Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin
Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin

Claire van Oeveren
Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin

Claire van Oeveren

Report

December 2008
**Client**

**Title**  
*Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin*

**Abstract**

This research has focussed on the identification of the relevant processes behind the long-term fine sediment dynamics. Three main influences were considered: the tide, wind waves and biological stabilization/destabilization. The study was performed by means of computational modelling, within the process-based model, Delft3D. By modelling several different scenarios, the separate influences of the tide, wind waves and biology were investigated.

The results showed that the tidal asymmetry, entering the basin from the sea, was the main contributor to the import of fine sediments. In general, the tide promoted a large import towards the intertidal areas below the MSL line, and only a very small import towards higher elevations, due to the limited transport capacity of the tidal currents in these areas.

Waves were the main contributor to the export-flux of fine sediments by the model, by increasing the bed shear stress in the intertidal areas and causing a relatively larger distribution of sediment towards the deeper areas. Waves were also the main contributor to the high suspended sediment concentrations inside the modelled basin, causing a substantial increase in the basin-average SPM concentrations.

In case of a combined influence of waves and biology, particularly the interaction between the seasonal variations appeared to be of importance, which further enhanced the export flux from the modelled basin during late autumn and early winter. With respect to the distribution of sediment, the biological influences caused a landward shift in the deposition and the sediment was distributed much more evenly than if no biological effects were included in the model.

**References**

<table>
<thead>
<tr>
<th>Ver</th>
<th>Author</th>
<th>Date</th>
<th>Remarks</th>
<th>Review</th>
<th>Approved by</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Claire van Oeveren</td>
<td></td>
<td></td>
<td>M. de Vries</td>
<td>T. Schilperoort</td>
</tr>
</tbody>
</table>

**Project number**

**Keywords**

**Number of pages** 128

**Classification** None

**Status** Final
Preface & Acknowledgements

This document concerns the thesis for my research, which forms the completion of my education at the Delft University of Technology, for the Master of Science degree in Civil Engineering, track Hydraulic Engineering. The focus of the research lies in the field of coastal morphology, as this forms my specialisation within the track of Hydraulic Engineering.

The research has been performed at WL | Delft Hydraulics, which, as of January 1st 2008, has joined forces with Geo Delft, TNO Subsurface and Water and parts of Rijkswaterstaat (DWW, RIKZ and RIZA), to form a new institute, Deltares. Deltares is an independent institute for applied research and specialist advice on the field of water, soil and the subsurface.

First, I would like to thank the people in my graduation committee, prof. dr. ir. M.J.F. Stive; drs. M.B. de Vries; dr. ir. T. van Kessel; ir. G.J. de Boer and B.W. Borsje M.Sc., for their enthusiasm during the meetings and their assistance and feedback in completing this research.

I would also like to give many thanks to: my fellow graduate students and colleagues at Deltares, for the good company and the relaxing walks after lunch; my parents, Harm and Marianne, who’s continuous support and faith helped me through all my turbulent student years; my brother, Vincent, for giving me someone to look up to; Pieter, for his endless patience and backing support, as well as his revisions of my report; and finally: Bali, just for who she is.

Claire van Oeveren

Delft, December 2008

Graduation committee:

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof. dr. ir. M.J.F. Stive</td>
<td>Delft University of Technology, faculty of Civil Engineering and Geosciences, track Hydraulic Engineering</td>
<td></td>
</tr>
<tr>
<td>Drs. M.B. de Vries</td>
<td>Delft University of Technology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>University of Twente</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deltares</td>
<td></td>
</tr>
<tr>
<td>Dr. ir. T. van Kessel</td>
<td>Deltares</td>
<td></td>
</tr>
<tr>
<td>Dr. ir. G.J. de Boer</td>
<td>Deltares</td>
<td></td>
</tr>
<tr>
<td>B.W. Borsje MSc.</td>
<td>University of Twente</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deltares</td>
<td></td>
</tr>
</tbody>
</table>
Summary

The sediment deposits that can be found in estuaries and tidal basins usually contain both sand and mud fractions. Fine sediments, like silt (D$_{50} \leq$ 63 µm), differ from larger sediment fractions when it comes to the response to hydrodynamic behaviour or cohesiveness. As a result, fine sediments accumulate in the intertidal areas and salt marshes, where they form important breeding and foraging grounds for a large variety of species. Therefore, the fine sediment balance in a tidal basin is a very important parameter for the management and preservation of these valuable ecological areas.

Within the perspective of integrated (or sustainable) coastal zone management, long-term effects become of major importance. Due to the almost imperceptible effects on the short term, the driving processes behind long-term impacts can sometimes be very difficult to identify. Vice versa, our knowledge on which short-term processes have residual effects in the long run is still insufficient [DE VRIEND et al., 1993].

This research has focussed on the identification of the relevant processes behind the long-term fine sediment dynamics. Three main influences were considered: the tide, wind waves and biological stabilization/destabilization. The study was performed by means of computational modelling, within the process-based model, Delft3D. By modelling several different scenarios, the separate influences of the tide, wind waves and biology were investigated.

The results showed that the tidal asymmetry, entering the basin from the sea, was the main contributor to the import of fine sediments by the model, and caused a substantial increase with respect to the semi-diurnal lunar tide (M2) alone. Adding the influence of a spring-neap variation caused a small reduction of the total import, but increased the transport to the marsh areas. In general, the tide promoted a large import towards the intertidal areas below the MSL line, and only a very small import towards higher elevations, due to the limited transport capacity of the tidal currents in these areas.

Waves were the main contributor to the export-flux of fine sediments by the model, by increasing the bed shear stress in the intertidal areas. In this way, they reduced the net total import and caused a relatively larger distribution of sediment in the deeper areas.

Waves were also the main contributor to the high suspended sediment concentrations inside the modelled basin, causing a substantial increase in the basin-average SPM concentrations.

In case of a combined influence of waves and biology, the interactions caused an additional reduction of the annual import, with respect to the computations without biology. Particularly the interaction between the seasonal variations appeared to be of importance: destabilization by benthic grazers was maximal when the wave intensity started to increase in early autumn. This interaction ultimately led to a net export of fine sediments from the modelled basin during late autumn and early winter.

With respect to the distribution of sediment, on the other hand, biology partially counteracted the influence of the waves, by re-enabling the net deposition in the intertidal areas, while at the same time reducing the deposition in the subtidal areas and secondary channels. The transport to the marsh areas had increased as well. Overall, the biological influences caused a landward shift in the deposition and the sediment
was distributed much more evenly than if no biological effects were included in the model.
## Contents

1 Introduction ............................................................................................................. 1  
   1.1 Background ....................................................................................................... 1  
   1.2 Framework ........................................................................................................ 1  
   1.3 Research objective and approach ..................................................................... 2  
   1.4 Outline of the report ......................................................................................... 3  

2 System description: the Dutch Wadden Sea .......................................................... 5  
   2.1 Study area ......................................................................................................... 5  
      2.1.1 Geomorphology ......................................................................................... 5  
      2.1.2 History ....................................................................................................... 5  
      2.1.3 Hydrodynamic conditions ....................................................................... 5  
   2.2 Sediment ........................................................................................................... 7  
      2.2.1 Fine sediment properties ........................................................................ 7  
      2.2.2 Transport processes of fine sediment ....................................................... 8  
   2.3 Biological influences ....................................................................................... 10  
      2.3.1 Bio engineers ............................................................................................ 10  
      2.3.2 Spatial and temporal variations ............................................................... 11  

3 Model set-up .......................................................................................................... 15  
   3.1 General ............................................................................................................. 15  
   3.2 Computational grid and bathymetry ................................................................. 15  
   3.3 Initial and boundary conditions ..................................................................... 18  
      3.3.1 Initial conditions and spin-up ................................................................. 18  
      3.3.2 Boundary conditions .............................................................................. 19  
   3.4 Hydrodynamic computation ........................................................................... 20  
      3.4.1 Hydrodynamic forcing .......................................................................... 20  
      3.4.2 Scenarios .................................................................................................. 21  
   3.5 Wave computation ........................................................................................... 21  
      3.5.1 Wave computation in Delft3D-WAQ ...................................................... 22  
      3.5.2 Wave computation in Delft3D-WAVE ................................................... 22
3.5.3 Scenarios .................................................................................. 22
3.6 Morphological computation .......................................................... 25
  3.6.1 Sediment transport ................................................................. 25
  3.6.2 Bottom layers ........................................................................ 25
  3.6.3 Biological influences ............................................................... 26
  3.6.4 Scenarios ................................................................................ 26
3.7 Evaluation data ............................................................................ 26

4 Modelling biological influences ...................................................... 29
  4.1 Formulations for biological influences on sediment erodibility ...... 29
    4.1.1 The initial formulations ......................................................... 29
    4.1.2 Potential problems regarding the initial formulations ............... 30
    4.1.3 Proposed adjustments ......................................................... 31
    4.1.4 New formulations ............................................................... 31
  4.2 Grazer biomass ........................................................................... 32
    4.2.1 Seasonal variation in biomass ................................................. 33
    4.2.2 Spatial variation in biomass ................................................. 33
    4.2.3 Variation in biomass composition ....................................... 35
  4.3 Chlorophyll-a concentration ......................................................... 35
    4.3.1 Seasonal variations in biomass ............................................. 35
    4.3.2 Spatial variations in biomass .............................................. 36

5 Hydrodynamic results ...................................................................... 39
  5.1 Tidal asymmetry ......................................................................... 39
    5.1.1 Spring tide .......................................................................... 39
    5.1.2 Neap tide ............................................................................ 41
  5.2 Tidal prism ................................................................................ 43
  5.3 Flow velocities ........................................................................... 43

6 Sediment transport – Tide .............................................................. 45
  6.1 Sediment balances ..................................................................... 45
    6.1.1 Total basin balance ............................................................ 45
    6.1.2 Distribution over the areas ................................................... 48
    6.1.3 Distribution over the bottom layers ...................................... 49
Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin

6.2 Average sediment concentrations ...................................................... 50

7 Sediment transport – Waves ..................................................................... 53

7.1 Sediment balances ............................................................................. 53

7.1.1 Total basin balance ......................................................................... 53

7.1.2 Distribution over the areas ............................................................... 54

7.1.3 Distribution over the bottom layers .................................................. 55

7.2 Average sediment concentrations ....................................................... 56

7.3 Discussion ............................................................................................. 59

8 Sediment transport – Biology ................................................................. 61

8.1 Sediment balances ............................................................................. 61

8.1.1 Total basin balance ......................................................................... 61

8.1.2 Distribution over the areas ............................................................... 62

8.1.3 Distribution over the bottom layers .................................................. 63

8.2 Average sediment concentrations ....................................................... 64

8.3 Discussion ............................................................................................. 65

9 Synthesis .................................................................................................. 67

9.1 Sediment balance according to literature ............................................. 67

9.2 Sediment balance in the modelled basin ............................................. 67

9.2.1 Seasonal variation in sediment import ............................................ 70

9.3 Fine sediment content in the bottom ................................................... 72

9.4 Horizontal and vertical fluxes .............................................................. 74

9.5 Deep basin ........................................................................................... 75

9.6 Discussion ............................................................................................. 76

10 Conclusions and recommendations ...................................................... 79

10.1 Conclusions ......................................................................................... 79

10.1.1 Conclusions per research question ................................................ 79

10.1.2 Comparison of the results with previous model studies ................ 81

10.1.3 Overall performance of the model ................................................ 81

10.2 Recommendations ............................................................................. 82
References .................................................................................................................. 83

Appendices .................................................................................................................. 87

Appendices
A Parameter settings ...................................................................................................... 89
B Sediment concentration at sea boundaries ................................................................. 91
C Hydrodynamic computation ......................................................................................... 93
   C.1 Fourier analysis on tidal wave propagation .......................................................... 93
      C.1.1 Amplitudes of the waterlevel variation ......................................................... 93
      C.1.2 Phases of the waterlevel variation ................................................................. 95
   C.2 Water level variation and flow velocity ................................................................. 96
      C.2.1 Scenario with 1 component: M2 ................................................................. 97
      C.2.2 Scenario with 3 components: M2 M4 M6 .................................................... 98
      C.2.3 Scenario with 5 components: M2 M4 M6 S1 S2 .......................................... 99
   C.3 Bed shear stresses .................................................................................................. 100
   C.4 Wave heights ........................................................................................................ 102
      C.4.1 Mean occurring wave heights ................................................................. 102
      C.4.2 Maximum occurring wave heights ............................................................ 104
      C.4.3 Wave heights in the deeper basin ............................................................... 107
D Biological influences ................................................................................................... 109
   D.1 Comparing the results with the old and the new formulations ......................... 109
      D.1.1 Destabilizing factors ................................................................................... 109
      D.1.2 Stabilizing factors ...................................................................................... 112
   D.2 Results with the new formulations ....................................................................... 113
      D.2.1 Critical bed shear stress ............................................................................ 113
      D.2.2 Resuspension parameter ........................................................................... 114
      D.2.3 Stabilized versus destabilized areas ............................................................ 115
   D.3 Grazer biomass ..................................................................................................... 119
      D.3.1 Spatial variations ....................................................................................... 119
      D.3.2 Seasonal variations .................................................................................... 121
1 Introduction

1.1 Background
Estuaries and tidal basins can be found in coastal regions throughout the world, where they form attractive areas for both nature and mankind. Sustainable management of these environmentally and economically important areas requires the ability to predict the dynamic behaviour of the sediments in these areas [VAN LEDDEN et al., 2004a]. The sediment deposits that can be found in estuaries and tidal basins usually contain both sand and mud fractions. Water movements (caused by river discharges, tidal motions and/or wind waves) can displace the sediments, which could locally result in erosion or sedimentation of material from/to the bed.

Sediment erosion results from hydrodynamic forcing and the erodibility of the sediment. The hydrodynamic forcing is represented by bottom shear stresses, which act upon the sediment in the bed. The erodibility of the sediment, which varies spatially and temporally, can be seen as a measure for the sediment’s resistance against the hydrodynamic forcing, before being eroded from the bed. It can be modelled by a critical shear stress and an erosion rate, which both depend on the interactions between physical processes, sediment properties and biological processes [WIDDOWS & BRINSLEY, 2002].

Fine sediments, like silt (D_{50} ≤ 63 µm), differ from larger sediment fractions when it comes to hydrodynamic behaviour or cohesiveness. They can stay in suspension for a long time and can thereby limit the penetration of sunlight into the water. Aquatic plants and diatoms depend on sunlight for photosynthesis and, in turn, provide valuable nutrients for various other organisms. Additionally, the tidal flats and salt marshes form important breeding and foraging grounds for large populations of birds, which feed on the benthic organisms in these muddy areas. Therefore, the fine sediment balance in a tidal basin is a very important parameter for the management and preservation of these valuable ecological areas. (For sake of conciseness, ‘fine sediments’ are simply referred to as ‘sediments’ in the report, unless specified otherwise in the context.)

1.2 Framework
Within the perspective of integrated (or sustainable) coastal zone management, long-term effects become of major importance. With the increasing awareness of the broad impacts of global climate change, the ability to predict the response of the system to these changing conditions has become even more important. Even though short-term changes may sometimes appear to be severe, their effects on the long term can be negligible, whereas long-term changes may hardly be noticed in a short period, but have considerable net effects in the long run. This often makes the driving processes behind long-term impacts much more difficult to identify.

This issue concerns the concept of scales, which was described by De Vriend (1991). According to De Vriend (1993), the variation of inputs and processes on much smaller scales is only relevant as far as there are residual effects, whereas variations on much larger scales can be considered as concerning the extrinsic or boundary conditions. However, our knowledge on which short-term processes are important in the long run is still insufficient [DE VRIEND, 1993].
1.3 Research objective and approach
The main objective of this research is:

… to gain more insight into the relevant processes involved in the long-term transport and distribution of fine sediments and their influences on the fine sediment balance in a tidal basin.

From this objective, several key questions can be derived that this study will seek to answer:

1. When focusing on long-term balances, what are the relevant scales of the processes to be modelled?

With respect to the tide, the focus will be on finding the minimal set of constituents that drive the relevant processes. With respect to wind, it might be important to find out whether seasonal changes in intensity or storms have a net effect on the sediment transport, or if they can simply be approached by a time-averaged wind. Concerning the biological influences, the sensitivity to seasonal or annual changes in biomass is considered.

2. Which process is the main contributor to the (expected) sediment import into the basin?

Estimates from literature [POSTMA, 1981; ELIAS et al., 2006b] point out a net import of fine sediments into the basin, in the order of $3.5 \times 10^6$ tons per year. Which processes drive this import and which processes can possibly counteract them?

3. How is the sediment distributed spatially inside the basin and what roles do the influences of the basin hypsometry, the tide, wind waves and biology play herein?

Each process can have its spatial region of influence, and drive the sediment in a certain direction. It could therefore be interesting to see at which elevations most fine sediment is deposited, and to identify which processes are responsible for this distribution.

4. What is the annual loss of sediment to the saltmarshes and which processes drive this transport?

Salt marshes are muddy areas that are flooded during spring tides or storm setup, but remain dry during normal conditions. They are the internal margin separating the basin from the land. The amount of sediment that is deposited there can therefore indicate whether a basin is gradually growing larger (extending landward) or getting smaller (retreating).

To find an answer to these questions, the study makes use of the process-based model Delft3D (Deltares | Delft Hydraulics). Since large variations in biomass, species and mud-content can exist between two adjacent basins, the effects that are induced by varying basin characteristics are more difficult to investigate, when modelling on Wadden Sea-scale. This study will therefore focus on the processes on a basin-scale. For this purpose, an idealized basin was set up, which was modelled after the Borndiep basin and in which the watersheds were replaced by land boundaries.
The influences of some main tidal components, wind waves and biology on the sediment transport will be investigated through several model computations with different scenarios. The focus lies on the residual transport between the basin and its environment (the North Sea on one side and salt marshes on the landside).

1.4 Outline of the report

**Background information**

<table>
<thead>
<tr>
<th>System description</th>
<th>Chapter 2</th>
</tr>
</thead>
</table>

**Set-up of the model**

<table>
<thead>
<tr>
<th>General model set-up</th>
<th>Modelling biological influences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 3</td>
<td>Chapter 4</td>
</tr>
</tbody>
</table>

**Analysis of the results**

<table>
<thead>
<tr>
<th>Hydrodynamic results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sediment transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 6 - Tide</td>
</tr>
<tr>
<td>Chapter 7 - Waves</td>
</tr>
<tr>
<td>Chapter 8 - Biology</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Synthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 9</td>
</tr>
</tbody>
</table>

**Conclusions**

<table>
<thead>
<tr>
<th>Conclusions and Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 10</td>
</tr>
</tbody>
</table>
2 System description: the Dutch Wadden Sea

2.1 Study area

2.1.1 Geomorphology
The Wadden Sea, with a surface area in the order of 10,000 km$^2$, is Europe’s largest tidal flat. It is separated from the North Sea by its barrier islands and is divided into a series of 33 tidal inlet systems. The (Dutch) western Wadden Sea is bounded to the south by the Afsluitdijk and the main land, to the west and north by the five barrier islands (Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog) and to the east by the watershed of Schiermonnikoog. The tidal basins range in length from 15 to 40 km and have inlet channels up to 50 m in depth.

A tidal basin extends landward from the inlet, and consists of a system of channels, shoals and intertidal flats. At the location where two tidal waves travelling through adjacent inlets meet, velocities become near-zero and sedimentation occurs. The resulting tidal flat, the watershed, separates the two adjacent tidal basins from one another, giving each its own individuality. The main hydrodynamic processes hold, however, with certain variations for all tidal inlets [POSTMA, 1982]. Because of the time lag between a tidal wave crest passing one inlet and the next (about 20 minutes), the watersheds are situated nearer to the downstream inlet.

2.1.2 History
After the last glacial period, the continuing rise in sea level caused the inundation of old river valleys and topographical lows, creating tidal basins and lagoons [ELIAS, 2006a]. From the Middle Ages on, human interventions (e.g. land reclamation, dike construction, peat excavation, damming of channels and basins, etc.) has had an increasing influence on the development of the Wadden Sea [VAN LOON, 2005]. Despite these influences and the rising water levels, the main characteristic features of the Wadden Sea have still remained intact [ELIAS, 2006a].

2.1.3 Hydrodynamic conditions

Tides
The tide in the southern part of the North Sea shows a very complex flow pattern, with anti-clockwise rotation and propagation around three amphidromic points (locations where the vertical tide is nearly zero). Along the Dutch coast, the result is a combination of a standing and a progressive tidal wave, propagating from the south to the north. [ELIAS, 2006a] This wave meets another tidal wave at Den Helder, propagating from the west to the east. This latter wave rotates around an amphidromic point off shore to the West of Denmark (see Figure 2.1). The tide is dominated by the semi-diurnal $M_2$-component.

Since the tidal amplitude increases with increasing distance from the amphidromic point, the vertical tide along the Dutch Wadden Sea increases from about 1,4 m at Den Helder to 2,5 m in the Ems estuary.
The maximum current velocities in the channels and gullies can vary in the order of 0.5 to 1 m/s [ELIAS, 2006a]. In the large inlets, very strong currents can occur of about 2 m/s, whereas on the shallows, tidal current velocities rarely exceed 0.5 m/s. Currents are generally about 30% stronger during spring than at neap tides. [POSTMA, 1982]

In the western Wadden Sea, due to tidal asymmetry, the rise of the tide through the inlets takes less time than the fall of the tide. This results in somewhat faster currents at flood than at ebb. Inside the Wadden Sea basin, the tidal wave is deformed even further, due to bottom friction and other non-linear effects that are associated with the basin geometry. Nonlinearities produce higher harmonics of the principal oceanic tide. The most significant overtide is M4, the first harmonic of M2. The asymmetry in tidal currents is mostly quantified by the ratio between the M2 and the M4 tidal current amplitude and their phase difference. [EISMA, 1998]

Waves

Waves develop when wind stresses act on a water surface. Large waves can be generated offshore, where the fetch is large. Due to wave breaking and refraction on the shoals of the ebb tidal delta, however, only a limited amount of this wave energy is able to penetrate into the basin.

The smaller and shorter waves that are generated inside the basin, however, can still play an important role in the sediment transport processes: Waves can drive sediment transport directly via currents (generated by e.g. radiation stresses and wave asymmetry) and indirectly by allowing more sediments into suspension (by enhancing bed-shear stresses and stirring-up sediment) [ELIAS, 2006a]. The influence of waves is felt most strongly on the tidal flats, where the depth is limited.
Salinity

Due to freshwater inflow from a river into a basin, the salinity inside the basin will decrease from the tidal inlet towards the point of river (or sluice) discharge. In partially or well-mixed basins, the layers of fresh and salt water are mixed vertically over the entire water column, resulting in a gradual vertical salinity gradient. This also causes a longitudinal density gradient, which drives a residual seaward flow in the upper layer and a landward flow in the lower layer. This vertical (gravitational) circulation is also referred to as the estuarine circulation. The bottom flow can hold either very low concentrations, or very high concentrations, as a fluid mud layer. [Eisma, 1998]

An overview of the salinity distribution in the Wadden Sea is given by Postma (1982). The main characteristics for the Dutch part of the Wadden Sea are summarized below.

Several areas in the Wadden Sea receive fresh water from river discharge, thus reducing the salinity in these areas. The salinity shows a temporal variation, with the highest values in October, when the river runoff is minimum. The lowest values occur around March-April.

In the most western part of the Wadden Sea, fresh water can only enter the area through a system of sluices. This induces some important differences compared to a normal river runoff:

- The sluices only discharge around low tide. The fresh water is discharged in a gully and is transported towards the inlet with the ebb flow. The following flood takes a brackish mixture through another gully towards the watershed. As a result, the watersheds have a minimum salinity.
- During summer, the sluices may be closed for a certain period, to build up water storage for inland lakes and waterways. In that period, the salinity can reach the same level of the North Sea. In this case, due to evaporation, salinity can become maximum on the watersheds.

Since most basins in the Dutch part of the Wadden Sea receive very little or no fresh water inflow, the effect of estuarine circulation is not included in the present model.

2.2 Sediment

2.2.1 Fine sediment properties

The sediment fractions less than 2 mm in diameter are commonly classified into: sand (0.063 — 2 mm); silt (0.004 — 0.063 mm) and clay (< 0.004 mm). Because clay and silt generally occur in a fairly constant ratio for a certain system, the sediment fraction comprising both is referred to as mud or fines (≤ 0.063 mm).

The main source of fine sediments in the Wadden Sea is the North Sea. Secondary contributions are from: dredge spoil discharges, net primary production and atmospheric deposition [Van Loon, 2005]. Contributions made by the discharge of fresh water from land and the erosion of older beds in deep channels are of subordinate importance [Van Straaten & Kuenen, 1957].

Compared to sand-fractions, the mud content in the Wadden Sea bed is relatively low (< 10%). Going inward from the inlets, the mud content increases to high values (> 50%) near the borders and the watersheds [Van Ledden, 2003] (See Figure 2.2).
The amount of fine sediment in the water column and in the bed is an important governing factor for the physical, chemical and biological functioning of any aquatic ecosystem. In estuaries, fine sediment availability is tied to the occurrence and the distribution of many species living on and in the bed [De Vries et al., 2005]. Suspended sediment concentrations can reduce the penetration of light into the water and therefore have a direct influence on the ecosystem. Moreover, pollutants have the tendency to adhere on the clay particles in the mud. Consequently, the mud content can be an important indicator for the (potential) degree of pollution in the sediment bed [Van Ledden et al., 2004b].

2.2.2 Transport processes of fine sediment
The transport behaviour of fine sediment particles is quite different from that of larger particles. Large particles (like sand) are transported more closely to the bottom and stay in suspension only when the water is in motion. This makes the transport of sand generally proportional to (the third power of) the current velocities. Fine sediments, on the other hand, have a smaller settling velocity ($w$), so that for most water depths they do not settle to the bottom during slack tide and remain fairly evenly distributed over the water column [Postma, 1982]. Hence, the transport of fine sediments also depends on a large variety of other processes. A brief summary of the most important processes is discussed in the following. (A more detailed overview was also given by Van Ledden, 2003.)

- Settling and scour lag effects: The strength of the tidal currents decreases with increasing distance from the inlet. When following a certain water mass with the flood flow, gradually a part of the silt load in the water will start to sink to the bottom. Because it takes time for a sediment particle to descend to the bottom, the particle is transported a bit further inward than it would have if settling took no time at all. At that location, the particle has to wait a bit longer to be picked up again on the returning tide, since the original water mass that embodied it is still not strong enough to erode it from the bed. If picked up at all, the particle has to be picked up at a later stage in the tide, when the current is stronger. This means that the water mass that picks up the particle comes from further inside the basin and thus travels a
shorter distance towards the sea before the low water slack (LWS) occurs. [VAN STRAATEN & KUENEN, 1957; POSTMA, 1961]

- Asymmetry in tidal flow velocities: In the Wadden Sea, current velocities during flood are somewhat larger than during ebb. Since the transport of sediment is (amongst others) related to current velocities, this results in a net inward transport of sediments over the tide.

- Asymmetry in duration of slack water periods: A longer duration of the high water slack (HWS), means that particles have more time to descend to the bottom during HW. Combined with the long settling time for fine sediments, much more particles are able to settle during high tide, compared to low tide. Consequently, the suspended sediment concentrations after HW are much lower and less sediments are transported back on the ebb flow [VAN LEDDEN, 2003].

- Spring-neap variations: During neap tides, the intertidal areas experience a longer exposure to air, as well as relatively calmer hydraulic conditions, resulting in consolidation of the bed [WIDDOWS et al., 2000; VAN LEDDEN, 2003]. The consolidation influences the time lag between the hydrodynamic forcing and the sediment transport, which forces a residual flux. [VAN LEDDEN, 2003]

- Salinity gradients: Longitudinal gradients in salinity can cause a circulation pattern in the vertical pane, where the near bed residual transport is directed up-estuary. [VAN LEDDEN, 2003]

- Waves: As mentioned earlier in section 2.1.3, waves can directly and indirectly drive sediment transport. In general, waves generate an onshore sediment transport. On the other hand, during rough weather and a large set-up inside the basin, large suspended sediment concentrations caused by wave action will be transported back to the North Sea when the set-up recedes.

The net import or export of fine sediments is the result of a difference between the deposition and resuspension fluxes that occur in the basin over a tidal cycle. During slack water, most sediments will be able to settle, while during maximum ebb or flood most fine sediments will be picked up again. These upward and downward fluxes are very large (in the order of 10 kilotons), compared to their net difference (in the order of 0.1 kiloton).

With respect to this repeated process of deposition and resuspension of sediments inside a tidal basin, two different regions can be distinguished [Van Kessel, pers. comm.]:

1. A region where the bed shear stress climate is so severe that no permanent deposits are formed. Temporary deposition is possible e.g. during slack water, neap tide or calm weather, but integrated over a long timescale net accumulation is zero.

2. A region where the bed shear stress climate is so mild that permanent deposits are formed. Temporary erosion is possible, e.g. during maximum flood velocity, spring tide or stormy weather, but integrated over a long timescale net accumulation does occur.

Typically, permanent deposition only occurs in sheltered areas, like mudflats and saltmarshes.
2.3 Biological influences

Biogeomorphology deals with the study of the interaction between organisms and the bed they are living on or living in. [PAARLBERG et al., 2005]. Biota are known to have a large influence on the transport and the distribution of sediments. These influences can either be stabilizing or destabilizing. The Wadden Sea, like most intertidal areas, has a very rich ecosystem in which these interactions take place at different scale levels. In the following paragraph, various aspects of these influences will be discussed. A more detailed description of the modelled bio-engineers and the parameterization of their influence can be found in chapter 4.

2.3.1 Bio engineers

The term 'bio engineers' refers to the species of organisms that rework and build their habitat by crawling, burrowing and feeding activities, thus changing the composition, chemistry, hydrodynamic properties or shape of the sediment. When this leads to instability or increased erodibility of the sediment, this process is known as bioturbation or biodestabilization [BAPTIST, 2006]. On the other hand, when the stability of the sediment in increased, it is referred to as biostabilization.

Table 2.1 gives an overview of some important benthic activities and their overall effects as well as examples of species that occur in the Wadden Sea. [REISE, 2002; BAPTIST, 2006; BORSJE, 2006b]
Table 2.1: Biological processes influencing morphology. (Based on [REISE, 2002; BAPTIST, 2006; BORSJÉ, 2006b])

<table>
<thead>
<tr>
<th>Activity</th>
<th>Effects</th>
<th>Species in Wadden Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition feeding (deep or surface)</td>
<td>Resuspension of sediment by ejection or movements of grazer</td>
<td>Hydrobia ulvae (Mudsnail)</td>
</tr>
<tr>
<td></td>
<td>Modification of sediment particle distribution by selective particle uptake</td>
<td>Macoma balthica (Baltic tellin)</td>
</tr>
<tr>
<td></td>
<td>Modification of particle composition by fractionation</td>
<td>Arenicola marina (Lugworm)</td>
</tr>
<tr>
<td></td>
<td>Increase of water content in sediment</td>
<td>Heteromastus filiformis (Thread worm)</td>
</tr>
<tr>
<td>Filter / Suspension feeding</td>
<td>Taking particles out of suspension by filter feeding and depositing them on the bed</td>
<td>Mya arenaria (Sand gaper)</td>
</tr>
<tr>
<td></td>
<td>Changing sediment particle composition by pellet-formation</td>
<td>Cerastoderma edule (Cockle)</td>
</tr>
<tr>
<td></td>
<td>(locally) Raising the sediment bed</td>
<td>Mytilus edulis (Blue mussel)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lanice conchilega (Sand mason)</td>
</tr>
<tr>
<td>Burrowing and tube-building</td>
<td>Enlarging the area of interface between sediment and water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Changing sediment particle distribution by mixing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loosening and fluidizing the sediment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facilitating drainage of sediment at low tide</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Altering the near-bed hydrodynamics by an irregular topography</td>
<td></td>
</tr>
<tr>
<td>Other biological influences</td>
<td>Are able to form large algal mats in spring, in which they glue sediment together by excreting a sticky substance, called Extracellular Polymeric Substance (EPS) or mucus.</td>
<td></td>
</tr>
<tr>
<td>Diatoms (algae)</td>
<td>Stabilize the sediment bed with root systems</td>
<td></td>
</tr>
<tr>
<td>Plants</td>
<td>Alter the near-bed hydrodynamic conditions</td>
<td></td>
</tr>
</tbody>
</table>

Since the destabilizers graze on the algae/diatoms in the bed and in the water, they are often referred to as grazers. The most important destabilizers in the Wadden Sea are the deposit feeders and the suspension feeders. The stabilizers are represented by diatoms in the bed, also referred to as microphytobenthos.

2.3.2 Spatial and temporal variations

Spatial variations

The areas in which certain organisms may occur, is related to emersion time and water depth (See Figure 2.4). From the edge of the gullies up to the flats, 3 depth zones are distinguished, which are dominated by different groups of species.

Since diatoms depend on the penetration of sunlight for photosynthesis, they are restricted to intertidal and shallow subtidal areas, to a level of 1 m below mean sea level.
(MSL). In this zone deep deposit feeders like *Arenicola marina* (lugworm) and filter feeders like *Mya arenaria* (sand gaper) are also abundant.

Below MSL – 1 m the occurrence of diatoms and deep deposit feeders is much smaller. The biological influence on the sediment stability in this zone is mostly dominated by surface deposit feeders like *Hydrobia ulvae* (mud snail) and filter feeders like *Mya arenaria*.

The (shallow subtidal) zone between the mudflats and the edge of the gullies is almost permanently submerged, resulting in much lower contents of silt, organic matter and nutrients. Most surface deposit feeders are much less abundant in this zone, only the filter feeders like *Cerastoderma edule* (cockle) and *Mytilus edulis* (blue mussel) and the *Hydrobia ulvae* (mudsnail) are still present in large numbers.

**Temporal variations**

The seasonal variation in the climate also brings a seasonal variation in biomass and biological activity. From early spring, temperatures and sunlight penetration increase, which is rapidly followed by an increase in microphytobenthos (see Figure 2.3). Since the grazer biomass is still small during spring, it may be concluded that stabilization of the bed will be dominant for that time of year.

When the microphytobenthos biomass is maximal at the end of spring, the grazer biomass also starts to increase. At the same time, the abundance of grazers puts a hold on the increase in microphytobenthos. In early autumn, when grazer biomass reaches its peak, the biomass of microphytobenthos has already decreased significantly. This leads to the conclusion that destabilization of the bed is maximum during autumn.

![Figure 2.3: Phase difference between the temporally varying biomasses of microphytobenthos and grazers](image)
Figure 2.4: Schematic diagram summarising some of the major biological and physical factors influencing sediment stability in the intertidal zone. The dotted line represents the general shoreward increase in sediment stability with increasing cohesiveness and consolidation due to increasing air exposure and declining currents/wave action. The solid lines represent the long-term increase in sediment stability as a result of biota that persist for many years to >100 years (e.g. mussel beds and salt marsh). The dashed oscillating line represents the spatial (and temporal) changes in sediment erodibility due to short-term shifts (0.1 to >1 year) in the balance between the biostabilizers (microphytobenthos) and biodestabilizers (Macoma balthica, Hydrobia ulvae). [WIDDOWS & BRINSLEY, 2002]
3 Model set-up

3.1 General
To gain more insight into the different factors that influence the transport of sediments in a tidal basin and in order to make predictions concerning the long-term sediment balance, a model area that represents a schematic Wadden Sea basin was set up. Within the process based Delft3D model, the modules Delft3D–FLOW, -WAQ (Water Quality) and -WAVE were used for computations.

_Delft3D-FLOW_ is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid [WL | DELFT HYDRAULICS, 2007a]. The output of the computation done by Delft3D-FLOW is stored in a so-called communication file, which serves as an input for the Delft3D-WAQ module.

_Delft3D-WAQ_ is a (2D or 3D) water quality model framework. It solves the advection-diffusion-reaction equation for a wide range of model substances. Delft3D-WAQ is not a hydrodynamic model, so information on flow fields is derived from Delft3D-FLOW [WL | DELFT HYDRAULICS, 2007b]. In this case, Delft3D-WAQ was also used to model the effects of (wind) waves and biology. This will be explained into more detail in the following section.

The _Delft3D-WAVE_ module is able to compute wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation, for a given bottom topography, wind field, water level and current field in waters of deep, intermediate and finite depth [WL | DELFT HYDRAULICS, 2007c].

The following chapter describes the set-up of the model for the computations. For the basic assumptions and the governing equations used by the modules, reference is made to the user manuals of the modules [WL | DELFT HYDRAULICS, 2007a;b;c].

3.2 Computational grid and bathymetry
Figure 3.1 gives a graphical presentation of the possible (combinations of) dimensions for modelling. The grid used in the present model is 2-dimensional depth averaged (2DH).

The rectangular grid has a minimum grid size of 100 by 100 metres in the area of interest and a maximum grid size of 500 by 500 metres near the boundaries.

Figure 3.1 (source: user manual Delft3D-FLOW [WL | DELFT HYDRAULICS, 2007a])
The use of a depth-averaged model was justified by Van Loon [2005], who investigated the concentration profile of suspended sediment in the Wadden Sea according to the analytical formula of for sedimentation in flowing water by Winterwerp and Van Kesteren (2004). She found that the concentration was distributed almost evenly over the vertical. However, if the model would have included fresh water discharge, vertical stratification and salinity differences could introduce much larger vertical gradients, which may require a 3-dimensional approach.

Model area

As mentioned in chapter 2, the Wadden Sea can be seen as a series of tidal basins, which are separated by the watersheds and each having its own individuality. For instance, the basins in the west tend to be much deeper an longer than the basin that lie more to the east. In addition, large variations in biomass, species and mud-content can exist between two adjacent basins. When modelling on Wadden Sea –scale, this aspect makes the interpretation of the results much more difficult. The effects that are induced by varying basin characteristics are more difficult to investigate on such a large scale.

In order to gain more insight into the individual contributions of the processes influencing the transport and the distribution of fine sediments, this study will first focus on the processes inside a single basin. An advantage of modelling on basin-scale is the reduction of the computation-time, which becomes even more important when long-term computations are involved. It must be noted, however, that for some basins residual transport over the watersheds does take place and that, in that way, separate basins can still influence each other. Nevertheless, modelling on basin-scale can provide useful insights that can be applied in future models on Wadden Sea –scale.

The Borndiep basin, between the islands of Terschelling and Ameland, was used as a reference basin with respect to the geometry. With an average tidal prism in the order of $450 \times 10^6$ m$^3$, the schematic basin represents a mid-sized western Wadden Sea basin. Empiric equilibrium relationships exist for the dimensions of the inlet throat, the channel volume and the area of mudflats, related to the tidal prism. These relationships were used to determine the characteristic basin geometry.

![Bathymetry of the model domain](image)

*Figure 3.2: Bathymetry of the model domain. Bed levels are in metres above MSL.*
At the land-boundaries, the bottom slope gradually runs up to a high beach (or dune) level. At the boundaries where the watersheds would be situated, the slope also gradually runs up to a high marsh level at 2 metres above MSL.

**Hypsometry**

The term hypsometry refers to the distribution of surface area at different elevations. (For example, the total area of channels in relation to the total area of tidal flats.) The hypsometry of a basin can affect the tidal asymmetry and the currents inside the basin and can therefore strongly influence the distribution of sediments. Due to man-made changes (for instance, the closure of part of a basin or the continuous dredging of channels), a basin can suddenly get far out of its equilibrium state. It may take a very long time (in the order of decades or centuries) for the basin to return to its equilibrium state. An example of such a basin in the Dutch Wadden Sea is the Marsdiep basin, below the island of Texel. After the closure of the Zuiderzee, the channels and the inlet have become too large for the reduced tidal prism, resulting in a very different hypsometry.

To investigate the influence of these changes on the sediment balance of the basin, some computations were performed with a deeper basin, which resembled the hypsometry of the Marsdiep basin (viz. wide and deep channels and small tidal flats). The hypsometric curves of both basins can be seen in Figure 3.3. Graphs of the corresponding zonation inside the basins are presented in Figure 3.4, which illustrates the large differences in intertidal surface area of the two basins.

![Hypsometry of the model basin](image)

**Figure 3.3:** Hypsometry of the model basin, for a regular basin with narrow channels and large tidal flats (left) and for a relatively deep basin with wide channels and small tidal flats (right).
3.3 Initial and boundary conditions

3.3.1 Initial conditions and spin-up

A simulation time of two years is used to spin up each computation, starting from an empty bottom. This ensures that the initial sediment layer for each computation is distributed realistically for that typical computation and no erosion or sedimentation occurs due to initial disturbances.

The initial suspended sediment concentration is set to a uniform concentration of 5 mg/l for the entire model area. Since the computation starts at high water, initial disturbances in the water will be transported out of the model area relatively fast, so the influence of the initial concentration on the results is assumed to be minimal.

Figure 3.5 shows the resuspension and the sedimentation fluxes inside the basin, for the spinup years and the computational year. Since the morphology of the basin is dominated by the (in)balance between resuspension and sedimentation, the graph demonstrates that a spin-up period of 2 years is sufficient to smooth out the initial disturbances inside the basin.
3.3.2 Boundary conditions

**Hydrodynamic forcing**

For the hydrodynamic computation, a water level boundary condition is set at the northern sea boundary and Neumann boundary conditions are set at the western and eastern sea boundaries. The water level gradient for all sea boundaries is the harmonic wave as described in section 3.4.1.

**Sediment concentrations**

For the sediment computation, the western and eastern boundaries are divided into three sections, with different boundary conditions for the suspended sediment concentration to represent the natural gradient perpendicular to the coast. From the DONAR database, provided by Rijkswaterstaat, average values were derived for several distances from the coast, at two locations. Distinction has been made between winter and summer seasons, see Table 3.1 for details.

For the boundary sections closest to the coast (0 – 2 km), a cosine function is modelled, with minimum value of 5 mg/l in summer and a maximum value of 90 mg/l in winter. For the second sections (2 – 5 km), a cosine function with a minimum value of 5 mg/l in summer and a maximum of 40 mg/l in winter is modelled. For distances of more than 5 kilometres from the coast, the variations in the measured concentrations were too small to indicate seasonal differences. Appendix C shows a graphical presentation of the measured and the modelled concentrations.
Table 3.1: Measurements (in mg/l) of suspended sediment concentrations for locations near Callantsoog and Terschelling. Distances represent the distances of the measurement sites from the coast.

<table>
<thead>
<tr>
<th>Winter (November – April)</th>
<th>Terschelling</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Callantsoog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km 60 mg/l</td>
<td></td>
<td>0 – 2 km 90 mg/l</td>
</tr>
<tr>
<td>2 km 40 mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 km 20 mg/l</td>
<td>4 km 10 mg/l</td>
<td>2 – 5 km 40 mg/l</td>
</tr>
<tr>
<td>10 km 5 mg/l</td>
<td>10 km 5 mg/l</td>
<td></td>
</tr>
<tr>
<td>20 km 5 mg/l</td>
<td>20 km 5 mg/l</td>
<td>5 – 20 km 5 mg/l</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summer (April – October)</th>
<th>Terschelling</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Callantsoog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 km 25 mg/l</td>
<td></td>
<td>0 – 2 km 5 mg/l</td>
</tr>
<tr>
<td>2 km 15 mg/l</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 km 10 mg/l</td>
<td>4 km 25 mg/l</td>
<td>2 – 5 km 5 mg/l</td>
</tr>
<tr>
<td>10 km 5 mg/l</td>
<td>10 km 5 mg/l</td>
<td></td>
</tr>
<tr>
<td>20 km 5 mg/l</td>
<td>20 km 5 mg/l</td>
<td>5 – 20 km 5 mg/l</td>
</tr>
</tbody>
</table>

3.4 Hydrodynamic computation

3.4.1 Hydrodynamic forcing
The only hydrodynamic forcing in the model is the tidal wave, which is imposed at the sea boundaries of the model area by means of a waterlevel variation (with a phase difference from west to east).

The tide was schematized as a harmonic wave with 3 astronomical constituents (M2, S2 and K1). The main constituent is the semi-diurnal lunar tide (M2), with an amplitude of about 0.9 m. The semi-diurnal solar tide (S2) introduces a spring-neap tidal cycle in the model. A fifth component, the diurnal K1- tide introduces a diurnal inequality. Since non-linear shallow water effects distort the astronomical tide when it reaches the coast, also 2 higher harmonics of M2 (viz., M4 and M6) are included to represent this distortion.

The phase differences between all constituents are according to realistic values for the North Sea just outside the Wadden Sea. They are based on data from the ZUNO-model, which simulates the movement and distortion of the tidal wave in the Southern North Sea.

To reduce computation time, the frequencies of the M- and K- components were adjusted to reach a combined tidal period of 15 days, meaning that on the 16th day, the phases of all constituents are equal to those on the first day. (Since the K1 component was given a frequency equal to half the frequency of S2, and is therefore from now on referred to as S1.) This has the advantage that the FLOW module only needs to compute the hydrodynamic conditions for a period of 15 days, which can be rewound continuously during the Delft3D-WAQ, computation, until an update of the hydrodynamics is desired (for example, due to changed bathymetry or mean sea levels).
Bottom roughness is modelled as a depth-varying Chezy coefficient, which is calculated according to the Manning formulation, with a constant Manning coefficient of 0.024 for the entire model area. In equation form, the Manning formulation reads:

\[ C = \frac{H^{\frac{1}{3}}}{n} \]  

(3.1)

Since for most Dutch Wadden Sea basins, the inflow of fresh water from discharging rivers is very small, this effect was not taken into account in the modelled basin.

3.4.2 Scenarios
To investigate the influence on the sediment transport of the separate tidal components, 3 different scenarios were used for the computations:

1. hydrodynamic computation with the diurnal lunar tide (M2) only;
2. hydrodynamic computation with M2, including tidal asymmetry from M4 and M6;
3. hydrodynamic computation with M2, M4 and M6, including a spring-neap variation from S2 and a daily inequality from S1.

3.5 Wave computation
Within a tidal basin, (wind-) waves are the main contributors to the stirring up of fine sediments, by enhancing the bottom shear stress. Currents are primarily dominated by the waterlevel variations from the tide, and are concentrated in a system of channels and gullies. Local wave driven currents do not substantially contribute to the sediment transport inside the basin and are therefore not taken into account. The contribution of the waves is therefore schematized as a contribution to the bottom shear stress only.

Waves are generated when wind stresses act on a water surface. Wind speeds are highly variable, which makes it very complicated to identify the relevant wind speed for a specific time scale. For instance, when focussing on the sediment transport with a time scale of several years, it might suffice to use only a constant average value for the wind velocity. However, one could argue, that the distinct increase in wind velocities during winter might also play an important part in the annual and multi-annual sediment transport. This effect could be taken into account by adding a harmonic seasonal variation to the average wind.

On the other hand, it might still be possible that the peaked variation of the wind, with a typical timescale in the order of several days, can have a strong influence on the long-term sediment transport as well. In example: suppose that for the areas above MSL the erosion threshold is only exceeded by waves caused by a wind velocity of at least 10 m/s. If the ‘typical’ upper and lower peaks of the wind velocity range between, say, 2 and 12 m/s, the average wind speed will be 7 m/s. When this average speed is applied in a computation, the erosion threshold in the areas above MSL will never be exceeded. If the same computation is done using real timeseries of the wind speeds, the erosion threshold in these areas will be exceeded about every three days. It can be expected that the results will show large differences after a computation of one year.
3.5.1 Wave computation in Delft3D-WAQ

The computation of the contribution of waves to the bottom shear stress can be done within Delft3D-WAQ, based on varying wind speeds and fetch. The main advantage of this simplified approach is that it involves less computation time and can be done within the sediment computation. In that way, waves can be computed for each time-step, based on the instantaneous waterlevels, without the need of additional time-consuming external computations. A disadvantage of the implementation in WAQ, is that the bottom shear stress (BSS) due to waves is added to the BSS from the tide as a scalar, instead of a vector. This can lead to an overestimation of the total bottom shear stress, because in reality, the angle between the two contributions would lead to a non-linear interaction.

However, regarding the bottom shear stress, the contribution from the tide will be very small in those areas where the contribution of the waves becomes important (the shallow areas), and vice versa. The overestimation caused by the non-linear interactions will therefore be very limited.

3.5.2 Wave computation in Delft3D-WAVE

Another approach is to do the wave computation in Delft3D-WAVE. The module can use the hydrodynamic conditions derived from Delft3D-FLOW, on which the wave action is superposed. In this way, the bottom shear stress due to waves is computed as a vector. When the computations by the two modules are coupled, wave driven currents can also be taken into account.

The model with Delft3D-Wave calculates the wave based on the actual fetch in each computational cell for the given wind direction. Multiple wave fields can be computed, representing a part of a wave spectrum. However, since this research has a more fundamental approach, and is focussed on long-term processes, these highly detailed computations would be superfluous and would take up too much computation time.

The computation was based on only one wind direction, representing a dominant wind direction from the north-west. One computation was done with a constant average wind velocity for the entire year. Twelve additional computations, each representing a monthly averaged wind velocity, were performed in order to model a harmonic seasonal variation.

Since a basin for a large part consists of intertidal areas, where the instantaneous depth is dominated by variations in the waterlevel, the waves would have to be calculated for each waterlevel separately (based on the computation with Delft3D-FLOW). The result will then be read into the morphological computation. This will have a strong negative impact on the overall computation time, so in this case the wave computation in Delft3D-WAVE is performed for only one waterlevel, at high water. This simplification will result in an overestimation of the waves in the intertidal areas. The impact of this overestimation on the results will be investigated in chapter 7.

3.5.3 Scenarios

In order to identify the relevant scales of the wind velocities, 4 different types of scenarios were used, based on the analysis of 20 years of wind speed data from the KNMI:

1. wave computation with a constant, average wind velocity;
2. wave computation with an average harmonic seasonal variation;

3. wave computation with an average harmonic seasonal variation, including a superimposed harmonic 3-daily variation. The amplitude of this variation is based on the standard deviation from the mean seasonal value. Since this deviation is larger in winter than in summer, the amplitude of the 3-daily variation is also larger during winter. Peaks that fall outside the range of the standard deviation, are considered as storms and are not represented by the 3-daily variation.

4. wave computation with real timeseries of the wind speed.

The scenarios above were computed inside the morphological computation in Delft3D-WAQ. Two additional scenarios were applied in Delft3D-WAVE, in order to determine the differences in performance between the two modules:

5. as scenario 1, but wave computation in Delft3D-WAVE;

6. as scenario 2, but wave computation in Delft3D-WAVE.

Figure 3.6 shows plots of the variation of the wind velocities throughout the year, for the different scenarios.
Figure 3.6: Wind speed scenarios for the wave computations
3.6 Morphological computation

3.6.1 Sediment transport
Due to the relatively small particle sizes and small settling velocities, the transport of fine sediment mainly takes place in suspension and is usually calculated from the local instantaneous flow conditions. Horizontal transport of fine sediments is described by the advection-diffusion equation, in which advection is determined by the velocity field and diffusion by the dispersion coefficient, to account for vertical deviations from the depth-averaged values in the model.

The vertical transport of fine sediment is described as a sedimentation- (downward) and a resuspension- flux (upward). Sedimentation is based on the fall velocity $w_s$ and the near-bed concentration [WINTERWERP, 2004]. Erosion occurs when the bottom shear stress exceeds the critical shear stress ($\tau_{crit}$) of the sediment, otherwise, sedimentation will occur. The rate at which erosion takes place is determined by the erosion parameter (M) and the ratio between the bed shear stress and the critical shear stress.

3.6.2 Bottom layers
Part of the fine sediment particles that are deposited on the bed, can become trapped in between the larger grains in the bed. As they sink deeper into the pores of the bed, they can erode less easily than the layer at the top of the bed. In this way, silt can accumulate in the bed, even in areas where the hydrodynamic climate is too severe for permanent depositions to develop on top of the bed.

This strengthening of the bed cannot be simulated properly by a single bottom layer, into and out of which sedimentation and erosion can take place. To resolve this issue, a second bottom layer is introduced. In this second layer, the erosion rate is not only proportional to the excess bed shear stress, but also to the mud fraction in the bed. A map of the soil composition is thus also obtained for areas without permanent deposition. [VAN LEDDEN et al., 2006; VAN KESSEL et al., 2007; VAN KESSEL, 2008 (personal communication)]

Sedimentation to the second bottom layer is modelled by distributing a fraction of 5% of all deposited sediment directly towards this layer (see Figure 3.7).

![Deposition and resuspension fluxes to and from the bottom layers.](image)

Figure 3.7: Deposition and resuspension fluxes to and from the bottom layers.
3.6.3 Biological influences
As mentioned in the previous chapter, biology can influence the transport and the distribution of fine sediments. Stabilization and destabilization by biology is modelled by reducing, respectively, enhancing the critical shear stress ($\tau_{crit}$) and additionally by reducing and enhancing the erosion parameter (M).

These processes all depend on the biomass and bioactivity of the stabilizers and destabilizers. The temporal variation of this bioactivity is modelled as a harmonic function, the spatial variation is determined by the depth zone. Chapter 5 goes into more details about the implementation of biology in the model.

3.6.4 Scenarios
Waves were also taken into account in the computations with biology. A seasonal varying wind with a synthetic inter-daily variation was used, since it bears the closest resemblance to the real wind speed data, while the harmonic signal makes the model more transparent and the results easier to interpret.

Based on a hydrodynamic computation with 5 tidal constituents, several scenarios were defined to determine the sensitivity of the modelled system to the biology:

1. Biological influences based on average grazer and average diatom biomass
2. Biological influences based on doubled grazer biomass and average diatom biomass
3. Biological influences based on average grazer biomass and doubled diatom biomass
4. Biological influences based on doubled grazer and doubled diatom biomass

3.7 Evaluation data
The modelled basin does not represent a real existing basin, but is only a schematic representation of a real Wadden Sea basin, which complicates the comparison of the results with measurements from reality. However, since the dimensions and boundary conditions were based on the Borndiep basin, the measurement data from that area can serve as an indication for the orders of magnitude and the occurrence of processes, as well as global trends in the basin. Since the focus of this research lies on gaining insight into the fundamental processes, this will be sufficient to validate the model results and to answer the research questions.

**Suspended sediment concentrations**
For the suspended sediment concentrations, the measurement data from the Donar database [RIJKSWATERSTAAT, 2007] are used. The Donar database gives the results of suspended sediment concentrations for all sediment fractions. This means that sediment fractions that fall outside the range of this study (sand particles, for example) are also included. This could lead to a slight overestimation of the fine sediment concentration in the water. On the other hand, suspended sediment transport is in general usually dominated by fine sediments, due to their limited settling velocity. Moreover, the slight overestimation is negligible compared to the large variations in the measured concentrations: the difference between subsequent measurements at one location can sometimes even be in the order of 200%. For the same reason, the
database can only be used as an indication of the order of magnitude of the concentrations.

Sediment distribution on the bed
Data on the distribution of fine sediments in the bed is derived from Sedimentatlas [RIJKSWATERSTAAT RIKZ, 1998]. Because the model is spun op from an empty bottom, the results after each computation can be compared with data from Sedimentatlas.
4 Modelling biological influences

4.1 Formulations for biological influences on sediment erodibility

To determine the influence of biota on the sediment, the biomasses of stabilizers (microphytobenthos) and destabilizers (grazers) need to be translated into modification factors for the two important parameters that determine the erodibility of the sediment: the critical bed shear stress and the resuspension parameter.

The formulations that were initially used to describe the influence of biota on the sediment are based on the formulations proposed by Holzhauer [2003], Paarlberg [2004] and Smits [2004] and on data from Widdows et al. [2000]. These formulations are explained in further detail in section 4.1.1.

While investigating the abovementioned formulas, some potential problems arose, which are explained in section 4.1.2. Consequently, several possible improvements are suggested in section 4.1.3. These adjusted formulations have already been implemented in the computations for the modelled schematic basin and are worked out in section 4.1.4.

Graphical representations of the differences between the formulations are presented in appendix B-1. The results for the model basin, calculated with the new formulations, can be found in appendix B-2.

4.1.1 The initial formulations

As mentioned before, the influence of biota is taken into account through modification of the critical bed shear stress and the erosion parameter by stabilizing and de-stabilizing factors:

\[ \tau_{\text{crit}} = \tau_{\text{crit}}^0 \cdot (f_s \cdot f_d) \]  \hspace{1cm} (4.1)

And:

\[ M = M^0 \cdot (g_s \cdot g_d) \]  \hspace{1cm} (4.2)

Where \( f_s \) and \( g_s \) represent the stabilising factors and \( f_d \) and \( g_d \) represent the destabilizing factors. \( M^0 \) and \( \tau_{\text{crit}}^0 \) are the values in absence of biological influences.

The formulations use a logarithmic relationship to determine the modification factors.

**Stabilization:**

The stabilizing factors \( f_s \) and \( g_s \) are a function of the chlorophyll-a concentration in the sediment layer:

\[ f_s = 1 + a \cdot \ln(\text{Chf}) \]

\[ g_s = 1 - b \cdot \ln(\text{Chf}) \]  \hspace{1cm} (4.3)

Where \( \text{Chf} \) is the concentration of chlorophyll-\( \alpha \) in the top sediment layer (\( \mu \text{gChfla/g} \))
Destabilization:
The destabilizing factors \( f_d \) and \( g_d \) are a function of the density of zoöbenthos in the bed \( B \). The formulas below calculate the influence of two different zoöbenthos species. In order to account for the possibility that the two different grazer types are reworking the same material (overlap), the quadratic terms are multiplied by a factor based on the relative biomass of each species. [De Vries, personal communication].

\[
\begin{align*}
    f_d(B) &= 1 + c_1 \cdot \left( \frac{Czb_1}{Czb_{tot}} \right) \cdot \left( \ln \left( \frac{Czb_1}{Mzb_1} \right) \right)^2 \\
        &\quad - d_1 \cdot \ln \left( \frac{Czb_1}{Mzb_1} \right) + c_2 \cdot \left( \frac{Czb_2}{Czb_{tot}} \right) \cdot \left( \ln \left( \frac{Czb_2}{Mzb_2} \right) \right)^2 \\
        &\quad - d_2 \cdot \ln \left( \frac{Czb_2}{Mzb_2} \right) \\
    g_d(B) &= 1 + e_1 \cdot \left( \frac{Czb_1}{Czb_{tot}} \right) \cdot \left( \ln \left( \frac{Czb_1}{Mzb_1} \right) \right)^2 \\
        &\quad - j_1 \cdot \ln \left( \frac{Czb_1}{Mzb_1} \right) + e_2 \cdot \left( \frac{Czb_2}{Czb_{tot}} \right) \cdot \left( \ln \left( \frac{Czb_2}{Mzb_2} \right) \right)^2 \\
        &\quad - j_2 \cdot \ln \left( \frac{Czb_2}{Mzb_2} \right)
\end{align*}
\]

(4.4)

(4.5)

Where:

- \( Czb_{1,2} \) = concentration of zoöbenthos species (1,2) in the top sediment layer [gC/m\(^3\)]
- \( Czb_{tot} \) = combined concentration of both zoöbenthos species [gC/m\(^3\)]
- \( Mzb_{1,2} \) = average biomass of a zoöbenthos individual of species (1,2) [gC]
- \( a,b \) = coefficients for microphytobenthos influence on taucrit and \( M \)
- \( c,d,e,j \) = coefficients for zoöbenthos species (1,2) influence on taucrit and \( M \)

For the complete formulations, the reader is referred to Smits [2004].

4.1.2 Potential problems regarding the initial formulations
As mentioned before, the initial formulations gave some problems:

- The logarithmic function goes to negative infinity when the input reaches zero. For input smaller than 1, the logarithmic function returns a negative value. To cope with this aspect, the computations do not allow input smaller than 1.
- The function has negative values within the domain. For very high biomass values, for instance when two species of grazers are present, the functions can return negative values, which have no physical meaning.
- The function has no upper limit, while one might expect that the influence on the erodibility would have a maximum value.
- To convert the input data from gC/m\(^3\) into individuals/m\(^2\), an estimate for the grazer’s individual biomass is used. Since the individual biomass shows a distinct spatial variation and has an inverse relation with the numbers of individuals, this could lead
to an over- or underestimation of the actual grazer density in an area. Instead of converting the original data, one could simply use the number of individuals found in biomass surveys as formula input. On the other hand, the difference between a small group of large grazers and a large group of small grazers will still not be accounted for. More details on this issue can be found in section 4.2.3.

- Subsequently, the grazer density per $m^2$ is converted even further into a density per $m^3$, before finally serving as input in the logarithmic functions. To convert the data to ind/m$^3$, the value is divided by a so-called benthos layer thickness, which has no real physical meaning for the influence on the erodibility. While the value for this thickness is chosen quite arbitrarily, it has a very large influence on the outcome of the logarithmic function, making it less reliable.

4.1.3 Proposed adjustments
With respect to the problems mentioned above, the following suggestions for improvement are proposed. These adjustments have already been implemented in the calculations with the schematic basin.

Instead of using a logarithmic function, a hyperbolic tangent (tanh) was used, which brings several advantages:

- The hyperbolic tangent goes to zero when the biomass reaches zero.
- It has no negative values within the domain.
- When the biomass continues increasing, the function gradually reaches a maximum value. In this case, extremely high biomass values will no longer return unrealistic values for the (de)stabilization factors.
- The function can very easily be adjusted to fit the data optimally.
- The input for the grazer influence is in gC/m$^2$. This solves the problem in defining a ‘benthos layer thickness’ as well as the inconsistencies between individual biomasses and numbers of individuals.
- When two species of grazers are present, the influences are combined inside the hyperbolic tangent, while maintaining the function’s upper limit. The added influence of the second grazer is reflected in a faster increase of the function towards this limit.
- Finally, when using a sub-routine to calculate the biological factors online with the Delft3D-WAQ computation, the calculations would lose their transparency and possible modelling errors or inconsistencies could remain unnoticed. It is therefore strongly advised to determine the biological factors prior to the model computations and to enter the modified tau crit and resuspension parameter as segment functions in the Delft3D-WAQ module.

4.1.4 New formulations
As mentioned in the previous section, the new formulations are based on a hyperbolic tangent. A square root has been added to give the relationship a slightly stronger increase for lower biomass values and a more gradual increase when the function approaches the limit value.

Several important comments must be made, regarding the formulas:

- In both formulations, the coefficients are not dimensionless! Since the input inside a hyperbolic function should always be dimensionless, it follows that the coefficients have a dimension that is the inverse of the biomass dimension. This means that
these coefficients are in fact not ‘clean coefficients’, but may also include some unknown biotic or a-biotic parameters. These formulations are based on (few) experimental data and still very little is known about all the possible parameters that could be involved in the interaction between biology and the sediment. For now, these formulations give only a circumstantial estimate of the actual influences.

- Only few and very circumstantial measurement data was on hand during the setup of the model, so the new formulations are adjusted to ‘fit’ the previous formulations. This means that some of the problems and inconsistencies of the old formulas could have influenced the new formulas through the definition of the coefficients. The coefficients that were used in the calculations are therefore merely indicative. Additional literature research and flume measurements are recommended to calibrate the new formulations.

**Stabilisation:**

The stabilising factor for the critical bed shear stress:

\[ f_s = 1 + (f_{s,\text{max}} - 1) \cdot \sqrt{\tanh\left(a \cdot Chf\right)} \]  
(4.6)

The stabilising factor for the resuspension parameter:

\[ g_s = 1 - (1 - g_{s,\text{max}}) \cdot \sqrt{\tanh\left(b \cdot Chf\right)} \]  
(4.7)

Where \( f_{s,\text{max}} \) and \( g_{s,\text{max}} \) are the limit values for maximum stabilisation. \( Chf \) is the chlorophyll-\( \alpha \) concentration in \( \mu \text{g} \) per g dry sediment. Coefficients \( a \) and \( b \) determine how rapidly the function reaches its limit value (NB: the dimension of these coefficients is \( g/\mu \text{g} \)).

**Destabilisation:**

The destabilising factor for the critical bed shear stress:

\[ f_d = 1 - (1 - f_{d,\text{max}}) \cdot \sqrt{\tanh\left(c_1 \cdot Czb_1 + c_2 \cdot Czb_2\right)} \]  
(4.8)

The destabilising factor for the resuspension parameter:

\[ g_d = 1 + (g_{d,\text{max}} - 1) \cdot \sqrt{\tanh\left(e_1 \cdot Czb_1 + e_2 \cdot Czb_2\right)} \]  
(4.9)

Where \( f_{d,\text{max}} \) and \( g_{d,\text{max}} \) are the limit values for maximum destabilisation. \( Czb \) is the biomass of the specific grazer species (subscript 1 or 2) in gC/m\(^2\). Again, the coefficients (\( c \) and \( e \)) determine how quickly the function reaches its limit value (Note: their dimension is m\(^2\)/gC).

### 4.2 Grazer biomass

The following biomass information biomass has been derived from a monitoring programme performed by the Royal Netherlands Institute for Sea Research (NIOZ). Along twelve transects in the Dutch Wadden Sea and the Ems-Dollard, biomasses of several important macrozoobenthos were determined, twice a year, for the years 2001, 2002, 2004, 2005 and 2006. For more information on these measurements and the sampling methods, the reader is referred to the original NIOZ reports (in Dutch): “Het..."
Up to now, most research on the influence of grazers on sediment stability has primarily focused on two macrozoobenthos in particular: the *Macoma balthica* (baltic tellin (English) or nonnetje (Dutch)) and the *Hydrobia ulvae* (mudsnail (EN) or wadslakje (DU)) [Austén et al., 1999; Andersen et al., 2002; Lumborg et al., 2006]. However, recently some additional research on the influence of *Arenicola marina* (lugworm or wadpier) has been performed by the author herself. Hopefully, this may lead to additional formulations for the sediment stability in the near future. Since this investigation is still running, for now only Macoma and Hydrobia were considered in this report.

Graphical representations of the spatial and seasonal variations in grazer biomass can be found in Appendix B-3.

4.2.1 Seasonal variation in biomass
Biomass counting was performed twice a year, to include seasonal variations. Winter counts were performed at the end of winter (February/March), when the grazer biomass is assumed to be at its minimum value. Summer counts were done at the end of summer in August/September. *Hydrobia* generally shows a distinct difference between summer and winter biomass, while the variation in *Macoma* biomass tends to be much smaller.

For modelling practise, the biomass is assumed to vary harmonically over the year. The peak value is defined by the average summer biomass; the minimum value equals the average winter biomass.

For both *Macoma* and *Hydrobia* the seasonal variation in biomass is mainly the result of a variation in numbers of individuals. This variation in numbers does not necessarily have to be the result of mortality; it can also partially be the result of migration.

4.2.2 Spatial variation in biomass
The twelve monitoring transects are situated at different levels with respect to MSL, thus providing an indication for the biomass distribution in relation with the elevation. It must be noted that using a depth-related spatial variation is a very simplistic representation of reality, since there are numerous other factors that can largely influence this variation (for instance: soil composition, abundance of predators, availability of nutrients, etc.). However, for large-scale modelling practice, it would be impossible or might even be superfluous to include all these factors. Moreover, some of these other factors show some correlation to the elevation as well, so for the schematic basin, using a spatial variation based on the elevation seems justified.

For *Hydrobia*, the biomass shows a relatively clear correlation with the elevation ($R^2=0.7$). Unfortunately, the correlation for *Macoma* appears to be rather faint ($R^2=0.1$). A possible explanation for this can be the strong decline in *Macoma* biomass over the years 2001 – 2006. In 2001, the average biomass on the transects was still 3.5 gC/m$^2$, in 2004 this average had already decreased to 1.6 gC/m$^2$ and in 2006 the value was only 0.8 gC/m$^2$ (a total decline of over 75%). This trend makes it rather difficult to determine a reasonable multi-annual relationship. Nevertheless, for this research, even
rough estimates of the spatial variation can still provide useful insights into the fundamental interactions between biota and their environment.

The absolute differences between summer and winter values show some spatial variation as well: for Hydrobia these differences are larger in deeper areas. (This makes sense, when one considers that the overall biomass of Hydrobia is also much larger in the deeper areas. Accordingly, the relative difference seems to remain fairly constant.) Quite the opposite is true for Macoma, for which the seasonal differences tend to be much smaller in the deeper areas. This too could be explained: the Macomas in the deeper areas are larger and more mature (25% are over 5 years old). These Macomas might therefore be less sensitive for temperature changes and the mortality rate will probably be dominated by age, rather than the season.

In the model, the grazers occur in a domain that extends from MSL -4.5 m to MSL +1m. At the edges of this domain, the biomass linearly reduces to zero over a distance of 1m (in height), in order to avoid large biomass gradients between computational cells.

The following plots show the (summer) biomass distribution in the schematic basin for Macoma and Hydrobia.

Figure 4.1: Biomass distribution inside the schematic basin for Hydrobia ulvae

Figure 4.2: Biomass distribution inside the schematic basin for Macoma balthica
4.2.3 Variation in biomass composition

Another possibly important aspect for modelling is the difference in biomass composition. Composition in this case refers to the number of individuals that contribute to the total biomass of the species, in a certain area. For instance, a large biomass can be the result of only some large individuals or hundreds of small individuals.

Especially for Macoma, there appears to be an inverse relationship between individual size and numbers of individuals. At high elevations, the biomass is dominated by a large number of small, juvenile Macomas. In the low-lying parts, on the other hand, the main contribution to the biomass comes from several large, mature Macomas. However, when comparing only the total biomass, the difference between the two areas is much smaller: about 2 gC/m$^2$ at high levels versus 3 gC/m$^2$ in deeper areas.

When investigating the influence on the sediment, this aspect gives rise to the following question: what would be the difference in impact between, say, 100 Macomas of 0.01 gC each or 20 Macomas of 0.05 gC each (both 1 gC/m$^2$)? It might very well be possible that the difference in size can balance the difference in numbers. If so, the sediment stability should best be related to the biomass in gC/m$^2$, rather than individuals/m$^2$. It is therefore recommended to pay some attention to this aspect in future studies.

4.3 Chlorophyll-$\alpha$ concentration

The largest contribution in chlorophyll-$\alpha$ in the top layers of estuarine sediments comes from benthic diatoms [DE JONG & DE JONGE, 1995]. The concentration in chlorophyll-$\alpha$ can therefore serve as a useful parameter when modelling the abundance of microphytobenthos.

De Jong and De Jonge (1995) performed several measurements over 2 consecutive years at different locations in the Western Scheldt, to investigate seasonal and spatial patterns in chlorophyll-$\alpha$ concentrations. Since the concentrations in the Western Scheldt are comparable to those in the Wadden Sea and Ems estuary [DE JONG & DE JONGE, 1995], their findings have also been used to define the concentrations in the modelled Wadden Sea basin.

4.3.1 Seasonal variations in biomass

For easier interpretation of the model results and a better understanding of the basic interactions between grazers and diatoms and their combined influence on sediment stability, the seasonal variation in the chlorophyll-$\alpha$ concentration is also modelled as a harmonic function, instead of using time series of measurement data. The peak of the function lies at the beginning of June, when the diatoms are assumed to have reached their spring bloom.

It must be noted, however, that a harmonic function might not be the best representation of the seasonal pattern, since diatom populations can adapt very quickly to changes in conditions (such as light penetration, temperature, availability of nutrients). As soon as conditions turn favourable, the diatom populations start to grow very rapidly (bloom) until the conditions become unfavourable again. This can sometimes result into multiple bloom periods. [CADEE & HEGEMAN, 1979; DE JONG & DE JONGE, 1995] However, the occurrence of secondary bloom periods can vary per year, so when investigating long term averages, the signal will probably show a stronger resemblance to a harmonic function.
While the maximum concentration in early summer can depend on many factors (e.g. location, temperature, nutrients) and shows much more variation, the minimum value in winter is almost uniform at about 2.5 µgChla/g [De Jong & De Jonge, 1995]. Accordingly, in the modelled schematic basin the minimum concentration in winter is also kept uniform at 2.5 µgChla/g. The maximum value in summer has been given a spatial distribution, as will be explained in the next section.

4.3.2 Spatial variations in biomass

Based on measurements done in the Western Scheldt, De Jong and De Jonge [1995] found a clear positive correlation between the elevation according to MSL and the mean annual chlorophyll-α concentration. The decrease in concentration with decreasing elevation could be explained by the turbidity of the water preventing sunlight from reaching the bottom. The highest maximum concentrations seemed to be reached around or just above MSL. Higher above this level desiccation, due to a reduction in submergence time, might have hampered the primary production.

De Jong and De Jonge also found some positive correlation between the clay content of the sediment and the chlorophyll-α concentration. They ascribe this to the phenomenon that areas with a high clay content are also areas with very low hydrodynamic energy, which has a significant influence on the occurrence of microphytobenthos [De Jonge, 1992; De Jonge & Van Beusekom, 1992]. Additionally, soil with high clay content is able to retain water more effectively, which might prevent desiccation at higher elevations, thus allowing for higher concentrations in these areas.

Since the measurement data suggested a possible interaction between elevation and clay content, De Jong and De Jonge classified the measurement stations into three classes per parameter. The annually averaged chlorophyll-α concentrations were calculated per class and they are presented in Table 4.1. Since no actual clay content for the schematic basin had been defined yet, the areas with the highest elevation were assumed to be also the areas with the highest clay content. The marked values in the table indicate the values that were used to define the mean annual concentration in the model. This approach seems somewhat simplistic but, for the schematic basin, it should suffice as an approximation.

Table 4.1: the annually averaged chlorophyll-α concentration per combination of elevation class / clay content class. [De Jong and De Jonge, 1995]

<table>
<thead>
<tr>
<th>CHLOROPHYLL-α (µg / g)</th>
<th>Clay content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m)</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>&lt; MSL</td>
<td>2.7</td>
</tr>
<tr>
<td>MSL to +1</td>
<td>4.1</td>
</tr>
<tr>
<td>&gt; +1</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Instead of using the elevation classes in the model, the model uses a linear approximation to prevent large concentration gradients between neighbouring computational cells. The three diagonal values in the table are plotted against a ‘characteristic’ elevation in the figure below. The linear approximation extends from
MSL -1.5m to MSL +1.5m. From MSL +1.5 to +2m, the concentration linearly decreases to zero. (See Figure 4.3)

**Figure 4.3:** modelled linear relationship between the annual mean Chlorophyll-a concentration and the elevation.

Since the annual mean concentration is defined spatially (as described above) and the annual minimum is kept uniform at 2.5 µgChfl/g, the amplitude for the seasonal harmonic variation follows from the difference between the former two. The modelled seasonal variation for three different transects are plotted in Figure 4.4.

Finally, Figure 4.5 shows the distribution of chlorophyll-α in the schematic basin, at its maximum spring value.

**Figure 4.4:** Seasonal variation in Chlorophyll-α concentration at different elevations with respect to MSL.
Figure 4.5: distribution of Chlorophyll-α in the schematic basin, maximum spring value
5 Hydrodynamic results

The tidal wave is the only hydrodynamic forcing in the model. As was explained in chapter 3, the tide has been schematised with 5 components (M2, M4, M6, S1 and S2), representing the most important features of the tidal wave (viz. tidal asymmetry, spring-neap variation and a diurnal inequality).

The different tidal components were imposed as waterlevel variations on the sea boundaries. To investigate the propagation and growth (or decay) of each of these components, a Fourier analysis has been performed for the scenario with 5 tidal components. The results for the amplitudes and phases of the water levels can be found in Appendix D-1.

5.1 Tidal asymmetry

As the tide propagates further into the modelled domain, the distortion due to shallow water effects becomes larger. Figure 5.2 and Figure 5.3 both show the waterlevels of the hydrodynamic computation, compared to the water levels of the predicted astronomical tide [RIJKSWATERSTAAT, 2008] for a secondary channel inside the Borndiep basin (measurement station Nes). The results from the model are calculated for a corresponding location in the modelled basin, called station Nes*. See Figure 5.1 for the position of both stations. The results are plotted for 36 hours during spring and neap tide.

![Figure 5.1: Position of measurement station Nes in the Borndiep and station Nes* in the modelled basin.](image)

Appendix C-2 shows graphs of the waterlevel variation in combination with the flow velocities at the modelled station Nes*, for each scenario. These results show a phase difference of nearly a quarter of a tidal period between the waterlevels and the velocities, indicating that the tidal wave inside the basin approximates a standing wave.

5.1.1 Spring tide

The calculated water levels during spring tide correspond very well with the water levels from the predicted astronomical tide. When looking at the change in water levels over time (dh/dt), as a measure for the flow velocities, the correspondence is also quite good (see Figure 5.2).
When comparing these results, important aspects to look at are:

- **differences in HW and LW amplitudes.** Half of the HW amplitudes are overestimated by some 25% and half of the LW amplitudes are overestimated by about 10%. (The term ‘amplitudes’ is used here, rather than the term ‘water levels’, to indicate that a lower LW level corresponds to an overestimated amplitude, instead of an underestimated water level.) A higher HW level means that the flood flow is able to transport sediments further inward (or landward). Correspondingly, a lower LW level means that the ebb flow is able to take transport sediments further backward (or seaward). Since the discrepancy between the modelled and the astronomical tide is largest for the HW levels, this could cause a small overestimation in the landward-directed transport during spring tide.

- **differences in ebb and flood duration.** When looking at Figure 5.2 (lower plot) the period between a zero-downcrossing and a zero-upcrossing indicates an ebb period. The following period (until the next zero-downcrossing) indicates a flood period. For both tidal waves, the duration of the ebb is shorter than the flood. Additionally, the time-averaged water levels during the ebb period are slightly lower than during the flood period (see appendix C-2), resulting in a smaller cross-sectional area of the ebb flow. Since the amount of water that is exported by the ebb must equal the amount of water that has entered during flood (continuity), this implies that the average velocity during ebb must be higher (ebb-dominance). The stronger currents during ebb can promote a larger seaward transport of sediments. During spring, the length of the ebb and flood periods of the modelled tide agrees well with the astronomical tide. The ebb dominance in 50% of the waves is a bit more pronounced.
in the modelled tide, which could lead to a small overestimation of this seaward-directed transport component.

- **differences between the duration of HW and LW slack.** For both tidal waves, the duration of HW slack is longer than the duration of LW slack. As a result, more sediment is able to settle during HW than during LW, causing a net landward-directed transport component. For the modelled tide, the slack periods at HW correspond very well with the predicted tide. The LW periods, on the other hand, are shorter for the modelled tide. In other words, the tidal asymmetry in slack periods is more pronounced for the modelled wave, possibly leading to an overestimation of this landward-directed transport component during spring tide.

Altogether, the differences between the modelled and the astronomical tide during spring are relatively small. Moreover, the influences on the net sediment transport caused by these differences can partially cancel each other out. The model gives a satisfying representation of the spring tide.

Even though the spring tide shows ebb-dominant behaviour, the relatively short slack periods at low water will prevent large sedimentation at low water. As the flood returns, the sediment will then be transported in landward direction to settle during the longer high water slack period. The result will be a net sediment import into the basin.

Due to the low settling velocities, the asymmetry in slack periods is a very important parameter in the transport of fine sediment.

### 5.1.2 Neap tide

During neap tide, the non-linear shallow water effects cause the wave to distort in a different way than during the spring tide. It is therefore important to evaluate the results for a neap tidal cycle as well. While the agreement with the predicted tide during spring was quite good, during neap, the (relative) differences are larger (Figure 5.3).
The most important differences are:

- **differences in HW and LW amplitudes.** All amplitudes are overestimated by the model: the HW levels are 20 to 25% higher and LW levels are even 60 to 70% lower. Since the discrepancy between the modelled and the astronomical tide is largest for the LW levels, this could cause a small overestimation in the seaward-directed transport component during spring tide.

- **differences in ebb and flood duration.** In the predicted tide, the ebb duration is shorter than the flood duration, so the ebb flow is dominant (just like during spring tide). However, in the modelled tide, the ebb period is longer than the flood, leading to flood-dominance. Since the dominant flow holds the largest transport capacity, the predicted tide would cause a net seaward transport component, whereas the modelled tide promotes a net landward-directed transport component.

- **differences in HW and LW slack duration.** Both the HW and LW slack periods are underestimated in the modelled tide. Since the periods for sediments to sink to the bottom have become shorter, this could lead to an underestimation of the net sediment import during neap tide. Additionally, the underestimation for the LW slack period is a bit larger than for the HW slack period, making the asymmetry between the slack periods a bit more pronounced. This could lead to a slight overestimation of the net landward-directed transport component.

Altogether, it can be expected that the modelled tide will cause a slight overestimation of the net landward-directed transport (import) during neap, compared to the
astronomical tide. Nonetheless, the difference on the entire spring-neap cycle is expected to be small.

The same plots were made for the other two tidal scenarios, the results can be found in Appendix D-2.

5.2 Tidal prism

The tidal prism is the total amount of water entering (or exiting) a basin during one tidal cycle. For the modelled basin, each different tidal scenario gives a slightly different tidal prism. The results are presented in Table 5.1. For reference with a real Wadden Sea basin, the tidal prism of the Borndiep basin is also indicated in the table.

Table 5.1: Tidal prisms of the different tidal scenarios for the modelled basin.

<table>
<thead>
<tr>
<th>Tidal scenario</th>
<th>Tidal prism ($10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 components (M2 M4 M6 S1 S2)</td>
<td>Spring tide 566</td>
</tr>
<tr>
<td></td>
<td>Neap tide 348</td>
</tr>
<tr>
<td></td>
<td>Average 457</td>
</tr>
<tr>
<td>3 components (M2 M4 M6)</td>
<td>Average 468</td>
</tr>
<tr>
<td>1 component (M2)</td>
<td>Average 475</td>
</tr>
<tr>
<td>Borndiep basin</td>
<td>Average 430</td>
</tr>
</tbody>
</table>

5.3 Flow velocities

Figure 5.4 shows the depth-averaged velocities in the model basin and the Borndiep basin for four characteristic stages in the tide (HW slack; maximum flood; LW slack and maximum ebb). The order of magnitude of the flow, as well as the flow patterns agree well with the results for the Borndiep basin. In the modelled basin, the flow is somewhat more concentrated in the deeper part of the channels, where the velocities are higher than in the Borndiep.

In the real basin, a system of smaller channels and gullies brings the water and the sediments to the tidal flats. Postma (1961) stated that the greatest asymmetry in deposition times between high and low tide occur in water masses moving in turn in a tidal channel and over a tidal flat. Hence, the most efficient accumulation must take place in areas located at the inner end of tidal channels and on the outer parts of the flats [POSTMA, 1961]. The modelled basin, however, is less detailed and does not include all these small channels and gullies. Additionally, the larger channels (below MSL-3.5 m) extend less far into the model basin. This means that the transport of fine sediments to the far side of the basin will be smaller, as many sediment particles will start to settle just after passing the channels, onto the flats.
Depth averaged velocity [m/s]

Modelled basin

Borniep basin

a) high water slack

b) maximum flood

c) low water slack

d) maximum ebb

Figure 5.4: Comparison of the depth averaged velocities between the Borniep and the modelled basin, for three specific phases in the tide. The blue line indicates a level of MSL – 3.5 m, which represents the edge of the channels.
6 Sediment transport – Tide

The morphological computations were performed within Delft3D-WAQ. After a spin up period of 2 years, a computation of one year started. The results were stored at intervals of 7.5 days (at HW spring and LW neap). To get a more detailed view of the suspended sediment concentrations and transport over a spring-neap cycle, an additional short computation of 15 days was performed, during which the results were stored at 30-minute intervals.

This chapter gives the analysis of the results for the tidal computations, in order to investigate the influence of the different tidal scenarios on the sediment balances, spatial distribution and suspended concentrations inside a tidal basin. Analogously, chapters 7 and 8 deal with the results for the wave and the biology scenarios, respectively. An intercomparison of the influences of tide, waves and biology and their interactions is discussed in the synthesis in Chapter 9.

For a better comprehension of the following results, each of the following chapters will start with a brief review of the basic settings of the group of scenarios that is discussed. See Table 6.1 for the scenarios of this chapter.

Table 6.1: review of main characteristics of the TIDE scenarios

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Tide</th>
<th>Wind</th>
<th>Biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>T01</td>
<td>1 component: M2&lt;br&gt;(semi-diurnal lunar tide only)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T02</td>
<td>3 components: M2 + M4 + M6&lt;br&gt;(introducing tidal asymmetry from higher harmonics)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T03</td>
<td>5 components: M2 + M4 + M6 + S1 + S2&lt;br&gt;(introducing spring-neap variation and daily inequality)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

6.1 Sediment balances

6.1.1 Total basin balance

Figure 6.1.a shows the total fine sediment import (in kilotons) in the basin after one year. The graph clearly shows the importance of tidal asymmetry on the sediment import into the basin: the inclusion of M4 and M6 on the boundary conditions in scenario T02 causes a nearly 4-fold increase in the annual import, with respect to scenario T01.
As explained earlier, tidal asymmetry is caused by non-linear shallow water effects. Even though no tidal asymmetry was imposed at the sea boundaries in scenario T01, a strong tidal asymmetry is generated *inside* the basin (see Figure 6.2). As this asymmetry is determined by the basin geometry, it can be very different from the asymmetry that is generated outside, in the shallow part of the sea. In scenario T02, the inclusion of this latter asymmetry counteracts the ‘internal’ asymmetry, causing a strong increase in net sediment import.

The two most important differences between the tide in T01 and T02, responsible for this increase are:

- **differences in LW slack periods.** Even though the duration of HW slack is practically the same for both tides, the duration of LW slack is much shorter for T02. This means that during low tide, when the water is mostly concentrated in the deeper channels, significantly less sediment is able to reach the bottom. At high tide, the water is mostly stretched out on the shallow flats. Because of the limited depth and the much slower increase of velocities after high tide, sediment is deposited much more easily. The result is that, for scenario T02, the sediment experiences a strong net forward shift with each flood.

- **differences in ebb and flood periods.** The ebb period for scenario T01 is much shorter than for T02, meaning that the ebb velocities will be higher for T01, showing a much larger ebb-dominant behaviour. As a result, sediment that has settled at HW, will be picked up much more easily (and sooner) by the returning ebb current, transporting further back seawards. The forward shift, caused by the flood and the settlement at HW, is for a large part compensated by the strong ebb current. As this effect is much smaller in scenario T02, the net forward shift per tide is much stronger for this scenario.
Because of the low settling velocities, an asymmetry in slack duration can have a large influence on the net transport of fine sediments. Therefore, the decrease in the duration of LW slack is expected to be the most important reason for the larger sediment import in scenario T02.

Scenario T03 used the same settings as scenario T02, but also included a spring-neap variation and a daily inequality. Remarkably, the calculated import under the influence of all five components was smaller than for tidal asymmetry alone. During neap tide (scenario T03), the tide shows less ebb-dominant behaviour than the tide in scenario T02. (Actually, in scenario T03, the tide shortly even switches to flood-dominance.) Additionally, the duration of HW slack during neap is longer for scenario T03. Both differences cause an increase in net import during neap for scenario T03, instead of a reduction. This would mean that the occurrence of neap tide could not be the reason for the reduction of import. During spring tide, on the other hand, the tide shows a stronger ebb-dominance, compared to scenario T02. Additionally, the HW slack periods during spring tide are a bit shorter. In contrast to neap tide, both differences cause a reduction in net import during spring tide. This means that the overall reduction of import is caused by processes that occur around spring tide.
From these results, it can be concluded that tidal asymmetry from the sea is one of the most important mechanisms driving a net import of fine sediment into the basin (increase of about 400% compared to a harmonic tide at sea). The diurnal solar tide (S2), causing the spring and neap variation, reduces the import by 10%. The occurrence of the daily inequality (S1) in the computation is not very pronounced and its influence is therefore assumed negligible.

6.1.2 Distribution over the areas
In order to analyse and quantify the internal transport and distribution of the sediment, 5 characteristic areas have been defined inside the basin:

Table 6.2: Definition of the characteristic areas

<table>
<thead>
<tr>
<th>Area</th>
<th>Lower boundary</th>
<th>Upper boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels</td>
<td>-</td>
<td>MSL – 3.5 m</td>
</tr>
<tr>
<td>Subtidal</td>
<td>MSL – 3.5 m</td>
<td>MSL – 1.5 m</td>
</tr>
<tr>
<td>Low Intertidal</td>
<td>MSL – 1.5 m</td>
<td>MSL</td>
</tr>
<tr>
<td>High Intertidal</td>
<td>MSL</td>
<td>MSL + 1.25 m</td>
</tr>
<tr>
<td>Marsh</td>
<td>MSL + 1.25 m</td>
<td>MSL + 2 m</td>
</tr>
</tbody>
</table>

See Figure 6.3, all scenarios show virtually no import to the marsh, and relatively little import to the high intertidal areas. This might be explained by two reasons:

- As mentioned before, the smaller channels and gullies are not included in the model. This means that, as the flood reaches the end of a large channel, it spreads out over a large surface and loses its transport capacity. In reality, the flow stays concentrated in the smaller channels for a longer period, before spreading out onto the higher tidal flats.

- These scenarios do not include the influence of waves, which is one of the main contributors to the bottom shear stress in the shallow areas. As the ‘stirring’ movement of the waves helps to keep sediments in suspension, the flood is able to transport these sediments further inward, towards the marsh.

Regarding the relative distribution of sediment over the areas (Figure 6.3), the difference between the runs is much smaller. Scenario T01 shows relatively more import to the deeper areas, which can be explained by the much longer slack period at low tide. In scenario T03, relatively more sediment is imported to the higher areas, due to the higher water levels during spring tide.
6.1.3 Distribution over the bottom layers

When regarding basin averages only (Figure 6.4), there is not much difference between the scenarios. As was mentioned in section 3.6.2, for each time that sedimentation occurs, 5% is buried directly in the second layer. Since all scenarios show a large distribution in layer S1, this indicates that some erosion in layer S1 may occur regularly, but permanent deposition in this layer is still possible for most parts of the basin.
Large differences can be seen for the marsh areas, where scenario T03 shows a deposition of almost 85% in the second bottom layer. This could indicate that substantial erosion does occur regularly in layer 1, but not in layer 2.

6.2 Average sediment concentrations

Figure 6.5 shows the annual average concentration of suspended (particulate) matter, or SPM, for the areas in the basin. Due to the increased mud accumulation in the intertidal areas for scenarios T02 and T03, the concentrations in these areas are much higher than in scenario T01. Scenario T01 shows an almost linear decrease in SPM concentrations from the channels towards the marsh.

![Figure 6.5: Annual average SPM concentrations per area, TIDE scenarios.](image)

The seasonal variation of the average concentration in the basin (Figure 6.6) is caused by the seasonal variation in SPM at the sea boundaries. The amplitude of this variation is larger for scenarios T02 and T03. Note that in all scenarios, the average concentrations remain lower than the average concentration at sea (≈15 mg/l). This could be explained by the fact that no waves are present, resulting in more sediments to be deposited permanently in the intertidal areas at high tide. As a consequence, the time-averaged concentration is much lower during ebb than during flood.

For all scenarios, the minimum concentrations are found in September / October, while the minimum concentrations at the sea boundaries occur in August. Since the scenarios had no other processes with a seasonal variation, this observation would imply that there is a phase lag of about 2 months, between the minimum concentration at the boundaries and the average minimum concentration in the basin. This could also mean that it takes about two months between the moment that a load of sediment has entered the basin during flood and the moment that this sediment has deposited at a location where it can no longer be picked up by the ebb.

Since all scenarios show the same phase lag in the concentrations, this delay is not influenced by the occurrence of tidal asymmetry or spring/neap tides. Probably, this delay will mainly be influenced by the settling velocity and the erodibility of the sediment.
Figure 6.6: Average SPM concentrations in the entire basin per month, TIDE scenarios.
7 Sediment transport – Waves

Table 7.1: Review of the basic settings for the WAVE scenarios

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Tide</th>
<th>Wind</th>
<th>Biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>5 components</td>
<td>Constant average wind, no seasonal variation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in WAQ</td>
<td></td>
</tr>
<tr>
<td>W02</td>
<td>5 components</td>
<td>Average wind, with harmonic seasonal variation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in WAQ</td>
<td></td>
</tr>
<tr>
<td>W03</td>
<td>5 components</td>
<td>Average wind, seasonal variation and 3-day variation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in WAQ</td>
<td></td>
</tr>
<tr>
<td>W04</td>
<td>5 components</td>
<td>Timeseries of wind data</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in WAQ</td>
<td></td>
</tr>
<tr>
<td>W05</td>
<td>5 components</td>
<td>Constant average wind, no seasonal variation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in Delft3D-WAVE</td>
<td></td>
</tr>
<tr>
<td>W06</td>
<td>5 components</td>
<td>Average wind, with harmonic seasonal variation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wave computation in Delft3D-WAVE</td>
<td></td>
</tr>
</tbody>
</table>

Based on a tidal forcing with 5 components (scenario T03), the influence of wind waves was added to the model. The characteristics for each scenario can be reviewed in Table 7.1.

7.1 Sediment balances

7.1.1 Total basin balance
Scenarios W01 and W02 show no large differences, with respect to the total annual import. This would indicate that the added seasonal variation in scenario W02 does not have much influence on the total net import. The same conclusion can be drawn from the results with scenarios W05 and W06.

The computation with timeseries from wind speed measurements (W04) calculates 30% less import than the computation based on an average wind speed (W01). Remarkably, the computation based on 3-daily wind peaks (W03), calculates practically the same import as scenario W04. First of all, this means that the peaks in the wind velocities indeed have a large influence on the total annual import. Secondly, the result of W03 shows that these peaks can be approached by modelling an average noise in the signal. This noise does not account for the large peak velocities, but does account for smaller peak values that occur very regularly (≈ every 3 days).

The computations in which the wave characteristics were calculated in Delft3D-WAVE (scenarios W05 and W06), give 30% more import than their corresponding computations W01 and W02. Possible explanations for this will be given in the next sections.
Net annual fine sediment import
Wave scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total annual import in basin [kilotons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>274</td>
</tr>
<tr>
<td>W02</td>
<td>261</td>
</tr>
<tr>
<td>W03</td>
<td>189</td>
</tr>
<tr>
<td>W04</td>
<td>188</td>
</tr>
<tr>
<td>W05</td>
<td>352</td>
</tr>
<tr>
<td>W06</td>
<td>344</td>
</tr>
</tbody>
</table>

Figure 7.1: Net annual fine sediment import in the basin, WAVE scenarios.

7.1.2 Distribution over the areas

Figure 7.2 shows the distribution of sediment over the areas. Again, little difference can be found between the scenarios based on constant average wind and the scenarios based on a seasonal varying wind (scenarios W01 and W02). The corresponding scenarios with Delft3D-WAVE show the same similarities (scenarios W05 and W06).

The scenarios W01 and W02 show less distribution to the deep channels than the scenarios with higher wind velocities (W03 and W04). The increased wave energy in the latter two causes more erosion in the low intertidal and subtidal areas, resulting in a larger transport towards the channels on the ebb flow. However, this increased erosion is not visible in the marsh areas (see the close-up in Figure 7.3). Apparently, these areas are too shallow to develop significant waves. While the increased erosion in the other areas will result in high concentrations of SPM, this sediment is subsequently transported to the marsh areas, where part of it will settle during the following high tide. Scenario W04 shows even 30% more import to the marsh areas than scenario W03. At the same time, the import to the high intertidal areas is negative (export) for scenario W04. This would mean that the high intertidal areas and the marsh areas are very sensitive to the occurrence of annual storms, which could lead to additional erosion in the high intertidal and accretion in the marsh area.

Scenarios W05 and W06 show a dominant distribution to the subtidal areas and less distribution to all other areas. As explained in section 3.5, these computations were based on a constant waterlevel, corresponding to the waterlevel at high spring tide. In deep areas, the waterlevel fluctuations caused by the tide will have relatively little impact on the calculated shear stress at the bottom, due to waves. In the intertidal areas, however, this simplification causes a severe overestimation of the wave induced bottom shear stress. As a result, virtually no sedimentation can occur in these areas at high tide, and large concentrations of sediment will be brought back on the ebb current. In the subtidal areas, the wave induced bed shear stress will be low enough for
sedimentation at the low tide. Figure 7.3 confirms that scenarios W05 and W06 show no net sedimentation in the areas above MSL.

![Relative distribution per m$^2$ over areas](image1.png)

Figure 7.2: Relative distribution per m$^2$ over the areas, WAVE scenarios.

![Relative distribution per m$^2$ to the marsh areas](image2.png)

Figure 7.3: Close-up – relative distribution per m$^2$ to the marsh areas, WAVE scenarios.

7.1.3 Distribution over the bottom layers
See Figure 7.4, scenarios W01 to W04 show similar results with a fraction of about 10% in the second layer. The scenarios W05 and W06 show a dominant distribution in the top layer as well. A relatively small fraction in the buffer layer S2, could be the result of 2 different situations:

- If hardly any erosion ever occurs in layer S1, the ratio between S1 and S2 will remain close to 95 % versus 5 %. Permanent deposition is possible in both layers.
• If erosion is so severe that layer S1 erodes completely, together with the majority of layer S2, the ratio between S1 and S2 will also remain close to 95 – 5%. In that case, no permanent deposition is possible in any of the layers.

Since the largest deposition in the basin occurred in the subtidal areas, where the deposition was even larger than in the scenarios without waves, it seems very unlikely that all deposited material comes from a temporarily deposition. The uneven distribution over the bottom layers will therefore be caused by the absence of substantial erosion in layer S1.

In the marshes, layer S2 plays an important role as a buffer for fine sediments. While the erodibility of the top layer is too high for sediments to stay on the bed, layer S2 is able to retain the fine sediments much more effectively.

Figure 7.4: Sedimentation to the bottom layers S1 and S2, WAVE scenarios.

7.2 Average sediment concentrations

Again, scenarios W01 to W04 show very similar results, where the highest concentrations can be found in the intertidal areas. For scenarios W05 and W06, only the lower part of the intertidal areas shows high concentrations. Even though the waves in the areas above MSL are highly overestimated for these scenarios, the negligible amount of sediment that is stored in these areas, result in relatively low concentrations. Moreover, the results in Figure 7.4 show the average concentrations over the year. Since the areas above MSL are submerged for only a limited period each tide, the time-averaged concentrations will be much lower than the maximum concentration that can occur during the maximum ebb or flood currents.
When looking at the seasonal changes in the average SPM concentrations (Figure 7.6), scenarios W01 to W04 all show the same mean value, but scenario W01 has the smallest variations. In this scenario, only the concentrations at the sea boundaries varied over the year. The seasonal changes in scenarios W02, W03 and W04 are all of the same order, indicating that the peak values in the wind speed have little impact on the seasonal concentrations.

The variations in scenarios W05 and W06 are also of the same order, but have higher mean values, caused by the overestimated waves.
Figure 7.6: Seasonal changes in average SPM concentrations [mg/l] in the entire basin, WAVE scenarios.

For scenario W01, the minimum concentrations are found in October, which points to a phase difference of about two months between the concentrations at the boundaries and the concentrations inside the basin, corresponding to the results with the TIDE scenarios. The scenarios W02 and W03 both had seasonal varying wind velocities, with minimum wind speeds occurring in August. For these scenarios, the phase shift is zero. This could still mean that the sediment takes about 2 months before it is permanently deposited, but this ‘flushing time’ is no longer reflected in the SPM concentrations, since the erosion is now dominated by the seasonal variation of the wind.
The irregular concentrations for scenario W04 (see Figure 7.6) are caused by the irregular wind velocities in the time-series input, which was used for this scenario.

7.3 Discussion
With respect to the scenarios without waves, the influence of waves caused a nearly ten-fold increase in the basin-average SPM concentrations. The annual net import, however, has only decreased by a factor 3.5. Moreover, in the presence of waves, the average concentrations in the basin are much higher than the average concentrations at sea. This implies that, despite the large concentrations on the land-side, a residual transport towards these areas does still occur, indicating that the transport is directed against the direction of the concentration gradient. This corresponds with observations in the Wadden Sea, where very large SPM concentrations are observed in the innermost areas.

The transport to the salt marshes is very sensitive for the wind speed data. Since the largest import to the salt marshes occurred in the computation with timeseries for wind, this indicates that the occurrence of storms might play an important role in this transport. Small, annual storms will probably lead to a net import into the marshes, since they are strong enough to erode material from the intertidal area, but may not be strong enough to cause severe erosion at the marshes during slack. Large storms are more likely to cause a net loss of sediment from the marshes.

Another important aspect, which is not accounted for by the model, is the wave setup against the inner land boundary. Especially for storms blowing from the north-west, due to the orientation of the North Sea, even a moderate storm will cause a large setup over the entire North Sea against the Dutch coast. A sufficiently large setup (possibly in combination with a period of high tide) can inundate the marshes, which could either result in extra deposition, or extra erosion (depending on the wave intensity, magnitude of the setup, storm duration and the phase of the tide at the end of the storm). If the retreat of the setup coincides with the retreat of the tide, the resulting ebb currents will be very strong and much of the eroded material will be washed away to the sea.

All these processes may eventually result in an event-driven morphological behaviour of the salt marshes. In the perspective of long-term modelling, it could be important to find out whether this ‘noise’ has a residual effect, or if the erosion from large storms annuls the extra deposition from small storms in the long run. A long computation (simulation time in the order of 20 years) with timeseries for 20 different years of wind could help to verify whether these storms are relevant for large timescales.
8 Sediment transport – Biology

Table 8.1: review of the settings for the BIOLOGY scenarios.

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Tide</th>
<th>Wind</th>
<th>Biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation</td>
<td>All biomasses 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wave computation in WAQ</td>
<td></td>
</tr>
<tr>
<td>B02</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation</td>
<td>Grazer biomass 200%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wave computation in WAQ</td>
<td>MPB biomass 100%</td>
</tr>
<tr>
<td>B03</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation</td>
<td>Grazer biomass 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wave computation in WAQ</td>
<td>MPB biomass 200%</td>
</tr>
<tr>
<td>B04</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation</td>
<td>All biomasses 200%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wave computation in WAQ</td>
<td></td>
</tr>
</tbody>
</table>

8.1 Sediment balances

8.1.1 Total basin balance
Scenario B02 is reached by adding extra grazers to the average scenario B01 (in formula: B02 = B01 + GRZ). Analogously, B04 is reached by adding extra grazers to the more stabilized scenario B03 (or: B04 = B03 + GRZ). In both cases, the influence of adding the extra grazers causes a reduction of the annual import with 16 – 17 % (see Figure 8.1). The increased destabilisation seems to be slightly more effective for the scenario that also had extra stabilizers (going from scenario B03 to B04).

Now look at the influence of increased stabilization: scenario B03 is reached by adding extra diatoms to scenario B01 and scenario B04 is reached by adding extra diatoms to scenario B02. In formula-notation: B03 = B01 + MPB and B04 = B02 + MPB. Again, in both cases adding the extra diatoms have almost the same effect, causing an increase in the annual import of 19 – 20 %. In this case, the increased stabilization seems to be slightly less effective for the scenario that also had extra destabilizers.

When both biomasses are doubled, as in scenario B04, the total annual import remains practically equal (99%) to scenario B01.

The results above indicate that the model is slightly more sensitive to an increase in destabilization than stabilization, but the difference is practically negligible. As long as the ratio between stabilizers and destabilizers remains equal, the net annual import will also remain equal. Note that a further increase of the biomasses would eventually result in a situation where the (de)stabilization functions have reached their maximum influence.
8.1.2 Distribution over the areas

The increased destabilization in scenario B02 mainly resulted in a loss of sediment from the intertidal areas (see Figure 8.2). At the same time, the transport to the marsh and towards the channels showed a minor increase (see Figure 8.3). Despite the fact that grazers are also present in the subtidal areas, the net import to these areas did not decrease, but also showed a small increase. It seems likely that the grazer biomasses in the subtidal areas were already close to their maximum influence, and the doubled biomass therefore did not result in a much more destabilized bed. As the increase in grazer biomasses was only effective in the intertidal areas, a net erosion from these areas could have been redistributed towards the other areas, including the subtidal.

In scenario B03, the increased stabilization generated an increase in the net import towards the intertidal and marsh areas, as could be expected. The import to the lower areas, on the other hand, has decreased. It can be concluded that, by stabilizing the sediments at higher elevations, less sediment is transported back on the ebb current, which reduces the net deposition in these areas.

In the case that both biomasses are doubled (scenario B04), the total import to the channels remains more or less equal to the average situation (B01). A small increase in transport to the high intertidal and marsh areas can be seen, which is counteracted by a small decrease in transport to the low intertidal and subtidal areas. In other words, the centre of gravity has shifted in landward direction, while the total import into the basin has remained more or less the same.
8.1.3 Distribution over the bottom layers

See Figure 8.4, all scenarios show a dominant distribution in layer S2, which demonstrates the higher erodibility of layer S1, due to destabilization. For the intertidal and the marsh areas, however, the stabilizing influence of the diatoms becomes visible, which is reflected in a larger fraction in layer S1. As expected, the destabilization of the top layer is larger in the scenarios with higher grazer biomasses (B02 and B04). Analogously, the stabilization of the top layer of the marsh areas is more effective in the scenarios with higher diatom biomasses (B03 and B04).
8.2 Average sediment concentrations

Regarding the average suspended sediment concentrations, the results between the different scenarios are very small. It can generally be noted that the concentrations increase from the channels to the intertidal areas. For the marsh areas, the submergence time and the amount of sediment that is deposited there is too small to lead to high average SPM concentrations.
previously glued to the bed by the diatoms, will now be destabilized and picked up by the increasing wave action. Thus releasing large amounts of sediment, which is reflected in a strong incline in the average concentrations. This gives the trend an asymmetrical or skewed character.

The skewness is most pronounced in the scenario with the doubled stabilizer biomass (B03), which also shows the largest maximum value in December. This can easily be explained by the more effective stabilization, entrapping larger amounts of sediment during summer. At the beginning of autumn, these large quantities will also lead to higher concentrations, if eroded in a short period.

8.3 Discussion

Since the relationships for the biological influences are not linear, the sensitivity to these influences will also be non-linear. The results could therefore be very different in case one influence is reduced to 50%. An important aspect to focus on, is the position (or elevation) of the ‘zero-influence line’, i.e. the transition between stabilized and destabilized area.

For the biomass settings in scenario B01 (all biomasses 100%), Figure 8.7 shows the shift in the position of the line of zero influence (corresponding to a (de)stabilization factor of 1) throughout the year. Appendix D.2.3 shows the same graph for all other scenarios.
Figure 8.7: Seasonal shift in position of the biological factors throughout the year.


9 Synthesis

The previous chapters have focussed on the relevant processes and scales of the tide, wind waves and biology, respectively. In the following context, the main scenarios of the previous chapters are reviewed and compared. A description of the main scenarios is summarized in Table 9.1. The same scenarios have been applied to additional computations with a deep basin.

Table 9.1: Summary of the main scenarios of the TIDE, WIND and BIOLOGY computations.

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Tide</th>
<th>Wind</th>
<th>Biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>T03</td>
<td>5 components</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W03</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation Wave computation in WAQ</td>
<td>-</td>
</tr>
<tr>
<td>B01</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation Wave computation in WAQ</td>
<td>Average biomasses</td>
</tr>
<tr>
<td>Deep basin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T04</td>
<td>5 components</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W07</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation Wave computation in WAQ</td>
<td>-</td>
</tr>
<tr>
<td>B05</td>
<td>5 components</td>
<td>Harmonic seasonal + 3 day variation Wave computation in WAQ</td>
<td>Average biomasses</td>
</tr>
</tbody>
</table>

9.1 Sediment balance according to literature

The results for the total annual import can be compared to estimates from literature. Studies by Sha (1986), Dronkers (1986, 1998), Louters and Gerritsen (1994), Ligtenberg (1998) and Elias et al. (2003) point to a net import of sediment in the order of $1 \times 10^6$ m$^3$/year [ELIAS, 2006b] for the entire Wadden Sea. Assuming a bulk density of 1.56 tons/m$^3$, this would correspond to a net deposition of $1.56 \times 10^6$ to $7.8 \times 10^6$ tons per year. However, it must be noted that these amounts may also include the import of larger sediment fractions.

Eisma (1979) estimated a permanent deposition of $3.5 \times 10^6$ tons per year [POSTMA, 1981] for fine-grained suspended matter in the Wadden Sea. The total quantity of water that enters the Wadden Sea with the flood tide through the various inlets, is about 10 km$^3$ [POSTMA, 1981]. For a single basin with an average tidal volume of about 0.45 km$^3$, corresponding to the Borphdiep basin, this would lead to an estimated deposition in the order of 150 kilotons per year.

9.2 Sediment balance in the modelled basin

From the settings in this study, the tide proves to be the largest import mechanism for fine sediments, resulting in a total annual import of nearly 700 kilotons (see Figure 9.1).
When the influence of locally generated wind waves is taken into account, the total import is reduced by about 75%, which can be explained by the increased bottom shear stresses in the shallow areas.

Addition of the influence of bio-stabilisation and bio-destabilisation, reduces the import with an additional 20%, compared to the computation with tide only. This indicates that the influence of destabilisation dominates over stabilisation. Biological influences are present in about 70% of the total surface area. In approximately 65% of the total surface area, both stabilization and destabilization occur simultaneously. This means that the position of the border between stabilization and destabilization can vary over the year, depending on the dominant influence for that season. On average, 25% of the total surface area is stabilized, while 45% of the area is destabilized.

<table>
<thead>
<tr>
<th>Net annual fine sediment import</th>
<th>Average basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide</td>
<td>686</td>
</tr>
<tr>
<td>Wave</td>
<td>189</td>
</tr>
<tr>
<td>Biology</td>
<td>43</td>
</tr>
<tr>
<td>Borndiep basin</td>
<td>150</td>
</tr>
</tbody>
</table>

Figure 9.1: Net annual fine sediment import, results for the TIDE, WAVES and BIOLOGY scenarios.

When comparing the calculated import for the Biology scenario with the estimated import for the Borndiep basin, the model shows an overall underestimation. As was concluded in chapter 5, the hydrodynamics of the modelled tide will probably result in a slight overestimation of the total import, so this could not be the reason for the overall underestimation.

When biological influences are not taken into account (only tide and wind), the calculated total import bears a much closer resemblance to the estimated import, but the distribution over the areas show practically no sedimentation in the intertidal and marsh areas (see Figure 9.2). This is not in accordance with reality, where the highest silt contents can be found at higher elevations. The scenario with biological influences shows a much more realistic distribution over the areas.

In general, it can be concluded that tidal asymmetry is the most important mechanism driving the import of fine sediments to the intertidal areas. Whether the sediment can remain deposited in these areas, depends on the influences of waves and biology. Under the influence of waves, the permanent deposition in the intertidal areas is largely reduced and more sediment is brought back to sea, or is deposited in the subtidal and deep areas during low water slack. With respect to the distribution of sediment,
biological influences can counteract the influence of the waves. Biological stabilization re-enables the net deposition in the intertidal areas, while at the same time biodestabilization reduces the deposition in the subtidal areas and channels.

![Image of Figure 9.2](image_url)

*Figure 9.2: Relative distribution per m² to the areas, results for the TIDE, WAVES and BIOLOGY scenarios.*

The transport towards the marsh areas, on the other hand, is not primarily driven by the tide (see Figure 9.3). The transport capacity of the tidal currents alone is insufficient to bring sediments up to the marsh areas. By stirring up the sediment, waves can contribute to the transport capacity, and thus increase the total transport to the marshes. Biological influences additionally increase this transport, in two ways. First of all, stabilization of the bed reduces the erosion in these areas. Secondly, destabilization of the bed at lower elevations causes higher suspended concentrations to be transported towards the marshes. So, with respect to the salt marshes, the influences of waves and biology do not counteract each other, but even enhance each other.
9.2.1 Seasonal variation in sediment import

**Tide**

See Figure 9.4.a, the scenario shows an almost linearly increasing deposition. From the end of the second quarter, the low SPM concentrations at the sea boundaries result in a slight decrease in the rate of deposition.

Since no erosion from waves is included, large scale permanent deposition is still possible in the intertidal areas, so most sediment remains in layer S1.

**Waves**

Due to increasing wave action and decreasing SPM concentrations at sea from the beginning of the third quarter, no permanent deposition is possible in both layers (see Figure 9.4.b). Gradually, material from layer S2 starts to erode, which is partially redistributed to layer S1 at the following slack tide. As a result, the proportionality between S1 and S2 slowly returns towards 95 / 5 %, while the total sediment content remains practically constant.

The differences between spring and neap are clearly visible throughout the year, except during summer. The low values represent the spring tides, when waves cause more erosion in the higher areas.

**Biology**

Corresponding to the computation with waves, permanent deposition is no longer possible in layer S1 from the beginning of the third quarter (see Figure 9.4.c). In this case, this effect is enhanced by the increasing bioturbation.

However, since bio-destabilization does not affect the second bottom layer, the content of S2 still continues to increase until the start of autumn. By that time, the increased wave action also prevents further deposition in layer S2, which eventually leads to a net erosion of sediments from the basin during winter.
The observed spring-neap variations are of the same order as for the computation with waves only.

Figure 9.4: Seasonal variation in net deposition for the TIDE, WAVE and BIOLOGY scenarios. S1 refers to the upper bottom layer, S2 represents the second bottom layer.
9.3 Fine sediment content in the bottom

The mud fraction in the model is based on the amount deposition in the second bottom layer. Assuming a layer thickness of 10 cm and a porosity of 40%, the percentage of mud can be calculated from the total deposited mass per m².

Unfortunately, the model was not able to give a satisfying prediction of the silt content in the bottom. Figure 9.5 shows the silt content in the Borndiep according to Sedimentatlas (RIKSWATERSTAAT RIKZ, 1998). In the inner areas, mud percentages between 10% and 50% are not uncommon. In the modelled basin, however, silt fractions hardly exceed the value of 5% (see Figure 9.6 – Figure 9.8).

When comparing the model results with the results from Sedimentatlas, however, it must be noted that the samples from Sedimentatlas had not been treated to remove calcium carbonate and organic matter, which causes an overestimation of the mud fraction [VAN LOON, 2005].

Somewhat higher mud fractions are computed when the critical bed shear stress is lowered to a value of 0.2 Pa (see Figure 9.9). This was also concluded from model computations done by Borsje [2006a], who found that the distribution towards the second bottom layer increases with decreasing critical shear stress.

Additionally, the wave energy in the shallow areas can have a large influence on the sediment distribution, and thus also on the mud fraction in the bed. Possibly, an overestimation of the wave energy in these areas may have contributed to the low fractions calculated with the model.

![Figure 9.5: Mud percentage in the Borndiep basin. (Source: Sedimentatlas)](image-url)
Figure 9.6: Maximum mud fraction in September in the second bottom layer after computation T03

Figure 9.7: Maximum mud fraction in September in the second bottom layer after computation W03

Figure 9.8: Maximum mud fraction in September in the second bottom layer after computation B01
Figure 9.9: Mud fraction in the second bottom layer after computation with scenario B01, while using a critical shear stress of 0.2 Pa.

9.4 Horizontal and vertical fluxes

Due to the high erodibility of fine sediments, large erosion fluxes can occur during maximum ebb and flood. Since most of this sediment will be deposited at the following slack tide, the vertical fluxes of sediment during each tide are very large, in the order of 25 kton/d. Compared to these vertical fluxes, the horizontal fluxes (sediment passing through the inlet) are relatively small, with an order of magnitude of 2.5 kton/d. Since only a small part of the import-flux is left behind after each tide, this implies that the net import or export of sediments from the basin is the result of only a very small difference in sedimentation and deposition fluxes. (For instance, for Wave-scenario W03 the net import is only 0.25 kton/tide.)

As an example, Figure 9.10 and Figure 9.11 respectively show the vertical and the horizontal fluxes inside the basin, for scenario W03.

Figure 9.10: Vertical fluxes inside the basin: sedimentation and resuspension.
Figure 9.11: Horizontal fluxes inside the basin: import and export through the inlet.

9.5 Deep basin
In the computation for a deep basin with a larger channel volume, the total import by the tide has increased with nearly 60%, compared to the computations with the average basin. In this case, waves and biology do not have a significant influence on the total import (see Figure 9.12), but can significantly influence the distribution over the areas (see Figure 9.13).

Figure 9.12: Total annual import in a deep basin for the TIDE, WAVE and BIOLOGY scenarios.

Because of the wide channels and small tidal flats, the velocities in the channels are relatively low. As a result, the transport to the intertidal areas has decreased. Large quantities of sediment are lost to the deep areas, in an attempt to restore the hydrodynamic equilibrium. Similar to the results of the average basin, the influence of the waves on the distribution is counteracted by biology. Bioturbation in the subtidal areas, in combination with stabilization in the intertidal areas lead to a dominant
deposition in the low intertidal areas, of over 60% of the net annual import. All scenarios show virtually no net deposition in the areas above mean sea level.

![Relative distribution per m² to the areas](image)

**Figure 9.13: Relative distribution per m² to the areas, results for a deep basin.**

### 9.6 Discussion

First computations with the average basin showed that the model was very sensitive for the hypsometry of the basin. When the channels are too large, the current velocities in the channels are low and the transport capacity to the higher elevations is limited. Most sediment is deposited at the end of the channels. In a real-life basin, the continuous deposition will eventually change the geometry of the channels, and thus alter the hydrodynamics, until a state of dynamic equilibrium is reached. This feedback was not implemented in the morphological computation, so additional hydrodynamic computations were performed to come to an initial bathymetry that resembled the equilibrium state. To limit the computation time, the bathymetry was updated in the hydrodynamic computation for only three times, before the final hydrodynamic computation was run. This may not have resulted in a true equilibrium bottom, but most natural basins are neither in their ‘true’ equilibrium state, since man-made or event-driven changes in the environment as well as climate changes makes the definition of a ‘true’ or static equilibrium state impossible.

The sediment balance shows some sensitivity to the value of the critical shear stress of the sediment. Higher critical shear stresses generally lead to higher values for the net import, since the sediment is less easily resuspended from the bed. For the Wave scenarios, this sensitivity is highest: a critical shear stress of 0.2 Pa, instead of 0.4 Pa, will result in 90% less import. Import values are about 20% lower for the Tide and Biology scenarios. Apparently, introducing biological influences into the computational model with waves, reduces its sensitivity for the value of the critical shear stress.

Figure 9.14 below, shows the ratio between the annual import for a critical shear stress of 0.2 and 0.4 Pa. If the model would not be sensitive to this parameter, the ratio between the computations would be 50 / 50%.
**Sensitivity to the value of the critical shear stress**

![Graph showing sensitivity](image)

*Figure 9.14: Sensitivity of the computational model to the chosen value of the critical shear stress, for the Tide, Wave and Biology scenarios. The graph shows the ratio between the calculated import with a critical shear stress of 0.2 and the import with a critical shear stress of 0.4.*

Compared to the estimates from literature, the model shows an underestimation of the net annual import. A possible reason for this can be the limited distribution to the second bottom layer. In the intertidal areas – especially in the areas above MSL – the exposure to the air enhances the consolidation of the bottom. In the marsh areas, the bottom can remain dry for over ten days, allowing for vegetation to grow, which stabilizes the sediment even further. These effects are currently not represented in the model, which can also explain the large underestimation of the silt fraction in the bottom of these areas.

Other important parameters that can have a large influence on the fine sediment morphodynamics are (amongst others) the settling velocity, the resuspension parameter and the bottom roughness. In general, it can be expected that a lower value of the settling velocity will lead to more deposition at the higher elevations. Additionally, it can be expected that a lower value of the resuspension parameter will reduce the amount of eroded mass, which may result in relatively more deposition at lower elevations and a larger net import into the basin. The influence of the bottom roughness, on the other hand, is more ambiguous. It can considerably alter the hydrodynamics, which may locally result in higher bottom shear stresses, but can thus also lead to more dissipation, resulting in a reduction of the hydrodynamic energy in other areas. It is therefore recommended that more research is done to the influence of this parameter on the morphodynamics.

The settings for most parameters were derived from previous model studies concerning the Wadden Sea, which were similar to this research. Since this study deals with a conceptual model, using these same values should still give satisfying results. However, the parameters for the second bottom layer (the first order erosion rate and the critical shear stress) were calibrated for a study on the Western Scheldt estuary. The values may therefore not have been optimal for computations on the mud distribution in the Wadden Sea. Further tuning with these values might already improve the results.
A final notion must be paid to the estimates for the annual import according to literature. These estimates are merely indicative and the differences between various estimates are in the order of a factor 2. Furthermore, the downscaling of a Wadden Sea –scale estimated import to a basin-scale import is non-trivial. As was indicated in this research, the characteristics of a basin can show large variations between two different basins and have a large influence on the magnitude of the import and export fluxes (and thus also on the size and direction of the residual flux).
10 Conclusions and recommendations

10.1 Conclusions

10.1.1 Conclusions per research question

The objective of the research was:

... to gain more insight into the relevant processes involved in the long-term transport and distribution of fine sediments and their influences on the fine sediment balance in a tidal basin.

Several different processes have been studied separately, by means of mathematical computations with a process-based model. The analysis eventually led to several conclusions, which are presented in this chapter, according to the initial research questions.

1. When focusing on long-term balances, what are the relevant scales of the processes to be modelled?

Conclusions with respect to the tide:

• The tide cannot simply be approached by the semi-diurnal lunar component (M2) at the boundaries, since the tidal asymmetry that is generated at sea (near the coast) has a large influence on the total balance, causing a 4-fold increase in import. This tidal asymmetry can be approached by the first two higher harmonics of the lunar tide, M4 and M6, which respectively introduce an asymmetry in ebb-flood duration and high-low slack duration.

• The spring-neap tidal variation has a smaller influence on the total balance than the tidal asymmetry, but can still cause a significant reduction of about 15% of the import. Moreover, the spring-neap variation causes larger variations in water levels, resulting in a relatively larger deposition at higher elevations.

• The influence of the diurnal inequality on the total sediment balance is negligible. However, since the inequality also causes larger variations in water levels, the influence on the distribution towards the higher elevations may be more significant.

Conclusions with respect to the wind:

• When using averages from long-term wind speed data, the influence of an average seasonal variation is very small, when compared to a constant average wind velocity. The seasonal variation did not result in a significantly different import, nor did it lead to a different distribution of the sediment.

• Adding a variation that accounts for the average short-term peaked signal of the wind, causes a reduction of 30% in total import, compared to a computation with a constant average wind. The variation also causes relatively more deposition in the deeper areas, as well as the marsh areas, while the deposition in the intertidal areas has decreased. It can therefore be concluded that the short-term ‘noise’ in the wind signal can indeed have a residual influence on the long-term morphological processes.
• The wind speeds can be modelled quite well by a variation that accounts for the average short-term peaked signal of the wind. The amplitude of this variation can be based on the standard deviation of the actual wind speed data. This way, large peaks (storms) are not included by the model and the signal remains harmonic, making the model more transparent. The results agree very well with the results from real wind speed data, on a basin scale. Only for the marsh areas, the occurrence of large storms might become of more importance.

• Calculating the waves within Delft3D-WAVE proved not to be very suitable for long-term morphological computations with a tidal basin. In order to model the waves in the intertidal areas accurately, time-consuming computations are needed. When a simplification is applied to reduce the computation time and additional operations, the waves in the intertidal areas may be modelled inadequately.

Conclusions with respect to the biology:

• The seasonal variations of biology interact with the seasonal variations in the peakedness of the wind velocity, resulting in a net export of sediments from August to December. It is this specific interaction which causes the rapid increase in suspended sediment concentrations in autumn and which has a strong influence on the annual sediment balance.

• The spatial variations of biology strongly influence the distribution of the sediments inside the basin.

2. Which process is the main contributor to the (expected) sediment import into the basin?

Based on the results of the computations, the following conclusions can be made regarding the (modelled) physical processes:

Tidal asymmetry from the sea is the most important mechanism driving the import of fine sediments towards the intertidal areas. Waves can effectively reduce this tidal import from the tide with 70%. The combined influence of waves and biology can even cause a reduction of the annual import with 95%.

Since the model had not been properly calibrated, it must be noted, however, that the abovementioned values should be seen in the perspective of the parameter settings (Appendix A). Nonetheless, it may still be expected that the direction of the influence of the separate processes (import or export promoting) will remain as mentioned above. Whether these combined influences will eventually result in an importing or exporting system will depend on the physical characteristics of the system, as well as the parameter settings of the model.

3. How is the sediment distributed inside the basin and what roles do the influences of the basin hypsometry, the tide, wind waves and biology play herein?

• The tide promotes a large import towards the intertidal areas below the MSL line. The tidal currents are not strong enough to drive large transports to higher elevations.

• Under the influence of waves, the permanent deposition in the intertidal areas is largely reduced and more sediment is brought back to sea, or is deposited in the subtidal and deep areas during low water slack. At the same time, the waves also
increase the transport towards the marsh areas, by keeping the sediment in suspension for a longer period.

- Biological influences can partially counteract the distribution by the waves, by re-enabling the net deposition in the intertidal areas, while at the same time reducing the deposition in the subtidal areas and secondary channels. The transport to the marsh areas increases as well, under the influence of biology.

Overall, in basins with large tidal flats, the largest part (in the order of 65%) of the imported fine sediment is deposited in the intertidal areas. Only 1% of the import is lost to the salt marshes. The second largest import is directed to the subtidal areas (30% of the total import).

In basins with wide channels and small tidal flats, practically no sediment is deposited at elevations above MSL. Almost 65% of the sediment is deposited in the intertidal areas just below MSL. The second largest import (20%) is directed to the deep channels.

4. What is the annual loss of sediment to the saltmarshes and which processes drive this transport?

In the model computations, the annual transport of fine sediments to the marsh is only 1.4% of the total annual import, but this value may be higher in reality. The transport of fine sediments appears to be strongly influenced by the occurrence of high (or extreme) water levels and the occurrence of storms. Further research should point out whether these short-term influences can cause a residual net import for the long term.

10.1.2 Comparison of the results with previous model studies

The results for the suspended sediment concentrations show good correspondence in orders of magnitude with the SPM concentrations found in studies by Borsje [2006a] and Cronin [2005]. The latter author found lower concentrations for computations with biology, but this can be explained by the fact that the computations did not include biodestabilization by grazers.

Additionally, both authors also noted an underestimation of the mud fraction in the bed, compared to the measured fractions in Sedimentatlas, which had also been the case in this research.

Model computations on the sediment balance by Van Loon [2005] found an import in the order of 700 kton/year for the entire Dutch Wadden Sea, which was about 30% less than the estimates from literature. (These estimates have been discussed in section 9.1.) The computations by Van Loon did not include the influence of biota. In the present research, on the other hand, a slightly larger import was calculated for the computation without biology (but with waves), when compared to the estimates from literature.

10.1.3 Overall performance of the model

The model was able to calculate a net import of fine sediment into the basin. However, this import was lower than the estimated import from literature.

The seasonal trends in the suspended sediment concentrations agree very well with observed trends inside the Wadden Sea.
With respect to the mud fractions in the bottom, the model was not able to predict the very high fractions at the tidal flats. Possibly, the spin-up time was not long enough for the second bottom layer to fill up. It might also be improved by applying a higher critical shear stress for the second bottom layer.

Nonetheless, for a conceptual model of a non-existing tidal basin, the model did perform very well in answering the research questions.

10.2 Recommendations

- To determine the influence of annual storms on the salt marshes, longer computations are needed, in the order of 10 or 20 years.

- For long term modelling, it might also be interesting to investigate the response of the system to changes in the environment, like increased storminess and sea level rise. The main question would be: “Can the basin still keep up with sea level rise, if at the same time the wave intensity increases?”. The increased storminess could in this case possibly be modelled by gradually increasing the amplitude of the ‘peaked variation’ (as defined for in scenario W03), superimposed on an increasing mean wind speed.

- The accuracy of the wave computation in Delft3D-WAQ can be improved by applying a spatially varying fetch, instead of a uniform fetch.

- One 3-dimensional computation, with a simulation time of one year, is recommended, to determine if the presence of vertical gradients have a residual effect on the long-term morphology, or whether a depth-averaged model is justified.

- It is recommended to investigate the effect of fresh water inflow into the basin. In that case, the computation should be done with a 3-dimensional grid, to be able to model the estuarine circulation adequately.

- Applying a time-effect in the bottom layers: the areas above MSL are submerged for a limited period during the tide, giving the newly deposited material time to consolidate, and sink in between the larger grains in the bed. As a result, the sediment is less easily eroded from the bed. In the model, however, this sediment remains in the top layer, with a high erodibility. By letting the sediment gradually shift towards the second bottom layer, depending on the ‘dry-time’, this effect could be taken into account. The result would be higher (and more realistic) mud percentages in the inner areas and a larger deposition in the salt marshes.
References


BORSJE, B. (2006b). Biological influences on geomorphology and bed composition on a large scale, *Literature study in preparation for the MSc thesis*, University of Twente.


DE VRIES, M.B.; S.J.M.H. HULSCHER; M.J.F. STIVE; D.C.M. AUGUSTIJN (2005). Influence of biota on estuary scale fine sediment transport; emergence of large scale bio-engineering?


VAN KESSEL, T. Personal communication (2008).


# Appendices

<table>
<thead>
<tr>
<th>A</th>
<th>Parameter settings</th>
<th>89</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Sediment concentration at sea boundaries</td>
<td>91</td>
</tr>
<tr>
<td>C</td>
<td>Hydrodynamic computation</td>
<td>93</td>
</tr>
<tr>
<td>C.1</td>
<td>Fourier analysis on tidal wave propagation</td>
<td>93</td>
</tr>
<tr>
<td>C.2</td>
<td>Water level variation and flow velocity</td>
<td>96</td>
</tr>
<tr>
<td>C.3</td>
<td>Bed shear stresses</td>
<td>100</td>
</tr>
<tr>
<td>C.4</td>
<td>Wave heights</td>
<td>102</td>
</tr>
<tr>
<td>D</td>
<td>Biological influences</td>
<td>109</td>
</tr>
<tr>
<td>D.1</td>
<td>Comparing the results with the old and the new formulations</td>
<td>109</td>
</tr>
<tr>
<td>D.2</td>
<td>Results with the new formulations</td>
<td>113</td>
</tr>
<tr>
<td>D.3</td>
<td>Grazer biomass</td>
<td>119</td>
</tr>
</tbody>
</table>
### A Parameter settings

The following table shows the general settings of the computations with the modelled basin.

<table>
<thead>
<tr>
<th>Description of parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical erosion shear stress layer $S_1$</td>
<td>$\tau_{\text{crit,ero}, S_1}$</td>
<td>0.4</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>Critical erosion shear stress layer $S_2$</td>
<td>$\tau_{\text{crit,ero}, S_2}$</td>
<td>0.5</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>Critical shear stress for deposition</td>
<td>$\tau_{\text{crit,sed}}$</td>
<td>1000</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>Fraction deposition towards layer $S_2$</td>
<td>$p_{S_2}$</td>
<td>0.05</td>
<td>-</td>
</tr>
<tr>
<td>Thickness of layer $S_2$</td>
<td>$d_{S_2}$</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>Minimum water depth for sedimentation</td>
<td>$d_{\text{sed,min}}$</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>Zeroth order resuspension flux</td>
<td>$M$</td>
<td>8640</td>
<td>g m$^2$day$^{-1}$</td>
</tr>
<tr>
<td>Settling velocity</td>
<td>$w_s$</td>
<td>43.2</td>
<td>m/day</td>
</tr>
<tr>
<td>Bed porosity</td>
<td>$p$</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Density sediment</td>
<td>$\rho_{\text{sed}}$</td>
<td>2600</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Density of (salt) water</td>
<td>$\rho_{\text{water}}$</td>
<td>1024</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Manning coefficient</td>
<td>$n$</td>
<td>0.024</td>
<td>m</td>
</tr>
</tbody>
</table>

1 Some additional computations were performed with a value of 0.2 N/m$^2$ of this parameter.
B Sediment concentration at sea boundaries

In order to account for the strong seasonal variation in suspended sediment concentrations in the sea near the coast, the western and eastern sea-boundaries were divided into three sections: a section closest to the coast (0 – 2 km) showing the largest variation in sediment concentrations; a second section (2 – 5 km) still showing some seasonal variation; a final section that shows no large seasonal variations.

The figures below show the measurements from the DONAR database, with the modelled boundary conditions. Through curve fitting with the measurement data, a cosine function for the seasonal variation in suspended sediment concentrations was determined.

Figure B.1. Measurement data and boundary condition for the suspended sediment concentration at boundary section 0 – 2 km from the coast. The maximum value of the boundary condition in winter is 90 mg/l, the minimum value in summer is 5 mg/l.

Figure B.2. Measurement data and boundary condition for the suspended sediment concentration at boundary section 2 – 5 km from the coast. The maximum value of the boundary condition in winter is 40 mg/l, the minimum value in summer is 5 mg/l.
Figure B.3. Measurement data and boundary condition for the suspended sediment concentration at boundary section 5 – 20 km from the coast. The fluctuations over the year are too small to be ascribed to a seasonal pattern. The modelled boundary condition is taken constant in time with a value of 5 mg/l.
C Hydrodynamic computation

C.1 Fourier analysis on tidal wave propagation

The waterlevel variation that was imposed at the sea boundaries can be regarded as a superposition of several harmonic tidal constituents, representing the tidal wave at sea. To investigate the propagation of each separate component inside the domain, a Fourier analysis has been performed. The results are presented in this appendix.

The first five graphs show the change in amplitude for each component, as the component travels through the domain. The next five graphs show the phase differences inside the domain.

C.1.1 Amplitudes of the waterlevel variation

Figure C.1

Figure C.2
Figure C.3

Figure C.4

Figure C.5
C.1.2 Phases of the waterlevel variation

Figure C.6

Figure C.7

Figure C.8
C.2 Water level variation and flow velocity

The following section shows one pair of graphs for each scenario (actually, the last scenario shows two pairs, one pair for spring tide and for neap tide), the first graph of which shows the water level variation in combination with the flow velocity at observation point Nes*. The second graph shows the water level in combination with the acceleration \(\frac{du}{dt}\) of the velocity at the same observation point in the modelled basin.

For all scenarios, the first graphs show that the average water level during the flood period is higher than during ebb. Additionally, the ebb period tends to be shorter than the flood period. In order to maintain continuity, this is compensated by a higher average flow velocity during ebb.

The phase difference between the water level variation and the velocity is almost a quarter of the total wave period, indicating that the tidal wave inside the basin approximates a standing wave.
The second graphs show that, for all scenarios, the acceleration during slack tide (represented by the peaks) is highest when the tide is low. This means that the duration of the slack period is shorter during LW slack than during HW slack.

C.2.1 Scenario with 1 component: M2

![Graph showing velocity and water level](image1)

*Figure C.11*

![Graph showing acceleration and water level](image2)

*Figure C.12*
C.2.2 Scenario with 3 components: M2 M4 M6

Figure C.13

Figure C.14
C.2.3 Scenario with 5 components: M2 M4 M6 S1 S2

![Graph 1](image1)

**Figure C.15**

![Graph 2](image2)

**Figure C.16**
C.3 Bed shear stresses
The following plots show the maximum exceedence of the critical bed shear stress that can occur, for the scenarios T03, W03 and B01. For some areas in scenario T03, the critical shear stress is never exceeded (light blue areas). In scenarios W03 and B01 the critical shear stress can be exceeded virtually everywhere (except for a narrow strip high up the marshes). Note that the graphs below do not indicate how often and for how long the critical value is exceeded. For some areas, permanent deposition will still be possible.
Figure C.19

Figure C.20

Figure C.21
C.4 Wave heights

C.4.1 Mean occurring wave heights
Local waves were generated inside the domain, for different scenarios of wind forcing. The following pictures show, for each scenario, the mean occurring wave heights in the modelled domain during a computation of one year.

Figure C.22

Figure C.23
C.4.2 Maximum occurring wave heights

The following pictures show, for each scenario, the maximum occurring wave heights in the modelled domain during a computation of one year.

Figure C.27

Figure C.28
Figure C.29

Figure C.30

Figure C.31
Figure C.32

Maximum occurring wave height per year
Run: W05-a

Figure C.33

Maximum occurring wave height per year
Run: W06-a
C.4.3 Wave heights in the deeper basin

The following pictures (Figure C.34, Figure C.35) show the mean and maximum occurring wave heights for the computation with the deeper basin.

**Figure C.34**

**Figure C.35**
D Biological influences

D.1 Comparing the results with the old and the new formulations

D.1.1 Destabilizing factors

![Destabilizing influence on the critical bed shear stress original formulations](image)

Figure D.1
Destabilizing influence on the critical bed shear stress
new formulations

Figure D.2

Destabilizing influence on the resuspension parameter
original formulations

Figure D.3
Destabilizing influence on the resuspension parameter
new formulations

Figure D.4
D.1.2 Stabilizing factors

**Figure D.5**

**Figure D.6**
D.2 Results with the new formulations

D.2.1 Critical bed shear stress
Values below 1 indicate destabilization and values above 1 indicate stabilization. Plots of the minimal (left) and maximal (right) destabilisation in the lower areas:

![Figure D.7](image-url)
D.2.2 Resuspension parameter

Values above 1 indicate destabilization and values below 1 indicate stabilization. Plots of the minimal (left) and maximal (right) destabilisation in the lower areas:

Figure D.8
D.2.3 Stabilized versus destabilized areas

With respect to the resuspension parameter, there is virtually no significant difference in the size of the stabilized area over the year. In other words, the border between stabilisation and destabilisation does not move. Only the degree of (de)stabilisation changes over the year.

Unlike the resuspension parameter, the critical bed shear stress does show a shift in stabilized and destabilized areas over the year, as can be seen in the graphs below, which show the seasonal shift in the position (elevation) of the factors representing biological influence.

Figure D.9
Factors of biological influence

Grazers 200% Microphytobenthos 100%

Elevation with respect to MSL

Figure D.10

Factors of biological influence

Grazers 100% Microphytobenthos 200%

Elevation with respect to MSL

Figure D.11
Bio-physical impacts on fine sediment dynamics in an idealised Wadden Sea basin

Figure D.12

Factors of biological influence
grazers 200% microphytobenthos 200%

Figure D.13

Factors of biological influence
grazers 50% microphytobenthos 100%
Factors of biological influence

Grazers 100% Microphytobenthos 50%

Factors of biological influence

Grazers 50% Microphytobenthos 50%

Figure D.14

Figure D.15
D.3 Grazer biomass

D.3.1 Spatial variations

Figure D.16

Figure D.17
Figure D.18

Figure D.19
D.3.2 Seasonal variations

**MACOMA - TOTAL BIOMASS**

difference between summer and winter value versus elevation

![Graph showing MACOMA biomass difference and R² = 0.2953](image)

Figure D.20

**HYDROBIA - TOTAL BIOMASS**

difference between summer and winter versus elevation

![Graph showing HYDROBIA biomass difference and R² = 0.2953](image)

Figure D.21
MACOMA - GRAZER DENSITY
difference between summer and winter value versus elevation

Figure D.22

HYDROBIA - GRAZER DENSITY
difference between summer and winter versus elevation

Figure D.23