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Modeling the influence of biological activity on fine sediment transport in the Dutch Wadden Sea.

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Master thesis

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Modeling the influence of biological activity on fine sediment transport in the Dutch Wadden Sea

Master thesis in Civil Engineering and Management

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Summery

Modeling the influence of biological activity on fine sediment transport in the Dutch Wadden Sea.

A large number of benthic organisms have been observed in the Dutch Wadden Sea. The biological activity of these organisms has impact on the fine sediment dynamics. Previous numerical models have been confined to focus on individual or limited number of benthic organisms. Up to now, no serious attempts, by using complex model, conducted to model the influence of biological activity on horizontal sediment fluxes between North Sea and tidal basins as well as for bed composition for different basins and depth zones. In addition the effect of combined tidal forces and wind waves on mussel beds is not known. Therefore this research aims to investigate the biological activity on cohesive sediment for different spatial scales.

The numerical model of this research is 3-dimensional approach with 10 sigma layer in Delft3D, developed by Deltares for Dutch tidal basins. The sea bed consists of fluff and buffer layers. The biological activity was incorporated into the numerical model by adjusting physical parameters in the reference situation, which are the critical bed shear stress, erosion rates and settling velocity. The biostabilization influence is presented by *Diatoms*, leading to increase the critical bed shear stress τ_{cri} and decrease the erosion rate ε. While, the bioturbation influences by *Cerastoderma edule, Arenicola marina, Hydrobia ulvae, Macoma balthica* are responsible for lowering the τ_{cri} and reduce ε. Finally, *Mytilus edulis* has biodeposition influence that give rise to increase τ_{cri} , ε and settling velocity.

The outcomes of the biological activity are compared with the reference situation. The suspended sediment concentrations for stations in the study area have been increased due to the dominant influence of grazers with temporal and spatial variations; these variations were associated with the growth of *Diatoms* and water depth respectively. The buffer layer of the salt marsh and the upper-intertidal zone was regarded to be a sink for fine materials, while an increase in the storage could occur in the lower-intertidal and channel zones for the short term, depending on the effect of wind waves; moreover erosion in the buffer layer occurred always in subtidal zone. The shallow Borndiep basin was much affected by the biological activity than the deep basin, Marsdiep. In addition the biological activity resulted in reducing 25% of the horizontal fluxes from the North Sea to the tidal basins and 7% of the sedimentation to the bed layers; table 1 illustrates the influence on basins. Finally the influence of mussel beds on sedimentation was associated with water depth and could be significantly affected by wind waves (figure1).

Actually, calibration for the model is needed because the results overestimated the field measurements (figure 2). Finally this extended model highlight the promising usefulness of the biological activity in prediction more accurate results and promote the assessment of biological activity on the marine system.

Table 1. The difference in import fluxes from North Sea to tidal basins and sedimentation to bed layer with and without biological activity for tidal basins in the Dutch Wadden Sea over a 4 months study period.

Basin	Import flux in Reference model [Kilo ton]	Import flux in Extended model [Kilo ton]	Sedimentation in Reference model [Kilo ton]	Sedimentation in Extended model [Kilo ton]
Marsdiep	711	615	633	515
Vlie	834	748	1090	1100
Borndiep	495	128	899	640

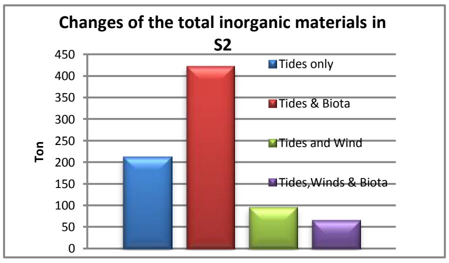

Figure 1: the accumulation of fine materials on the mussel beds in Marsdiep basin.

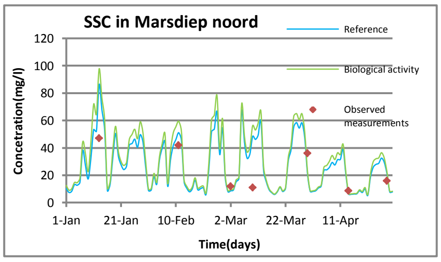

Figure 2: The suspended sediment concentration with the field measurements for Marsdiep station.

Samenvatting

Modelleren van het effect van biologische activiteit op transport van fijn sediment in de Nederlandse Waddenzee.

Een groot aantal benthische organismen zijn waargenomen in Nederlandse Waddenzee. De biologische activiteit van deze organismen heeft een impact op het transport van fijn sediment. Eerdere numerieke modellen zijn beperkt tot individuele of een klein aantal benthische organismen. Tot nu toe zijn er geen serieuze pogingen gedaan, door gebruik te maken van complexe modellen, om de invloed van biologische activiteit te modelleren op horizontaal sediment fluxen tussen de Noordzee en getijdebekkens alsmede het effect op de bodem compositie van verschillende bekkens en diepte zones. Daarnaast is het gecombineerde effect van getijdekrachten en wind golven op mosselbedden niet bekend. Het doel van dit onderzoek is daarom om het effect van biologische activiteit op cohesief sediment te bestuderen voor verschillende ruimtelijke schalen.

Voor dit onderzoek is een 3-dimensionaal Delft3D model gebruikt met 10 sigma-layers dat is ontwikkeld door Deltares voor de Nederlandse getijdebekkens. De zeebodem bestaat uit 'fluff' en 'buffer' lagen. De biologische activiteit is meegenomen in het numerieke model door het aanpassen van fysische parameters in de referentie situatie, namelijk de kritische bed schuifspanning, de erosie snelheid en zinksnelheden. De invloed van bio-stabilisatie is gerepresenteerd door *Diatoms*, wat lijdt tot een toename in τ_{cri} en een afname in ε. Bioturbatie effecten door *Cerastoderma edule, Arenicola marina, Hydrobia ulvae en Macoma balthica* zijn verantwoordelijk voor het verlagen van τ_{cri} en ε. Tenslotte heeft *Mytilus edulis* een bio-depositie effect dat resulteert in een toename in τ_{cri}, ε and W_s .

De effecten van de biologische activiteit zijn vergeleken met de referentie situatie. De concentraties van gesuspendeerd sediment op stations in het studiegebied zijn toegenomen ten gevolge van de dominant invloed van grazers met variaties in ruimte en tijd; deze variaties zijn geassocieerd met de groei van *Diatoms* en waterdiepte respectievelijk. De buffer laag van het zout-moeras en de bovenste laag van de inter-getijde zone kan worden beschouwd als put voor fijn sediment, terwijl een toename in het bergingsvolume kan optreden in de lage inter-getijde zone en kanaal zones op korte termijn, afhankelijk van het effect van wind golven; daarnaast trad erosie in de buffer laag altijd op in de sub-getijde zone. Het ondiepe Borndiep bassin werd veel meer beïnvloed door de biologische activiteit dan het diepe Marsdiep. De biologische activiteit resulteerde in een afname van 25% in de horizontale fluxen tussen de Noordzee en de getijdebekkens en een afname van 7% in de sedimentatie van de bodemlagen; tabel 1 illustreert het effect op de bekkens. Tenslotte kan het effect van mosselbedden op sedimentatie worden geassocieerd met de waterdiepte en zou significant beïnvloed kunnen worden door wind golven (figuur 1).

Kalibratie van het model is noodzakelijk omdat de modelresultaten een overschatting geven t.o.v. van de veldmetingen (figuur 2). Tenslotte benadrukt dit uitgebreide model de bruikbaarheid van biologische activiteit in het maken van meer nauwkeurige voorspellingen en het bestuderen van biologische activiteit in kustsystemen.

Tabel 2. Het verschil tussen import fluxen van de Noorzee naar de getijdebekkens en sedimentatie van de bed-lagen met en zonder de biologische activiteit, voor de Nederlandse Waddenzee over een periode van 4 maanden..

Basin	Import flux in Reference model [Kilo ton]	Import flux in Extended model [Kilo ton]	Sedimentation in Reference model [Kilo ton]	Sedimentation in Extended model [Kilo ton]
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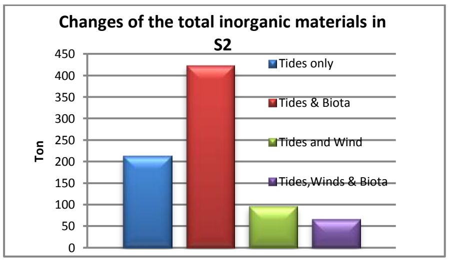


Figure 1: the accumulation of fine materials on the mussel beds in Marsdiep basin.

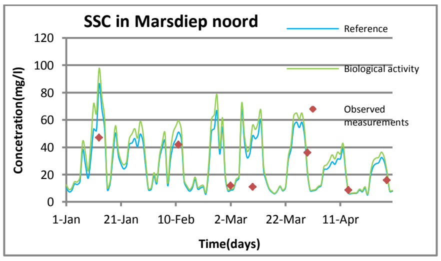


Figure 2: The suspended sediment concentration with the field measurements for Marsdiep station.

Preface

This thesis is written as part of the master program Water Engineering and Management at Twente University, The Netherlands. This research has been conducted at Deltares in Delft. Deltares is an independent and non-profit institute for applied research in the field of water and subsurface with five areas of expertise. The subject of this research is Modeling the influence of biological activity on fine sediment transport in the Dutch Wadden Sea. This research started in the mid of September 2015 and continued until April 2016.

Firstly, I would like to thank the member of my graduation committee, Prof. dr. Suzanne Hulscher, Drs. M. de Vries and Dr.ir.B.Borsje for lots of great inspiration, ideas, comments and enthusiastic support. Also, special thanks goes to dr. ir. Thijs van Kessel, although he is not a member of my committee for helping me with the model.

Other people also supported and helped me at Deltares during my study and here I would like to thank Qinghua Ye, Jos van Gils, Katherine Cronin, Michel Jeuken, Claire van Oeveren and Sandra Gaytan Aguilar for that. Further I would like to thank my fellow graduate student in Twente University and Deltares for their time and cooperation

Finally, I would like to thank my parents, Inaam and Mowafak, my brother Bashar and my sister Heba for being the wonderful people in my life.

Zaid Bashir

Delft, April 2016

List of symbols

f_s	the stabilizing factor by Diatoms for the critical bed shear stress	[-]
g_s	the stabilizing factor by Diatoms for erosion rate	[-]
f_d	the destabilizing factor by grazers for the critical bed shear stress	[-]
g_d	the destabilizing factor by grazers on erosion rate	[-]
a	coefficient affect the stabilizing factor	[g/μg]
b	coefficient affect the stabilizing factor	[g/μg]
c	coefficient affect the destabilizing factor	[m^2/gC]
d	coefficient affect the destabilizing factor	[m^2/gC]
Chf	chlorophyll- α concentration	[μg/g]
Czb	biomass of grazers	[g/m^2]
τ_e	critical shear stress for erosion	[Pa]
τ	critical shear stress for deposition	[Pa]
ε	erosion rate	[g DM/m^2/d]
D_1	deposition towards fluff layer	[g/m^2/s^1]
D_2	deposition towards buffer layer	[g/m^2/s^1]
α	the fraction of deposition flux	[-]
E_1	resuspension from fluff layer	[g /m^2/s]
E_2	resuspension from buffer layer	[g/m^2/s]
W_s	settling velocity	[m/d]
c	the near-bed concentration	[kg/m^3]
ρ_w	density of water	[kg/m^3]
ρ_{grain}	density of materials	[kg/m^3]
D_{50}	median bed materials size	[μm]
g	Gravitational acceleration	[m/s^2]

Contents

1- Introduction

The first chapter contains an introduction of this research, which is organized as follows. Background in section 1-1, followed by problem definition in section 1-2, section 1-3 the research objective and finally report outline in section 1-4.

1-1 Background

Fine sediment transport in the sea water columns is the movement of particles as a result of a combination of gravity force and the movement of the water by tidal currents and wind waves. Fine sediment transport is important in the field of civil engineering since knowledge of sediment transport has been used to determine whether erosion or deposition could take place, the time and distance over which this would happen, and the quantities of these processes. Actually, fine sediment transport is not only affected by hydrodynamic forces, but also by the presence of benthic organisms in the water body, for instance phytobenthos and macrozoobenthos (Austen et al., 1999). These benthic organisms, which can be found on and in the bottom of the water bodies, could have an impact on the surrounding environment because of their roles in creating and maintenance their habitats as well as searching for food. Jones et al. (1994) were the first to name the organisms which are responsible for creating and maintaining their habitats as Ecosystem Engineers and the process was called ecosystem engineering, Lee and Swartz (1980) classified the effects of biological activities in four processes. The first process is biosuspension influence, causing suspension of sediment by the movement of fauna. The second process is biodeposition influence which takes place when organisms contribute to clean water through filtering small particles out of the water volume, like mussel and cockle. The third process is bioturbation influence, leading to redistribution of the sediment within the bed and increase the erodability of sediment. Finally, biostabilization influence, whereas the organisms cover the bed or produce substances that bind the sediments particles such as algae mats and mussel beds. Therefore, these influences by benthos affect the stability of bed materials, which leads to change, the roughness of the sea bed, suspended fraction concentration in the water column and the transport of bed load materials. Thus, biogeomorphology is defined as the study of how the benthic organisms form the landscape of their environment and their activities are mediated by other geomorphological processes. Recently, the interest in the relation between the biotic and abiotic environments has been increased for the water bodies such as estuaries, rivers and seas for the last years because biological activities by biota can significantly influence sediment dynamic(Paarlberg et al., 2005; Borsje et al., 2008; van Oeveren, 2008a and van Leeuwen et al., 2010 and Garacia, 2011)

The area of interest for this research is the Dutch Wadden Sea, which consist of several tidal basins and they are connect to the North Sea through tidal inlets. Actually, these basins contain several kinds of benthic organisms according to field measurements (Dekker, 2009; Compton et al., 2013). This research aims to understand the impact of benthic organisms on fine sediment transport in the Dutch Wadden Sea.

1-2 Problem definition

Various numerical models have been used to study the impact of biological activities on sediment dynamics (Paarlberg et al., 2005; Borsje et al., 2008; van Oeveren, 2008 and van Leeuwen et al., 2010). These models examined the effects of specific types of benthos and the outcomes reflect the influences of these types on sediment transport. Algae bed, Baltic tellin and Mud snail have been shown to have (de)stabilizing influences on sea beds (Paarlberg et al., 2005; Borsje et al., 2008 and van Oeveren, 2008a), while van Leeuwen et al., (2010) have examined the biodeposition as well as biostabilization influences of Blue mussels on sediment dynamics. These studies show that those benthic organisms are significant factors, which could affect the sea bed. In other words, stabilizing organisms could be responsible for an increase in critical bed shear stress and significantly reduce in erosion rate. As a result, deposition of suspended sediment takes place and an increase of mud content in the bed layer occur. On the other hand, destabilizing organisms lead to reduce the critical bed shear stress and increase the erosion rate, causing resuspension of fine materials from the bottom.

So far, investigations in the previous studies have been confined to focus on either (de)stabilizing benthos or biodeposition species, while the real basins contain all these types of benthic organisms. The reason for selecting few types of species in the previous models is that algae bed, Baltic tellin and Mud snail were the dominant species, which could have significant impact on sediment transport processes. Moreover, none of the models has examined the effects of other types of organisms such as Cockles and Lugworms on fine sediment transport due to and lack of both field and laboratory experiments, which can illustrate the role of these species in fine sediment dynamics. Therefore, this research will address the effects of multiple benthic organisms in order to examine their combined roles in transporting fine sediment in the Dutch Wadden Sea.

The previous study (van Oeveren, 2008a) has shown that biological activity may influence sediment dynamics, through developing an idealised tidal basin model, to explain the effect of biological activity on multiple depth zones. Actually the previous study could not address the interaction between adjacent tidal basins because fine sediment could also be transported between basins. Thus this research will involve multiple tidal basins in order to address the biological activity on the whole Wadden Sea and to assess the outcome in different special scales by using complex model. Up to know, there is a lack of research on the impact of biological activity on the horizontal sediment fluxes between the tidal basins of the Dutch Wadden Sea and North Sea, therefore a study has to be conducted to investigate the influence of the biological activity on the magnitude of horizontal sediment fluxes between North Sea and tidal basins.

The implementation of mussel beds in the previous study, conducted by van Leeuwen et al., (2010), was aimed to understand the direct impact of mussel beds on fine sediment dynamics in a small scale of Borndiep basin without the effect of wind waves; however it is still unknown how the mussel beds will develop in different locations of the Dutch Wadden Sea with different hydrodynamic processes. Thus this research will improve the knowledge gained by analysing mussel beds in different depth zones with the effect on wind waves.

These investigations of the biological activity will provide valuable insight into the effects of benthic organisms on fine sediment dynamics, in order to increase the accuracy of the numerical models and promote the assessment of biological activity on the marine system.

1-3 Research objective and questions

The objective of this research is stated as follows:

- ***To investigate the influence of benthic organisms on fine sediment transport and bed composition in the Dutch Wadden Sea by using the numerical model, Delft3D.***

Based on this objective, five main questions are proposed in this research to explain the process of the model in more details, these are:

1- ***Which benthic organisms have effects on the erosion and deposition of sediment in the Dutch Wadden Sea? And, how can the biological activities of these organisms be incorporated into the numerical model?***

2- ***What is the influence of biological activity on suspended sediment concentration, compared to the situation without biological activity and comparing also with actual measurements from the field in the Dutch Wadden Sea?***

3- ***What is the difference in mud content between simulations with and without biological activities? For different temporal and special scales***

4- ***How could the biological activity affect the sediment fluxes between North Sea and tidal basin of the Dutch Wadden Sea?***

5- ***What is the role of mussel bed on sediment stability in the Dutch Wadden Sea?***

1-4 Thesis outline

Figure 1-1 presents a roadmap of this research; in which chapter 2 present the system description. Chapter 3 describes the model description. Chapter 4 provides the results. Chapter 5 presents a sensitivity analysis. The discussion will be given in chapter 6. The last chapter covers the conclusion and the recommendations.

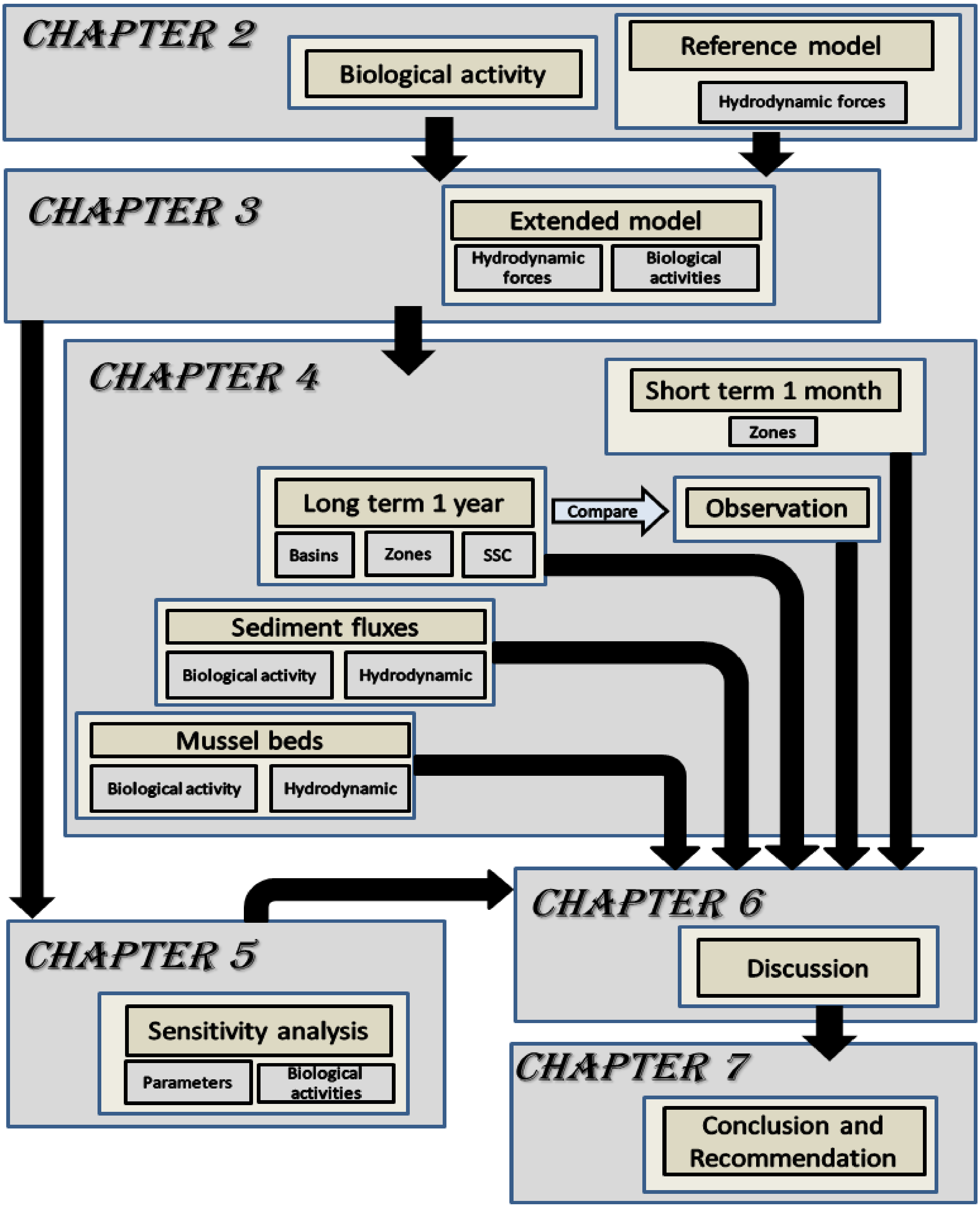


Figure 1–1, an overview of the Roadmap of this thesis.

2- System description

2-1 Study area

The Dutch Wadden Sea is used as study area for this research. This section is structured as follows, section 2-1-1 discuss the history of the area, section 2-1-2 explains the existing study area and finally section 2-1-3 is the hypsometry of the Dutch Wadden Sea.

2-1-1 History

The retreat of the glaciers about 7500 years ago and the subsequent sea level rise resulted in the creation of the Wadden Sea (figure 2-1.a), which is regarded as a unique coastal ecosystem in the southeast part of the North Sea and the largest intertidal area worldwide. Recently, the Wadden Sea was declared one of the Natural World Heritage sites by UNESCO (Committee, 2009), what's responsible for this achievement is a particular attention that has been paid since the early years of the last century by the Netherlands, Germany and Denmark with the goal of protecting the Wadden Sea. In contrast to these concerns, human interventions have caused ongoing changes to the geomorphology of the Wadden Sea. Specially, before 1932 the western part of the Wadden Sea in the Netherland was part of the larger Zuiderzee, which was shallow and brackish. After 1932, the brackish inland sea became freshwater Lake IJsselmeer due to the construction of the enclosure dyke, Afsluitdijk, between Cornwerd and Den Oever. The split of the Zuiderzee has led to changes in the surface areas of the tidal flats due to the hydrodynamic forces (Elias & van der Spek, 2006).

2-1-2 Existing model

The study area of the existing model, i.e. the *PACE* model, is the Dutch Wadden Sea, which is located between the mainland and the North Sea. Exchange of mass between the study area and the North Sea occur through a series of tidal inlets. The boundaries of this model are the watershed between Rottumerplaat Island and the main land, the Afsluitdijk and five islands, which are Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog. Additionally, dike rings were built within intertidal areas in order to protect the land and the islands from floods. The Dutch Wadden Sea can be divided into several basins and this model contains the most basins excluding the eastern part such as Ems estuary because the existing model was mostly concerned with the western part of the domain (figure 2-1.b).

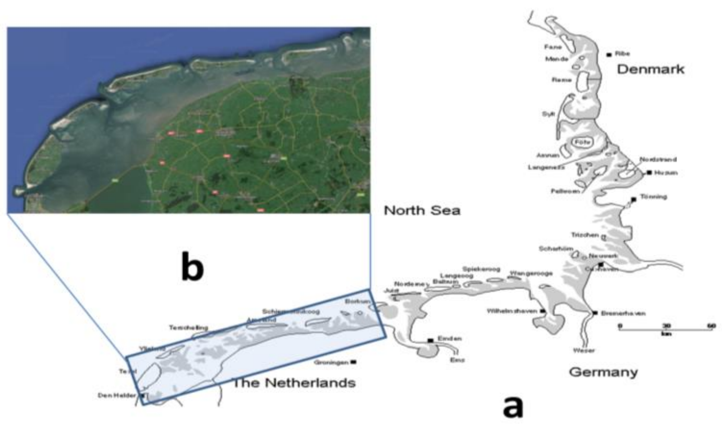


Figure 2–1, the Wadden Sea along the three countries Denmark, Germany and the Netherlands (Müller, 2004) (a) an overview of the study area, the Dutch Wadden Sea (Google earth) (b).

2-1-3 Hypsometry

The Earth's hypothemetry is the distribution of surface area at various elevations of land and depth of ocean (Menard and Smith, 1966).This concept provides a new perspective on large-scale seabed morphology. There are five zones of sea elevation in the Dutch Wadden Sea; salt marsh, upper-intertidal, lower-intertidal, subtidal and channel zones (van Oeveren, 2008a). Table 2-1 illustrates the upper and the lower limits of depth elevation for every zone according to the mean sea leve (MSL). The salt marsh zone is only flooded during storms or spring tides, while the intertidal zones are completely dry during ebb tides. The subtidal zone is permanently flooded and channel networks are mostly located in the tidal inlets. Figure 2-2 shows the the five zones in the study area.

Table 2-1, Definition of the characteristic zones in the Dutch Wadden Sea.

Zones	*Upper limit[m]*	*Lower limit[m]*
Salt Marshes	MSL-4	MSL-1,25
Upper intertidal	MSL-1,25	MSL
Lower intertidal	MSL	MSL+1,25
Subtidal	MSL+1,25	MSL+3,5
Channels	MSL+3,5	MSL+40

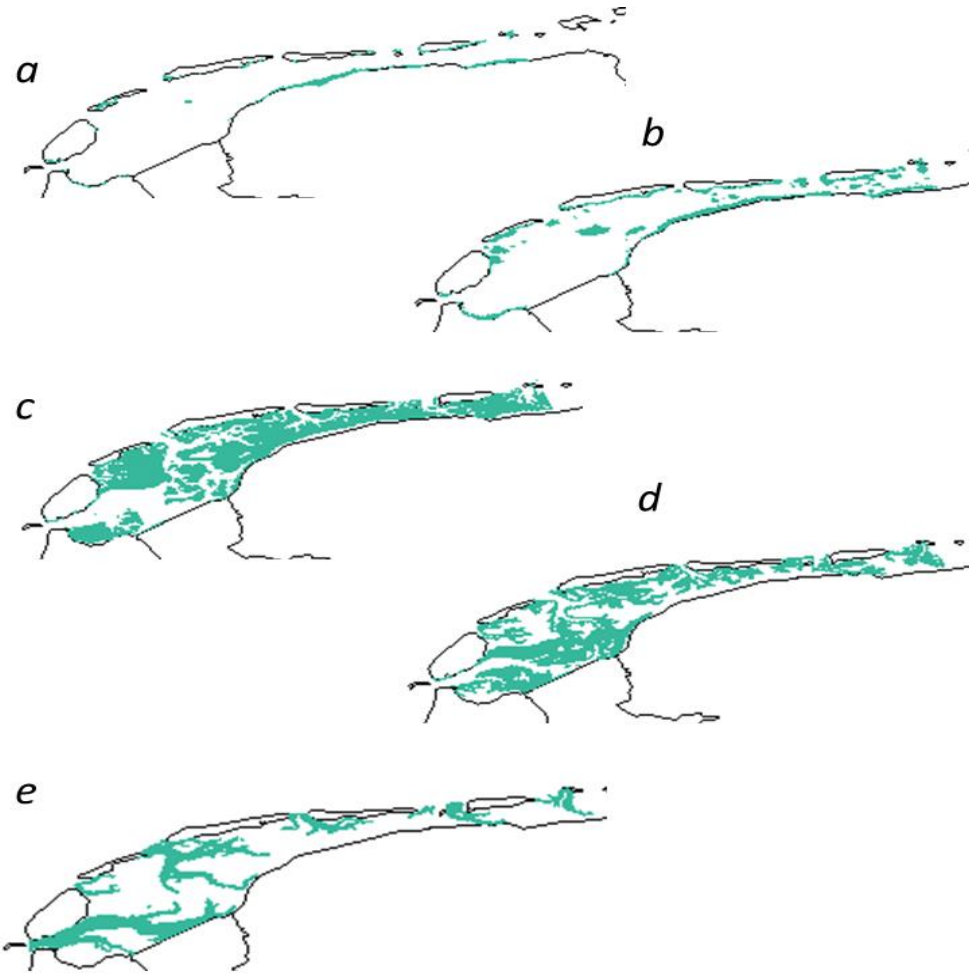


Figure 2–2, the hypothemetry of the Dutch Wadden Sea, of which salt marsh zone a, upper-intertidal zone b, lower-intertidal zone c, subtidal zone d and channel network e.

From figure 2-3 it may be estimated the hypsometry for the tidal basins, of which it shows variation in the distribution for zones for each basin. Importantly, the Marsdiep intertidal basin is regarded to be a deep basin due to the dominated subtidal and a large relative ares of channel networks. On the other hand, regular basins, such as Borndiep basin, have larger intertidal zones than subtidal or channel networks and the relative area of salt marshes in the this basin is larger than the wester basins. Actually, all these variation in surface area distribution is likely to affect the abundance of benthos, which will describe later, and might have influence on fine sediment distribution within different zones (van Oeveren, 2008a). Moreover, the human intervention in the Dutch Wadden Sea has led to change the hypsometry of the basin for instance the closure part in Marsdiep basin, in this case time is needed to reach the equalibrium state within the basin.

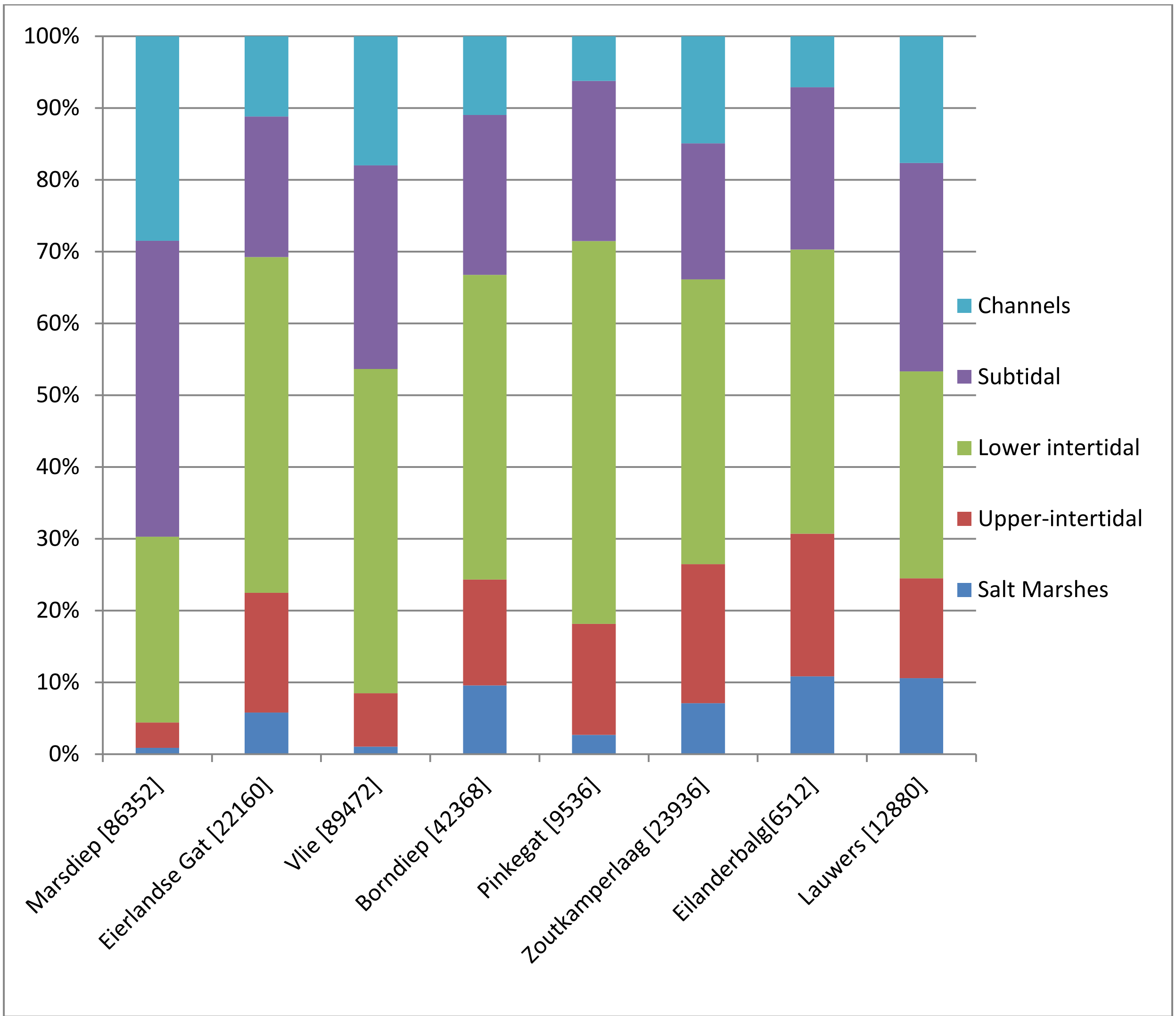


Figure 2–3, the hypsometry for intertidal basins in the Dutch Wadden Sea; the y-axis is the percentage of each zone to the total area and the X-axis is the tidal basins with their total surface areas between brackets.

2-2 Sediment dynamics

Sediment transport in the marine environment is caused by several factors. The hydrodynamic forces by tidal currents and wind waves are regarded as the main contribution to sediment transport. These forces cause suspension load of fine sediment. In addition, the benthic species play a significant role in stabilizing and destabilizing inorganic materials, depending on their biological activities. Therefore, these combined processes can change the balance of fine sediment in the study area. In this section, an overview of the types of sediment in the Dutch Wadden Sea will be given, followed by the processes which are responsible for sediment transport and finally the observed measurements in the field.

2-2-1 Fine sediment characteristics

In general, the sediment fractions are divided into cohesive and non-cohesive particles. The cohesive sediment, mud particles, are only transported as suspension load, while the non-cohesive sediments, sand particles, are transported as bed load and when the grain size (<60 um), sand particles could transported as suspension load. Table 2-2 illustrates upper and the lower size ranges for non-cohesive sediment, i.e. sand particles, and cohesive sediments, which means mud particles.

Table 2-2, the classification of sedimentary particles according to size (Butterworth-Heinemann, 1999).

Type	*Characteristic*	*Upper range[mm]*	*Lower range[mm]*
sand	*very coarse*	*2*	*1*
sand	*coarse*	*1*	*0,5*
sand	*medium*	*0,5*	*0,25*
sand	*fine*	*0,25*	*0,125*
sand	*very fine*	*0,125*	*0,0625*
mud	*silt*	*0,0625*	*0,002*
mud	*clay*	*0,002*	*0,0005*

In the Dutch Wadden Sea, the sediment on the bed consists of fine to medium sand, while the mud content is less than 5% and this ratio highly occurs at the landward boundaries and at the division of the tidal basins (Dronkers, 2005). Figure 2-4 below shows the distribution of mud in the Dutch Wadden Sea, whereas the samples have been taken from the top (5 to 10 cm) layer depth at the periods 1990-2000. In fact, higher concentration of mud can be seen in the salt marsh and upper intertidal zones by comparing with figure 2-2.

Figure 2–4, the percentage of mud content in the Dutch Wadden Sea, (Dronkers, 2005).

2-2-2 Fine sediment dynamics

Many observations about the distribution of the suspended matter in the Dutch Wadden Sea have concluded that the increase in suspended sediment concentration resulted from the exchange of water mass between the North Sea and the Wadden Sea by the tidal inlets (Postma, 1961); in spite of the fact that there are other sources of suspension load by rivers, sluices, but their contribution is less than 4% of the total input.

Postma (1961) explained the mechanisms of fine sediment accumulation in the Dutch Wadden Sea, which depend on the current velocity and the behaviours of the silt, in fact, the suspended sediment concentration on a certain location rises through increasing the current velocity and vice versa.

The first mechanism is explained by time lags, which occur when the current velocity decreases, consequently, the suspended materials need some time to reach the sea bed (Settling lag). The second mechanism takes place when the current velocity increases. In that case, material takes time before brought again in suspension (scour lag). As a consequence of these mechanisms, sediment is settled farther inward during the flood tide and the currents are too weak to carry the settled sediments back during ebb tides.

Moreover, higher concentrations of silt have been observed close to the coastline due to the decrease of tidal currents from the tidal inlet towards the shore. In other words, the water mass travel faster in the channels than further inward during flood tide. This means the flow velocity decreases gradually and suspended materials start to settle on the seabed. Usually sand particles deposit first as a result of the higher settling velocity comparing with the mud particles, which are transported further inward because the lower settling velocity. As a result of all these processes, a certain amount of fine sediments have settled at the end of the flood tide and water mass contains lower suspended concentration when it travels outward to the North Sea.

2-2-3 Observed measurements

Model evaluation is a systematic way to collect information about the study area. This information can be obtained from measurements in the field and outcomes from previous models and researches in order to make decisions about the model results. Evaluation of the model can help to determine whether the processes within the model are functioning as intended in order of meet the objectives and also improve the outcomes by adjusting the input processes and parameters

The model in this research represents realistic tidal basins of the Dutch Wadden Sea. Therefore, the modelled results ought to be in good agreements with the field observation that has been taken in 2009. The suspended sediment concentration measurements from the Rijkswaterstaat database will be used to assess the model results for different stations in the study area. Figure 2-5 shows the locations of the observed measurements in the tidal basins and the measured data is shown in figure 2-6 for the eight stations in 2009.

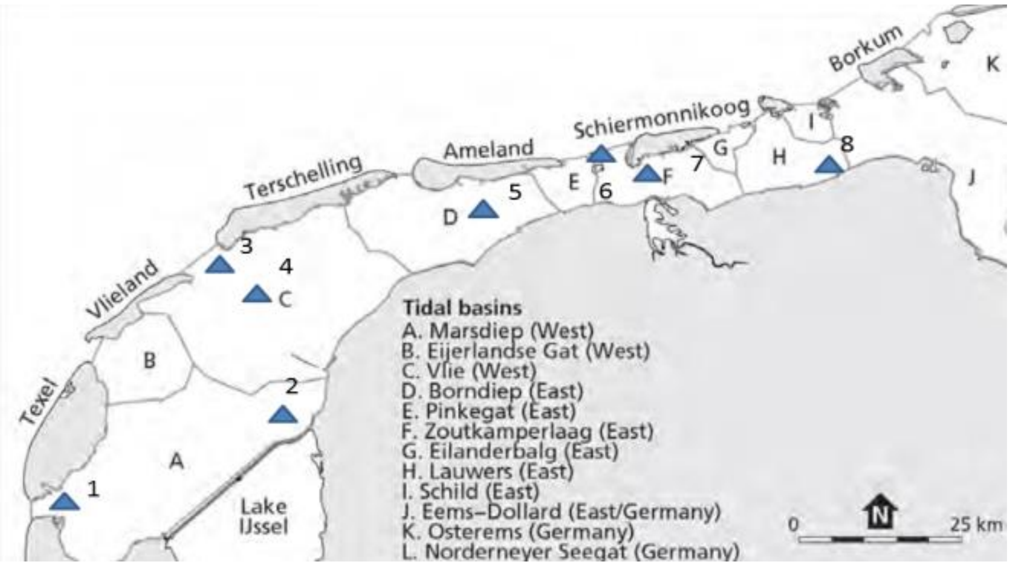


Figure 2–5, the locations of the stations in the Dutch Wadden Sea (▲) source http://kml.deltares.nl/kml/ Rijkswaterstaat / waterbase and the map from (Donker, 2015).

The data from the observed stations could be used to compare the results of the model; however, station *8, Zuid Oost Lauwers oost* (figure 2-6-b), is located close the boundary of the study area, so it might be insufficient to compare the modelled date with filed measurements because the result could be significantly influenced by the values of boundaries. Not only is the uncertainty in the modelled data but also the field data, the outlier in the field measurement is hardly ever happen. Moreover, the suspended sediment concentrations for *Blauwe Slenk oost* and *Dantziggat* stations are higher than other stations in figure 2-6-a; this might be stemmed from the location of the stations in intertidal zones where the flow velocities are lower than the subtidal and channel zones such as *Marsdiep noord*, *Doove Balg west* and *Vliestroom* stations.

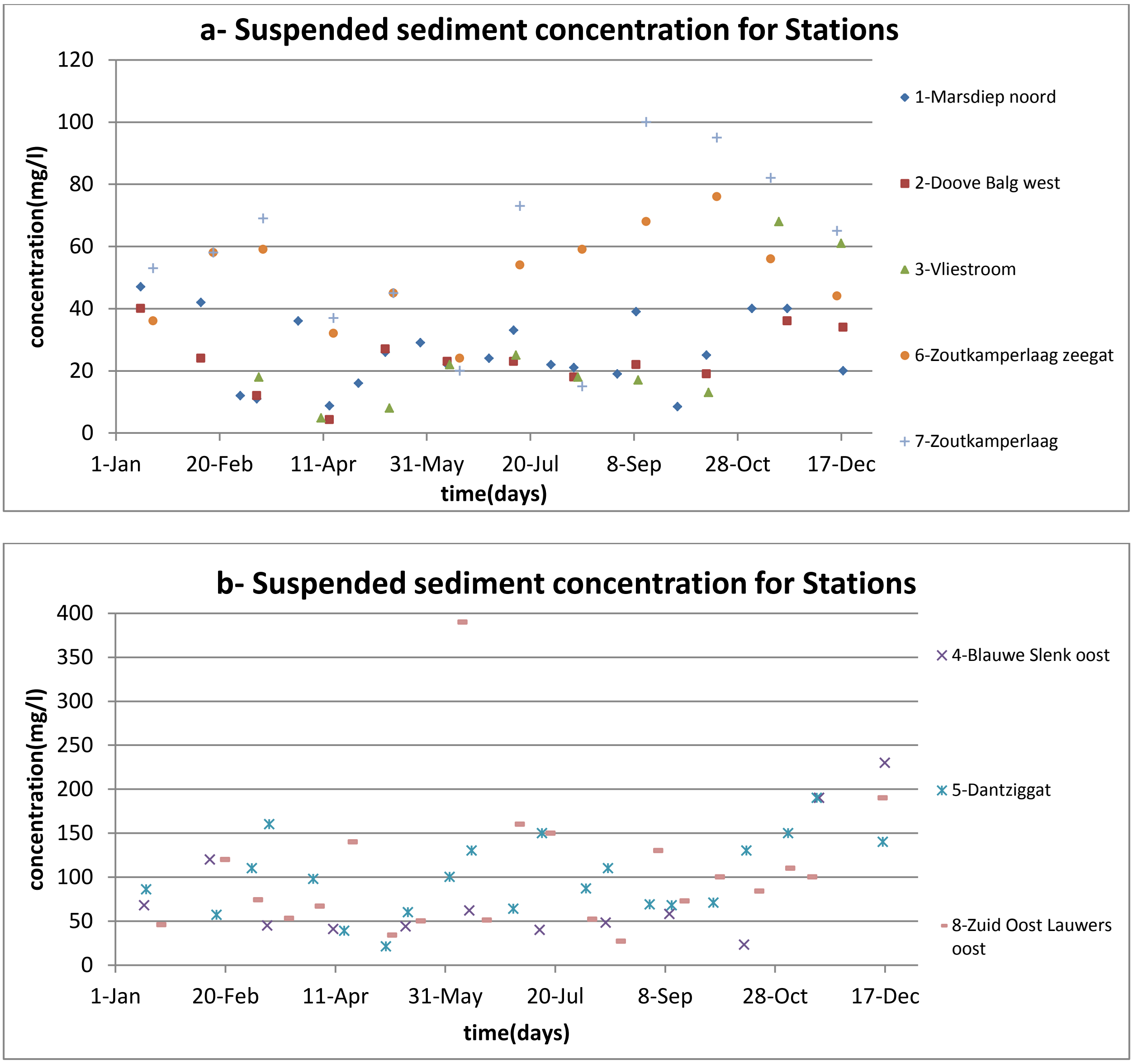


Figure 2–6 b, field observation measurement of the suspended sediment concentration in 2009 for stations in the Dutch Wadden Sea, source http://kml.deltares.nl/kml/rijkswaterstaat/waterbase, the stations with lower concentration than 100[mg/l]are presented in a and with the higher concentration in b.

2-3 Benthic species

There are a large number of methods to classify benthic organisms, depending on their food web, abundance, size, habitat use, commercial importance etc. In this study, the role of benthic organisms in transport of fine sediment will be used. Several types of benthic organisms have been observed in the Dutch Wadden Sea, leading to (de)stabilize the fine materials in the seabed. In this section, the types of benthic organisms are given with their biological activity, followed by their methods to convert the biological activities into physical terms and finally the temporal and spatial variations for the abundance of organisms are discussed.

2-3-1 Types of benthic organisms

Various types of benthos have been found in the tidal basins of the Dutch Wadden Sea. These benthic organisms have biostabilization, bioturbation and biosuspension influences on fine sediment. From Table 2-3, it can be seen the most common organisms and macro fauna, which have been observed in the Dutch Wadden Sea (van Oeveren, 2008; Compton et al., 2013). These organisms could change the stability of fine sediment in the Dutch Wadden Sea due to their biological activity.

Table 2-3, the common benthic organisms observed in the Dutch Wadden Sea.

Biology activity	Type of organisms/species
Biostabilization effect	Algae (*Diatoms*)
Biodeposition effect	Cockle(*Cerastoderma edule*)
	Sand gaper(*Mya arenaria*)
	Sand mason (*Lanice conchilega*)
	Blue mussel (*Mytilus edulis*)*
	Pacific oyster (*Crassostrea gigas*)*
Bioturbation effect	Lugworm (*Arenicola marina*)
	Baltic tellin (*Macoma balthica*)
	Mud snail (*Hydrobia ulvae*)
	Thread worm (*Hetermastus filiformis*)
	Atlantic jacknife clam (*Ensis directus*)
	Ragworm (*Hediste diversicolor*)
	(*Scoloplos armiger*)
	(*Scrobicularia plana*)
	(*Marenzelleria viridis*)
	(*Alitta virens*)
	(*Nephtys hombergii*)
	(*alitta succinea*)

** Species have also biostabilization effect*

The selection of benthic organisms in this study depends on the available approaches that can be used to convert the biological activities into physical parameters. Therefore, this study will also focus on *Diatom*, *Macoma balthica*, *Hydrobia ulvae* and *Mytilus edulis* benthos because the previous models examined their impact on fine sediment transport. In addition to that, the influence of other type of species, such as *Cerastoderma edule* and *Arenicola marina,* on sediment transport could also be included in this research since information from flume experiments are available (Ciutat et al., 2007; van Oeveren , 2008b). The biomass of these six organisms can reflect more than 50% of the average biomass for the whole study area (Dekker, 2009; Compton et al., 2013), but the biological influence of these species is an important factor of this research; this will be describe in the next sections.

2-3-2 The parameters of biological activities

The biological activities can be incorporated into the numerical models in terms of parameters. The existing formulations by van Oeveren, (2008a) are adapted in this research to involve other types of destabilizing species. The equations have been calibrated according to literature research and flume measurements, equations 1 and 2 describe the influence of stabilization by *Diatoms* on the critical bed shear stress and the resuspension parameter respectively.

$$f_s = 1 + (f_{s,max} - 1) . \sqrt{\tanh(a . Chf)} \qquad \text{Equation 1}$$

$$g_s = 1 - (1 - g_{s,max}) . \sqrt{\tanh(b . Chf)} \qquad \text{Equation 2}$$

Where $f_{s,max}$ and $g_{s,max}$ are considers to be the limit values for maximum stabilization. The coefficients a and b $\left[{}^{g}/_{\mu g}\right]$ determine how rapidly the function could reach its limit value. Chf is chlorophyII-α concentration$\left[{}^{\mu g}/_{g}\right]$ for dry sediment.

The destabilizing influences by grazers are being incorporated into equations 3 & 4; these equations are extended to deal with more than two types of species

$$f_d = 1 - (1 - f_{d,max}) . \sqrt{\tanh\left[\sum_{i=1}^{n} c_i . Czb_i\right]} \qquad \text{Equation 3}$$

$$g_d = 1 + (g_{d,max} - 1) . \sqrt{\tanh\left[\sum_{i=1}^{n} e_i . Czb_i\right]} \qquad \text{Equation 4}$$

Where $f_{d,max}$ and $g_{d,max}$ are considers to be the limit values for maximum destabilization. n is the number of biodestabilizing species in the area of interest. c and e are coefficients $\left[{}^{m^2}/_{gC}\right]$, which determine how rapidly the function could reach its limit value, while Czf is the biomass of the grazer$\left[{}^{g}/_{m^2}\right]$. Appendix (A) illustrates the influences of (de)stabilizing benthos on physical parameters in more details, depends on the previous equations 1 through 4.

The parameters of (de)stabilizing organisms are incorporated into the numerical model, Delft3D, through changing both the critical bed shear stress for erosion and the erosion rate as described in the equations below Equations 5 and 6;

$$\tau_e = \tau_e^{\circ} * f_s * f_d \qquad \text{Equation 5}$$

$$\varepsilon = \varepsilon^{\circ} * g_s * g_d \qquad \text{Equation 6}$$

Where τ_e° and ε° are the value for the critical bed shear stress and the erosion rate without biological activity, namely the values of the reference model.

2-3-3 The implementation of mussel beds

Another type of macro fauna is Blue mussel, this benthic organism propagate in the tidal basins of the Dutch Wadden Sea. The existing model of Van Leeuwen et al., (2010) have been studied the influence of mussel beds on the morphology of the sea bed. In other words, the trachytope functionality was used to convert these species to vegetation in flow model, which can absorb part of the total bed shear stress that causes by the tidal current, the erosion rate was increased by a factor 4 due to the (pseudo-)faecal pellets content and the effective filtration rate was set to 0,5 $mm\ s^{-1}$. Assuming a mussel bed has a density of 1800 $ind.m^{-2}$.

In this research, the values of the erosion rate and the filtration rate for the mussel beds can be used as described by Van Leeuwen et al. (2010). The filtration rate will be combined with the settling velocity for the cells in segment function where the blue mussel beds are existed. While, biostabilizing influence of mussel beds on sediment dynamics will be similar to the algae mats. Thus the critical bed shear stress will increase 66% when the bed is 100% covered by mussel beds. This factor is obtained according to flume experiment Widdows et al. (2002). These values for mussel beds have temporal variations due to the variation of the biomass.

From table 2-4 it can be seen the influences of each benthic organism on the critical bed shear stress and the erosion rate. The biomasses of these organisms are equal, excluding blue mussel and the concentration of *Diatoms* because they cover the seabed.

Table 2-4, the influences of benthos on the critical bed shear stress and the erosion rate where (+) means increasing in the value and (-) reflect the decreasing of the values.

Benthos	$\tau_{cri.}$	ε	*Reference*
Diatoms	+++	-	(van Oeveren C., 2008 a)
Mytilus edulis	+	+++	(Widdows et al., 2002; van Leeuwen et al., 2010)
Cerastoderma edule	-	++	(Ciutat et al., 2007)
Arenicola marina	--	+	(van Oeveren C. , 2008 b)
Macoma balthica	---	++	(van Oeveren C. , 2008 a)
Hydrobia ulvae	-	+	(van Oeveren C. , 2008 a)

2-3-3 Variation in biological activities

There is a variation of the biological activities for benthic organisms in the Dutch tidal basins. These changes are caused by different factors such as the seasonal variation, the abundance of nutrients and water depth. Therefore, spatial and temporal variations of the abundance of species have been found, according to the field measurements.

2-3-3-1 temporal variation in biological activities

Seasonal variation for the abundance of benthic organisms can be observed in the Dutch Wadden Sea. The seasonal variation in climate is the main reason for the changes in the biomass of benthic organisms. *Diatoms* concentration increases from early spring due to increasing of temperature and sunlight penetration. While, the concentration of *Diatom* is lower in the winter according to field measurements (Staats et al., 2001; Philippart et al., 2013). Grazers feed on micro-phytobenthos, therefore the biomass increase until September (Dekker, 2009). Then the biomass gradually decreases because food is less available in their environment after Sep. and some species cannot survive during winter.

In this research, the mussel beds is considered to be a young bed and spatfall takes place in the end of Jun. and the beginning of July, while about 50% of the bed will erode during winter. Figure 2-7 shows the temporal variation of the biological biomass in the Dutch Wadden Sea for one year. These curves are used for the segments in Dutch Wadden Sea, of which the influences of *Diatoms* and grazers are applied for same segments with different spatial variation, while the segments with mussel beds are only influenced by mussel curve.

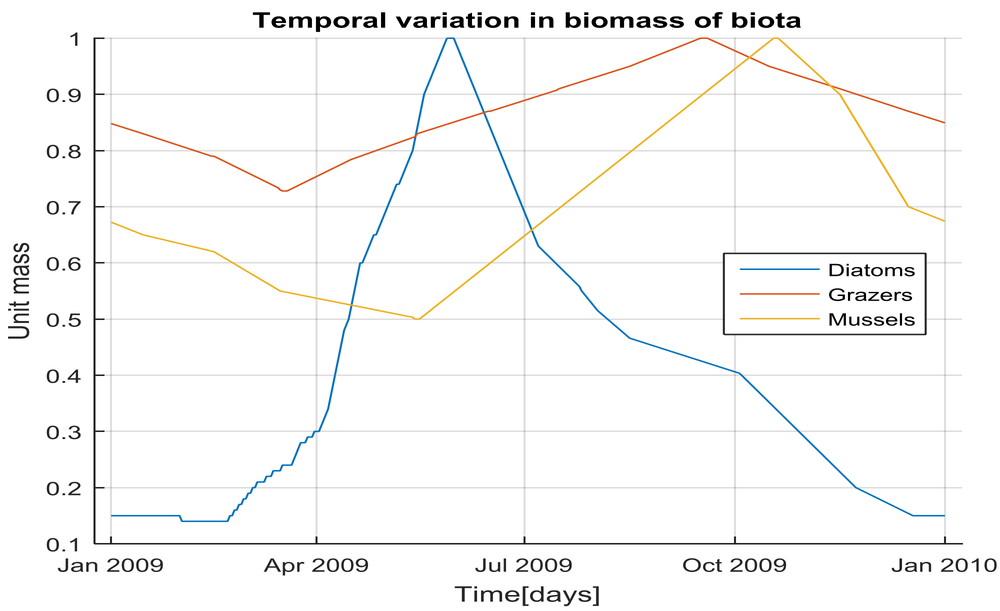


Figure 2–7, temporal variation of the biomass for different benthic organisms.

2-3-3-2 spatial variation in biological activities

There is the spatial distribution of the benthic organisms in the Dutch Wadden Sea. The *Diatom* depends in their growth on light penetration, therefore it can be only found in the zone between the Mean Sea Level (MSL) and about *1,5 meter* below MSL, while other types of grazers i.e. *Macoma balthica, Hydrobia ulvae, Cerastoderma edule, Arenicola marina*, are observed till MSL+3,5 , but with different densities. Table (2-5) illustrates the depth in the study area with the potential densities of benthic organisms as described in figure 2-8.

Table 2-5, the distribution of average benthic organisms [g.m-2] in different depth zones (Compton , et al., 2013; Dekker, 2009; Staats et al., 2001 and de Jong,D. &de Jonge,V., 1995).

Zone	Depth	Diatoms$(\frac{\mu g}{g})$	Grazers$(\frac{g}{m^2})$
1	< (-0,5)	90	Non
2	(-0,5) - 0	28	<18
3	0 - 1	28	>18
4	1 - 1,5	10	> 18
5	1,5 - 3,5	Non	<18
6	> 3,5	Non	Non

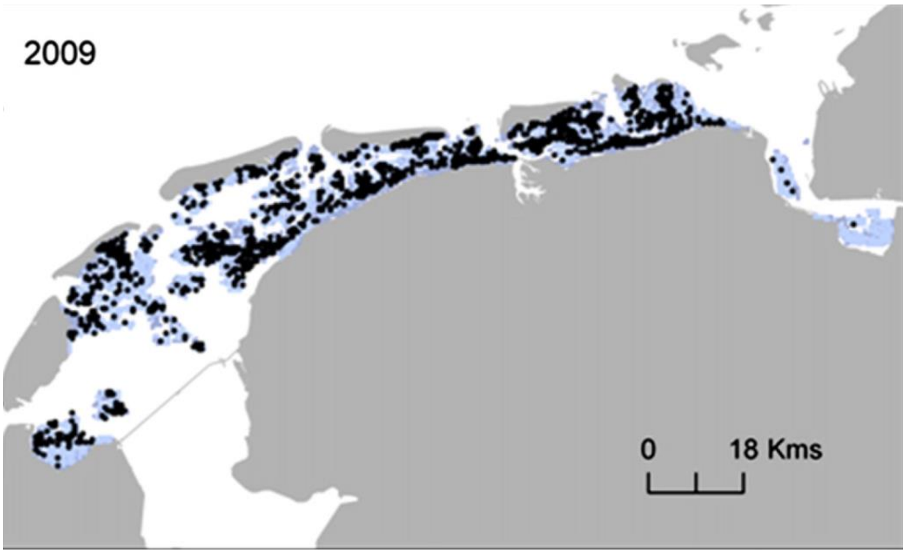


Figure 2–8, the distribution of benthic species in the tidal basins, the black dots reflects the density of grazers for more than 18 g/m2 and blue dots are for less than 18 g/m2 (Compton , et al., 2013).

The maximum grazer's biomass in this study area for different zones are illustrated in table 2-6, these values reflect the maximum average for individual species in September for the whole Wadden Sea, where the total biomass of species is 30 g/m^2 in depth zones 3 and 4 and 18 g/m^2 in depth zones 2 and 5 for all observed species (Compton et al., 2013 and Dekker, 2009). Appendix (B) shows the changes in equations 5 and 6 for the critical bed shear stress and the erosion rates in each hypsometry for the whole Dutch Wadden Sea, depending on the temporal and spatial variations of biomass in each hypsometry.

Table 2-6, the Maximum average biomass of grazers (g/m^2) in different depth zones.

Species	Max. biomass For zones ***3*** and ***4***	Max. biomass For ***2*** and ***5***
Cerastoderma edule	8,10	4.86
Arenicola marina	3,00	1.8
Macoma balthica	1,80	1.08
Hydrobia ulvae	1,54	0.92

Likewise, the spatial distribution of the mussel beds, *Mytilus edulis*, in this research is according to the field observations (Nehls et al., 2009). This spatial distribution of mussel beds can be selected in the segment functions, where cells can only be occupied by mussels with their characteristic, assuming a mussel bed has a maximum density of 1800 $ind.m^{-2}$ as described by Van Leeuwen et al., (2010). Figure 2-9 shows the cells that contant only mussel beds in the Marsdiep and Borndiep basins.

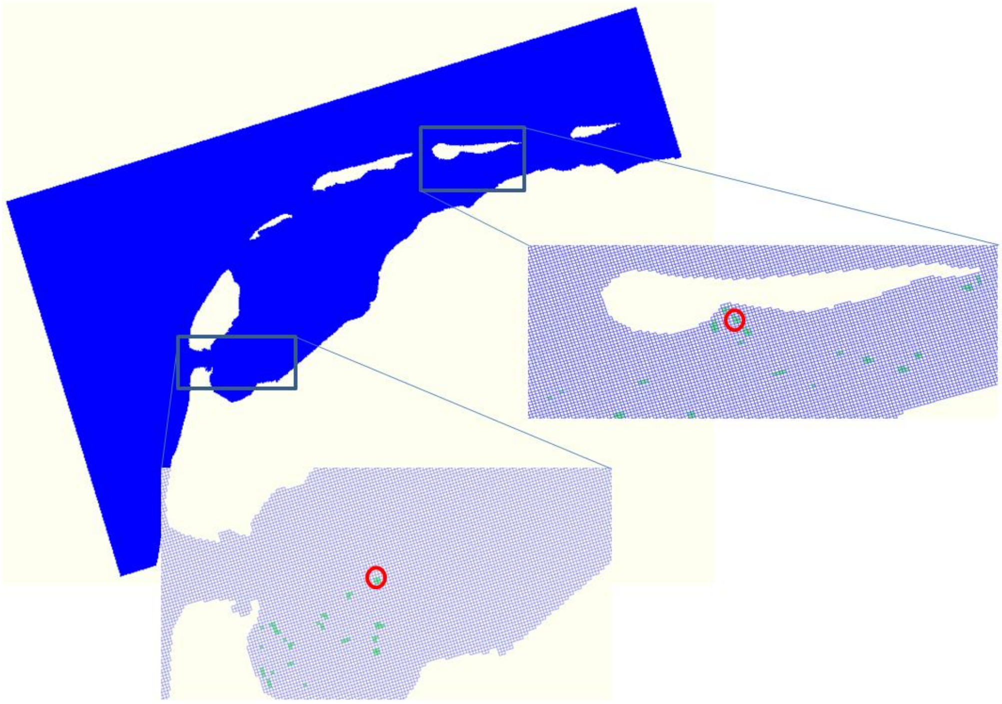


Figure 2–9, the distribution of the mussel beds in the Dutch Wadden Sea; the red markers are the segments which will be used later for the small scale results.

3- Model description

The *PACE* model, complex model, will be used to be the Reference model in this research, it was designed by van Kessel et al., (2009). This model contents the most basins in the Dutch Wadden Sea and will be further extended to involve the biological activity by benthic organisms to find out their impacts on fine sediment transport in the Dutch Wadden Sea. This chapter firstly describes the numerical model and secondly the types of simulations.

3-1 Numerical model

The reference model is a process based model, Delft3D model, and was used to determine suspended sediment concentration, bed composition and sediment balance in the Dutch Wadden Sea. The Flow, WAVE and WAQ modules were used for computations in the reference model. In other words, the hydrodynamic forces were obtained by Flow and WAVE modules and WAQ- module computes suspended sediment transport. This section describes the numerical model in more details.

3-1-1 Hydrodynamic setup

Delft3D-Flow had used to calculate non-steady flow and transport phenomena, being produced by tidal currents. The outcome from the Flow-module was used as input files to WAVE and it stored as communication files for WAQ-module, whereas WAVE-module computed wave propagation, wave generation by wind, dissipation and non-linear wave-wave interactions. The hydrodynamic forces by Flow are only used in WAQ-module, while WAVE-module can add extra bottom shear stress to the WAQ input. The most important characteristics of these modules are described in this section. The numerical model is 3D with 10 sigma layers. Meteorological forcing includes wind speed and direction. The reference model was forced at open boundaries in the North Sea with sea surface elevation, whereas a close boundary was placed on the watershed at the eastern boundary. Furthermore, several sources of freshwater discharges were included into the domain from 12 sluices. The bathymetry of the reference model was constructed using high-resolution depth-sounding, which was made available by the Ministry of Public Works (Rijkswaterstaat) as shown in figure 3-1. The time step in Flow-module for simulation was one minute. Equally important, the outcomes of the hydrodynamic forces of the existing model were only for the first four months of 2009.

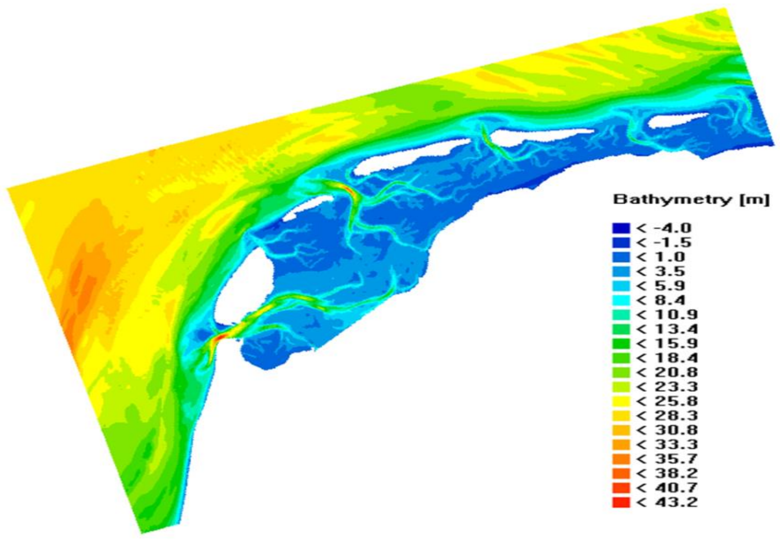


Figure 3–1, the bathymetry of the numerical model, Reference model.

3-1-2 Setup sediment module

The water quality module, Delft3D-WAQ, was used to compute fine sediment transport by solving the advection-diffusion equation. Thus the hydrodynamic forces were derived from Flow module and total bottom shear stress in this module was computed by Flow and WAVE modules. The bottom layers in the reference model were implemented as the buffer model (Van Kessel et al., 2011). To be more precise, the sea bed consists of two layers, sand and mud layers (figure 3-2). The top layer is a thin fluff layer and contains mud only. This fluff layer forms during slack tide and it can be easily eroded by tidal currents because the critical bed shear stress of this layer is very low. Therefore a huge amount of fluxes exchange between the top layer and water column and the residence time of mud in this layer is short. The underneath thick layer is a sandy layer, of which mud could entrain within the pores of sand grains and could be stored in this thick layer. The resuspension of fine materials from this buffer layer occurs when the impact of currents or wind waves on this layer is significant, for instance spring tides and storms. Subsequently, the residence time of fine materials in this buffer layer might be larger than the fluff layer. Moreover the fraction of the deposited materials to the fluff layer is much larger than the buffer layer. The exchange of sediment fluxes between water column and layers, fluff and buffer layers, are described in the equations below.

$$D_1 = (1-\alpha)W_s C$$ Equation 7

$$D_2 = \alpha W_s C$$ Equation 8

$$E_1 = min(m_1 M_1, M_0\left(\tau/\tau_{cr,1} - 1\right)$$ Equation 9

$$E_2 = p_2 M_2 c\left(\tau/\tau_{cr,2} - 1\right)^{3/2}$$ Equation 10

$$c = \rho_{grain} D_*^{0.3} \sqrt{\left(\frac{\rho_{grain}}{\rho_w} - 1\right) g D_{50}}$$ Equation 11

$$D_* = D_{50}\left(\left(\frac{\rho_{grain}}{\rho_w} - 1\right)\frac{g}{\nu^2}\right)^{1/3}$$ Equation 12

Where $D_{1\ and\ 2}$ are deposition fluxes towards fluff and buffer layers, $E_{1 and\ 2}$ resuspension fluxes from layers, α the fraction of deposition flux, W_s the settling velocity, C the near-bed suspended sediment concentration, $\tau_{cr,1\ and\ 2}$ the critical shear stress, $M_{1\ and\ 2}$ the resuspension parameters for layers, m_1 the sediment mass per unit area in layer1 and p_2 the fine fraction in layer 2, ρ_w is the density of water, ρ_{grain} is the density of materials, D_{50} is median bed materials size and g is gravitational acceleration.

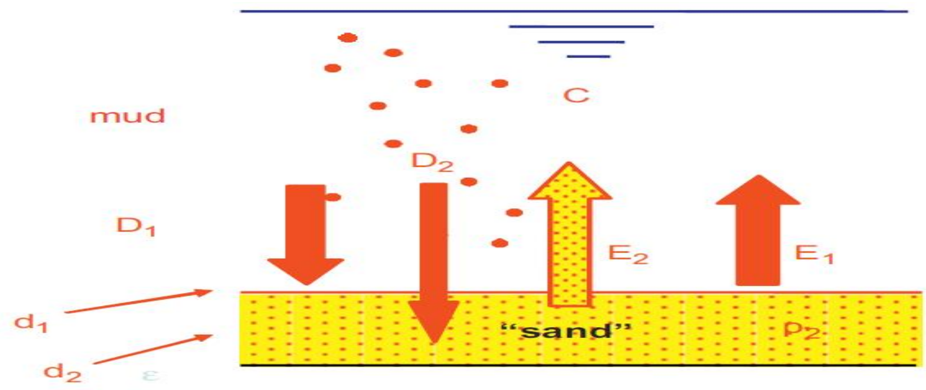


Figure 3–2, schematization of the buffer bed model, d_1 is thin fluff layer, d_2 thick buffer layer, Di deposition flux, Ei erosion flux and C suspended sediment concentration (Van Kessel et al., 2011).

The applied parameters setting is shown in Table 3-1 as established in the reference model. There are two sediment classes, IM1 and IM2, which could be simulated independently and defined by their fixed settling velocity to reproduce the observed vertical sediment concentration gradient during storm conditions and the observed baseline concentration during calm weather. Moreover, the sand layer in this model is passive, which means that no transport of sand particles between the water column and bed layers, while the erosion of the buffer model is only for the mud fraction (van Kessel et al., 2009).

Table 3-1, the initial values for the buffer model in the reference model.

Parameters	*Values*	*Units*
$\tau_{cr,2}$ (Tau Shields)	1	N/m2
$\tau_{cr,1}$ (Tau c RS)	0.1	N/m2
M_1 (V Res)	0.04	g DM/m2/d
M_0 (Z Res)	8640	g DM/m2/d
M_2 (Fact Res Pup)	0.00000035	g DM/m2/d
Settling IM1	129	M/day
Settling IM2	17	M/day
Fraction of deposition	5%	[-]

Additionally, the biological activities by *Diatoms, Macoma balthica, Hydrobia ulvae*, *Mytilus edulis Cerastoderma edule* and *Arenicola marina* are incorporated into the numerical model, *Extended model*. In other words, some of the physical parameters have variable values, for instance the critical bed shear stress for erosion, erosion rates and settling velocity. These changes are incorporated into WAQ-module by segment functions, which can compute the changes in the physical terms, depending on temporal and spatial variations of species biomass.

Figure 3-3 illustrates the influence of benthos on critical bed shear stress at a certain times in the study area. The initial value is 1 N/m2 in channel networks and North Sea, whereas the values is higher in salt marshes due to algae beds and lower than 1N/m2 in the subtidal zone because of the biological activity of grazers. In addition to that temporal variation can be observed by comparing the values between January and May duo to the stabilizing influence of *Diatoms* in increasing the critical bed shear stress in May.

The change in the erosion rate is shown in figure 3-4, so that the values are gradually increased from the salt marshes to subtidal zones. Again, temporal variation can be seen in the erosion rate, whereas the values are higher in January as a result of the dominant influence of grazers.

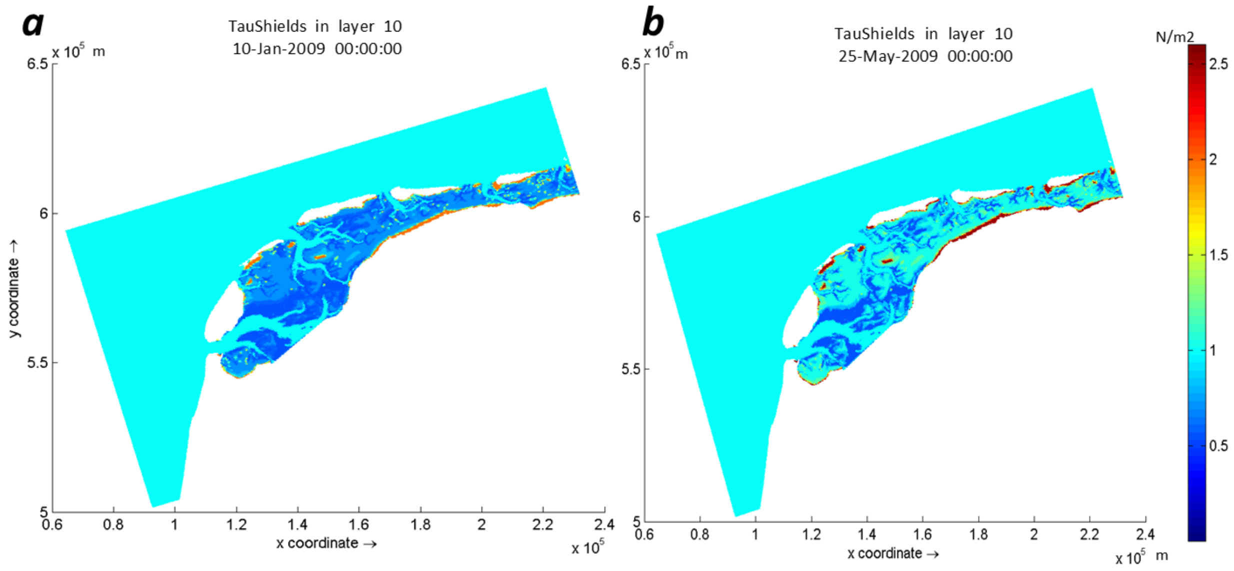


Figure 3–3, the critical bed shear stress for the buffer layer (Tau Shields) at a certain time in January left panel (a) and in May right panel (b); the value without biological activity is 1N/m2.

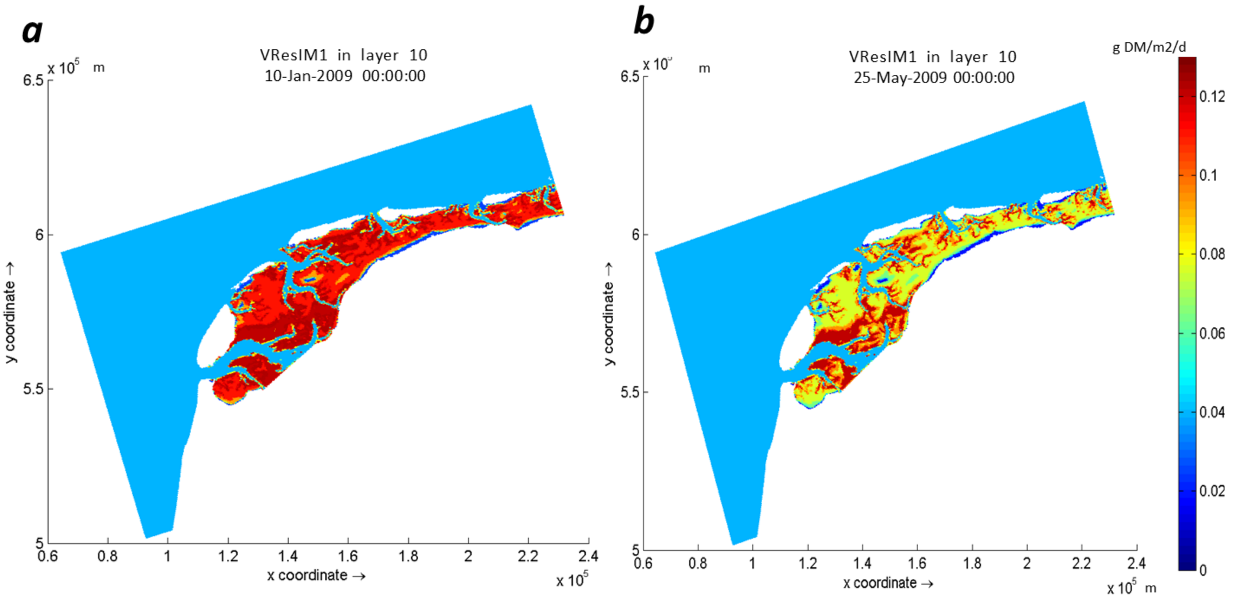


Figure 3–4, the erosion rate for the buffer layer (V Res) at a certain time in January left panel (a) and in May right panel (b); the value without biological activity is 0.04 g DM/m2/d.

3-2 Types of simulations

There are several kinds of simulation in this research. The reason of simulate several scenarios is to investigate the influence of separate or combined hydrodynamic and biological components on the behaviour of the fine inorganic materials in the Dutch Wadden Sea. The scenarios are illustrated in table 3-2.

Table 3-2, the runs of the numerical model, the values in this table reflect the maximum unit biomass of benthos.

Nr	Runs	Algae[Biomass]	Grazers[Biomass]	Mussel Tcri	Mussel E-rate	Settling velocity
1	Tide only	0%	0%	Reference value	Reference value	Reference value
2	Tide + Biota(Normal biomass)	100%	100%	+ 66%	+ 400%	+ 0,5 mm/s
3	Tide + wind	0%	0%	Reference value	Reference value	Reference value
4	Tide+ wind +Biota (normal biomass)	100%	100%	+ 66%	+ 400%	+ 0,5 mm/s
5	Tide+ wind +Stabilizing influence only	100%	0%	+ 66%	Reference value	+ 0,5 mm/s
6	Tide+ wind +Destabilizing influence only	0%	100%	Reference value	+ 400%	Reference value
7	Tide+ wind +Double Stabilizing+ Normal destabilizing	200%	100%	+ 132%	+ 400%	+ 1 mm/s
8	Tide+ wind +Normal stabilizing+ Double destabilizing	100%	200%	+ 66%	+ 800%	+ 0,5 mm/s
9	Tide+ wind +Double Stabilizing+ Half destabilizing	200%	50%	+ 132%	+ 200%	+ 1 mm/s
10	Tide+ wind +Double Stabilizing+ Double destabilizing	200%	200%	+ 132%	+ 800%	+ 1 mm/s
11	Tide+ wind +Biota (normal biomass without mussel beds)	100%	100%	Reference value	Reference value	Reference value

As can be seen from the table above, the first run contains only tidal forces, because it provides an important insight into the role of tidal currents in fine sediment transport. The second run contains both tidal forces and average biomass of benthos to see the combined impacts of these components on sediment dynamics. The effect of wind waves on the bottom shear stress was neglected in the previous runs as illustrated in figures 3-5-a and 3-6-a In the next runs, the simulations are combined with wind waves and the total bottom shear stress is derived by tidal currents and wind waves as illustrated in figure 3-5-b and 3-6-b, of which the wind waves can certainly increase the bed shear stress and the total bottom shear stress is about one order of magnitude higher close to the Islands from the North Sea side and within the channels in the inlets. Also, strong wind waves in January could significantly increase the total bottom shear stress.

To investigate the influence of biota on the stability of sediment transport, a large number of scenarios with different biomass and parameters of benthos are defined. These scenarios are normally based on the dominated (de)stabilizing influences of biological activities to examine the significant impacts of biological activity on fine sediment transport in the Dutch Wadden Sea. The last run in table 3-2 contains normal biomass of benthos but without mussel beds because the role of mussel beds in fine sediment dynamics can be investigated on a small scale, this means the locations of mussel beds, the segments, have initial values.

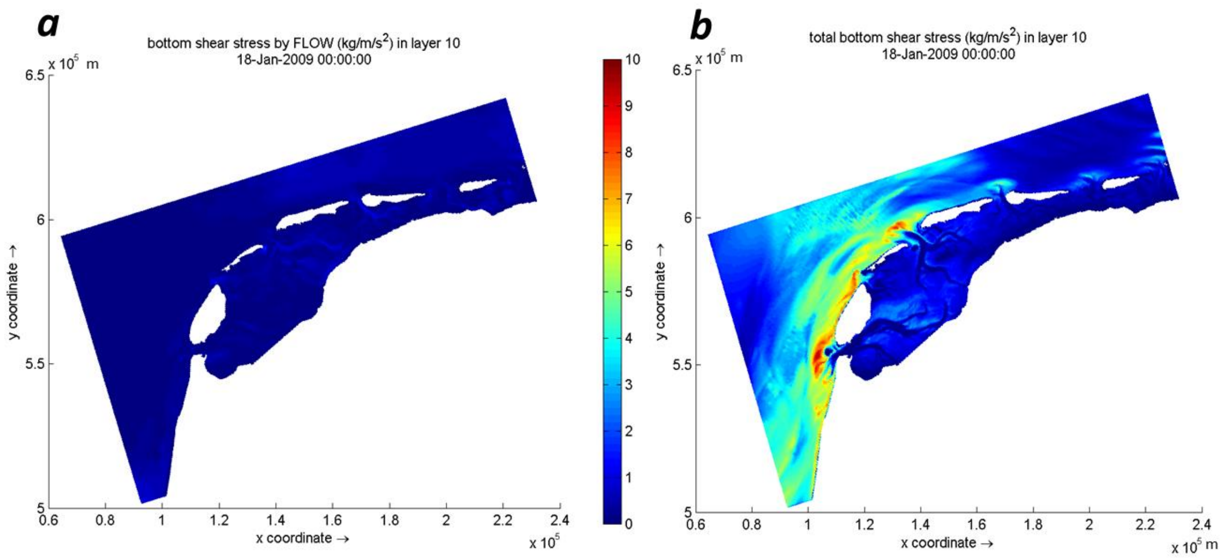


Figure 3–5, the bottom shear stress due to tidal currents only [kg/m/s2] in January (a), the total bottom shear stress caused by tidal currents and wind waves [kg/m/s2] (b).

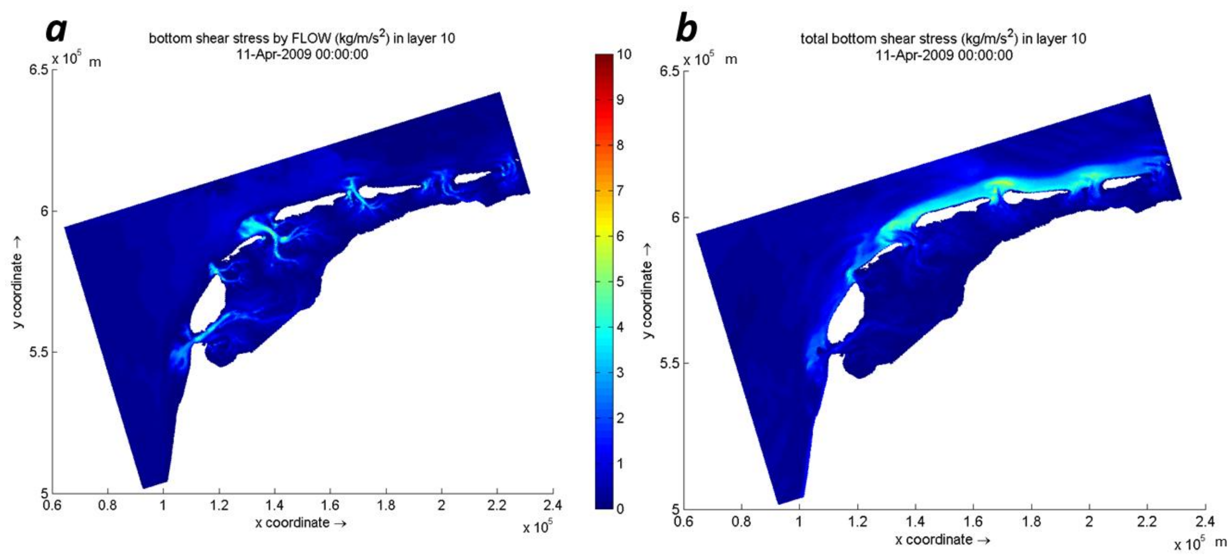


Figure 3–6, the bottom shear stress due to tidal currents only [kg/m/s2] in April (a), the total bottom shear stress caused by tidal currents and wind waves [kg/m/s2] (b).

Likewise, sensitivity analysis is very useful when attempting to find the impact of one variable or more on the outcomes of the model. These variables are the characteristic for the inorganic matters, initial values, for the whole study area in the reference model. Therefore, by creating a given set of cases, the analyst could compute how could be the changes in one variable will affect the fine sediment dynamics in the extended model. Thus, various cases are illustrated in table 3-3 to examine how the model is affected by changing the settling velocity, fraction for buffer layer and the erosion rates. The outcomes of the sensitivity analysis will provide insight into the combined effect of variable physical parameters and normal biological activity for different hypsometry and tidal basins. Equally important, all simulations of WAQ-module were spin-up in this research for a period one month towards equilibrium state.

Table 3-3, the runs of the sensitivity analysis.

Run	Settling velocities	Fraction S2	Erosion rates
SE01	+25%	Initial value	Initial value
SE02	+50%	Initial value	Initial value
SE03	Initial value	10%	Initial value
SE04	Initial value	20%	Initial value
SE05	Initial value	Initial value	+100%

4- Simulation results

The physical parameters have been changed due to the impact of the biological activities in the previous chapters. This chapter discusses the outcomes of both the reference model and the extended model for different time scales. The hydrodynamic forces from May through August and from September through December are the repeated first four months of the reference model in 2009, in order to examine the influence of the variation of biological activities during one year simulation. The outcomes from different scenarios have to be assessed and compared with each other to see the influences of benthos on sediment transport. This chapter is organized as follows; section 4-1 discusses the differences of suspended sediment concentrations and comparing the outcomes with the observed field measurements for stations, section 4-2 discuss the results in different zones for the short term, section 4-3 illustrates the results in zones and basins scales for the long term simulations, section 4-4 is about sediment fluxes between North Sea and tidal basins and finally section 4-5 deals with the mussel beds.

4-1 Suspended sediment concentration

The measurement of suspended sediment concentration data is central to understanding many physical processes and biological activity. Thus figure 4-1 shows the profiles of the suspended sediment concentrations of the reference and the extended models for four stations in the study area. The suspended sediment concentration of the extended model follows the same trend as the reference model and the suspended sediment concentrations of the extended model show almost an increase in the total suspended materials. The reasons for these variables are caused by the influences of the dominant destabilizing benthos in the Dutch Wadden Sea, leading to decrease the critical bad shear stress for erosion and increase the erosion rates. However, stabilizing influences by *Diatoms* and mussel beds could reduce the resuspension processes of fine materials from the bed, but their effects are limited to this area. Given this, it can be inferred that the biological activity could certainly increase the suspended sediment concentration of the Dutch Wadden Sea as a result of dominant influences by grazers.

To provide a more detailed illustration of the variation on both models, figure 4-2 shows the differences in suspended sediment concentrations between the extended and the reference models for the Marsdiep noord and Dantziggat stations for one year simulations. The suspended sediment concentrations are increased during the whole year for the extended model for both station, and temporal variation is obvious there. In other words, the extended model is much more influenced by the biological activity in the first three months of the year due to the lower concentration of *Diatoms* in the sea bed. In this case, the settled fine materials on the sea bottom are brought to sea water columns by the influence of grazers, although the biomass of grazers has been also decreased but the biological influence on the physical parameters has reached a plateau. Moreover, the differences are higher in Dantziggat station because it locates in shallow basin whereas benthic organisms are more available than in the Marsdiep noord station because it is in deep zone. In addition, the combined effects of extreme wind waves and biological activity result in higher difference of suspended sediment concentrations, for instance peaks in Jan. On the other hand, the high concentration of *Diatoms* in May and Sep could be responsible for reducing the differences between both models because the hydrodynamic forces are repeated. Therefore, it can be deduced that temporal variation of *Diatoms* plays a significant role in decreasing the suspended sediment concentration in the Dutch Wadden Sea. The outcomes for other stations with their differences between the extended and the reference models are illustrated in Appendix **C**.

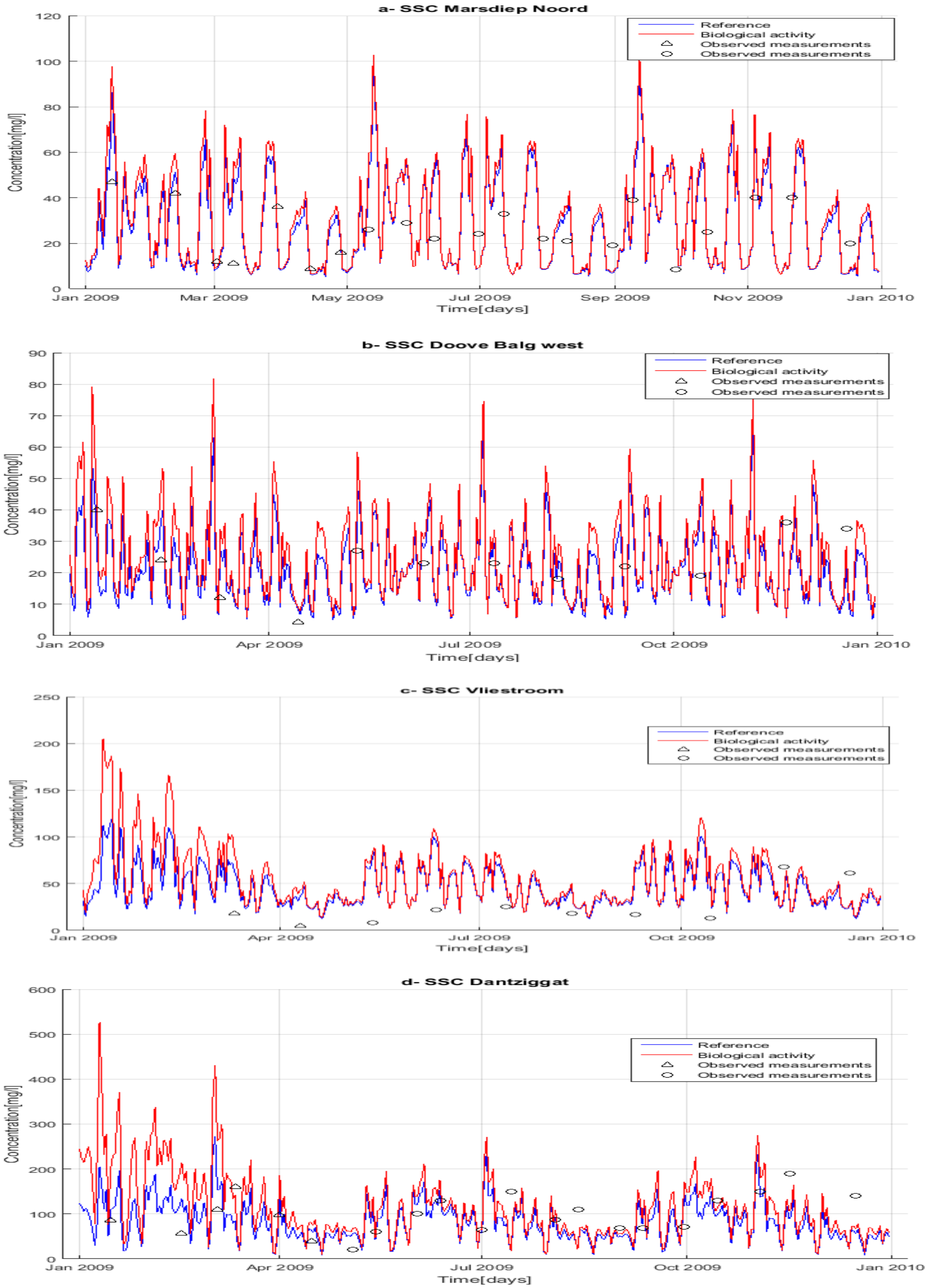


Figure 0–1, the suspended sediment concentration of the western stations in the Dutch Wadden Sea, the blue line means the outcomes of the reference model, the red line is simulation with biological activity, the triangular markers are field measurements during real hydrodynamic forces and the circular markers are field measurements during the repeated hydrodynamic forces.

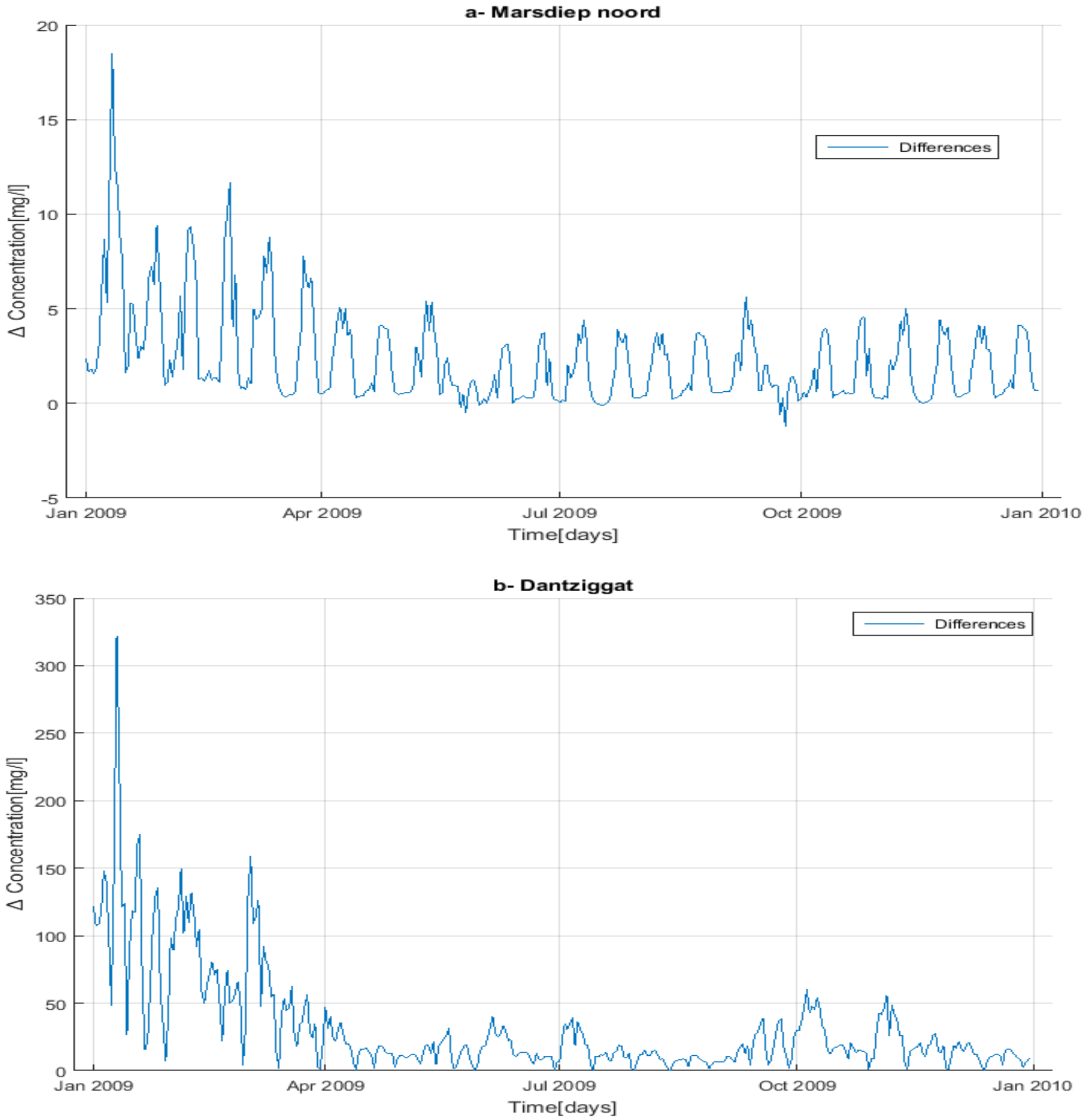


Figure 4–2, the differences in suspended sediment concentrations between the extended and reference models for Marsdiep Noord station (a) and Dantziggat station (b).

Additionally, the influence of biological activity could also have spatial variation. To illustrate that, table 4-1 shows the averages of suspended sediment concentrations of the reference and the extended models and the ratio of the increasing during one year simulation. The ratios are higher for the eastern stations than the western; this means the eastern stations were strongly influenced by biological activity. The one explanation for this variation is that the western stations are mostly located in channels or subtidal zones, of which biological activity is absence or limited. Contrary to the east part, stations are normally located in intertidal zones, whereas the tidal basins are ecologically rich with grazers. As we have seen, the eastern part of the Dutch Wadden Sea was much more affected than the western part as a result of higher biological activity in the east part.

Table 4-1, Average total suspended sediment concentration [mg/l] with and without biological activity, and the ratios of the increasing in 2009.

Nu.	Station	Location	Reference	Biological activity	Ratio%
1	Marsdiep noord	west	28.57	30.88	8.11
2	Doove Balg west	west	21.27	24.92	17.14
3	Vliestroom	west	46.70	55.36	18.54
4	Blauwe Slenk oost	west	47.16	60.89	29.11
5	Dantziggat	east	82.56	114.58	38.79
6	Zoutkamperlaag zeegat	east	112.94	148.86	31.80
7	Zoutkamperlaag	east	94.89	131.11	38.16
8	Zuid Oost Lauwers oost	east	34.55	49.14	42.25

As have mentioned earlier in section 2-2-3, the suspended sediment concentrations measured in the field have to be compared with those derived from Delft3D to evaluate the numerical model input parameters. Figure 4-1 also contains the observed measurements as well as the modelled suspended sediment concentrations. It seems fair to say that the modelled data are in the same order of magnitude with the field measurements and the most of the results overestimate the field measurements. On the other hands, the outcomes of both models in *Zuid Oost Lauwers oost* (figure 4-3) are underestimated the majority of observed measurements, as expected earlier. This could be caused by several reasons, for instance the accuracy of the field data or the influence of boundaries on the station because it locates close to the boundaries in the numerical model.

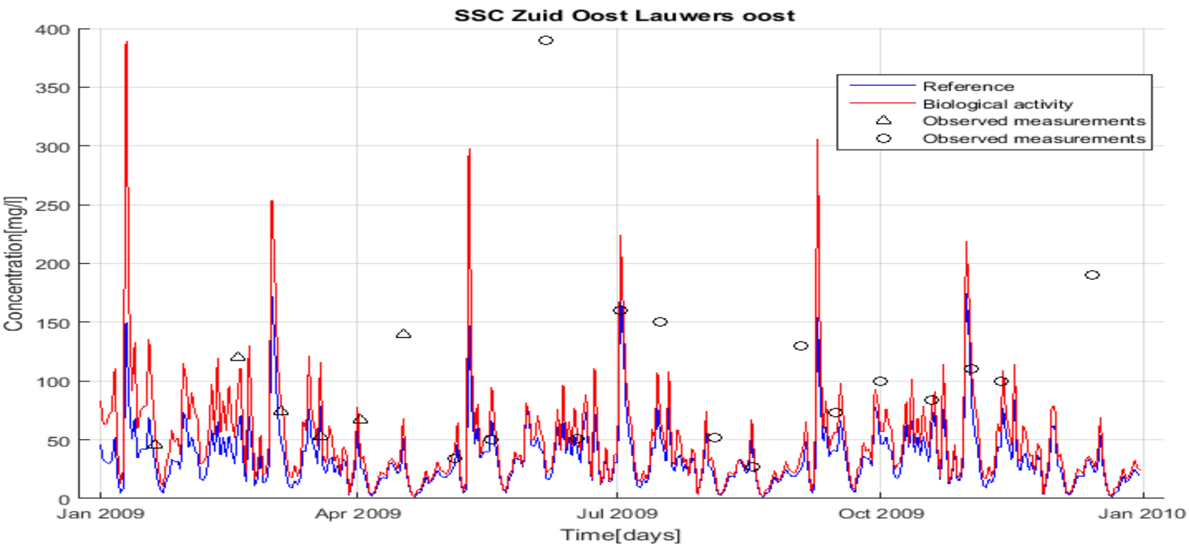


Figure 4–3, the suspended sediment concentration of the Zuid Oost Lauwers oost station, the blue line means the outcomes of the reference model, the red line is simulation with biological activity, the triangular markers are field measurements during real hydrodynamic forces and the circular markers are field measurements during the repeated hydrodynamic forces.

Actually the numerical model is also able to store hourly data as shown in figure 4-4; this variation is used to evaluate both outcomes because the daily range is huge and the results from the previous figures were daily rates, in which the flood and ebb tides cannot be observed. Therefore the Box-and-Whisker plot is used in this research to evaluate the modelled data, whereas 50% of all data is represented on a boxplot and the largest and the smallest 25% of the values are represented in upper and lower whiskers respectively. As a rule the daily modelled outcomes are accepted, provided that the observed measurement is corresponded within the range of box plot, in other cases the outcome is rejected even it corresponds with whisker ranges. In fact, the triangle markers in figures 4-1 can only be used in Box-Whisker-plot because the concurrent modelled outcomes represent the non-repeated hydrodynamic forces.

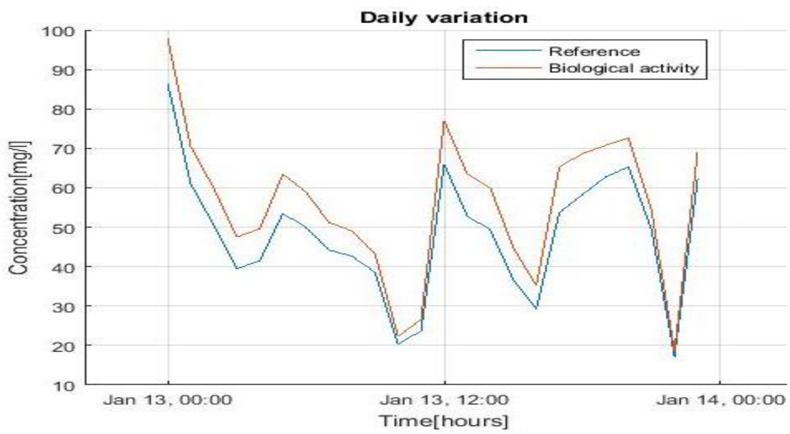


Figure 4–4, the modelled data with hourly variations with and without biological activity for Marsdiep noord station.

From figure 4-5 it may be seen that the results of both reference and extended models, in Box-Whisker-plot, with the observed measurements for Marsdiep noord station. The successive boxes represent the outcomes of the same day from the reference and the extended models; the successive markers are the observed measurements from the field and have the same value for that day. In general, there is slightly difference between the reference model and extended model. Actually, all the modelled data, daily ranges of box and whiskers, are corresponded with the field data, the markers, but half of them have to be rejected, i.e. the blue markers, because the boxes are not corresponded with the observed measurements.

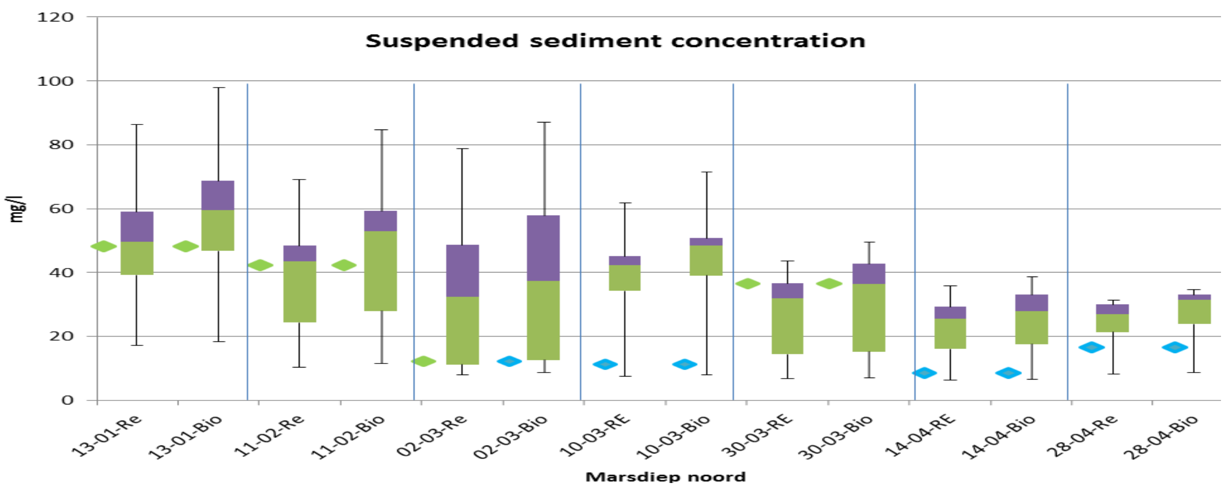


Figure 4–5, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Marsdiep noord station, the green markers means the modelled data are accepted and the blue markers means the modelled data are rejected.

Moreover, figures 4-6 illustrates also the comparison between the modelled data and field measurements for Vliestroom station, whereas a majority of the modelled outcomes have to be rejected because the data ranges are not in good agreements with the field measurements. This means that both modelled data overestimate the field measurements.

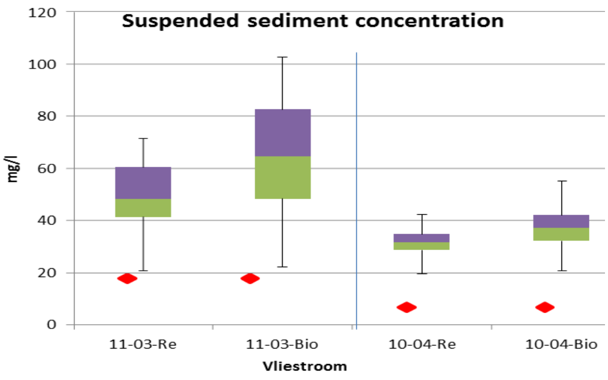


Figure 4–6, Box-Whisker-plots from models, in which field measurements are available as markers for Vliestroom station, the red markers means the modelled data are strongly rejected.

Overall, the suspended sediment concentration is higher in the extended model due to the dominated destabilizing influences by grazers. This benthos is responsible for increasing the daily rang of suspended sediment concentration. The results of the eastern station, Dantziggat, are illustrated in the figures 4-7. In fact, the daily ranges become larger for this eastern station because the benthic organisms are much more available in this eastern tidal basin than the western.

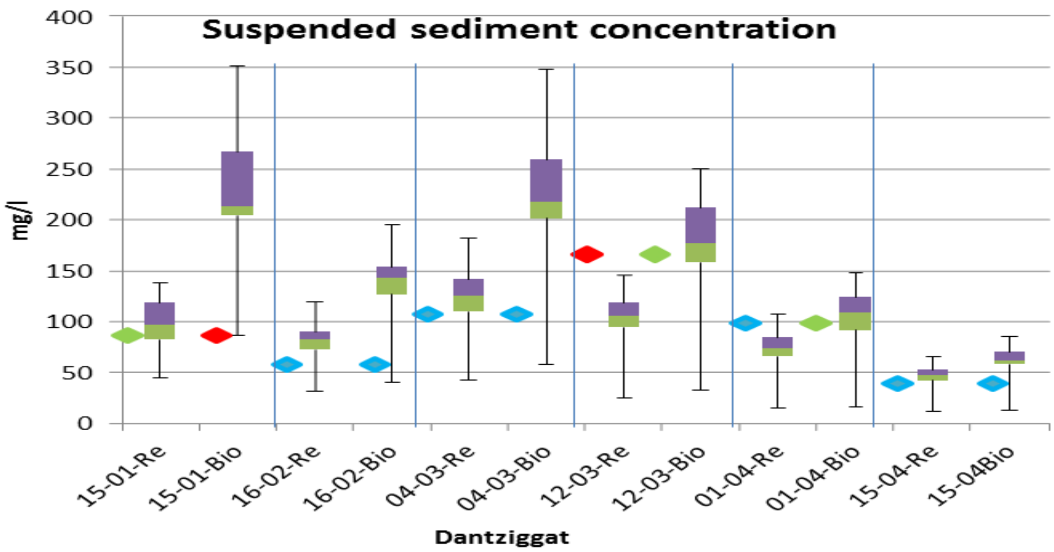


Figure 4–7, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Dantziggat station, , the green markers means the modelled data are accepted , the blue markers means the modelled data are rejected and the red markers means the modelled data are strongly rejected.

The mismatches between the observed suspended sediment concentrations and modelled values may be caused by several reasons. The first reason could result from shortcoming field measurements. Another reason is that the calibration for reference model was not sufficient because the majority of the modelled suspended sediment concentrations are higher than the observed measurements. On these bases it can be concluded that the biological activity are responsible for increasing the suspended sediment concentrations for all stations with temporal and spatial variations. In addition the most of the modelled data from both the reference and the extended models are overestimated the filed measurements. The box-whisker-plots for other stations are also described in Appendix **C**.

4-2 short term simulations for different zones

In this section the results of the reference model and the extended model are presented for short term simulations. The biological activity is implemented with the normal biomass as described in section 3-2. The reason for short term simulation, i.e. in month, is to compare the outcomes for the same zones but with different hydrodynamics processes and biological biomass. Thus, the changes in the storage of fine materials are discussed in this section for the buffer layer in January and February.

Figure 4-8 shows the computed fine sediment storage of the buffer layer during January and February in the salt marshes. There is always deposition of fine materials in the salt marsh zone with different situations. Actually, the simulations with tides only gives rise to increase the sedimentation of fine sediment in the salt marshes because tidal currents are usually responsible for importing suspended materials from the North Sea to the Dutch Wadden Sea. Moreover, the wind waves play a key role in increasing the bottom shear stress in different zones, causing more erosion of bed materials in lower zones, and then the suspended materials will be transported to the salt marshes during flood tides.

The present of benthic organisms caused more sedimentation in salt marshes. The explanation for this accumulation is that the critical bed shear stress was always increased and erosion rates decreased due to the influence of *Diatoms* through covering the bed layer and preventing erosion of the fine materials while grazers are absence in the salt marsh zone. Not any significant differences can be observed between the successive months, except the amount of the deposited materials with biological activity, which is less in February. That's because the wind waves during February were not strong enough to erode bed materials from the lower-intertidal zone combining with destabilizing influences of grazers and to the upper zones. In fact, the biomass of grazers decreased in February, but the influence of grazers on the physical parameters had also reached the plateau. Thus, it is fairly certain that biological activities, combined with wind waves, leading to an increase of the accumulation of fine materials in the salt marsh zones in the short term.

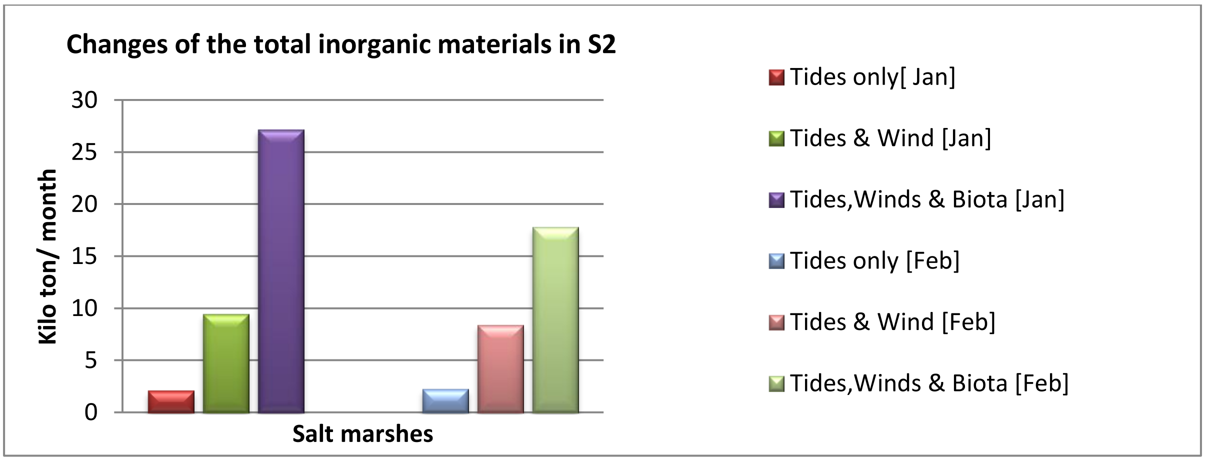


Figure 4–8, sedimentation to the buffer layer, S2, for Salt marsh zone in the Dutch Wadden Sea.

Figure 4-9 displays the changes of the mass for the buffer layer in the upper intertidal zone. The increase in mass can be found for all situations and the amount of increasing could be one order of magnitude higher than in the salt marshes because the total area of salt marshes are very small compared with other zones. The wind waves caused a decrease of the storage during January, comparing with the situation with tidal forces only, due to the higher total bottom shear stresses. On the other hand, the storage of fine materials in the buffer layer increased in February because fine materials had been transported from the deep zones to the upper zones during calm weather. The normal biomass of species has a direct stabilising influence on the bed layer due to the dominated influence of *Diatoms* in the upper intertidal zones. The grazers were present in this zone but their biomass was limited. Moreover, the combined influences of biological activity and physical process resulted in a huge deposition of fine materials to this zone during February. That's because the bottom shear stress is lower in this zone and erosion of bed materials took place in subtidal and channel zones by tidal forces and dominate influences of grazers, then the eroded materials transported to the intertidal zones. Therefore it can be recognised that there is always deposition of fine materials in the upper-intertidal zone.

Looking at figure 4-10, the impact of wind waves on the storage in the lower-intertidal zone is significant important. Erosion of bed materials occurred in January as a consequence of higher total bottom shear stress. On the contrary, the wind waves during February is not strong enough as in January to exceed the critical bed shear stress of erosion, thus the accumulation of fine materials took place in February. Actually, the grazers are dominated in this zone, this means the situation with strong wind waves and normal biomass gave rise to a decrease in the storage of the buffer layer. On the other hand the total bottom shear stress during calm weather could not always exceed the modified critical bed shear stress. In this case the eroded fine materials from the subtidal and channels zone might be transported to this buffer layer. Therefore, it seems obvious that the lower-intertidal zone reacted in different way as the upper-intertidal zone due to wind waves.

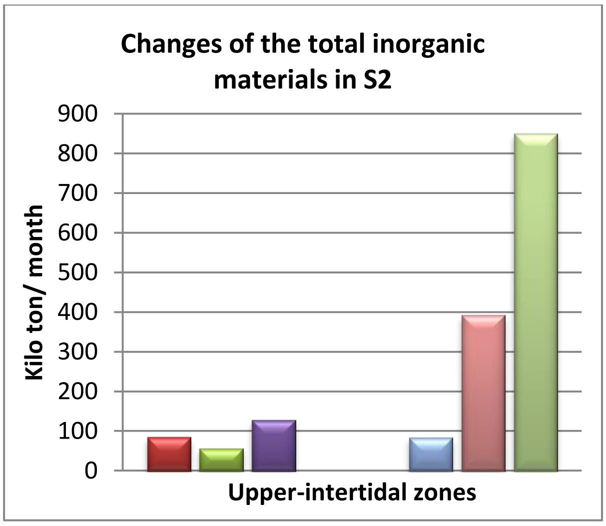


Figure 4–9, sedimentation to the buffer layer, S2, for Upper-intertidal zone in the Dutch Wadden Sea.

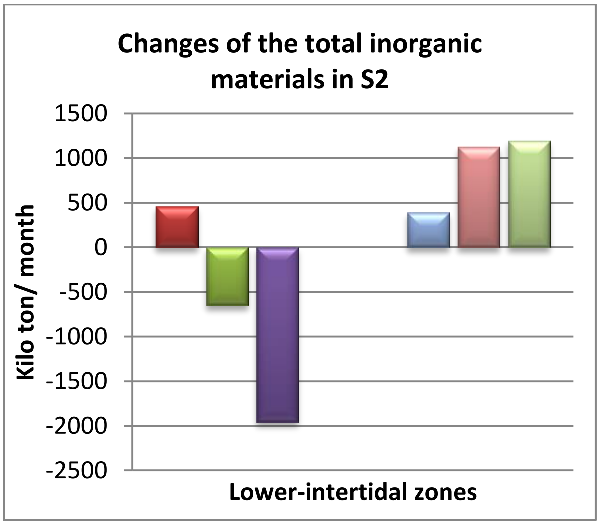
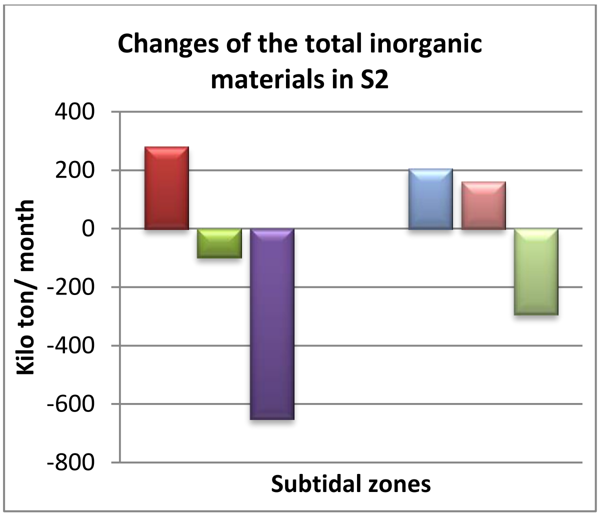


Figure 4–10, sedimentation to the buffer layer, S2, for Lower-intertidal zone in the Dutch Wadden Sea.

From figure 4-11 it may be inferred that the only tidal currents can increase the storage in the subtidal zones, while wind waves and biological activity resulted in decreasing the storage by tidal forces. What caused these decreases in the storage is the higher bottom shear stress by wind waves combining with the dominant destabilizing influences by benthic organisms. In other words, the critical bed shear stress drop to the half and the erosion rates have been increased through the destabilizing activities of grazers.



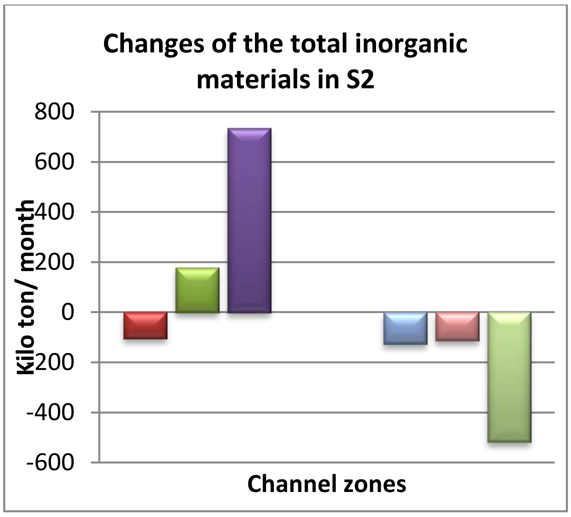


Figure 4–11, sedimentation to the buffer layer, S2, for Subtidal zone in the Dutch Wadden Sea.

Figure 4–12, sedimentation to the buffer layer, S2, for channel zone in the Dutch Wadden Sea.

Figure 4-12 illustrates the mass balance changes in the short terms within channel network. As mentioned earlier in table 2-5, not any biological activity takes place in this zone, but the consequences of biological activity in other zones lead to change the storage of the channels. The channel zones in the Dutch Wadden Sea are clearly located in the tidal inlets. Therefore, the flow velocities may be higher in this zone, producing higher bottom shear stress, which might exceed the critical bad shear stress of erosion; therefore tidal currents could decrease the storage of the buffer layer in channel zone. The situation with strong wind waves is responsible for fine sediment accumulation in the channel zone, that's because erosion of bed materials took place in subtidal and intertidal zones and the eroded materials could be transported later to channels during ebb tides and to the salt marshes with flood tides. On the other hand, the storage of the buffer layer was almost constant during February because no erosion had taken place in the upper zones. Lastly, the biological activity during January with wind waves resulted in an increase in the storage of the buffer later due to enormous erosion of bed materials in lower-intertidal and subtidal zones. On the contrary, the suspended materials had deposited in the upper zones during February, leading to less supply of suspended materials to the channel zone. Therefore, it is believed that the behaviour of the system in February for channel zone is undoubtedly unlike during January due to the impact of wind waves.

It seems fair to say that the accumulation of fine sediment takes place always in the salt marshes and Upper-intertidal zone as a result of tidal current, wind waves and normal biomass for benthos. In contrast, the distribution of fine materials in lower-intertidal, subtidal and channel zones has seasonal variation as a consequence of the impact of wind waves on the total bottom shear stress. To illustrate that, strong wind waves lead to transport fine sediment from lower-intertidal and subtidal zones to the channels, while tidal currents result in transporting fine materials from lower zones to higher zones during calm weather. This corresponds exactly to the observed measurements in the Dutch Wadden Sea because the high concentrations of fine materials have been observed in the salt marshes and intertidal layer as shown in figure 2-4. In fact, the influences of the biological activity on the physical parameters do not have significant variations between the first two months as shown in figure 2-7.

4-3 Long term simulation for zones and basins

The results of this section are the outcomes of one year simulation with different physical processes and biological scenarios. The hydrodynamic forces from May through August and from September through December are the repeated first four months of the reference model in 2009, in order to examine the influence of the variation of biological activities during one year simulation as illustrated in figure 2-7. Also the results are presented in two types, for zones and basins. The last can provide valuable insight into the effects of different bathymetry on sediment dynamic.

Figure 4-13 shows the long term effects of various hydrodynamics processes and different biological components on the accumulation of fine materials in the buffer layer for salt marsh zone. It is widely accepted that sedimentations of fine materials can always occur in salt marshes for the short and long terms. Obviously, the maximum amount of deposited fine materials with biological activity occurs when the stabilizing influences are omission with normal destabilizing influences, namely 0% Stabilizing and 100% Destabilizing, that's because the large amount of fine materials have been eroded from the lower zones and then transported to the salt marshes. On the contrary, the minimum accumulation takes place without destabilizing effects, 0% destabilizing, because more sedimentation can occur in the intertidal zones, as a result, less supply of fine materials are transported to salt marshes.

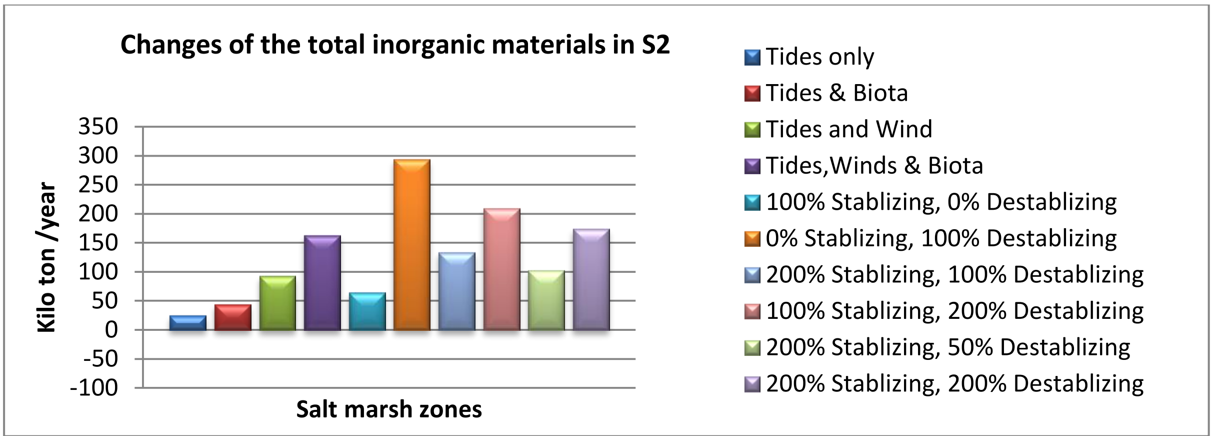


Figure 4–13, sedimentation to the buffer layer, S2, for Salt marsh zone in the Dutch Wadden Sea.

From figure 4-14 it can be seen the sedimentation in the upper-intertidal zone for the long term, there are remarkable similarities in the response of the system with salt marshes, but the biological scenarios shows more sensitivities to the bioturbation influence. That's because the grazers can be found in the upper intertidal layer, causing resuspension of fine materials. Therefore it is believed that the behaviour of fine sediment dynamics between salt marshes and Upper-intertidal zone is not fairly similar as a result of different biological activity.

Comparing with the short term simulations, it is totally certain from figure 4-15 that the lower intertidal zone is very sensitive to the wind waves as described earlier in the previous section and to the fluctuation of biomass for the long term. The total bottom shear stress is higher than the critical shear stress due to the influence of wind waves, thus it tends to be more erosion from the buffer layer. The increase in the concentration of *Diatoms* could have positive effect on suspended materials accumulation due to the increasing of the critical bed shear stress in this zone. The dominant influence of grazers leads to more erosion of fine materials from the buffer layer in this zone.

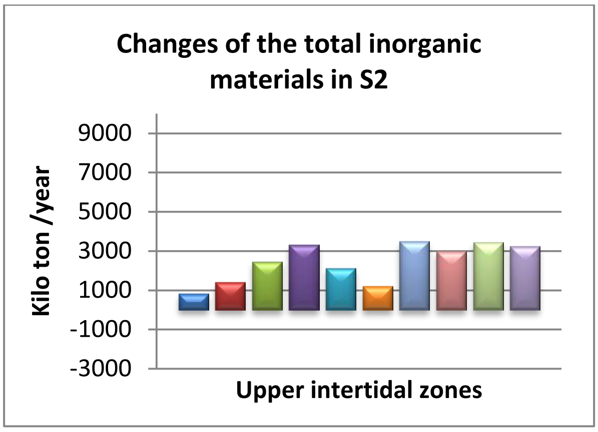


Figure 4–14, sedimentation to the buffer layer, S2, for Upper-intertidal zone in the Dutch Wadden Sea.

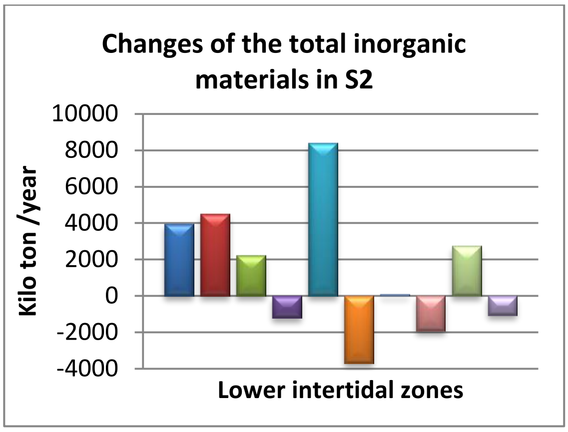


Figure 4–15, sedimentation to the buffer layer, S2, for lower-intertidal zone in the Dutch Wadden Sea.

The tidal prism in subtidal zone is regarded to be the main contributor for suspended sediment accumulation, comparing with other types of scenarios (figure 4-16). That's because the grazers are generally dominant in this zone, leading to resuspension of fine materials from the bed and then transported to higher zones. Equally important, the bottom shear stress by wind waves gives rise to more erosion from the buffer later for the long term.

As have been mentioned before, there is no biological activity in the channel zones. The decrease of the storage for the buffer layer results from the high flow velocity in the tidal inlets, producing high bottom shear stress in this zone. Therefore tidal currents cause erosion of fine materials in the buffer layer for the long term (figure 4-17). The wind waves reduce the amount of erosion as a result of transporting inorganic materials from the upper zones to the channels during ebb tides. The presence of benthic organisms in the system causes a decrease in the mass storage for the buffer layer in this zone for the long term, that's because the suspended materials are deposited through the stabilizing activity of biota in upper zones.

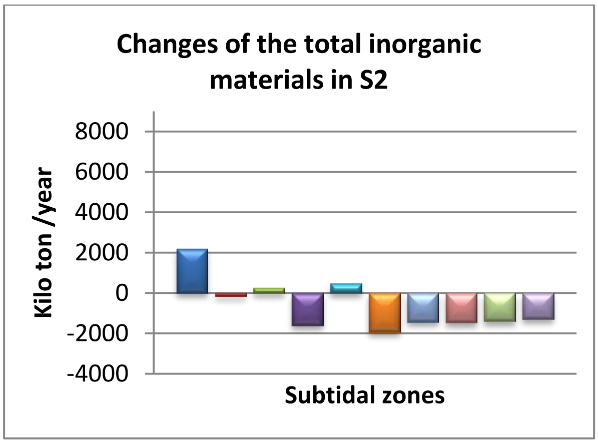


Figure 4–16, sedimentation to the buffer layer, S2, for subtidal zone in the Dutch Wadden Sea.

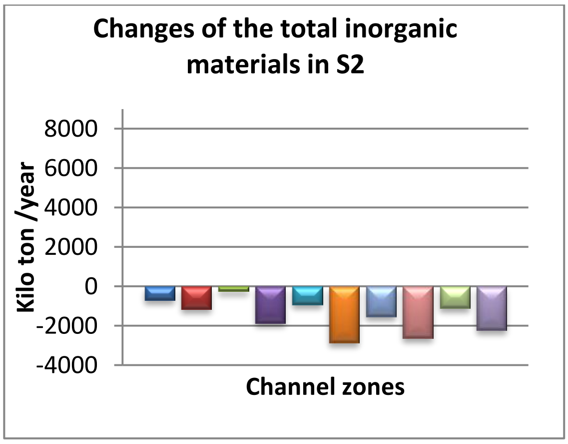


Figure 4–17, sedimentation to the buffer layer, S2, for channel zone in the Dutch Wadden Sea.

As mentioned earlier, the second sort of results is about the changes in mass balance within each tidal basin for long term. Actually, each basin in the Dutch Wadden Sea has own characteristics such as the total area, hypsometry and distribution of benthos. These variations could affect the storage of mass balance and sediment fluxes between North Sea and the tidal basins of the Dutch Wadden Sea. The next figures detect the mass balance of the buffer layer for Marsdiep, Vlie and Borndiep basins, which they have different hypsometry.

There is a clear increase in the accumulation of the inorganic materials in the Marsdiep basin for all types of simulation as illustrated in figure 4-18, stemming from the limitation of biological activity in this deep basin. The maximal deposition of fine materials is triggered by tidal currents. The wind waves reduce the mass storage in this basin as result of increasing the bottom shear stress. In addition to that, destabilizing species are more dominated in the lower and subtidal zones, causing more erosion from the buffer layer. Since there is small relative intertidal zones in this basin, the fluctuation of benthos could not show significant variables of the buffer layer in this deep basin. This means that the influences of benthic organisms are limited for different biological activity on fine sediment accumulation in the buffer layer.

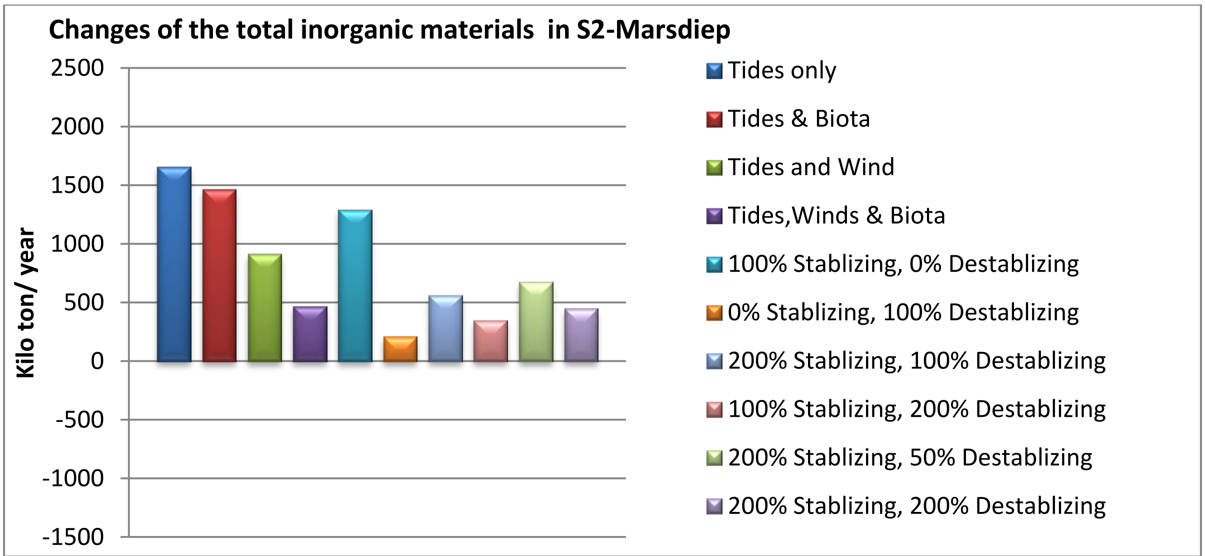


Figure 4–18, sedimentation to the buffer layer, S2, for the Marsdiep basin.

The Vlie basin is located in the west part of the Dutch Wadden Sea and it has boundaries with three other basins. Figure 4-19 illustrates the mass balance of Vlie basin with various scenarios. Since the intertidal zones are dominated, as described earlier in figure 2-3, the buffer layer in this basin is more sensitive to the biological fluctuation than Marsdiep basin. The influence of biological activity, combined with tide, the 2nd bar, could increase the storage in the buffer layer of this basin, that's because the intertidal zones are dominated in this basin, of which *Diatoms* lead to increase the critical bed shear stress. The wind waves reduce the storage because the bottom shear stress is higher than the critical shear stress in the lower zones of this basin. The erosion from the bed takes only place with the dominant destabilizing influences.

From figure 4-20, it can be seen that the normal biological activity with tidal currents lead to reduce of the storage in buffer layer of Borndiep basin, although the salt marsh and intertidal zones are dominated in this basin, comparing with Vlie basin. The reasons for this outcome might be due to the lower supply of sediment fluxes from the North Sea and from the adjacent basins. Also mussel beds are more available in this basin, which might have negative influence of buffer layer when the shear stress by tidal current exceeds the critical shear stress of mussel beds. The influence of tidal currents and wind waves gives rise to sedimentation in this basin. That's because the relative intertidal zones and salt marshes are bigger in this basin comparing with Marsdiep basin as well as Vlie basin, in other word, fine sediment transported form lower zones of this basin and other adjacent basins to the salt marshes and intertidal zones in this basin. Equally important, the dominated simulation with stabilizing influences shows higher accumulation of inorganic materials owning to the higher relative areas of salt marsh and upper intertidal zone in sinking suspended sediment, and vice versa for destabilizing influences because of the bigger intertidal zones.

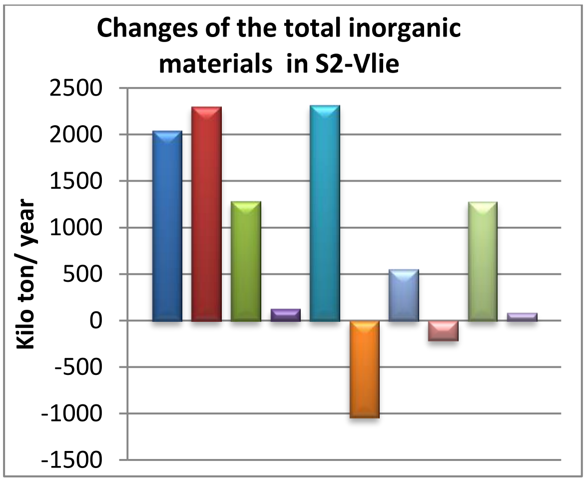


Figure 4–19, sedimentation to the buffer layer, S2, for the Vlie basin.

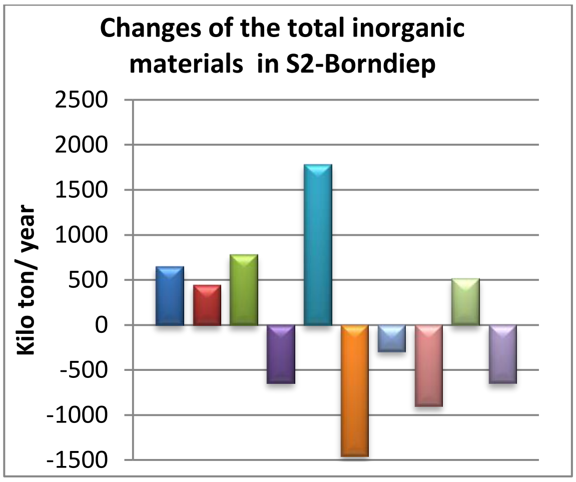


Figure 4–20, sedimentation to the buffer layer, S2, for the Borndiep basin.

Thus it can be concluded that the decrease in total fine materials in deep basin is not significant comparing with regular basins because biological activity has more influences on fine sediment distribution in the shallow basins than deep basin.

The responses of the fluff layer is unlikely important as the buffer layer for different zones and basins because the residence time for settled materials is short, this makes it too difficult to assess the response of the system to the physical processes and biological fluctuation. Appendix **D** discussed the outcomes of the fluff layer for different zones while Appendix **E** illustrates the outcomes of the rest of basins for both buffer and fluff layers.

4-4 Sediment fluxes between tidal basins and North Sea

This section attempts to understand the impact of physical processes and biological activity on horizontal sediment fluxes dynamics between the North Sea and different tidal basins. The tidal forces are responsible for an import and an export of horizontal fluxes between the North Sea and tidal basins, as well as between adjacent basins. Figure 4-21 shows the import and export of total inorganic materials from the North Sea to the Marsdiep basin without biological activity. The import of fine materials take place during flood tides and the amount of sediment flux could reach 20 kiloton per hour during spring tides. The amounts of horizontal fluxes during flood and ebb tides are superficially similar, but there is about 7% remained in the basin of the total import fine materials during four months simulation.

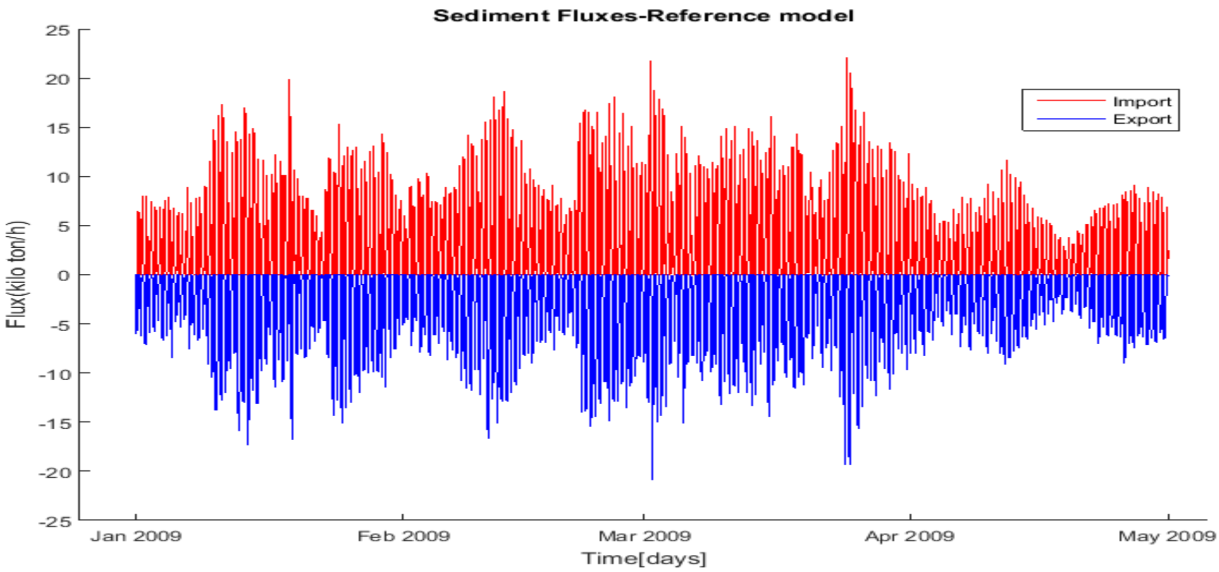


Figure 0–21, horizontal sediment fluxes between the North Sea and the Marsdiep basin through the Texel-Den Helder inlet, the red lines is the fluxes from North Sea to the basin during flood tides and the blue lines is the fluxes from Marsdiep basin to the North Sea during ebb tides.

To illustrate that, figures 4-22 and 4-23 show the net import and export of sediment fluxes with accumulative fluxes, i.e. remaining fluxes, from the North Sea to the Marsdiep and Borndiep basins respectively through the tidal inlets with and without biological activity. Net import of fine materials could usually occur in deep basin, Marsdiep basin, with and without biological activity. That's because fine materials could be easily deposited in the bed layers as a result of lower total bottom shear stress, while a small amount of fine materials could be transported to the North Sea during January due to strong wind waves, but import of fine materials have increased gradually since the mid of January as shown from the accumulative curves. The biological activity is responsible for a slight decrease of accumulative materials in the deep basin because of the dominant destabilizing benthic organisms. The sediment fluxes in shallow basin, Borndiep basin, are much more sensitive to the wind waves and biological activity than the deep basin. The wind waves could lead to a dramatic export of fine materials to the North Sea during January and then net import have taken place with calm weather since February. The biological activity is responsible for a sharp decline for the import of fine materials, because the intertidal zones is larger in this basin with a dominate destabilizing benthic organisms, causing the resuspension of settled materials from the bed to the sea water columns.

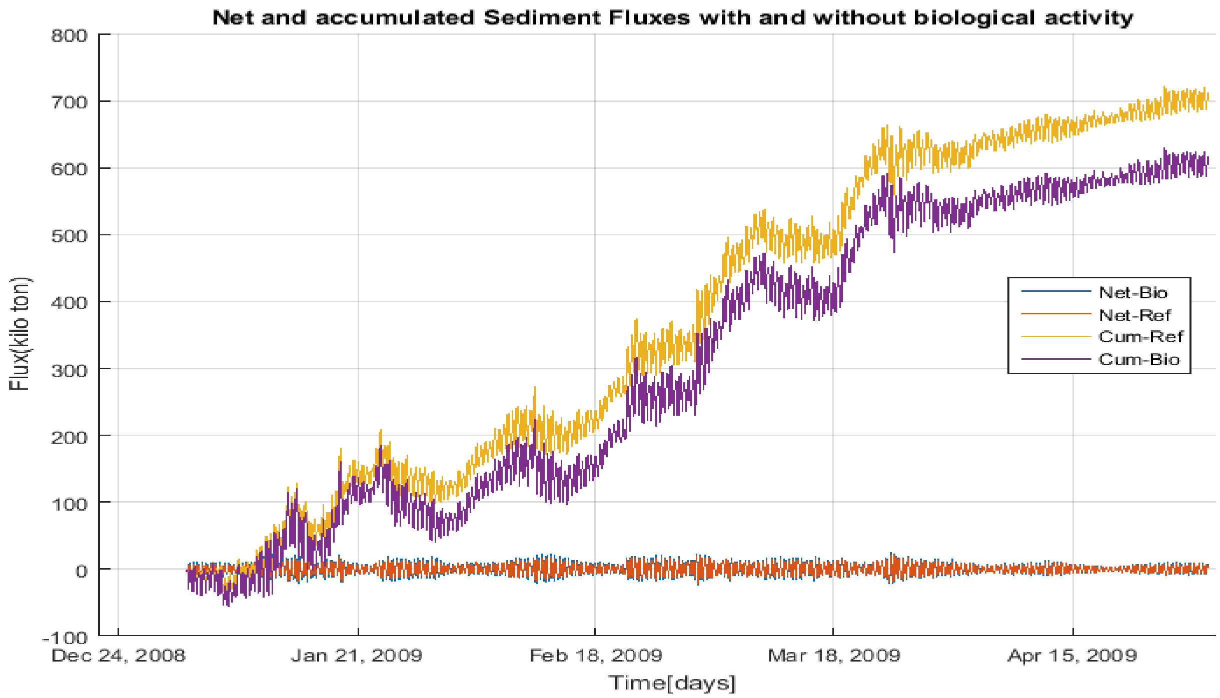


Figure 4–22, net import-export of fine materials and accumulated sediment fluxes with and without biological activity in Marsdiep basin.

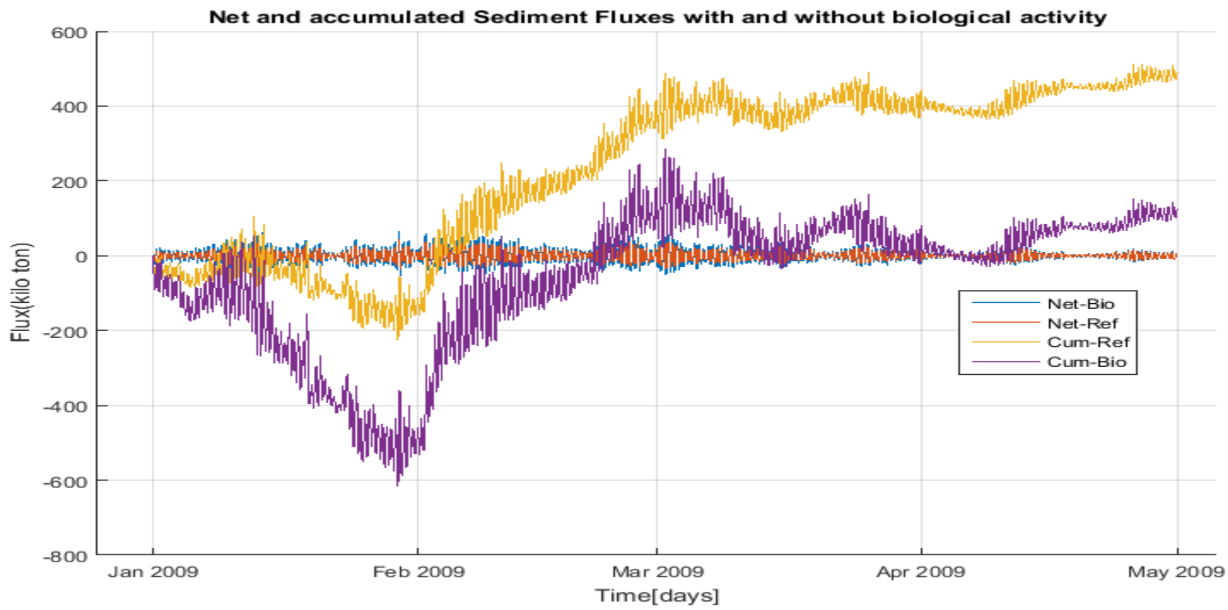


Figure 4–23, net import-export of fine materials and accumulated sediment fluxes with and without biological activity in Borndiep basin.

Moreover, the eastern basins could have different response than the western. To illustrate that, figure 4-24 shows the accumulative sediment fluxes from the North Sea to the Zoutkamperlaag basin, which it is regarded as regular basin. The sediment fluxes in this basin is not significantly affected by the wind waves as Borndiep basin during January, this might be due to the lower wind speed in this basin because the direction of dominate wind waves is from the South-West. Equally important, the total import of sediment fluxes is higher in the extended model with biological activity in this basin than the western basins. The one explanation for this is that the sea water column in the North Sea could contain much more suspended materials because less amount of sediment fluxes could enter in the western basins with biological activity, in other words, a large amount of suspended materials might be transported to the east part of the North Sea by the hydrodynamic forces.

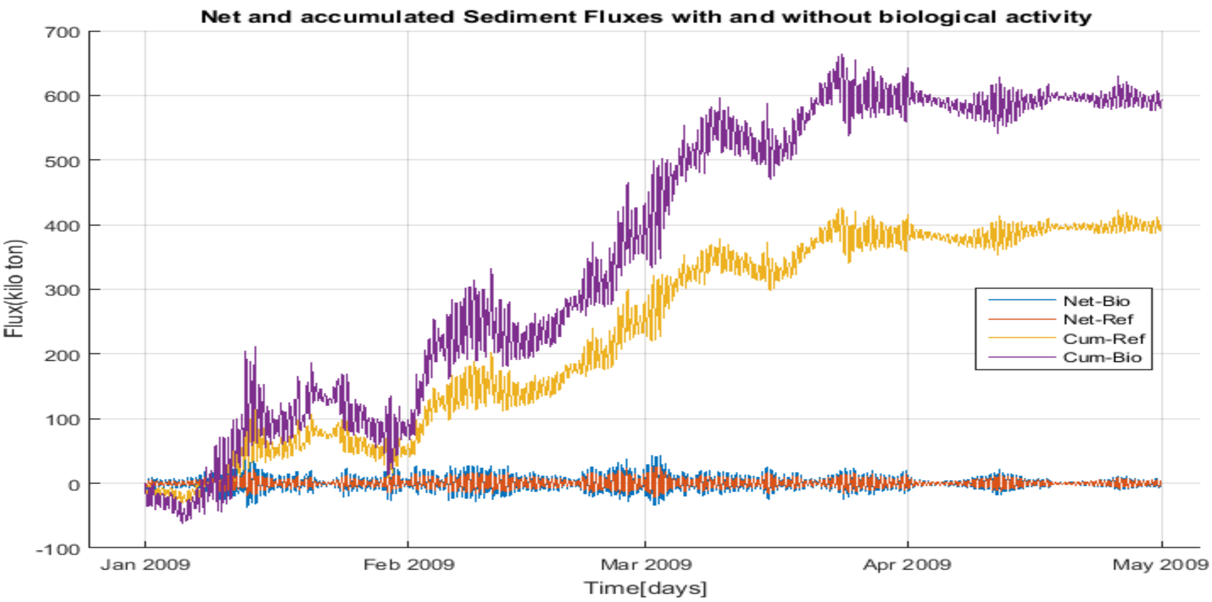


Figure 4–24, net import-export of fine materials and accumulated sediment fluxes with and without biological activity in Zoutkamperlaag basin

Table 4-2 shows the total quantities of import, export, accumulative fluxes and the ratios of the remaining sediment fluxes from the North Sea to the basins through the tidal inlets [R=(*T. import-T .export)/ T. import)*100*].The total amount of import and export fluxes with biological activity is always larger than the reference situations, that's because the sea water columns contain more suspended materials, however the remaining ratios, as well as the most remaining quantities, are higher for the reference model. Further, the accumulative fluxes are positive in these basins; this means import on fine materials could usually occur from the North Sea to these tidal basins unless wind waves could have serious impact on sediment dynamics. Moreover, the amount of exchange fluxes between North Sea and Borndiep basin is larger than the Marsdiep basin, but the total accumulative fluxes are lower than the deep basin as well as the ratios. That's because the total bottom shear stress is higher due to wind waves, also the critical bed shear stress is lower as a result of the dominate destabilizing species in the intertidal and subtidal zones.

Table 4-2, the in –out sediment fluxes between North Sea and tidal basin and total accumulative fluxes [kilo ton] for four months simulation with the ratios of residence fluxes.

Basin	*Benthic organisms*	*Total import*	*Total export*	*Total accumulative fluxes*	*Ratio %*
Marsdiep	*No biological activity*	*10158*	*9446*	*712*	*7.01*
	biological activity	*11631*	*11015*	*616*	*5.29*
Borndiep	*No biological activity*	*15854*	*15361*	*493*	*3.11*
	biological activity	*23369*	*23369*	*125*	*0.54*
Zoutkamperlaag	*No biological activity*	*8165*	*7763*	*401*	*4.90*
	biological activity	*13087*	*12493*	*594*	*4.50*

From figure 4-25 it may be seen the quantities of the net cross sediment flux over a 4 months study period between tidal basins and North Sea, caused by tidal currents, wind waves, exchange with bed layers and other sources of loads from land. In general, a large amount of fine sediment fluxes are transported between these water bodies. The results indicate that residual sediment fluxes appear to transport from the North Sea to the Dutch Wadden Sea, and net depositions of inorganic materials occur in all intertidal basins. The major passage of the imported fluxes from the North Sea is through Vlie inlet; this might be due to the larger area, of which huge amount of mass water can enter Vlie basin and propagate there. In contrast, net export of sediment flux occur through Eijerlandse Gat inlet to the North Sea, this might mainly happen because it is located between three water bodies , also the deep zones are directed landward and shallow zones are closed to the inlet.

The biological activity could affect the sediment fluxes for the whole system as shown in figure 4-26. By comparing with the reference model, significant differences can be observed, for instance there is a decrease in sediment deposition for the bed layers in most basins.in addition to that, net erosion from the bad layers in Eijerlandse Gat basin takes place, causing an increase of export of fine materials to the North Sea. Also the direction of sediment fluxes between Borndiep and Pinkegat has been changed. To be more precise, the total amount of deposition in bed layers was dramatic decrease from *4018* in the reference model to *3737 kilo ton* with biological activity and the total net imported sediment fluxes to the tidal basins have also decreased from *3470* to *2621 kilo tons* with biological activity. What responsible for this reduction in the net-import of sediment fluxes is that a slow process of diffusion takes place as a result of higher suspended sediment concentration in the whole system, because of the influences of the dominated destabilizing by grazers, which cause more erosion of the bed materials and preventing deposition of fine materials as well as resuspension of settled bed materials.

Likewise, the deposition of fine materials in the eastern basins, Zoutkamperlaag, Eilanderbalg and Lauwers basins, have increased with the biological activity in spite of the dominate influences by grazers. What caused these increases in bed layers is that the larger amount of horizontal sediment fluxes could enter these basins as well as from the Pinkegat basin to the Zoutkamperlaag basin.

What's more, the total amount of suspended materials within the sea water columns in each basin is not fixed. To illustrate that, the mass of the total suspended maters in the water columns of Marsdiep basin are decreased *106* in the reference model and *198 kilo tons* in the extended model by computing the net of the sediment fluxes in figures 4-25 and 4-26 for this basin. Also, the total amount of suspended materials in Borndiep basin have been decreased *305* in the reference model and *512 kilo tons* in the extended model. The reason for these changes within the sea water columns might be the influences of tidal components and wind waves. These numbers are the result during 4 months simulations; this means the suspended sediment concentration for the sea water column have been decreased during this period. By taking the suspended sediment concentration of Dantziggat station in Borndiep basin as a sample in this basin (figure 4-1-d), the concentration was lower in May than the initial value in January. This might validate these changes within the basins.

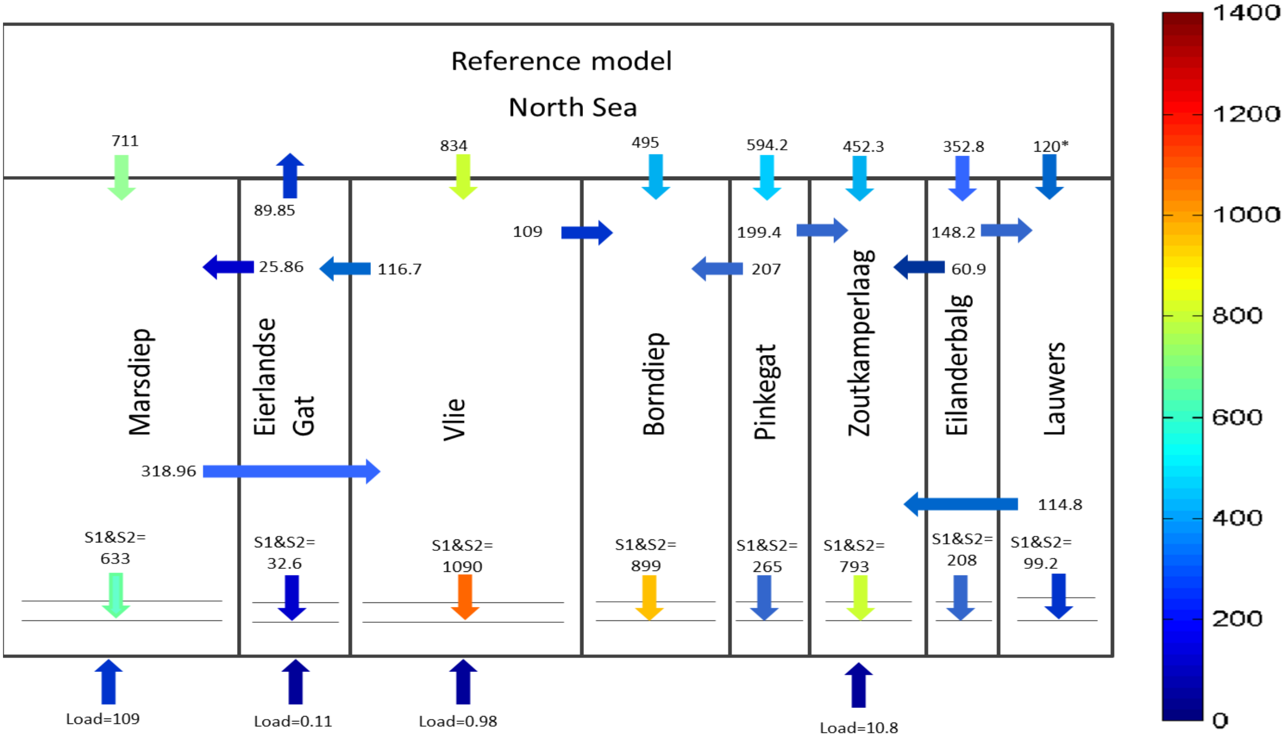


Figure 4–25, fine sediment fluxes in the Dutch Wadden Sea in the reference model waves for the period, January through April, Kilo ton. * means the basin in the numerical model does not represent the whole area.

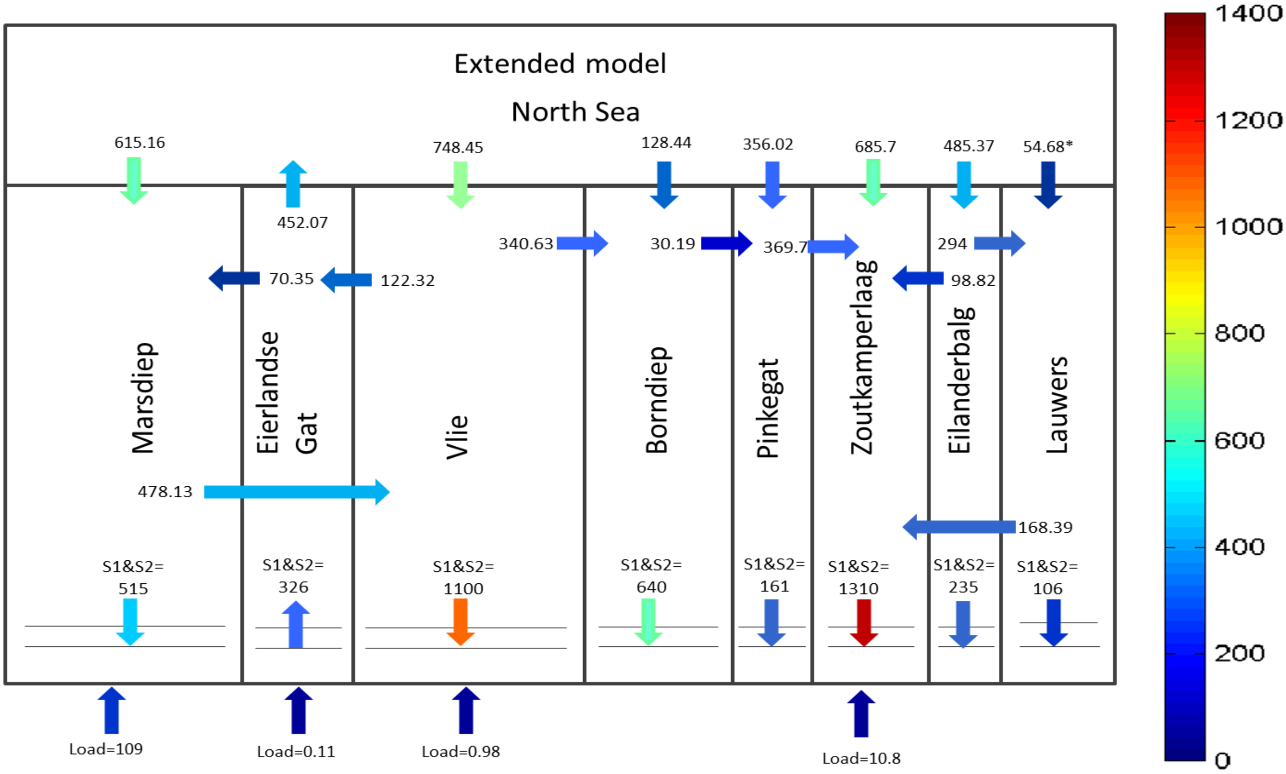


Figure 4–26, fine sediment fluxes in the Dutch Wadden Sea in the extended model for the period, January through April, Kilo ton. * means the basin in the numerical model does not represent the whole area.

4-5 changes in mussel beds

The previous sections discussed the results on the large scale, for instance zones and basins, with different physical processes and biological scenarios. This section focuses particularly on a segment scale in which the cell could only occupied by blue mussel beds, as shown earlier in figure 2-9, in this case the impact of mussel beds on fine sediment dynamics become more clear.

Figures 4-27 and 4-28 show the changes in the storage of fine materials over a 4 months study period for the selected areas in the buffer layer with different physical processes and biological scenarios in Marsdiep and Borndiep basins respectively. The combined effects of tidal forces and biological activity by mussels give rise to an increase in the mass storage for these small areas of mussel beds, brought about by the filtration of the sea water column and the higher critical bed shear stress of erosion, which it could exceed the bottom shear stress by tidal currents. Further, the wind waves, without any biological activity, could have different impact on the selected areas. To demonstrate that, the selected location of the mussel beds in Marsdiep basin might be in the lower-intertidal or subtidal zones; this means the total bottom shear stress is able to exceed the critical bed shear stress, therefore erosion of bed materials occur there. On the contrary, the location of the selected mussel beds in Borndiep basin is in the upper-intertidal zone, whereas deposition of fine materials takes place in this zone as described earlier in this chapter.

Moreover, the combined effects of physical processes and biological activity 4th bar in figure 4-27 are responsible for decreasing the storage of the mussel beds in the selected area of Marsdiep basin, comparing with physical processes by tides and winds 3rd bar, due to the higher erosion rates of the faecal pellet when it subjected to higher total bottom shear stress, while an increase of accumulation of fine materials occur in the selected mussel beds of Borndiep basin, as a result of lower total bottom shear stress which could not normally exceed the critical bed shear stress.

By comparing the 4th and the 5th bars in the figures 4-27 and 4-28, the total mass storage of the 5th bar is slightly higher in Marsdiep basin and the highest in Borndiep basin, provided that no any influence of blue mussel occurs in these selected areas. To illustrate that, the blue mussel could increase the sedimentation of fine materials as a result of higher critical bed shear stress and filtration of water column, but significant erosion of bed materials takes place when the mussel beds subject to stronger hydrodynamic forces, because of the higher erosion rates. In other words, the mussel beds in upper-intertidal zone could prevent the erosion of bed materials unless the total bottom shear stress is able to exceed the critical bed shear stress, in this case a large amount of the bed materials would be brought to the sea water column as shown in Borndiep basin. Again the bottom shear stress above the selected mussel beds in deeper zone, such as in Marsdiep basin, is usually higher than the critical bed shear stress with and without mussel beds, thus larger amount of eroded materials occur with mussel beds.

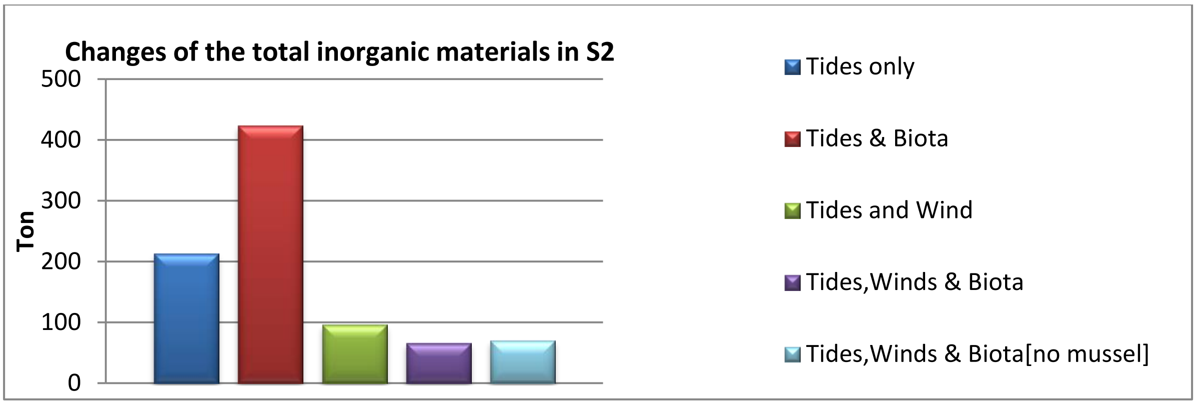


Figure 4–27, the sedimentation of fine materials in the buffer layer for the selected mussel beds in Marsdiep basin.

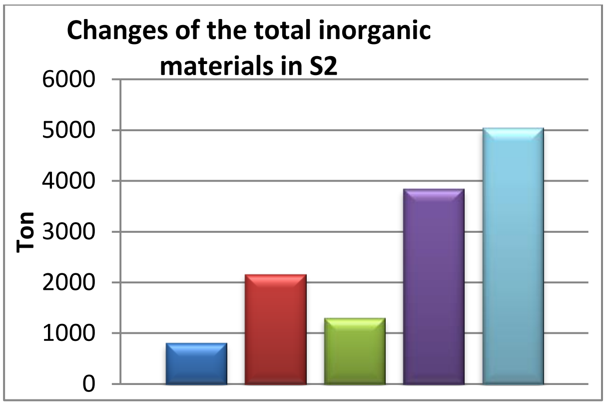


Figure 4–28, the sedimentation of fine materials in the buffer layer for the selected mussel beds in Borndiep basin

On the basis of these arguments, the normal biomass of blue mussels could increase the accumulation of fine materials of the buffer layer in upper-intertidal zone because of the higher critical bed shear stress and filtration rate, while the mussel beds in the deeper zone would reduce the storage of the second layer, comparing without biological activity situation, because of the higher erosion rates of mussel beds.

5- Sensitivity analysis

The outcomes presented in the previous chapter were based on a certain set of physical parameters. The values of theses parameters in the reference model are to an extent uncertain due to the overestimation of the suspended sediment concentrations for different stations. Therefore, this chapter could provide an insight into the impact of set of variables, as shown earlier in table 3-3, on sedimentation in different zones and basins of the Dutch Wadden Sea, combined with the effects of tidal currents, wind waves and normal biomass of benthic organisms.

The settling velocities for the inorganic materials, IM1 and IM2, have been varied to 25 % and 50% above the original values during one month simulation. The results of the model runs are displayed in the next figures. The sedimentations of fine materials in salt marsh and channel zones are inversely proportional to the increase values of the settling velocities as shown in figures 5-1 and 5-5, comparing with the 4th bars, because a large amount of suspended materials are deposited in the intertidal and subtidal zones, which illustrated in figures 5-2, 5-3 and 5-4. This means the sea water columns above the salt marshes and channel networks contain less suspended matters. The fraction of the deposited materials for the buffer layer was estimated in the reference model with 5% from the total deposited fine materials. To represented different condition, 10 and 20% are used. The results from different zones indicate that the mass storage for the second layer is always increase and the storages of the fluff layers in most zones are dramatic decrease as shown in figures 5-6 through 5-10.

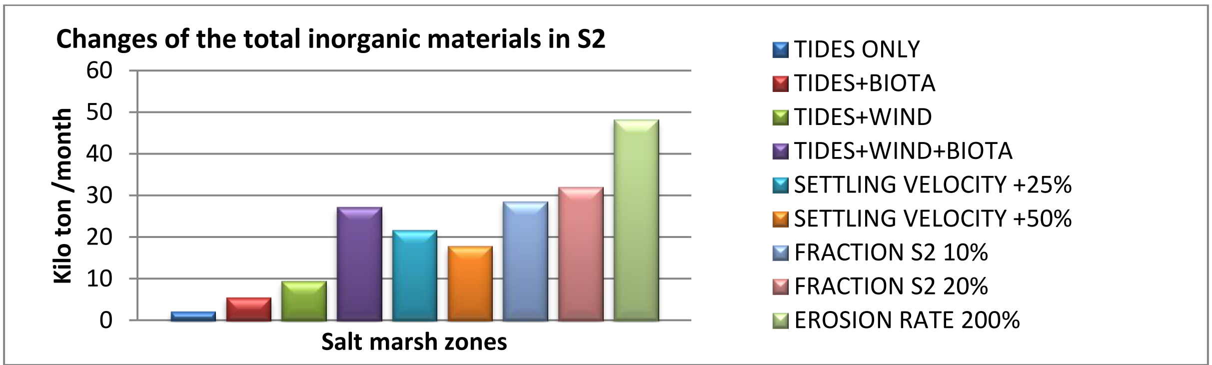


Figure 5–1, sedimentation in the buffer layer of salt marshes in January.

The results of the previous factors have positively influence on fine sediment stability in the buffer layer, in spite of the consequences in salt marshes and channel networks. To investigate a destabilizing parameter, the erosion rates have varied to double of the original values. The results in the buffer layer for different zones shows undoubted influence of the mass storage in all zones. Depositions of fine materials occur in salt marshes and channel networks, while erosions of the inorganic materials take place in intertidal and subtidal zones. That's because a large amount of the eroded materials transported to the salt marshes and channel zone, in which the total bottom shear stress might not exceed the critical bed shear stress during this month. On the contrary, the critical bed shear stress for the fluff layer in the channel zone is not higher enough as the buffer layer to store fine sediments as a result of increasing the erosion rates (figure 5-10).

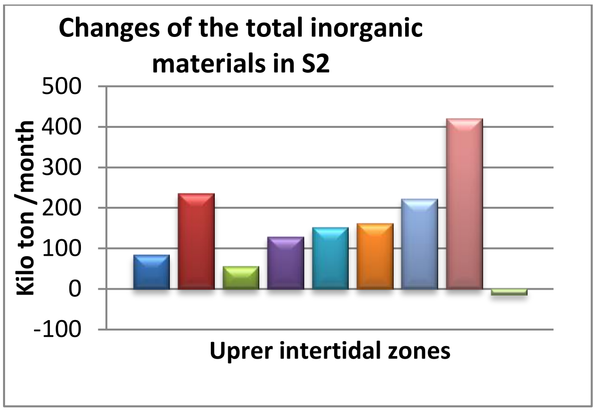


Figure 5–2, sedimentation in the buffer layer of the Upper-intertidal zone in January.

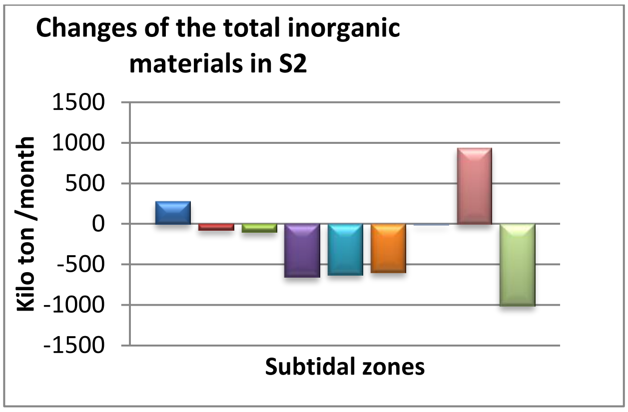


Figure 5–4, sedimentation in the buffer layer of the Subtidal zone in January.

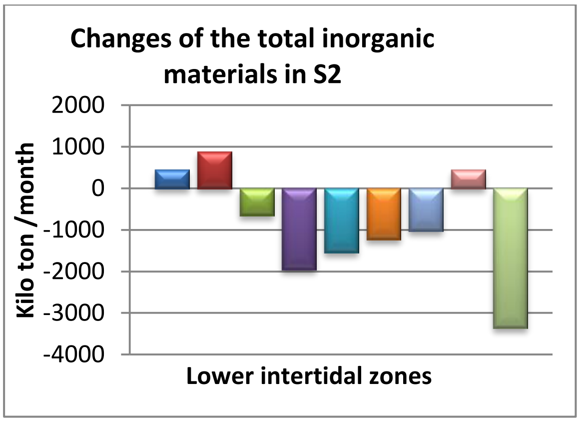


Figure 5–3, sedimentation in the buffer layer of the Lower-intertidal zone in January.

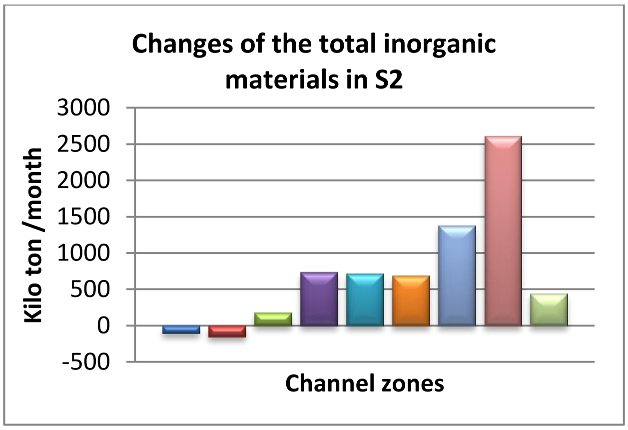


Figure 5–5, sedimentation in the buffer layer of the Channel zone in January.

The fluff layers for the most zones, excepted for the salt marshes, show a decrease of the fine sediment storage because of the lower critical beds shear stresses for erosion.

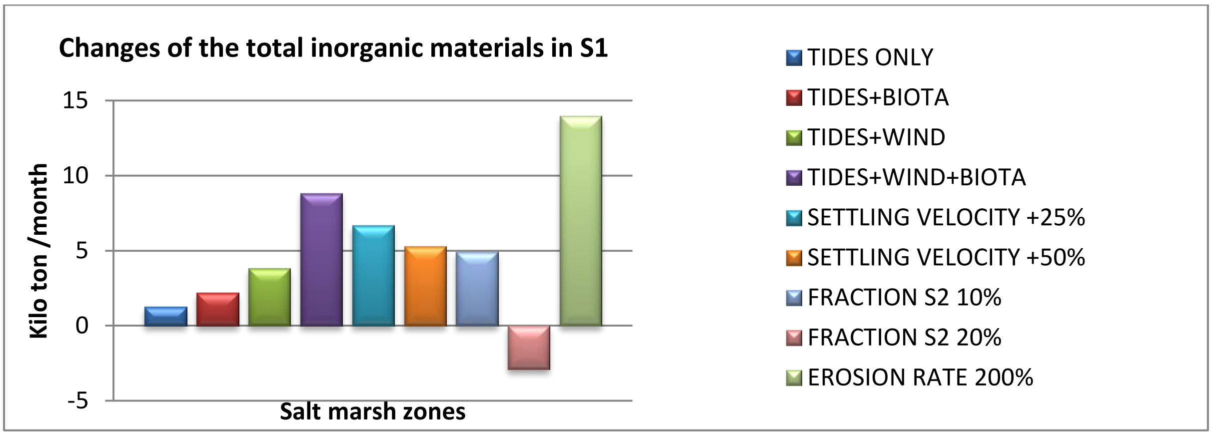


Figure 5–6, sedimentation in the fluff layer of salt marshes in January.

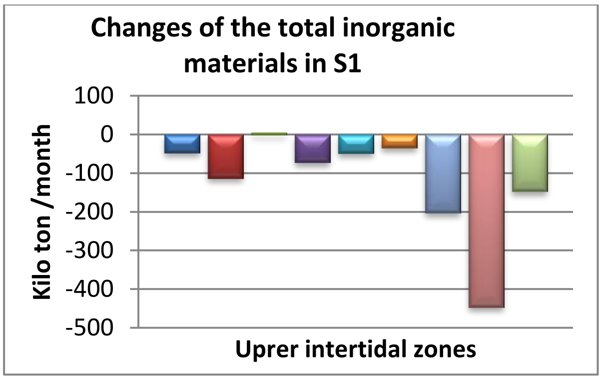


Figure 5–7, sedimentation in the fluff layer of the Upper-intertidal zone in January

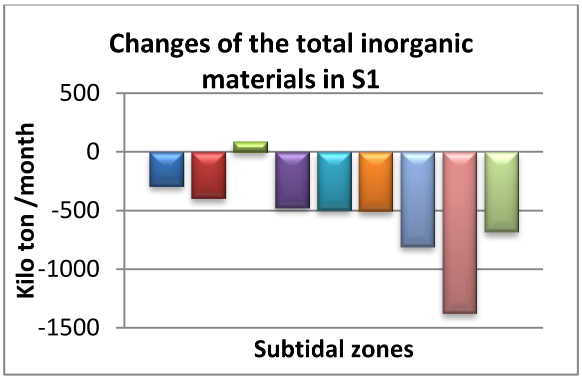


Figure 5–9, sedimentation in the fluff layer of the Subtidal zone in January

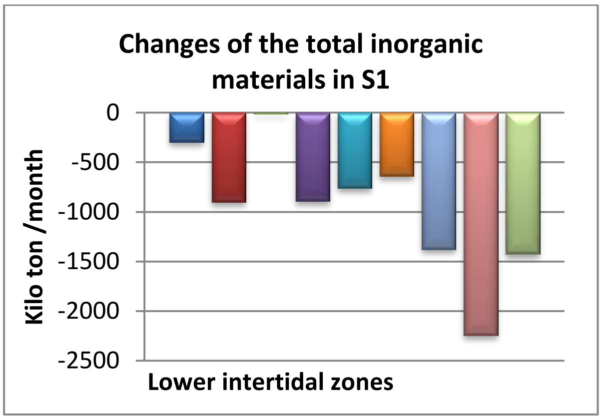


Figure 5–8, sedimentation in the fluff layer of the Lower-intertidal zone in January

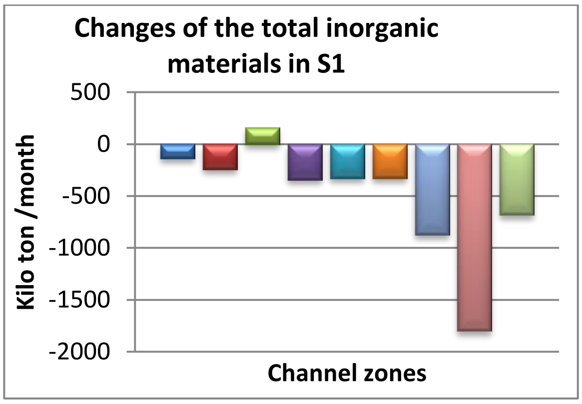


Figure 5–10, sedimentation in the fluff layer of the Channel networks in January

The impact of these parameters can be examined for basin scale as illustrated in figures 5-11, 5-12 and 5-13 for the buffer layer. The response of the deep basins, Marsdiep, is superficially similar to the regular basins, Vlie basin. However, the biological activity in Borndiep basin could significantly reduce the sedimentation of fine materials. The settling velocities are not highly sensitive as the fractions values. That's because 95% of the settled materials deposited in the fluff layer, which could be easily eroded.

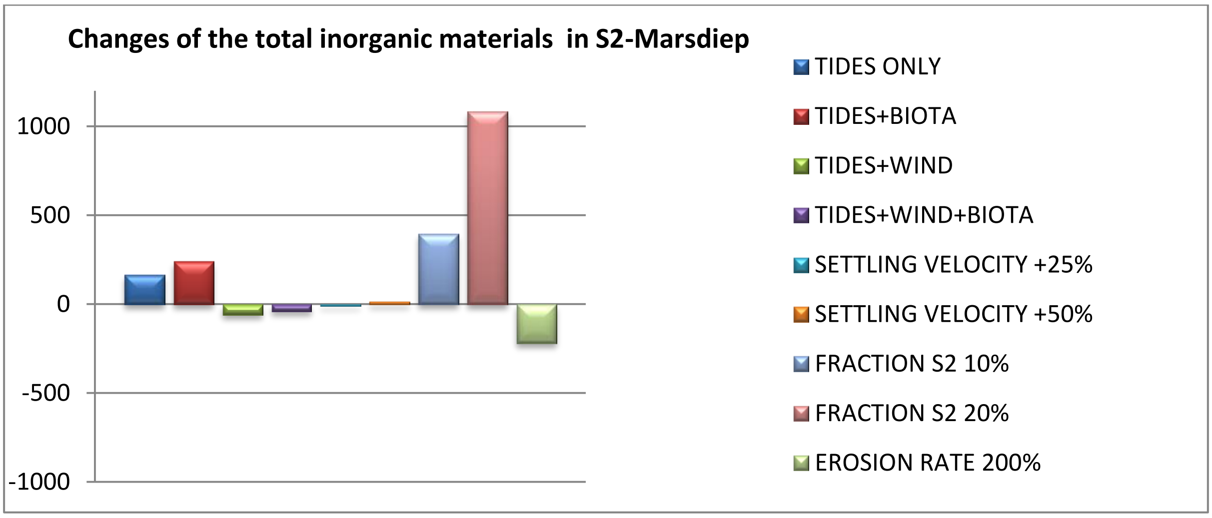


Figure 5–11, sedimentation in the buffer layer in Marsdiep basin.

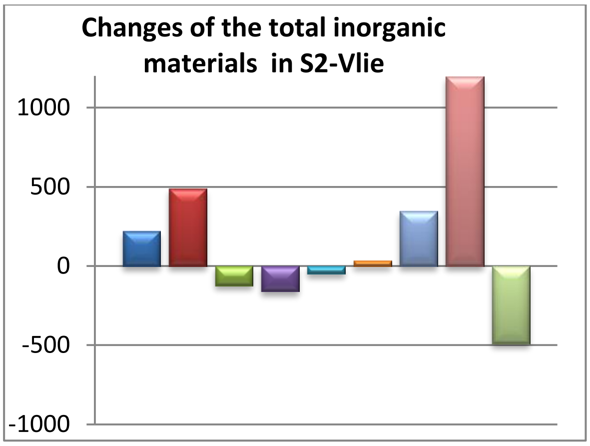


Figure 5–12, sedimentation in the buffer layer in Vlie basin.

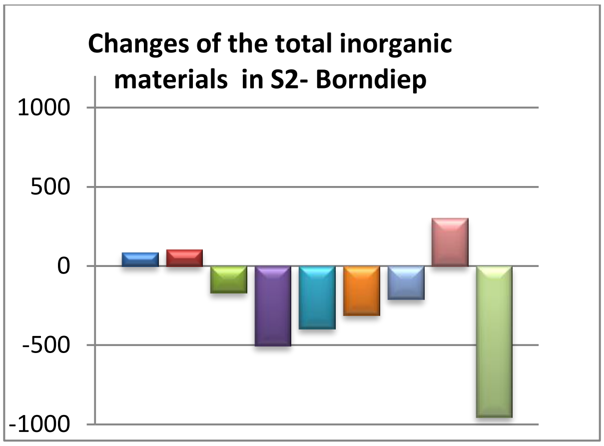


Figure 5–13, sedimentation in the buffer layer in Borndiep basin.

6- Discussion

This research has provided sequential implementation of the impact of biological activity on fine sediment dynamics, using the numerical model, Delft3D. The impact of biological activity on fine sediment dynamics in the Dutch Wadden Sea was investigated combining with the tidal currents, wind waves and the parameters from the reference model. The results of the extended model indicated that benthos display significant influence on the stability of inorganic materials due to their biological activities. This chapter discusses the uncertainties in both reference and extended models and the importance of finding. The uncertainties stem from the existing parameters and the assumptions of the biological activity. This chapter firstly discusses the methodology, namely assumptions, and secondly the results.

Discussion for the methodology

The numerical model, Delft3D, used data and physical parameters in order to reflect the real conditions. In addition to that, the literature researches and data from flume experiments had been used to convert the biological activity into physical parameters. In general, the biological activity is more complex than the implementation in this model. The biological parameters in this research were based on the effect of different benthos on the erosion of fine sediment as measured in the individual-flume experiments. Actually, these experiments are a simplification of the natural condition because in nature, several benthic organisms are present in the same place and the abundance of these organisms is influenced by several factors, for instance bed level changes, interaction between each other, pollution, nutrients and etc. The mussels in this research presented as young mussel bed, therefore no seed beds could take place in the other cells in this model and no emigration could occur in this numerical model as described by Van Leeuwen et al. (2010). Moreover, the biomass of each grazer in this research was equal for all basins, in fact there spatial variation in the biomass of every grazers in basins. In addition, other types of benthic organisms, for example *Mya arenaria, Crassorstrea gigas, Ensis directus* and etc. were also presented in the Dutch Wadden sea but this model could not deal with their impact of fine sediment dynamics because the limited data for the biomass of species and lack of both field and laboratory experiments. In spite of these shortcoming in the assumptions and the uncertainties, the extended model highlight the promising usefulness of the biological activity in prediction more accurate results because it identified key potential parameters that could improve the numerical models in the future.

Discussion for the results

Suspended sediment concentration

The results indicated that the biological activity lead to an increase in the suspended sediment concentration with temporal and spatial variations for the all stations in the Dutch Wadden Sea. The suspended sediment concentration measurements from the Rijkswaterstaat database were used to evaluate the modelled data for different stations in the Dutch Wadden Sea and the hourly data was used to compare the modelled outcomes with field data. The field data is normally suspended mater; this means it contains both organic and inorganic materials from the sea water surface. In general, the extended model overestimated the observed measurements as well as the reference model. A large number of reasons have been discussed about these dissimilarities, such as shortcoming resulted from the possible error in measuring device and the improperly defined parameters, but this might be also to the imperfections of the theoretical approach of the numerical model (Rahbani, 2015), because the numerical model is not able to simulate the interaction between individual fractions and it used constant settling velocity for the whole area in the reference model, this means there is no variation in the value of settling velocity due to flocculation on fine materials during slack tides.

Fine sediment content in zones and basins

Salt marshes

It is definitely clear that the salt marshes are regarded to be a sink for fine suspended sediment. That's because wind waves promote the bottom shear stress in lower zones, causing more transporting of suspended materials to the water column, not only wind can increase the suspended materials but also destabilizing influences by benthic organisms through decreasing the critical bed shear stress and increasing the erosion rates in lower zones. Also, the biostabilizing species are dominated in salt marshes, causing deposition of suspended materials. Actually, the large amount of sedimentation takes place in the buffer layer because the critical bed shear stress for this layer is one order of magnitude higher that the fluff layer as shown in figure D2. The result of this research is in close agreements with field observation as shown in figure 2-4, because high percentage of mud content can be found close to the coast line, mainly in salt marshes and also in upper-intertidal zone as shown in figure 6-1 below. Moreover, coastal salt marshes are valued as import habitats for plants life; this means vegetation in salt marshes plays a key role in reducing wave height and trap fine sediments (Leonard & Croft, 2006). therefore the next study ought to involve the influnces of vegetations in salt marshes.

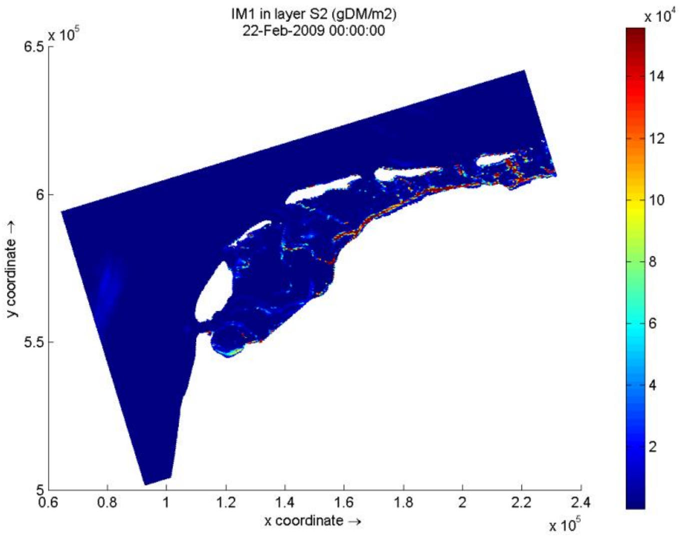


Figure 6–1, the accumulation of inorganic material (IM1) in the buffer layer in the Dutch Wadden Sea.

Upper intertidal zone

Likewise, permanent deposition is possible in the buffer layer of the upper-intertidal zone as a result of stabilizing influence by *Diatoms* and wind waves. Actually this zone is sensitive to wind waves because wind waves could reduce the deposition of fine materials for the short term. Also the biological activity is important in this zone because this coastal zone is vulnerable to climate change (Puente-Rodríguez, et al., 2015), this means the presence of *Diatoms,* light penetration, could be affected by the sea level rise, and grazers will be propagated in this area. Therefore it is expected that erosion of fine materials will occur in this place, unless the accumulation of sediment can exceed the sea level rise. On the contrary, it appears that the fluff layer in this zone could not store fine sediment.

Lower intertidal zone

Most basins of the Dutch Wadden Sea have relatively bigger lower-intertidal zones. And it is now generally recognised that these basins would be very sensitive to the fluctuation of biological activity because this zone the more sensitive to the fluctuation of biomass. The *Diatoms* could play a significant role in stabilizing the buffer layer in this zone. Therefore it can be expected in the future that the concentration of *Diatoms* would increase in this zone due to higher temperature, climate change, without taking the sea level rise into account. In the same way, grazers could extremely affect the stability of the bed layer of this zone. Thus, more nutrients and appropriate conditions for grazers would dramatic affect sedimentation in this zone. Moreover, the wind waves play a role in stabilizing fine materials in this zone. During calm weather, for example February, the suspended sediment could be deposited in this zone from the sea water column or transported from subtidal and channel zones, but the long term simulation led to erosion from the buffer zone.

Subtidal zone

On the basis of the results in this research, it may be inferred that the storage of the buffer layer in the subtidal zone would always decrease, as a result of wind waves and destablizing influences by grazers because the tidal prism is the only source and process which could increase the storage of fine materials in this zone. The wind waves engorge the erosion in the buffer layer by increasing the bottom shear stress. The eroded materials would transport to upper zones by flood tides. The concentrationof *Diatoms* in this zone is very limited. Thus the stablizing influence in this zone can also be drived by the influence of mussel beds , which increse the critical bed shear stress. Moreover, the grazers are dominated in this zone, leading to more erosion from the bed materials.

Channel zone

The biological activity is completely absent in the channel network of the Dutch Wadden Sea. Thus the physical parameters, critical bed shear stress and erosion rate, have the reference values. At the same time, the consequences of benthic organisms in upper zones could affect the storage of fine materials in this zone. In general, the channel networks are more complex than other zones in term of flow dynamics, especially after closing the Zuiderzee (Elias & van der Spek, 2006); the tidal inlets are located in the channel zones, causing higher flow velocities in the channel networks as shown earlier in figure 3-5 and 3-6. The long term result indicates that erosion occurs for all scenarios, but these results might reflect the dominant calm weather because seasonal variation was found in January and the outcome of the long term simulations depends on the repeated hydrodynamic forces; this means the strong wind waves produces high bottom shear stress in lower intertidal and subtidal zones, as a result a large amount of fine materials was transported to the channel zone. In contrast, erosion in the buffer layer of the cannel zone takes place during calm weather due to the flow velocity by tidal currents and the extra bed shear stress by normal wind waves.

Basins

The tidal prism is the main source of the fine sediment comes from the North Sea to the tidal basins. The hypsometry of the basin certainly affects the behaviour of sediment dynamics in the tidal basin. Wind waves reduce the storage of the buffer layer for the basins with a relative large subtidal and channel zones because the bottom shear stress exceed the critical shear stress in the lower zones, then the flood and ebb tides are responsible for transporting eroded materials from the lower zones to the salt marshes, upper-intertidal zones and to the North Sea. It is widely accepted that the fluctuation of biological activity could profoundly affect the storage of fine materials of the regular basins, such as Borndiep basin, and slightly for the deep basin. These results are in good agreement with the previous study by (van Oeveren, 2008a), however the normal biomass of benthic organisms in the Borndiep basin tended to adversely affect the storage of inorganic materials in this research, that's because the reference model was overestmated field measurements as well as the extended model which have been illustrated in section 4-4-1, therefore calibration of the extended model is needed. Apart from this, sea level rise appears to have severely impact on the hypsometry of each basin. To illustate that, figure 6-2 shows the possible hyposometry after incresing the bed depth *50 cm* for the whole study area, without taking into account the morpgological changes for this assumption. The basins become more deeper and the relative salt marshea and upper-intertidal zones seem to be smaller than for 2009. For instance Vlie basin will be regarded as deep basin and the fluctuation of biological activity would slightly affect the storage of the buffer layer due to the dominant channel and subtidal zones. The Marsdiep basin would become deeper and the influences of the biological activity on fine sediment dynamics will be less important than in 2009.

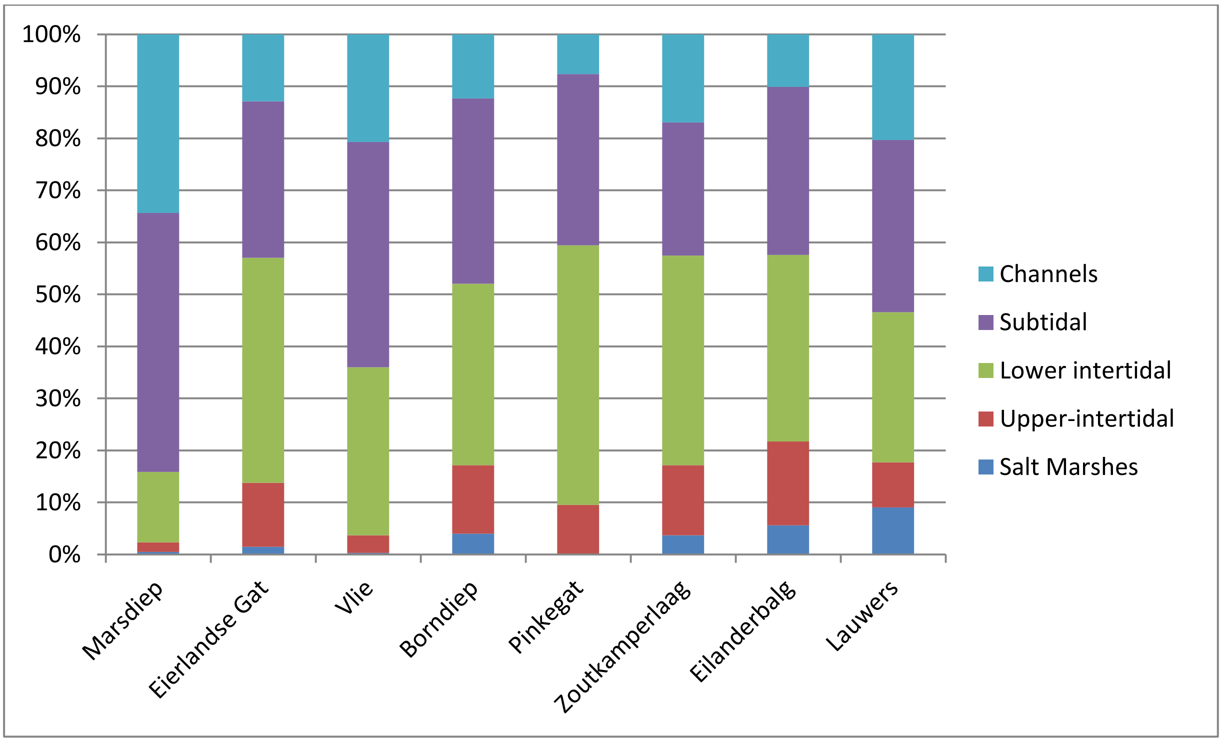


Figure 6–2, the possible hypsometry for intertidal basins in the Dutch Wadden Sea; the y-axis is the percentage of each zone to the total area of the basin and the X-axis is the tidal basins

Scenarios without wind forcing

As have been described earlier, the lower-intertidal zone is the most sensitive to fluctuation of biological activity, provided that the bottom shear stress is combined effects of tidal forces and wind waves. On the other hand, subtidal zone is the most sensitive zone to fluctuation of biological activity, but without the effects of wind waves because the bottom shear stress by tidal forces could not exceed the critical bed shear stress in the lower-intertidal zone. Moreover, erosion of fine materials can always occurs in the channel networks for two reasons, the first reason is due to the higher bottom shear stress by tidal currents, the second reason because there is not supply of fine sediment from upper zones as a result of combined effects of wind waves and tidal currents. Appendix G shows these simulations without wind waves over a 4 months study period.

Sediment fluxes

The key goal of coastal and basin engineering is to model the movement of fine sediment across the basin boundary and between the Dutch Wadden Sea and North Sea, make a better prediction of the accumulation and erosion of fine materials. In fact the intertidal basins in the Dutch Wadden Sea are highly dynamic and complex region, that's because water mass exchanges occur between the North Sea and Wadden Sea through several inlets as well as between adjacent basins. The results of both situations provided valuable insight into the hydrodynamic processes and biological influences on horizontal sediment transport. The permanent deposition was estimated at 3-5 % of the input to the Dutch Wadden Sea (Postma, 1961; Eisma, 1979), actually, this research discovered that the ratio of the permanent deposition is associated with each basin characteristic. In other words, the depositions are estimated in Marsdiep basin 5-7% and 0.5-3% in Borndiep basin. Postma (1961) also estimated that the loads of suspended materials from rivers, sluices is less than 4% of the total input, this research also estimated these loads at 3,5% of the total input to the Dutch Wadden Sea. Moreover, the biological activity leads to more deposition in the bed layers for eastern basins as a result of larger horizontal fluxes could enter to the eastern basins. Equally important, the computation of sediment fluxes described here was somewhat approximate. This means that these results are the averages between two water bodies, for example the net import of sediment flux to Vlie from Marsdiep is 332, while the net export from Marsdiep to Vlie was 306 kilo tons, the average is 318 kilo ton as shown in figure 4-25. The enormous gap is the sediment flux between Borndiep and Pinkegat in the extended model because the both values are positive, no export between basins. The reason for these errors stems from the limitation of the numerical model, the accuracy of Delft3D. Thus the processes within the numerical model ought to be improved in order to deal with these types of processes. Appendix F illustrates the horizontal transport between Vlie and Marsdiep basins.

Mussel bed

It appears that the influence of the mussel beds with the wind waves is not always able to increase the storage of fine materials. Actually, mussel beds in this study area could have different behaviours depending on the impact of wind waves and the locations of the blue mussels. The locations of the mussel beds in this research are mostly in the intertidal and subtidal zones, and if the mussel beds are not included in this research then these locations will be occupied by other dominant destabilizing species. In this case it can be expected more erosion from the bed materials, therefore mussel beds could be responsible for increasing the stability of the buffer layer. The result of this research could be in good agreements with outcomes of previous study (Van Leeuwen et al. 2010), however the roughness of mussel beds was not implemented in this research because this research simulated WAQ-module only. The previous study limited the hydrodynamic forces on the tidal forces only, namely during calm weather without wind waves effects, therefore the results from the previous study has to be compared with the 2^{nd} bars of this research in figure 4-27. Actually the implementation of mussel beds in this research might be in good agreements with the field measurements because 50% of mussel beds exposed to erosion during winter conditions. On the other hand, this implementation of mussel beds has uncertainly in the assumption; for instance, the value of the filtration rate by mussels was implemented and divided for the last three water layers, 50% for layer 10, 30% for layer 9 and 20% for layer 8. In fact the water depth for every layer above the mussel beds are variables and it could increase with flood tides and vice versa with ebb tides.

Sensitivity analysis

It is now generally recognised that an increase in the fraction of the deposited materials could have same consequences on each zones for the buffer layer. On the other hand, the changes of the settling velocities and the erosion rates result in different response for each zone. As indicated earlier, calibration for the extended model is needed to decrease the suspended sediment concentrations for the most stations; therefore the values of the settling velocity or the fraction to the buffer layer could be increased to meet the observed measurements. Moreover, an increase in the storage of Borndiep basin might occur by increasing the fraction of the buffer layer, more than 10%. Thus it seems fair to say that the destabilizing influences by benthos are significant in this basin.

7- Conclusion and recommendations

This research examined the biological activity of fine sediment transport in the Dutch Wadden Sea. The objective of this research was formulated as follows:

To investigate by using the numerical model, Delft3D, the influence of benthic organisms on fine sediment transport and bed composition in the Dutch Wadden Sea.

Based on this objective, five main questions were proposed in this research. The conclusions of this research are done by addressing these questions:

1- Which benthic organisms have effects on the erosion and deposition of sediment in the Dutch Wadden Sea? And, how can the biological activities of these organisms be incorporated into the numerical model?

This study examined three types of biological activities, which are:

a) The biostabilization influence, presented by *Diatoms*, which could maximally increase the critical bed shear stress by a factor of 2.5 and maximally decrease the erosion rate with a factor 0.5
b) The bioturbation influences by *Cerastoderma edule*, *Arenicola marina, Hydrobia ulvae, Macoma balthica*. These combined influences by grazers could maximally decrease the critical bed shear stress with a factor 0.4 and maximally increase the erosion rates by factor 5.5
c) The biodeposition influence, presented by *Mytilus edulis,* this benthos is able to maximally increase the critical bed shear stress by a facto1.6 as well as increasing the erosion rates with a factor 4 and finally can maximally increase the settling velocity 0.5 mm/s.

2-What is the influence of biological activity on suspended sediment concentration, compared to the situation without biological activity and with actual measurements from the field in the Dutch Wadden Sea?

The biological activity caused an increase in the suspended sediment concentration for stations in the Dutch Wadden Sea due to the dominant influences of grazers. The growth of *Diatoms* resulted in significant temporal variation in suspended sediment concentration due to increase the erosion threshold. The ratios of increasing in the concentrations between the two models were larger for the eastern stations than the western because the distribution of benthic organisms is associated with the water depths, thus spatial variation was observed. Further, the majority of both suspended sediment concentrations from both modelled data were overestimated the field measurements. The reasons for these overestimations are that the calibration of the reference model was insufficient in term of the input parameters and the shortcoming of field measurements might cause that for some stations.

3- What is the difference in mud content between simulations with and without biological activities? for different depth zones and basins

Based on the outcomes of the modelled data, the biological activity resulted in an increase of the storage for the buffer layer in salt marsh and upper-intertidal zones, erosion of the buffer materials always occurred in subtidal zone, while an increase in the storage could take place in the lower-intertidal and channel zones for the short term, depending on the effect of wind waves. In addition to that the lower-intertidal zone is more sensitive to the biological fluctuation. Actually, the deep basin was slightly influenced by the biological activity comparing with the regular basin, which it was significantly affected by the influence of benthic organisms.

4- How could the biological activity affect the sediment fluxes between North Sea and tidal basin of the Dutch Wadden Sea?

In general, huge amount of sediment fluxes have been transported from the North Sea to the tidal basins and between adjacent basins with and without biological activity during four months simulation caused by tidal currents. The biological activity could reduce 25% of the total net fine sediment import from the North Sea to the tidal basins as well as reducing 7% of the sedimentation to the bed layers. The remaining fluxes is much more in Marsdiep basin, than the Borndiep basin, despite the total import is larger in the last, this caused by the influences of wind waves and grazers in shallow basin.

5- What is the role of mussel bed on sediment stability in the Dutch Wadden Sea?

The mussel beds could increase the storage of the buffer layer as results of higher critical bed shear stress and to the influence of the filtration rates. Unless, the bottom shear stress by tidal currents and wind waves exceed the critical bed shear stress, in this case the model showed lower storage of fine materials due to the higher erosion rates. Actually the location of mussel beds within tidal basin determines the storage of the buffer layer. In other words, the mussel beds in upper intertidal zone lead to increase the sedimentation of the buffer layer, while the influence of mussel beds in deep zones is not significant important for sedimentation .

To conclude, it can be said that, this research examined the influences of the biological activity on the suspended sediment concentration, fine sediment storage of the bed layers and sediment fluxes between North Sea and the tidal basins of the Dutch Wadden Sea. The suspended sediment concentrations for different stations in the study area have been increased as a result of the dominant influences of grazers with temporal and spatial variations. The salt marshes and the upper-intertidal zone were regarded to be a sink for inorganic materials, while other zones suffered from erosion processes for the long term. The deep basin was not significantly influenced by the biological activity, while the regular basins were more sensitive to the presence of benthic organisms. The amount of sediment fluxes from the North Sea to the tidal basins was decreased about 25% with biological activity. Finally, the influence of mussel beds on sedimentation is associated with the depth.

Recommendations

- In this research, the influences of biological activity on the fine sediment materials were modelled using WAQ-module, thus the interaction among sand-mud –bio is needed to see the impact of biological activity on the morphology on the tidal basins using Flow-module, this means both suspended load and bed load.
- There is a continuing need for flume experiment to investigate the combined effects of destabilizing benthic organisms on the sediment transport, this would reduce the uncertainly in the proposed equations.
- Implementation of flume experiment for other kinds of species in the Dutch Wadden Sea, such as *Mya arenaria*, *Lanice conchilega* and *Ensis directus* is strongly recommended, because these species have been observed with relative large biomasses and might have significant impact on sediment dynamics.
- It is strongly recommended to include the impact of salt marshes vegetation on fine sediment transport in this model, as well as, sea grass which might also have stabilizing influence on the sea bed; therefore research is needed to study the influence of sea grass on sediment dynamics.
- The extended model examined the influence of mussel beds on fine sediment transport; it could be more interested to investigate the combined effects of mussel beds and oyster reefs in this study area.
- The filtration rate in this research was only associated with the blue mussel, while another type of benthic organisms, for instance *Cerastoderma edule*, could also filtrate the water column, this should be done in the next studies.
- It is advisable to use an idealized model to model sediment balance between the North Sea and tidal basins with biological activity for the long term, for instance 50 years, because the computational time for this extended model is very long.
- Benthic organisms could (de)stabilizing fine materials in tidal basins, these processes might be exploited by experts to involve it under the concept, build with nature.

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Appendix A Biological activities on physical parameters

The biological activities have been incorporated into physical terms, i.e. critical shear stress and erosion rate as described in section 2-3-2. The influence of *Diatoms* on the critical shear stress is illustrated in figure (A.1), the erosion threshold increase with increasing the concentration of the biomass. Figure (A.2) shows how the erosion rate could be affected when chlorophyII-α is presence on the bottom of the sea.

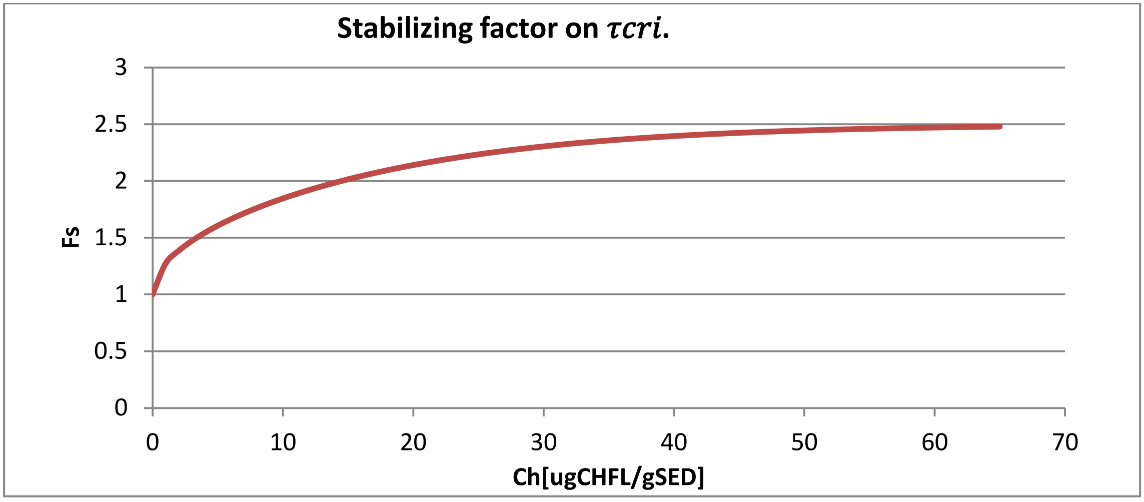

Figure A.1, the stabilizing factor for the critical bed shear stress when Diatoms are presence on the sea bed, the initial value is arbitrary number.

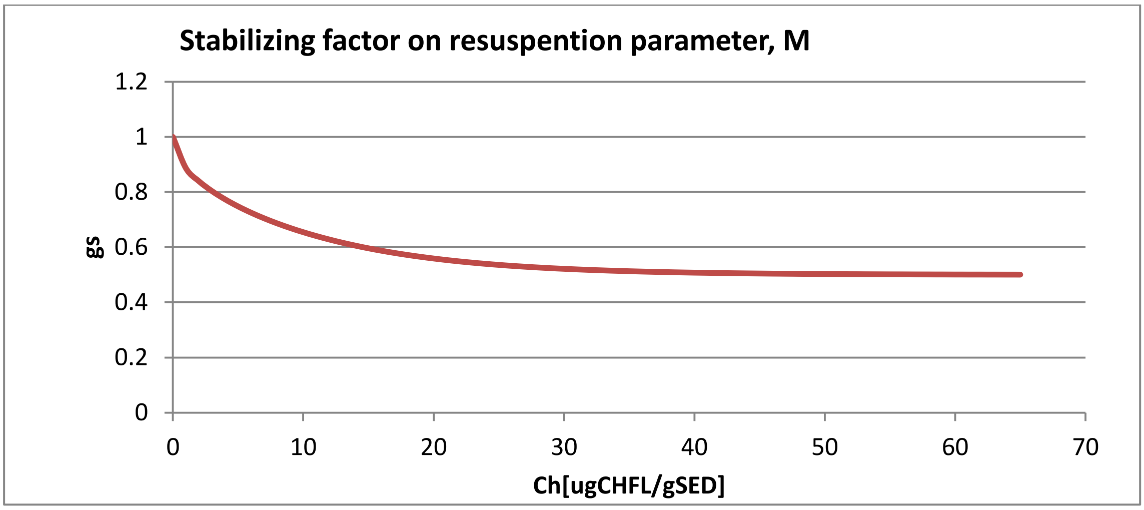

Figure A.2, the stabilizing factor for erosion rate when Diatoms are presence on the sea bed, the initial value is arbitrary number.

The destabilizing activities by grazers lead to decrease the erosion threshold and to increase the erosion rate of sediment. The results are clear in figures A.3 &A.4, where there are four types of grazers Macoma balthica, Hydrobia ulvae, Cerastoderma edule and Arenicola marina. The maximum biomass of each type of grazers is the same[$45\ gC/m^2$] , while the combined effect of grazers reflect equal fraction of biomass for the species. The results of biological activities show that the impact of grazers on the erosion rate is larger than on the critical shear stress.

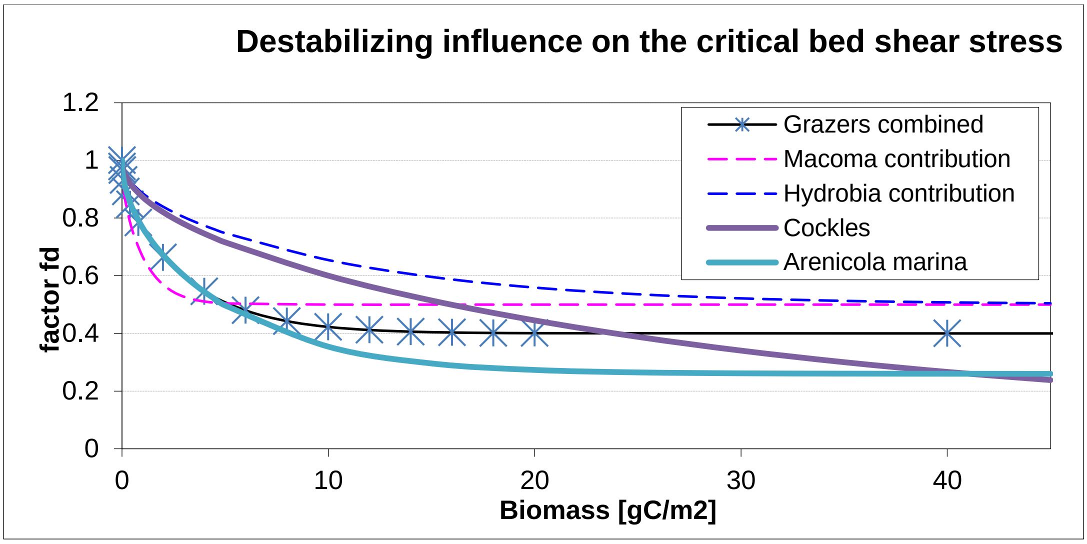

Figure A.3, the destabilizing factor for the threshold due to the influences of grazers; the initial values are arbitrary numbers.

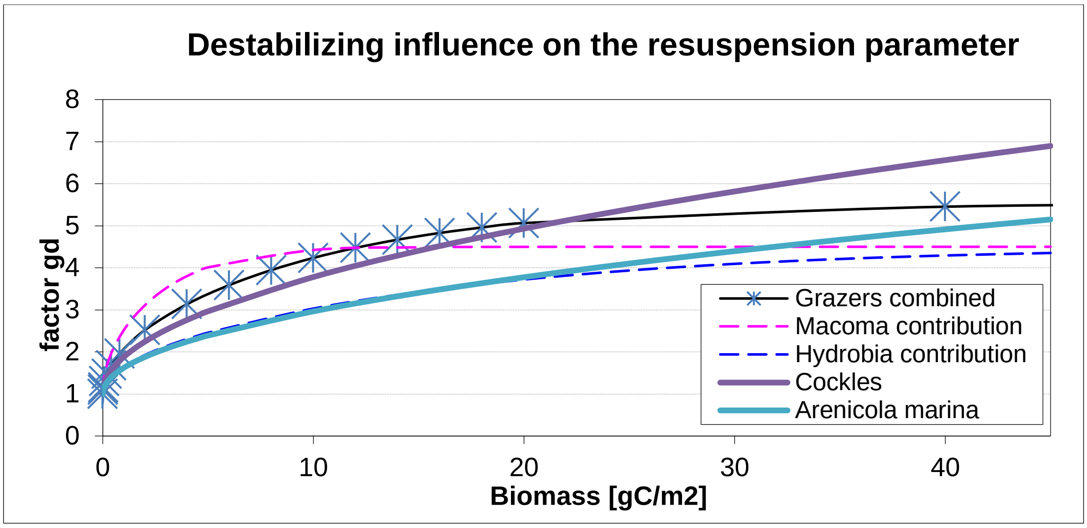

Figure A.4, the destabilizing factor for the erosion rate when grazers are presence, the initial values are arbitrary numbers.

Actually, the values of the individual grazer such as $f_{d,max}$, $g_{d,max}$ *and* c, e *coefficients* are the same values that described by van Oeveren, (2008), while the values of the Cockles are based on the flume experiment by Ciutat, et al., (2007); they investigated the impact of *Cerastoderma edule* density on the erosion threshold and sediment erodability. The data for *Arenicola marina* is also based on the flume experiment that has been conducted (van Oeveren, 2008).

Appendix B physical parameters for zones in the Dutch Wadden Sea

The physical parameters could be affected by the biological activity of the benthic organisms, such as *Diatoms*, *Cerastoderma edule*, *Arenicola marina, Hydrobia ulvae, Macoma balthica*. These benthic organisms are responsible for changes the critical bed shear stresses for erosion and the erosion rates for the references model as described earlier in equations 5 and 6. Therefore the initial values in table 5 have been changed as a result of the biological activity. The figures below show the input values in the extended model for different zones.

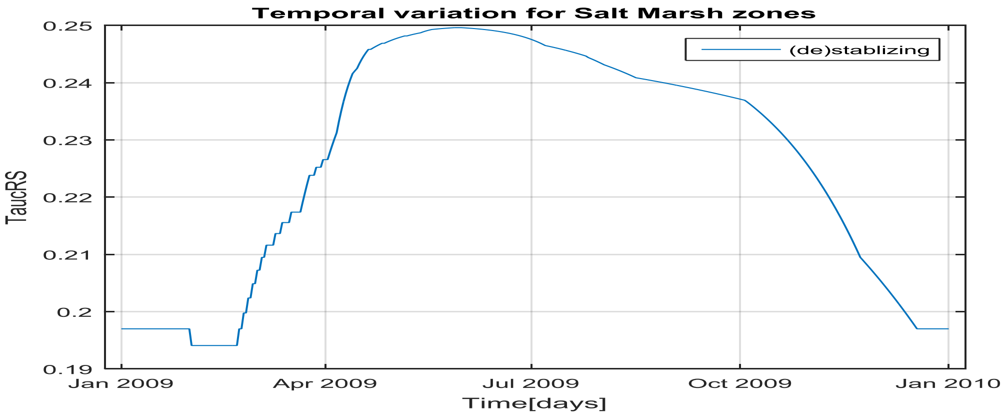

Figure B1, the critical bed shear stress for the fluff layer in Salt marshes, the initial value is 0, 1 N/m2.

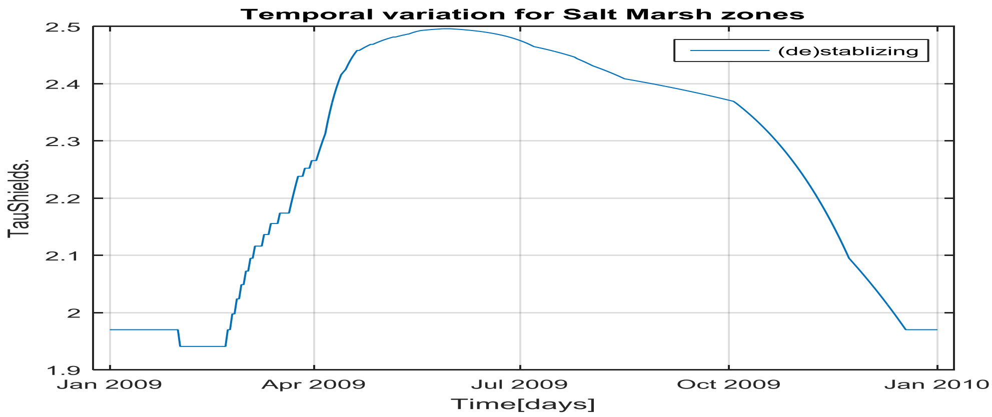

Figure B2, the critical bed shear stress for the Buffer layer in Salt marshes, the initial value is 1 N/m2.

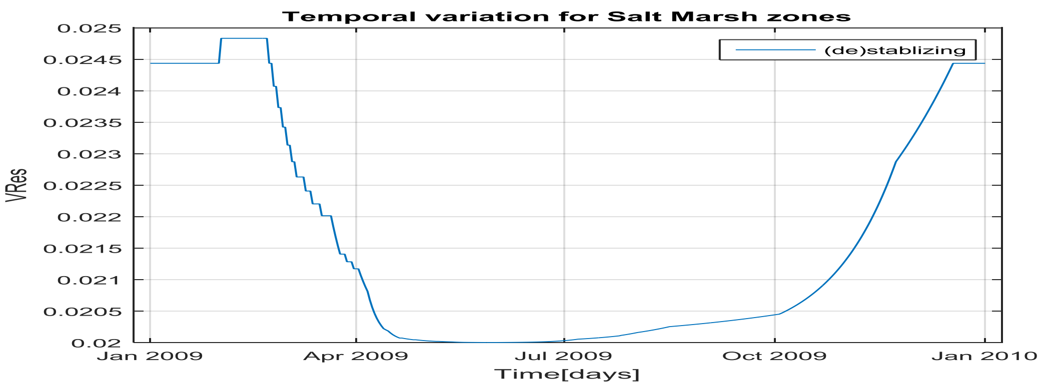

Figure B3, the erosion rate in the Salt marshes; the initial value is 0, 04 g DM/m2/d.

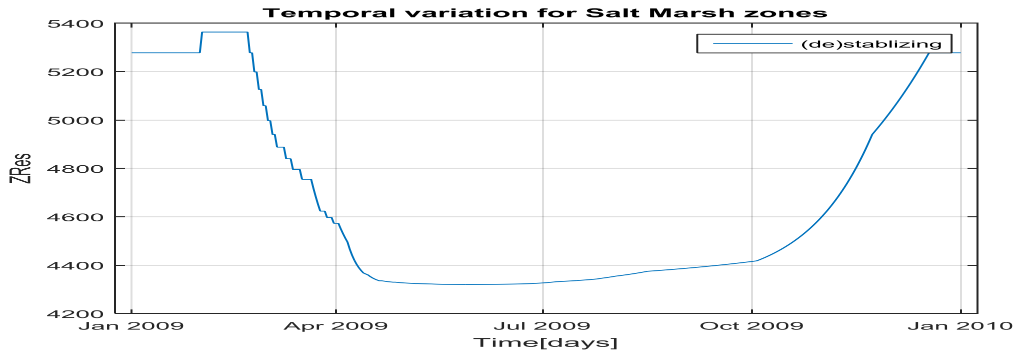

Figure B4, the erosion rate in the Salt marshes; the initial value is 8640 g DM/m2/d.

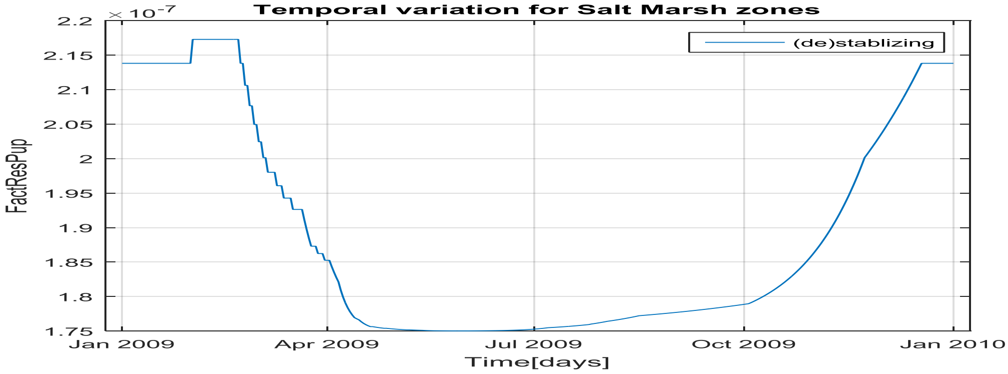

Figure B5, the erosion rate in the Salt marshes; the initial value is 0.00000035 g DM/m2/d.

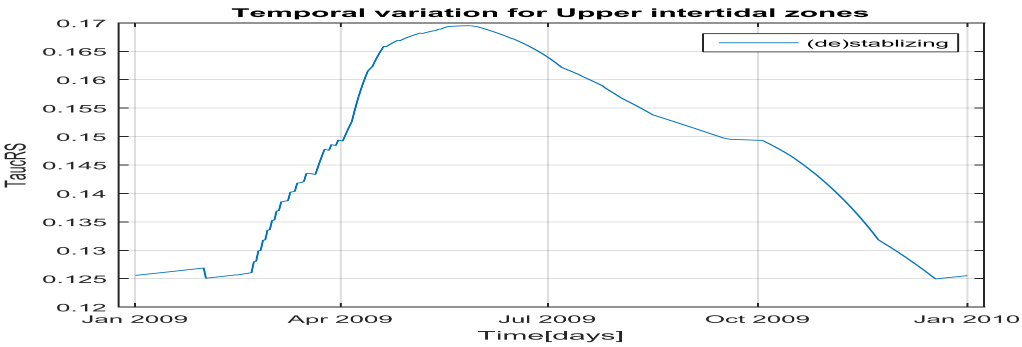

Figure B6, the critical bed shear stress for the fluff layer in Upper-intertidal zone, the initial value is 0, 1 N/m2.

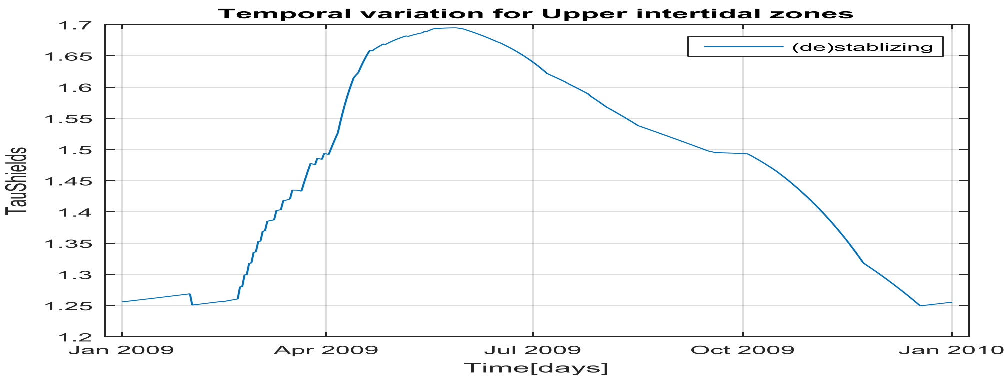

Figure B7, the critical bed shear stress for the Buffer layer in Upper-intertidal zone, the initial value is 1 N/m2.

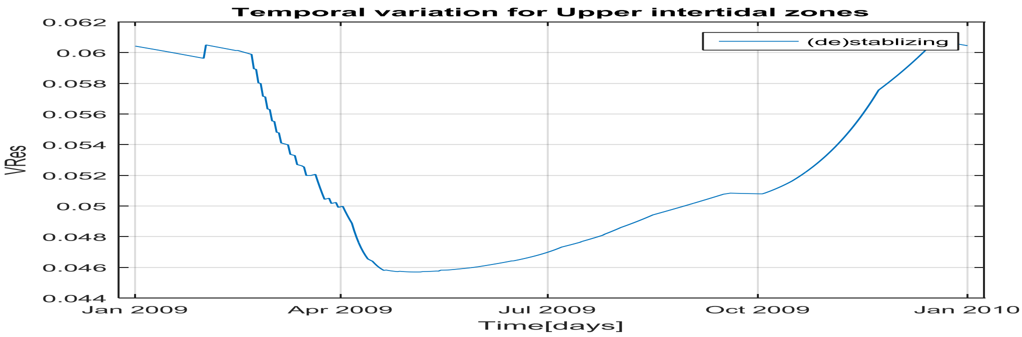

Figure B8, the erosion rate in Upper-intertidal zone; the initial value is 0, 04 g DM/m2/d.

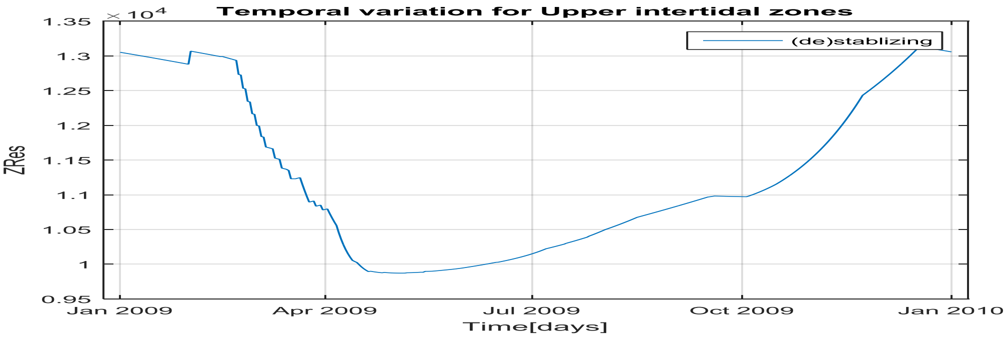

Figure B9, the erosion rate in Upper-intertidal zone; the initial value is 8640 g DM/m2/d.

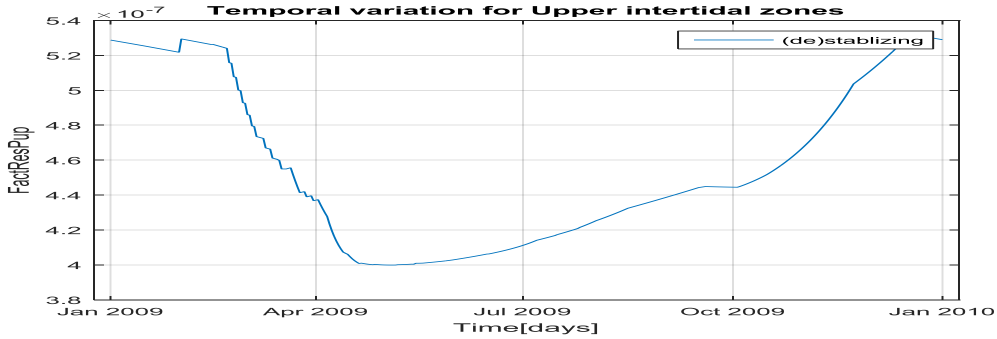

Figure B10, the erosion rate in Upper-intertidal zone; the initial value is 0.00000035 g DM/m2/d.

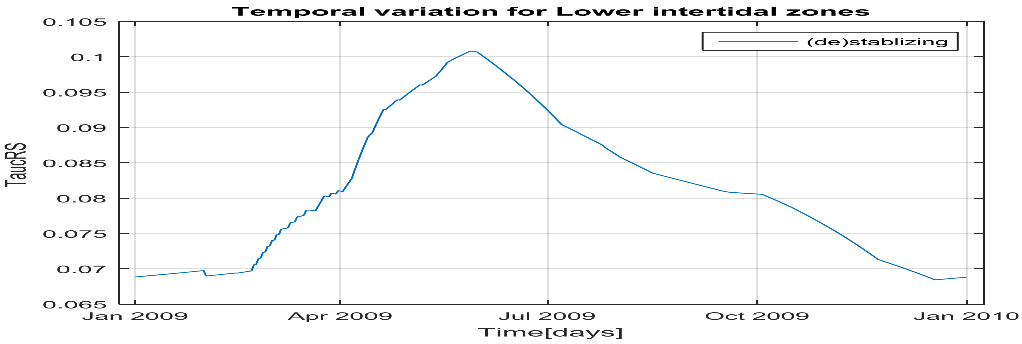

Figure B11, the critical bed shear stress for the fluff layer in Lower-intertidal zone, the initial value is 0, 1 N/m2.

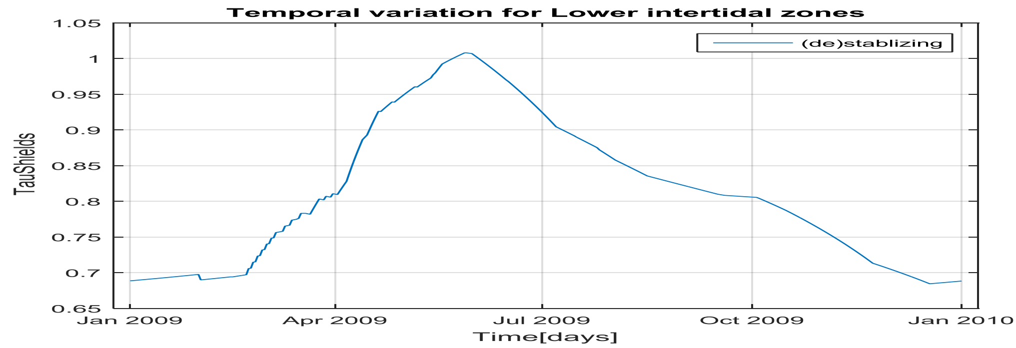

Figure B12, the critical bed shear stress for the Buffer layer in Lower-intertidal zone, the initial value is 1 N/m2.

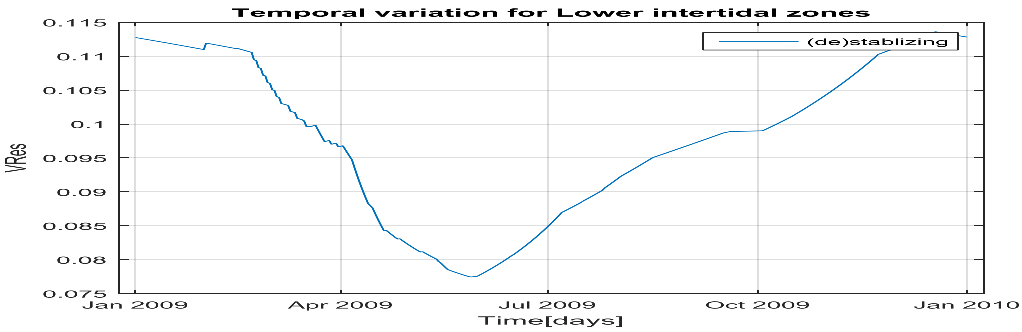

Figure B13, the erosion rate in Lower-intertidal zone; the initial value is 0, 04 g DM/m2/d.

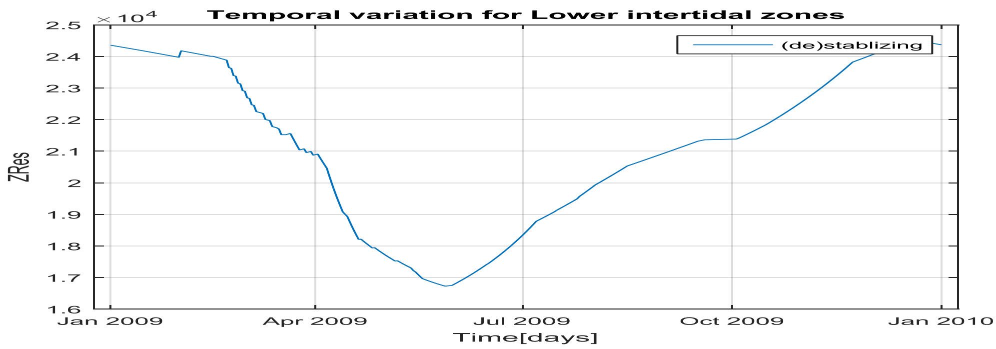

Figure B14, the erosion rate in Lower-intertidal zone; the initial value is 8640 g DM/m2/d.

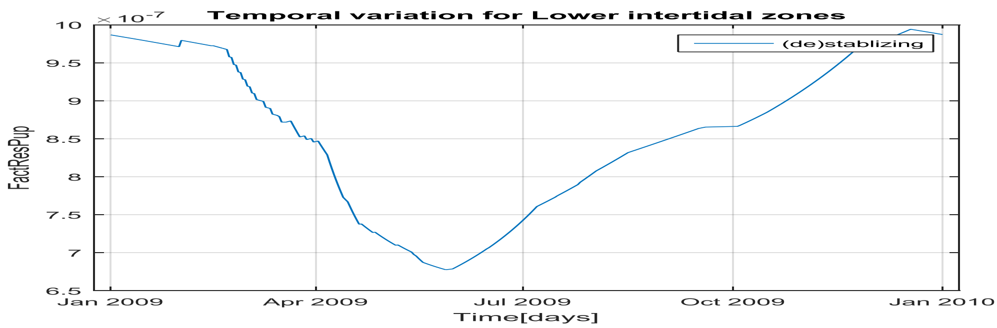

Figure B15, the erosion rate in Lower-intertidal zone; the initial value is 0.00000035 g DM/m2/d.

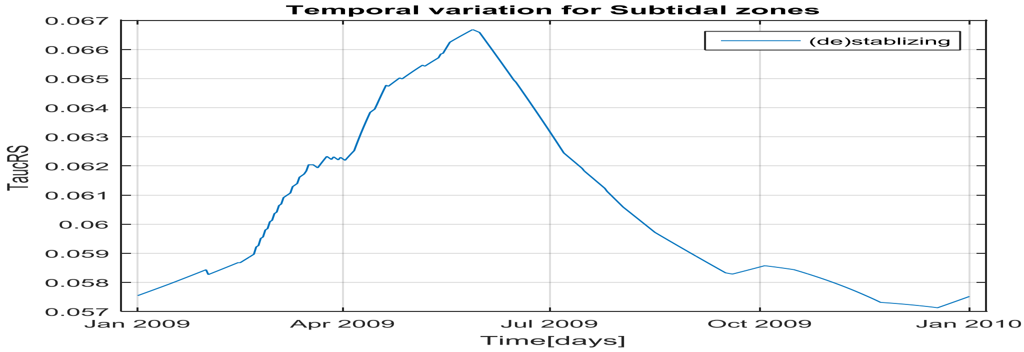

Figure B16, the critical bed shear stress for the fluff layer in Subtidal zone, the initial value is 0, 1 N/m2.

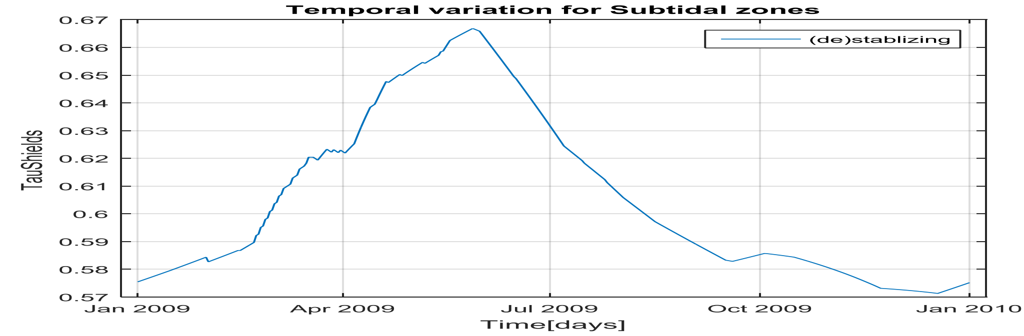

Figure B17, the critical bed shear stress for the Buffer layer in Subtidal zone, the initial value is 1 N/m2.

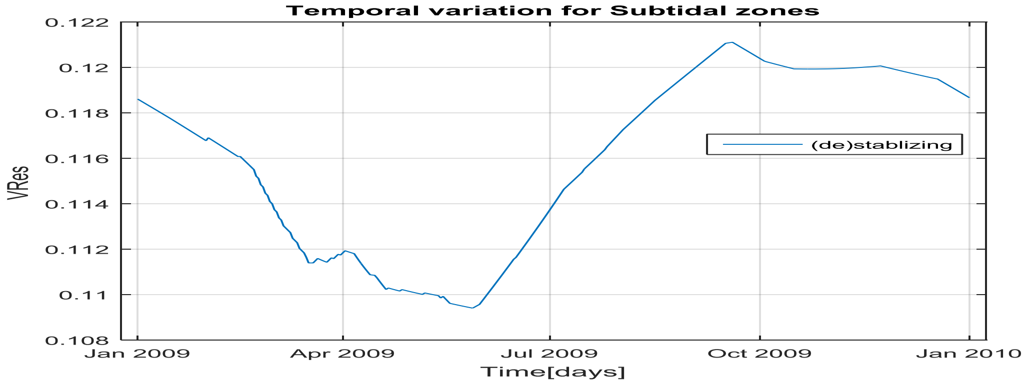

Figure B18, the erosion rate in Subtidal zone; the initial value is 0, 04 g DM/m2/d.

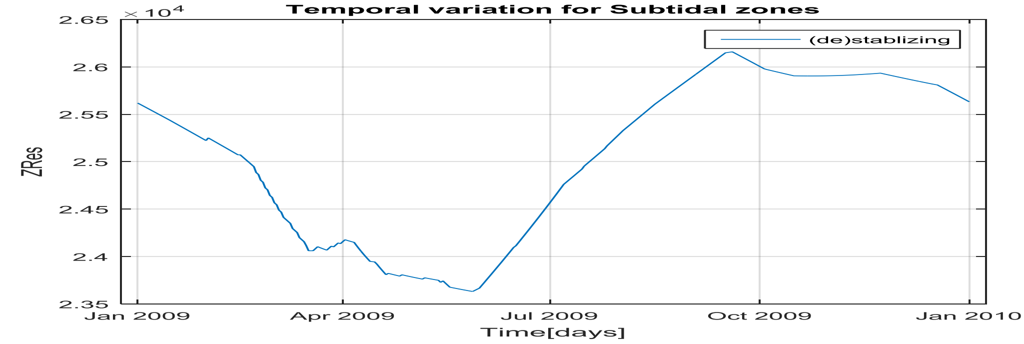

Figure B19, the erosion rate in Subtidal zone; the initial value is 8640 g DM/m2/d.

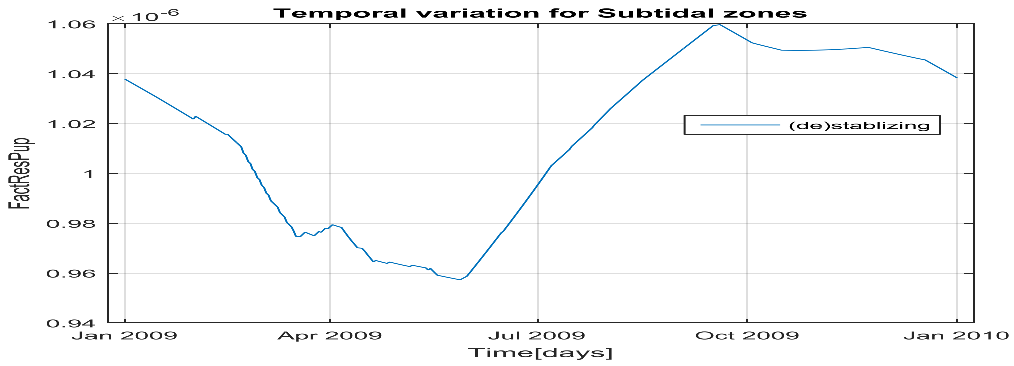

Figure B20, the erosion rate in Subtidal zone; the initial value is 0.00000035 g DM/m2/d.

Appendix C Results for the suspended sediment

This appendix shows the results of both modelled data with the field measurements for Blauwe Slenk oost, Zoutkamperlaag zeegat and Zoutkamperlaag stations for one year simulation in figures C1, C2 and C3.

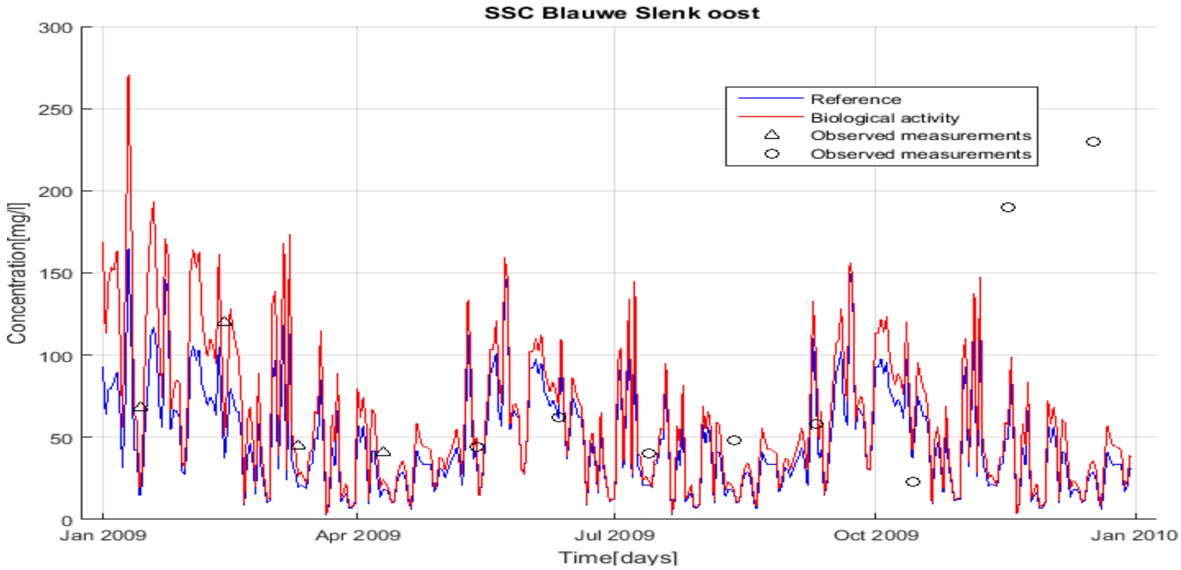

Figure C1, the suspended sediment concentration of the Blauwe Slenk oost station, the blue line means the outcomes of the reference model, the red line is simulation with biological activity, the triangular markers are field measurements during real hydrodynamic forces and the circular markers are field measurements during the repeated hydrodynamic forces.

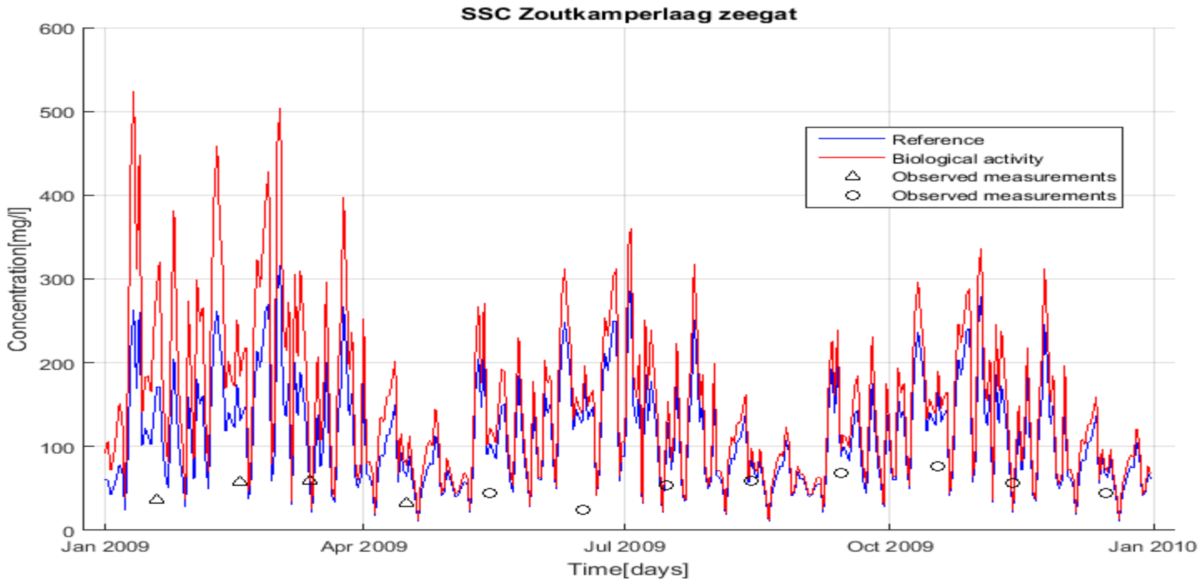

Figure C2, the suspended sediment concentration of the Zoutkamperlaag zeegat station, the blue line means the outcomes of the reference model, the red line is simulation with biological activity, the triangular markers are field measurements during real hydrodynamic forces and the circular markers are field measurements during the repeated hydrodynamic forces.

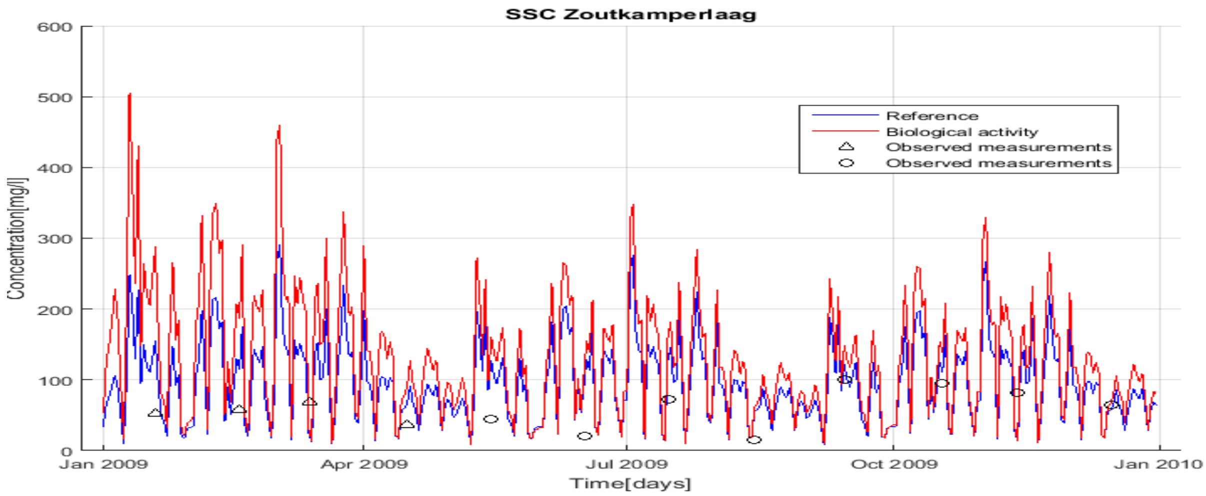

Figure C3, the suspended sediment concentration of the Zoutkamperlaag station, the blue line means the outcomes of the reference model, the red line is simulation with biological activity, the triangular markers are field measurements during real hydrodynamic forces and the circular markers are field measurements during the repeated hydrodynamic forces.

Figures C4 through C9 shows the differences in suspended sediment concentrations between the extended model with biological activity and the reference model. The differences in Doove Balg west station is not significant because the Marsdiep basin is not ecological rich, comparing with the eastern basins (figures C4 and C5).

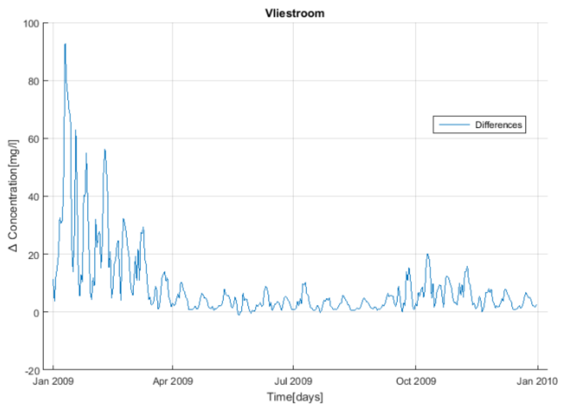

Figure C4, the differences in suspended sediment concentrations between the extended and reference models for Vliestroom station.

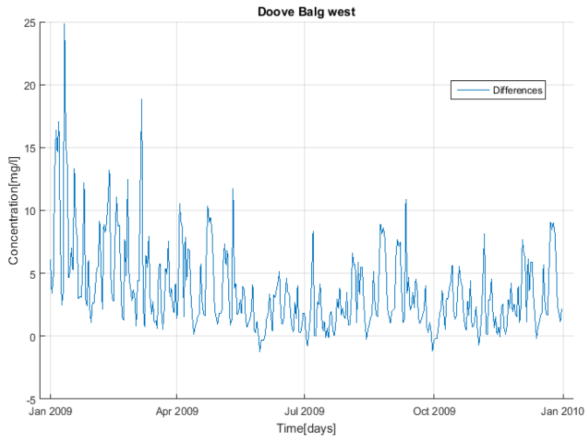

Figure C5, the differences in suspended sediment concentrations between the extended and reference models for Doove Balg west station.

The temporal variations for the suspended sediment concentrations are more clearly in the eastern stations or in shallow basins, as described earlier in section 4-1, (figures C6, C7 and C8), while the difference for Zuid Oost Lauwers oost station shows enormous peaks, resulting from the impact of boundary condition on the location of this station.

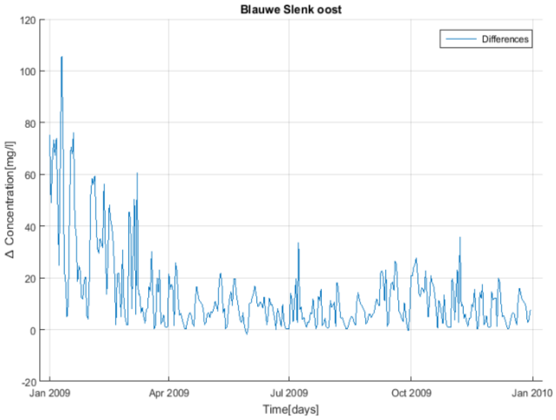

Figure C6, the differences in suspended sediment concentrations between the extended and reference models for Blauwe Slenk oost station.

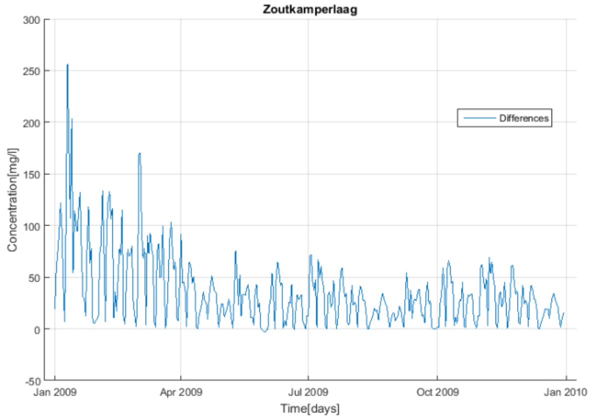

Figure C8, the differences in suspended sediment concentrations between the extended and reference models for Zoutkamperlaag station.

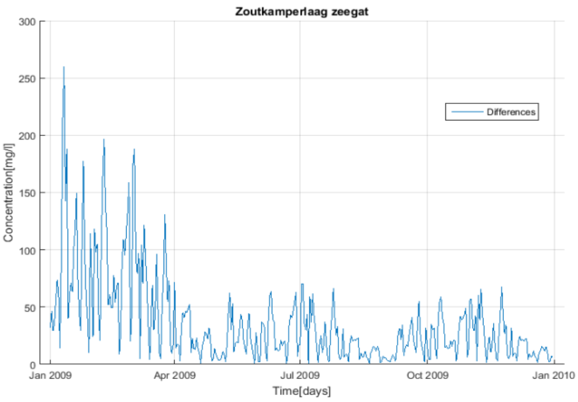

Figure C7, the differences in suspended sediment concentrations between the extended and reference models for Zoutkamperlaag zeegat station.

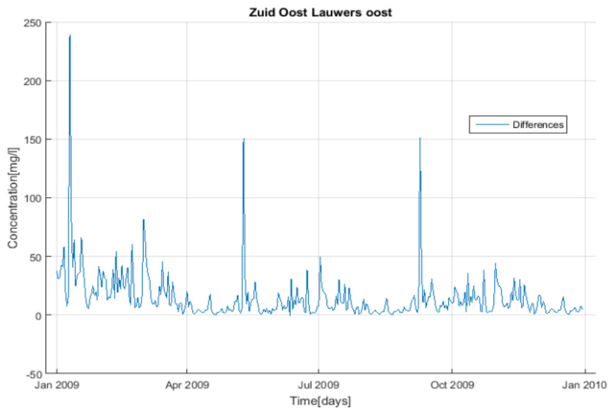

Figure C9, the differences in suspended sediment concentrations between the extended and reference models for Zuid Oost Lauwers oost station.

The next figures C10 through C13, illustrate the Box-Whiskers-plots for the rest of the stations.

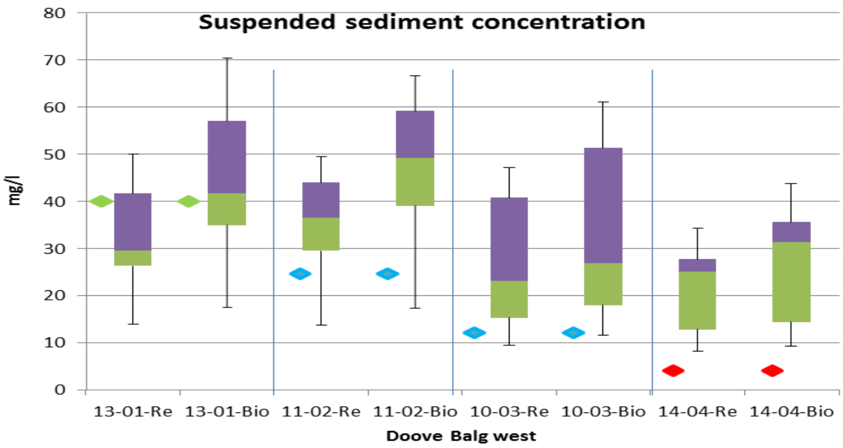

Figure C10, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Doove Balg west station, , the green markers means the modelled data are accepted , the blue markers means the modelled data are rejected and the red markers means the modelled data are strongly rejected.

Actually, the model results of Blauwe Slenk oost station are in close agreement with the observed measurements as shown in figure C11, because all the markers are corresponded with the modelled date from the extend model, while there is one outlier in the reference model.

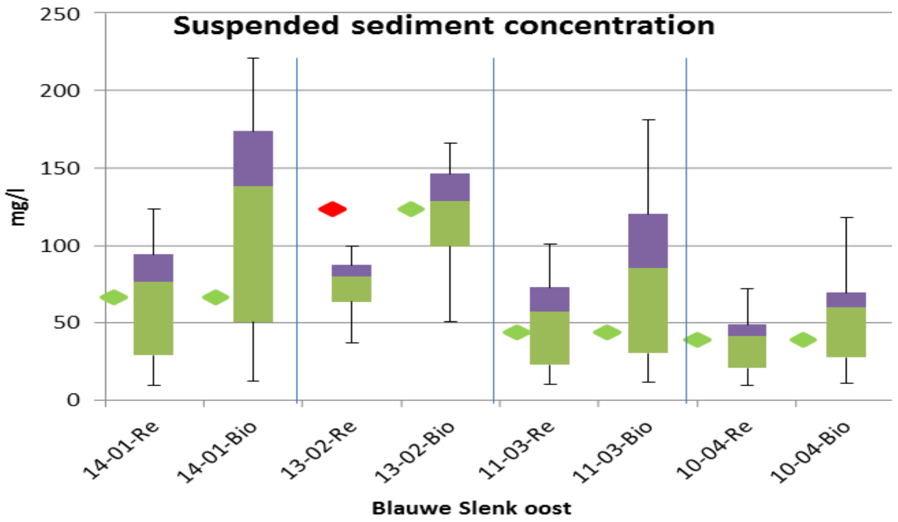

Figure C11, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Blauwe Slenk oost station, , the green markers means the modelled data are accepted and the red markers means the modelled data are strongly rejected.

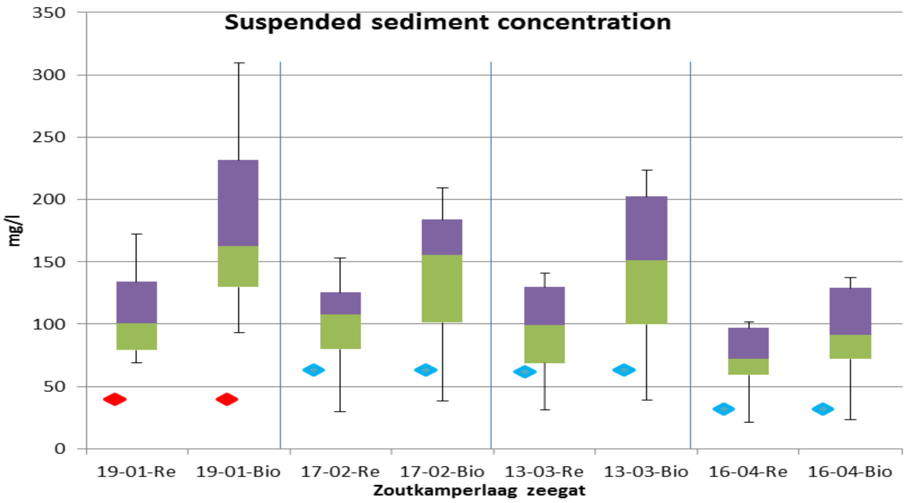

Figure C12, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Zoutkamperlaag zeegat station, , the green markers means the modelled data are accepted , the blue markers means the modelled data are rejected and the red markers means the modelled data are strongly rejected.

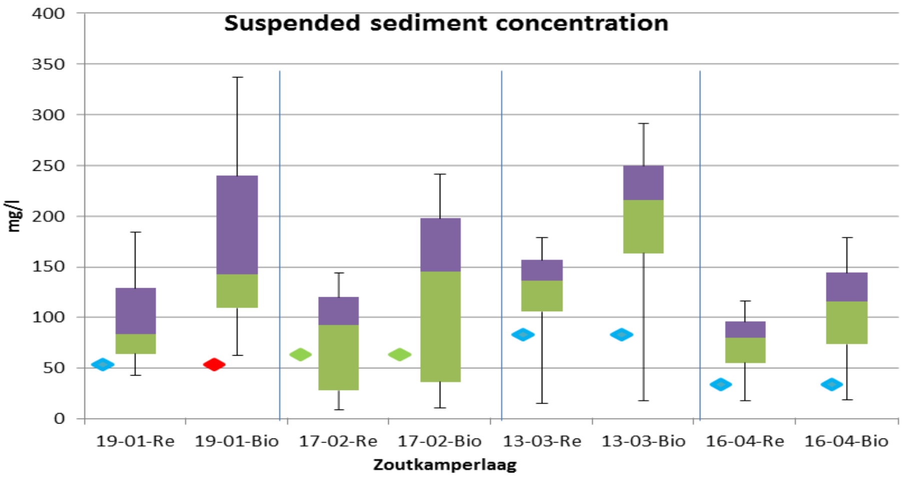

Figure C13, Box-Whisker-plots from both the reference and the extended models for some days, in which field measurements are available as markers for Zoutkamperlaag station, , the green markers means the modelled data are accepted , the blue markers means the modelled data are rejected and the red markers means the modelled data are strongly rejected.

Appendix D Results of the fluff layer for the long term in different zones

In this model, a large percentage of the deposited inorganic materials, 95%, settled to the top layer of the bed, fluff layer, of which the critical bed shear stress of this layer is one order of magnitude lower than the buffer layer, therefore the resuspension of deposited materials in this fluff layer could occur rapidly. These processes make it difficult to assess the dynamic of system depending on the fluff layer in the numerical model.

From figure D1 it can be seen that each simulation with different physical processes and biological scenarios is responsible for an increase in the mass balance in the salt marshes and the behaviour of the system in this layer is similar to the buffer layer as have been described earlier in section 4-3. What is responsible for these similarities that the flow velocity in this zone is very slow; this means that the bottom shear stress by different physical processes could not always exceed the critical bed shear stresses for both layers.

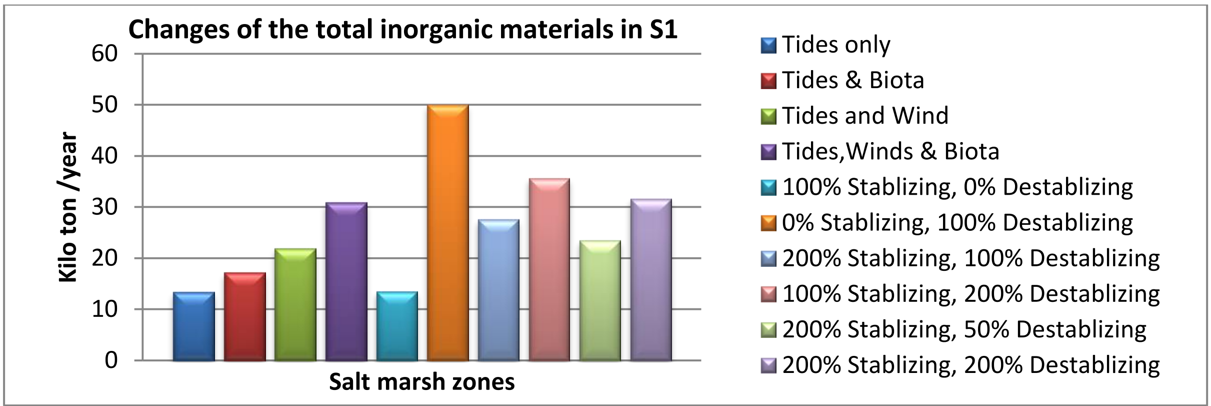

Figure D1, sedimentation to the fluff layer, S1, for Salt marsh zone in the Dutch Wadden Sea.

All the features of the outcomes in fluff layer of salt marshes are superficially similar to the buffer layer of the same zone by comparing with figure 4-13, but the amount of accumulation is lower than the buffer layer. To demonstrate that, figure D2 shows the relative deposition of fine materials in bed layers. The buffer layer could store more sedimentation than the fluff layer, although 95% of the deposited materials have settled in the fluff layer, but erosion happened easily in the top layer, otherwise, the ratios had to remain 95% for the fluff layers.

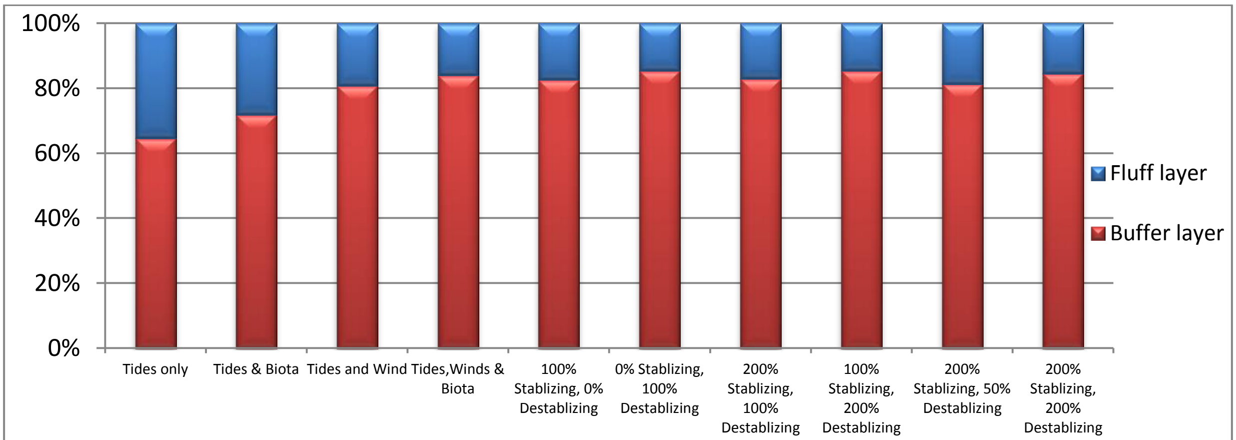

Figure D2, the relative sedimentation to the bottom layers, Fluff layer s1 and Buffer layer S2.

From the figures D3 and D4 below it may be shown that the effect of tides could not contribute to stabilizing the fluff layer in the intertidal zones since the bottom shear stress exceeds the critical shear stress for erosion. On the other hand, the dominated stabilizing benthos could clearly increase the mass storage in the intertidal zones, as a result of an increase in the critical bed shear stress and decrease in the erosion rates. Moreover, accumulation of fine materials might occur in upper-intertidal zone with combined effects of tides and winds because erosion of fine materials take place in lower zones and the effect of wind waves is not always strong enough to exceed the critical one of the fluff layer.

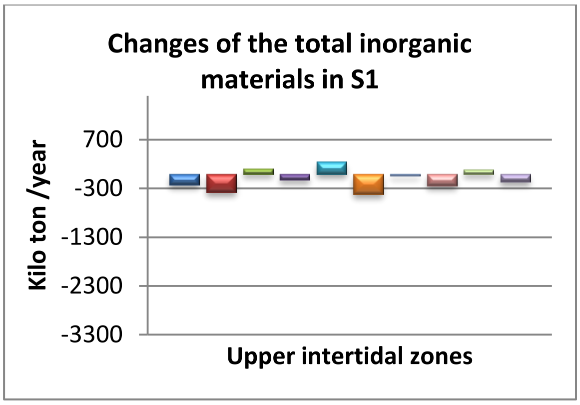

Figure D3, sedimentation to the fluff layer, S1, for Upper-intertidal zone in the Dutch Wadden Sea.

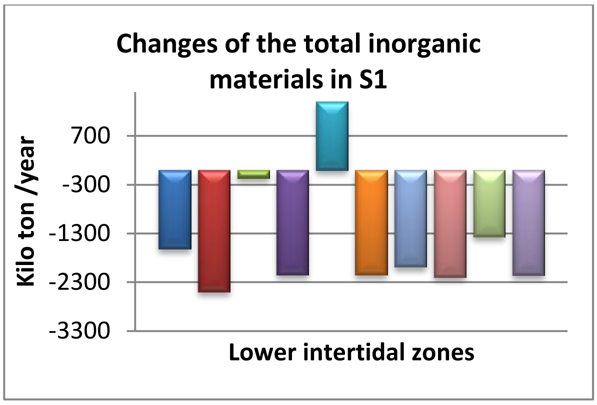

Figure D4, sedimentation to the fluff layer, S1, for Lower-intertidal zone in the Dutch Wadden Sea.

The subtidal and channel zones show always a decrease in the storage of fine materials as illustrated in figures D5 and D6 for different physical processes and biological scenarios. That's because the bottom shear stress by tidal currents only or with wind waves is higher than the critical shear stress of erosion and the maximum erosion of fine materials could happen with the dominant destabilizing influences.

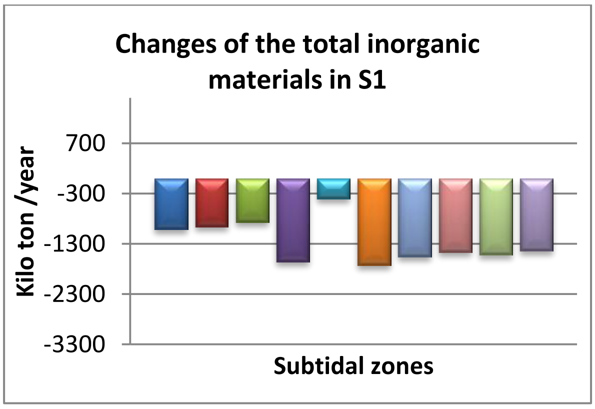

Figure D5, sedimentation to the fluff layer, S1, for Subtidal zone in the Dutch Wadden Sea.

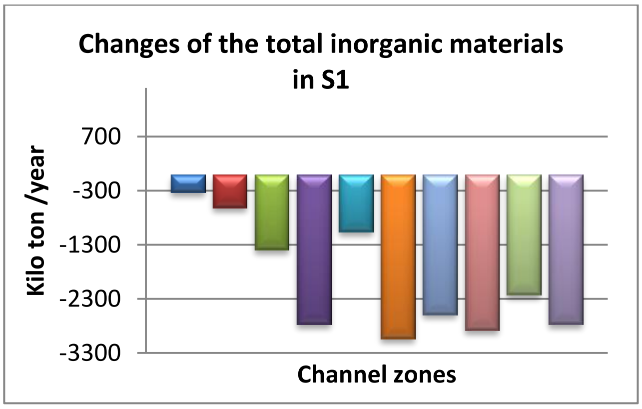

Figure D6, sedimentation to the fluff layer, S1, in the Channel networks of the Dutch Wadden Sea.

It can be concluded that the response of the majority of the fluff layers in different zones showed little similarities with the buffer layers for the long term simulations, for a simple reason that the critical bed shear stress is much lower than the buffer layer and higher erosion rates. Thus fine materials would be easily resuspended from the fluff layer during flood and ebb tides.

Appendix E Results of the rest of basins for the long term

The results of the rest of the basins are illustrated in this appendix, for both the buffer and the fluff layers. The storage of the buffer layers in theses basins, figures E1 through E5, is very sensitive to the fluctuation of the biological activity. That's because theses basins are regarded as regular basins.

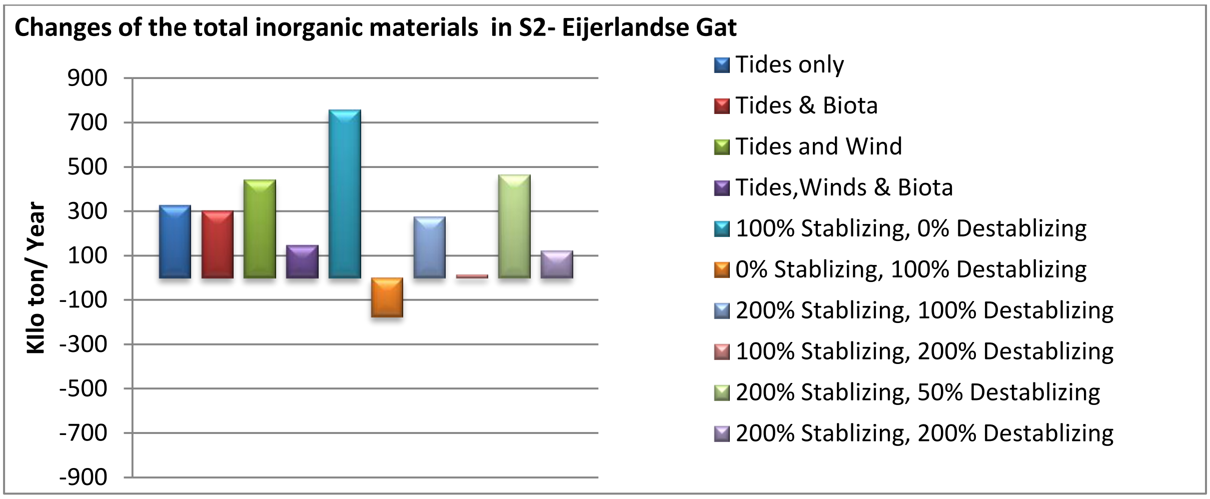

Figure E1, the sedimentation in the buffer layer for Eijerlandse Gat.

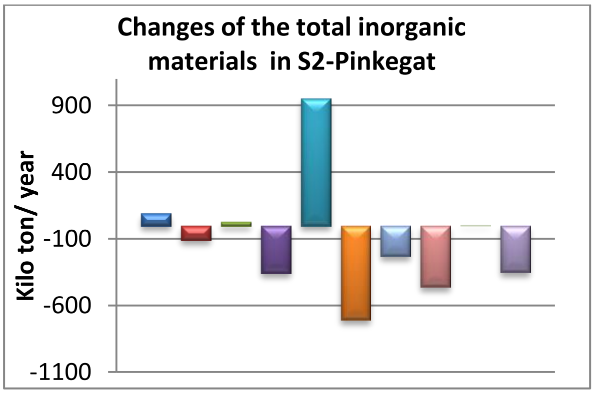

Figure E2, the sedimentation in the buffer layer for Pinkegat.

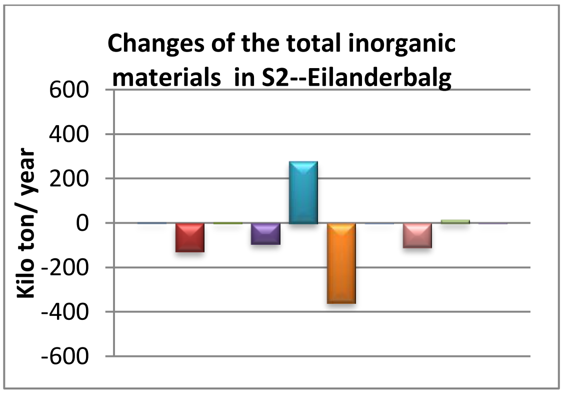

Figure E4, the sedimentation in the buffer layer for Eilanderbalg.

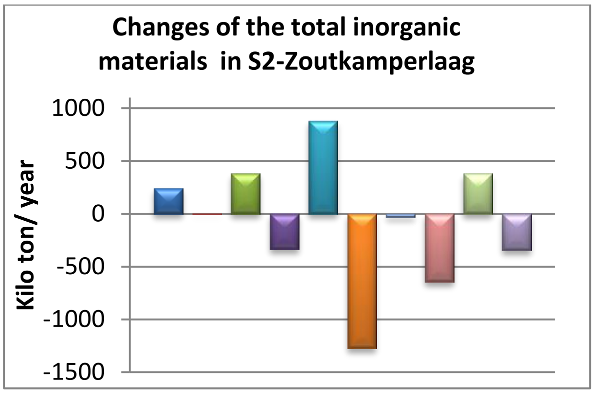

Figure E3, the sedimentation in the buffer layer for Zoutkamperlaag.

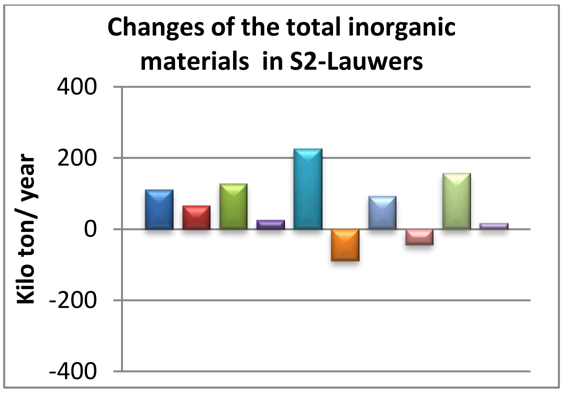

Figure E5, the sedimentation in the buffer layer for Lauwers.

The responses of the fluff layer are unlikely important for basins. In general, the physical processes and a majority of the biological scenarios show a decrease in the storage in this top layer because the deposited fine sediment could be easily eroded through tidal forces as illustrated in figures E6 through E12. However, the only dominated stabilizing influences are responsible for increasing the storage in the top layer in most basins. In contrast to the buffer layer, there is not significant variation in fine sediment storage between deep basin, Marsdiep basin, and other regular basins. That's because the bottom shear stress by tides could exceed the critical shear stress of the top layer.

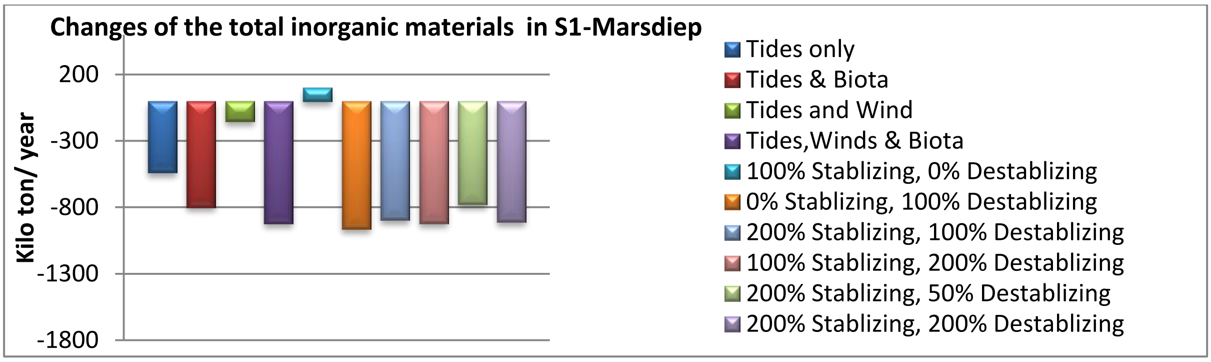

Figure E6, sedimentation to the fluff layer, S1, for the Marsdiep basin.

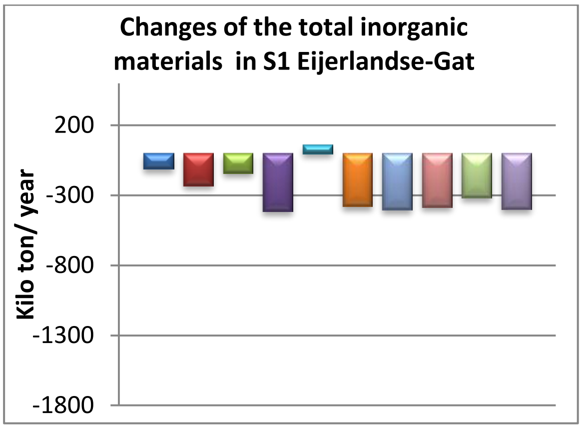

Figure E6, the sedimentation in the fluff layer for Eijerlandse Gat.

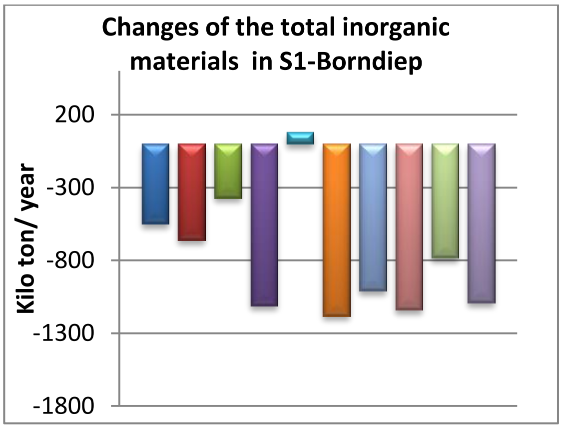

Figure E8, sedimentation to the fluff layer, S1, for the Borndiep basin.

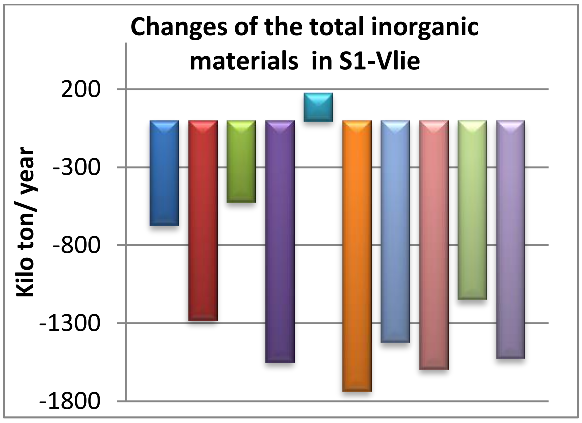

Figure E7, sedimentation to the fluff layer, S1, for the Vlie basin.

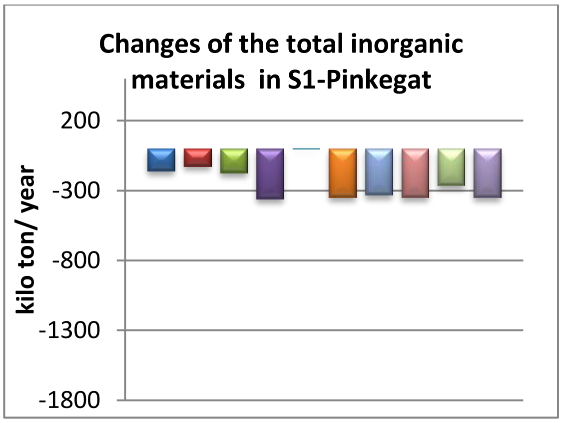

Figure E9, the sedimentation in the fluff layer for Pinkegat.

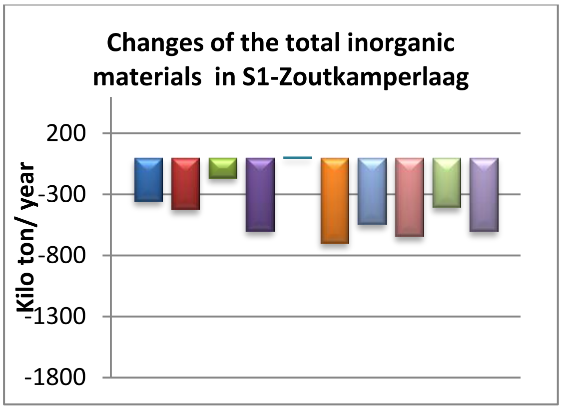

Figure E10, the sedimentation in the fluff layer for Zoutkamperlaag.

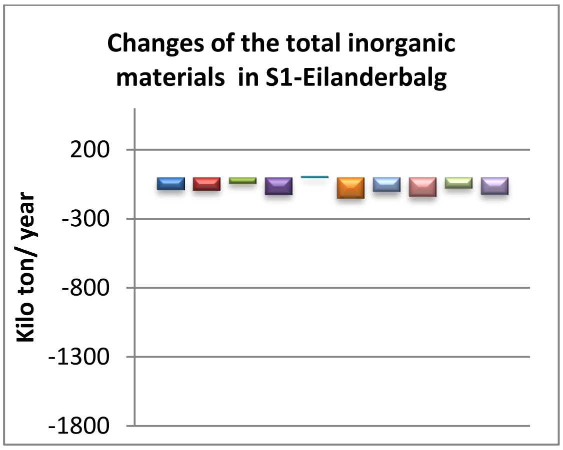

Figure E11, the sedimentation in the fluff layer for Eilanderbalg.

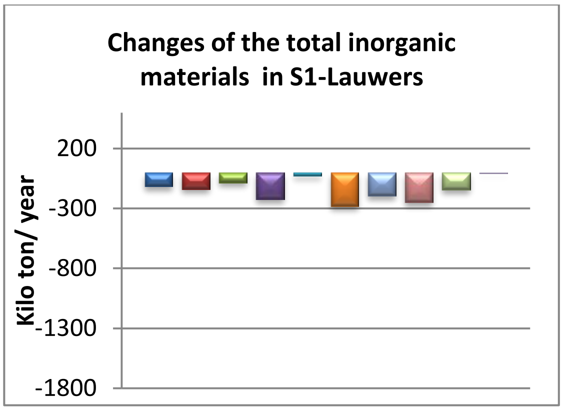

Figure E12, the sedimentation in the fluff layer for Lauwers.

It can be concluded that the hypsometry of the basin is not able to affect the sedimentation of fine materials in the fluff layer comparing with the buffer layer because the bottom shear stress by tidal currents could always exceed the critical beds shear stress for this thin layer.

Appendix F Result of the sediment fluxes between adjacent basins

Figure F1 shows the horizontal import-export sediment fluxes for Vlie basin with the adjacent basin, Marsdiep basin. By comparing with figure4-21, the influence tidal cycle, spring-neap cycle, on horizontal fluxes is not clear in the figure below. Also, it can be seen that the amount of import fluxes to Vlie basin is larger than the export.

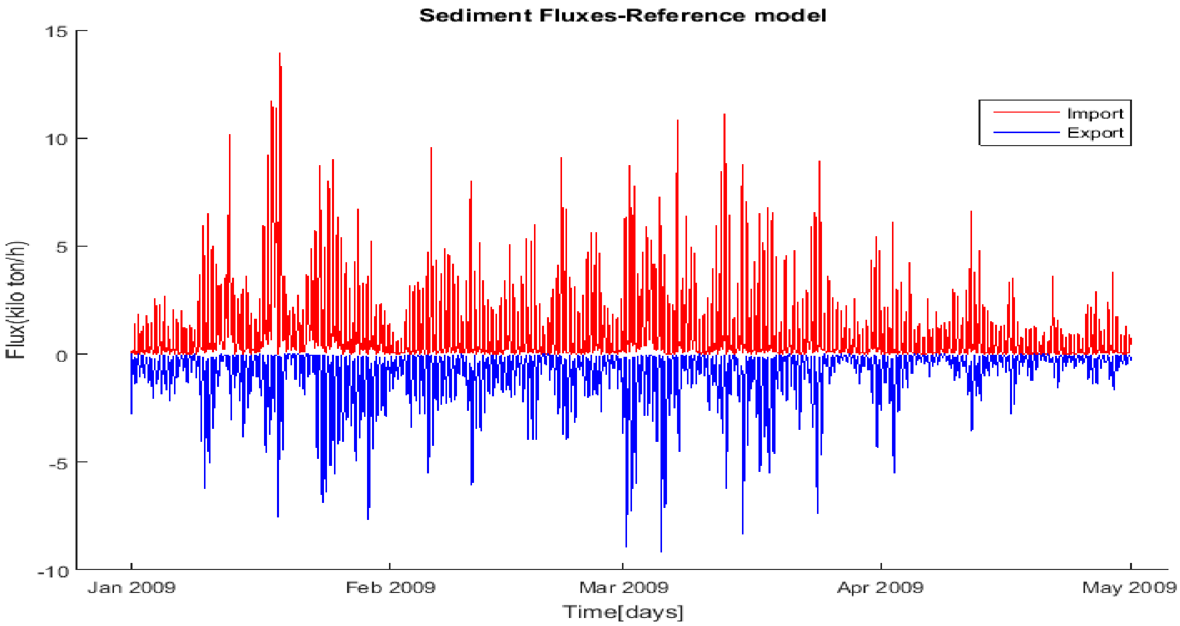

Figure F1, horizontal import-export sediment fluxes for Vlie basin with Marsdiep basin in the reference model.

The biological activity lead to more import of sediment fluxes to Vlie basin from Marsdiep basin, that's because the grazers in Marsdiep basin caused more erosion of bed materials, which might be transported to the Vlie basin by the flow.

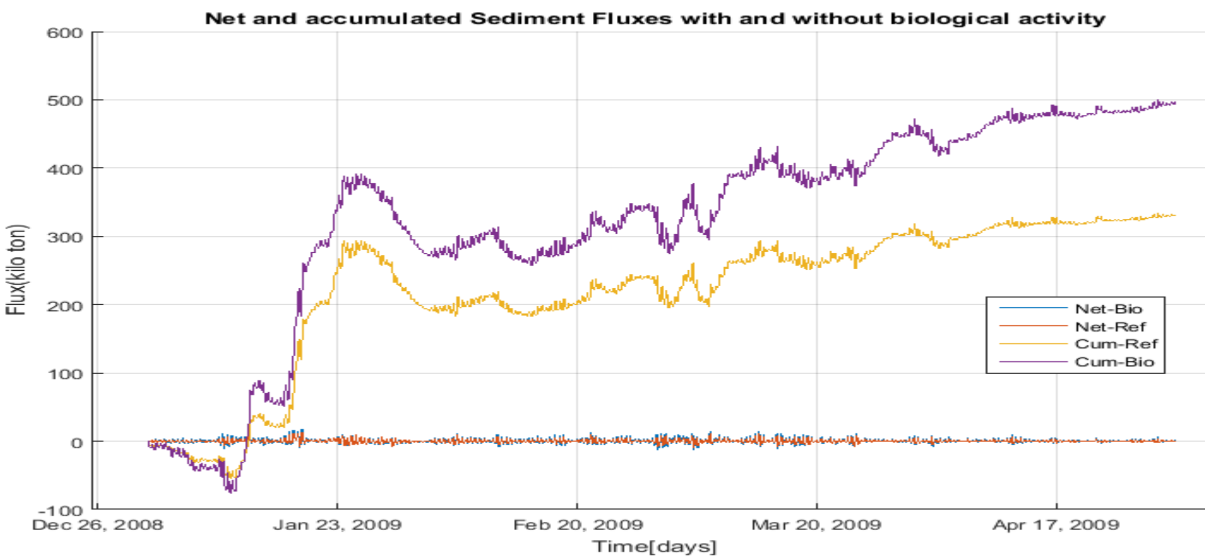

Figure F2, net import-export of fine materials and accumulated sediment fluxes with and without biological activity for Vlie basin with Marsdiep basin.

Appendix G Results without winds effects

This appendix shows the results of different scenarios but without any influences of wind waves, this means the total bottom shear stress of these simulations is only from tidal forces, such as the forces in figures 3-5-a and 3-6-a. These results are the outcomes for 4 months simulations.

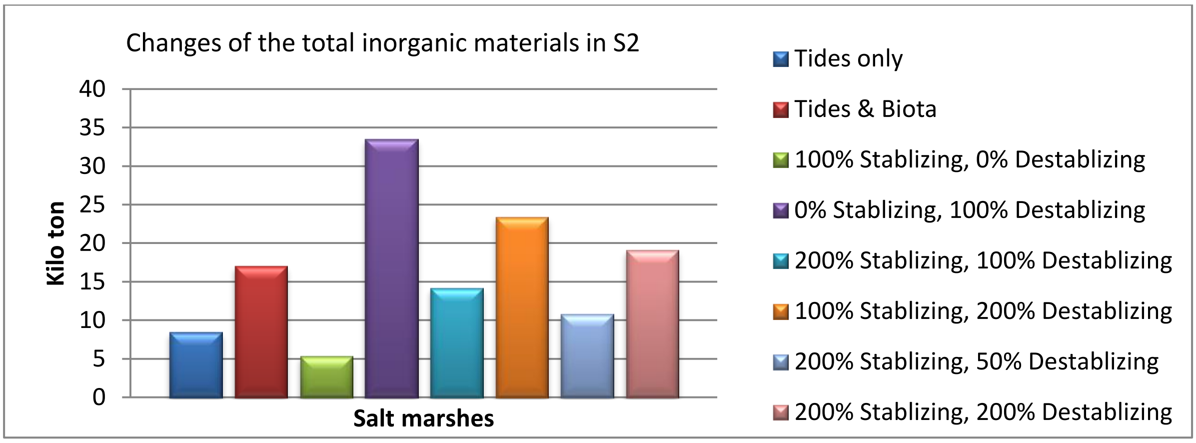

Figure G1, sedimentation to the buffer layer, S2, for Salt marsh zone in the Dutch Wadden Sea.

Compare with Figure D2, the relative sedimentation to the bottom layers of salt marshes zone indicates that the fluff layer could store more settled fine sediments without any impact of wind waves figure G2.

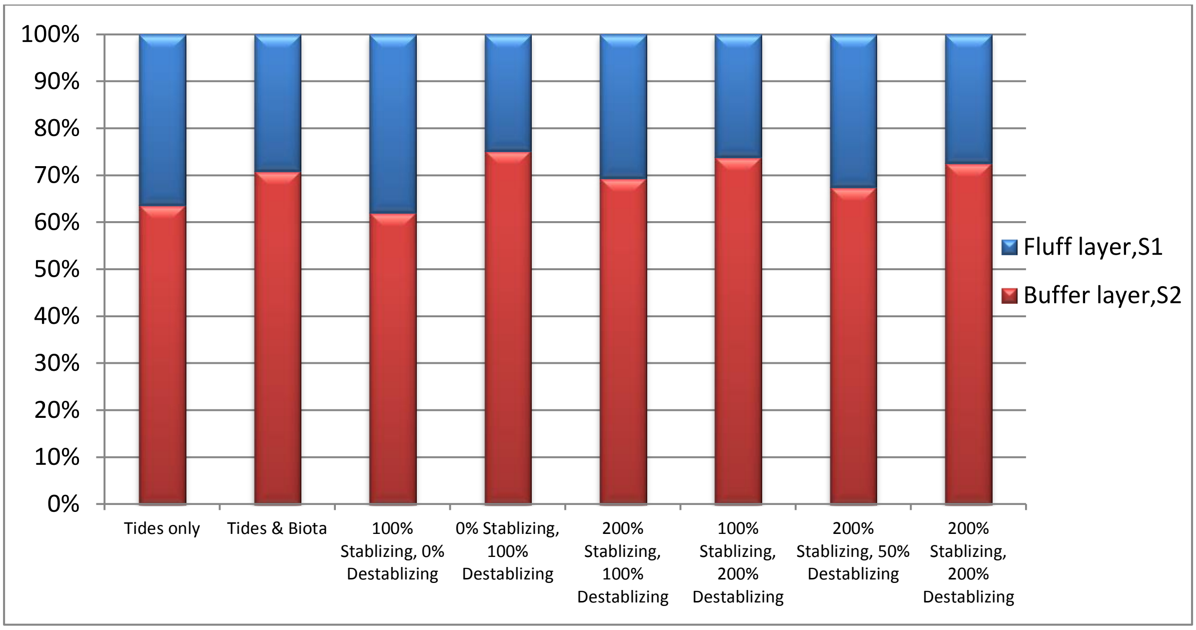

Figure G2, the relative sedimentation to the bottom layers, Fluff layer S1 and Buffer layer S2.

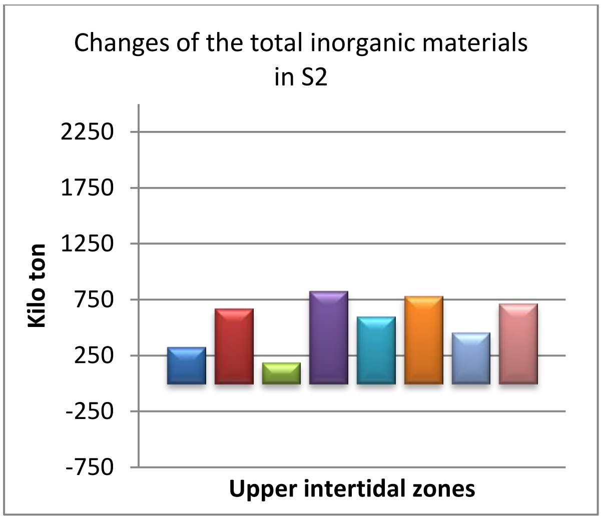

Figure G3, sedimentation to the buffer layer, S2, for Upper-intertidal zone in the Dutch Wadden Sea.

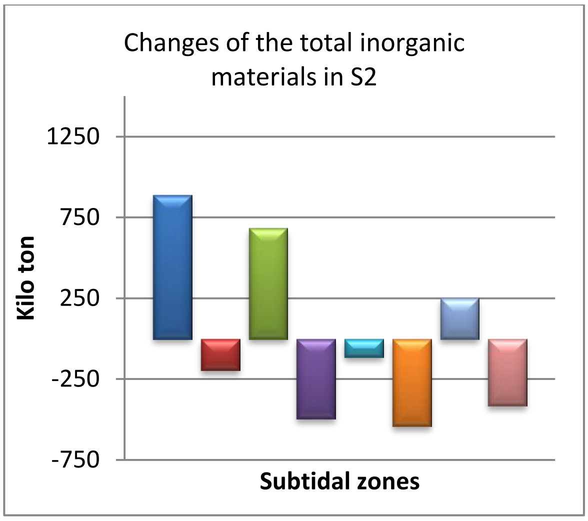

Figure G5, sedimentation to the buffer layer, S2, for subtidal zone in the Dutch Wadden Sea.

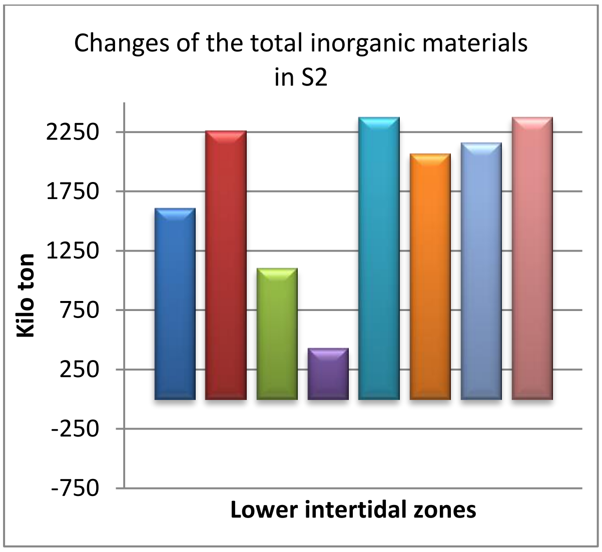

Figure G4, sedimentation to the buffer layer, S2, for lower-intertidal zone in the Dutch Wadden Sea.

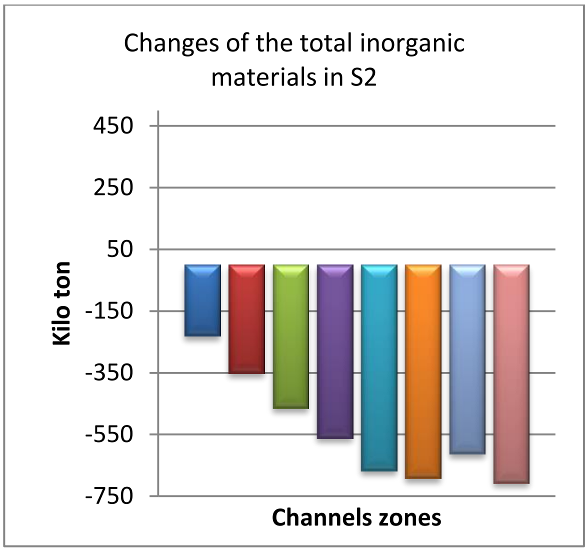

Figure G6, sedimentation to the buffer layer, S2, for channel zone in the Dutch Wadden Sea.