Biological influence on sediment transport and bed composition for the Western Wadden Sea

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Bas Borsje

Supervisors:
Prof. Dr. S.J.M.H. Hulscher
Drs. M.B. de Vries

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Preface

This MSc thesis forms the completion of my study Civil Engineering and Management at the University of Twente, The Netherlands. This report describes the influence of biota on the fine sediment transport and bed composition for the Dutch Western Wadden Sea. The project is carried out at WL | Delft Hydraulics.

Fine sediment is generally known as mud, and the similarity with my research is obvious:

Executing research is similar to playing with mud; you sink in it, and you are not able to get released of it.

Therefore, I am very grateful to some people, who supported me during my 'mud playing activities'. I thank prof. dr. Suzanne Hulscher (University of Twente) for her helpful suggestions and constructive feedback. Moreover, I would like to thank drs. Mindert de Vries for his enthusiastic supervision and providing me the opportunity to play with mud (even literarily). Furthermore, I would like to thank ir. Gerben de Boer (Delft University of Technology), who provided the source-code of the model used in this study.

Finally, I would like to thank my colleagues and fellow graduate students at WL | Delft Hydraulics for their interest in my research topic and the great working atmosphere. I also would like to thank my parents for the opportunity to study and for their support, confidence and their interest in my study. At least, I would like my brother, sister, friends and especially Eline, not only for supporting me, but also for releasing me from the mud during the weekend breaks and holidays.

Bas Borsje

Delft, October 2006

Summary

Biological activity is known to have significant influence on sediment transport and bed composition on a small spatial scale. However, the large scale effects of biological activity are not known. These large scale effects could be of great importance for bringing up recommendations for the conservation and management schemes of different estuaries. Combined with a large spatial scale, also a large temporal scale is required, in order to provide a realistic assessment of the biological contribution to the fine sediment dynamics.

By applying the process-based model Delft3D, the physical system combined with three biological processes is simulated. The biological influences are expressed in stabilising and destabilising of the bed by biota and the downward movement of sediment in the bed caused by the digging and feeding activities.

For the Dutch Western Wadden Sea, a correlation exists between the wave direction and wave height, showing the largest wave heights for the wind directions between west and north. However, no clear seasonal variation in wind speed is observed. As a result, the seasonal variation in suspended sediment is not simply caused by the wind induced waves.

To include the (de)stabilising of the bed, a parameterization of the influence of biological activity on sediment strength parameters (critical bed shear stress and erosion rate) is implemented in the model, based on measurements in the Wadden Sea. The downward movement of sediment in the bed is imitated by an increase in the porosity of the top layer of the bed.

The bio-destabilisers are represented by the mud snail *Hydrobia ulvae* and the clam *Macoma balthica.* Bio-stabilisation is caused by microphytobenthos, which are known to form algae mats, which prevent the bed from erosion. Based on the temporal variation in biomass biota, it can be concluded that during spring stabilising is dominant while during autumn de-stabilising is dominant in the Western Wadden Sea.

Compared to the situation without biological influences, the suspended sediment concentrations are influenced on an estuarine scale. However, every tidal basin is influence in a different way, resulting in a classification of the different tidal basins. The amount of fine sediment on the bed shows a distinct increase just outside the destabilised areas, showing the biological influences.

Based on sensitivity analysis, it is determined that the suspended sediment concentrations are mainly influenced by microphytobenthos, while bio-destabilisers are responsible for the fine sediment distribution on the bed.

In order to bring up recommendations for the management schema of estuaries, two systems acting on different (temporal and spatial) scales need to be mentioned. The lowest level system determines the vertical transport of fine sediment and is influenced both by the wind and the biological activity. The highest level system determines the import of fine sediment from the North Sea and is the outcome of the combined effect of the tide and the seasonal varying suspended sediment concentration at the North Sea.

Contents

List of symbols

Symbol	Unit	Description
c	g m^{-3}	Suspended sediment concentration
C	m$^{1/2}$ s^{-1}	Chezy coefficient
D	m^{2} s^{-1}	Dispersion coefficient
F	m	Fetch
h	m	Waterdepth
H	m	Wave height
H_b	m	boundary water level
L	m	Wave length
M	g m^{-2} s^{-1}	Resuspension flux
T	s	Wave period
V	m s^{-1}	Depth averaged velocity
V_w	m s^{-1}	Wind speed
w_s	m s^{-1}	Settling velocity
z_b	m	Bottom height (above reference datum)
τ_b	N m^{-2}	Bottom shear stress
$\tau_{b,cr}$	N m^{-2}	Critical shear stress for resuspension

List of abbreviations

Abbreviations	Meaning
2DH	Two dimensional, depth averaged
Delft3D-Flow	Hydrodynamic module within the Delft3D framework
Delft3D-WAQ	Water Quality Module within the Delft3D framework
DONAR	(In Dutch) Data Opslag Natte Rijkswaterstaat
EPS	extracellular polymeric substances
ICZM	Integrated Coastal Zone Management
KNMI	(in Dutch) Koninklijk Nederlands Meteorologisch Instituut
RIVO	(in Dutch) Nederlandse Rijksinstituut voor Visserijonderzoek
RWS	(in Dutch) Rijkswaterstaat
ZUNO-model	(in Dutch) Zuiderlijk Noordzee model

1 Introduction

Biogeomorphology is the study of the interactions between geomorphological processes and biota. Research on biogeomorphology has become of growing interest since the introduction of the Habitats Directive [Edwards and Winn, 2006]. This directive aims to contribute towards ensuring bio-diversity through the conservation of natural habitats and of wild fauna and flora both in aquatic and terrestrial environments [Habitats Directive, 1992]. Based on this directive, insight is needed in the interactions between geomorphological processes and biota.

1.1 Problem definition

Up to now, much research on biogeomorphology is executed on a small spatial scale, like different mudflats in the Western Scheldt estuary [Paarlberg *et al.*, 2005; Holzhauer, 2003; Widdows and Brinsley, 2002] and the Humber estuary [De Deckere *et al.*, 2001; Widdows and Brinsley, 2002] and different tidal basins in the Wadden Sea [Van Ledden, 2003; De Koning, 2005; Andersen *et al.*, 2005]. All these studies have shown that biological activity has significant influence on morphological change and bed composition. However, it is recommended to take a wide-ranging geographically perspective, understanding the specific conditions in the coastal zone, in order to bring up recommendations for the Wadden Sea conservation and management scheme [Enemark, 2005; Thrush *et al.*, 1997; Orvain *et al.*, 2006]. This scheme aims at preserving the integrity and functioning of the system and allows for a sustainable use of the area within that framework. This scheme is based on an Integrated Coastal Zone Management (ICZM) strategy. In this management strategy, ecological processes need to be linked to the physical system [Klinger, 2004]. Unfortunately, the studies executed so far are difficult to extrapolate to long-term morphological changes, due to the complexity of the morphodynamic processes as stated by Knaapen *et al.* [2003]. On the other hand, Widdows and Brinsley [2002] argued that using a large spatial scale, a large temporal scale is required as well. Naylor *et al.* [2002] also support a large temporal scale, in order to provide a realistic assessment of the biological contribution to geomorphology.

1.2 Methodology

Using a large temporal scale not only leads to identify the variation in biological processes during a year but also the variation in hydrodynamic conditions and even changes in the natural system (e.g. future developments). De Vries *et al.* [2005] stated that for the Wadden Sea ecosystem, relevant time and spatial scales are annual and estuary wide. Adopting these scales, relevant processes need to be identified. To identify these relevant processes, De Vriend [1991] introduces the so-called 'scale concept' (Figure 1-1).

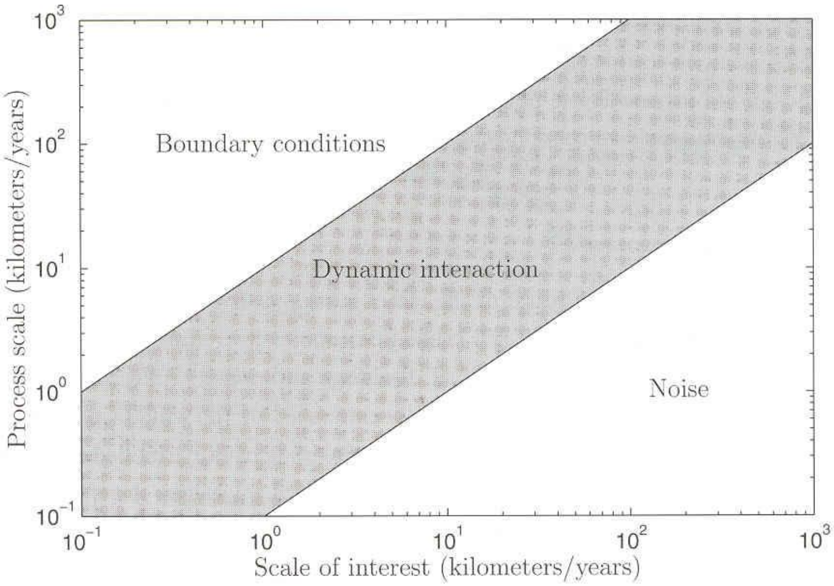


Figure 1-1: Scale concept [Van Ledden, 2003, modified after De Vriend, 1991].

De Vriend [1991] suggests that a phenomenon of interest is likely to be related to the underlying (physical) processes on a similar temporal and spatial scale. Influences from higher scales are described as boundary conditions, where influences from lower scales are considered noise. Noise does not mean that these processes are irrelevant, but that only the net effects of these processes are important [Van Ledden, 2003]. Applying this 'scale concept', sediment transport is the linking process between the biological processes and the morphological processes [De Vries, 2006]. The different scales are summarized in Table 1-1 [Borsje, 2006].

Table 1-1: Different scales in biogeomorphological research.

Process	**Temporal scale**	**Spatial scale**
Biological processes	Small time scale with seasonal variations	Intertidal and subtidal areas
Hydrodynamic processes	Tidal variations and seasonal variations (wind, air pressure) spring neap cycle	Estuary wide
Geomorphological processes	Slow time scale (>>tidal cycle)	>Estuary wide

1.3 Research objective

When confronting the problem definition with the methodology, the question arises to what extend the sediment transport in the Dutch Western Wadden Sea is influenced by biological activity. To answer this question a modeling approach will be adopted. A first successful step in the issue of aggregation of smaller estuarine process scales to larger ones is derived with the so called process-based models, as stated by Hibma *et al.* [2004] and Elias *et al.* [2006]. These models consist of modules that describe waves, current and sediment transport. Delft3D is an example of a process-based model, in which the process knowledge is applied to the physical system by mathematical representations.
Based on this information the research objective can be formulated:

The main research objective of this research is to determine the influence of biology on sediment transport and bed composition during one year on a large scale, by implementing the stabilizing and destabilizing effect which organisms have on the surface of the bed in the process-based model Delft3D.

Based on this aim, four research questions are addressed in this research:

1. *In what way can the destabilising and stabilising effect of organisms be parameterised in the Delft3D model, and how can the spatial and temporal variation in biological activity be modelled?*
2. *What is the influence of the biological activity on the fine sediment dynamics, compared to the situation without biological activity?*
3. *Do the model results show agreement with actual measurements?*
4. *What are the dominant processes in the influence of meso scale biogeomorphological interactions on the macro scale fine sediment dynamics?*

1.4 Study Area

The Dutch Western Wadden Sea is a shallow coastal sea (Figure 1-2) located along the South-East coast of the North Sea. The study area covers about 2163 km^2, of which 40% is comprised of intertidal flats. The Dutch Western Wadden Sea is bounded by the Afsluitdijk, the watershed of the island Schiermonnikoog and five islands. Tides are diurnal ranging from 1 to 2 m amplitude. The average quantity of water entering the area through the various inlets is estimated at 2200 x 10^6 m^3 [Ridderinkhof, 1988]. The current velocities in the area vary, with the highest speeds in excess of 2 m s^{-1} in the different tidal inlets where waterdepths are up to 50 m.

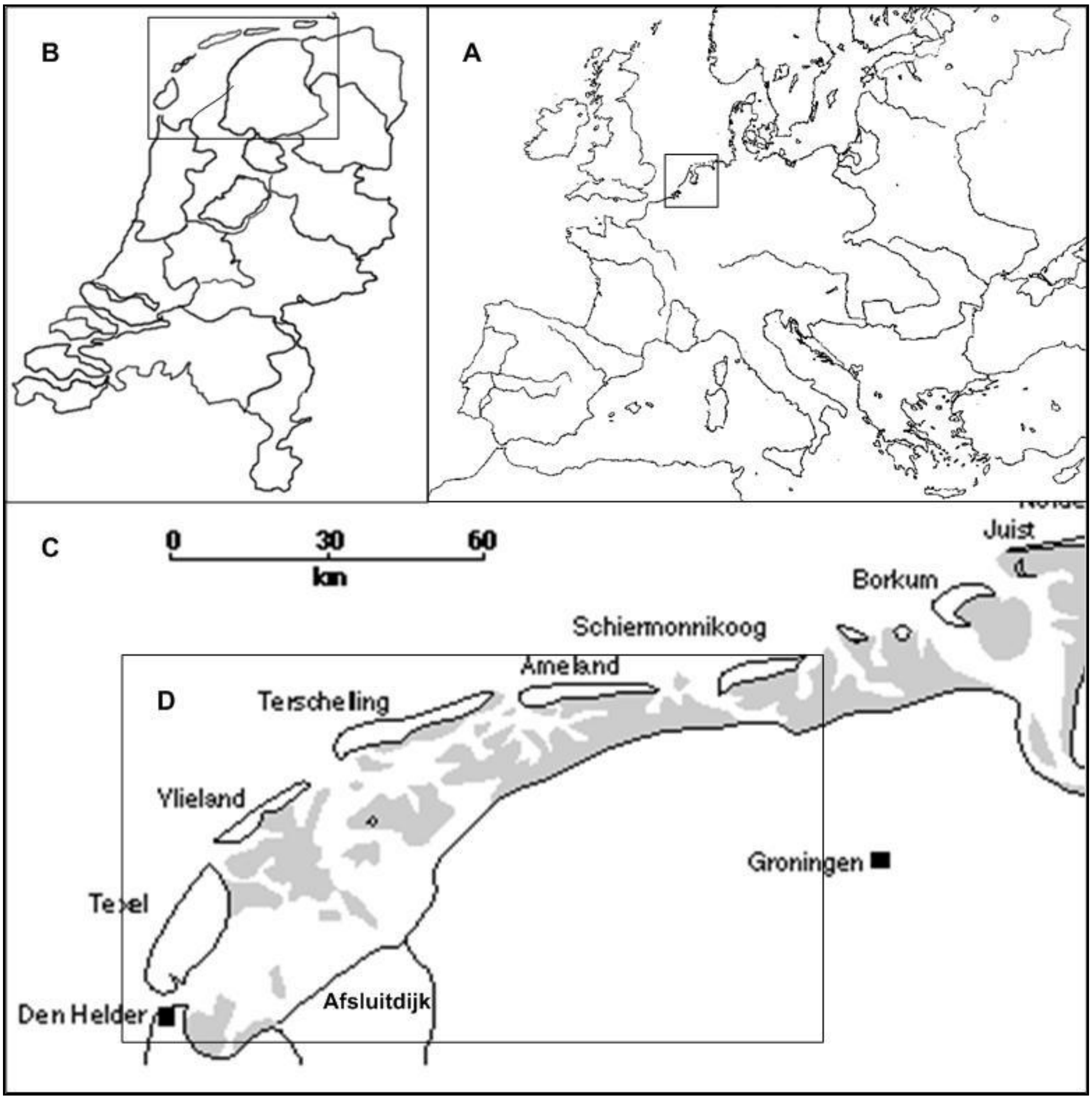


Figure 1-2: Location of the Dutch Western Wadden Sea (D) in the southern Wadden Sea (C) of the Netherlands (B) in Europe (A).

1.5 Outline of the report

The layout of the report is graphically presented in Figure 1-3. While this report aims at bringing together both the field of ecology and civil engineering, a relative simple description of the processes and model is included in this report. A more technical description is included in the appendices.

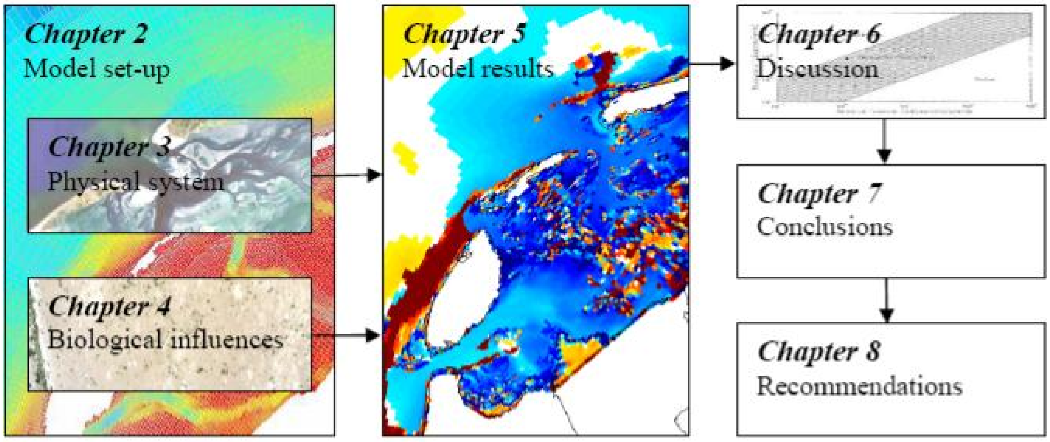


Figure 1-3: Graphical representation of the report.

The structure of this report is based on recommendations given by Naylor *et al.* [2002] for future biogeomorphological research. They emphasize the necessity to discuss the physical system and biological influences separately, before discussing the model results, in order to determine the scale interactions.
After describing the model (Chapter 2), the mechanisms and processes of the physical system are discussed and analyzed (Chapter 3). Next, the biological influences are discussed in Chapter 4. The linking between the physical system and the biological influences are discussed in Chapter 5; Model results. This chapter is followed by a discussion of the main findings, conclusions and recommendations for possible follow-up research are listed.

2 Model set-up

To determine the influence of biological activity on the sediment transport of fine sediment and bed composition in the Western Wadden Sea, the process-based Delft3D model is used. This chapter discusses the set-up of the model and the two modules used within this model (Section 2.1-2.4). The parameterisation of the biological influences is explained in Section 2.5 and Section 2.6. The data to evaluate the model are discussed in Section 2.7. Finally, the assumptions and constraints in and the linking between these modules are discussed in Section 2.8.

2.1 Used modules

The transport of fine sediment in the Wadden Sea is modelled in the water quality module Delft3D-WAQ (Paragraph 2.1.2). The hydrodynamic conditions are obtained from the FLOW-module (Paragraph 2.1.1). A technical description, including the governing equations of both modules, is given in Appendix A.

2.1.1 Hydrodynamic conditions

The hydrodynamic conditions are obtained from the FLOW-module. In this module, the hydrodynamic conditions for the year 1998 are calculated. In the used model, the land boundaries are closed. At the North Sea boundaries the water levels are imposed, based on the ZUNO-model. The ZUNO-model simulates the astronomic tidal movement in the southern North Sea. Fresh water inflows from the IJsselmeer (sluices of Den Oever and Kornwerderzand in the Afsluitdijk) are included based on daily data provided by Rijkswaterstaat. The wind forcing is based on KNMI data on wind speed. The bottom roughness is set at a constant Chézy value. The output of the model is calibrated with measured waterlevels from the observation points in the area. Based on these results, Cronin [2005] investigated the influence of a change in bottom roughness on the waterlevels. The waterlevels corresponded better with reality using a spatial varying Chézy Coefficient. However, the calculated area of exposed area at low tide is only 5% of the total area of the Western Wadden Sea, whereas the average exposed area for the Western Wadden Sea is estimated at 30% [EON, 1998].
Using the hydrodynamic conditions, the waterlevels during low tide are overestimated, while the high water levels correspond well with reality. This overestimation will be taken into account when discussing the results of the model.

2.1.2 Transport of fine sediment

The transport of fine suspended sediment is usually calculated from the local instantaneous flow conditions [Wang and Ribberink, 1986]. The transport of fine suspended sediment in the model is based on the advection-diffusion equation (Formula 2-1) as described by e.g. Teisson [1991], in which advection is determined by the velocity field and diffusion by the dispersion coefficient.

$$\frac{\partial \bar{c}}{\partial t}+V_x\frac{\partial \bar{c}}{\partial x}+V_y\frac{\partial \bar{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial \bar{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial \bar{c}}{\partial y}\right) \qquad (2\text{-}1)$$

in which:

$\bar{c}$	= depth averaged suspended sediment concentration	[g m^{-3}]
$D_{x,y}$	= dispersion coefficient	[m^2 s^{-1}]
$V_{x,y}$	= depth averaged velocity	[m s^{-1}]
h	= waterdepth	[m]

The model is two dimensional depth averaged (2DH), in which the sediment is transported in the horizontal direction by advection and diffusion. The vertical sediment transport is based on the sedimentation and resuspension flux, which are graphically represented in Figure 2-1, and are based on the settling velocity (w_s) and erosion coefficient (M) respectively. In the model, the bottom shear stress (τ_b) plays an essential role in defining whether or not sedimentation of suspended particles or erosion of bed material will occur. Sedimentation takes place when the bottom shear stress drops below a critical value ($\tau_{b,sed}$). On the other hand, erosion occurs when the bottom shear stress exceeds the critical value for resuspension ($\tau_{cr,res}$). The bottom shear stress is based on the shear stress due to waves and currents.

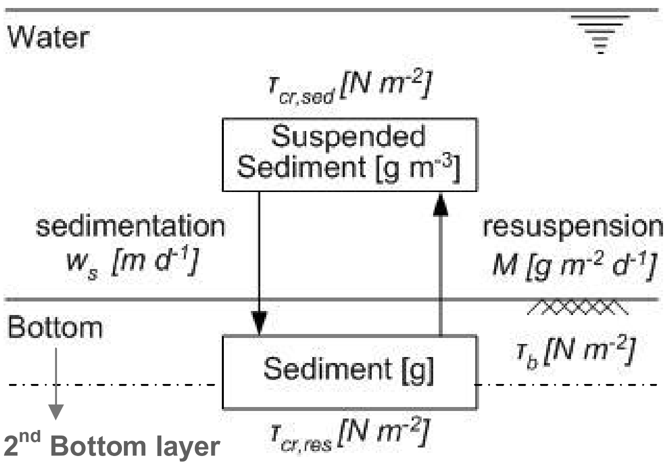


Figure 2-1: Governing parameters for sedimentation and resuspension of sediment.

A second bottom layer will account for the fact that sediment is buried downward by grazers (bioturbation). In the original concept this downward movement of sediment is not modelled. By using a second bottom layer, only biological influence is limited to the upper bottom layer, and the second bottom layer serves as buffering during calm weather. Moreover, the porosity for the two bed layers is different. Due to bioturbation, the porosity increases, especially in the top centimetres of the bed, as proven by e.g. Widdows and Brinsley [2002] and Orvain *et al.* [2006].

Based on the porosity, the flux of sediment to the second bottom layer is calculated. Transport of sediment between the two sediment layers is only possible, when the thickness of the upper bottom layer exceeds a user-defined thickness. Resuspension from the second bottom layer is only possible when the upper bottom layer is completely eroded. The user-defined thickness of the upper bottom layer is discussed in Chapter 5.

Only one substance is used in the model. This substance is characterised based on the settling velocity and critical shear stress for sedimentation and resuspension. Because of the use of fine sediment no bed load transport is modelled. There is no feedback from the vertical sediment transport processes to the hydrodynamic conditions (bed level changes).

2.2 Computational grid and bathymetry

When modelling the sediment transport in the Western Wadden Sea, it is recommended to consider the sediment transport in the North Sea, due to the exchange of suspended sediment between both areas [Van Ledden, 2003; Dittmann, 1999; Postma, 1981]. The model boundaries are located approximately 70 km from the coast and the grid shown in Figure 2-2 is used. The resolution in the Wadden Sea is about 100-300 m and between 2000 and 3000 m in the open sea area.

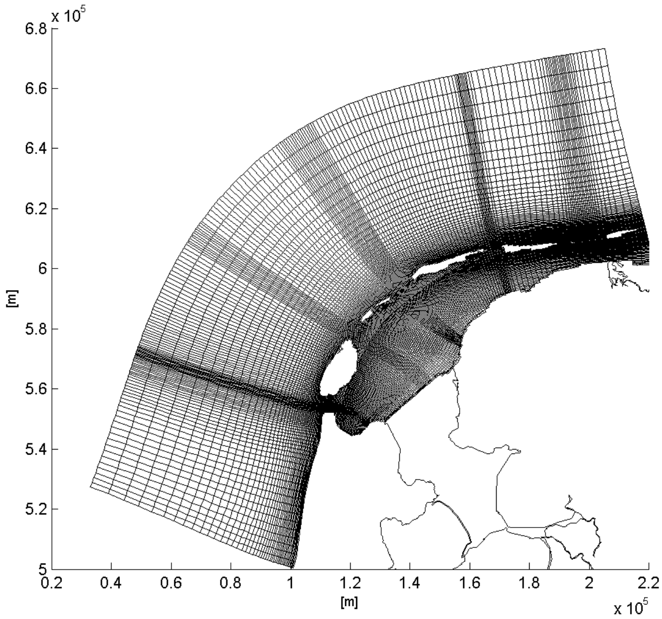


Figure 2-2: Computational grid of the Western Wadden Sea. Coordinates in m.

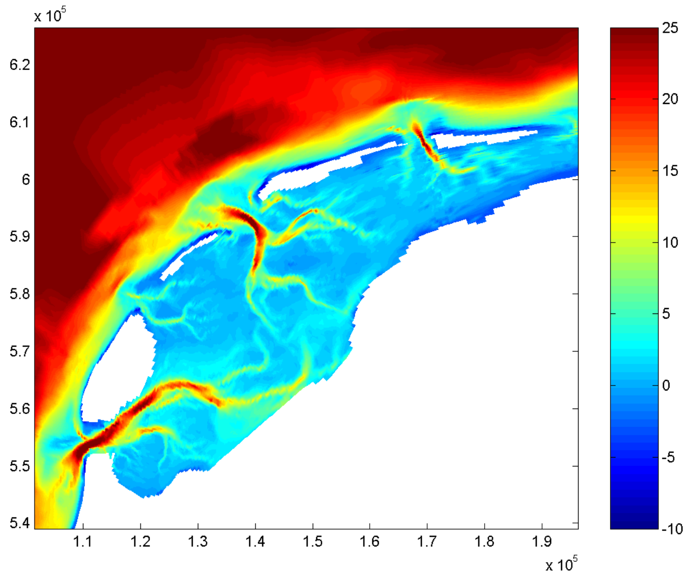


Figure 2-3: Bathymetry of the Western Wadden Sea in m above Mean Sea Level.

The bathymetry of the Western Wadden Sea (Figure 2-3) is based on data provided by Rijkswaterstaat for the period between 1997 and 1999. The error in these data is assumed to be 0.10 - 0.25 m [Van Kessel, 2004].

2.3 Initial and boundary conditions

The model is bounded by three open boundaries (North Sea) and one closed boundary (mainland), as shown in Figure 2-2. The eastern boundary between the island of Schiermonnikoog and the mainland coincides with a tidal flat that separates two tidal basins. In the model this boundary has been schematized as a closed boundary. At the open boundaries, the suspended sediment concentrations are imposed (see Table 2-1). These concentrations are based on measurements, executed by Rijkswaterstaat (DONAR database) and data provided by RIKZ [2002]; Figure 2-4.

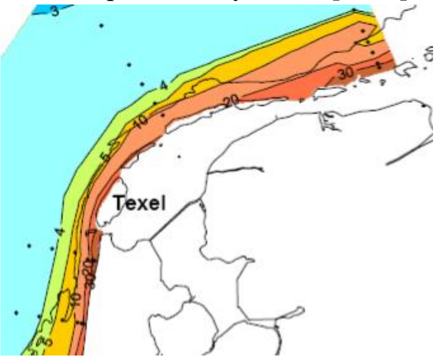


Figure 2-4: Yearly mean near-surface total suspended matter concentrations in the Dutch coastal zone [g m^{-3}].

In order to take into account the concentration gradient perpendicular to the coast [Suijlen and Duin, 2001], the southern and eastern boundary is divided in three zones, as shown in Table 2-1. The suspended sediment concentrations show a seasonal variation, which is discussed in Appendix E. Table 2-1 shows the yearly averaged suspended sediment concentrations at the model boundaries.

Table 2-1: Yearly averaged suspended sediment concentrations at the model boundaries [g m^{-3}].

Name	**Suspended sediment concentration [g m^{-3}]**
South 2 km	50
South 5 km	15
South 50 km	5
West and North	3
East 2 km	40
East 5 km	15
East 50 km	3

During the simulation, the first year is used for spinning up the model. A spin-up time of one year is sufficient according to Van Kessel [2004], based on a modelling experiment for the fine sediment dynamics for the Dutch Western Wadden Sea. The simulation starts with an empty bottom and a uniform suspended sediment concentration of 5 g m^{-3}. As a consequence, the DONAR database and the Sedimentatlas can be used as evaluation tools, as will be discussed in Section 2.7.
Daily data on fresh water discharge of Rijkswaterstaat from the sluices in the Afsluitdijk (Den Oever and Kornwerderzand) is implemented in the model. The suspended sediment concentration of the discharge is set at 25 g m^{-3}.

2.4 Process parameters

The substance included in the model is characterised as inorganic, cohesive fine sediment. The settling velocity of this substance is set at 0.5 mm s^{-1}. This value is in accordance with the value used by Van Ledden [2003] for cohesive fine sediment, who investigated the sand-mud segregation in the Friesche Zeegat (a tidal inlet in the Dutch Wadden Sea). The critical shear stress for erosion is set at 0.4 N m^{-2}. This value is similar to the value used by Van Ledden [2003] and Paarlberg *et al.* [2005]. The latter investigated the transport of cohesive fine sediment on an intertidal flat in the Western Scheldt estuary. A critical bed shear stress for deposition does not exist [Winterwerp and Van Kesteren, 2004]. By using a critical shear stress of 100 N m^{-2} continuous sedimentation is allowed. Bottom roughness is prescribed by a global Chézy coefficient of 62 $m^{1/2}$ s^{-1}, which is in accordance with the value used by Elias *et al.* [2006] applied in a modelling experiment for the Dutch Western Wadden Sea.
The dispersion coefficient is set at 10 m^2 s^{-1}. The wind fetch is set variable between 1500 and 9500 m (Appendix F), and is uniform for the modelling area. Based on the wind fetch, the wave height and the wave length are calculated. Table 2-3 shows the used databases. The parameters indicated with a star in Table 2-2 are subjected to a sensitively analysis. This analysis is discussed in Chapter 3.

Table 2-2: Process parameters.

Description of variable	Symbol	Value	Unit
Dispersion coefficient*	D_x,D_y	10	m^2 s^{-1}
Settling velocity*	w_s	0.5	mm s^{-1}
Critical shear stress for resuspension	$\tau_{cr,res}$	0.4	N m^{-2}
Critical shear stress for sedimentation	$\tau_{cr,sed}$	100	N m^{-2}
Resuspension flux	M_{res}	0.1	g m^{-2} s^{-1}
Chézy coefficient*	C	62	$m^{1/2}$ s^{-1}
Fetch*	F	1500-9500	m

*sensitivity analysis is executed on these variables

Table 2-3: Used databases.

Description of variable	Symbol	Database
Wind speed	V_{wind}	KNMI
Fresh water inflow	Q_{in}	Rijkswaterstaat
Boundary water levels	H_b	ZUNO-model
Concentration of fine sediment	c	DONAR
Bottom height	z_b	Rijkswaterstaat

2.5 Bio-engineers

The Western Wadden Sea is a very rich ecosystem [e.g. Dijkema, 1991; Dittmann, 1991] in which sediment erodibility is dependent on the interactions between physical processes, sediment properties and biological processes [Jumars and Nowell, 1984; Widdows and Brinsley, 2002]. In order to include the biological processes in the model, the representative bio-engineers in the Western Wadden Sea are determined. In Section 2.6, the parameterization of these bio-engineers is explained.
The influence of two groups of biota is important when describing the suspended sediment transport and bed composition; bio-stabilisers and bio-destabilisers [Paterson and Black, 1999]. Bio-stabilisation is caused by physically covering the bed by benthic species (e.g. mussel beds) or binding the substrate by roots. Moreover, bio-stabilisation can result from extracellular polymeric substances (EPS) excreted by diatoms, that glues the sediment together and therefore protects the sediment against erosion. Bio-destabilisation is caused by digging and feeding activities by benthic fauna (also called bio-turbation). The two groups affect the suspended sediment transport in different ways as summarized in Table 2-4. An extensive overview of the biological influence on the sediment dynamics is given by Borsje [2006].

Table 2-4: Overview of the effect of bio-stabilisation and bio-destabilisation on the sediment dynamics.

Group	Effect
Bio-stabilisation	Reducing sediment resuspension
Bio-destabilisation	modify properties of surficial sediments (sediment water content, faecal pellets) and increasing sediment resuspension

In this research, the biological influence of diatoms (bio-stabilisers) and the shell fish *Macoma balthica* and the mudsnail *Hydrobia ulvae* are analysed (both bio-destabilisers). These biota are representatives of organism with bio-stabilizing and bio-destabilizing effects in the Western Wadden Sea [Wijsman, 2004]. In reality, bio-destabilising is caused by much more organisms. The influence of these organisms is discussed in Chapter 6.
Diatoms are restricted to the intertidal or shallow subtidal zone, due to lack of light available for photosynthesis in deeper water. During a bloom period in spring, large densities of diatoms are known to form algae mats (Figure 2-5). These mats are reduced in winter.

Figure 2-5: Algal mats in the Wadden Sea.

The clam, *Macoma balthica* (Figure 2-6) is present at very high but variable densities and is found from the upper part of the intertidal flat to the shallow subtidal zone. The clam has a broadly oval shell and is up to 25 mm in length. The main breeding period lies between February and May, with a second spawning in autumn. The clam lives approximately 2-3 cm buried below the surface in the Western Wadden Sea.

Figure 2-6: *Macoma balthica.*

The mudsnail, *Hydrobia ulvae,* (Figure 2-7) is present at the intertidal flat. The snail has a small, spiralling shell and is very small (around 4 mm in length). Breeding occurs in spring and autumn.

Figure 2-7: *Hydrobia ulvae.*

Both bio-destabilisers graze on microphytobenthos from the sediment grains. *Macoma balthica* is buried in the sediment and has tubes that protrude through the surface. *Macoma balthica* feeds both on pelagic (suspension feeding) and benthic microalgae (surface-deposit feeder). In this study *Macoma balthica* is characterized as a surface-deposit feeder. *Hydrobia ulvae* feeds primarily on the microphytobenthos present at the sediment surface (surface-deposit feeder).

2.6 Modelling approach bio-engineers

The stabilising and destabilising effects of organisms can be brought to expression in the model by means of modification of the formulations for the critical bed shear stress and the erosion rate. The terms to describe the effects of microphytobenthos and grazers on erosion in the model are based on the formulations proposed by Holzhauer [2003] and Paarlberg *et al.* [2005], using formulations and data produced by Widdows and Brinsley [2000; 2002].
Bio-stabilisation by diatoms is represented by the chlorophyll-a content, which is an indicator of microphytobenthos biomass [Staats *et al.*, 2001]. Bio-destabilizing organisms are represented by the abundance of surface-deposit feeders [Austen *et al.*, 1999]. The parameterisation of the influence of biological activity on the sediment strength is represented in Formula 2-2 and 2-3.

$$\tau_{cr,res} = \tau_{cr,res0} f_s(Chf) f_d(Nzb) \quad (2\text{-}2)$$

$$M_{res} = M_{res0} g_s(Chf) g_d(Nzb) \quad (2\text{-}3)$$

in which:

$\tau_{cr,res0}$	= critical shear stress for erosion at absence of organisms	[N m^{-2}]
M_{res0}	= erosion coefficient at absence of organisms	[g m^{-2} s^{-1}]
f_s,g_s	= stabilisation function	[-]
f_d,g_d	= destabilisation function	[-]
Chf	= Concentration of chlorophyll-a in the sediment layer	[µgChl gC^{-1}]
Nzb	= Density of zoobenthos species	[ind. m^{-2}]

The (de)stabilisation functions are discussed in Appendix G. The biological influence on the critical shear stress and the erosion coefficient is given in Figure 2-9 and 2-10 respectively. The maximum biomass of zoobenthos and the maximum chlorophyll-a content reflect the maximum values found in the Western Wadden Sea, as will be discussed in Section 4.3.
The relation between depth zone and organisms is given in Table 2-5.

Table 2-5: Distribution of organisms in the depth zones; the colours are related to Figure 2-8.

	depth zone 1	**depth zone 2**	**depth zone 3**
Macoma balthica	x	x	x
Hydrobia ulvae		x	x
Microphytobenthos	x		

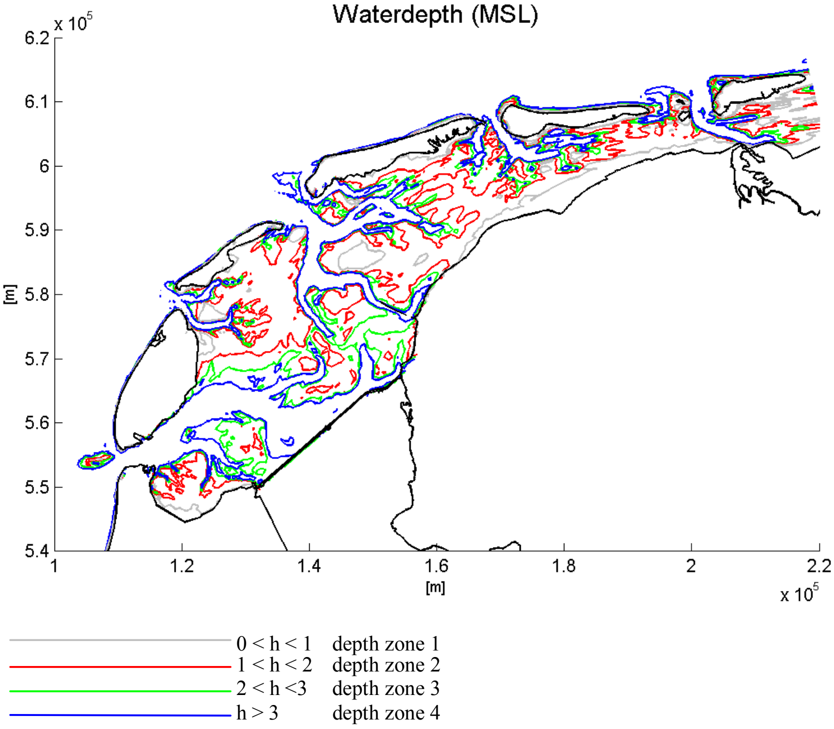


Figure 2-8: Overview of depth zones based on waterdepth (Mean Sea Level [m]).

The destabilisation functions are corrected for the contribution of the individual biomass to the total biomass in depth zone 2 and 3, as proposed by Wijsman [2004], showing the much larger biomass *Hydrobia ulvae* in the Western Wadden Sea.

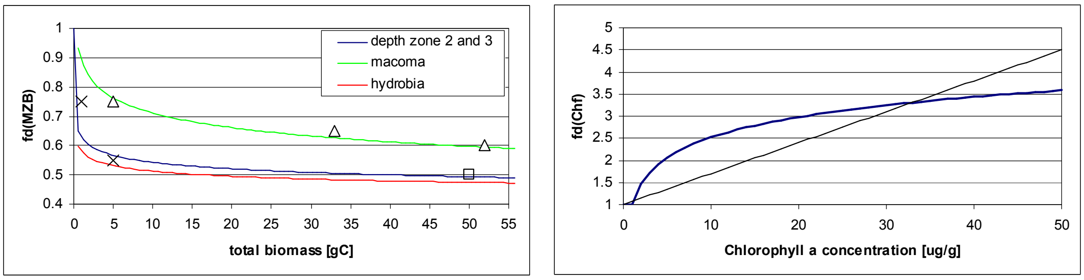


Figure 2-9: The effect of amount of biomass on the destabilisation factor (f_d(Nzb)) and chlorophyll-a content on the stabilisation factor (f_s(Nzb)) for the critical shear stress.

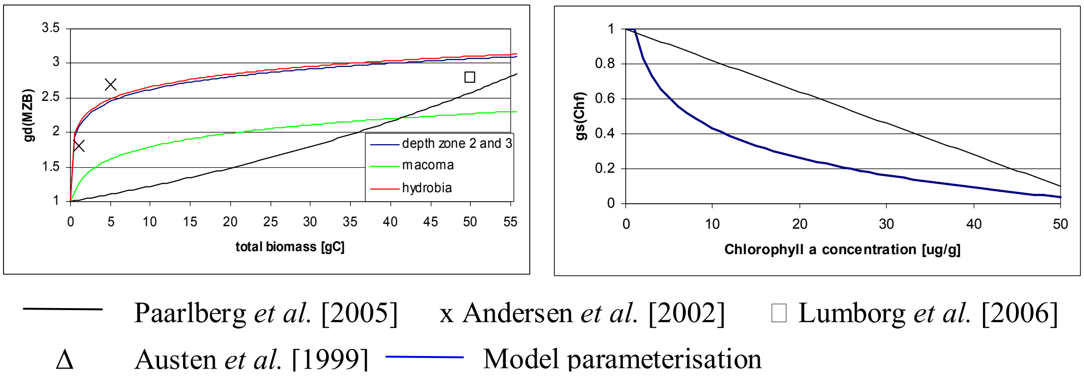


Figure 2-10: The effect of the amount of biomass on the destabilisation factor (g_d(Nzb)) and chlorophyll-a content on the stabilisation factor (g_s(Nzb)) for the erosion coefficient.

It should be noted that only few data are used to derive the relationships presented in Figure 2-9 and 2-10. The relationships show in Figure 2-9 and 2-10 differ from the relationships proposed by Paarlberg *et al.* [2005], indicated with the black line in both figures.
The relationships proposed by Paarlberg *et al.* [2005] are based on measurements executed in the Western Scheldt estuary (The Netherlands) and Humber estuary (England), while the relationships used in this research for bio-destabilisation are based on measurements executed in the Danish and German Wadden Sea [Andersen *et al.*, 2002; Lumborg *et al.*, 2006]. The relationship found by Austen *et al.* [1999] is based on measurements in the Danish Wadden Sea for *Macoma balthica*. The relationships for bio-stabilisation show strong similarity with the relationship found by Colijn and Mayerle [2004], which are deduced from experimental data of a tidal flat located in German Wadden Sea. These data show a non-linear relationship reaching an asymptote.
Based on Figure 2-9 and 2-10, it can be concluded that biological modification of the erosion rate is larger than biological modification of the erosion threshold. Andersen *et al.* [2005] stated that the erosion threshold only reflects the threshold for the surface particles that are easily eroded, e.g. faecal pellets. Such particles will generally be present even at low densities of macrozoobenthos and the erosion threshold will consequently be low and not decrease significantly for increasing density of bioturbators (Figure 2-9). In contrast, the rate at which particles are eroded is strongly dependent on the degree of bioturbation, as the availability of easily eroded aggregates will determine the erosion rate.
In this parameterisation, interactions between organisms and the effects of sediment transport and bed composition changes on biological activity are not taken into account.

2.7 Data for evaluation

The most important evaluation parameters are the suspended sediment concentration and the distribution of fine sediment on the bed. Data to evaluate the suspended sediment concentration are obtained from the DONAR-database. This database contains measurements of suspended sediment concentrations at a depth of 1 m below the water surface. To evaluate the distribution of fine sediment on the bed, the Sedimentatlas is used, in which the mud content in the top 10 cm of the bed is given for the period 1989 – 1997.
For the year of interest, 1998, and for the model domain, all measuring stations with suspended sediment concentrations are the four stations shown in Figure 2-11 (squares). Van de Kreeke and Hibma [2005] concluded that these measurements can hardly be compared with depth averaged concentrations. Only the order of magnitude of the suspended sediment concentration can be determined. Moreover, all the particles in the water column are measured (i.e. both organic and inorganic matter). Data on the suspended sediment concentrations in the intertidal areas is not available. In total, only 45 measurements are available at the measuring stations.
The samples used to set up the Sedimentatlas are not treated to remove calcium carbonate and organic matter, through which the fine sediment concentration on the bed is overestimated. Measurements in the Sedimentatlas are taken at every square kilometre, which is comparable to the resolution of the computational grid, as discussed in Section 2.2.
As a consequence, the results of the model can only be evaluated with the above mentioned databases. Calibration of the model results is not possible, due to the (unknown) overestimation in both the fine suspended sediment concentration and the fine sediment distribution on the bed. The evaluation data are analysed in Section 4.3.

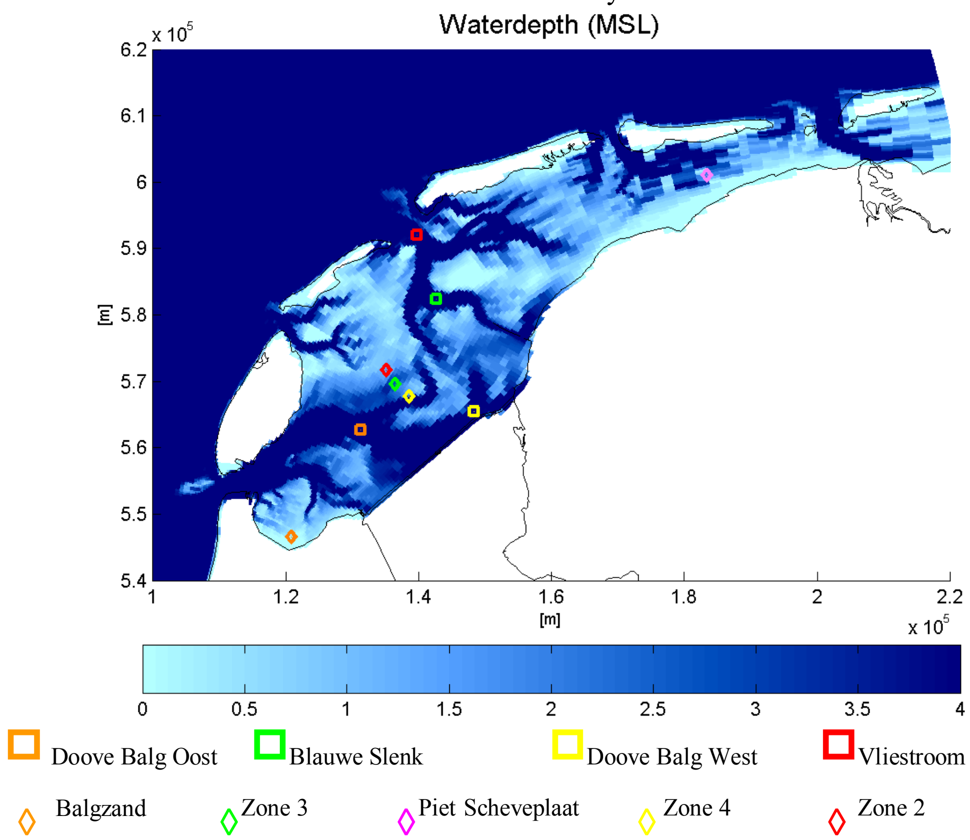


Figure 2-11: Observation points in the Dutch Western Wadden Sea combined with waterdepth (Mean Sea Level) [0-4 m]. Squares are the measuring stations in the DONAR database, diamonds are included for later reference.

2.8 Discussion

The used model is two dimensional depth averaged (2DH). As a consequence, variations in parameters in vertical direction are not modelled. Generally, a two dimensional schematisation is applied when the scale of interest (horizontal) is much larger than the vertical scale (waterdepth) [Wang and Ribberink, 1986]. Van Loon [2005] concluded that the concentration profile in the Wadden Sea is relatively uniform, based on the model of Winterwerp and Van Kesteren [2004]. Therefore, using a two dimensional model is justified. Observations of suspended sediment concentration above a tidal flat in the Western Wadden Sea also show that suspended sediment is mostly homogeneously distributed over the entire water column [Ridderinkhof *et al.*, 2000]. However, using a 2DH model a uniform velocity profile is assumed, which is not in accordance with reality. Moreover, at the inflow areas water movement in the vertical plan caused by density gradients are not modelled. These density gradients cause a net landward sediment transport [Winterwerp, 2001]. Due to the relative low inflow of fresh water (on average 1.5 % of the total inflow during flood tide), this process is assumed to be not important in the Western Wadden Sea.
Based on research by Winterwerp [2003], a constant suspended sediment concentration is justified at the boundaries, when examining the yearly sediment balance of the Wadden Sea. However, examining the yearly variation in the fine sediment concentrations in the Western Wadden Sea, a seasonal variation in the suspended sediment concentration need to be imposed [Postma, 1981; Lumborg and Pejrup, 2005; Van Kessel, 2004], with the highest values occurring in February (see Appendix E).
By scaling the advection-diffusion equation, dominant processes can be determined. It can be concluded that diffusion is dominant in the shallow areas and advection is dominant in the deeper areas with high flow velocities (see Appendix B). Based on this knowledge, it is interesting to examine the sensitivity in the suspended sediment transport as a result of a variation in the dispersion coefficient.
In the model, only a constant settling velocity is used. This assumption is not in accordance with results found by Winterwerp [2002]. He argued that due to flocculation and hindered settling large variations in settling velocity over a tidal cycle occur, with the higher values around slack water. Moreover, a large range in settling velocity is used in different modelling studies. As discussed in Section 2.4, Van Ledden [2003] uses a settling velocity for cohesive fine sediment of 0.5 mm s^{-1}, while Paarlberg *et al.* [2005] uses a settling velocity of 0.058 mm s^{-1} for the same substance, based on Van Rijn [1993].
The process of consolidation is also not taken into account. Consolidation of the bed results in an increase of the strength of the bed, and therefore in an increase of the critical shear stress for erosion [Amos *et al.*, 1988].
Data on wind speed and wind direction showed that 1998 was a representative year. Also the yearly averaged concentration of suspended sediment in the Western Wadden Sea in 1998 was comparable to preceding and subsequent years. The numerical stability of the model is proven by Van Loon [2005].
Modelling of cohesive sediment dynamics is connected with some inaccuracy as discussed by Lumborg *et al.* [2006]. They stated that fine-grained sediment characteristics are usually varying and complex in estuaries with large intertidal areas. On the other hand, they argued that numerical modelling may be a valuable tool in predicting the effects on sediment transport of different biological communities.

3 Physical system

Suspended sediment transport is determined and influenced by tide, wind and sediment exchange between the seabed and the water by erosion and resuspension processes [De Vriend *et al.*, 2002]. The goal of this chapter is twofold: first to discuss the processes in the physical system and secondly to examine the sensitivity in the suspended sediment transport with respect to the physical parameters.
In Section 3.1, the influence of waves and tides together and separately will be discussed. The sediment transport parameters will be discussed in Section 3.2. Finally, the import of suspended sediment will be discussed in Section 3.3. All sections are constructed in the same way: first the physical processes are analysed and secondly the processes are compared to processes described in field and laboratorial studies.

3.1 The influence of waves and tides

The processes of erosion and sedimentation are dependent on the bottom shear stress. The bottom shear stress is based on the bottom shear stress due to waves and currents, which are caused by the wind and tide respectively (see Appendix A4). The wind speed varies during the year, as shown in Figure 3-1. The wind speed is assumed to be uniform over the modelling area. The wind speed is discussed in Appendix C.

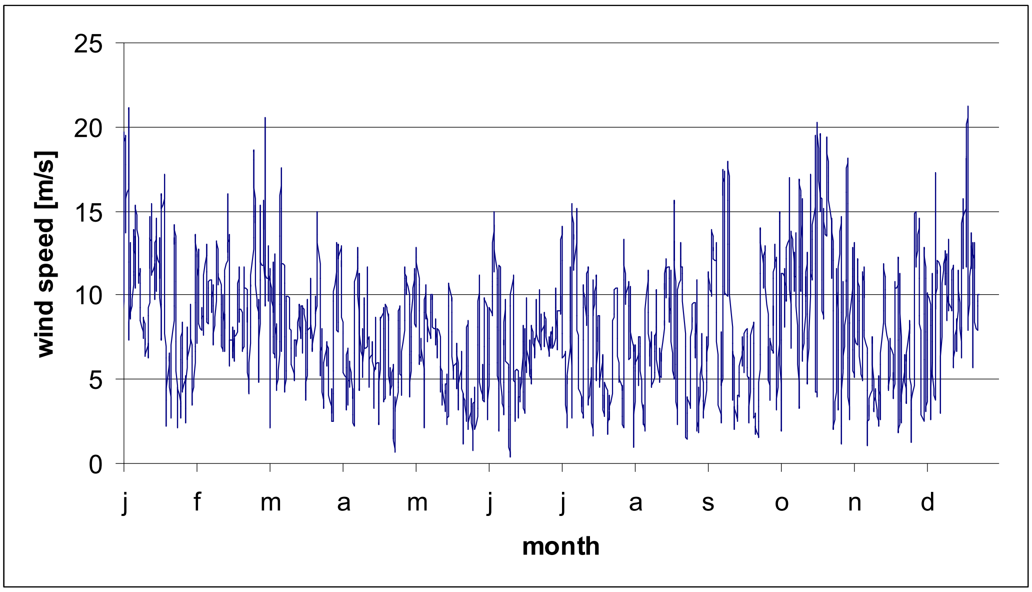


Figure 3-1: Wind speed [m s^{-1}] during the year 1998, based on 6-hourly KNMI data measured near Den Helder.

The results presented in Figure 3-1 (combined with the statistic analysis executed in Appendix C) contradict the assumption that the seasonal variation in suspend sediment concentration in the Wadden Sea is simply caused by the seasonal variation in wind speed, as stated by different authors [Ridderinkhof *et al.,* 2000; Suijlen and Duin, 2001; Van de Kreeke and Hibma, 2005].
In order to investigate the influence of waves and tides, two periods are investigated: a rough weather period during January and a calm weather period during June. The characteristics of both periods are presented in Table 3-1.

Table 3-1: Characteristics of the two investigation periods.

Period	January	June
date	01-01 - 03-01 1998	15-06 - 17-06 1998
average wind speed [m s^{-1}]	8.2	2.6
maximum wind speed [m s^{-1}]	21.2	9.1
minimum wind speed [m s^{-1}]	6.7	0.4

The bottom shear stress caused by waves is calculated according to Soulsby [1997] and is based on the parameters shown in the first right hand side of Formula 3-1. The wave characteristics are calculated after Groen and Dorrestein [1976] and are based on the parameters shown in the second right hand side of Formula 3-1.

$$\tau_{wind} = f(H, L, T, h) = f(V_{wind}, F, h) \qquad (3\text{-}1)$$

in which:

H	= wave height	[m]
L	= wave length	[m]
T	= wave period	[s]
h	= waterdepth	[m]
V_{wind}	= wind speed	[m s^{-1}]
F	= fetch	[m]

By varying the parameters on the right hand side of Formula 3-1, the dependency of the waves on the bottom shear stress caused by wind can be visualized, as shown in Figure 3-2.

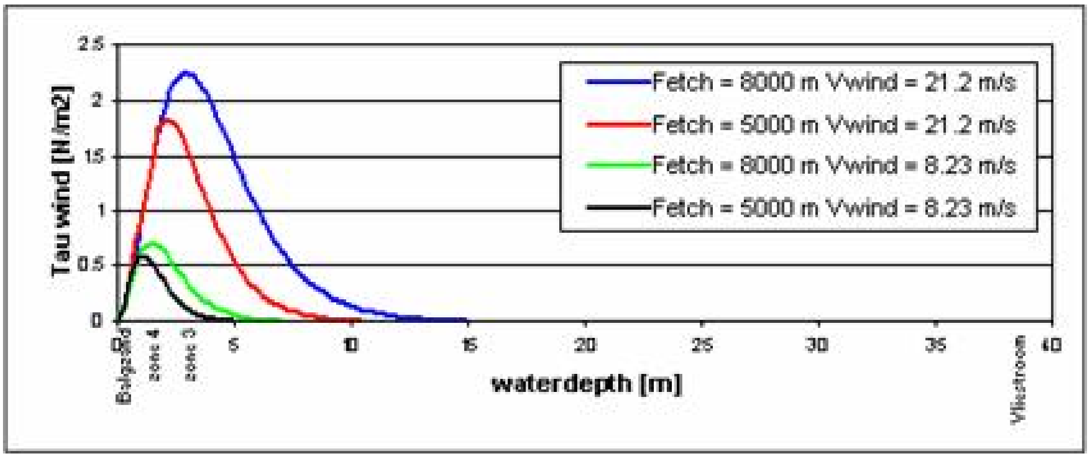


Figure 3-2: Relation between the waterdepth [m] and the bottom shear stress caused by wind [N m^{-2}], using different values for the (maximum and average) wind speed [m s^{-1}] and fetch [m]. For reference see Figure 2-11.

On the x-axis the observation points are added, based on the average waterdepth, as shown in Figure 2-11. It can be concluded that waves only have significant influence on the bottom shear stress on an intermediate depth, dependent on the wind speed and the fetch. Even during rough weather conditions, the bottom shear stress caused by wind is very low at places near the coast and in the channels, as shown in Figure 3-3.

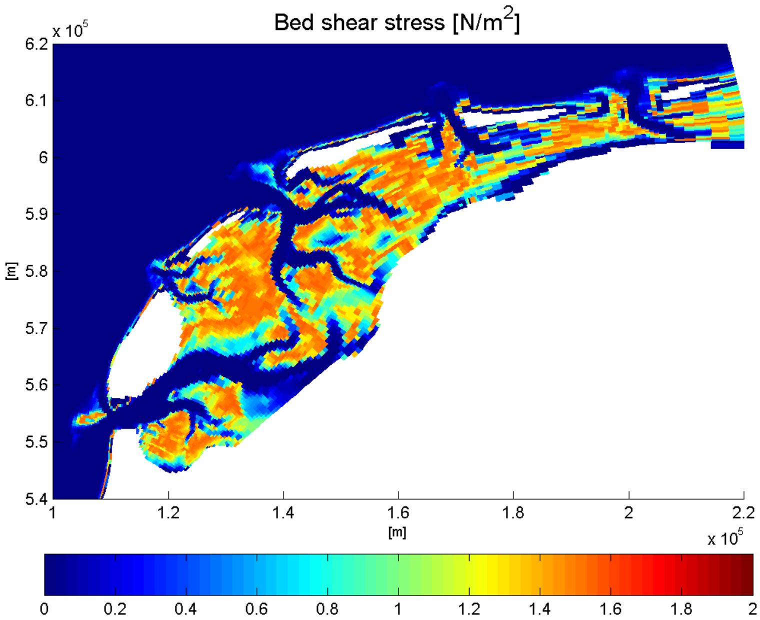


Figure 3-3: Overview of the bottom shear stress [N m^{-2}] caused by wind during the rough weather period. Fetch = 5000 m and wind speed is 21.2 m s^{-1}. For reference see Figure 2-3.

In order to compare different situations, the relative contribution of the bottom shear stress caused by wind with respect to the total bottom shear stress is shown in Figure 3-4. It can be concluded that during rough weather (upper part of Figure 3-4) the relative contribution of the bottom shear stress caused by wind is larger than during calm weather. Moreover, using a larger fetch, the relative contribution of the bottom shear stress caused by wind is larger, especially during rough weather. On the other hand, the relative contribution of the bottom shear stress caused by wind at a shallow place (Balgzand) is large during calm weather, because of the small contribution of the bottom shear stress caused by the tide at this location.

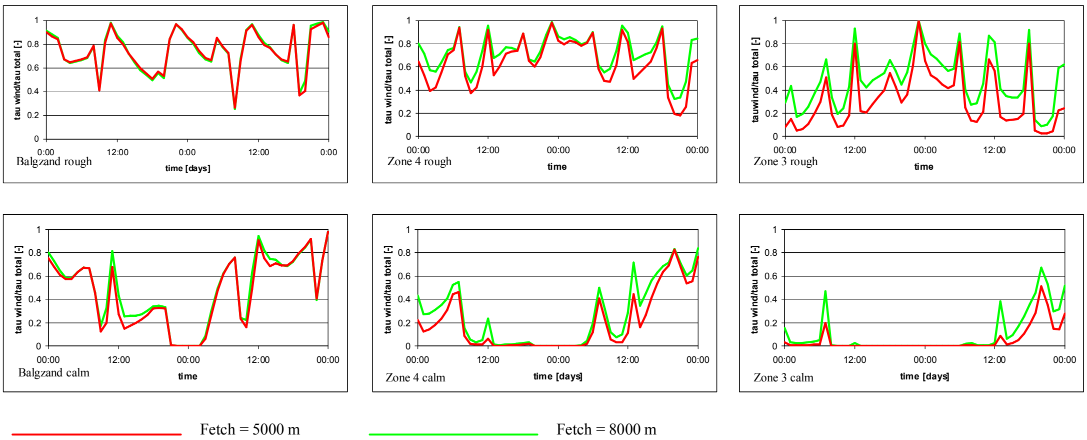


Figure 3-4: Relative bottom shear stress (τ_{wind}/τ_{total}) during rough weather (January) and calm weather (June). For reference see Figure 3-2.

The absolute value of the bottom shear stress is presented in Figure 3-5. In order to show the variation in the bottom shear stress due to the tide, a complete spring-neap cycle is modelled. Based on these plots, it can be concluded that the bottom shear stress caused by wind is of significant influence on the total bottom shear stress in the intertidal area.

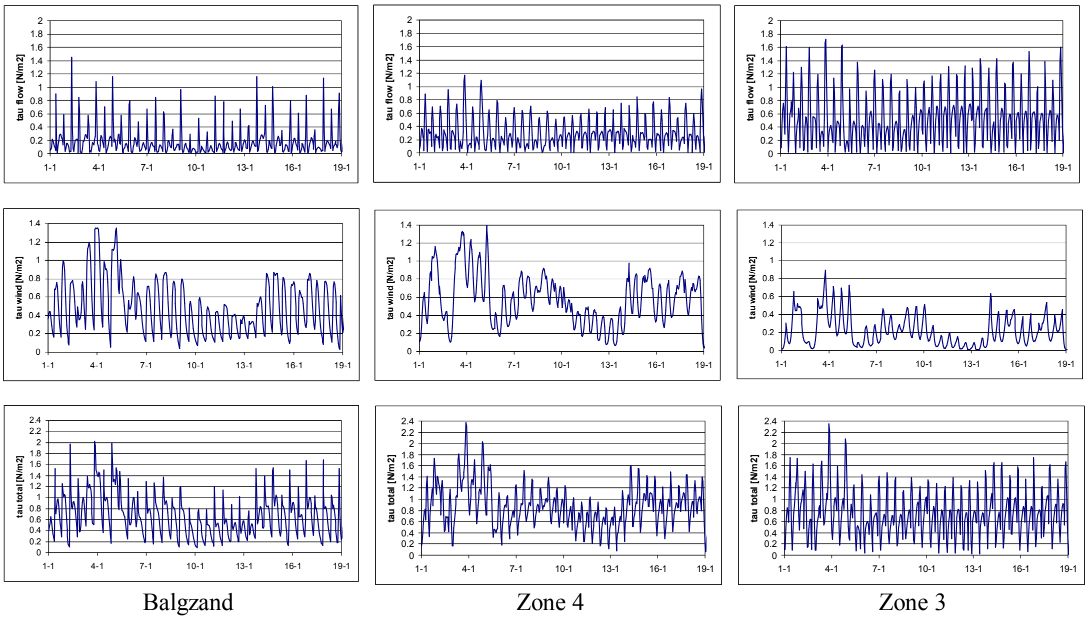


Figure 3-5: Absolute value of the bottom shear stress [N m^{-2}] caused by tide (upper) and wind (middle) during a spring-neap cycle at different locations.

In the model, the bottom shear stress caused by wind is added as a scalar to the bottom shear stress caused by the tide. However, there is a correlation between the wind direction and wind speed, as shown in Figure 3-6. By applying the bottom shear stress caused by wind as a scalar, the bottom shear stress will be overestimated.

In reality, the wind can hold back or reinforce a high tide [Brown *et al.*, 2002] by setting-up or setting-down the water levels, as shown by Ridderinkhof *et al.* [2000] and Janssen-Stelder [2000] for the Dutch Western Wadden Sea. This interaction is not included in the model.

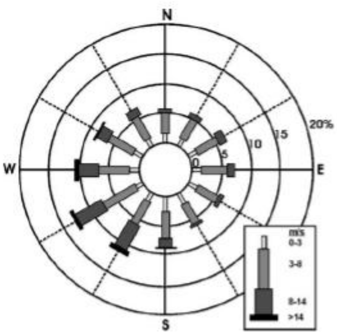


Figure 3-6: Overview of the wind direction [°] and wind speed [m s^{-1}] near Den Helder (based on data between 1971- 2000). source: www.knmi.nl.

The results found in this section correspondent with results found by Janssen-Stelder [2000], who executed a field experiment on a mudflat in the Dutch Wadden Sea. She found wave action to be the dominant process in sediment transport during stormy conditions (average onshore wind speed of 14 m s^{-1}). The study area is comparable with zone 4 in this experiment, based on the average waterdepth. As shown in Figure 3-4, the total bottom shear stress is almost completely determined by the bottom shear stress due to waves in zone 4 during rough weather. Moreover, during calm weather (average offshore winds) a combination of currents and waves is responsible for the sediment transport. This result is comparable with the relation found in Figure 3-4 in zone 4 during calm weather.

Additionally, Lumborg and Pejrup [2005] found that due to short period wind activity, the bed shear stress at the intertidal flats can be enlarged by a factor 4, which is in accordance with the results found in Figure 3-5.
Finally, during a measurement campaign in the Dutch Western Wadden Sea, de Jonge and van Beusekom [1995] found that the wind speed influences the suspended sediment concentration above the flat much more than in the channel.

3.2 Transport parameters

In this section the transport parameters will be discussed. The transport of fine sediment takes place through advection and diffusion. Diffusion, as defined here, differs from the physical concept of molecular diffusion as it stands for all transport that is not described by the advective velocities. This implies that dispersion is much larger than molecular diffusion [Zimmerman, 1986; Vermeulen, 2004]. As a consequence, in this 2DH model, the diffusion coefficient is set at 10 $m^2 s^{-1}$, following Hibma [2004] and Schramkowski *et al.* [2002]. The order of magnitude of this value is in agreement with calculations based on observations in the Zeegat van Texel [Veth and Zimmerman, 1981].
Another important parameter in modeling the sediment transport is the settling velocity of the suspended sediment. For fine suspended sediment, the settling velocity can strongly vary in time and space as a result of flocculation [e.g. Van Leussen, 1994; Winterwerp, 2002]. On the other hand, turbulent shear stresses result in the break up of bonds between these mud flocs [Van Ledden, 2003]. Pejrup [1988] found that fine suspended sediment concentration is a major determinant for the formation of sediment flocs. For the Western Wadden Sea, strong variations in settling velocity are not expected during a tidal period, due to the relative low suspended sediment concentration and the high turbulent shear stresses [Van Ledden, 2003; De Vries *et al.*, 2005]. The settling velocity of fine suspended sediment is also influenced by a biological process (pelletization).
Finally, the sediment transport is influenced by the bottom roughness. Wright *et al.* [1997] stated that in relatively shallow ecosystems bottom roughness for a large part is determined by biogenic structures. These roughness elements (e.g. mussel beds) tend to slow down the current velocities close to the bed and generate turbulence as demonstrated by Van Duren *et al.* [2006]. For the Dutch Western Wadden Sea, the location of mussel banks is shown in Figure 3-7. In 1998 less than 200 ha of mussel beds were present [Dankers *et al.*, 2001], which is less than 1% of the total area of the Dutch Western Wadden Sea. Based on this information, it is assumed that biogenic structures do not influence the sediment transport on a large scale by adding roughness to the bed.

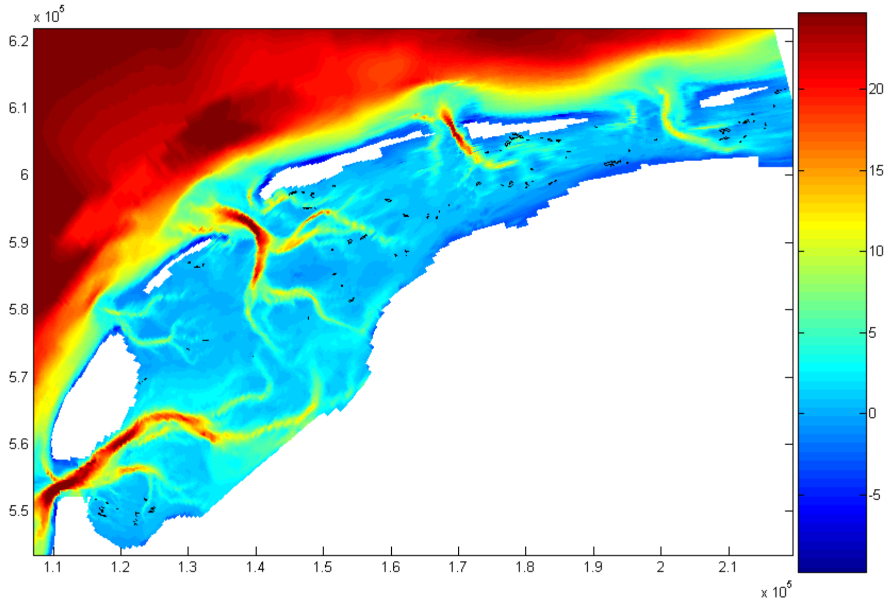
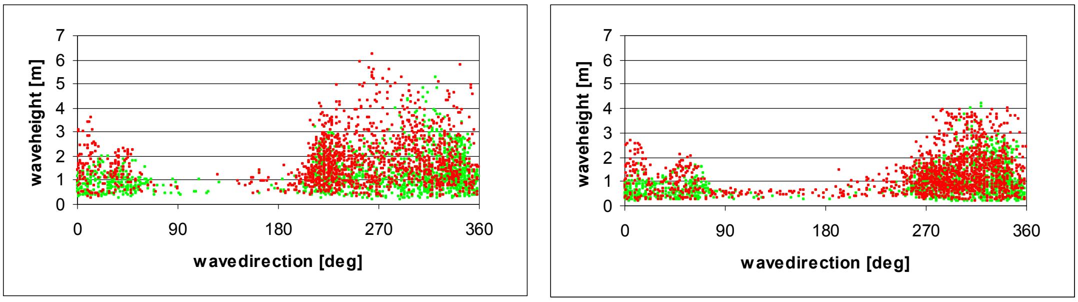


Figure 3-7: The distribution of mussel banks (enclosed by the black contours) in the Wadden Sea in 1998 (source: RIVO).

3.3 Import of suspended sediment

Based on data provided by Rijkswaterstaat, Figure 3-9 is constructed, in which an investigation is made in the relation between the wave direction and wave height. In order to determine the seasonal variation, a summer and winter period is distinguished.



Summer: April-September winter: January-March, October-December

Figure 3-8: Relation between wave height [m] and wave direction [°] for Eierlandsegat (left) and Schiermonnikoog (right). Source: Rijkswaterstaat.

The wave heights at Eierlandsegat (near Vlieland) are relative large due to the larger waterdepth at this location. Based on Figure 3-8 a correlation is found between the wave height and the wave direction. Based on this information, the wind fetch in the model is corrected for the wave direction, resulting in a variable fetch (Appendix G).
To obtain an estimate of the dominant components of the wave climate for sediment transport, the Schiermonnikoog observations are sorted. A sub-division in four wave-height classes and six direction classes is made. Wave directions between 90º and 180º are generated by offshore directed wind and of negligible height near Schiermonnikoog. For each class the representative morphological wave height (H_{mor}) is determined according to Formula 3-2 [Elias *et al.*, 2006].

$$H_{mor} = \left(\frac{1}{n} \sum_{i=1}^{i=n} H_{m0}(i)^k \right)^{\frac{1}{k}} \tag{3-2}$$

in which:

n	= Total number of observations	[-]
H_{mor}	= Wave height	[m]
k	= Power relation between transport and wave height a value of 2.5 is used as in CERC formulation	[-]

The proportionality power 2.5 is derived from the CERC-formula for wave induced sediment transport. By multiplying the morphological wave height with the probability of occurrence, the total morphological impact (MI) can be obtained. Table 3-2 shows the morphological impact for each of the individual wave-height and direction classes. The frequency of occurrences per class is related to a three hour period.

Table 3-2: Morphological impact (MI in %) of selected wave height and direction classes at Schiermonnikoog.

wave dir	**H_{m0}[m]**								**Total**	
	0-1		1-2		2-3		>3			
	Freq.	M1	Freq.	M1	Freq.	M1	Freq.	M1	Freq.	M1
0-45	222	4.0	75	3.0	14	1.0	0	0	311	8.0
45-90	181	3.3	60	2.5	2	0.1	0	0.1	243	6.0
180-225	33	0.6	5	0.2	0	0	0	0	38	0.8
225-270	172	3.5	116	4.5	6	0.4	0	0	294	8.4
270-315	425	8.8	428	18.0	156	7.1	1	5.6	1010	39.5
315-360	425	8.7	341	14.8	180	10.3	3	3.5	949	37.3
Total	1458	28.9%	1025	43.0%	358	18.9%	4	9.2%	2845	100%

Waves from the direction classes between west (270°) and north (360°) contribute near-equal to the morphological impact. Almost 50 % of the observations exceed the 1 m wave height, and these waves account for 71 % of the morphological impact. This conclusion is consistent with the conclusion found in Section 3.1, showing the non-linear relation between waves and sediment transport [De Vriend *et al.*, 2002]. At the Schiermonnikoog wave buoy the eastward component of the morphological impact exceeds the west-ward component, which results in a net south-eastward directed wave-driven transport. Combined with the northerly directed littoral drift along the North-Holland coastline [Van Rijn, 1997], the import of fine suspended sediment in the Wadden Sea is determined. The exchange of suspended sediment between the coupled system of the Wadden Sea and the North Sea is dependent on the hydrodynamic conditions.

4 Biological influences

This chapter discusses the biological activity in the Western Wadden Sea, which is based on different field measurements. The biomass bio-engineers shows both a spatial and a temporal variation. Section 3.1 describes the spatial variation in biological activity, while the temporal variation in biological activity is described in Section 3.2. The data, which will be used to evaluate the model results, are analysed in Section 3.3.

4.1 Spatial variation in biological activity

The spatial variation in biological activity is based on the immersion time, which is assumed to be proportional to depth, resulting in four depth zones, as discussed in Section 2.6. The biomass of the two destabilisers in the different depth zones are based on data gathered during a measurement campaign executed at Balgzand and Piet Scheveplaat in 1998 (for reference see Figure 2-11) [Dekker and De Bruin, 1999]. These data are assigned to the whole Western Wadden Sea.

Microphytobenthos is restricted to a waterdepth of 1 meter, due to the lack of light available for photosynthesis in deeper water. The biomass of microphytobenthos is calculated as a function of depth [Cadee and Hegeman, 2002].

The mean biomass destabilisers (*Hydrobia ulvae* and *Macoma balthica)* and stabilisers (microphytobenthos) is shown in Figure 4-1.

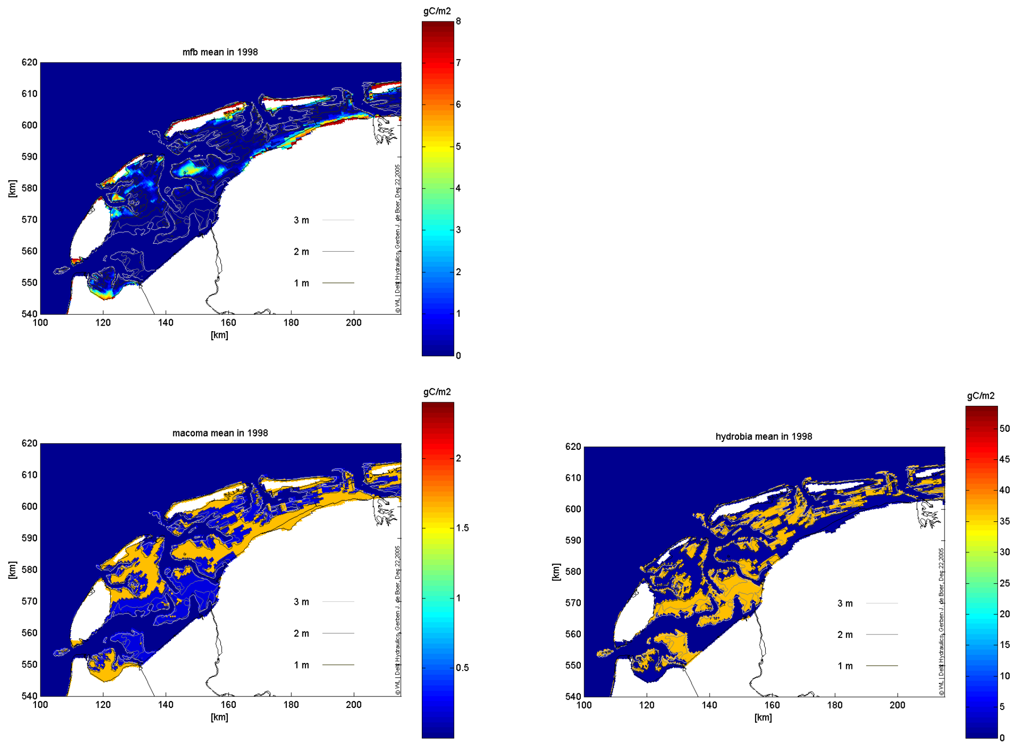


Figure 4-1: Mean biomass [gC m^{-2}] microphytobenthos (up), *Hydrobia ulvae* (left) and *Macoma balthica* (right).

The spatial variation in biological activity results in a change in the critical bed shear stress and erosion coefficient, based on the parameterisation presented in Section 2.6. The relative change in critical bed shear stress and erosion coefficient is shown in Figure 4-2, by applying Formula 4-1.

$$\tau_{rel} = \tau_{bio} / \tau_{phy}$$
$$M_{rel} = M_{bio} / M_{phy} \qquad (4\text{-}1)$$

in which:
rel = relative change
bio = biological activity
phy = physical; without biological activity

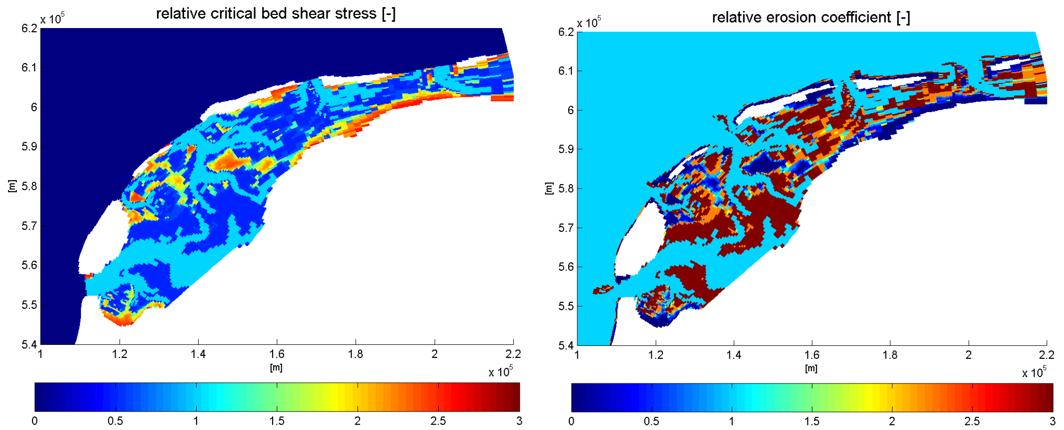


Figure 4-2: Relative change [-] in critical bed shear stress (left) and erosion coefficient (right).

Based on Figure 4-2, it can be concluded that the total destabilised area is much larger than the stabilised area. However, the relative change in critical bed shear stress and erosion coefficient is much larger for the stabilised areas.
In reality, the biological activity shows much more spatial variation than shown in Figure 4-1. This variation is discussed in Section 6.2.

4.2 Temporal variation in biological activity

The biological activity not only shows a variation in space but also in time. The temporal variation for biomass microphytobenthos and biomass grazers is shown in Figure 4-3. The temporal variation in biomass destabilisers is based on research executed by Wijsman [2004]. In the model, this variation is modelled with a harmonic function.
The temporal variation in chlorophyll-a content on the bottom is based on the monthly measured chlorophyll-a content in the water column (DONAR database). The corresponding biomass microphytobenthos also shows a seasonal variation, with the largest densities occurring in spring.

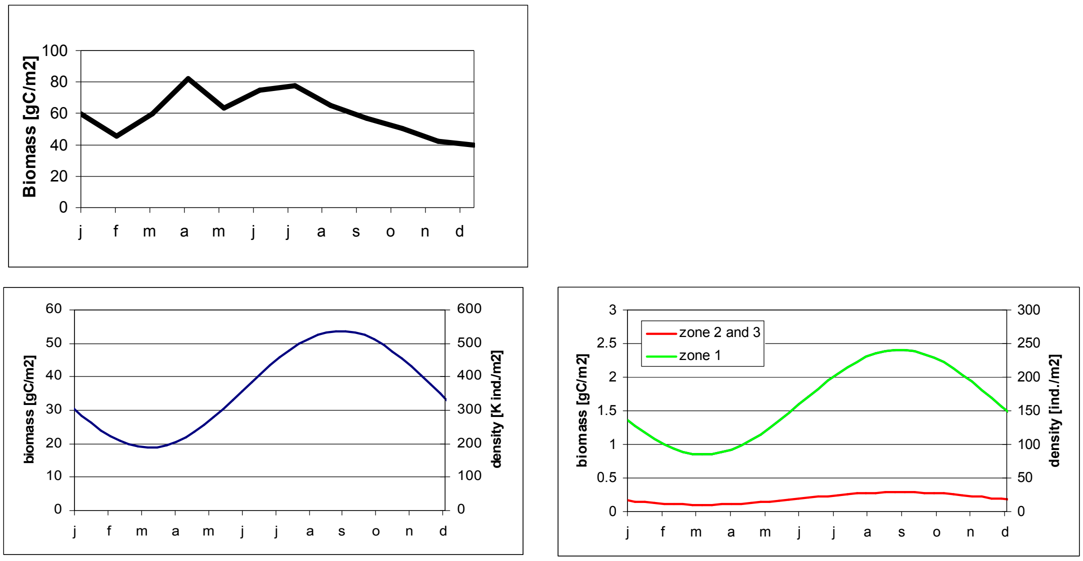


Figure 4-3: Seasonal variation in biomass [gC m^{-2}] microphytobenthos (up), and biomass [gC m^{-2}] and density [ind m^{-2}] for *Hydrobia ulvae* (left) and *Macoma balthica* (right).

Based on the temporal variation in both stabilisers (microphytobenthos) and de-stabilisers (*Hydrobia ulvae* and *Macoma balthica),* it can be concluded that during spring stabilising is dominant while during autumn de-stabilising is dominant in the Western Wadden Sea.
The temporal variation in biomass grazers and microphytobenthos results in a temporal variation in critical bed shear stress and erosion coefficient (Figure 4-4).

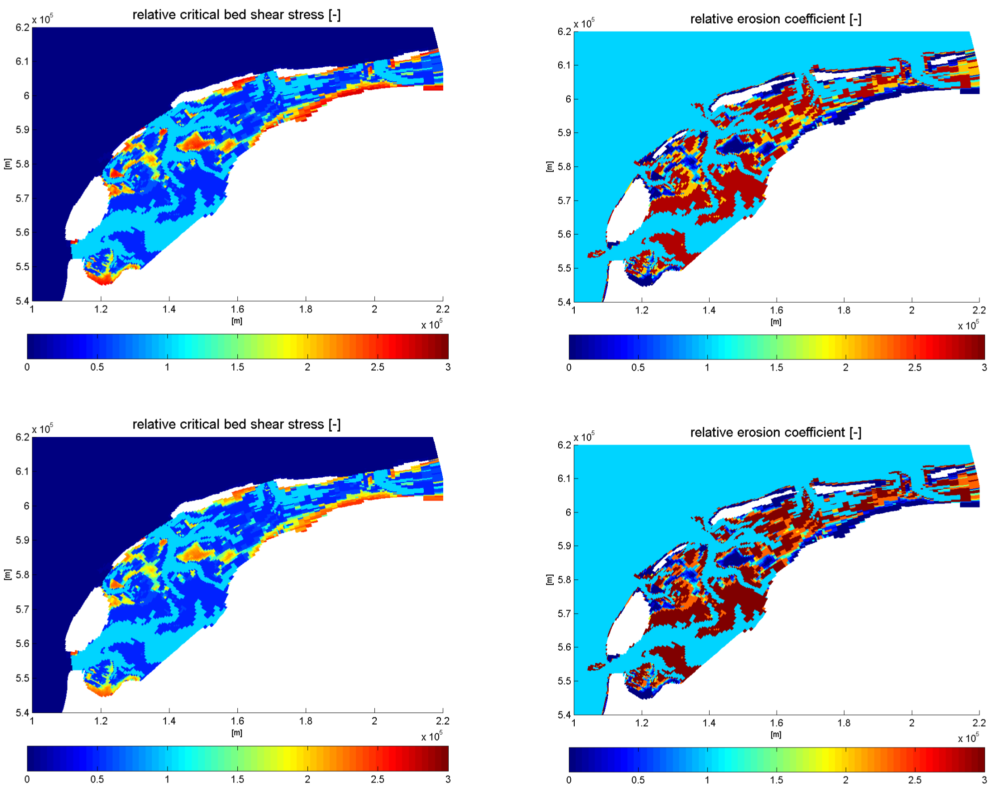


Figure 4-4: Relative change in critical bed shear stress (left) and erosion coefficient (right), during maximum stabilising (spring, top) and maximum destabilising (autumn, bottom).

On places where both *Macoma balthica* and *Hydrobia ulvae* (biomass varying between 22 and 55 gC m^{-2}) are present (depth zone 2 and 3), the critical shear stress and erosion coefficient show not a clear temporal variation (Figure 2-9 and 2-10). However, at places where only *Macoma balthica* is present (depth zone 1) also microphytobenthos is present, leading to a net stabilising effect throughout the year (see Figure 4-4). As a consequence, the seasonal variation in the critical bed shear stress and the erosion coefficient is mostly determined by the variation in the density of stabilisers.

4.3 Analysis of the evaluation data

As discussed in Section 2.7, two different databases are used for evaluating the model results; the Sedimentatlas and the DONAR database.
The fine sediment content in the Western Wadden Sea is presented in Figure 4-5, combined with the stabilised and destabilised areas. In the destabilised areas, the biological critical shear stress (τ_{bio}) is smaller than the physical critical shear stress (τ_{phy}), as defined in Formula 4-1.

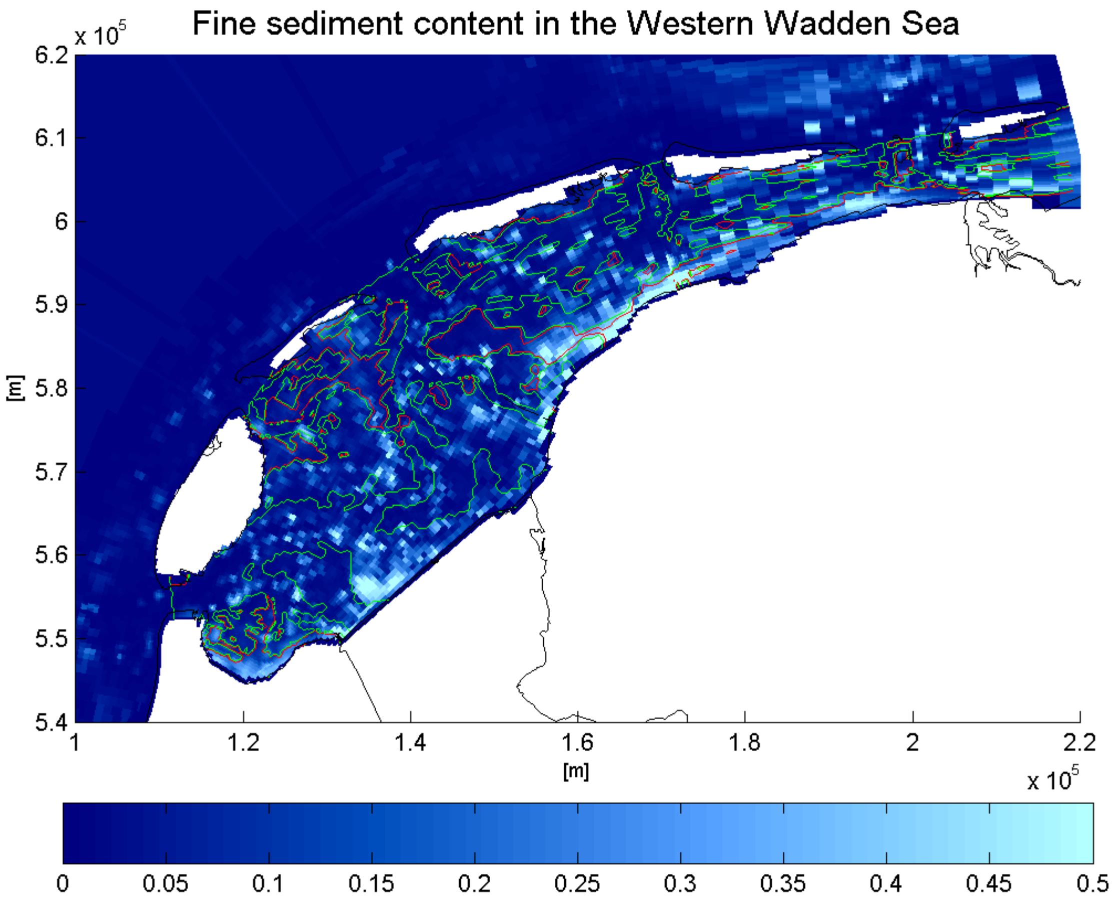


Figure 4-5: Fine sediment content in the Western Wadden Sea (blue map, based on the Sedimentatlas) combined with the areas of stabilising (red polygons; microphytobenthos) and destabilising (green polygons; *Hydrobia ulvae* and *Macoma balthica*).

Based on Figure 4-5, two interesting observations can be made. Firstly, in the stabilised areas, the fine sediment content in the top 10 centimetres of the bed is low except for the areas near the mainland. This observation will be discussed in Chapter 5.

Secondly, fine sediment on the bed seems to be concentrated just outside the destabilised areas (green polygons in Figure 4-5). By plotting the amount of fine sediment on the bed against the depth, this observation is examined (Figure 4-6).

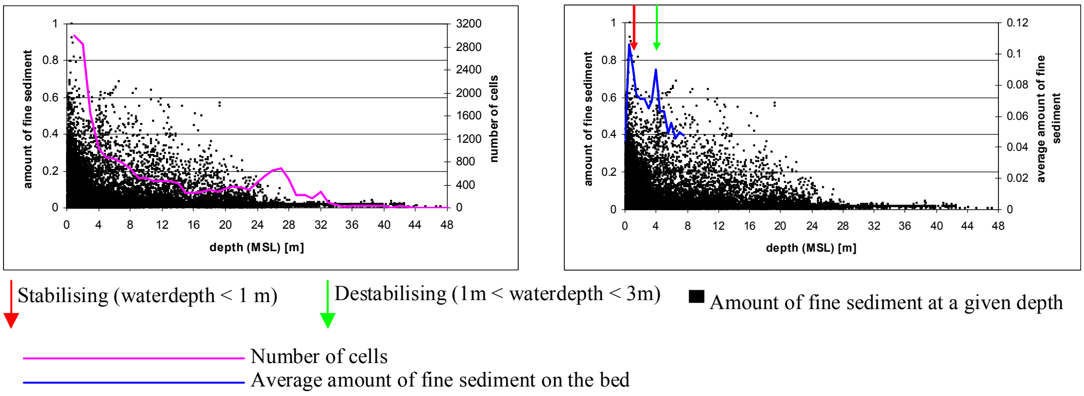


Figure 4-6: Relation between the amount of fine sediment and waterdepth (MSL) based on the Sedimentatlas, including the number of cells (left) and the average amount of fine sediment (right).

To construct Figure 4-6; right, the fine sediment content between 0 and 8 m waterdepth (MSL) are divided in 16 equal depth classes. Within these depth classes the average amount of fine sediment is calculated, using the number of cells in each depth class (Figure 4-6; left). Figure 4-6; right shows the biological influence on fine sediment content in the bed. In the destabilised areas, the amount of fine sediment on the bed is significant lower (on average 40%), compared to the stabilised area and the area just outside the destabilised area. Based on physical processes, the average amount of sediment decreases for increasing depth [Postma, 1981; Van Straaten and Kuenen, 1958]. This finding proves the influence of bio-destabilisers on the bed between a waterdepth of 2 and 4 meter (MSL).
The suspended sediment concentrations at the four measuring stations are shown in Figure 4-7.

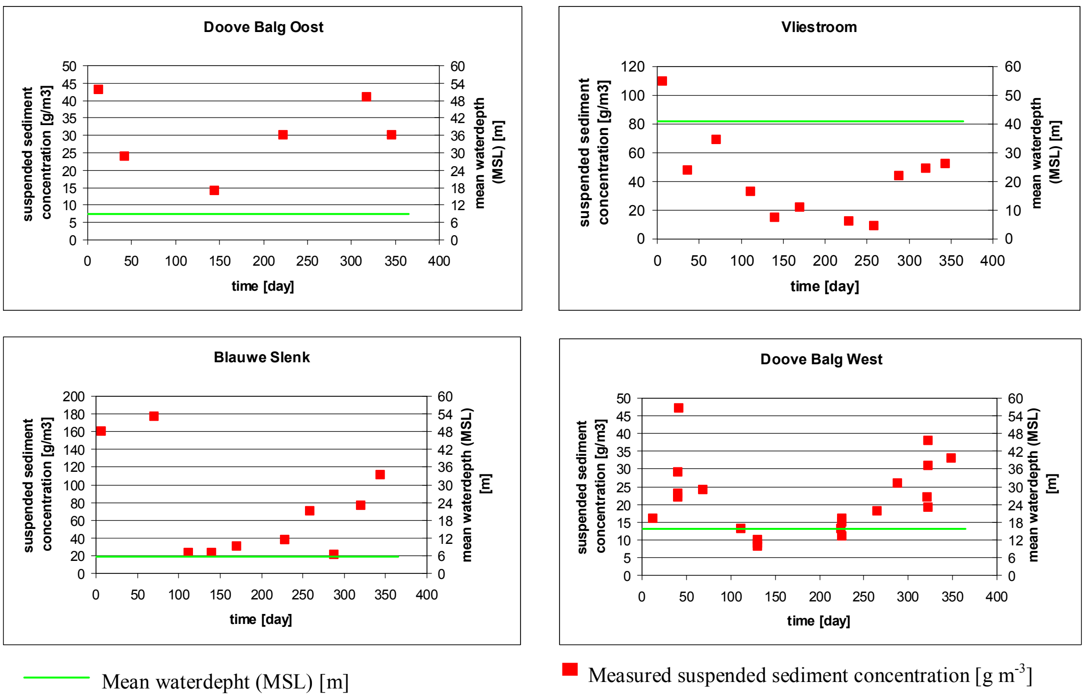


Figure 4-7: Overview of the measured suspended sediment concentration [g m^{-3}] from DONAR in 1998 at the four measuring stations, combined with the mean waterdepth [m] (MSL), for reference see Figure 2-11.

The seasonal pattern in the measured suspended sediment concentration is comparable at all the four measuring stations, showing a seasonal variation in the suspended sediment concentration. This pattern is also visible near Texel, based on weekly executed NIOZ measurements (Figure 4-9). Remarkable is the relative difference in the suspended sediment concentration, which is comparable for the five measuring locations, despite the difference in waterdepth. This seasonal pattern in suspended sediment is not simply caused by the seasonal variation in wind speed, as discussed in Section 3.1. The seasonal variation in the suspended sediment concentration is caused by complex scale interactions, in which biological processes have significant influence, as will be discussed in Section 6.5.

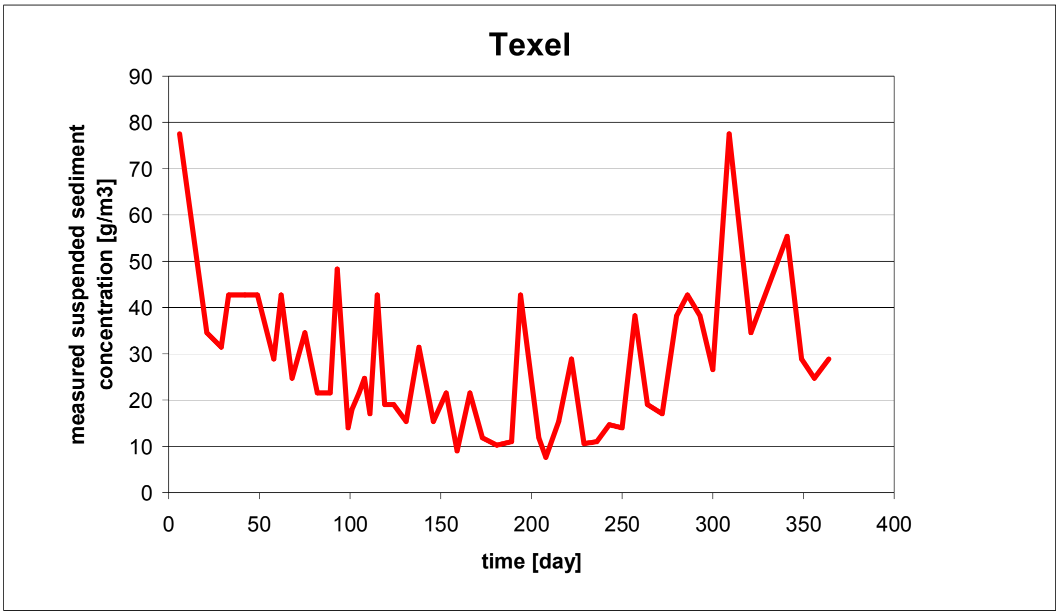


Figure 4-8: Overview of measured suspended sediment concentration [g m^{-3}] based on NIOZ measurements.

5 Model results

In the previous chapters, both the physical system and the biological influences are discussed. Furthermore, the model set up is described. This chapter discusses the results of the model, in which the biological influences are included in the physical system.
Section 5.2 discusses the results of the model in which the biological activity is varied spatial. The results of the temporal variation in biological activity are discussed in Section 5.3. The addition of a second bottom layer to the model is discussed in Section 5.4. In the sensitivity analysis (Section 5.5), the model sensitivity is tested against several parameters. The model results show interesting similarities with model results presented by Andersen *et al.* [2005], which are discussed in Section 5.6. Finally, the quantification of the agreement of the model results with the evaluation data (DONAR database and Sedimentatlas) is discussed in Section 5.7.

5.1 Introduction

Using the parameters presented in Section 2.4, the model is run for two years in which the first year is used for spinning up the model. The second year is used for evaluation. For both years, the hydrodynamic conditions for 1998 are used. At the start of the spin up year, the bottom is empty and the suspended sediment concentration in the water column is set at a uniform value of 5 g m^{-3}, as discussed in Section 2.3.
The simulation of the model is also executed for three and four years, in order to examine the influence of the initial conditions on the model results. The suspended sediment concentrations and the fine sediment distribution on the bed are hardly influenced by using a spin up time of two and three years, which justifies the use of a spin up time of one year.
In order to assess the effect of both the spatial and temporal variation in biological activity, three cases have been defined. These cases are listed in Table 5-1.

Table 5-1: Description of the different cases.

Case	Description	Analysis	Explanation
Case I	spatial variation in biological activity	Month	Section 4.1
Case II	spatial and temporal variation in biological activity	Year	Section 4.2
Case III	spatial and temporal variation in biological activity and 2^{nd} bottom layer	Year	Section 2.1

5.2 Case I: spatial variation in biological activity

By varying the biological activity spatial, the critical shear stress for resuspension and the resuspension flux changes at different locations. The influence of the biological activity on the suspended sediment concentration is shown for different locations in Figure 5-1.

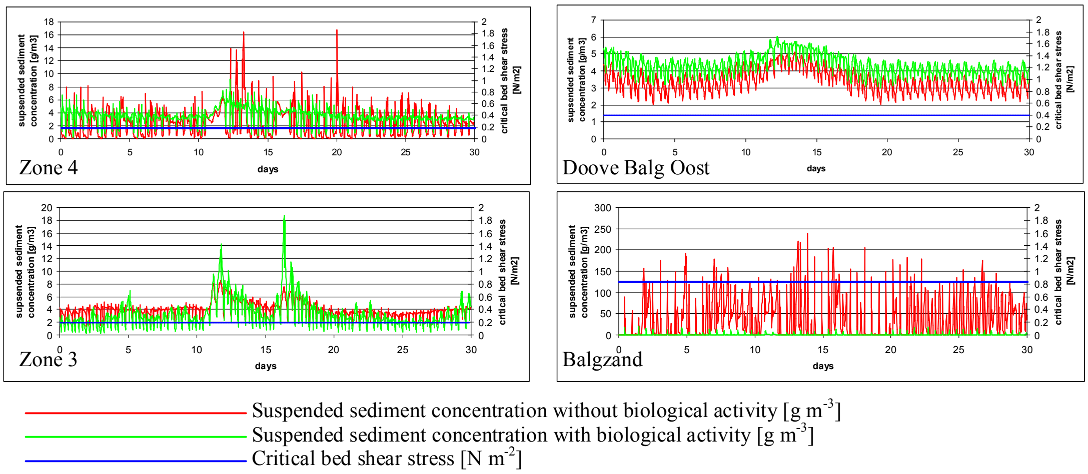


Figure 5-1: Overview of suspended sediment concentration [g m^{-3}] on different places during a summer month (June). The blue lines indicate the critical bed shear stress, >0.4 N m^{-2} stabilising, <0.4 N m^{-2} destabilising.

The concentration of suspended sediment is directly related to local instantaneous flow conditions [Wang and Ribberink, 1986]. As discussed in Chapter 3, the bottom shear stress in the channels is mainly influenced by the tide, while the bottom shear stress in the shallow areas is mainly influenced by the wind. Due to this difference, the suspended sediment concentration in the channel (Figure 5-1; Doove Balg) is much more regular than the suspended sediment concentration in the shallow areas (Figure 5-1; Zone 4).

The amount of fine sediment in the bed is different for the case with and without biological activity. This difference is caused by two mechanisms. First of all, due to the stabilising effect by microphytobenthos, the resuspension flux is much smaller at these locations, resulting in a larger amount of sediment in the bed with respect to the situation without biological influences. Secondly, due to the destabilising effect of biota, the amount of sediment in the bed is smaller at these locations. These observations are visible in Figure 5-2; left, based on Formula 5-1.

$$S_{b,w,rel} = S_{b,w,bio} / S_{b,w,phy} \qquad (5\text{-}1)$$

in which:

S_b = Amount of sediment in the bed [g m^{-2}]

S_w = Amount of sediment in the water column [g m^{-3}]

An increase in amount of sediment in the bed is observed at places where no biological activity is present. This increase is observed near the Afsluitdijk and the watersheds of the islands Terschelling and Ameland (Figure 5-2; left, red spots). The increase in sediment on the bed is in the first place caused by the deposition of the material eroded from the areas grazed by bio-destabilisers. In the second place, the sediment which normally deposits on the higher areas (i.e. shallower places) is now deposited on the deeper areas due to the lower critical bed shear stress for resuspension at these places (Figure 4-2).

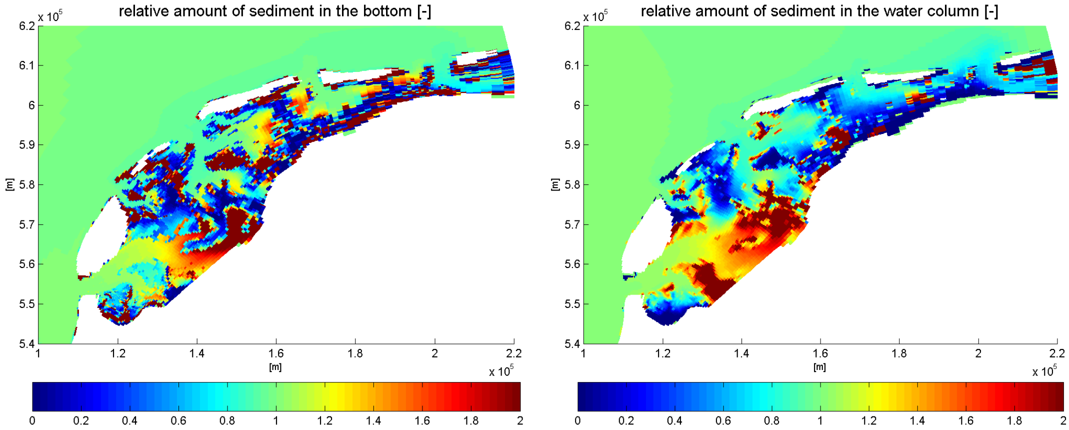


Figure 5-2: Relative amount of sediment in the bottom (left) and relative amount of sediment in the water column (right), during a storm condition (11-06-1998) >1 indicates increase in sediment in the bottom/water column due to biological activity.

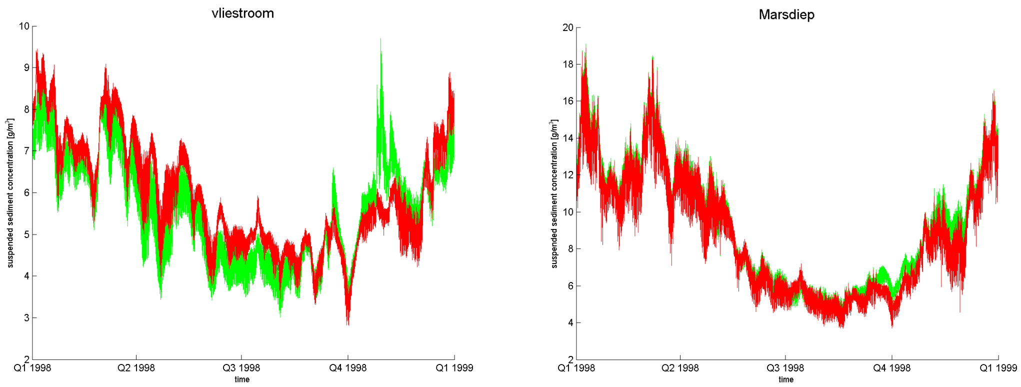
The suspended sediment concentration in the channels is increased (Figure 5-1; Doove Balg), and the suspended sediment concentration in a large part of the Western Wadden Sea is decreased (Figure 5-2; right). This decrease can be explained, due to the larger critical shear stress and lower erosion coefficient at places where microphytobenthos is present (Figure 5-1; Balgzand). However, microphytobenthos is only present in a small area (Figure 4-1). The decrease in the concentration of suspended sediment is caused by the decrease in amount of sediment in the bottom which decreases to zero at some places. This mechanism causes the lower suspended sediment concentrations at places where grazers are present; in the east part of the Western Wadden Sea. At places where the suspended sediment concentrations increases (south west part of the Western Wadden Sea), sufficient fine sediment is available for erosion (Appendix H).

It can be concluded that spatial varying biological activity causes a change in distribution of sediment with lower values of sediment on the bed at places where bio-destabilising is present and higher value where bio-stabilising is present. Moreover, an increase of sediment on the bed is observed at places where no biological activity is present, just outside the destabilised areas. The suspended sediment concentrations are highly dependent on the available amount of sediment on the bottom.

5.3 Case II: spatial and temporal variation in biological activity

By applying both spatial and temporal variation in biological activity, a seasonal analysis is enabled in the biological influence on sediment transport and bed composition. This analysis is executed in both the different tidal inlets and the different tidal channels, leading to a classification of the different tidal basins.

The suspended sediment concentration for two tidal inlets is shown in Figure 5-3. Vliestroom is the tidal inlet between the islands Vlieland and Terschelling, Marsdiep is the tidal inlet between the mainland and the island Texel.



Suspended sediment concentration without biological activity [g m^{-3}]
Suspended sediment concentration with spatial and temporal biological activity [g m^{-3}]

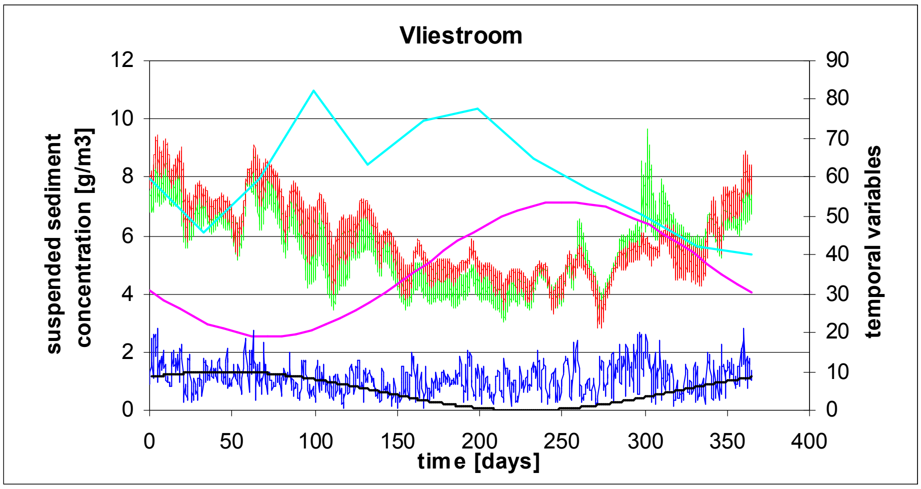
Figure 5-3: Suspended sediment concentrations [g m^{-3}] during one year in two tidal inlets.

At both inlets, a seasonal variation in suspended sediment concentrations is visible. The tidal basin connected to the Vliestroom tidal inlet is much more influenced by biological activity, compared to the tidal basin connected to the Marsdiep tidal inlet (Figure 4-4).

It can also be concluded, that most of the time the stabilising effect of microphytobenthos is dominant. Only during autumn, the decrease in biomass microphytobenthos causes an increase in suspended sediment concentrations in both the Marsdiep and Vliestroom tidal inlet. The comparison with other tidal inlets and the difference between spatial varying biological activity is described in Appendix I.

Figure 5-4 shows the plot of Figure 5-3; left, combined with the different temporal variables.

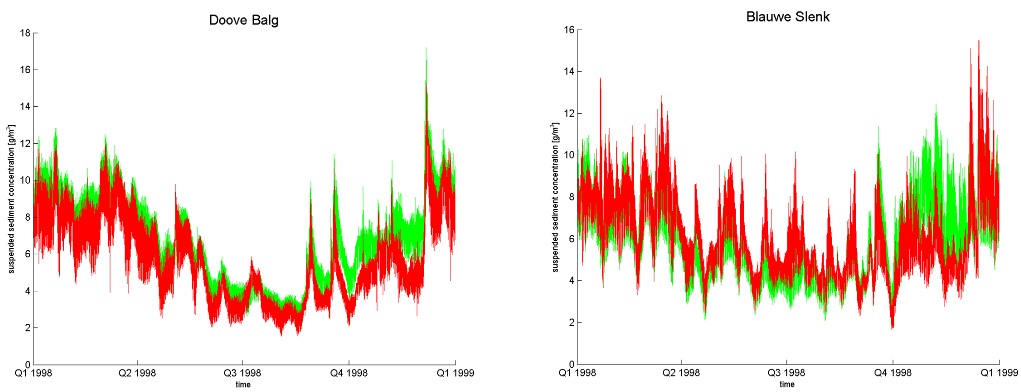
It can be concluded that all temporal variables influence the suspended sediment concentration to some degree. First of all, the yearly variation in the suspended sediment concentration is caused by the yearly variation in the boundary suspended sediment concentration. Secondly, on a small temporal scale, the wind speed influences the suspended sediment concentration, leading to an increase in suspended sediment concentration during storms. Finally, the variation in biological activity causes a difference compared to the situation without biological activity, as discussed before.



Suspended sediment concentration without biological activity [g m^{-3}]
Suspended sediment concentration with spatial and temporal biological activity [g m^{-3}]
Wind speed [m s^{-1}]
Biomass *Hydrobia ulvae* [gC m^{-2}]
Suspended sediment concentration at the boundary, 2 km off the coast [0.1g m^{-3}]
Maximum biomass microphytobenthos [gC m^{-2}]

Figure 5-4: Comparison between the suspended sediment concentration in the Vliestroom tidal inlet and the different temporal variables (on the second y-axis).

The suspended sediment concentrations in the corresponding tidal channels are shown in Figure 5-4. The channel Doove Balg is connected to the Marsdiep and the channel Blauwe Slenk is connected to the Vliestroom. The variation in suspended sediment is smaller compared to the variation in suspend sediment in the tidal inlets, showing the smaller influence of the variation in suspended sediment on the North Sea. On the other hand, the influence of wind is much more visible on a small temporal scale (Figure 5-6). Finally, the biological influence on the suspended sediment concentration is also visible in the channels, showing the largest influence during autumn. Interesting is the relation between different temporal variables and the suspended sediment concentration. The largest difference between the suspended sediment concentrations between the two situations (with and without biological influences) is in particular caused by a decrease in biomass stabilisers in combination with a high biomass grazers and a rough weather period, about day 300 (November).



Suspended sediment concentration without biological activity [g m^{-3}]
Suspended sediment concentration with spatial and temporal biological activity [g m^{-3}]

Figure 5-5: Suspended sediment concentrations during one year in two channels.

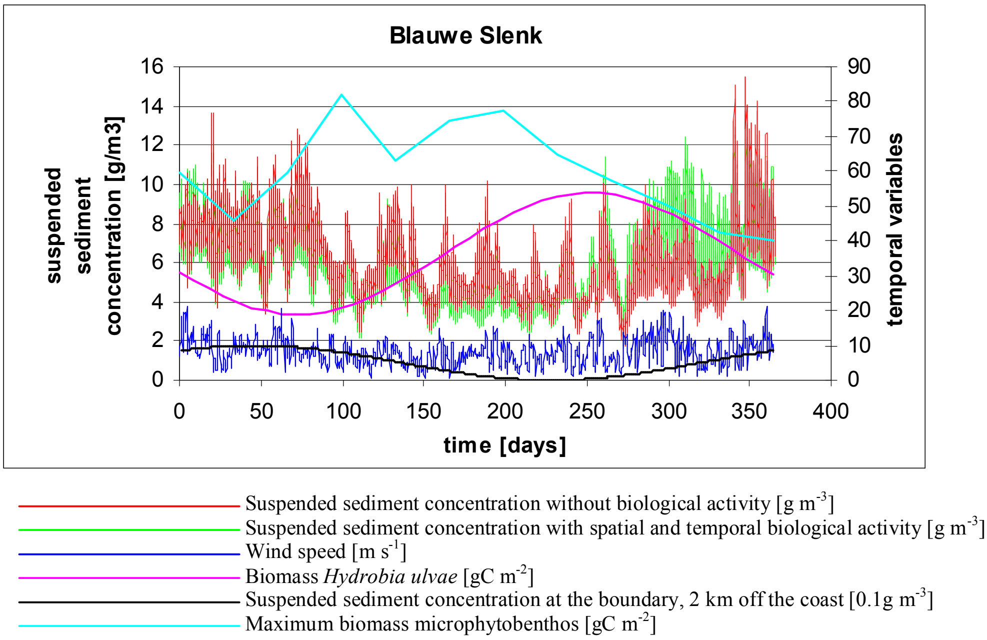


Figure 5-6: Comparison between the suspended sediment concentration in the Blauwe Slenk channel and the different temporal variables.

Based on the difference in suspended sediment concentration between the situation with and without biological influences, each tidal basin can be classified. This classification is shown in Table 5-2, based on Formula 5-2 (as example given for the first 3 months). The corresponding tidal basins are shown in Figure 5-7.

$$\text{Influence} = \left(\frac{\frac{1}{90}\left(\sum_{n=1}^{90} c_{no\,bio} - \sum_{n=1}^{90} c_{bio} \right)}{\frac{1}{90}\sum_{n=1}^{90} c_{no\,bio}} \right) * 100\% \qquad (5\text{-}2)$$

in which:

$c_{no\,bio}$ = Suspended sediment concentration without biological influence [g m^{-3}]

c_{bio} = Suspended sediment concentration with biological influence [g m^{-3}]

The comparison of the suspended sediment concentrations in each tidal basin is executed in the tidal inlets, showing the large influence of biological activity on the suspended sediment concentration. Stabilising is indicated in red, while destabilising is indicated in green. Due to the relative large waterdepth, the suspended sediment concentration in the Marsdiep tidal inlet is only limited influenced by the biological activity. Conversely, the Vlie tidal basin is relatively shallow, resulting in a relative large biomass microphytobenthos which leads to stabilising. To demonstrate the biological influences, the depth zones are shown in Figure 5-8. Stabilising is restricted to depth zone 1 (waterdepth <1 m), whereas destabilising occurs at depth zone 1, 2 and 3 (waterdepth <3 m). Based on Table 5-2, it can be concluded that the biological influences act on an estuarine scale. Although the suspended sediment concentrations in all tidal basins are influence by biological activity, no general pattern is observed in the difference in suspended sediment concentrations. The difference in the suspended sediment concentration is the outcome of the scale interaction between biological and physical process, which will be discussed in Section 6.5.

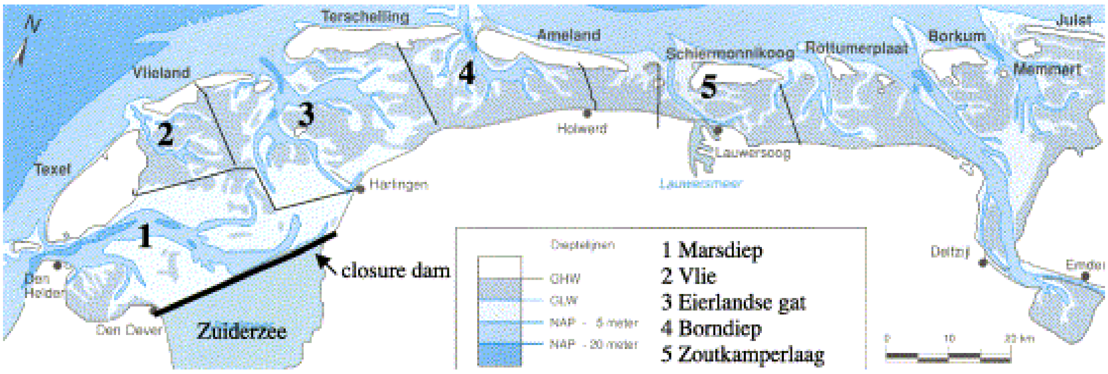


Figure 5-7: Overview tidal basins Western Wadden Sea with approximate tidal divides [Kragtwijk *et al.*, 2004].

Table 5-2: Predominantly type of biological influence in the different tidal basins, based on the suspended sediment concentration in the tidal inlets, separated in 3 month periods. Green cells indicate destabilising. Red cells indicate stabilising. For comparison, the average waterdepth (MSL) is included.

Name of tidal basin	Q1	Q2	Q3	Q4	Waterdepth [m]
Marsdiep	+2.5	+2.5	+4.4	+7.4	5.4
Vlie	-9.0	-16	-6.8	-1.1	2.4
Eierlandse gat	-8.2	-12	-6.5	+5.4	3.5
Borndiep	-23	-9.8	-24	-25	2.8
Zoutkamperlaag	-34	-18	-28	-40	3.0

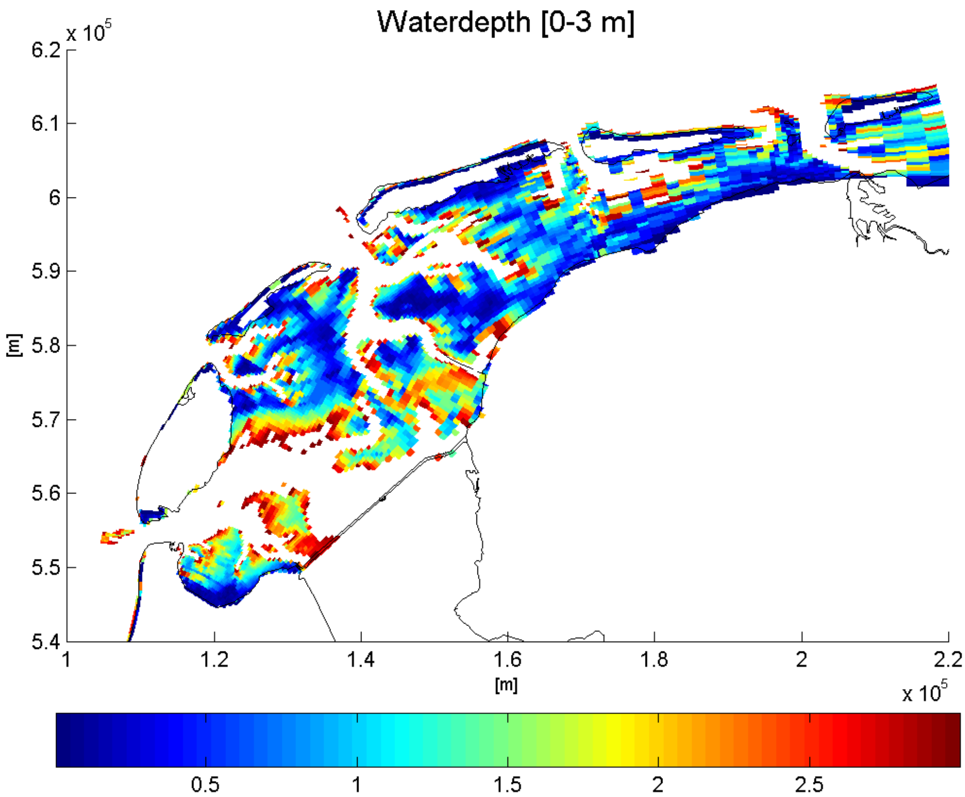


Figure 5-8: Overview of waterdepth [0-3 m]. Stabilising is restricted to 1 m, destabilising is restricted to 3 m.

5.4 Case III: biological influences combined with second bottom layer

Although the biological influence on suspended sediment concentration is demonstrated in the previous cases, the calculated suspended sediment concentrations do not correspondent to the measured concentrations from the DONAR-database. The concentrations measured in the Wadden Sea are much larger and much more variable (as illustrated for the Vliestroom in Figure 5-9, notice the secondary y-axis).

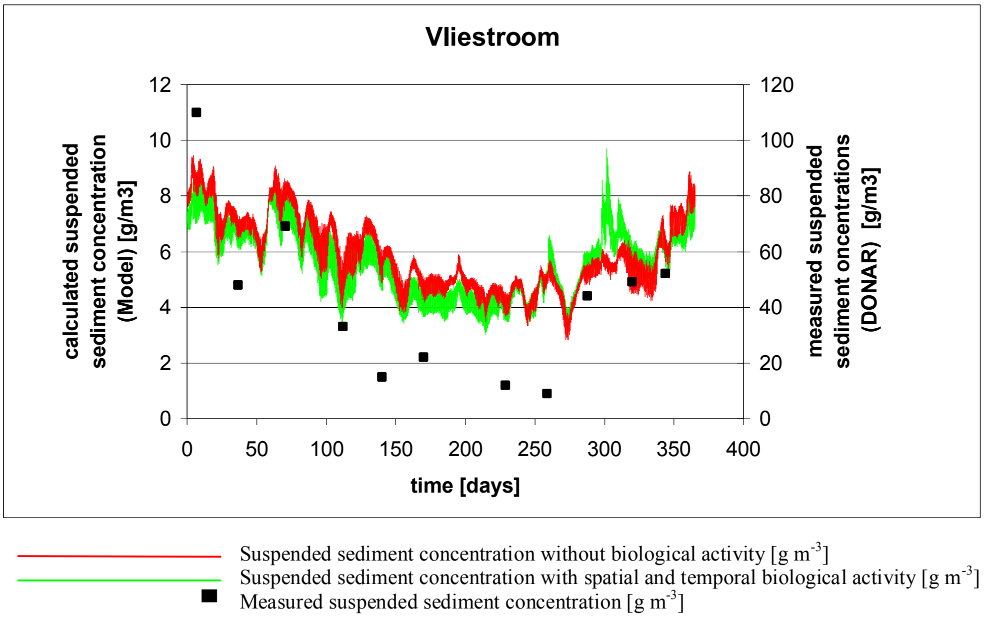


Figure 5-9: Comparison between the calculated suspended sediment concentrations and the measured suspended sediment concentrations [g m^{-3}] (DONAR).

By extending the model with a second bottom layer, the calculated suspended sediment concentrations are tried to agree better with reality. The concept of the second bottom layer is explained in Paragraph 2.1.2.

The results of the extended model are shown in Figure 5-10, in which the measured and the calculated suspended sediment concentrations are compared.

Based on Figure 5-10, it can be concluded that the calculated suspended sediment concentrations show good agreement with the measured suspended sediment concentrations. However, the measured suspended sediment concentrations in the Eierlandse gat (Vliestroom and Blauwe Slenk) are much more variable compared to the calculated suspended sediment concentrations.

The small temporal variation in the calculated suspended sediment concentration must be attributed to insufficient sediment fluxes between the water column and the bed. Vertical fluxes may be enhanced by lowering of the critical shear stress for resuspension or by varying the biological forcing functions. The sensitivity in the model results for the change in the critical shear stress for resuspension and biological forcing functions will be discussed in Section 5.5.

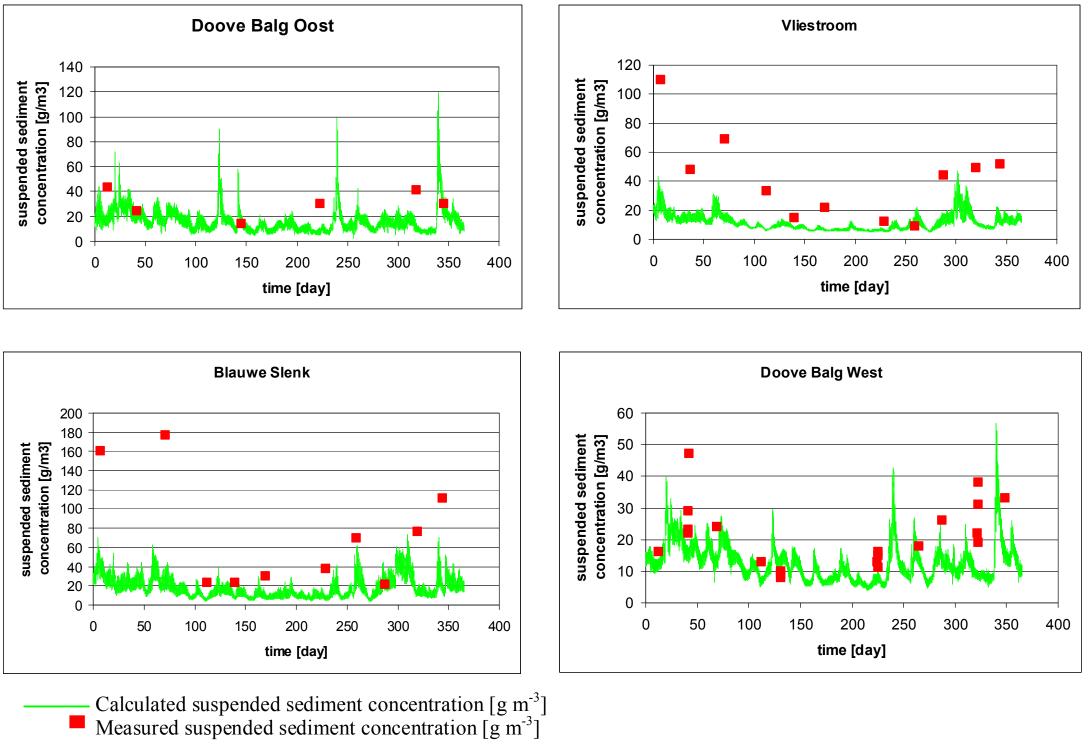


Figure 5-10: Comparison between measured and calculated suspended sediment concentrations at different locations in the Western Wadden Sea.

By comparing the calculated sediment distribution on the bed with the sediment distribution on the bed provided by the Sedimentatlas, the biological influence on bed composition can be analysed. This comparison is executed in Figure 5-11, in which the situation without (top) and with (under) biological activity is distinguished.

The fine sediment distribution in the bed is in reality much more scattered, compared to the model results. This observation will be discussed in Section 5.7. Moreover, the locations stabilised by microphytobenthos show an overestimation in the fine sediment content in the bed (see Figure 4-1). By varying the biological forcing functions (Section 5.5), the fine sediment distribution on the bed is tried to agree better with reality.

By applying a second bottom layer in the model, the suspended sediment concentrations are higher and show more variation. The suspended sediment concentration is highly dependent on the availability of fine sediment on the bed, as concluded in Case I. By applying a second bottom layer, sediment is buffered in the second bottom layer during calm weather. As a result, during storms, the availability of fine sediment is much larger, resulting in higher suspended sediment concentrations and more variation in the suspended sediment concentrations.

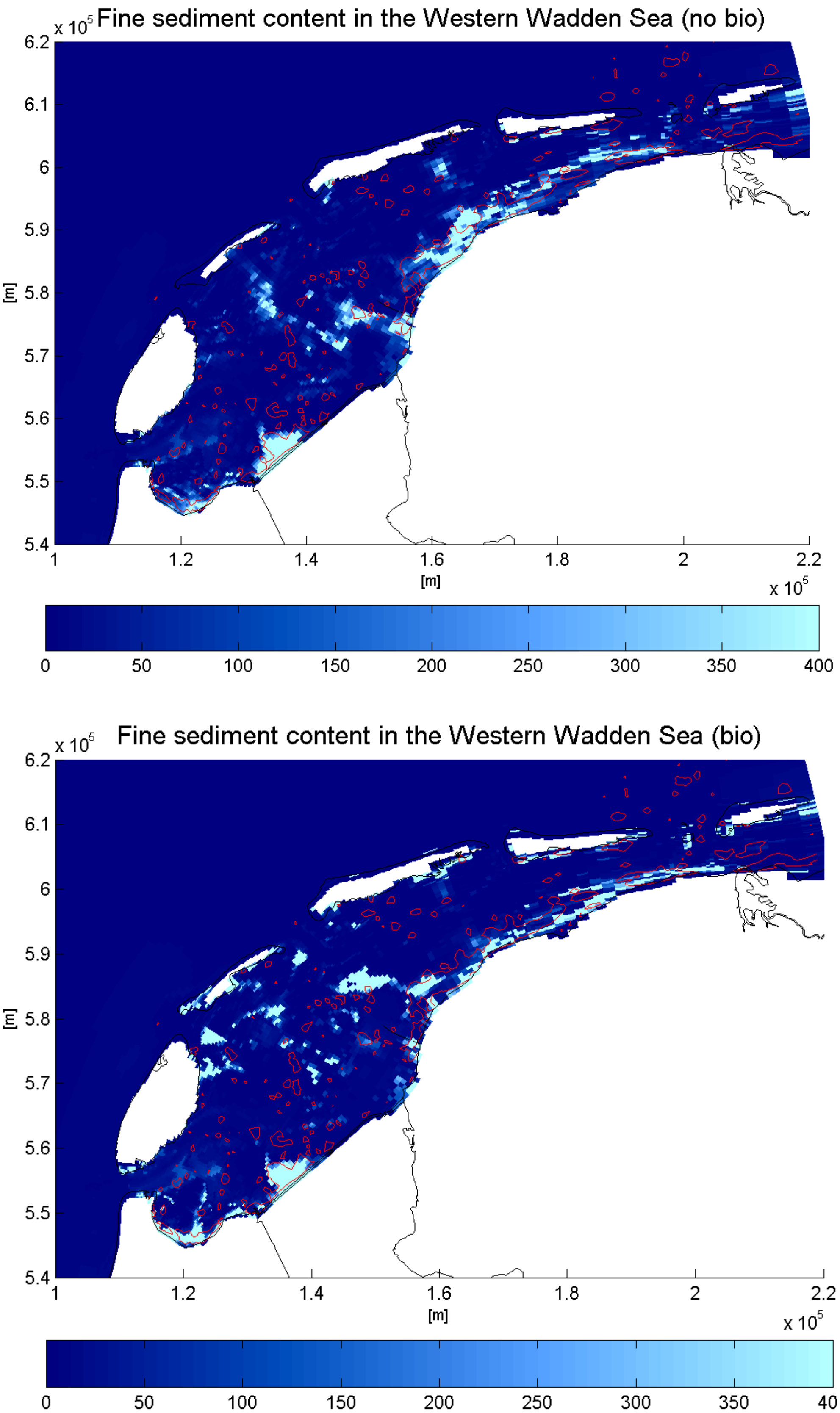


Figure 5-11: Comparison between the calculated amount of fine sediment in the bed (blue map) and the measured amount of fine sediment (red polygons), for the situation without (top) and with biological activity (under).

5.5 Sensitivity analysis

As concluded in the previous sections, the stabilising effect by microphytobenthos is overestimated (see e.g. Figure 5-11). By varying the physical critical shear stress for resuspension and the biological forcing functions, the sensitivity in the biological forcing on the suspended sediment concentration and sediment distribution is investigated. The outcome of the sensitivity analysis is a distinction in the influence of the bio-stabilisers and bio-destabilisers on the suspended sediment concentrations and the fine sediment distribution in the bed.

Firstly, the physical critical shear stress for resuspension is varied. This parameter is only varied for the top ten centimetres of the bed, following the recommendation given by Van Kessel [2004], in order to prevent excessive resuspension from the bed. The influence of the varied physical critical shear stress on the bed composition and thickness of the top layer (layer S1) is presented in Figure 5-12.

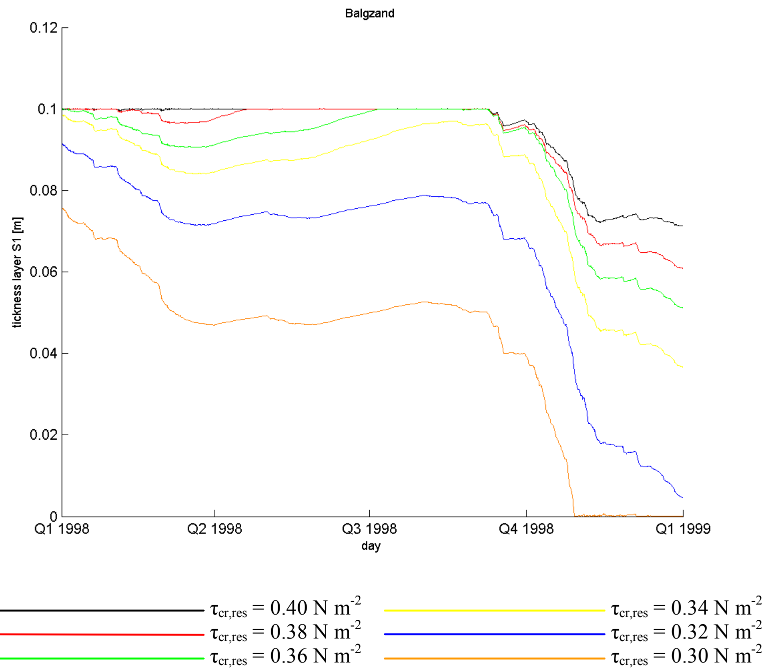


Figure 5-12: Sensitivity analysis physical critical shear stress top layer; thickness top layer. For reference see Figure 2-11.

The thickness of the top layer is to a large extent dependent on the physical critical shear stress. The thickness of the layer is plotted for Balgzand (Figure 5-12), in which the bottom is dominantly stabilised by microphytobenthos. The temporal variation in biomass microphytobenthos is also visible in Figure 5-12; the thickness of the top layer increases during high biomass microphytobenthos and decreases during low biomass microphytobenthos (for reference see Figure 4-3).

The fine sediment distribution on the bed is hardly changed with respect to the reference situation (Figure 5-13), leading to the conclusion that the biological processes are responsible for the overestimation in fine sediment content in the bed at some places.

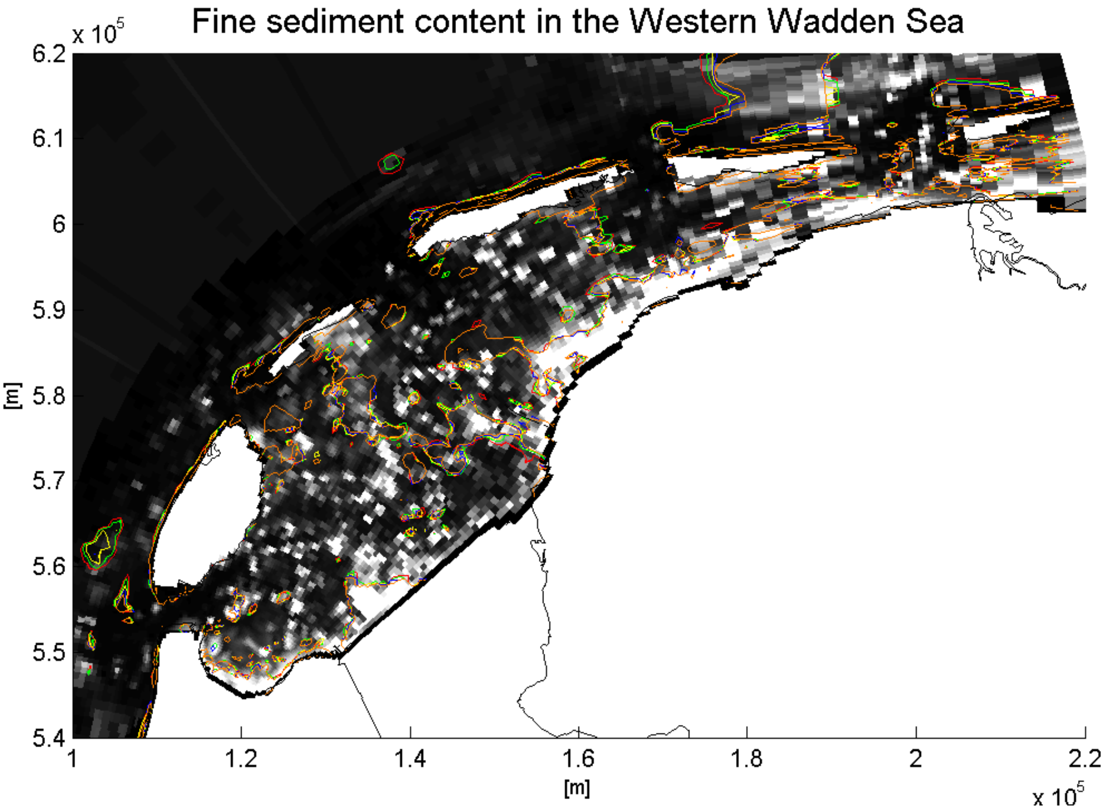


Figure 5-13: Sensitivity analysis physical critical shear stress top layer; distribution of fine sediment. Colours are related to Figure 5-12.

Based on Figure 5-12, it can be concluded, that the fine sediment dynamics are not in equilibrium at Balgzand; showing a constant decrease in the thickness of the top layer. The amount of sediment in the bed is not decreasing in the entire Western Wadden Sea, which is visualised in Figure 5-14, based on Formula 5-3.

$$S_{rel} = \frac{S_{end} - S_{start}}{S_{start}} \qquad (5\text{-}3)$$

in which:

S_{rel} = *relative difference in amount of sediment in the bottom*

S_{end} = *amount of sediment in the bottom at the end of the second year (31-12-1998)*

S_{start} = *amount of sediment in the bottom at the start of the second year (01-01-1998)*

Figure 5-14 shows the highly spatial variation in sediment dynamics for the Western Wadden Sea. The increase in amount of sediment in the bed at some places is partly caused by the settling and scour lag processes, which are discussed in Appendix J. Moreover, the transport of fine sediment in the Wadden Sea is caused by biological processes, as will be discussed in Section 6.5, following the conceptual model of Andersen *et al.* [2005].

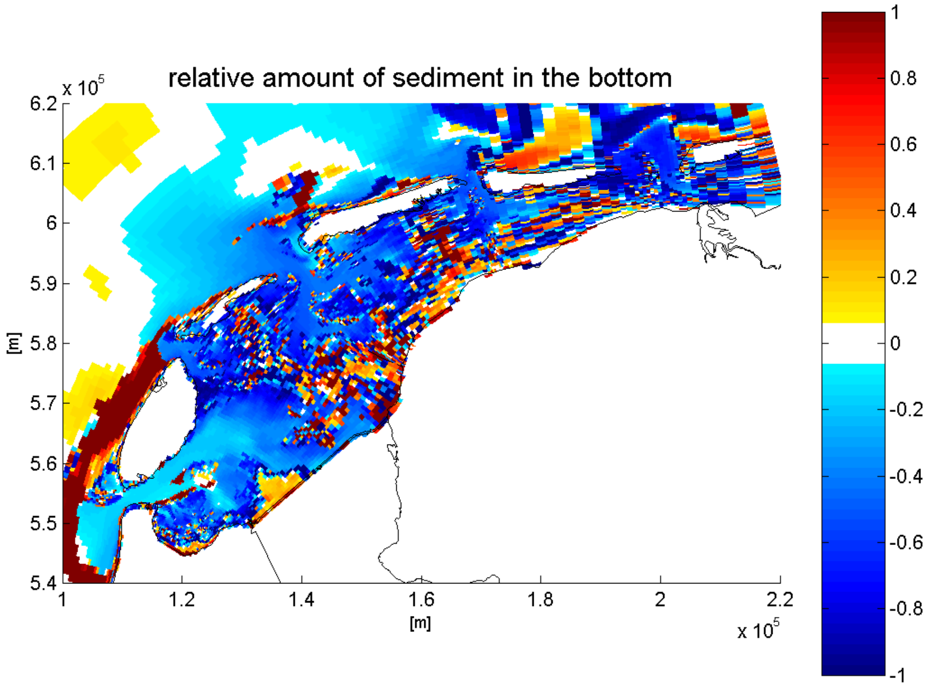


Figure 5-14: Relative amount of sediment in the bottom. >1 indicates an increase in amount of sediment in the bottom.

Secondly, the destabilising biological forcing functions are varied. By applying the destabilising functions proposed by Paarlberg *et al.* [2005] (as shown in section 2.6; Figure 2-9; 2-10), the distribution of fine sediment on the bed is hardly influenced. However, looking at the relative difference in fine sediment distribution (Figure 5-15), the influence of bio-destabilising on the sediment distribution is visible.

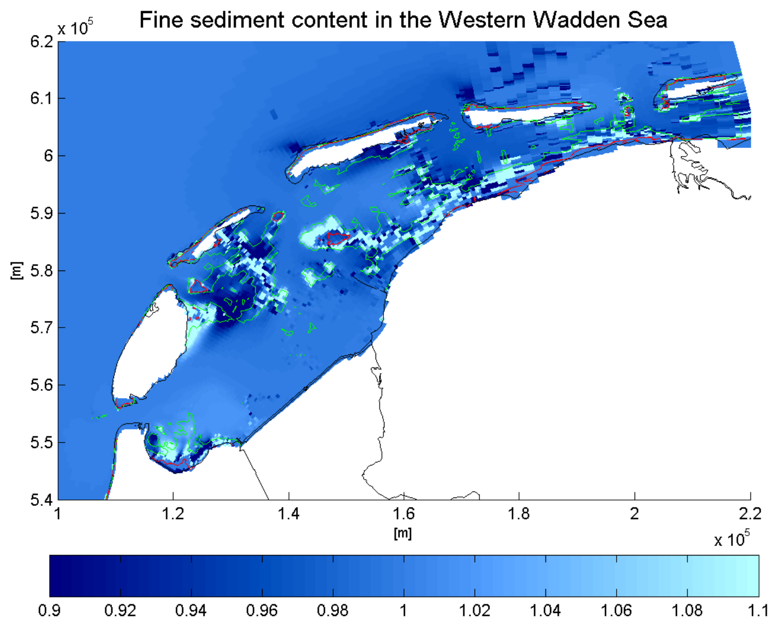


Figure 5-15: Sensitivity analysis destabilising biological forcing functions; relative difference in distribution of fine sediment, >1 decrease in fine sediment on the bed. Stabilised areas by microphytobenthos (red polygons) and destabilised areas by *Macoma balthica* (green polygons).

At places where *Macoma balthica* is present (mainly depth zone 1), the fine sediment content is decreased, showing the relative larger influence on sediment distribution by small biomass using the relations proposed by Paarlberg *et al.* [2005]. However, by varying the destabilising biological forcing functions, the fine sediment distribution is hardly influenced in the stabilised areas (red polygons).
Thirdly, the stabilising biological forcing functions are varied, as shown in Figure 5-16.

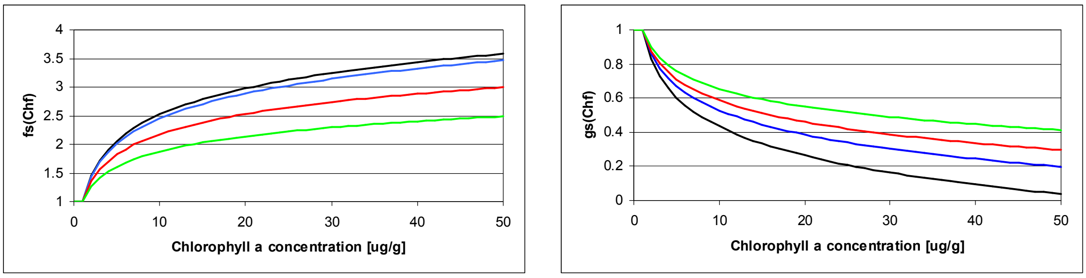


Figure 5-16: Sensitivity analysis stabilising biological forcing functions. Left: the effect of *chlorophyll-a* concentaration [μg g^{-1}] on the stabilisation factor (f_s(Nzb)) for the critical shear stress. Right: the effect *chlorophyll-a* concentration [μg g^{-1}] on the stabilisation factor (g_s(Nzb)) for the erosion coefficient.

The black line in Figure 5-16 indicates the reference situation (Case III), whereas the coloured lines show the decreasing influence of microphytobenthos on the critical shear stress and erosion coefficient. The influence of the varied stabilising biological forcing functions on the sediment distribution is shown in Figure 5-17. A decrease in fine sediment content in the bed is related to a decrease in influence of the microphytobenthos on the critical shear stress and erosion coefficient, through which can concluded that the overestimation of fine sediment in the bed is caused by an overestimation of the biomass microphytobenthos. The suspended sediment concentration is mainly influenced at the Vliestroom and Blauwe Slenk observation points (Figure 5-18). At the other observation points, the surrounding areas are mainly influenced by bio-destabilisers, resulting in hardly a difference between the suspended sediment concentrations by varying the stabilising biological forcing functions. However, the suspended sediment concentrations show more variation, which is in agreement with reality.

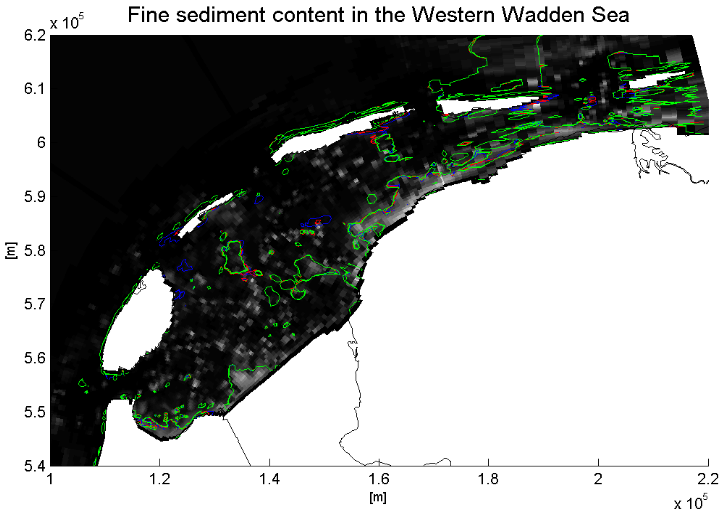


Figure 5-17: Sensitivity analysis stabilising biological forcing functions. Distribution of fine sediment in the Western Wadden Sea. The colours are related to Figure 5-16. Gray map shows the measured fine sediment content (Sedimentatlas).

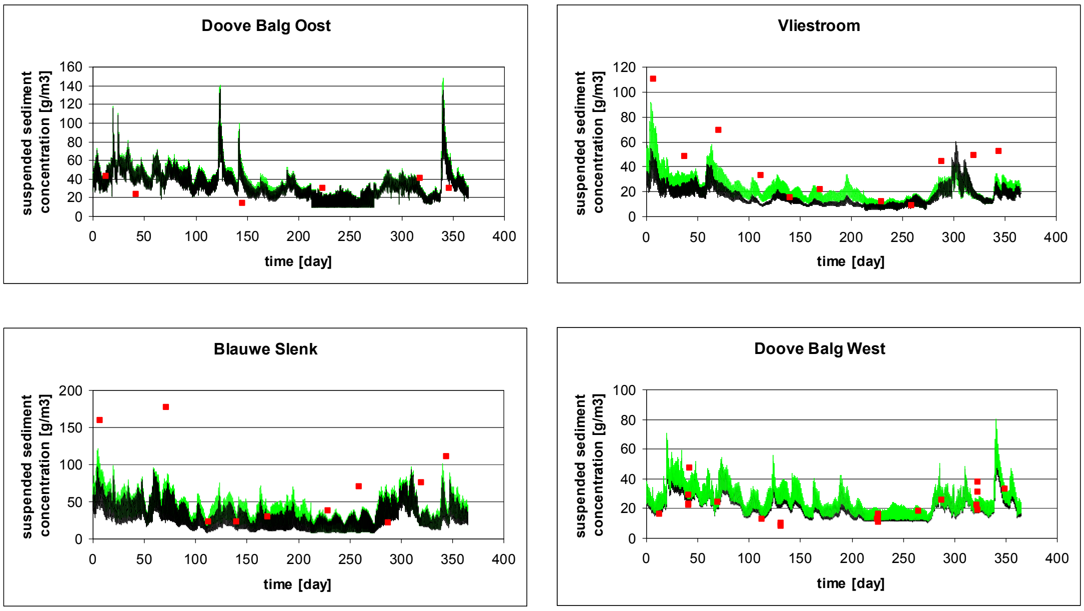


Figure 5-18: Sensitivity analysis stabilising biological forcing functions. Comparison between measured and calculated suspended sediment concentrations at different locations in the Western Wadden Sea. The colours are related to Figure 5-16.

A further decrease in the influence of microphytobenthos on the critical shear stress and erosion coefficient (Figure 5-16) will result in generally lower suspended sediment concentrations, combined with less variation in suspended sediment concentrations and finally in a shortage in availability of fine sediment to resuspend in the destabilised areas.

As a result of the variation in the stabilising biological forcing function, the green line in Figure 5-18 will be used to evaluate the model results, and this case will be called optimised bio-stabilisation.

Based on the result of the sensitivity analysis, it can be concluded that bio-stabilisers mostly influence the suspended sediment concentrations while the bio-destabilisers mostly influence the fine sediment distribution in the bed. This difference is partly caused by the much larger destabilised areas compared to the stabilised areas in the Western Wadden Sea and the much larger influence for the stabilised area on the critical bed shear stress and the erosion coefficient. These differences are shown in Table 5-3. The maximum influence on the critical shear stress is indicated with the parameter $f(\tau_{cr})$, while the maximum influence on the erosion coefficient is indicated with the parameter $g(M_{res})$. The average destabilised and stabilised areas are given. In April (maximum bio-stabilisation), the bio-stabilised area is 11% larger (439 km^2), compared to the situation in September (395 km^2; maximum bio-destabilisation). Channels are defined as a waterdepth larger than 3 m (MSL).

Table 5-3: Overview of the differences between bio-stabilised and bio-destabilised areas.

	Area [km^2]	**% of total area**	**$f(\tau_{cr})$ [-]**	**$g(M_{res})$ [-]**
Bio-stabilised	417	19	0.4	2.5
Bio-destabilised	1130	52	3.1	0.1
Channels	616	29	1	1

5.6 Comparison between model results and previous research

Many authors attribute the seasonal variation in suspended sediment concentration and bed composition in the Wadden Sea to the combined effect of wind and biology [e.g. Andersen *et al.*, 2005; Lumborg and Pejrup, 2005; Paterson and Black, 1998; Lumborg *et al.*, 2006; Austen *et al.,* 1998]. Following the conceptual model of Andersen *et al.* [2005] this hypothesis can be visualised, as shown in Figure 5-19.

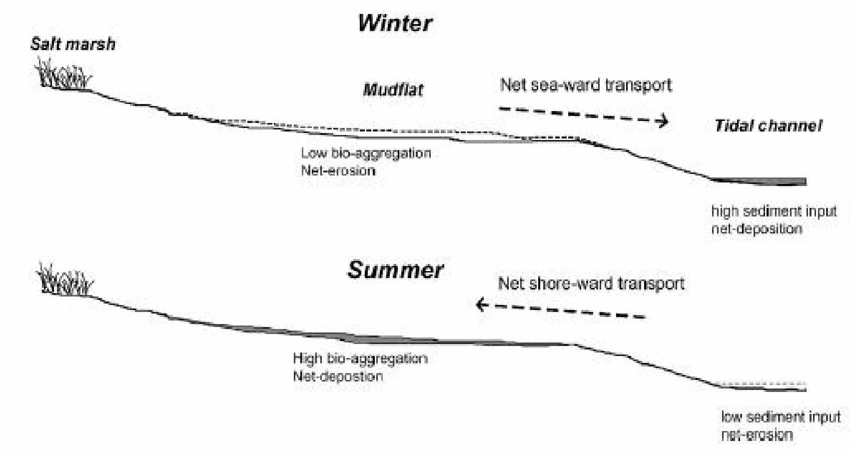


Figure 5-19: Conceptual model showing the general net-transport direction of fine sediment during winter and summer [Andersen *et al.,* 2005].

The conceptual model is based on measurements at the Koningsmark mudflat in the Danish Wadden Sea. This conceptual model does not only apply to this specific area, but is of a more general nature. Seasonal variations of the bed level were also found by Frostick and McCave [1979] for the Deben estuary and Widdows and Brinsley [2000] for the Humber estuary. Both estuaries are located in the United Kingdom.
The results of the model also show a seasonal pattern in transport direction of fine sediment. The suspended sediment input from the tidal channel is high during winter, and low during summer (see e.g. Figure 5-6 for Blauwe Slenk).
An indication for the net-transport direction of fine sediment is received, by applying Formula 5-3 for a winter (October-December) and a summer period (May-July). The results are given in Figure 5-20.

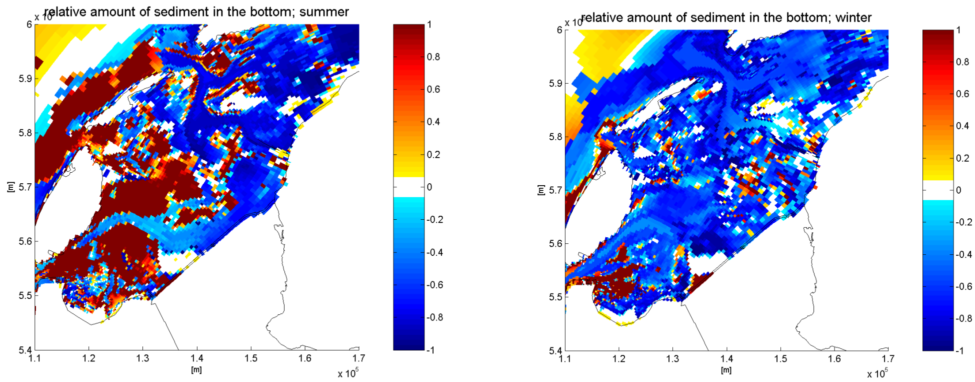


Figure 5-20: Indication for the net-transport direction of fine sediment during summer (left) and winter (right). >1 indicates an increase in fine sediment content in the bed for the given period.

In general, during summer (Figure 5-20; left), the fine sediment content in the bed is increased. However, a decrease in the fine sediment content in the bed is observed at places destabilised by grazers. This decrease is caused by an increase in biomass grazers in the summer period, resulting in a decrease in the critical shear stress for resuspension.
During winter (Figure 5-20; right), the fine sediment content in the bed is decreased, except for places destabilised by grazers. Due to the decrease in biomass grazers during the winter period, the fine sediment content in the bed is increased at these places.

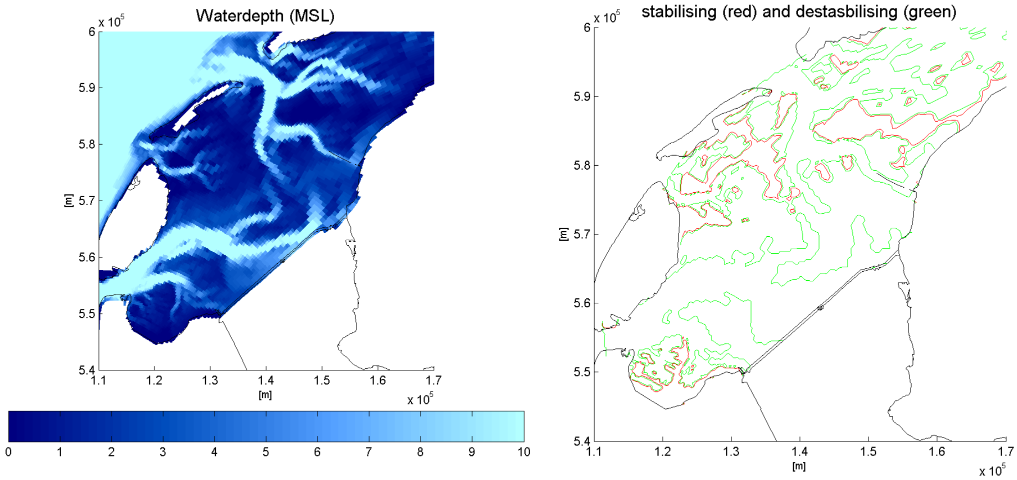


Figure 5-21: Waterdepth (MSL) [m] and stabilised (red polygons) and destabilised (green polygons) areas.

The results of the model can be used to expand the conceptual model for the combined effect of bio-stabilisers and bio-destabilisers on the net-transport direction of fine sediment, while the conceptual model by Andersen *et al*. [2005] is only based on bio-stabilisers.
Based on the model results, bio-destabilisers show an opposite influence on the net-transport direction of fine sediment, compared to bio-stabilisers. During winter, the net-transport of fine sediment is directed towards the destabilised areas. At the start of the winter period, the fine sediment content in the destabilised areas is low due to the high biomass destabilisers in autumn. During winter the biomass decreases, resulting in an increase in the fine sediment content at these places.
During summer, the transport direction is opposite; from the destabilised areas towards the stabilised areas and just outside the destabilised areas. This transport direction is caused by an increase in biomass bio-destabilisers during the summer period.

5.7 Evaluation of the model results

The agreement in suspended sediment between the model results and the DONAR-database is given in Figure 5-22. In this figure, the calculated suspended sediment concentrations are plotted against the measured suspended sediment concentration at exactly the same time.

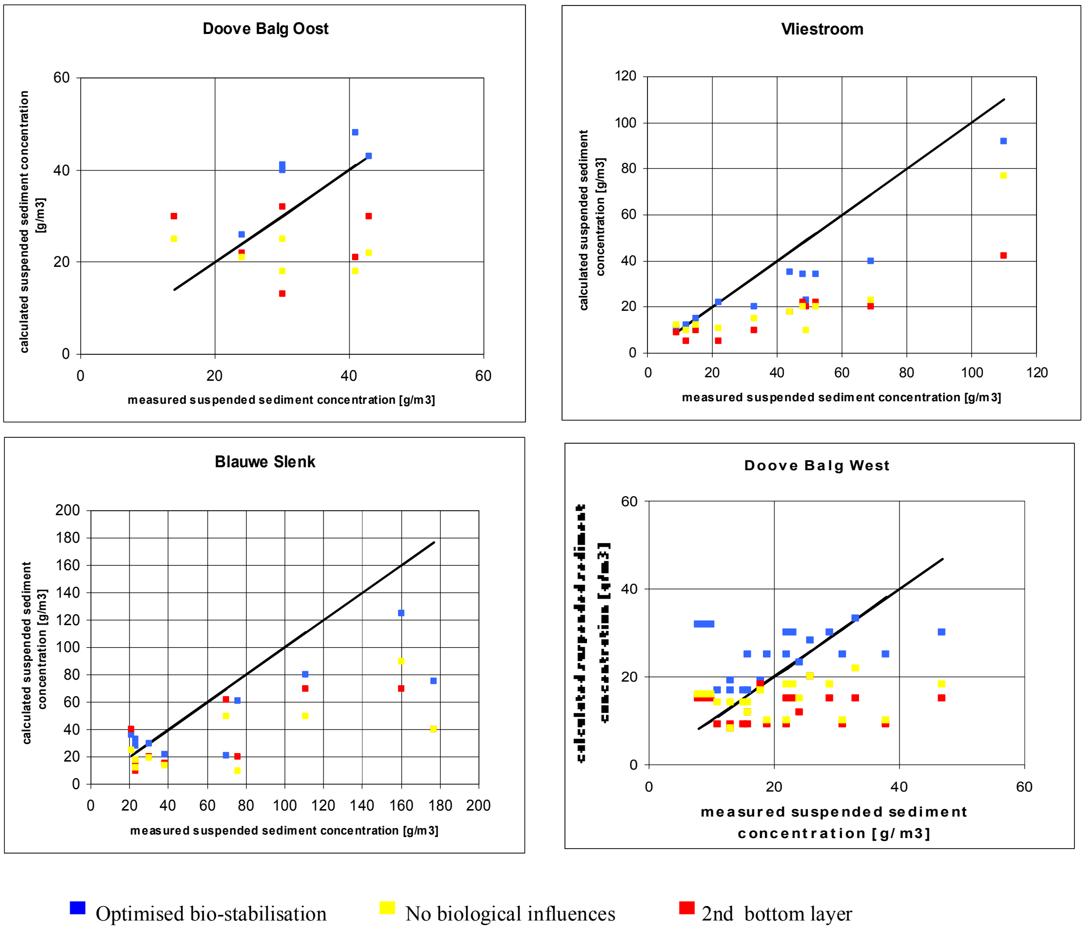


Figure 5-22: Comparison between the measured (DONAR database) and the calculated (model) sediment concentrations at the different observations points.

It must be noticed, that the results showed in Figure 5-22 are all based on the model in which a second bottom layer is included. The suspended sediment concentrations without a second bottom layer are an order of magnitude lower.

The results of the model show good agreement with reality for the Vliestroom and Blauwe Slenk observation points. However, the suspended sediment concentrations at Doove Balg West are much more scattered. This is caused by the great variation in the suspended sediment concentration at almost the same time (see Figure 4-7). The underestimation at the Vliestroom and Blauwe Slenk observation points is probably caused by the overestimation in suspended fine sediment concentrations in the DONAR database. As discusses in Section 2.7, the DONAR database contains measurements of all material in the water column, while in this model only fine sediment is modelled. Comparing the calculated and measured suspended sediment concentrations for the Vliestroom and Blauwe Slenk observations points leads to an average underestimation of 30% compared to the measured suspended sediment concentrations.

The evaluation between the modelled fine sediment distribution and the fine sediment distribution provided by the Sedimentatlas is presented in Figure 5-23. The upper plots in Figure 5-23 are constructed based on the agreement between the data provided in the Sedimentatlas (higher than 10% fine sediment) and the model, in which the minimum fraction fine sediment is plotted on the x-axis. The lower plots in Figure 5-23 are constructed based on the overestimation of area fine sediment on the bed. A distinction is made between depth zone 2 and 3 (left) and depth zone 1 (right).

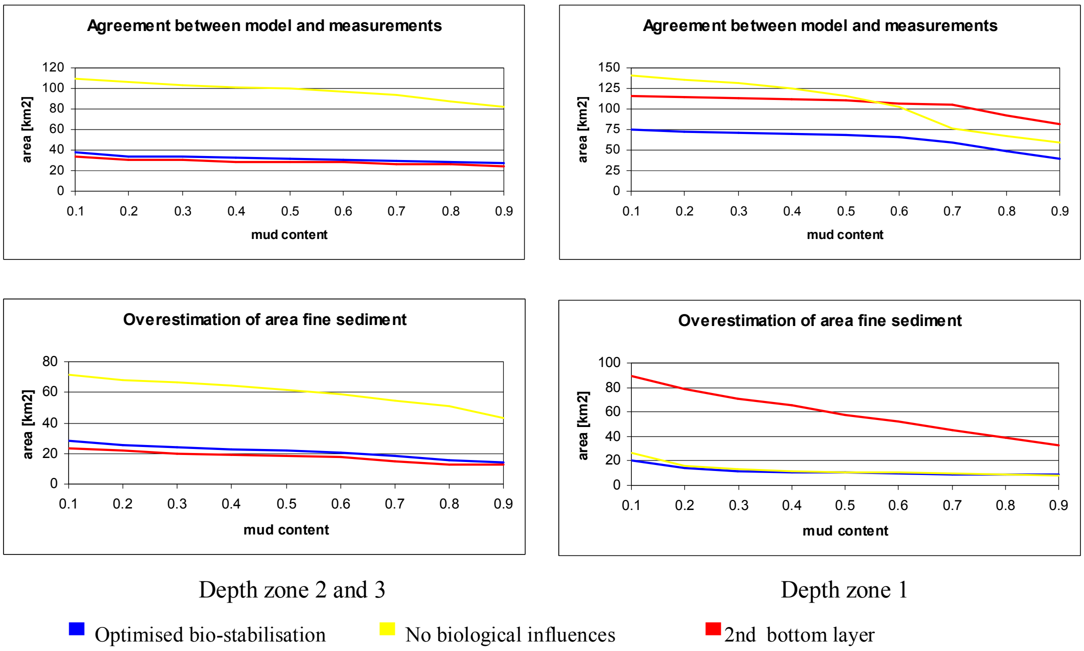


Figure 5-23: The evaluation between the modelled fine sediment distribution, and the measured fine sediment distribution (Sedimentatlas). Left: depth zone 2 and 3, right: depth zone 1.

For depth zone 2 and 3, the agreement between modelled and measured area fine sediment on the bed, without including biological processes, is high. However, the overestimation in area fine sediment is also high, without including biological influences. The total area fine sediment on the bed in zone 2 and 3 is 371 km^2, based on the Sedimentatlas, leading to the conclusion that simulating the fine sediment distribution is very difficult in the used model.
The fine sediment distribution in depth zone 1 shows an interesting result, comparing biological influences and no biological influences. Based on the agreement between measurements and modelling results, the results of the model without including biological influences, shows a strong decrease in the fine sediment content in depth zone 1 (indicated by the strong decrease in area agreement for the model without biological influences for increasing minimum mud content). However, by including biological influences in the model, the fine sediment content is overestimated, showing the overestimation in biomass microphytobenthos in Case III (red line), which results in an accumulation of fine sediment in the bed. The total area fine sediment in depth zone 1 is 414 km^2, based on the Sedimentatlas.
The agreement between modelled and measured area without fine sediment on the bed is comparable for all model runs, and for this reason not included in Figure 5-24.
In the Sedimentatlas, the fine sediment content in the bed is much more scattered, compared to the model results (for reference: see Figure 4-5). However, by applying a comparison in pattern between the measured fine sediment content and the modelled fine sediment content, the agreement is reasonable (Figure 5-25).

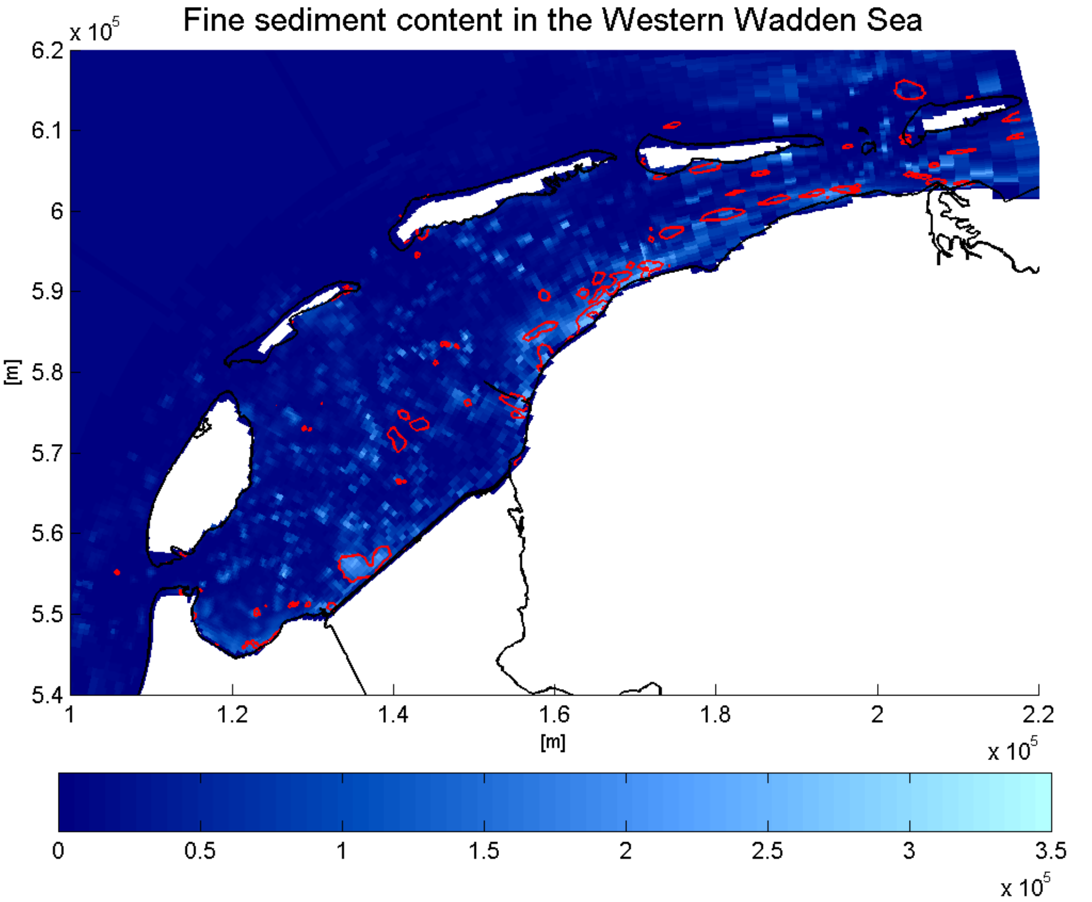


Figure 5-24: Fine sediment distribution in the Western Wadden Sea, based on measurements (Sedimentatlas), combined with the places in which the second bottom layer is filled (red polygons).

At places where the second bottom layer is filled, storage of fine sediment is simulated. These places supply fine sediment during high energy levels. Due to the agreement in pattern of fine sediment distribution in the model and measurements, the fine suspended sediment concentrations show good agreement between the modelled suspended sediment concentrations and the data provided by the DONAR database.

Three causes can be identified to explain the difference in the modelled fine sediment distribution and the measured fine sediment distribution. These three causes all represent one of the three fields in biogeomorphology (hydrodynamics, morphodynamics and biota). First of all, the wave energy is overestimated at the shallow places. This overestimation is caused by the used formulation of wave characteristics. The overestimation of wave energy is visible in figure 5-24, which shows hardly any storage of fine sediment at the tidal flats. The use of a more sophisticated modelling tool is recommended in Chapter 8, which results in a more realistic representation of the wave field.

Secondly, only fine sediment dynamics are modelled. In reality, the interaction between fine sediment and sand causes a more scattered pattern of fine sediment on the bed, as proven by Van Ledden [2003].

Finally, the influence of different species on the bed can result in a more scattered pattern of fine sediment on the bottom. These species are discussed in Section 6.2.

6 Discussion

At the Western Wadden Sea, the model shows that the fine suspended sediment concentration and the distribution of fine sediment on the bed is controlled by a combination of physical processes and biological activity. Based on the results of the model, some subjects of discussion can be identified. Section 6.1 discusses the assumptions and the simplifications made in the model. The spatial and temporal variation in biological activity is discussed in Section 6.2. In Section 6.3 the future changes in the physical processes and biological activity are discussed. The used evaluation tools are discussed in Section 6.4. Finally, the results of the model show interesting scale interactions in the sediment dynamics for the Western Wadden Sea (Section 6.5).

6.1 The used model

One of the shortcomings of the model is the underestimation of the exposed area during low tide. The high waterlevels are well predicted with the used hydrodynamic module [Cronin, 2005], while the low water levels are underestimated. Based on an aerial photograph of the Wadden Sea, an important reason for the overestimation of the low waterlevels can be determined. As can be seen in Figure 6-1, the surface of these tidal flats is not plain, but gullies are present. Due to these gullies, the transport of water is much more efficient. While these gullies are present on a subgrid scale, these gullies can not be modelled. However, the total roughness of the tidal flats is lower, compared to a plain flat. By decreasing the roughness of the tidal flats in the FLOW-module, the low water levels can be better modelled, as will be recommended in Chapter 8. The use of a finer grid is not recommended, while the calculation time will be increased, and the scale of interest is much larger than the ‘gully scale’ as discussed in Section 2.8.

Figure 6-1: Aerial photograph of the Dutch Western Wadden Sea, showing a part of a tidal flat, 1998, scale unknown. (Source: RIKZ, J. de Vlas).

The resuspension of fine sediment is dependent on the bottom shear stress, which is dependent on the current velocity and the bottom roughness (Appendix A). While the bottom roughness both influences the exposed area and the bottom shear stress, a lowering of the bottom roughness will result in a lower bottom shear stress. It is assumed that the used bottom roughness predicts the bottom shear stress more accurate compared to a lower bottom shear stress. As a result, the underestimation of the exposed area is assumed to hardly influence the results of the model.
The use of the method proposed by Soulsby [1997] for the calculation of the bottom shear stress due to waves, results in an overestimation of the bottom shear stress. The bottom shear stress due to waves is added as a scalar to the bottom shear stress due to the tide. In reality, both the bottom shear stress due to waves and tide is a vector, resulting in a non-linear interaction of wave and current bed shear-stresses [Soulsby *et al.,* 1993]. This interaction is shown in Figure 6-2.

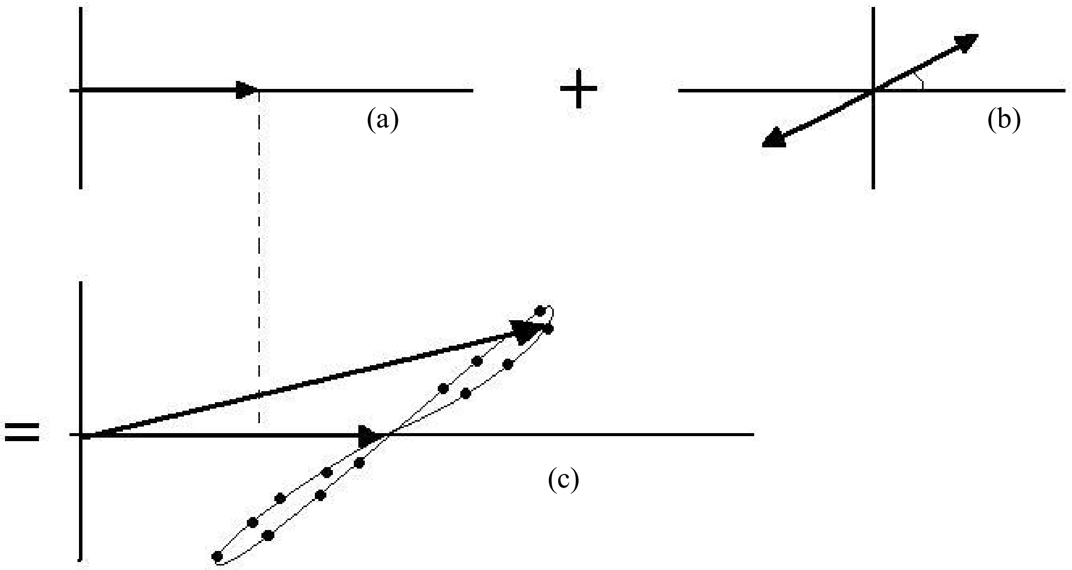


Figure 6-2: Schematic view of the interaction (c) of wave (b) and current (a) on the total bottom shear stress [WL|Delft Hydraulics, 2005a].

By using the SWAN module in the Delft3D environment, the wave and current interaction can be modelled, as will be recommended in Chapter 8.
On a large scale, the results are assumed to be not much influenced by the shortcomings mentioned above. However, after determining the influence of biological processes on the sediment transport and the fine sediment distribution on the bed in this report, it is a challenge to improve the formulation of the sediment dynamics, and in this way improving the model and thereby the recommendations for the management of the Western Wadden Sea.
Finally, the feedback between the vertical sediment transport processes and hydrodynamics is not modelled, as discussed in Section 2.1. This feedback is necessary for the investigation of the long term development of the sediment dynamics of the Western Wadden Sea. Especially, the long term sediment balance between the North Sea and the Wadden Sea is interesting to investigate. In this investigation, the biological processes need to be included in the model, as will be recommended in Chapter 8.

6.2 Biological activity

In this report, the biological activity is related to the waterdepth, as discussed in Section 2.6. However, the biological activity shows much more spatial variation. Based on the limited field studies executed in the Western Wadden Sea, it is difficult to assign the biomass for the complete Western Wadden Sea, as stated by Dekker and De Bruin [1999]. Moreover, numerical models will always call for site-specific measurements in order to be calibrated properly [Lumborg *et al.,* 2006; Elias *et al.,* 2006; Widdows and Brinsley, 2002; Defew *et al.,* 2002]. Next to this, the relation between biological activity and sediment strength is highly variable. Based on field experiments executed in the German Wadden Sea, Colijn and Mayerle [2004] found on an intertidal flat with an area of approximately 9 km^2 strong spatial variation in sediment strength. At all the sampling stations, the critical shear stress for erosion generally increased with increasing chlorophyll-a content, but the slope of the increase differed from station to station. The results of this field experiment are a possible explanation for the differences in the biological forcing functions proposed by Paarlberg *et al.* [2005], based on field experiments in the Western Scheldt estuary, and the relations used in this report for the biological influences on sediment strength for the Western Wadden Sea.
The large spatial variation in biological activity requires extensive sampling programs, in order to provide recommendations for the management of the Western Wadden Sea [Thrush *et al.,* 1997]. However, the conventional methods (of sampling) are often difficult to carry out and expensive in terms of time and manpower [Carrère *et al.,* 2004]. Moreover, the spatial microphytobenthos biomass distribution is characterized by a few dense patches and a wide range of low density patches [Seuront and Spilmont, 2002], which makes it difficult to derive general relations between biomass microphytobenthos and sediment strength. The patchiness in microphytobenthos biomass is also observed in the Dutch Western Wadden Sea (Figure 6-3).

Figure 6-3: Aerial photograph of the Dutch Western Wadden Sea, showing the patchiness in biomass microphytobenthos, 1998, scale unknown. (Source: RIKZ, J. de Vlas).

Recently, several non-destructive techniques to generate large scale maps of surface sediment stability are developed. Chlorophyll-a in the uppermost sediment surface can be detected and quantitatively estimated by means of optical remote sensing techniques [Colijn and Mayerle, 2004]. Based on Figure 6-3, it can be concluded that for large scale research, these optical remote sensing techniques will result in the use of a covering factor, which corrects for the patchy distribution of microphytobenthos. The use of a covering factor for the Dutch Western Wadden Sea is in agreement with the results found in Section 5.4, in which the overestimation of microphytobenthos is demonstrated.

In conclusion, the biomass of bio-destabilisers and bio-stabilisers shows a great temporal and spatial variation. While the variation in bio-destabilisers and bio-stabilisers will influence the sediment distribution on the bed and the suspended sediment concentration respectively, measuring of this variation is recommended, as concluded in Section 5.3.

In the model, bio-destabilisation is based on the activity of two bio-destabilisers: *Macoma balthica* and *Hydrobia ulvae.* In reality, much more bio-destabilisers are present in the Western Wadden Sea. Table 6-1 lists the other biodestabilisers in the Western Wadden Sea [De Vries *et al.*, 2006], based on data given by Wijsman [2004], which are measured at Balgzand and Piet Scheveplaat.

Table 6-1: Contribution of various species to yearly average total benthos biomass in the Western Wadden Sea (gC/m2).

Specie	**Common Name**	**Feeding type**	**Depth zone 1**	**Depth zone 2 and 3**
Mya arenaria	Sand gaper	Suspension feeder	11.8	5.5
Cerastoderma edule	Cockle	Suspension feeder	4.2	3.3
Mytilus edulis	Blue mussel	Suspension feeder	2.4	3.3
Lanice conchilega	Sand-mason	Suspension feeder	1.2	0.0
Hydrobia ulvae	Mud snail	Deposit feeder	1.1	24.2
Macoma balthica	Baltic tellin	Deposit feeder	0.8	1.1
Arenicola marina	Lugworm	Deep deposit feeder	2.3	0.0
Heteromastus filiformis	Thread worm	Deep deposit feeder	2.0	1.9
Others			3.4	0.8
Total			**34.5**	**40.1**

In the model, the yearly average biomass at depth zone 1 is 1.5 gC m^{-2}, while the yearly average biomass at depth zone 2 and 3 is 30 gC m^{-2} (Section 4.3). In reality, the biomass in depth zone 1 is much larger. Table 6-1 also lists the feeding type of the different species. Suspension feeders filter particles from the water column, while deposit feeders retrieve their food from the sediment.

Based on Table 6-1, it can be concluded that the biomass in depth zone 1 is underestimated. By increasing the biomass in depth zone 1, the sensitivity in suspended sediment concentrations and fine sediment distribution is investigated. By applying a higher biomass for depth zone 1, it is assumed that the reworking of the sediment is comparable to the reworking by *Macoma balthica.* Moreover, the temporal variation in the total biomass is assumed to be the same as the temporal variation in biomass *Macoma balthica*. Both assumptions are discussable. First of all, the reworking of sediment is not comparable for species with different feeding types [Reise, 1994]. Secondly, Widdows and Brinsley [2002] argue that all ecosystems are controlled and organised by a relatively small set of key species.

By increasing the biomass bio-destabilisers in depth zone 1, also the spatial distribution of bio-stabilisation and bio-destabilisation is influenced, while microphytobenthos is also present in depth zone 1. As a result of the assumptions, the results of this run only show the sensitivity in the change of bio-stabilisation and bio-destabilisation on the suspended sediment concentrations and fine sediment distribution.

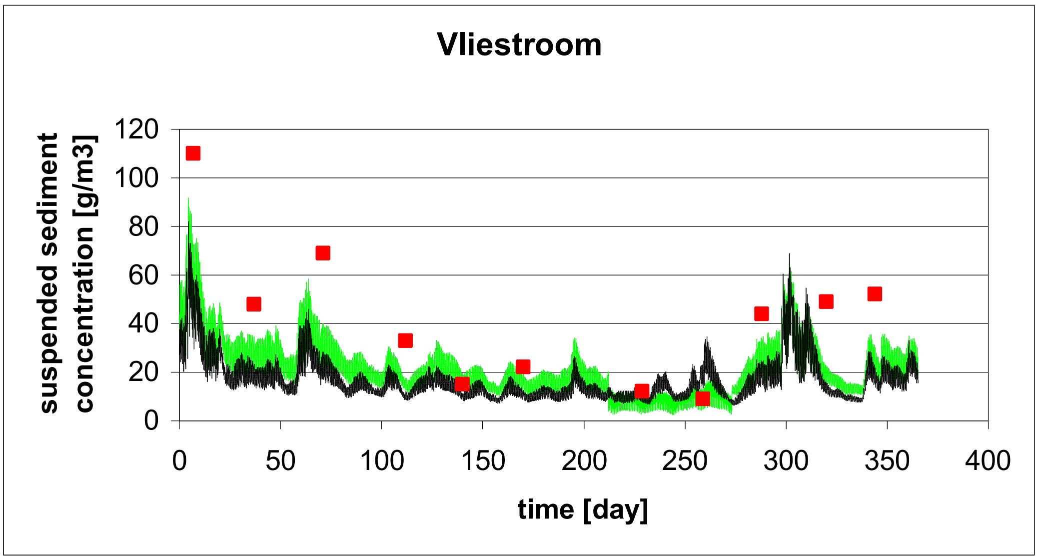


Figure 6-4: Suspended sediment concentrations in the Vliestroom. Green: optimised bio-stabilising, black: high biomass de-stabilisers in depth zone 1. The DONAR measurements are indicated with red spots.

To indicate the influence of the changed biomass destabilisers in depth zone 1 on the suspended sediment concentration, Figure 6-4 is constructed. The suspended sediment concentration is decreased, compared to the situation with little biomass destabilisers in depth zone 1. Only in autumn, the suspended sediment concentration is increased, due to the temporal variation in the biomass bio-destabilisers. Due to this increase in suspended sediment concentration, the availability of fine sediment is decreased, resulting in a lower suspended sediment concentration throughout the year. It can be concluded, that bio-destabilisation is overestimated using the biomass given in Table 6-1. This overestimation could be caused by the assumptions. First of all, not all species rework the sediment in the same way as *Macoma balthica.* Moreover, the temporal variation in the species is not comparable to the temporal variation in *Macoma Balthica.* The overestimation is probably caused by the proposition given by Widdows and Brinsley [2002], that all ecosystems are controlled and organised by a relatively small set of key species. For depth zone 1, this specie is *Macoma balthica*, while for depth zone 2 and 3 the key specie is *Hydrobia ulvae.*

Based on observations by the author in the Mokbaai (Texel) during autumn 2006, key species for depth zone 1 can also be the cockle or the lugworm instead of *Macoma balthica.* These species are assumed to rework the sediment in the same way as *Macoma balthica.*

6.3 Future changes in physical processes and biological activity

The Western Wadden Sea attracts a variety of human activities, such as navigation, recreation and fishing [De Vriend *et al.*, 2002; Hibma *et al.,* 2004; Defew *et al.*, 2002]. On the other hand, the intertidal mud flats in the Western Wadden Sea are rich in flora and fauna and important in the ecology of wading birds and wildfowl [Bale *et al.,* 2006]. Sustainable management and development of the Western Wadden Sea requires profound knowledge and reliable predictive modelling tools for estimating the effects of human interventions or natural changes on the system behaviour, as stated by Van Ledden [2003]. In this section, only natural changes on the system behaviour are discussed, an overview of the effect of human interventions on the system behaviour is discussed by Enemark [2005].
As a consequence of the expected climate change (global warming), sea level may rise during future decades at a faster rate than the present ca 2 mm per year in the North Sea area [Beukema, 2002]. Due to this faster sea level rise, intertidal sand and mud flats will be lost and the level of remaining tidal flats over the Wadden Sea will be lowered [Eysing *et al.*, 1998]. While there is a relation between intertidal level and abundance of benthic organisms [Wijsman, 2004] the distribution of benthic organisms will change. Also the zone where benthic organisms live will be narrowed or broaden and in this way affect the total biomass. Moreover, as stated by Widdows and Brinsley [2002], there is increasing evidences that the development and persistence of macroalgal blooms may be driven by large-scale climatic factors. As discussed in Chapter 5, every tidal inlet is influenced by biological activity in a different way. As a result of change in distribution and zoning of benthic organisms a tidal inlet may for example change from generally stabilising to generally destabilising biological influences.
Besides the change in zoning of benthic organism, also higher species richness and higher abundance of these species are expected due to global warming [Beukema, 1992]. Based on measurements during three successive mild winters (winter water temperatures where 3º C above the long-term winter average).
Moreover, due to climate change, the rainfall is expected to be more intense in future. As a result, the fresh water inflow in the Wadden Sea, from the sluices in the Afsluitdijk, will be influenced. Due to larger fresh water inflow in the Western Wadden Sea, the abundance of benthic organisms may be influenced.
Finally, bottom subsidence as a consequence of gas extraction is expected to be too small to cause any measurable change in the benthic fauna [Beukema, 2002].
As discussed by Reise [1994], it is not sufficient to discuss possible effects of sea-level changes in isolation; substantial changes in the present climate would almost certainly be accompanied by drastic changes in several environmental factors [Beukema, 2002]. Moreover, serious effects of sea-level rise on bottom animals may be expected only if the sea level rise is larger than 4 mm a year [Oost, 1995]. A smaller sea-level rise will fully be compensated by sedimentation [Hibma *et al.,* 2004]. Furthermore, benthic organisms show a self-structuring potential, through which the effect of above mentioned changes are difficult to predict [Reise, 2002].

6.4 Availability of data to evaluate the model

The model is evaluated based on the DONAR database and the Sedimentatlas. In order to improve the model and thereby the prediction of the consequences of the changes in future as discussed in Section 6.3, data series of suspended sediment concentrations on a more frequent basis need to be obtained. These records can also be used to examine the influence between extreme events (e.g. storms) and biological influences. The data series received by NIOZ are on a weekly base (Section 3.3), but are measured close to the coast, which is not representative for the sediment concentrations in the Western Wadden Sea [Van de Kreeke and Hibma, 2005].

6.5 Scale interactions

Scale interactions are an interesting topic in biogeomorphological research, in which scale interactions are assumed to link local processes to larger-scale phenomena [Murray *et al.,* 2002]. Starting at a small scale, up-scaling from the action of individuals to the action of whole communities is the first challenge. Especially, when communities are composed of different individuals, this step is difficult. Following the proposition stated by Widdows and Brinsley [2002]; all ecosystems are controlled and organised by a relatively small set of key species. In this research, three key species are adopted.
Based on the results of the model, it can be concluded that there is a dynamic interaction between physical and biological processes. This dynamic interaction can only be achieved when the biological and physical processes act on the same spatial or temporal scale, following the 'scale concept' as discussed in Section 2.1 [De Vriend, 1991]. Temporal scales in geomorphology have extensively been studied in the past, while spatial scales have received considerably less attention [De Boer, 1992]. In particular, the spatial scale is essential in investigating the biogeomorphological scale interactions, while the biological activity shows a clear spatial variation. De Boer [1992] argued that a geomorphologic system must be viewed in its complex, hierarchical context. In this study the geomorphologic system is the Western Wadden Sea. Within this system, an array of smaller, lower-level systems is present [Odum, 1996]. Using this array approach, a distinction can be made in two systems, which is graphically shown in Figure 6-5.
The outcome of the lowest level system (I) is based on the dynamic interaction between biological activity and the activity by waves (physical process). These two processes act on the same spatial scale, and provide the noise in the suspended sediment concentration. The temporal scale, on which wave action varies is much smaller (daily), compared to the temporal scale on which biological activity varies (seasonal). The difference in this temporal scale causes a different influence on the suspended sediment concentration, showing higher concentrations during autumn and lower concentrations during spring, with respect to the simulations without biological activity (Section 5.3). On a larger spatial scale, system II is based on dynamic interaction between the tide and the suspended sediment concentration in the North Sea. The outcome of this system is the boundary condition in the suspended sediment concentration, visible in the seasonal variation.
For discussing the fine sediment distribution in the Western Wadden Sea, the system must be viewed in the reverse direction. The sediment is provided by the highest level system (import from the North Sea by the tide), and based on the outcome of the lowest level system (critical bed shear stress and actual bed shear stress), the spatial distribution of fine sediment on the bed is determined.

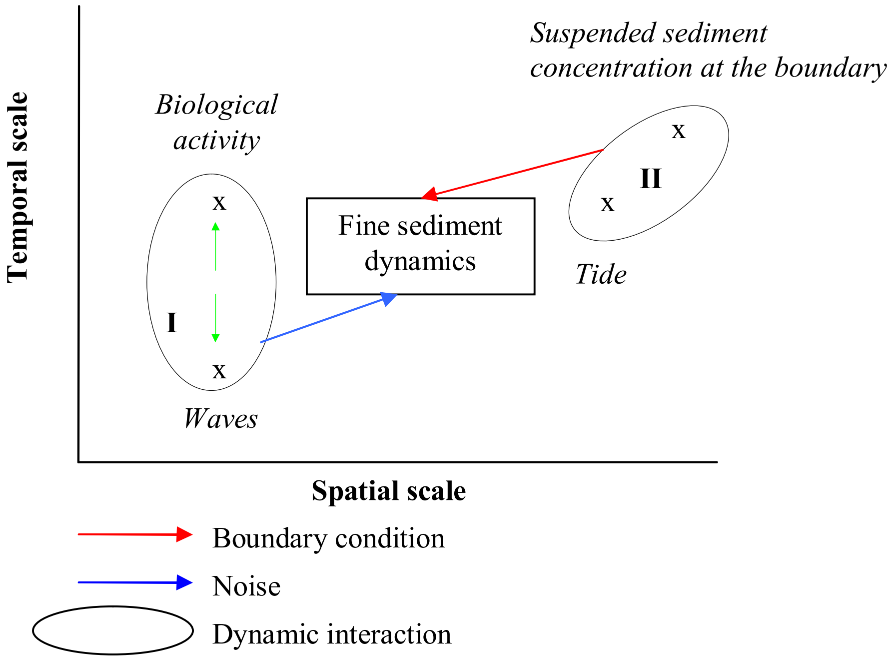


Figure 6-5: Conceptual framework for explaining the scale interactions in biogeomorphology. Two systems can be distinguished. The crosses indicate the position of the processes placed in both the temporal and spatial dimension. The green arrows indicate the processes which will be influence by climate change. For reference see Figure 1-1.

As discussed in Section 6.3, the expected changes in future, due to climate change are diverse. Based on the conceptual framework, only changes which directly influence one of the two systems are important to consider, while the climate change itself act on a large temporal and spatial scale. The influences are indicated with the green arrows in Figure 6-5 (change in biomass and zonation of organisms and increased storminess). As a consequence, the change in climate can result in a direct influence on the fine sediment dynamics, as it influences the dynamic interaction in the lowest level system.

Improvements in the model can only be achieved by including processes on the same temporal and spatial scale as the scale of one of the two systems. For example, consolidation is an interesting process to include (same spatial scale as the lowest level system), while including the roughness caused by mussel banks is not influencing the outcome or the input of one of the two systems. When the area of the mussel banks will become the same order of magnitude, as the spatial scale of the lowest level system in future, the influence need to be included in the model.

It can be concluded, that the variation in biological activity is important to know, for the influence on the fine sediment dynamics in the Western Wadden Sea. This conclusion supports the recommendation to monitor the biological activity on a great temporal and spatial scale.

In the conceptual model, the interaction between hydrodynamics and sediment dynamics on the biological activity is not taken into account. Despite this shortcoming, the conceptual model is a useful tool to determine the important processes in managing the Western Wadden Sea.

7 Conclusions

This thesis concerns the biological influence on fine suspended sediment transport and fine sediment distribution in the bed for the Western Wadden Sea. The research objective, as introduced at the beginning of this thesis, is formulated as follows:

To determine the influence of biology on sediment transport and bed composition during one year on a large scale, by implementing the stabilizing and destabilizing effect, which organisms have on the surface of the bed, in the process-based model Delft3D.

The conclusions of this thesis are given by answering the research questions.

In what way can the destabilising and stabilising effect of organisms be parameterised in the Delft3D model, and how can the spatial and temporal variation in biological activity be modelled?

The biological activity influences the resuspension of fine sediment in two ways. First of all, the critical bed shear stress is maximally halved if the bed is destabilised and maximally 3.5 times increased if the bed is stabilised. Secondly, the resuspension coefficient is maximally increased with a factor 3 and maximally decreased with a factor 10. These factors are derived from measurements in the German and Danish Wadden Sea, in which biomass is related to the two sediment strength parameters.
Bio-stabilisers are represented by microphytobenthos, and are restricted to a waterdepth of 1 m Mean Sea Level (MSL). Bio-destabilisers are represented by the clam *Macoma balthica;* restricted between a waterdepth of 1 and 3 m MSL and the mudsnail *Hydrobia ulvae*; restricted between a waterdepth of 2 and 3 m MSL. For a waterdepth larger than 3 m MSL, no biological activity is assigned. The biomass of the different organisms is based on measurements in the Western Wadden Sea.
The biological activity shows a temporal variation, with the highest biomass bio-destabilisers in autumn and the lowest biomass in March. The maximum biomass bio-stabilisers is measured in spring and the lowest biomass in February.

What is the influence of the biological activity on the fine sediment dynamics, compared to the situation without biological activity?

The suspended sediment concentrations are biological influenced on an estuarine scale. However, every tidal basin is influenced in another way, resulting in a classification of the different tidal basins. This classification is related to the average waterdepth of the different tidal basins. For a shallow tidal basin (Zoutkamperlaag), the effects are significant as the suspended sediment concentrations can be up to 40% lower (compared to the reference situation without biological activity, measured in the tidal inlet) over a three month period. For a deep tidal basin (Marsdiep), the suspended sediment concentrations can be up to 7% higher for the same three month period. The largest difference between the suspended sediment concentrations between the two situations (with and without biological influences) is caused by a decrease in biomass stabilisers in combination with a high biomass bio-destabilisers and a rough weather period, in November.

The fine sediment content in the bed shows a distinct decrease in the destabilised areas, and is increased in the stabilised areas and just outside the destabilised areas (3-4 m MSL), compared to the reference situation. During winter, the net-transport direction of fine sediment is directed to the destabilised areas, due to a decrease in biomass grazers. During summer, the net-transport direction is opposite; from the destabilised areas towards the stabilised areas and just outside the destabilised areas. As a consequence, there is a strong seasonal variation in fine sediment content in the bed.

Do the model results show agreement with actual measurements?

The modelled seasonal pattern of suspended sediment shows good agreement with the measured suspended sediment concentrations from the DONAR database. However, the suspended sediment concentrations are mostly underestimated (on average 30% compared to the measured suspended sediment concentrations). This underestimation is probably caused by the overestimation in the measurements from the DONAR database (containing both inorganic and organic matter).
The distribution of fine sediment given in the Sedimentatlas shows much more variation, compared to the modelled fine sediment distribution. The measured fine sediment distribution is also overestimated, while the samples used to set up the Sedimentatlas are not treated to remove calcium carbonate and organic matter. However, the pattern in fine sediment distribution is reasonable compared to the measurements.

What are the dominant processes in the influence of meso scale biogeomorphological interactions on the macro scale fine sediment dynamics?

The seasonal variation in the suspended sediment concentrations is the outcome of two systems, acting on a different temporal and spatial scale. The lowest level system is the dynamic interaction between biological activity and the wind, acting on the same spatial scale. The outcome of this system provides the noise in the suspended sediment concentrations. The highest level system is the dynamic interaction between the suspended sediment concentration in the North Sea and the tide, which provides the boundary condition in the suspended sediment concentrations. As a consequence of climate change, the dynamic interaction in the lowest level system can be influenced due to an increase in storminess and a change in zonation and biomass of organisms. As a result, the large scale climate change can have a large influence on the small scale fine sediment dynamics.

In summary, the present research demonstrates the influence of biology on fine suspended sediment and fine sediment distribution on an estuarine scale. A good qualitative agreement has generally been obtained between model results and field data. The analysis of biological influences has revealed that bio-stabilisers mainly influence the suspended sediment concentration, while bio-destabilisers mainly influence the fine sediment distribution. The current process-based model is a step forward to a better understanding and modelling of biological influences on an estuarine scale, and is especially important in bringing up recommendations for the management of the Western Wadden Sea.

8 Recommendations

Recommendations for future research include:

- Improvement of the model. In the current model, the waves are calculated according to Soulsby [1997], using wave characteristics calculated after the method proposed by Groen and Dorrestein [1976]. In the Delft3D environment, a more sophisticated tool is available: SWAN module (Simulating WAves Nearshore). This module gives a realistic representation of the wave field, and thereby, a realistic representation of the bottom shear stress caused by wind, for which the suspended sediment concentrations is highly sensitive. Moreover, the exposed area at low tide needs to be improved. Currently, the SWAN module is being coupled to the model and the areas of exposed area is investigated in a different Msc thesis.
- Laboratory studies have shown the impact of biological influences on the critical bed shear stress and the erosion coefficient. However, due to the highly temporal and spatial variability of erosion parameters, it is recommended to execute field studies on these parameters in the Western Wadden Sea.
- The sediment balance between the North Sea and the Wadden Sea is not discussed in this research. By modelling a longer time period (order of 20 years), the balance between both areas can be investigated. The impact of the biological influences on the long-term fine sediment balance is highly valuable for bringing up recommendations for the Wadden Sea conservation and management scheme.
- For the long term balance it is necessary to make a coupling between the fine sediment accumulations, bed level changes and hydrodynamics. Moreover, it is interesting to include the interaction between sand and mud in the model, using the formulations proposed by Van Ledden [2003].
- Currently, a module for the break up and transport of pellets is under construction at WL|Delft Hydraulics. This module can be applied in the current model, resulting in a better representation of the fall velocity and the spatial and temporal distribution of the pellets produced by *Macoma balthica* and *Hydrobia ulvae*.
- In this research, only the interaction between biology and sediment transport is modelled. It would be an improvement to also include the interaction between the hydrodynamics and the biology as hypothesised by Jumars and Nowell [1984].
- In this research, the biological influences on sediment transport and bed composition is determined for the Dutch Western Wadden Sea. It will be a challenge to determine the biological influences for other estuaries, and in this way improving the management of these estuaries with respect to changes in the future for the physical system and the human activities.
- To start the discussion between civil engineers, ecologist and managers, conceptual tools need to be developed, as presented in this report.

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A Delft3D – governing equations

A.1 Introduction

In this research, the process-based model Delft3D is used, which has been developed by WL|Delft Hydraulics. The program can make two- and three-dimensional computations for oceanic, marine, coastal, estuarine and river areas. It can carry out simulations of flows, sediment transport, waves, water quality, morphological developments and ecology. The program is composed of several modules, grouped around a mutual interface, while being capable to interact with each other.
In this Appendix, only the modules are discussed which has been used in this study, namely the modules FLOW and WAQ. The connection between the two modules is given in Figure A-1.

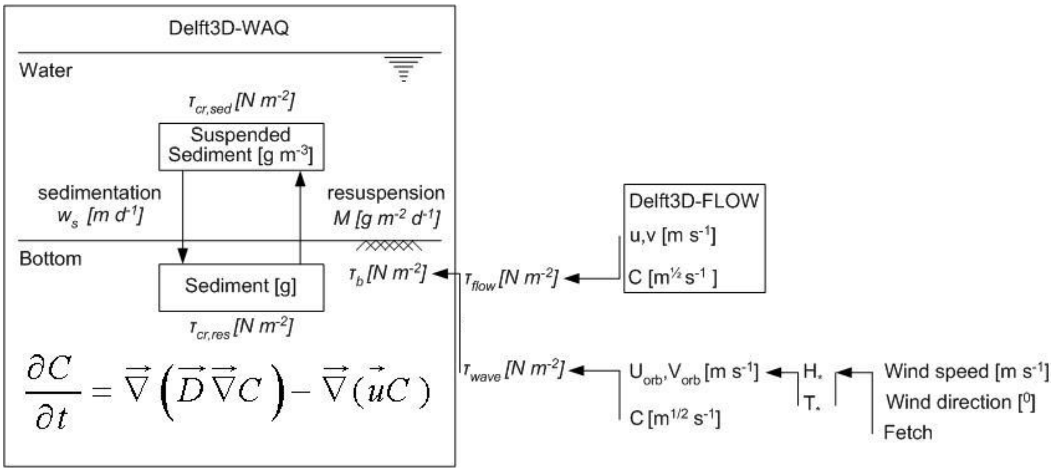

Figure A-1: Connection between the two modules and used parameters.

A.2 Delft3D-FLOW

The module Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic simulation program, which calculates non-steady flow resulting from tidal and/or meteorological forcing at the boundaries, wind stress at the surface and pressure gradients due to free surface gradients and density gradients on a curvilinear, boundary fitted grid. The numerical system of the program solves the unsteady shallow water equation in two (depth average) or in three dimensions. These equations are derived from the three dimensional Navier Stokes equations for incompressible free surface flow, under the assumption of shallow water and Boussinesq. In shallow water, the depth is assumed to be much smaller than the horizontal length scale. For such a small aspect ratio the shallow water assumption is valid, which means that the vertical momentum equation is reduced to the hydrostatic pressure relation; vertical accelerations are assumed to be small compared to the gravitational acceleration and are therefore not taken into account. The effect of variable density is only taken into account in the pressure term (Boussinesq approximation).
The depth and density averaged momentum equation in x- and y-direction are given in Formula A-1 and A-2 respectively. The continuity equation is given in Formula A-3.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial x}+g\frac{\partial \eta}{\partial x}+c_f\frac{\|U\|u}{(d+\eta)}-fv-\frac{F_x}{\rho_w(d+\eta)}-\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=0 \quad \text{(A-1)}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial y}+v\frac{\partial v}{\partial y}+g\frac{\partial \eta}{\partial y}+c_f\frac{\|U\|v}{(d+\eta)}-fu-\frac{F_y}{\rho_w(d+\eta)}-\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)=0 \quad \text{(A-2)}$$

(1) (2) (3) (4) (5) (6) (7) (8)

$$\frac{\partial \eta}{\partial t}+\frac{\partial (d+\eta)u}{\partial x}+\frac{\partial (d+\eta)v}{\partial y}=0 \quad \text{(A-3)}$$

in which:

u,v	= depth average velocity	[m s^{-1}]
η	= water level variation above plane of reference	[m]
g	= gravitation acceleration	[$m^{1/2}$ s^{-1}]
c_f	= coefficient of friction, (c_f = g/C^2)	[-]
C	= Chézy coefficient	[$m^{1/2}$ s^{-1}]
$\|\|U\|\|$	= absolute magnitude of total velocity ($\|U\|=\sqrt{(u^2+v^2)}$)	[m s^{-1}]
d	= waterdepth below reference	[m]
f	= Coriolis parameter	[s^{-1}]
$F_{x,y}$	= external force	[N m^{-2}]
ρ_w	= density of water	[kg m^{-3}]
ν	= diffusion coefficient	[m^2 s^{-1}]

Formula A1 and A2 consist of the following terms:

(1) velocity gradient
(2),(3) advective terms
(4) barotropic pressure term
(5) bottom stress
(6) Coriolis force
(7) external force (wind)
(8) viscosity

It is assumed that a velocity point is set dry when the actual waterdepth is below half of a user-specified threshold. If the point is set dry, then the velocity at that point is set to zero. The velocity point is set wet again when the local waterdepth is above the threshold grid. For more details see Delft3D-FLOW manual [WL|Delft Hydraulics, 2005a].

A.3 Delft3D-WAQ

The module Delft3D-WAQ is a 3-dimensional water quality model framework, in which the transport of sediment can be modelled by solving the advection-diffusion equation. The model is based on a closed mass balance, bounded by open and closed boundaries. Within this closed mass balance, one substance is included, in two different forms; suspended inorganic matter (IM1) and inorganic matter in the bed (IM1 S1). Delft3D-WAQ is not a hydrodynamic model, so information on flow fields is derived from Delft3D-FLOW.
The advection-diffusion equation is given in Formula A-4, and discussed in Appendix B.

$$\frac{\partial C}{\partial t} = \vec{\nabla}\left(\vec{D}\vec{\nabla}C\right) - \vec{\nabla}(\vec{u}C) \qquad \text{(A-4)}$$

The processes of sedimentation and resuspension are based on the Partheniades-Krone formulations [Partheniades, 1962; Krone, 1962] and are shown in Formula A-4 and A-5 respectively. The graphical representation of Formula A-4 and A-5 is given in Figure A-1.

$$D = P_{sed} w_s c$$
$$P_{sed} = \max\left(0, 1 - \frac{\tau_b}{\tau_d}\right) \qquad \text{(A-5)}$$

in which:

D	= deposition flux of suspended sediment	[g m^{-2} d^{-1}]
P_{sed}	= probability for sedimentation	[-]
w_s	= settling velocity of suspended sediment	[m d^{-1}]
c	= concentration of suspended sediment	[g m^{-3}]
τ_b	= bottom shear stress	[N m^{-2}]
τ_d	= critical shear stress for deposition	[N m^{-2}]

With the limitation that the sedimentation in one model time step cannot exceed the available amount of substances in the water column.

$$E = P_{res} M$$
$$P_{res} = \max\left(0, \frac{\tau_b}{\tau_e} - 1\right) \qquad \text{(A-6)}$$

in which:

E	= resuspension flux	[g m^{-2} d^{-1}]
P_{res}	= probability for resuspension	[-]
M	= first order erosion rate	[g m^{-2} d^{-1}]
τ_b	= bottom shear stress	[N m^{-2}]
τ_e	= critical shear stress for erosion	[N m^{-2}]

With the limitation that the erosion in one model time step cannot exceed the available amount of substances in the bed layer.
For more details see Delft3D-WAQ manual [WL|Delft Hydraulics, 2005b].

A.4 Bottom shear stress

The linking parameter between the two modules is the bottom shear stress. The bottom shear stress due to currents is calculated by using the FLOW-module. The bottom shear stress due to waves is calculated in the WAQ-module. The total bottom shear is calculated as the sum of the two components, see Formula A-7.

$$\tau_b = \tau_{flow} + \tau_{wave} \qquad \text{(A-7)}$$

in which:

τ_{flow}	= bed shear stress due to currents	[N m^{-2}]
τ_{wave}	= bed shear stress due to waves	[N m^{-2}]

$$\tau_{flow} = \frac{\rho g u^2}{C^2}$$

$$C = 18\log\left(\frac{12h}{k_s}\right) \qquad \text{(A-8)}$$

in which:

u	= depth average velocity	[m s^{-1}]
ρ	= water density	[kg m^{-3}]
h	= waterdepth	[m]
C	= Chézy coefficient	[m$^{1/2}$ s^{-1}]
g	=gravitational acceleration	[m s^{-2}]
k_s	= roughness height	[m]

$$\tau_{wave} = \frac{1}{4}\rho f_w U_{orb}^2$$

$$f_w = 0,237 r^{-0.52}$$

$$r = \frac{A}{k_s} \qquad \text{[Soulsby,1997]} \qquad \text{(A-9)}$$

$$U_{orb} = \frac{\pi H}{T\sinh(2\pi h / L)}$$

$$A = \frac{U_{orb} T}{2\pi}$$

in which:

U_{orb}	= amplitude of the wave orbital velocity	[m s^{-1}]
H	= wave height	[m]
L	= wave length	[m]
T	= wave period	[s]
r	= relative roughness height	[-]
f_w	= wave friction factor	[-]
A	= semi-orbital excursion	[m]

The wave length L and the wave height H are calculated based on the fetch and wind speed [Groen and Dorrestein, 1976].
The WAQ module uses the hydrodynamic conditions as a boundary condition. As a consequence, there is no feedback from the sediment transport to the hydrodynamics. Even the biological processes do not influence the hydrodynamics.

B Advection-Diffusion equation

B.1 Introduction

The transport of sediment is based on the advection-diffusion equation in two directions, see Formula B-1.

$$\frac{\partial C}{\partial t} = \vec{\nabla}\left(\vec{D}\vec{\nabla}C\right) - \vec{\nabla}(\vec{u}C) \tag{B-1}$$

in which:

c	= concentration of suspended sediment	[g m^{-3}]
D	= dispersion coefficient	[m^2 s^{-1}]
$\vec{\nabla}$	$= \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$	

Dispersion is done according to Fick's diffusion law, in which the proportionality constant D is called the dispersion (or diffusion) coefficient [m^2 s^{-1}]. Dispersion causes net transport from higher to lower concentrations.

B.2 Scaling the Advection-Diffusion equation

The Advection-Diffusion equation can be made dimensionless with relevant scales in order to enable study on the behaviour of the transport of fine suspended sediment. The following typical scales will be introduced in the Advection-Diffusion equation:

$$u^* = u / U$$
$$x^* = x / L$$
$$t^* = t / T$$

The parameters denoted with the index * are of order one. The non-dimensional Advection-Diffusion equation in x-direction is given in Formula B-3. The derivation is given in Formula B-2.

$$\begin{aligned}
\frac{\partial}{\partial t} &= \frac{\partial t^*}{\partial t}\frac{\partial}{\partial t^*} = \frac{1}{T}\frac{\partial}{\partial t^*} \\
\frac{\partial}{\partial x} &= \frac{\partial x^*}{\partial x}\frac{\partial}{\partial x^*} = \frac{1}{L}\frac{\partial}{\partial x^*} \\
\frac{1}{T}\frac{\partial C}{\partial t^*} &= \frac{1}{L^2}\frac{\partial}{\partial x^*}\left(D\frac{\partial C}{\partial x^*}\right) - \frac{U}{L}\frac{\partial u^* C}{\partial x^*} \\
\frac{\partial C}{\partial t^*} &= \frac{DT}{L^2}\frac{\partial^2 C}{\partial x^{*2}} - \frac{UT}{L}\frac{\partial u^* C}{\partial x^*}
\end{aligned} \tag{B-2}$$

Assuming:

$$T = \frac{L}{U}$$

$$\frac{\partial C}{\partial t^*} = \frac{D}{UL}\frac{\partial^2 C}{\partial x^{*2}} - \frac{\partial u^* C}{\partial x^*}$$

$$\mathrm{Re} = \frac{UL}{D}$$

Gives:

$$\frac{\partial C}{\partial t^*} = \frac{1}{\mathrm{Re}}\frac{\partial^2 C}{\partial x^{*2}} - \frac{\partial u^* C}{\partial x^*} \tag{B-3}$$

The non-dimensional Advection-Diffusion equation in the y-direction is given in Formula C.4.

$$\frac{\partial C}{\partial t^*} = \frac{1}{\mathrm{Re}}\frac{\partial^2 C}{\partial y^{*2}} - \frac{\partial u^* C}{\partial y^*} \tag{B-4}$$

Conclusion:

Re < 1: Diffusion dominant
Re > 1: Advection dominant

In areas with small velocities, the transport of sediment is mainly based on diffusion (the shallow areas). In areas with high velocities, the transport of sediment is mainly based on advection (the tidal inlets and the channels).

C Wind speed and wind direction

The wind speed is measured at a height of 10 meters above the land. The data given in Figure C-1 are measured at station De Kooy, near Den Helder. Other stations in the research area show comparable wind speeds and directions.
By adding a trend line to the plot (Figure C-1), the relation between the wind speed and the time is investigated. The relationship gives a coefficient of determination of $R^2 = 10^{-5}$ and $R^2 = 0.1022$ with field measurements. Although the coefficient of determination for a seasonal dependency of the wind speed is greater than the coefficient of determination for an average wind speed, the relation is not significant.

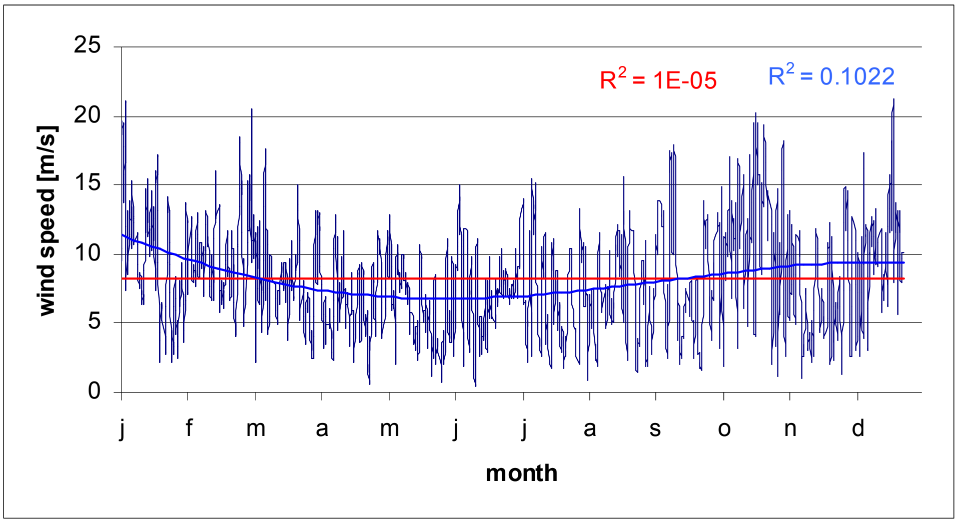

Figure C-1: Investigation of the correlation between wind speed and date, based on 6-hourly KNMI data.

By applying the bottom shear stress caused by wind as a scalar, the bottom shear stress will be overestimated. As shown in Figure C-2, there is a strong relation between the wind speed and the wind direction.

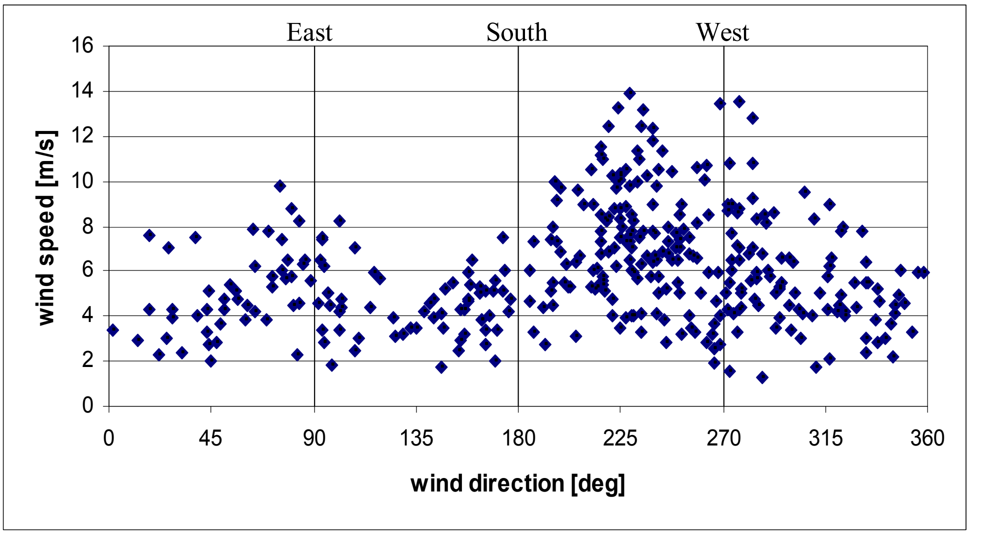

Figure C-2: Wind direction and wind speed in de Kooy (near Den Helder), based on daily averaged KNMI data.

D Overview of runs

Empty places imply that the parameter setting is equal to the previous run.

Table D-1: Parameter settings for sensitivity analysis tides and waves.

run	P01	P02	P03	P04	P05	P06	P09
D [$m^2 s^{-1}$]	10						
w_s [$mm\ s^{-1}$]	0.5						
C [$m^{1/2} s^{-1}$]	62						
F [m]	5000	0	8000		0	8000	
C_{bound}	v						
Remark	rough weather	rough weather	rough weather	calm weather	calm weather	calm weather	spring-neap cycle

Table D-2: Parameter settings for sensitivity analysis dispersion coefficient.

run	P10	P11	P12	P13	P14
D [$m^2 s^{-1}$]	10	10	1	1	50
w_s [$mm\ s^{-1}$]	0.5				
C [$m^{1/2} s^{-1}$]	65				
F [m]	5000				
C_{bound}	v				
Remark	2 days	20 days	2 days	20 days	20 days

Table D-3: Overview of basic biological runs.

run	B04	B05	B08	B09	B10
Biology	spatial	spatial and temporal			
Bottom	no		Sedimentatlas	2nd layer	
Remark					Long term development

Table D-4: Overview of runs sensitivity critical shear stress top sediment layer.

run	**G01**	**G02**	**G03**	**G04**	**G05**
τ_{cr} [N m^{-2}]	0.38	0.36	0.43	0.32	0.30
Remark	2nd and spatial and temporal biology				

Table D-5: Overview of runs pellet production.

run	**G11**	**G12**
w_s [m s^{-1}]	[0.5-5]	5 during 8th and 9th month
Remark	τ_{cr} = 0.3 N m^{-2}	

Table D-6: Overview of runs sensitivity patchiness microphytobenthos.

run	**F01**	**F02**	**F03**	**F04**	**F05**
a_1	0.66	0.63	0.51	0.38	no mfb
a_2	0.246	0.205	0.18	0.15	no mfb

E Boundary conditions

The suspended sediment concentration in the North Sea shows a seasonal variation, especially close to the coast. In order to take this temporal and spatial variation into account, the model boundary input is imposed, based on data given in the DONAR database. The model input is only an approximation of the realistic seasonal variation. The variation in suspended sediment concentration 2 and 4 km off the coast is given in Figure E-1 and E-2 respectively. The other boundary conditions are kept constant in time.

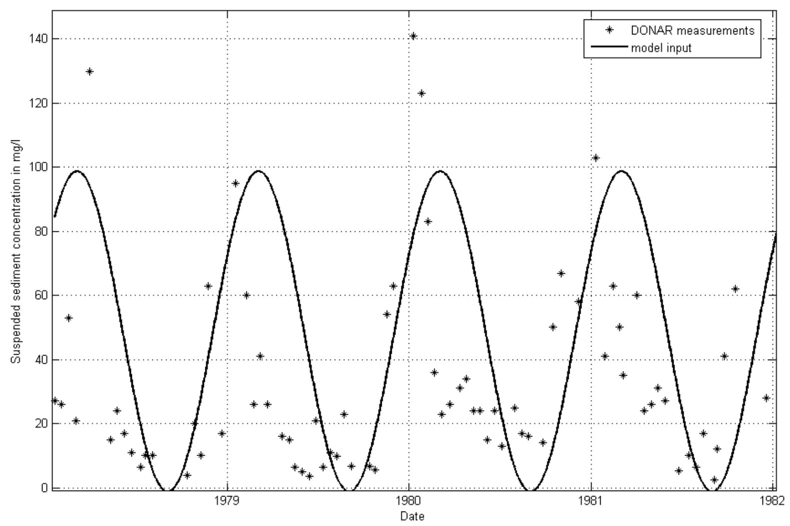

Figure E-1: Data of suspended sediment concentrations 2 km off the coast and the model input (source: DONAR database).

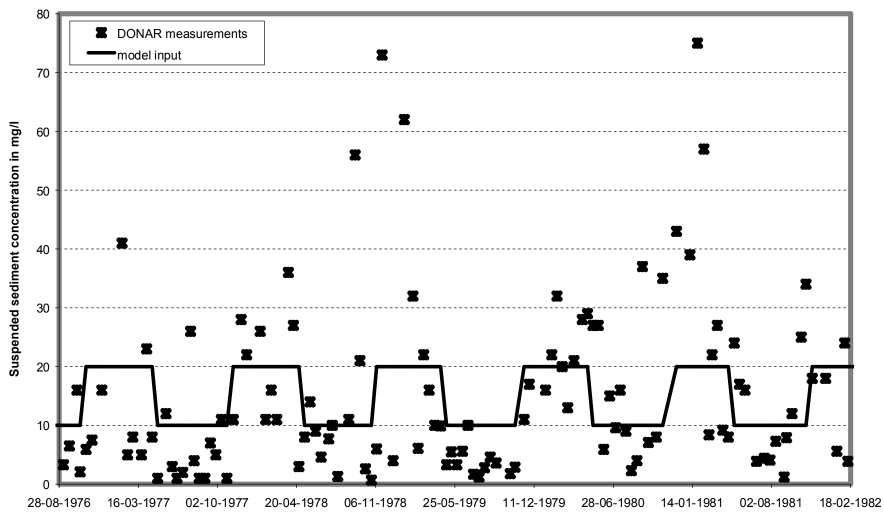

Figure E-2: Data of suspended sediment concentrations 4 km off the coast and the model input (source: DONAR database).

F Variable fetch

The correlation between the wave height and wave direction is shown in Figure F-1. Based on these data, a variable fetch is determined (black line). The data shown in Figure F-1 are measured at the North Sea side of Schiermonnikoog. De Vriend *et al.* [2002] stated that the Frisian inlands do not significantly influence the wind speed in the Wadden Sea compared to the wind speed in the North Sea. As a consequence, the fetch can be determined based on the data measured at Schiermonnikoog. Moreover, the wind speed is assumed to be uniform over the modelling area. The maximum fetch is set at approximately 9500 m and the minimum fetch is set at approximately 1500 m. A second order polynomial is determined to fit these data. The variable fetch equation is given in Formula H.1

$$F(dir) = 0.1783(dir)^2 - 53.519(dir) + 5541.6$$

in which:

dir = wave direction [º]

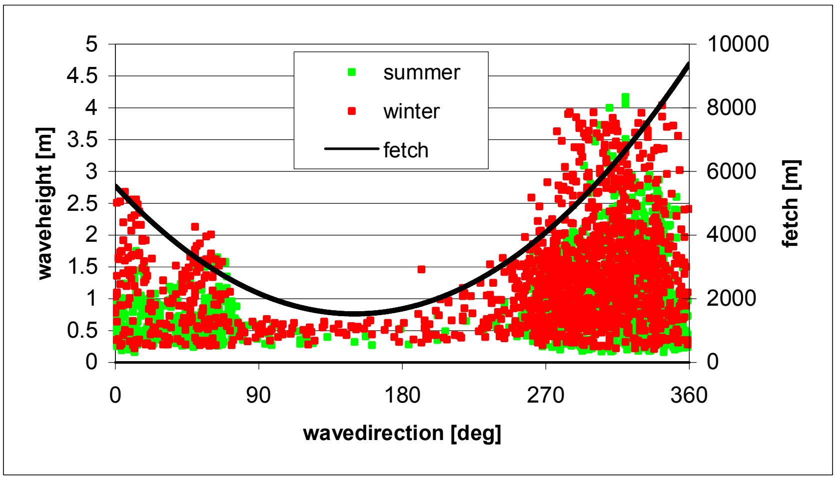

Figure F-1: Relation between wave height and wave direction for Schiermonnikoog and the corresponding fetch.

The variable fetch is included in the model based on 6 hourly Rijkswaterstaat data on the wavedirection.

G Parameterisation of biological activity

The parameterisation of the biological activity is based on the formulations proposed by Holzhauer [2003] and Paarlberg *et al.* [2005]. The biodestabilisation function is based on two organisms (viz. *Hydrobia ulvae* and *Macoma balthica*). In order to correct for the reworking of the same material by two different organisms, the formulations are corrected. This correction is based on the contribution of the organism to the total biomass. The (de)stabilisation functions are given in Formula I-1 and I-2.

$$\begin{aligned}
&\tau_{cr,res} = \tau_{cr,res0} f_s(Chf) f_d(Nzb) \\
&f_s(Chf) = 1 + 0.66\ln(Chf') \\
&f_d(Nzb) = 1 + (Mzb_1 / Mzb_{tot}) * (0.0016\ln(Nzb'_1)^2 - 0.085\ln(Nzb'_1)) + \\
&(Mzb_2 / Mzb_{tot}) * (0.0015\ln(Nzb'_2)^2 - 0.06\ln(Nzb'_2))
\end{aligned} \qquad \text{(I-1)}$$

$$\begin{aligned}
&M_{res} = M_{res0} g_s(Chf) g_d(Nzb) \\
&g_s(Chf) = 1 - 0.246\ln(Chf') \\
&g_d(Nzb) = 1 + (Mzb_1 / Mzb_{tot}) * (0.016\ln(Nzb'_1)^2 + 0.15\ln(Nzb'_1)) + \\
&(Mzb_2 / Mzb_{tot}) * (0.01\ln(Nzb'_2)^2 + 0.03\ln(Nzb'_2)) \qquad \text{(I-2)} \\
&Chf' = achl * Cba \\
&Nzb_1 = Czb_1 / Mzb_1 \\
&Nzb_2 = Czb_2 / Mzb_2
\end{aligned}$$

in which:

$\tau_{cr,res0}$	= critical shear stress for erosion at absence of organisms	[N m^{-2}]
Chf’	= Concentration of chlorophyll in the sediment layer	[µgChl gC^{-1}]
Nzb	= Density of zoobenthos species in the top sediment	[ind. m^{-2}]
Mzb	= average biomass of zoobenthos individual	[gC]

Realistic values for the average biomass of a *Macoma balthica* individual and a *Hydrobia ulvae* individual are 0.01 gC and 0.0001 gC respectively, based on Wadden Sea observations in 1998 [Dekker and De Bruin, 1999].

The stabilisation term proposed by Holzhauer [2003] has been modified; the dependency of the chlorophyll-a content is logarithmic in stead of linear because this seems more realistic with reality [Smits, 2004].

H Sediment distribution in the bed

The distribution of fine suspended sediment on the bed is shown in Figure H-1. This figure is based on data provided by RIKZ, and shows the average distribution of sediment in the bed over the period 1989 – 1997.
During the simulation, the first year is used for spinning up the model. The simulation starts with an empty bottom. After one year the distribution of sediment is given in Figure H-2. The substance used in the model is fine sediment. It can be concluded that the distribution of sediment on the bed is in agreement with reality. In the model, the bottom level is constant in time. As a consequence, only the pattern of the sediment distribution can be compared with observations. In Figure H-2 the sediment distribution is shown during the winter (December). During winter the biological activity is low and the sediment distribution is not influenced by the biological activity, which makes it possible to compare the situation without biological activity with reality.

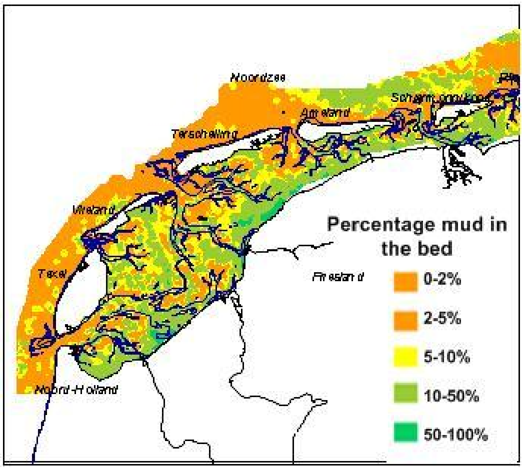

Figure H-1: mud distribution in top 10 centimetres in the bed [RIKZ, 1998]

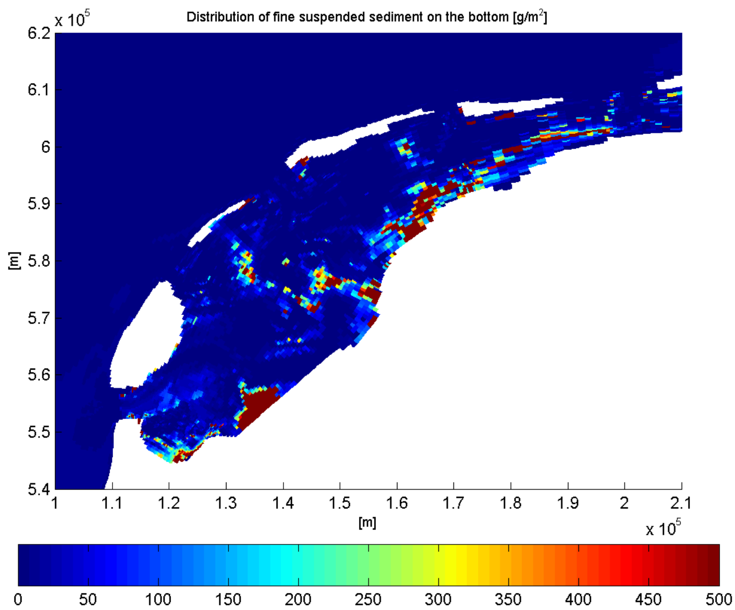

Figure H-2: Distribution of fine suspended sediment on the bed.

I Spatial and temporal variation in biological activity

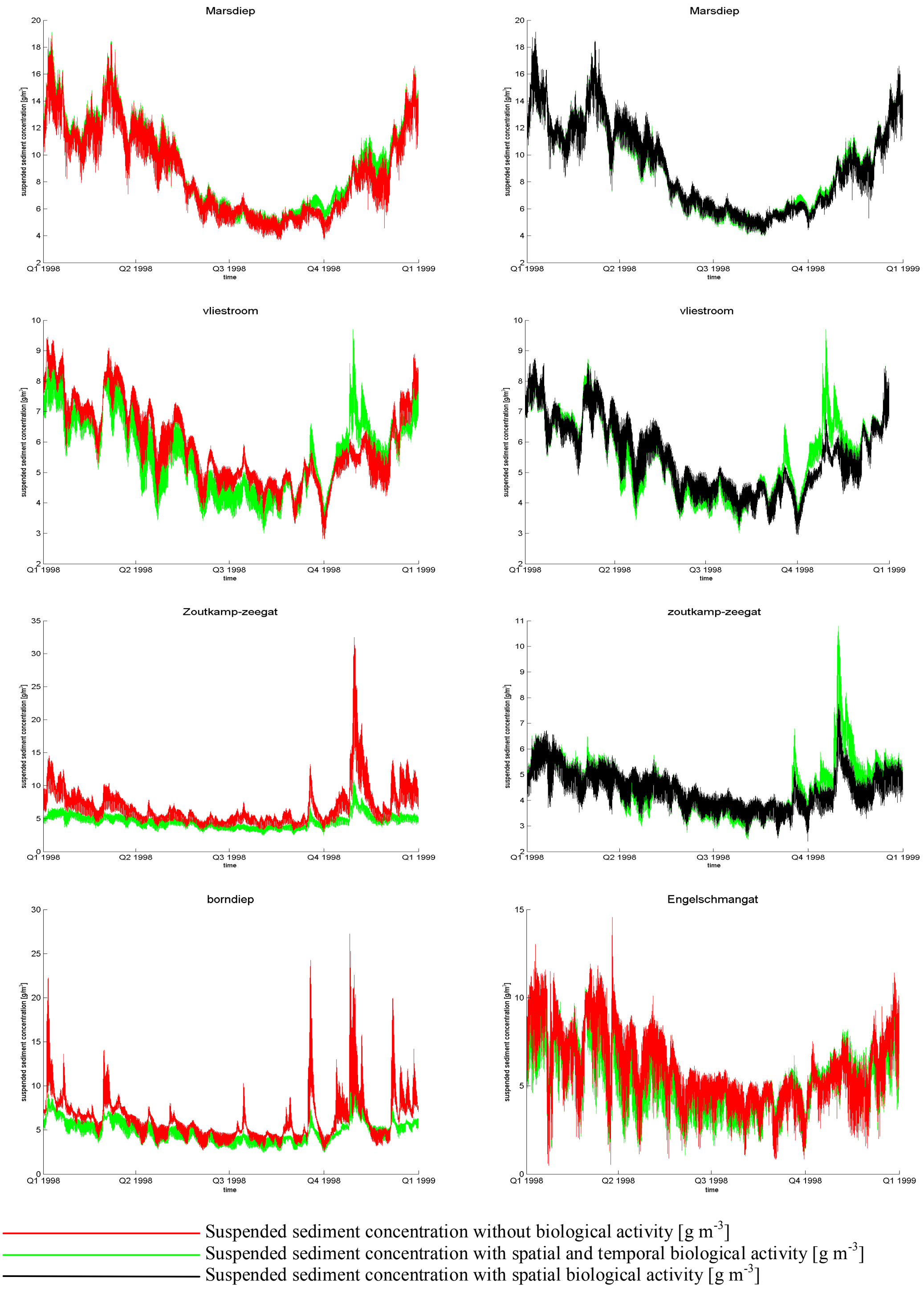

Figure I-1: Suspended sediment concentrations during one year in different tidal inlets.

The suspended sediment concentration at Borndiep and Engelschmangat do not show a clear difference comparing spatial and spatial and temporal biological activity. At the other tidal inlets, a clear difference is observed during autumn. During rough weather conditions, the suspended sediment concentrations are much larger, due to a decrease in biostabilisation and an increase in biodestabilisation (compared to the situation with constant biological activity throughout the year; black line).
Another clear difference is observed at Zoutkamp-zeegat and Borndiep. Due to the relative large area of microphytobenthos in both tidal basins, the suspended sediment concentration in both tidal inlets is constantly lower, compared to the situation without biological activity.
The suspended sediment concentrations in different channels are shown in Figure I-2. The constantly higher suspended sediment concentrations at Doove Balg (compared to the situation without biological activity) are caused by the absence of microphytobenthos at this place, leading to a smaller critical bed shear stress and higher erosion coefficient and consequently a larger suspended sediment concentration. The lower suspended sediment concentrations at Dantziggat and Zoutkamperlaag are caused by the abundant presence of microphytobenthos at these places, causing the opposite effect as described for Doove Balg. Blauwe Slenk is located in an area influenced by both biostabilers and biodestabilsers, resulting in a lower suspended sediment concentration during spring and a higher suspended sediment concentration during autumn.

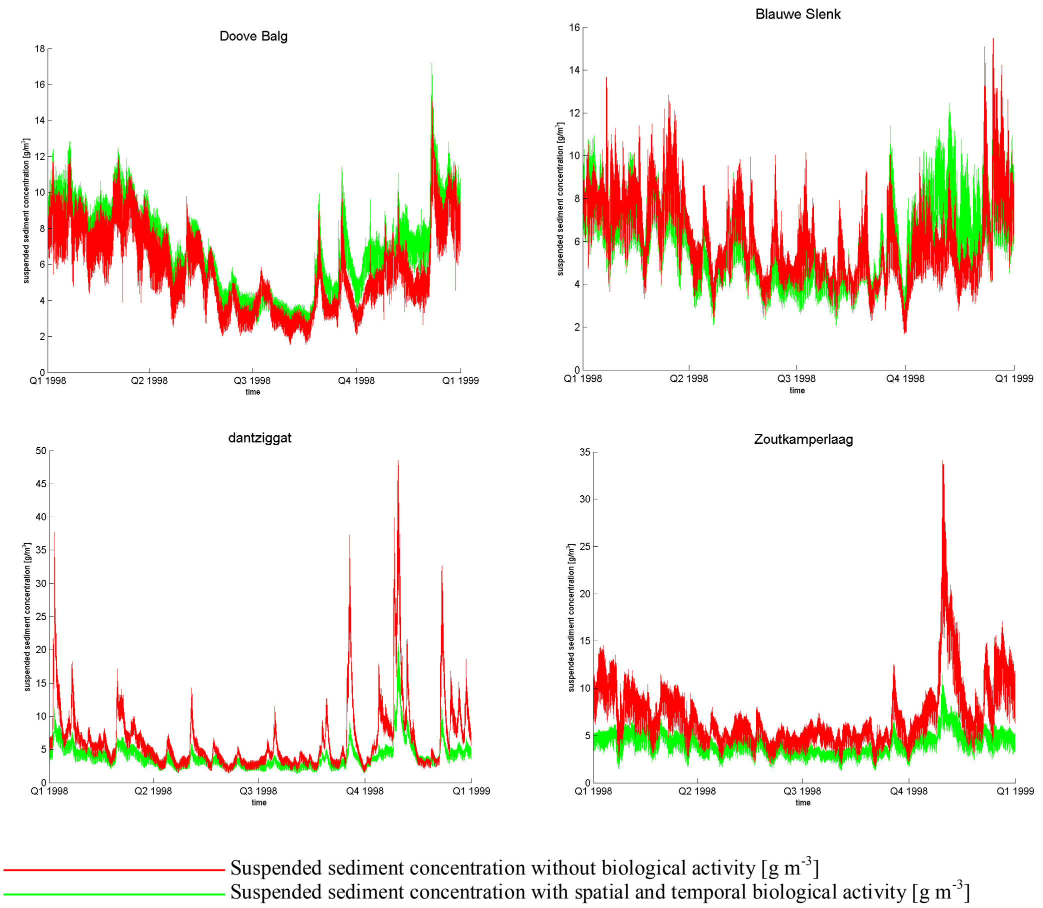

Figure I-2: Suspended sediment concentrations during one year in different channels.

J Settling and scour lag

The settling velocity for fine suspended sediment is set at 0.5 mm s^{-1}. Assuming a waterdepth of 2 meter and a typical current velocity of 0.2 m s^{-1} around high water at a tidal flat, it will take about 1 hour to settle. As a consequence, the suspended sediment can be transported hundreds of metres landwards during the time of deposition. This phenomenon is defined as settling lag [Postma, 1954; Straaten and Kuenen, 1958]. Due to pellet production by *Hydrobia ulvae* the sediment will be eroded at higher velocities than those prevailing during deposition. This phenomenon is defined as scour lag [Postma, 1954, Straaten and Kuenen, 1958]. The combined effect of the settling and scour lag processes is a net landward flux of suspended sediment [Pejrup, 1998, Andersen *et al.*, 2002, Andersen and Pejrup, 2002].
Different studies have calculated that suspended sediment is exported from the Wadden Sea to the North Sea (for an overview see Pejrup [1988]). This founding is not in accordance with reality; most of the suspended sediment supplied to the Wadden Sea originates from the North Sea [e.g. Postma, 1981]. In order to investigate the net import of sediment in the Wadden Sea (validation), sediment is placed at different locations sediment on an empty bottom in the model. The results are visible in Figure J-1 and J-2. The red spots are the initial places where the sediment is placed. The green contours show the distribution of fine sediment on the bottom after three days of stormy weather (first three days of January, see Table 3-1).

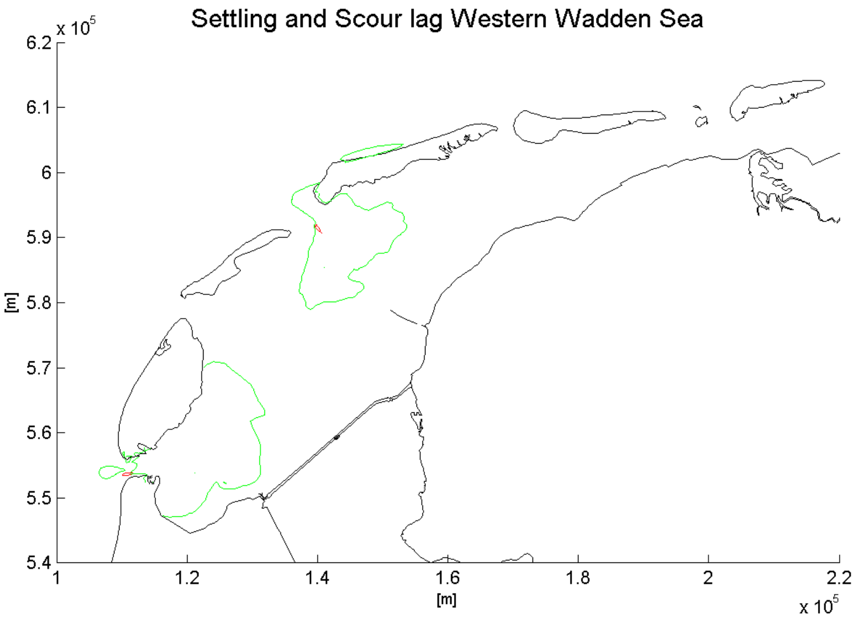

Figure J-1: Settling and scour lag in two different inlets.

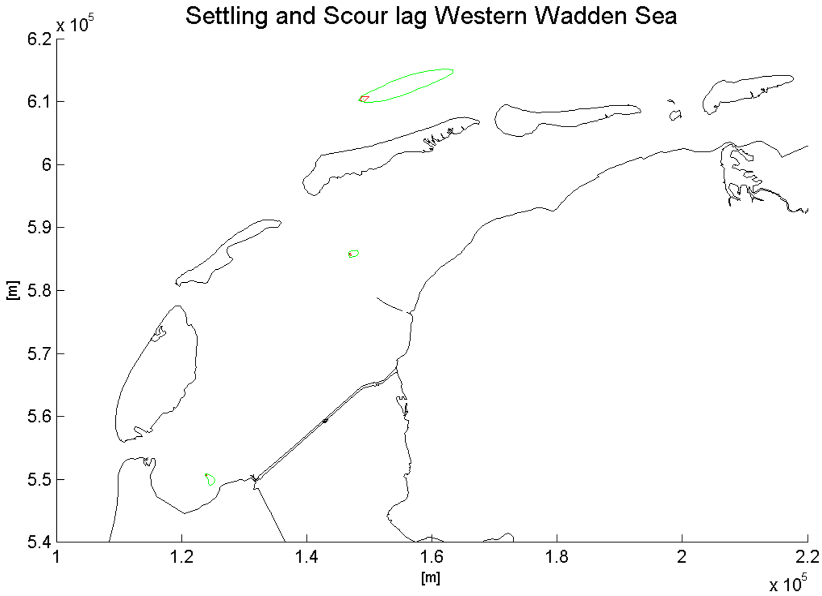

Figure J-2: Settling and scour lag in the Western Wadden Sea and the North Sea.

The model shows a net import of fine sediment into the Wadden Sea (Figure J-1) from two different tidal inlets. This result is in agreement with reality. Moreover, the net transport direction in the North Sea is also in agreement with reality (net east-ward directed transport, as discussed in Section 3.3). Finally, at places with a small waterdepth, the sediment is hardly transported, which is in accordance with results found in Section 3.1.