 1975 - 1978 the destruction of natural mussel beds by fisheries and storms lead to a considerable loss of sediment.

Mussel beds protect the bed surface from resuspension and erosion at times of maximum current speeds (spring tides), but also enhance the flux of suspended particulate matter (SPM) to the bed. Mussels increase the sedimentation of SPM by filtration and production

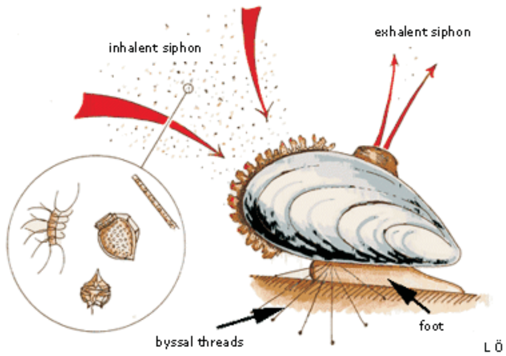


Figure 2.4: *Mytilus edulis* (directly from the website: http://www.weichtiere.at).

of faeces and pseudofaeces around mussel beds. These biodeposits partly settle between the shells of the colony. Resuspension is restricted by the protection of the byssal threads (strong threads which attach the mussel to the bed) and by the shells. In order to remain at the sediment-water interface, the mussels move by using their foot and releasing byssal threads. The upward movement of the shells creates holes, which are filled with clay and/or sand (Oost, 1995). The sediment underneath the mussel beds is accumulated by biodeposition and physical accretion. This results in an a strong vertical deposition of several dm/year. A juvenile mussel bed filtrates considerable amounts of fine silt between August and November and these beds can rise up to 30 - 40 cm above the surroundings. These unstable beds often disappear during winter storms. If the bed survives the winter the silt consolidates and forms a stable clay layer. In old mussel beds, the majority of the underlying sediment consists of sand and clay (Dankers et al., 2001).

The height of the mussel bed is restricted because feeding duration decreases during vertical growth. The mussel beds on the intertidal flats of the Wadden Sea normally grow up to mean sea level. At higher levels mussels have to spend more energy to withstand the higher wave energy and longer duration of aerial exposure. Furthermore the vertical growth is limited because of the increased erosion of sediment from the mussel bed (Oost, 1995).

2.3.1 Mussel bed location

According to Brinkman et al. (2002) the presence of mussel beds depends on the wave action, distance to a gully, emersion time and bed composition. A high orbital velocity and flow velocity would be unfavourable for mussel beds appearance. Washing away of settled mussels and sediment, and the resuspension of sand and silt, negatively affects filtration possibilities. In case of very low flow velocities there is hardly any refreshment of water and thus feeding conditions might turn out to be poor. A large distance of the site to a gully causes less favourable feeding conditions for mussels, because a gully serves as a transport route for food. According to (Brinkman et al., 2002) close to the water line (Mean Sea Level), less mussel beds appeared and when emersion time was above 50% hardly any mussel bed could be found. Very coarse sand or silty environments were not preferred, however the larger part of the Wadden Sea has suitable median grain size conditions.

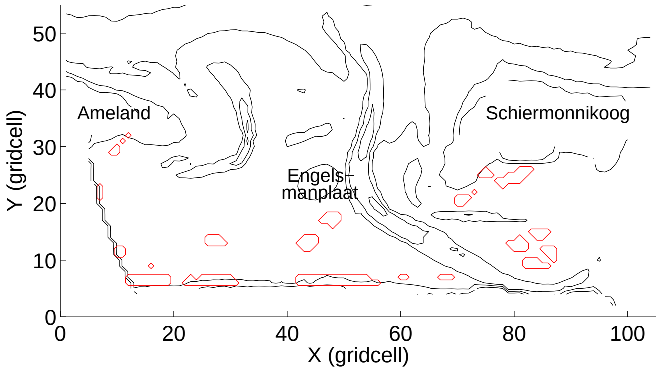


Figure 2.5: Schematisation of the mussel beds in the Friesche Zeegat.

The size of the mussel population in the Dutch Wadden Sea strongly fluctuates from year to year, as a result of climate-influenced population dynamics and fishery. Mussels can survive prolonged periods of frost, but the abrasion of mussel beds by moving ice can be catastrophic according to Dankers and Koelemaij (1989), as was observed in several winters (1962/'63, 1971/'72 and 1984 - 1987). Besides variation in population during several years, seasonal differences also influence the amount of biodeposits of mussels. In order to investigate the effect of seasonal variation on the filtration rate of mussels, Prins et al. (1994) carried out measurements of particulate matter uptake by a mussel bed in a concrete tank with a continuous supply of natural seawater from December 1988 till December 1989. Weight loss of the mussel occurred during the winter period (December - April) and also between May and June. The fastest growth rates were observed between April and May and in the period June till September. These changes in biomass lead to highly significant differences in clearance rates between months.

In Figure 2.5 a schematisation is shown of the locations of the mussel beds. This data is based on actual mussel bed locations in spring 2004 (Steenbergen et al., 2004). The total area of mussel beds at that time was 430 acres. The parametrisation of the mussel bed is modelled in the same way as the diatoms. A constant concentration of 50 μg/g is used to model the effect on the critical bed shear stress and erosion coefficient by the mussels.

Chapter 3

Morphological and biological interaction

The application of the sand-mud model to the Friesche Zeegat by Van Ledden (2003) is based on the numerical modelling system Delft3D. Morphodynamic and hydrodynamic simulations of coastal, river and estuarine areas are performed in Delft3D.

In this chapter the different modules of the sand-mud model are described, detailed information about non-cohesive and cohesive sand-mud mixtures can bed found in the PhD-thesis by Van Ledden (2003). Furthermore, an outline of the implementation of the biological characteristics is given.

3.1 Sand-mud model description

3.1.1 Flow Module

A crucial parameter for sediment transport processes is the bed shear stress. The bed shear stress is the result of water motion, caused by currents and waves, over the bed and the roughness of the bed itself. Currents are mainly driven by tide, wind, river discharge and density differences due to salinity or sediment concentrations. Wind driven waves are locally generated or penetrate from the open sea into the estuary or tidal basin.

The three-dimensional behaviour of currents is described by a mass balance equation and three momentum equations (Van Rijn, 1993). Two important assumptions are made. The vertical accelerations are small compared to the gravitational acceleration and the density variations are small with respect to the water density itself and are only maintained in the gravity term (i.e. 'shallow water' and 'Boussinesq' approximation). The remaining dependent variables in the mass balance and momentum equations are the water level (ζ) and the three velocity components (u, v, w). By solving these equations the currents induced by tide, short waves, river discharge, wind and earth rotation can be modelled.

3.1.2 Sediment transport module

The sand transport can be divided into bed load and suspended load transport. Bed load occurs near the bed surface and is affected by the flow conditions, while suspended load is also determined by the upstream conditions. Sediment erosion occurs once the critical erosion shear stress exerted by moving fluids is exceeded. The critical erosion shear stress is an important parameter in sediment transport mechanics. Below this value little or no erosion occurs, whereas once exceeded significant erosion occurs.

An important distinction in erosional behaviour is made between non-cohesive and cohesive sediment beds. In the non-cohesive regime a sediment bed has a granular structure and does not form a coherent mass. The particle size and weight are the most important parameters for erosion. Whereas, cohesive beds form a coherent mass because of electrochemical reactions between the sediment particles. These reactions dominate the erosional behaviour and not particle size and weight. The transition between non-cohesive and cohesive beds is determined by the clay ($d_50 \leq 0.002$ mm) content.

In the sand-mud model a non-cohesive and cohesive regime is applied. The erosion behaviour of the sediment mixture is considered non-cohesive if the mud content is lower than the critical mud content ($p_{\mathrm{m,cr}}$) or it is considered cohesive if the mud content exceeds the critical mud content.

The exchanges of sediment between the bed and the water column depend on the bed composition at the bed surface. In Delft3D, the bed load sand transport rate is calculated after (Van Rijn, 1993). The net vertical fluxes of suspended sand (F_s) and mud (F_m) near the bed are as follows (Van Ledden and Wang, 2001):
Non-cohesive regime ($p_{\mathrm{m}} \leq p_{\mathrm{m,cr}}$):

$$F_{\mathrm{s}} = w_{\mathrm{s}}(c_{\mathrm{a}} - c_{\mathrm{s}}) \tag{3.1}$$

and

$$F_{\mathrm{m}} = p_{\mathrm{m}} M_{\mathrm{(n)c}} \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{(n)c}}} - 1\right) H \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{(n)c}}} - 1\right) - w_{\mathrm{m}} c_{\mathrm{m}} \left(1 - \frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{d}}}\right) H \left(1 - \frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{d}}}\right) \tag{3.2}$$

Cohesive regime ($p_{\mathrm{m}} > p_{\mathrm{m,cr}}$):

$$F_{\mathrm{s}} = (1 - p_{\mathrm{m}}) M_{\mathrm{c}} \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{c}}} - 1\right) H \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{c}}} - 1\right) - w_{\mathrm{s}} c_{\mathrm{s}} \tag{3.3}$$

and

$$F_{\mathrm{m}} = p_{\mathrm{m}} M_{\mathrm{c}} \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{c}}} - 1\right) H \left(\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{c}}} - 1\right) - w_{\mathrm{m}} c_{\mathrm{m}} \left(1 - \frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{d}}}\right) H \left(1 - \frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{d}}}\right) \tag{3.4}$$

where w_{s} is the settling velocity for sand at 20 °C [m s^{-1}], c_{a} a reference sand volume concentration [-], c_{s} the sand volume concentration near the bed surface [-], M_{nc} the erosion coefficient for the non-cohesive regime [m s^{-1}], τ_{b} the bed shear stress [N m^{-2}], τ_{nc} the critical erosion shear stress for the non-cohesive regime [N m^{-2}], M_{c} the erosion coefficient for the cohesive regime [m s^{-1}], τ_{c} the critical erosion shear stress for the cohesive regime [N m^{-2}],

w_m is the settling velocity for mud at 20 °C [m s^{-1}], c_m the mud concentration [-] near the bed surface, and τ_d the critical shear stress for mud deposition [N m^{-2}]. The heavyside function H is equal to 1 when the argument is positive and 0 when the argument is negative. For a detailed description the reader is referred to Van Ledden and Wang (2001) and Van Ledden (2003).

3.1.3 Bed module

By applying the bed composition concept developed by Armanini (1995), spatial and temporal variations are taken into account. The first term of Eq. 3.5 gives a description of the local change in mud content at a certain level below the bed level. The second term represents the effect of the moving origin of z_c due to the changing bed level, and is used because of the Lagrangian coordinate[1] system. In the sediment bed, the mud content in the surface of the bed is calculated explicitly. The sand content follows from continuity. The third term gives an expression of the fluxes by physical and/or biological mixing in the bed.

$$\frac{\partial p_m}{\partial t} + \frac{\partial z_b}{\partial t}\frac{\partial p_m}{\partial z_c} - \frac{\partial}{\partial z_c}\left(\theta_{mix}\frac{\partial p_m}{\partial z_c}\right) = 0 \tag{3.5}$$

where z_c is the distance below the bed surface z_b [m] and θ_{mix} consists of a physical mixing component (θ_p) and a biological mixing coefficient (θ_b): $\theta_{mix} = \theta_p + \theta_b$. The physical mixing component is caused by small-scale bed level disturbances. It is proportional to the shear velocity (u_*) and the sand grain size (d_{50}), and decreases exponentially with the distance from the bed surface (Armanini, 1995). The biological mixing coefficient is constant according to Van Ledden and Wang (2001).

3.2 Parameterisation of biological activity

To include the effect of the biological activity in the process-based sand-mud model, the influence of *Macoma balthica*, diatoms and mussel beds is parameterised as an effect on the critical erosion shear stress (τ_{cr}) and erosion coefficient (M) (Widdows and Brinsley, 2002). Paarlberg et al. (2005) stated that *Macoma balthica* are modelled by a reduction of the critical bed shear stress and an increase of the erosion coefficient. The diatoms and mussel beds are modelled as an increase of the critical bed shear stress and a decrease of the erosion coefficient. The parameterisation of the influence of biological activity on the sediment strength is represented in the following expressions:

$$\tau_{(n)c} = \tau^0_{(n)c} f_s(B) f_d(C) \tag{3.6}$$

$$\tau_c = \tau^0_c f_s(B) f_d(C) \tag{3.7}$$

$$M_{(n)c} = M^0_{(n)c} g_s(B) g_d(C) \tag{3.8}$$

[1]Coordinates used in fluid dynamics in which the coordinates are fixed to a given parcel of fluid, but move in space.

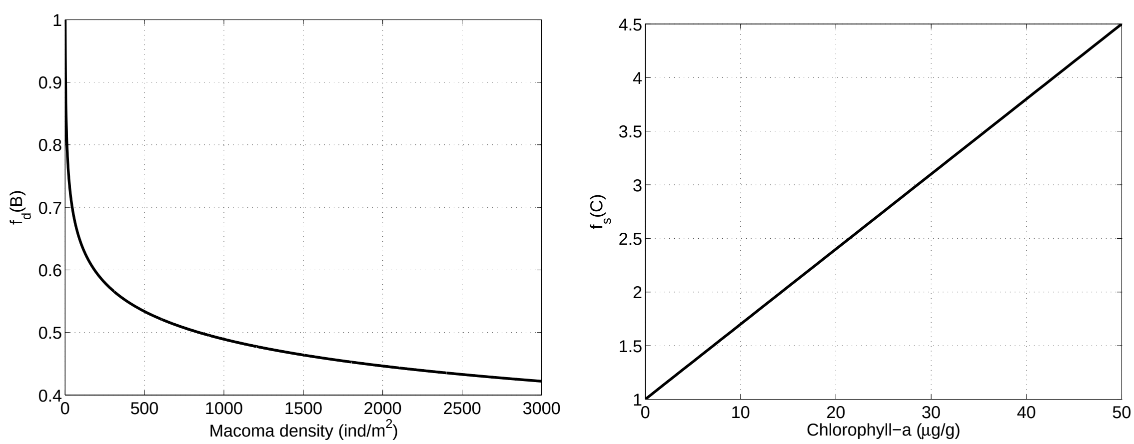
$$M_{\mathrm{c}} = M_{\mathrm{c}}^{0} g_{\mathrm{s}}(B) g_{\mathrm{d}}(C) \tag{3.9}$$

$$\theta_{\mathrm{d}} = \theta_{\mathrm{b}}^{0} g_{\mathrm{d}}(B)) \tag{3.10}$$

where τ_{nc} and τ_{c} are the critical bed shear stress for the non-cohesive and cohesive regime, respectively, M_{nc} is the non-cohesive and M_{c} cohesive erosion coefficient and θ_{d} is bioturbation coefficient including biological activity. Parameters without biological influences are denoted with the superscript '0'. f_{s} and g_{s} represent the stabilising and destabilising influences on the critical bed shear stress and erosion coefficient, respectively. The destabilising influence on the critical bed shear stress is denoted by f_{d} and for the erosion coefficient by g_{d}. B is the dimensionless *Macoma* abundance and C is the Chlorophyll-a content in the sediment. In the next two paragraphs B and C will be explained.

3.2.1 Effect on the critical shear stress

Two factors can be distinguished, a destabilising factor by the clam *Macoma balthica* and a stabilising factor caused by diatoms and mussel beds (Knaapen et al., 2003). The assumption is made that the sediments which deposit at the location of a mussel bed remain at the bed surface and are not resuspended. Therefore, the stabilising factor for the critical bed shear stress $f_{\mathrm{s}}(C)$ is also used to increase the critical bed shear stress and decrease the erosion coefficient so that no erosion occurs at the location of a mussel bed.



(a) (b)

Figure 3.1: The effect of (a) *Macoma balthica* density on the destabilisation factor $(f_{\mathrm{d}}(B))$ and (b) Chlorophyll-a content on the stabilisation factor $(f_{\mathrm{s}}(C))$ for the critical bed shear stress.

The expressions for the destabilising and stabilising factors are:

$$f_\mathrm{d}(B) = 0.0016\ln[Macoma^*]^2 - 0.085\ln[Macoma^*] + 1 \quad (3.11)$$
$$B = \frac{Macoma}{Macoma_\mathrm{ref}}$$

$$f_\mathrm{s}(C) = 0.07[C] + 1 \quad (3.12)$$
$$C = \frac{Chla}{Chla_\mathrm{ref}}$$

where B and C are made dimensionless using a reference density of 1 m^{-2} and a reference content of 1 μg/g. In Figure 3.1(a) the relationship between *Macoma balthica* density and the destabilisation factor $f_\mathrm{d}(B)$ is given. In Figure 3.1(b) the relation between the stabilisation factor $f_\mathrm{s}(C)$ and the Chlorophyll-a content is given.

3.2.2 Effect on the erosion coefficient

The destabilising effect on the erosion coefficient (M) is expressed by the following equation (Paarlberg et al., 2005):

$$g_\mathrm{d}(B) = \frac{b_2\gamma}{(b_2 + \gamma[b_1]^B)\,I} \quad (3.13)$$

and the stabilising effect on the erosion coefficient by:

$$g_\mathrm{s}(C) = -0.018C + 1 \quad (3.14)$$

where $b_1 = 0.995$ and $b_2 = 5.08 \times 10^{-8}$, I the erosion coefficient without biological activity is 4.68×10^{-8} m s^{-1} and γ the maximum erosion coefficient is 6×10^{-7}. In Figure 3.2(a) the relation between the destabilisation factor ($g_\mathrm{d}(B)$) and the *M. balthica* density is given. The

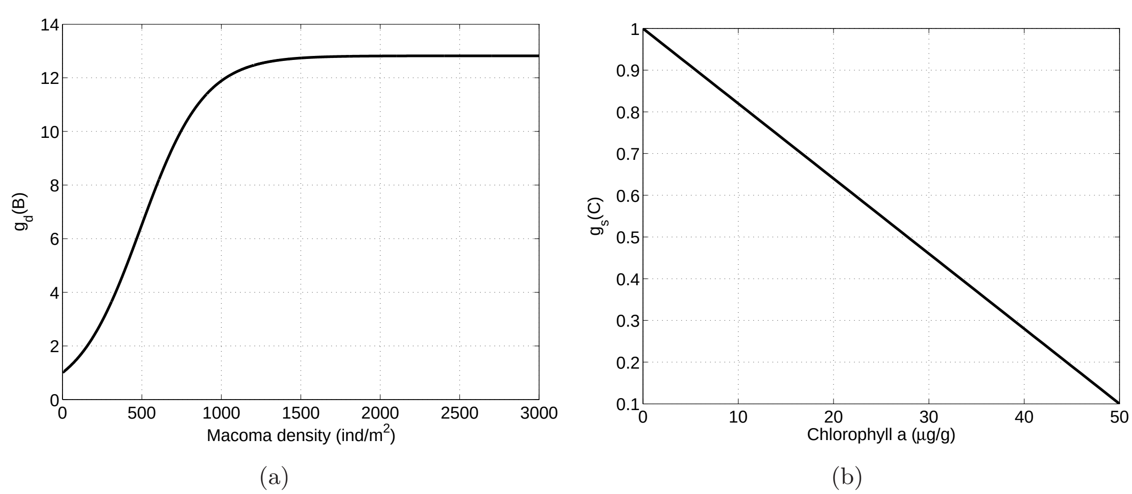


Figure 3.2: The effect of (a) *Macoma balthica* density on the destabilisation factor ($g_\mathrm{d}(B)$) and (b) Chlorophyll-a content on the stabilisation factor ($g_\mathrm{s}(C)$) for the erosion coefficient.

S-shaped curve (logistic function) starts at one because the factor g_{d} is always larger than one. If the factor is smaller than one, it will have an unwanted stabilising effect on the erosion rate.

3.3 Sand-mud-bio model

In the previous sections the parameterisation of biology and morphology is described. To determine the influence of biological activity on the suspended sediment transport in the Friesche zeegat, Eqs. 3.6 - 3.10 are implemented in the sand-mud model by Van Ledden (2003). In Figure 1.3 the setup of the original process-based sand-mud model is given. This model is extended with the description of the biological activity and a schematisation is given in Figure 3.3.

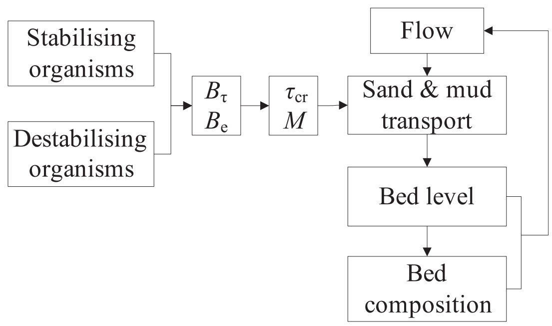


Figure 3.3: Set-up of the original sand-mud model included with influence of the biological activity (Paarlberg et al., 2005).

Chapter 4

Model set-up of the reference situation

In order to study the effects of the biological influence by stabilisers and destabilisers on the fine-grained sediment transport, first a model set-up of the reference situation is made. This model set-up is based on the original process-based sand-mud model by Van Ledden (2003) with addition of the biologically parameters described in the previous chapter.

First, a description of the model simulation is given in. Second, a schematisation of the model area is given in. Finally, the boundary conditions and the initial conditions are described.

4.1 Simulation of the model

The process-based sand-mud model simulates two tides starting at high water. The duration of one tidal period is 12 hours and 24 minutes and the model uses a time-step of one minute. In order to decrease the model simulation time a morphological scaling factor is used. As it name reveals, this scaling factor exaggerates the morphological features like the bed level change and bed level composition. The scaling factor is set at 116, this means that one single simulation of two tides is in fact 116 times two tides which approximately corresponds to 120 days. In order to perform simulations longer than one third of a year, the morphological data and the mud content of each simulation is saved and used as input for the next simulation. So, 3 or 6 repeated simulations approximately correspond to one year or two years respectively.

During each simulation the first tidal period is used for spinning up the model, because small artificial errors in the bed shear stress might easily spoil the initial bed level and composition (De Boer, 2002). The morphological computation starts at the beginning of the second tidal period. During the repeated simulations the first tidal period is also used for spinning up and only the results of the second tide are used to assess changes in bed level and composition.

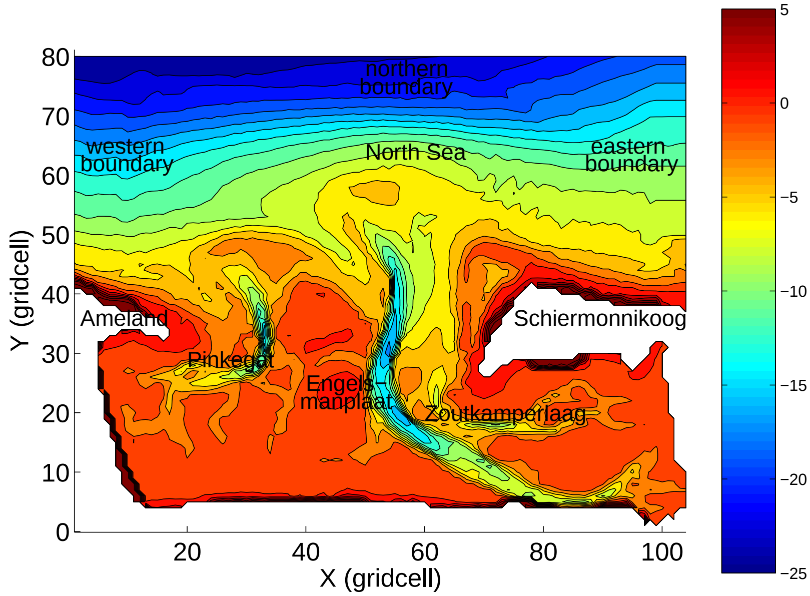


Figure 4.1: Numerical grid (X,Y) and depth contours (m) of the Friesche Zeegat. The open boundaries are situated in the North Sea, the basin is surrounded by closed boundaries in the east, south and west.

4.2 Computational grid and bathymetry

The numerical grid for the Friesche Zeegat is based on the topography of 1991. This resulted in a horizontal grid of 105×81 with a resolution of 250 to 600 m. In the center of the grid the size of the cells is smaller than at the boundaries. The model area is approximately 20 km wide (north south) and 35 km long (east west). The three open boundaries are located in the east, west and north of the North Sea. The water sheds, areas where the tidal currents meet, south of Ameland and Schiermonnikoog are natural boundaries and almost show no interaction with the adjacent tidal basins. Therefore these boundaries are assumed to be closed. The dike situated in the south of the basin is also modelled as a closed boundary. The model area is shown in Figure 4.1.

4.3 Boundary conditions

4.3.1 Hydrodynamics

The boundary condition at the North Sea can be composed of the semi-diurnal (M_2) and the quarter-diurnal tide (M_4), in addition to the mean water level (M_0). The M_2-tide is a principal lunar tidal component with a period of 12 hours and 24 minutes. The quarter-diurnal M_4-tide is a non-linear overtide generated by the M_2 signal in the region. The effect of a spring-neap cycle was not considered. Detailed information about the possible effect of a spring-neap cycle on the long-term morphological behaviour and the tidal constituents is

	Wierumergronden	Huibertgat	Western boundary	Eastern boundary
M_0	0.006	-0.036	0.019	-0.028
M_2	0.951	1.029	0.928	1.014
M_4	0.097	0.087	0.099	0.089

Table 4.1: Water level amplitudes at Wierumergronden, Huibertgat, Western and Eastern model boundary (Van Ledden, 2003).

presented in Van Ledden (2003).

The water level amplitudes of the M_0, M_2 and M_4 tidal constituents are based on two water level stations (Wierumergronden and Huibertgat) near the eastern and western model boundary (see Table 4.1). The station Wierumergronden is located inside the model area, approximately (25,75), but the station Huibertgat is situated about 5 km outside the eastern boundary in the North Sea. Towards the eastern and western boundary the amplitudes are interpolated and extrapolated linearly and are taken constant along these boundaries. Between the eastern and western boundary the tidal characteristics vary linearly along the northern boundary.

The water column in vertical direction is divided in five layers with a distribution from the water surface to the bed of 50, 30, 10, 5 and 5% of the local water depth (Van Ledden, 2003).

4.3.2 Waves

The effects of short waves on the bed shear stress is taken into account, whereas wave-current interactions are neglected. The effect of waves is calculated with the SWAN package (Delft3D). Steady wave fields are calculated at 4 moments during the tide: high water, low

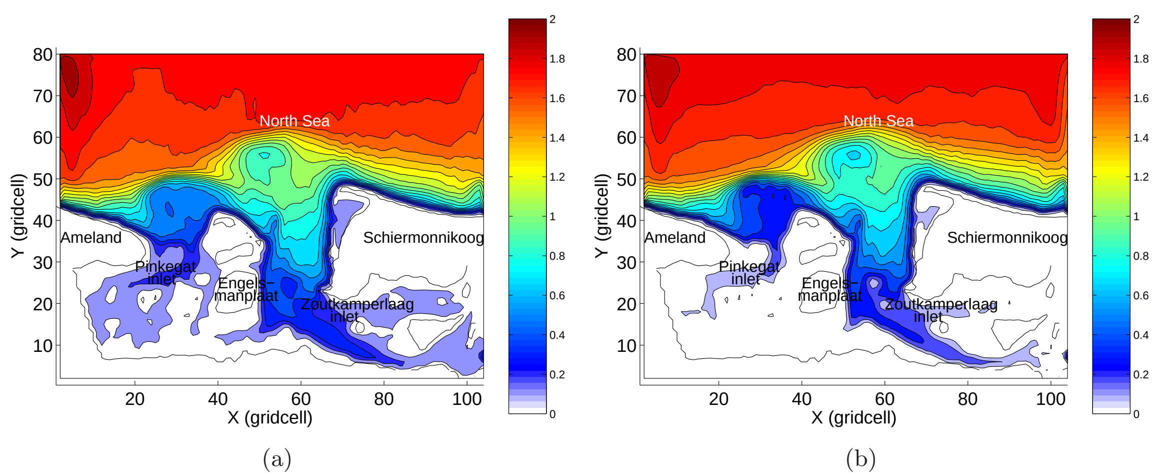


Figure 4.2: Wave heights (m) during (a) maximum ebb currents and (b) low water.

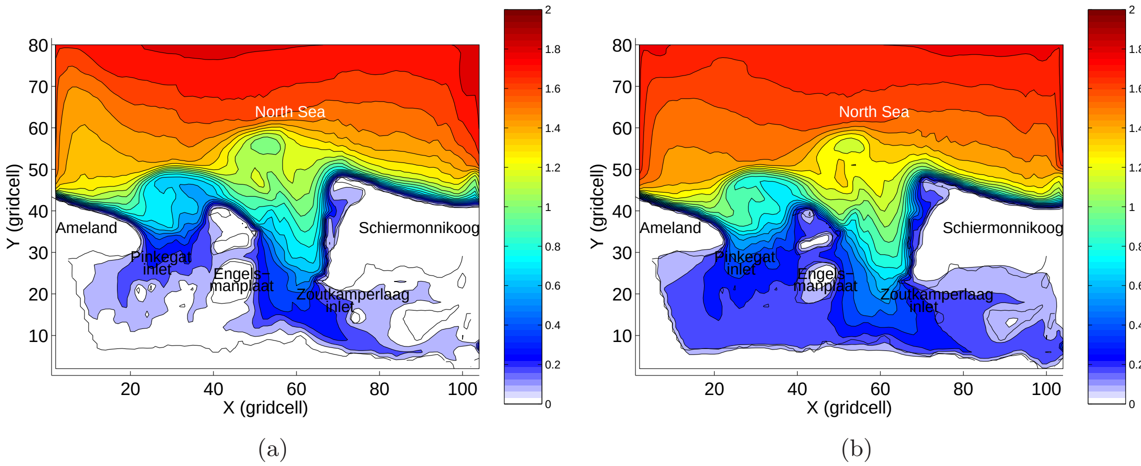


Figure 4.3: Wave heights (m) during (a) maximum flood currents and (b) high water.

water and at maximum ebb and flood current. In Figure 4.2 and 4.3 the four different wave fields are presented. A cyclic time frame is used to ensure that the waves are always calculated at the same moment in time during the tidal period. The wave conditions are obtained from measurements buoys near the Friesche Zeegat and represent different values of the long term distribution. The wave fields are linearly interpolated in time between the calculated wave times.

The long-term wind direction and the wave direction show a large spreading between SSW and NNE. The wave distribution has peaks between 240°N and 360°N (nautical notation),

Description	Symbol	Value	Unit
Sand grain size	d_{50}	140	μm
Mud grain size	d_{50}	63	μm
Sediment density	ρ_s	2650	kg/m^3
Settling velocity sand	ω_s	0.015	m/s
Settling velocity mud	ω_m	0.00025	m/s
Critical erosion shear stress:			
- Non-cohesive erosion	$\tau_{cr,s}$	0.25	N/m^2
- Cohesive erosion	τ_e	0.5	N/m^2
Erosion coefficient:			
- Non-cohesive erosion	M_{nc}	10^{-4}	m/s
- Cohesive erosion	M_e	10^{-8}	m/s
Critical mud content	$p_{m,cr}$	0.3	-
Coefficient for critical shear stress for non-cohesive mixtures	β	1.5	-
Critical deposition shear stress mud	$\tau_{cr,d}$	0.15	N/m^2

Table 4.2: Settings of the physical parameters of the reference computation.

therefore a direction of 355°N is chosen (De Boer, 2002). This will result in waves approaching perpendicular to the coast of the backbarrier islands in the Wadden Sea. The wave driven currents along the coasts of the islands will almost be absent, which makes the neglecting of the wave-current interaction less significant.

4.4 Initial conditions

The applied sand concentration at the inflow of the open sea boundaries is kept constant for suspended sand transport. The mud concentration offshore appears to be low (5 - 10 mg/l), but increases up to 100 mg/l at 5 - 10 km from the coast. Because the northern model boundary is located approximately 10 km of the coast, a uniform mud concentration profile is used with a constant value of $c_{\mathrm{m},0} = 100$ mg/l at all open boundaries (Van Ledden, 2003).

In the reference situation the initial current velocity, water level and suspended sediment concentrations are set to zero. Also, the initial mud content is zero and the simulation starts with a full sand bed. The mud content at the end of each simulation is used as the initial mud content for the next simulation.

Chapter 5

Reference situation

In this chapter the results of the reference situation are presented. The reference situation is the model simulation without the influence of biology. The model set-up of this reference situation is described in the previous chapter. The results are the outcome of a simulation two years. The results without biology are compared with the results including biology, which are shown in Chapter 6. Only the results of the second tidal period are presented (see Chapter 4). In the following sections the results, based on computed data in different observation points, are shown. These observation points are shown in Figure 5.1. The area of interest is smaller than the total model area, because a part of the North Sea is of minor importance. In this part of the model area there is no biological activity.

First, the water level and the current velocities during a tidal period are presented. Second, the bed shear stresses as a result of the tidal currents are presented. Finally, the changes in mud content and bed level change in the Friesche Zeegat are given.

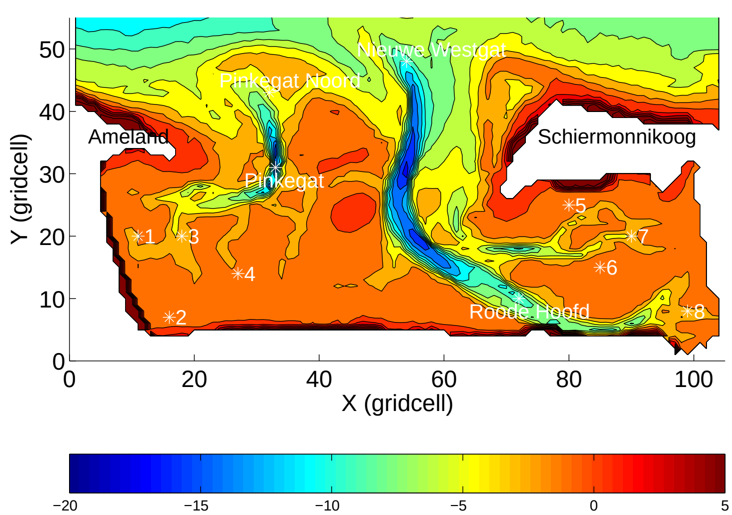


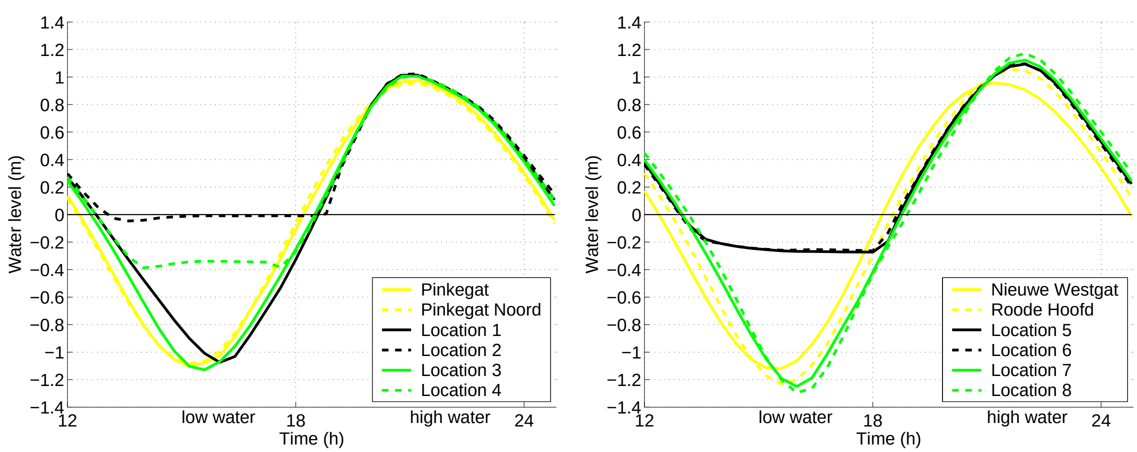
Figure 5.1: Observation points and depth contours (m) in the Friesche Zeegat according to Mean Sea Level.

5.1 Water level and tidal currents

The water level as a result of the the semi-diurnal (M_2) and the quarter-diurnal tide (M_4) (see Section 4.3.1) is presented for the different observation points in the Friesche Zeegat. The depths of the observation points in the Pinkegat channel and the Zoutkamperlaag channel are shown in Table 5.1. The locations of these observation points are shown in Figure 5.1 and the corresponding water levels during a simulation are presented in Figure 5.2(a) and 5.2(b). Location 2, 4, 5 and 6 are shallow which causes drying of these mud flats during ebb. The minimum water level at location 2, 4, 5 and 6 does not correspond with the depth in Table 5.1. This is caused by the drying and flooding routine in Delft3D. The sand-mud model always leaves a thin layer of water on the mud flats when the water level becomes lower than the bed level.

The amplitude of the tide in the deeper areas (Pinkegat and Nieuwe Westgat) is smaller than the amplitude in the shallow areas. Due to a decrease in water depth the tidal wave speed and wave length decrease, therefore the energy per unit area of the wave has to increase. This 'shoaling'-effect results in an increase of the tidal wave height, but the tidal wave period remains the same. Especially, in Figure 5.2(b) these differences are clear, while in Figure 5.2(a) these differences are less significant. The propagation of the tidal wave through the basin results in a difference in tidal phase at each observation point. The larger the distance between the observation points the larger the tidal phase difference. This difference is especially visible between observation point Nieuwe Westgat, Roode Hoofd and location 7 and 8.

An indication of the tidal induced current velocities for the 12 observation points is given in Figure 5.3. The presented velocities are taken from the fifth layer of the water column, which is the closest to the bed surface at a height of 5% of the local water depth. This height is chosen because the highest current velocity is expected to be found close to the bed surface, which will generate the highest bed shear stress. During ebb and flood the largest tidal



(a) (b)

Figure 5.2: Water level during a single tidal period at location: (a) 1 - 4, Pinkegat and Pinkegat Noord and (b) 5 - 8, Nieuwe Westgat and Roode Hoofd.

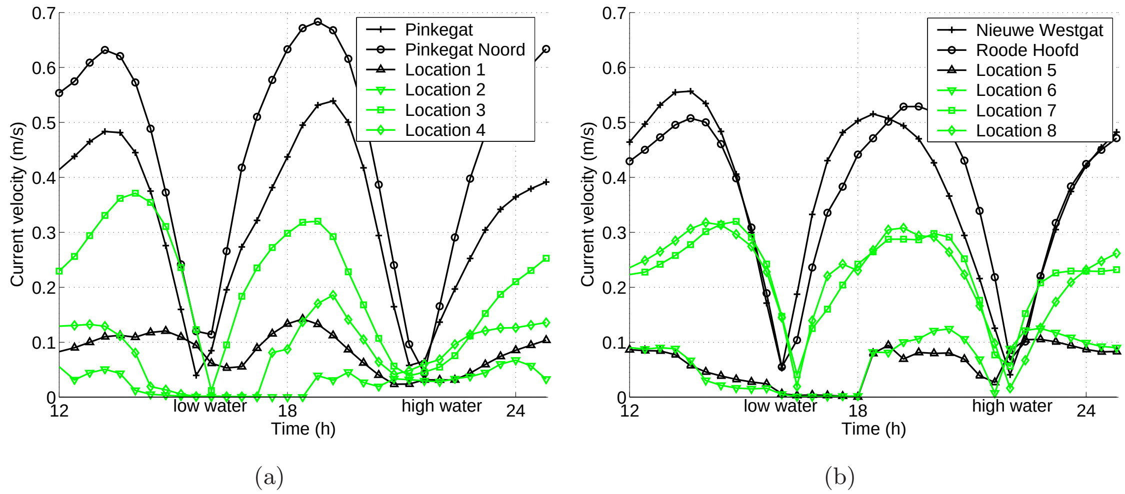
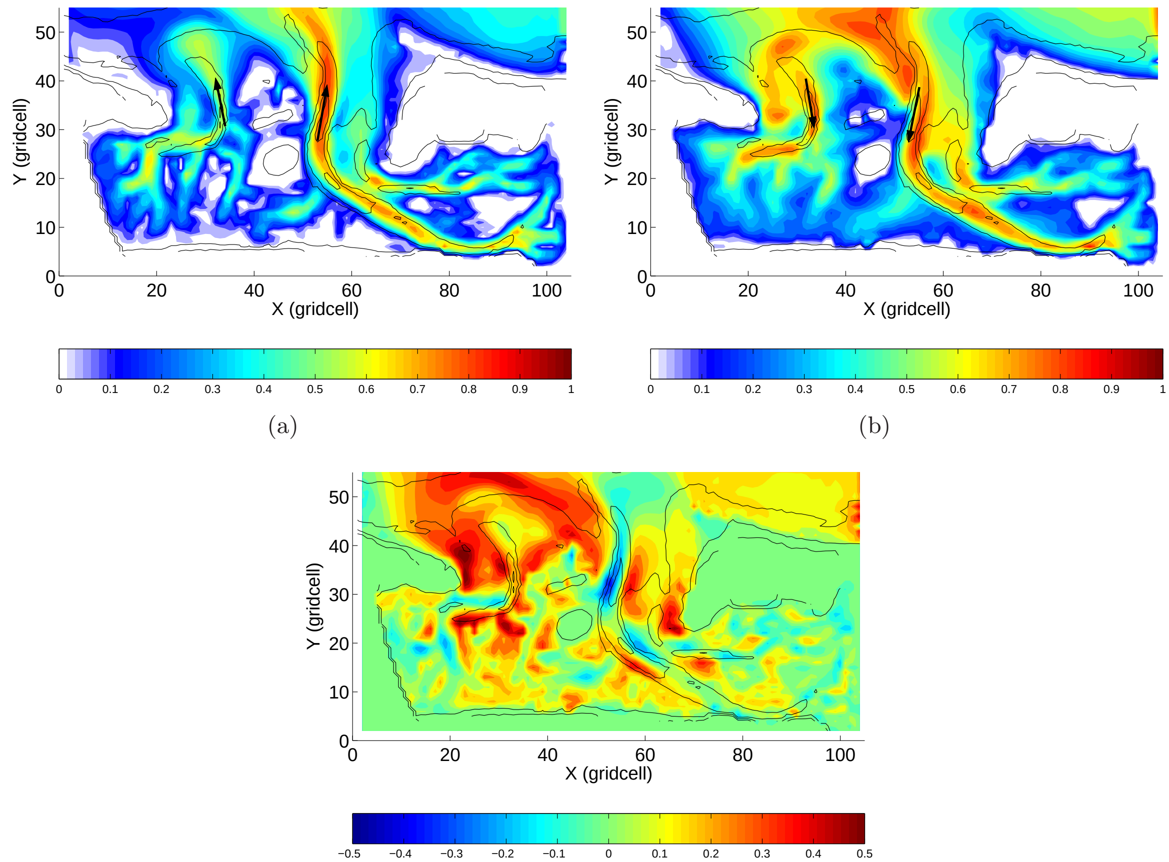


Figure 5.3: Current velocities (m/s) during a tidal period at location: (a) 1 - 4, Pinkegat and Pinkegat Noord and (b) 5 - 8, Nieuwe Westgat and Roode Hoofd.

currents can be seen and during low and high water the tidal currents are at its minimum.

The largest maximum ebb and flood current velocities can be found in both channels, location Pinkegat and Pinkegat Noord (see Figure 5.3(a)) and location Nieuwe Westgat and Roode Hoofd (see Figure 5.3(b)). Because of the earlier explained 'shoaling'-effect, a decrease in water depth results in a decrease in current velocity. The decrease in current velocities at the shallow mud flats is clearly visible, however the difference between ebb and flood velocities for each location is not very significant. Location Pinkegat, Pinkegat Noord, Roode Hoofd, 1 and 4 show higher maximum flood currents than maximum ebb currents. At the other locations the maximum ebb current is more or less equal or slightly stronger than the maximum flood current.

Figure 5.4 shows the maximum ebb and flood currents, but also the difference between these two. In Figure 5.4(c) the negative values for the current velocity are ebb dominated and the positive values are flood dominated. Looking at these figures, the differences between maximum ebb and flood currents are more clearly visible. Because of the tidal wave propagation through the basin not all maximum ebb and flood currents occur at the same time for the entire area. The minimum and maximum currents shown, are taken when the maximum ebb and flood currents occur at location Roode Hoofd. Figure 5.4(c) shows an overall larger flood current than ebb current, not only in the channels but also on the mud flats. Taking into account that Figure 5.4 shows the moments of approximately the maximum ebb and flood velocities in the entire basin, the differences in some areas can be slightly exaggerated or underestimated. Because of the constant mud concentration of 100 mg/l (see 4.3) at the boundaries in the North Sea during each simulation, an increase of the mud content in the entire basin is expected.



(a) (b)

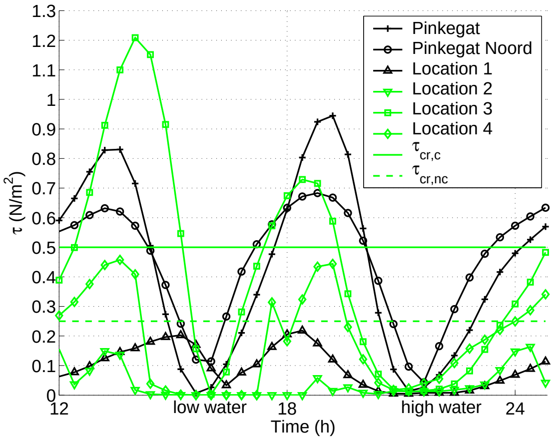
(c)

Figure 5.4: Tidal current velocities (m/s) in the Friesche Zeegat: (a) maximum ebb, (b) maximum flood currents and (c) difference between the maximum ebb and flood currents (positive value indicates higher flood current velocities, negative value indicates higher ebb current velocity).

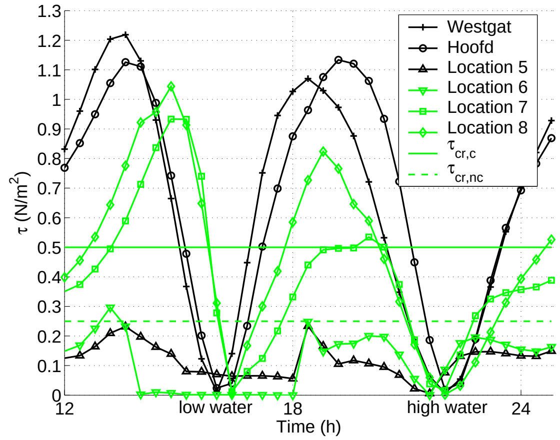
5.2 Bed shear stress

In Figure 5.5 the bed shear stress is presented for all observation points. In both figures the critical bed shear stress in the non-cohesive regime and the critical bed shear stress for the cohesive regime are shown, where the critical bed shear stress for non-cohesive mixtures is 0.25 N/m^2 and 0.5 N/m^2 for cohesive mixtures. The switch from a non-cohesive to a cohesive regime takes place if the mud content exceeds 30% ($p_{\mathrm{m,cr}}$).

From Figure 5.5, one can see that the maximum bed shear stress at location 1, 2 and 5 does not exceed the critical bed shear stress for non cohesive mixtures (τ_{nc}). At location 4 and 6 the bed shear stress does not exceed the critical bed shear stress in the cohesive regime (τ_{c}). When the bed shear stress is smaller than the critical bed shear stress, no erosion will occur. At all other locations, with a depth larger than 2 m, the bed shear stress exceeds the critical bed shear stress. This means that in these areas erosion occurs. The percentage in time exceeding the critical bed shear stress in the cohesive and non-cohesive regime during



(a)



(b)

Figure 5.5: Bed shear stress (N/m^2) during a tidal period at location: (a) 1 - 4 and Pinkegat (Noord) and (b) 5 - 8, Nieuwe Westgat and Roode Hoofd. The horizontal lines represent the critical bed shear stress for non-cohesive mixtures ($\tau_{\text{cr,nc}}$) and for cohesive mixtures ($\tau_{\text{cr,c}}$).

one tidal period for all observation points is shown in Table 5.1.

The comparison of Figure 5.3 with Figure 5.5 indicates that small current velocities result in low bed shear stresses and in these areas no erosion occurs. In the deeper areas, where high current velocities and high bed shear stresses occur, erosion of the bed leads to bed load transport or suspended sediment transport. The latter is important for this research, because the fine-grained sediment transport is believed to be influenced by biological activity. As described before in Chapter 3.1.2, suspended sediment transport is also influenced by upstream conditions. The passing water is influenced by local flow conditions upstream of

Location	Depth (m)	% exceeding τ_{nc}	% exceeding τ_{c}
1	1.25	0	0
2	0.12	0	0
3	2.39	45	38
4	0.42	35	0
5	0.19	0	0
6	0.13	5	0
7	2.21	58	26
8	2.25	74	46
Pinkegat	15.76	60	42
Pinkegat Noord	3.80	79	53
Nieuwe Westgat	9.31	77	62
Roode Hoofd	9.18	80	66

Table 5.1: Percentage in time exceeding τ_{nc} and τ_{c} during one tidal period for each observation point.

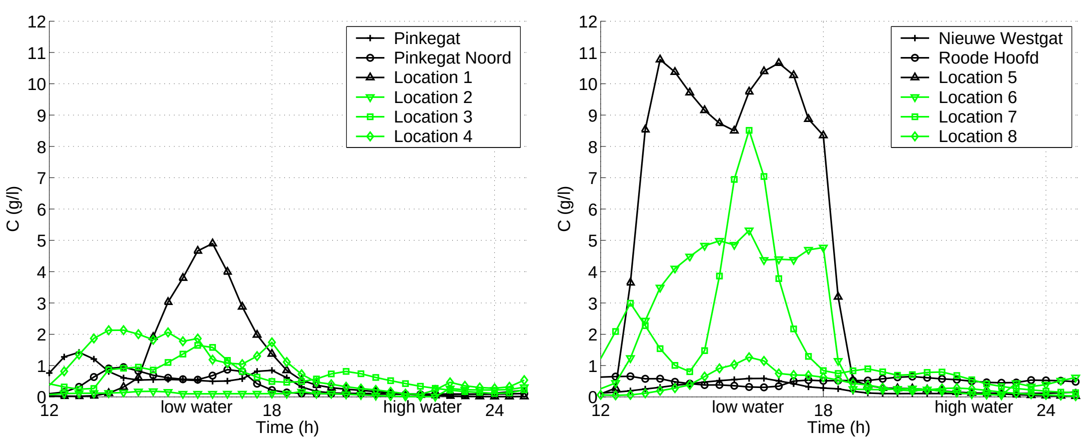
the area of interest.

During 60 - 80% of the tidal period the critical bed shear stress in the non-cohesive regime is exceeded for location 7, 8, Pinkegat, Nieuwe Westgat en Roode Hoofd. This means that erosion occurs and this results in bed load and suspended sediment transport. At the shallow mud flats (location 1, 2, 4, 5 and 6) bed shear stresses are very small and if current velocities are small enough, no erosion occurs.

The switch between the non-cohesive and cohesive regime lies around a critical mud content of 30%. The critical bed shear stress is doubled and for locations 7, 8, Pinkegat, Nieuwe Westgat and Roode Hoofd about 50% of the time, no erosion will take place, this is caused by the cohesive bed which forms a coherent mass caused by the electrochemical interactions between the sediment particles. This does not mean, that no suspended sediment transport will occur, once in suspension, particles can remain in suspension when current velocities are high enough.

5.3 Suspended sediment

The computed suspended mud concentration is measured in the lower 5% of the water column, at the same height above the bed surface as the current velocities (see Section 5.1). The suspended mud concentration during the tidal period is shown in Figure 5.6. It can be noted that for location 1, 5, 6 and 7 the suspended mud concentration are excessively high during low water. In the model a thin layer of water remains on the mud flats during low water, because of drying this results in very high unrealistic mud concentrations. Location 2, 4, 5 and 6 are shallow and during low water these mud flats emerge, but only at location 5 and 6 this results in high suspended mud concentrations.



(a) (b)

Figure 5.6: Suspended mud concentration (g/l) profiles during a tidal period in: (a) location 1 - 4 and Pinkegat and (b) location 5 - 8, Nieuwe Westgat and Roode Hoofd.

	Pinkegat Noord		Nieuwe Westgat	
	Ebb	Flood	Ebb	Flood
Concentration (g/l)	0.41	0.45	0.23	0.27

Table 5.2: Average suspended mud concentration (g/l) during the ebb and flood period.

Looking at the computed suspended mud concentrations during ebb and flood in the Zoutkamperlaag channel and the Pinkegat channel, the following differences can be noted. In Table 5.2 the average suspended mud concentration for location Nieuwe Westgat and Pinkegat Noord during ebb and flood is shown. At location Nieuwe Westgat the average concentration during ebb is 0.23 g/l and during flood is 0.27 g/l. At location Pinkegat Noord the suspended mud concentrations are 0.41 g/l during ebb and 0.45 g/l during flood. These two locations are chosen because these are positioned in a tidal channel, where the tidal flow during ebb and flood is more or less in the same direction. Assuming that the amount of water flowing through the Zoutkamperlaag is twice the amount of water flowing through the Pinkegat channel during ebb and flood Van Leeuwen et al. (2003), the amount of mud remaining in the tidal basin during one tidal period is estimated at 9,500 ton.

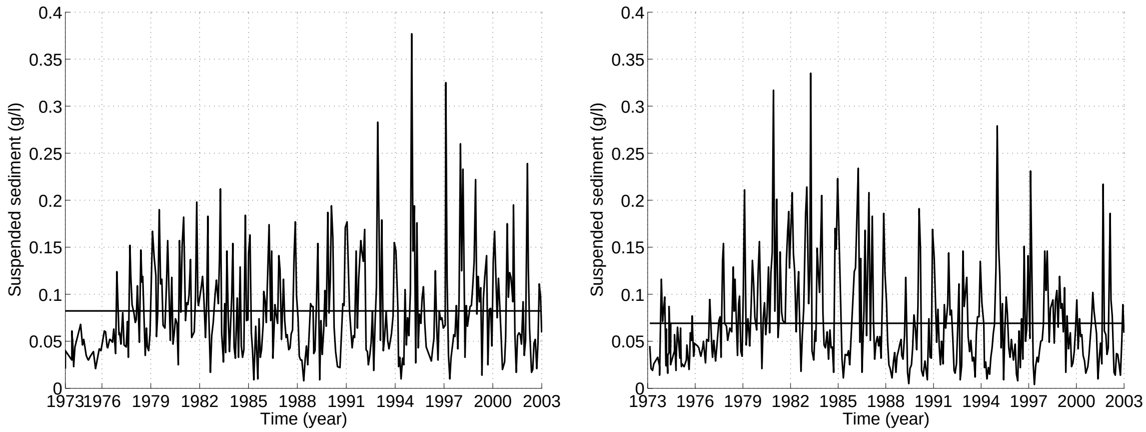
To give an indication of the reliability of the results, the locations Nieuwe Westgat and Roode Hoofd are compared with observed data obtained at the Zoutkamperlaag (corresponds with location Nieuwe Westgat) and Roode Hoofd from 1973 - 2003 shown in Figure 5.7. An outline of all concentrations is given in Table 5.3.

The observed average concentration for the Zoutkamperlaag is 0.082 g/l and the Roode Hoofd and 0.069 g/l (directly from the website: http://www.waterbase.nl). These are low compared to the computed concentration shown in Figure 5.6, 0.26 g/l for location Nieuwe Westgat and 0.52 g/l for location Roode Hoofd. The results show the concentration during a single tidal period instead of a long-term calculation, like the period during which the observed data are obtained. It is more likely to compare the computed maximum concentrations with the maximum observed concentrations.

The maximum observed mud concentration in the Zoutkamperlaag is 0.38 g/l and the accompanying computed concentration in the Nieuwe Westgat is 0.59 g/l. The maximum observed concentration at Roode Hoofd is 0.34 g/l and the corresponding computed concentration is 0.66 g/l. The maximum observed and computed mud concentration are in the same order (10^{-1}), while the average observed mud concentrations are about a factor 10 lower (10^{-2}) than the computed average mud concentrations. The computed values for the maximum sus-

	Average mud concentration (g/l)		Maximum mud concentration (g/l)	
	Observed	Computed	Observed	Computed
Nieuwe Westgat	0.082	0.24	0.38	0.59
Roode Hoofd	0.069	0.49	0.34	0.66

Table 5.3: Observed and computed average and maximum suspended mud concentrations for location Nieuwe Westgat and Roode Hoofd.



(a) (b)

Figure 5.7: Observed suspended sediment concentration (g/l) at (a) Nieuwe Westgat and (b) Roode Hoofd from 1973 - 2003 (http://www.waterbase.nl). The horizontal lines represent the average concentration during that period.

pended sediment concentration are almost twice as high as the observed data. As one can see from Table 5.3, the observed concentrations are larger at location Nieuwe Westgat than at location Roode Hoofd, while this is the opposite for the computed mud concentrations. It is uncertain at which moment during the tidal period the observed data is taken and the height at which the measurements are taken is not available.

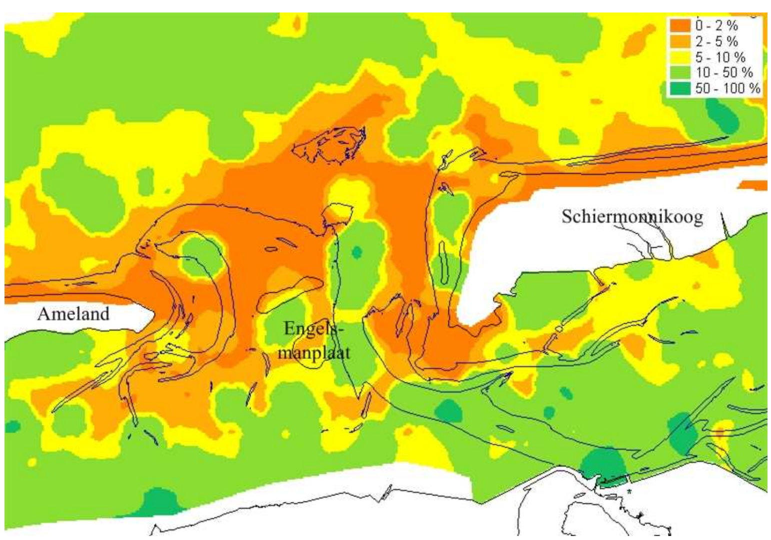


Figure 5.8: Observed mud content in the Friesche Zeegat (Van Rijsewijk, 2002).

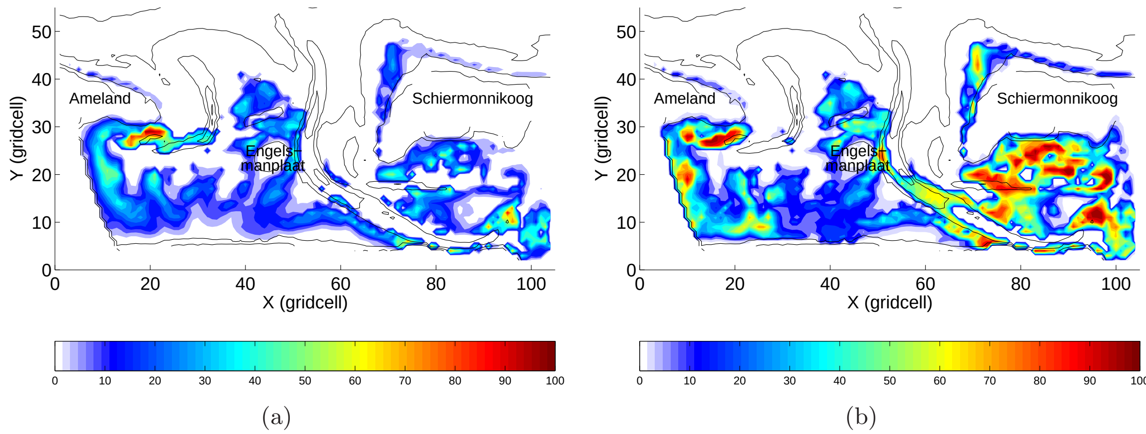


Figure 5.9: Mud content (%) after (a) 1 year and (b) 2 years.

5.4 Mud content

In Figure 5.9 the development of the computed mud content in the top layer of the bed surface is presented. The model starts with a plain sand bed and as can be seen, after 1 year there is a significant increase in mud content. High concentrations of mud (about 40%) can be found close to the shore and on the mud flats. Exceeding the critical mud content of 30% results in a switch from a non-cohesive to a cohesive regime. The increased critical bed shear stress and decreased erosion coefficient will lead to less erosion and most likely more mud deposition.

After two years, in a large area of the basin, the critical mud content of 30% is exceeded. In the eastern part of the tidal basin and also along the western water shed, high mud content can be observed. Looking at the center of the basin, the mud content remains about 20%. After 4 and 8 years, the rapid increase in mud content becomes smaller and the system tends to an equilibrium. Comparing Figure 5.4 with Figure 5.9 and 5.10 one can see that when the

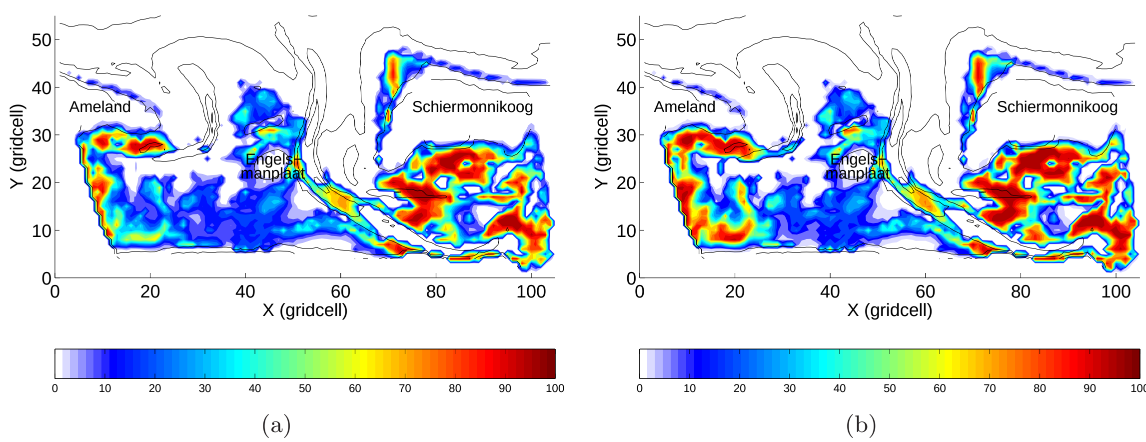


Figure 5.10: Mud content (%) after (a) 4 year and (b) 8 years.

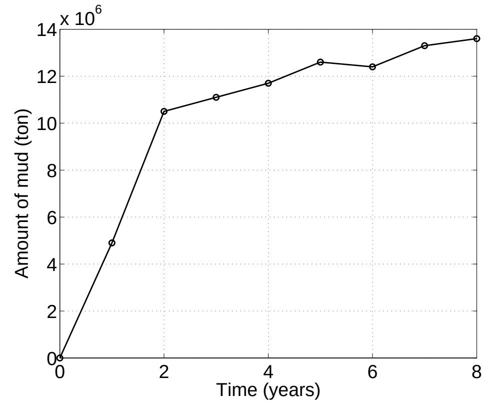
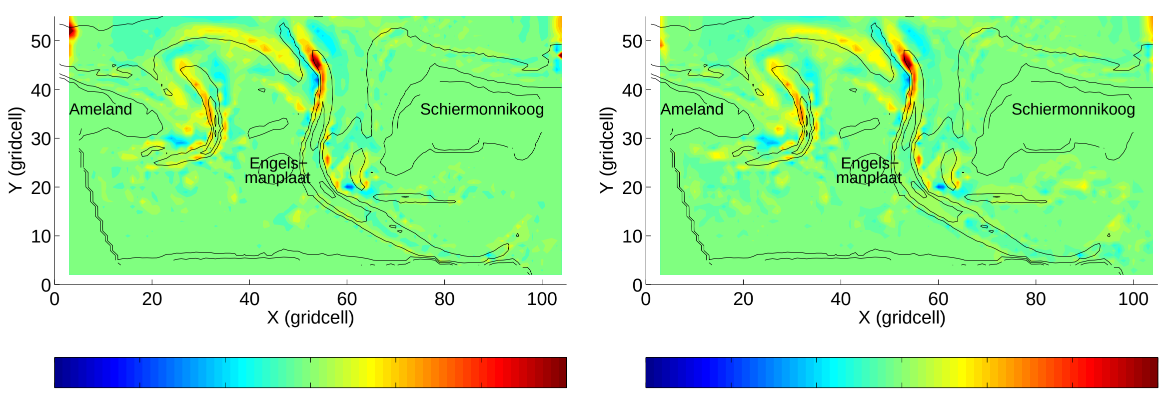


Figure 5.11: Computed net sedimentation of mud (ton) in the Friesche Zeegat.

maximum current velocities (ebb and flood) in the tidal basin do no exceed 0.2 m/s, mud content can increase up to 100%. When the critical mud content of 30% is exceeded, hardly any erosion can take place.

Comparing Figure 5.10(b) with the observed mud content in the Friesche Zeegat shown in Figure 5.8, one can see that the computed mud content show similarities and differences with the observed data. In both figures, high mud contents are visible in the shallow areas along the border of the tidal basin and low mud contents in the channels and entrance of the tidal basin. The observed high mud contents (darkest green) south of Ameland and in the Zoutkamperlaag channel show good agreement with the computed mud content in the same area. But, in the eastern part of the tidal basin the observed mud content is much lower than the computed.

In order to determine the net sedimentation of mud in the top layer (0.1 m) of the bed a rough calculation is made. The surface of each grid cell is multiplied with the mud content



(a) (b)

Figure 5.12: Bed level change (m) after: (a) 1 year (b) 2 years.

and using a porosity of 0.4 (60% of the bottom contains solids) and a density of 2650 kg/m^3 the net sedimentation of mud after 1 year is 4.9×10^6 ton, this corresponds with an average of 6,600 ton during each tidal period. After two years the net sedimentation is about twice as high, namely 10.5×10^6 ton which is an average of 7,200 ton per tidal period. After 4 years the sedimentation of mud increases up to 11.7×10^6 ton and after 8 years 13.6×10^6 ton. The development of the net sedimentation of mud in 8 years is shown in Figure 5.11. According to Oost (1995) the total net sedimentation of sand and mud in the period from 1979 - 1987 for the Pinkegat and Zoutkamperlaag drainage basin is 10.6×10^6 m^3, this corresponds with 28×10^6 ton (density of 2650 kg m^{-3}). The computed and observed net sedimentation are in the same order of 1×10^7, but the total amount of mud depends on the mud content in the basin, unfortunately no such data is available.

5.5 Bed level change

Figure 5.12 shows the bed level change after 1 year and 2 years. Comparing these with the observed bed level change in the Zoutkamperlaag from 1970 - 1994 (see Figure 5.13), one can see that in the Zoutkamperlaag, bed level changes show quite some similarities. In the tidal basin net erosion is observed, while in the model some sedimentation is visible. Large bed level changes are mainly limited to deeper channel of the Zoutkamperlaag. The observations show strong sedimentation in the channel, whereas sedimentation is mainly visible in the entrance of the channel and erosion is predicted in the central section of the channel. The magnitude of the computed bed level change strongly differs from the observations. The observations are based on a period of 25 years, while the sand-mud-bio model only simulates 2 years.

From Figure 5.12(a) and Figure 5.12(b) it can be noted that there are no large differences in bed level change in the entrance of both tidal channels, but an increase in erosion and sedimentation is visible in the tidal basin. Sedimentation is shown in the deeper parts of the tidal basin (below the island Schiermonnikoog), while erosion is mainly visible along the borders of the deeper gullies.

5.6 Conclusion

In a large area of the tidal basin, the critical bed shear stress is exceeded. In these areas no sedimentation of mud occurs, except for the shallow mud flats with depths up to 2 m (MSL). In these areas, current velocities are too small and the critical bed shear stress is not exceeded. Accumulation of mud is visible in these areas and due to the increase in critical bed shear stress caused by the switch from a non-cohesive regime to a cohesive regime, no erosion will occur.

Suspended sediment concentration are strongly affected by the physical conditions upstream of the area of interest. Looking at difference between the mud concentrations during ebb and flood in the entrance of both tidal channels, a netto flux into the basin remains. This leads to an accretion of mud in the shallow areas. The mud content in the basin shows a strong increase in the first 2 years and after 8 years the accumulation of mud decreases or

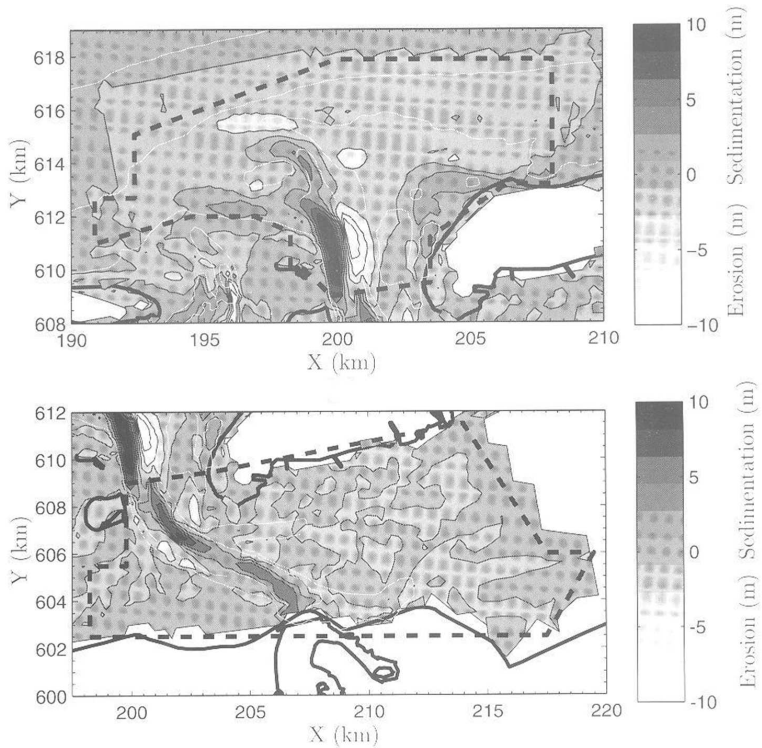


Figure 5.13: Observed bed level change in the ebb-tidal delta and in the tidal basin of the Zoutkamperlaag (Van Ledden, 2003).

stops. The observed mud content in the Friesche Zeegat 5.8 shows strong similarities with the distribution of the computed mud content. However, the computed mud content in the entire basin, especially in the eastern part, is larger than the observed mud content.

The computed bed level shows similarities and differences with the observed bed level. The model results and observed data both show sedimentation in the channel entrance and gullies of the Zoutkamperlaag and Pinkegat. In the model, erosion is visible in the central section of the Zoutkamperlaag channel, while sedimentation is observed. In the shallow areas erosion is observed, but in the model a slight increase in bed level is shown. The magnitude of erosion and sedimentation does not correspond, because the model simulation is over 2 years instead of 25 years.

Chapter 6

Influence biological activity

In this chapter the result of the simulations with biological activity are presented. All figures show the results after 2 years of simulation[1], which are compared with the results presented in the previous chapter. To examine the influence of biological activity on the fine-grained sediment transport four scenarios are simulated. A scenario with a destabilising effect caused by the bivalve *Macoma balthica*, a stabilising effect caused by algae, a stabilising effect caused by mussel beds and a scenario with a combination of all organisms.

In the first two sections the influence of the biological activity on the bed shear stress and erosion coefficient is described. Subsequently, the mud content for each scenario and the difference with the reference situation are shown. Next, the changes in bed level for each scenario compared to the reference situation is presented and finally, a summary of the results is given.

6.1 Bed shear stress

Biological activity affects the critical bed shear stress. In Table 6.1 the observation points with their corresponding correction factor for the critical bed shear stress and the corrected critical bed shear stress in the non-cohesive and cohesive regime are presented for each scenario. The critical bed shear stress in the non-cohesive regime is 0.25 N/m^2 and in the cohesive regime 0.50 N/m^2. The locations Pinkegat, Pinkegat Noord, Nieuwe Westgat en Roode Hoofd are not presented. At these locations there is no biological activity and therefore the critical bed shear stress is not corrected. The exceeding of the critical bed shear stress remains the same as given in Table 5.1. This also applies to location 1, 3, 7 and 8. Because there is no influence of diatoms and mussel beds at these locations, the critical bed shear stress for these two scenarios is not affected. On the other hand, it is affected by *Macoma balthica*.

Comparing Table 5.1 with Table 6.2, one can see that for the scenario with *M. balthica* the critical bed shear stress (non-cohesive and cohesive) is lowered. In the non-cohesive regime all locations exceed the critical bed shear stress and at these locations erosion will occur.

[1]The model with biological activity could not be simulated for a period of 8 years, because of errors during the simulation.

	M. balthica			Diatoms			Mussel beds			Combination		
Loc.	B_τ	τ_{nc}	τ_{c}	B_τ	τ_{nc}	τ_{c}	B_τ	τ_{nc}	τ_{c}	B_τ	τ_{nc}	τ_{c}
1	0.62	0.16	0.31	-	-	-	-	-	-	0.62	0.16	0.31
2	0.48	0.12	0.24	3.42	0.81	1.62	4.50	1.13	2.25	2.16	0.54	1.08
3	0.62	0.16	0.31	-	-	-	-	-	-	0.62	0.16	0.31
4	0.48	0.12	0.24	1.99	0.50	1.00	4.50	1.13	2.25	2.16	0.54	1.08
5	0.48	0.12	0.24	3.24	0.81	1.62	4.50	1.13	2.25	2.16	0.54	1.08
6	0.48	0.12	0.24	3.24	0.81	1.62	4.50	1.13	2.25	2.16	0.54	1.08
7	0.62	0.16	0.31	-	-	-	-	-	-	0.62	0.16	0.31
8	0.62	0.16	0.31	-	-	-	-	-	-	0.62	0.16	0.31

Table 6.1: Observation points with corresponding correction factor for the critical bed shear stress ($B_\tau = f_{\mathrm{d}}(B) \cdot f_{\mathrm{s}}(C)$) [-] and corrected critical bed shear stress [N/m^2] for each scenario.

Looking at a depth range from MSL to 3 m water depth in the entire basin , it is likely that if the critical mud content is not exceeded erosion will occur, but this strongly depends on the magnitude of the local current velocities. In the cohesive regime the critical bed shear stress at location 1, 2, 5 and 6 is still to high to have an influence on erosion.

The scenarios with diatoms and mussel beds both affect the critical bed shear stress. In the cohesive and non-cohesive regime the critical bed shear stress is not exceeded for location 2, 4, 5 and 6. In the entire basin from MSL to 1 m water depth, the diatoms increase the critical bed shear stress, which results in no erosion. At the locations of the mussel beds, no diatoms are present. The critical bed shear stress is only affected by the mussel beds and at these locations no erosion occurs.

In the scenario with the influence of all organisms, one can see that where *M. Balthica* is present a decrease in bed shear stress and an increase in erosion is expected. The combination of *M. Balthica* and the mussel beds at location 2, 4, 5 and 6 results in an increase in critical bed shear stress. Where no mussel beds are present it depends on the Chlorophyll- a content

	Reference		*M. balthica*		Diatoms		Mussel beds		Combination	
	% exceeding		% exceeding		% exceeding		% exceeding		% exceeding	
Location	τ_{nc}	τ_{c}	τ_{nc}	τ_{c}	τ_{nc}	τ_{c}	τ_{nc}	τ_{c}	τ_{nc}	τ_{c}
1	0	0	20	0	-	-	-	-	20	0
2	0	0	7	0	0	0	0	0	0	0
3	45	38	71	58	-	-	-	-	71	58
4	35	0	59	38	0	0	0	0	0	0
5	0	0	52	0	0	0	0	0	0	0
6	5	0	57	0	0	0	0	0	0	0
7	58	26	75	70	-	-	-	-	75	70
8	74	46	75	70	-	-	-	-	75	70

Table 6.2: Percentage in time exceeding the critical bed shear stress in the non-cohesive (τ_{c}) and cohesive regime and (τ_{c}) for each observation point and scenario.

if the critical bed shear stress increases or decreases. The *M. Balthica* density from MSL to 1 m water depth is 1078 individuals per m^2, the destabilising factor ($f_{\mathrm{d}}(B)$) is 0.62. In order to have an increase on the critical bed shear stress, the stabilising factor ($f_{\mathrm{s}}(C)$) has to be larger than 1.61. Looking at Figure 3.2(b), this value is reached at a Chlorophyll- a content of approximately 9 μg/g. From Table 2.2 it can be noted that this Chlorophyll- a content is exceeded below an average water depth of 0.5 m. It is likely that from mean sea level to a water depth of 0.5 m, the critical bed shear stress increases in the entire basin as a result of the stabilising effect of the diatoms.

6.2 Erosion coefficient

In Table 6.3 an outline of the correction factors for the erosion coefficient is given. The destabilising effect of *M. Balthica* has the largest contribution to the benthos correction factor for the critical erosion coefficient. Even with a significant stabilising effect of the mussel beds, in combination with *M. Balthica*, the erosion coefficient still increases. Looking at the water depth from MSL to 3 m, the destabilising effect of *M. Balthica* results in an increase of the erosion coefficient in the entire basin.

Location	*M. balthica*	Diatoms	Mussel beds	Combination
1	1.78	-	-	1.78
2	12.17	0.42	0.10	1.22
3	1.78	-	-	1.78
4	12.17	0.75	0.10	1.22
5	12.17	0.42	0.10	1.22
6	12.17	0.42	0.10	1.22
7	1.78	-	-	1.78
8	1.78	-	-	1.78

Table 6.3: Observation points with corresponding correction factor for the erosion rate ($B_{\mathrm{e}} = g_{\mathrm{d}}(B) \cdot\ g_{\mathrm{s}}(C)$) [-].

6.3 Mud content

In this section the difference between the mud content in the Friesche Zeegat with and without biological activity is presented. Based on the influence of the biology on the critical bed shear stress and the erosion coefficient, it is expected that the simulation with *Macoma balthica* shows a decrease of the mud content, the diatoms and mussel beds increase the mud content and a combination of all organisms results in a slower increase of the mud content than in the reference situation. The difference is determined by subtracting the reference situation from the simulation including biological activity.

In Figure 6.1(b) it is clearly visible that there is a destabilising effect caused by *M. balthica.* In the area with depths up to 3 meters the mud content is 10 - 30% smaller than in the reference

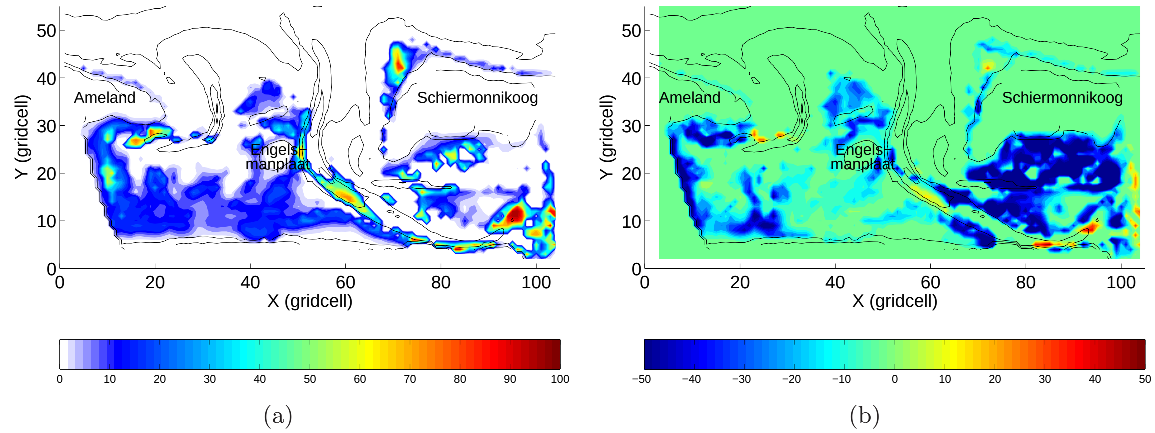


Figure 6.1: Destabilising effect caused by the *M. balthica*: (a) mud content (%) in the top layer of the bed and (b) difference in mud content (%). '+' denotes areas where the mud content increases and '-' denotes a decrease of the mud content as a result from the influence of biology.

situation and in the more shallow areas up to 50%. This is due to the sudden increase of *M. balthica* (from 129 - 1078 individuals per m^2). In the areas where no *M. balthica* is present, e.g. the channels and gullies, no differences are visible. In some areas, around gridpoint (25,30), along the border of the eastern water shed and in the Zoutkamperlaag channel near gridpoint (60,15) and (85,5), the erosion and redistribution of mud results in a slight increase in mud content. The total amount of mud that remains in the basin after 2 years is estimated at 4.9×10^6 ton (for the calculation see Section 5.4). This is less than half of the amount

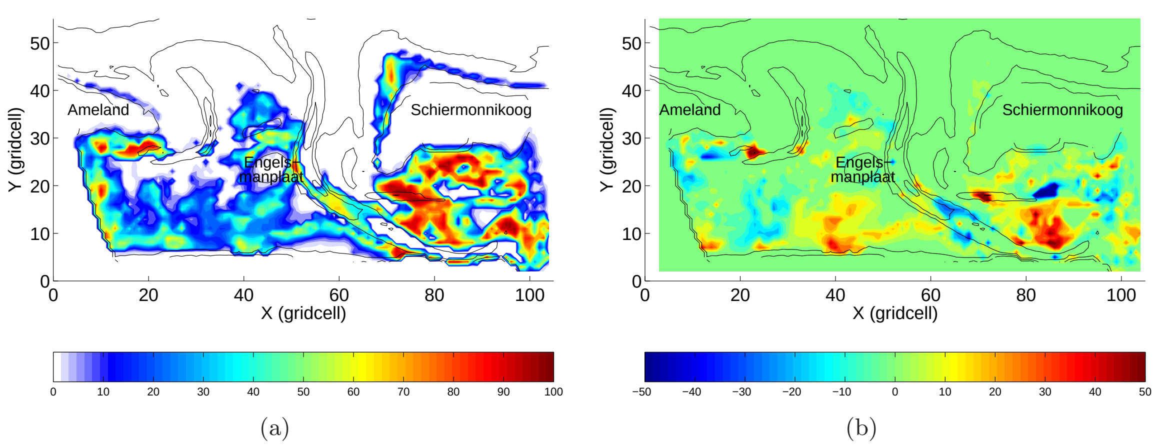


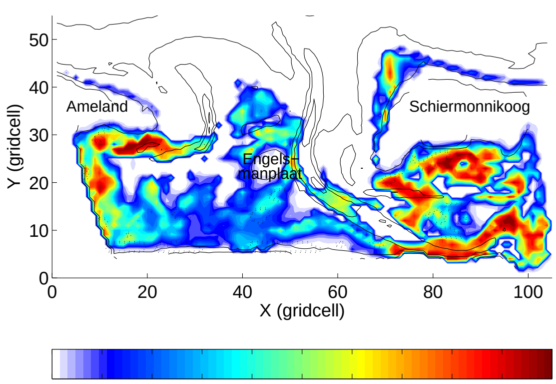
Figure 6.2: Stabilising effect caused by algae: (a) mud content (%) in the top layer of the bed and (b) difference in mud content (%). '+' denotes areas where the mud content increases and '-' denotes a decrease of the mud content as a result from the influence of biology.

that remains in the reference situation. After starting with a plain sand bed, it appears that the mud content in the entire basin continues to increase, but at a lower rate than in the reference situation. The slower increase of mud in the top layer prevents the transition from a non-cohesive to a cohesive regime, which increases erosion of fine sediments. In Table 6.4 an outline of the total amount of mud and the average amount of mud which remains in the Friesche Zeegat after on tidal period is given.

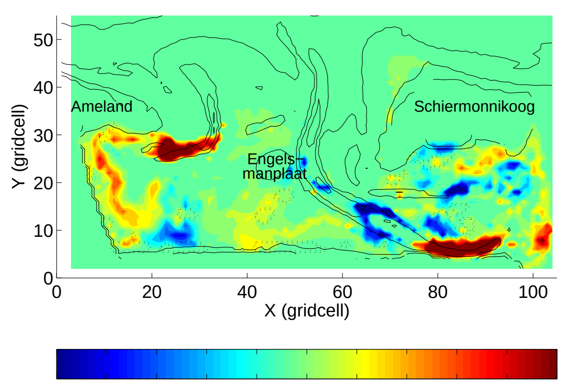
From Figure 6.2(b) one can see that the diatoms have a distinct stabilising effect on the bed, especially in the shallow areas (0 - 1 m water depth) the mud content increases. Comparing the depth contours in Figure 5.1 with the mud content, it becomes clear that in the areas where no Chlorophyll-a is present (channels and gullies), the mud content decreases. Not only causes the stabilising effect of the diatoms a redistribution of the mud in the Friesche Zeegat, also the total amount of mud in the basin has increased with $1.0\times, 10^6$ ton. The stabilising effect by the diatoms causes the rate, at which the mud content increases during each model simulation, to be larger than in the reference situation.

Looking at Figure 6.3(b) two areas with a significant increase in mud content stand out. There are also areas where the mud content decreases, while mussel beds are present. Keeping in mind that the mussel beds are implemented in the model in the same way as the diatoms, these results are different than expected. Like the diatoms, the mussel beds have a significant stabilising effect, even more than the diatoms. However, there are only two locations where a distinct increase in mud content is visible due to the presence of mussel beds. Namely, along the border of the western water shed and around gridpoint (45,10). But there is not only an increase at these locations, also in the area surrounding the mussel beds the mud content increases.

Compared to the reference situation, the total amount of mud that remains in the basin has increased with $0.7\times, 10^6$ ton. This shows that the mussel beds increase the stability of the bed, but from these results the mud distribution does not correspond with the expected



(a)



(b)

Figure 6.3: Stabilising effect caused by mussel beds: (a) mud content (%) in the top layer of the bed and (b) difference in mud content (%). '+' denotes areas where the mud content increases and '-' denotes a decrease of the mud content as a result from the influence of biology. The contours represent the mussel beds.

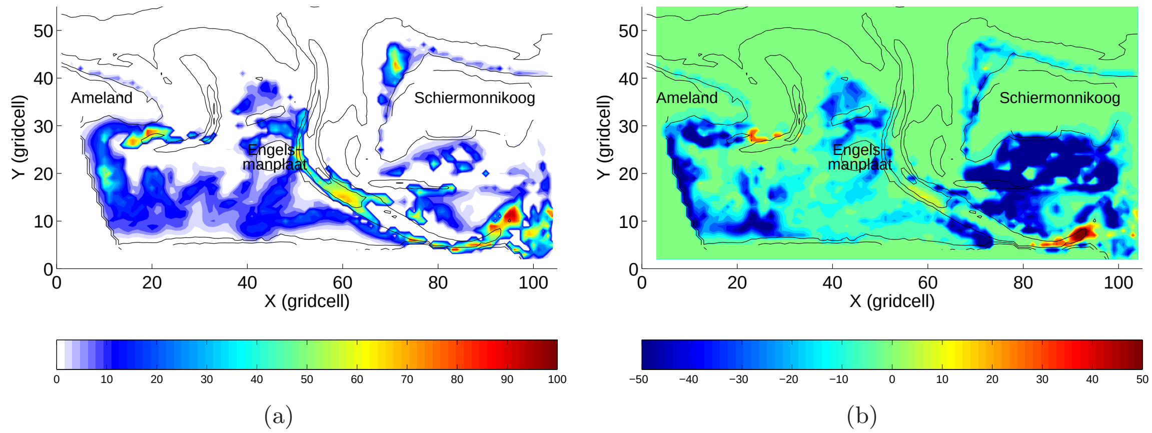


Figure 6.4: Combination of (de)stabilising effect caused by all organisms: (a) mud content (%) in the top layer of the bed and (b) difference in mud content (%). '+' denotes areas where the mud content increases and '-' denotes a decrease of the mud content as a result from the influence of biology.

distribution. The decrease of mud content in certain areas is probably due to the redistribution of mud to the areas with high concentrations of mud. The increase of mud content around gridpoint (30,30) and (85,5) is probably caused by an error in the model. Unfortunately, the error could not be identified.

In Figure 6.4(b) all three scenarios are combined to show the effect of destabilisers and stabilisers on the mud distribution. It is clearly visible that the influence of the destabilising *M. balthica* is dominant. Except for two spots where an increase in mud content can be seen (Pinkegat and at the end of the Zoutkamperlaag), the mud content in the entire basin is decreasing as a result of biological activity. The destabilising effect of *M. balthica* decreases the critical bed shear stress in the entire basin, except for the areas with a water depth smaller than 0.5 m and in the areas where mussel beds are present. The erosion coefficient in the entire basin increases as a result of this destabilising effect.

The total amount of mud remaining in the basin is estimated at 4.8×10^6 ton after two years. This is less than half of the total amount that remains in the basin after the simulation of the reference situation. Compared to the scenario with the influence of *M. balthica* alone, the remaining amount of mud is lower. Because of the problem with the model run including the influence of mussel beds, this also affects the scenario with the influence of all organisms.

	Reference	*M. balthica*	Diatoms	Mussel beds	Combination
ton/2 years	$10.5\times, 10^6$	4.9×10^6	11.5×10^6	11.2×10^6	4.8×10^6
ton/tide	7,200	3,400	7,900	7,700	3,300

Table 6.4: Estimation of the total amount of mud remaining in the Friesche Zeegat after 2 years and average amount during a tidal period.

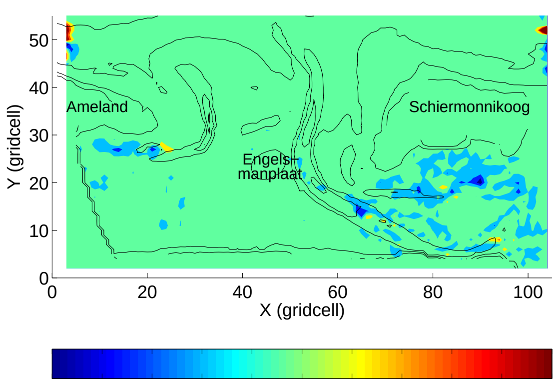
Therefore a model run with only the destabilising effect by *Macoma balthica* and the stabilising effect by the diatoms is done. The total amount of mud remaining in the basin is $5.0\times, 10^6$ ton, $0.1\times, 10^6$ ton more than in the scenario with all three organisms (see Table 6.4), that is an anomaly of about 2%. This shows that an unsatisfying decrease of the total amount of mud is caused by the influence of the mussel beds, but it does not seem to have a large impact on the mud content. It does have a large impact on the mud distribution.

Comparing the observed mud contents in Figure 5.8 with Figure 6.4(a), the results do show better agreement than the reference situation. Not only the mud distribution, but also the computed mud content show strong similarities with the observed data. Because of the destabilising effect, the mud content in the entire basin is lower and agrees better with the observed than the reference situation. Assuming the development of the mud content is the same as in the reference situation, after 8 years the model results still show good agreement with the observed data, because the rate at which the mud content increases becomes lower and it inclines towards an equilibrium.

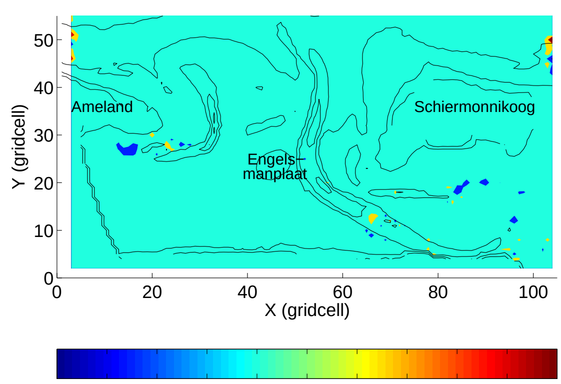
6.4 Bed level change

In the following section the change in bed level caused by the influence of biological activity is presented. This difference is determined by subtracting the reference situation from the the simulations with biological activity.

In Figure 6.5(a) the difference between the reference situation and the destabilising effect by the *Macoma balthica* is shown. The destabilising effect decreases the critical bed shear stress and increases the erosion coefficient. This effect causes a slower increase in mud content during 2 years of simulation than in the reference situation, which results in a lower bed level in the areas where the *Macoma balthica* is present. In the eastern part of the tidal basin a difference in bed level can be seen, in this area also, the mud content is significantly lower (see Section 6.3).

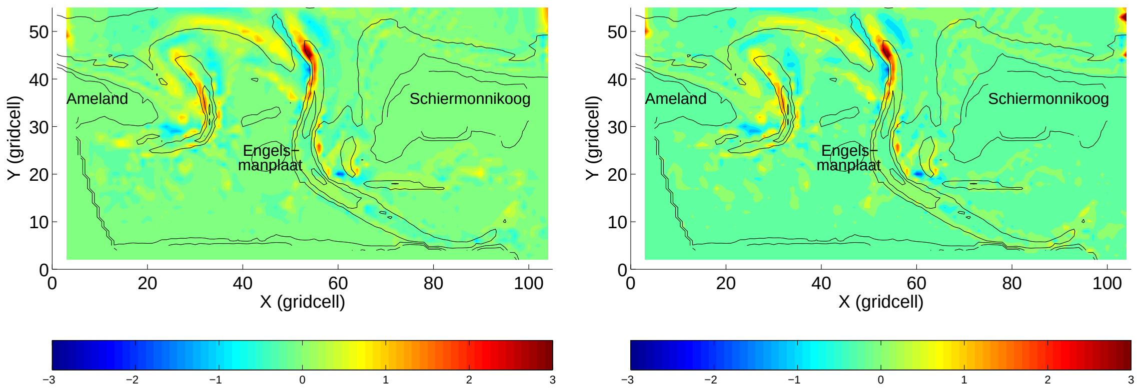


(a)



(b)

Figure 6.5: Difference in bed level (m) as a result of (a) the destabilising effect caused by *M. balthica* and (b) the stabilising effect caused by algae compared to the reference situation.



(a) (b)

Figure 6.6: Difference in bed level (m) as a result of (a) the stabilising effect of the mussel beds and (b) the combination of (de)stabilising effect caused by all organisms compared to reference situation.

The difference (see Fig. 6.5(b)) in bed level caused by the stabilising effect of the diatoms is minimal. Although an increase of mud content is visible in Figure 6.2(b), there is no significant increase in sedimentation. This is probably caused by the fact that the increase of mud content by the stabilising effect of the diatoms is much smaller than the decrease of mud content by the *M. balthica*. This also appears from the total amount of mud that remains in the basin after 2 years for both scenarios (see Table 6.4).

Comparing Figure 6.6(a) and Figure 6.3(b) one can see that the significant increase of mud content results in large patches of sedimentation at the same locations and in the surrounding areas, this is also the result of an error in the model. But it shows that an increase of mud results in sedimentation in the same areas.

In the scenario with a combination of all three organisms, *M. balthica*, diatoms and mussel beds, the influence of the destabilisers on the erosion coefficient and the critical bed shear

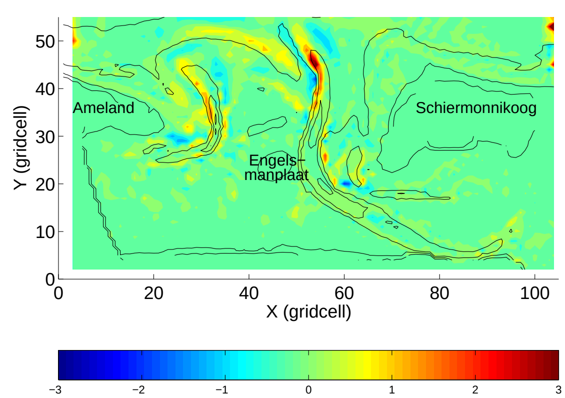


Figure 6.7: Bed level change (m) as a result of the influence of biological activity.

stress is dominant in almost the entire basin. Because large amount of mud settle at gridpoint (25,30) and (85,5) as a result of the influence of the mussel beds, sedimentation can be seen in these areas (see Figure 6.7). Because of the error in the model, this sedimentation has to be neglected. The observed data shows sedimentation in the channels and erosion in the more shallow parts (see Figure 5.13). In the shallow areas with a water depth of 3 m, the destabilising effect causes erosion and this bed level change corresponds more with the observed data.

6.5 Conclusion

Looking at the water depth from 0.5 m to 3 m, *M. Balthica* has a destabilising effect in the entire basin. Even in combination with diatoms, the critical bed shear stress decreases and the erosion coefficient increases. Only in the areas where mussel beds are present, there is still an increase in the critical bed shear stress, with an expected decrease of erosion. From mean sea level to a water depth of 0.5 m, most likely the diatoms have a stabilising effect and the critical bed shear stress is increased.

The mud content decreases as a result of the bivalve *Macoma balhica* and increases as a result of the diatoms. For the scenario with the mussel beds, an increase of the mud content was expected, but not of this magnitude and distribution. Probably, an error in the model simulation, which has not been cleared up at this time, is the cause of the huge amount of mud settling around gridpoint (30,30) and (85,5), while no mussel beds are present at these locations. This error probably also affects the scenario with a combination of all organisms. It does not seem to have a large impact on the mud content, but it does have an impact on the mud distribution. The simulation with a combination of all organisms shows a better agreement with the observed mud content.

The destabilising effect causes a significant decrease in bed level, while the stabilising effect has a minor influence on the bed level. This is caused by the fact that the amount of mud in the entire basin as a result of the diatoms does not increase at the same rate, as it decreases because of *Macoma balthica*. The influence of all organisms results in decrease of the bed level, especially in the areas with a water depth up to 3 m. Sedimentation is dominant in the entrance of the basin and this is also observed. There is still an increase in bed level in the shallow areas, while that is not observed, but the destabilising effect decreases the sedimentation. Despite the unreliable sedimentation due to the presence of mussel beds, the simulation with the influence of all organisms shows a better agreement with the observed data than the reference situation.

Chapter 7

Discussion

This report describes the influence of biological activity on bed level and composition. In general, the biogeomorphological interaction is more complex. In reality species abundance is influenced by bed level changes or interactions between organisms occurs. Large numerical models like Delft3D use a huge amount of data and parameters in order to give a representations of reality.

In this chapter uncertainties in the model set-up and assumptions in the implementation of the biological characteristics are discussed and the possible effects of these assumptions for the results in chapter 5 and chapter 6. Because this research is based on the original sand-mud model by Van Ledden (2003), a detailed discussion of the morphological computations can be found in his PhD-thesis. Also, the discussion about the implementation of *Macoma balthica* and diatoms in the sand-mud-bio model is described in Paarlberg et al. (2005).

7.1 Sand-mud-bio model

Mud concentration at the boundaries

The model uses a variety of parameters which are used as initial conditions at the beginning of the model run. At the boundaries in the North Sea the initial mud concentration is set at 100 mg/l. The model starts with a plain sand bed and in the first two years a rapid increase of the mud content can be seen in the reference situation. Looking at simulation over a period of 8 years, the mud content increase slows down and the system tends to an equilibrium. Comparing the reference situation with to the observed data, after 8 years the mud distribution shows good agreement but the mud content is too high in the entire basin. Looking at the simulation with all organisms both the mud distribution and the mud content after 2 years show better agreement with the observed data.

The mud concentration at the boundaries is set at 100 mg/l, looking at observed suspended sediment data (direclty from the website: http://www.waterbase.nl) at 10 km offshore of the backbarrier islands, a more suitable value is 10 - 20 mg/l. In this report a mud concentration of 100 mg/l is maintained in order to resemble the research by Van Ledden (2003) and an additional advantage is the decrease of calculation time of the model.

Model simulation

The model uses the first tidal period to spin up, because small artificial errors in the bed shear stress might easily spoil the initial bottom level and composition. According to De Boer (2002) the erosion fluxes cannot be switched off in Delft3D during the spinning up and the model will therefore calculate the erosion fluxes with the initial bed composition.

The biological activity affects the bed shear stress and erosion coefficient directly from the start of the simulation. Paarlberg et al. (2005) runs his model for half a year without biological activity to create a reference situation. In the latter case, biological activity is implemented with an initial mud content which is more realistic than with a plain sand bed. In this research the objective is to investigate the influence of biology on morphology and bed composition, therefore biology is implemented directly from the start of the simulation.

Switch between non-cohesive and cohesive regime

The critical mud content is assumed at 30%, which causes a switch from a non-cohesive to a cohesive regime. This switch causes a sudden increase of the critical bed shear stress (0.25 to 0.50 N/m^2) and a decrease of the erosion coefficient. In the cohesive regime the mud content increases rapidly in the reference situation and for all scenarios. This probably results in an overestimation of the mud content and accompanying increase of the bed level. In reality, the transition from a non-cohesive to a cohesive regime is smoother.

Mixing coefficient

The sand-mud model already uses a coefficient for local biological mixing (see Chapter 4) of sediment in 10 - 15 cm of the sediment bed. Van Ledden (2003) stated that the mud content may be an important parameter, as the mixing coefficient of organisms presumably decreases with increasing cohesion between sediment particles. Reasonable values for the biological mixing coefficient appear to be 10^{-6}-10^{-2} m^2/year. This coefficient is also included in the sand-mud-bio model and most likely causes an overestimation of the biological influence on the suspended sediment concentration and mud content in the tidal basin.

Waves

The influence of the waves on the bed shear stress is implemented in the model, but the influence of the waves on the critical bed shear stress is not very clear. It is of considerable influence on the sediment transport and the mud content in the entire basin. The results without waves show higher mud contents in the entire basin than the results including waves (these are not included in this report).

7.2 Biological characteristics

Macoma batlhica

The biomass per m^2 or the amount of individuals per m^2 of the destabiliser *Macoma balthica* consists of a collection of different organisms. It also consists of the *Hydrobia ulvae*. The high densities of *Macoma balthica* mainly exits from MSL to 1 m water depth and *Hydrobia ulvae* lives from 1 m to 3 m water depth. Also, the lug worm can be added or certain birds, which feed from the bottom, like the Oystercatcher (De Vries, 2005). All these organisms are fitted into in one parameter to simplify the implementation in the sand-mud-bio model

Diatoms

The Chlorophyll-a content is depth dependent, but their are also seasonal differences which are not taken into account. During spring, diatoms have a blooming period, while in winter these concentration are significant lower (Wolfstein et al., 2000). Also, the interaction between the three different organisms is no taken into account. In reality, mussel beds and large densities of *M. balthica* do not often live together at the same location (Knaapen, 2005). Diatoms and *M. balthica* can not exist together because the latter feeds on diatoms.

Mussel beds

In order to investigate the stabilising effect of the mussel beds, which influence the critical bed shear stress and erosion coefficient, the same implementation is used as the diatoms. A constant maximum concentration of 50 μg/g is used in order to have a maximum increase of the bed shear stress and maximum decrease of the erosion rate. By using this implementation of the mussel beds, the increase of roughness by the shells is neglected, as well as the filtration and depositing of faeces and pseudo-faeces (Dankers and Koelemaij, 1989). This implementation is used because it is difficult to model the actual filtration and especially the transport and deposition of pellets by the mussels (Oost, 1995), but it will give an indication of the stabilising effect by mussel beds.

Unfortunately, the results of the influence by the mussel beds are unreliable because of an error in the implementation. The exact reason is not identified at the time of the writing of this report. In order to diminish the unwanted effect by the mussel bed, also a simulation is performed with biological activity but without mussel beds. The results show a slightly larger total amount of mud in the tidal basin. So, the stabilising effect of the mussel beds on the total amount of mud is not significant, but especially the difference in mud distribution is of greater importance.

Chapter 8

Conclusions & Recommendations

8.1 Conclusions

To investigate the influence of the biological activity on the bed composition and bed level changes in the Friesche Zeegat, the effect of biological activity on the critical bed shear stress and erosion coefficient is proposed. Using the sand-mud-bio model, based on the process-based sand-mud model in Delft3D by Van Ledden (2003), one can see that the influence of both destabilisers and stabilisers on the bed level and bed composition in the Friesche Zeegat is significant.

Destabilising effect

The destabilising organisms cause a decrease in critical bed shear stress and an increase in the erosion coefficient. *Macoma balthica* has a destabilising effect on the surface of the bed in the entire basin at water depth from mean sea level to 3 m. The increase of mud content is lower than in the reference situation, and in a large area the switch from a non-cohesive to cohesive regime does not occur. This also prevents a rapid increase of the mud content. The destabilisers cause a significant increase of erosion. The mud content in almost the entire basin is 40 - 50% lower than in the reference situation. The total amount of mud in the basin according to the reference situation is twice as high as the amount of mud remaining according to the simulation with *Macoma balthica*.

Because of the erosion of mud, in the shallow areas the bed level in the basin is lower than in the reference situation. In most areas the bed level is decreased with 0.4 m and even a maximum decrease of 0.8 m is observed.

Stabilising effect

The increase of critical bed shear stress and the decrease of the erosion coefficient by stabilising organisms, like diatoms or mussel beds, cause an increase of the mud content. Diatoms are present in large concentrations from mean sea level to a water depth of 1 m. The increase of mud in the basin is not of the same rate as the the decrease of mud caused by the destabilising effect. At water depths from mean sea level to 1 m, the mud content in the entire basin increases with 10% - 30%, with a maximum of 50%. In the deeper areas also a decrease of mud content of about 10% with a maximum of 50% is observed. Exceeding the critical mud content results in a switch from a non-cohesive to a cohesive regime. The critical bed shear stress is twice as high which causes a decrease of erosion. There is a small increase in the total amount of mud remaining in the basin (factor 1.1), but in contrast to the destabilising situation, the diatoms cause a significant redistribution of the mud in the entire basin. The increase of the mud content in the shallow areas leads to a decrease of the mud content in deeper areas.

Because of an error in the model, which has not been identified at the time of writing this report, the results of the simulation with the mussel beds are not reliable. The increase of the mud content and the distribution is not as expected. The stabilising effect of the mussel beds causes large quantities of mud to deposit at locations where no mussel beds are present (increase of more than 50%). Because of the switch to a cohesive regime, the total amount of mud remaining in the basin increases even more. Looking at the redistribution of the mud, one can see that there are some similarities with the simulation including the diatoms. In certain areas a decrease of the mud content is visible, these locations more or less correspond with those in the scenario with the diatoms. The decrease of the mud content is between 30% to 50%.

Bed level change caused by the stabilising effect of the diatoms is not as significant as the change caused by the destabilisers. In the destabilising situation, large quantities of mud disappear from the system, while the stabilising effect mostly causes redistribution. Also, the increase of the mud content is not as high as the decrease of the mud content caused by *Macoma batlhica*. In a small area, an increase in bed level of about 0.4 m is observed. Because of the redistribution of mud, in some areas even a decrease of 0.6 m of the bed level is observed. Because of the large quantities of mud deposited in the scenario with mussel beds, there is a significant increase of the bed level in these areas, about 0.3 - 0.6 m. Also, small patches with a decrease of 0.4 - 0.6 m are observed.

Combination

The error in the simulation including the mussel bed also affects the scenario including a combination of all organisms. Therefore, a simulation with the destabilising effect by *Macoma balthica* and a stabilising effect by the diatoms is performed to investigate the influence of the mussel beds. These results show that in the simulation including all organisms, the mussel beds do not seem to have a large impact on the total amount of mud, but they do have an impact on the mud distribution.

At the water depth from 0.5 m to 3 m, the destabilising effect by *M. Balthica* is dominant in the entire basin, except at the locations of the mussel beds. This is caused by the decrease of the critical bed shear stress, but most of all by the increase of the erosion coefficient. At the locations of the mussel beds the increase of the critical bed shear stress is the dominant factor. From mean sea level to a water depth of 0.5 m, the diatoms have a dominant stabilising effect.

This is also caused by the increase of the critical bed shear stress.

Because the destabilising effect is dominant, the mud content in the entire basin decreases. Comparing these results with observed mud contents in the Friesche Zeegat, the mud content and distribution show better agreement than the results from the reference situation. The decrease of the bed level in the tidal basin, also correlates better with the observed bed level change.

8.2 Recommendations

Although the model shows that it can predict the influence of destabilisers and stabilisers on bed level and composition, there are still some recommendations for further research.

First of all the biological parameters have to be implemented in the most recent version of sand-mud model in Delft3D. In this version the effect of the waves on the bed shear stress is not fully understood, in reality they have a significant impact on sediment transport. It is also recommended to increase the time-scale of the model simulation. In the new version, also the drying of the mud flats during ebb is better simulated.

In order to get a better understanding of the model it is necessary to get a better understanding of the influence of the transition between a non-cohesive and cohesive regime. In the sand-mud-bio model it is an instant switch, but this switch has to be smooth, with a gradual transition from non-cohesive to cohesive. This will probably result in a lower mud content, because the critical bed shear stress more often exceeded.

The influence of destabilisers is to such an extent that it may be necessary to make a distinction between different species. Some organisms only have influence on the bed composition, but do not necessarily cause erosion. By burrowing and motion through the bed other organisms redistribute the sediment and cause resuspension of the sediment. It is interesting to model the filtration and biodeposition by mussel beds, therefore detailed data of mussel bed densities and information about the transport of the excreted pellets is necessary.

The addition of seasonal differences in biomass or densities is an improvement. In this research all biological parameters are kept constant, while in reality hardly any diatoms exist during winter and often during severe storms mussel beds disappear. Also, the interaction between the different organisms has to be taken into account.

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