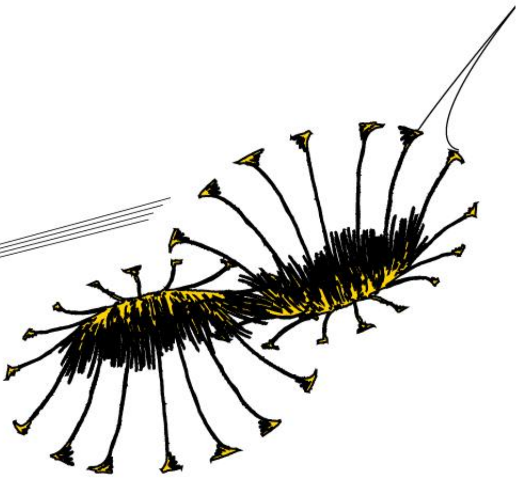
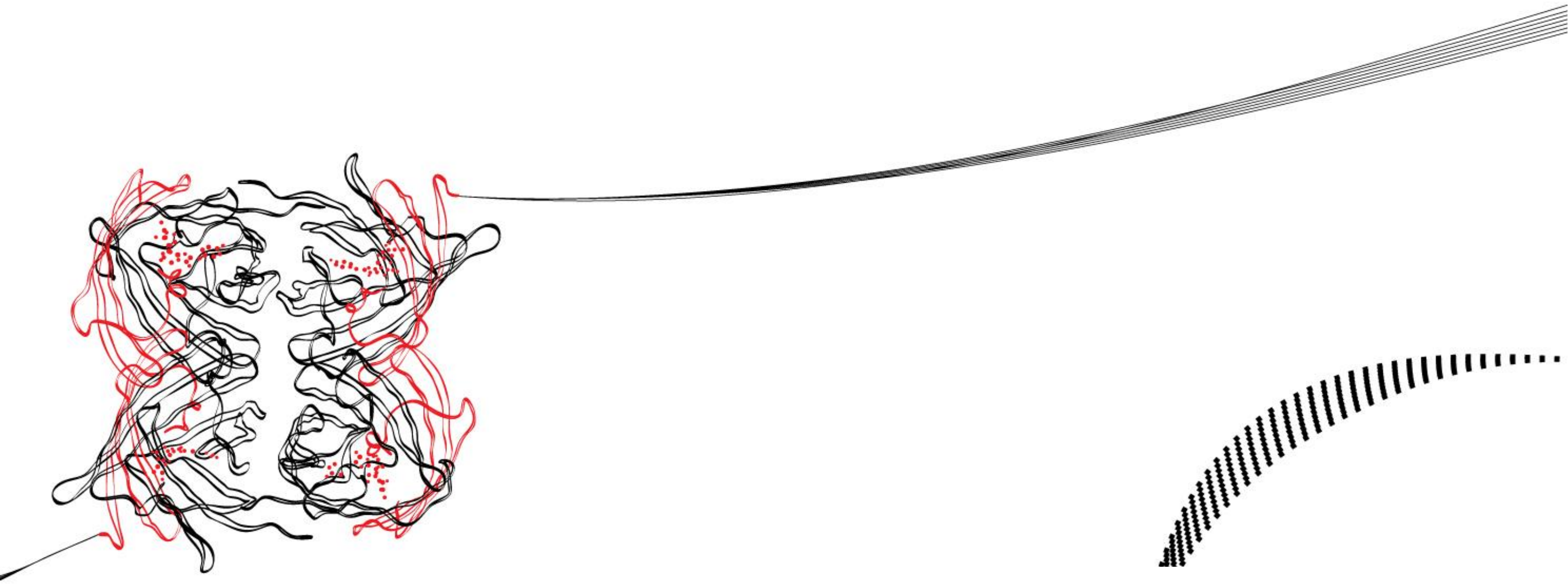
“MODELLING THE INFLUENCE OF SAND-MUD INTERACTION AND WAVES ON SALT MARSH DEVELOPMENT”

Wouter Vreeken





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Modelling the influence of sand-mud interaction and waves on salt marsh development

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PREFACE

This thesis is about modelling the influence of sand-mud interaction and waves on salt marsh development. I made this thesis at Svašek, a hydraulic engineering company located in Rotterdam. During my research I worked with FINEL2D (model developed by Svašek) which increased my modelling skills. In addition, I gained more knowledge about salt marshes and processes influencing salt marsh development.

I would like to thank my supervisors. First I would like to thank Bas van Leeuwen, my daily supervisor at Svašek. Whenever I had questions he was able to answer them. Furthermore I would like to thank him for his enthusiasm during my research. I would also like to thank Bas Borsje, my daily supervisor at University of Twente. He really helped me structuring my research and supported me with suggestions. I would also like to thank Suzanne Hulscher for her critical view during our meetings.

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ABSTRACT

Sea level rise requires innovative solutions in flood protection. Salt marshes could be such a solution because of their adaptive ecological characteristics. Salt marshes are tidally influenced ecosystems between land and sea. They attenuate waves and decrease fetch length. In addition, salt marshes are able to capture sediment and rise in elevation, making it an effective flood protection. The recent interest in salt marshes leads to questions and this thesis therefore analyses the significance of different processes in salt marsh development. This could eventually help in maintenance of current marshes but also in the construction of artificial marshes.

FINEL2D is used for analysing long-term development of salt marshes. FINEL2D is a depth-average numerical model developed by Svašek Hydraulics. With the use of FINEL2D, 100 years of salt marsh development is simulated. The dimensions of the test case are based on Paulinaschor, a relative small salt marsh located in the Western Scheldt, Netherlands. First a simulation is done with sand as only sediment fraction. Then the interaction between sand and mud was implemented in the model. Sand and mud show cohesive behaviour when a certain percentage of mud is present in the soil. This cohesive behaviour leads to higher critical shear stresses. Finally plants were added. Vegetation influences flow velocities as higher plant densities cause more friction. Also growth and decay of vegetation is present in FINEL2D. The simulation with vegetation in combination with sand-mud interaction functioned as reference simulation to compare with adapting processes. Results show that the implementation of mud is essential for a salt marsh environment to arise. Mud leads to significant higher bed levels due to settling lag. Plants establish on locations where no creeks are present. Vegetation determines the creek pattern as plants obstruct flow leading to more creeks which are needed to discharge all water after high tide.

Validation of results showed similarities with Paulinaschor. The height of the marsh platform and the location of the marsh edge correspond well with Paulinaschor but there are also some differences. The simulations showed a marsh edge of about 4 meters high as there is no mudflat. Paulinaschor has an edge of 2 meters high. This difference could be caused by only taking two sediment fractions in consideration. Therefore is recommended to further research the effect of implementing multiple sediment fractions.

The following processes are evaluated: tidal amplitude, mud availability, critical deposition shear stress (continuous deposition), critical mud content (determines when bed is cohesive), settling velocity and maximum bottom slope. The availability of mud determines lateral expansion of the marsh, while tidal amplitudes influence the expansion of the marsh but also the height. Because of high critical shear stresses sediment is able to constantly deposit and this results in an extended marsh towards the channel. The effect of a lower critical mud content was minimal, however, also this simulation showed a slight expansion compared to the reference simulation. When a low settling velocity for mud was implemented, mud was not able to settle and a small salt marsh arose. Nevertheless, the simulation with low settling velocities was the only simulation which shows higher mud percentages with distance from the channel. With a maximum bottom slope is meant that when a certain slope is reached, erosion occurs according to avalanche formulations. In this simulation a maximum bottom slope of 0.5 is applied. This results in erosion of the marsh edge. All simulation show establishment of plants over the entire marsh platform except for locations where creeks are present.

Subsequently one-day storm events are modelled on the bed level, mud content and plant density obtained from the reference simulation. These storm events caused erosion of the marsh

edge. Plants were not able to survive the storm. The effect of waves on plant establishment and decay is not extensively studied yet, and therefore this result cannot be validated.

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List of symbols

C_{dv}	Plant drag coefficient	[-]
C_{fb}	Bed-friction coefficient	[-]
E_{mud}	Erosion rate of mud	$[m^2/s]$
M_c	Erosion coefficient cohesive	$[kg/m^2\ s]$
M_{nc}	Erosion coefficient non-cohesive	$[kg/m^2\ s]$
T_A	Morphological adaptation time	$[s]$
c_{eq}	Equilibrium concentration	$[kg/m^3]$
d_{50}	Median grain size	$[m]$
n_b	Plant density	$[stems/m^2]$
p_m	Mud content	[-]
w_s	Settling velocity	$[m/s]$
ρ_s	Dry bulk density of sediment	$[kg/m^3]$
ρ_w	Density of water	$[kg/m^3]$
τ_b	Bed shear stress	$[N/m^2]$
τ_c	Critical bed shear stress	$[kg/m^3]$
τ_s	Critical sedimentation shear stress	$[kg/m^3]$
h	Water depth	$[m]$
C	Chézy coefficient	$[m^{\frac{1}{2}}/s]$
c	Sediment concentration	$[kg/m^3]$
g	Acceleration of gravity	$[m/s^2]$
k	Vegetation stem height	$[m]$
u	Depth-averaged velocity	$[m/s]$
ϵ	Porosity	[-]
ϕ	Vegetation stem diameter	$[m]$

1 INTRODUCTION

The Dutch have a long history of defending against water. Because 26% of the Netherlands is below mean sea level this challenge is still a hot topic. For a prolonged period the policy was to construct hard solutions to defend land from water. Nowadays interest also goes out to dynamic measures, especially ecological measures. The study of “ecological engineering” attempts to integrate ecology and engineering into flood-protecting solutions .These measures promise cost-effectiveness and sustainability. Furthermore there is a need for solutions which minimize human impact on ecosystems (Borsje et al., 2011). These solutions can be implemented in two ways: the first is by adapting current hard structures, the second by implementing entirely new ecosystems. Ecosystems are locations where living organisms and non-living components interact with and influence each other. Systems which are able to trap sediments can therefore be considered ecosystems. Examples of these kinds of ecosystems are salt marshes, mussel beds and mangroves.

Constructing salt marshes is a good example of ecological flood protection and anti-erosion measure. Salt marshes are coastal ecosystems which are located along the sea and are regularly flooded by salt water (see figure 1). In general, salt marshes inundate during flood while during ebb tide the marsh dries. During flood sediments are transported towards the salt marsh. When flooded, flow velocities decrease and sediments are able to settle. The settlement of sediments leads to increased bed levels on the marsh. This positively influences wave attenuation (Möller & Spencer, 2002). Furthermore, salt marshes also tend to expand laterally and thereby decrease the fetch of waves (Bouma et al., 2005).

FIGURE 1 LAND VAN SAEFTINGHE, SALT MARSH IN THE WESTERN SCHELDT, NETHERLANDS

In the Netherlands most salt marshes are located in the Scheldt estuary and the Wadden Sea. These salt marshes have developed naturally over tens of years. There are already some studies which determine the effect of different processes influencing salt marsh development. For example Temmerman (2005) did a study on the relative impact of different processes on the spiral flow and sedimentation pattern in a tidal marsh landscape. He found that vegetation has the strongest control on flow routing and spatial sedimentation pattern during single inundation events. However, he did not study the long-term effect of vegetation. In addition, no study has yet been undertaken which combines the effect of multiple sediment fractions with the effect of vegetation-related processes.

New insights in salt marsh development could provide recommendations towards salt marsh maintenance and could also be useful in constructing artificial marshes. This thesis can contribute to defining the influence of processes in the development of salt marshes, which improve the construction of artificial salt marshes.

1.1 Problem definition

Many processes affect salt marsh development. Hydrodynamics cause marshes to inundate, morphological process lead to sedimentation of marshes and vegetation influences salt marsh patterns. These processes also influence each other which make salt marshes complex ecosystems. In order to evaluate different processes, FINEL2D is used. FINEL2D is a depth-average numerical model developed by Svašek Hydraulics and already has a lot of these processes included (Dam et al., 2014). However, the effect of interacting sand and mud fractions in combination with vegetation-related processes on the development of salt marshes has not yet been studied. Modelling marsh development can contribute to understanding the different processes. Models are capable of assessing the influence of different processes by isolating the effects of different input.

In the past years there has been an increase in knowledge about modelling salt marsh development. Examples of these advances are the incorporation of hydraulic roughness induced by vegetation (Baptist, 2005; Klopstra et al., 1997) but also vegetation dynamics (growth and decay of vegetation) (Balke et al., 2011; van Wesenbeeck, 2007).

Temmerman (2005) has conducted a study on the relative impact of different processes on the spiral flow and sedimentation pattern in a tidal marsh landscape. Attema (2014) extended the study of Temmerman by including the window of opportunity model developed by Balke (2011). The window of opportunity model simulates growth and decay of vegetation. Attema concludes that in a system where vegetation is leading the morphological development bio-geomorphological modelling (simulating of vegetation establishment and growth in interaction with geomorphological- and hydrodynamic processes) is very important. Attema undertook a case study on the “Land van Saeftinghe”, a salt marsh located in the Western Scheldt. Although the model was able to simulate the major creeks system and lateral extension, he still found some differences between the model and the actual development of the marsh. The model was not capable of predicting the exact bed level elevation. Attema states that this difference in bed level elevation could be the result of taking only one sediment fraction into account. For the “Land van Seaftinghe” case study an unrealistic fine sand fraction was used causing sand to settle on high locations. The grain size of mud is lower and therefore implementing mud could tackle this problem. Mud in combination with sand can form a cohesive mass which makes the bed hard to erode. More about the interaction between sand and mud is presented in chapter 2.2.

1.2 Research objective

The objective of this report is to evaluate the contribution of hydrodynamic, morphological and vegetation processes on the overall development of salt marshes. “Overall development“ is understood as the development from a flat bed towards a salt marsh environment. A novel aspect of this study is modelling salt marsh development with influences of plants as well as the interaction between sand and mud. The development will be evaluated based on bed level, mud content and vegetation. In addition an initial step towards modelling salt marsh development in combination with storm events is executed.

1.3 Research questions

The overall aim of this thesis is to evaluate the importance of different processes contributing to salt marsh development. To reach this goal the following sub questions are addressed.

1. Which processes contribute to salt marsh development according to literature?
2. How can sand-mud interaction be taken into account when simulating salt marsh development?
3. How can the influence of storms on salt marshes be modelled?
4. How can the marsh model be validated?
5. What is the influence of the following processes on salt marsh development?
    a. Sand-mud interaction
    b. Vegetation
    c. Tidal amplitude
    d. Mud availability
    e. Continuous deposition
    f. Settling velocity mud
    g. Critical mud content
    h. Maximum bottom slope
    i. Storms

1.4 Report outline

This report is structured as follows: chapter 2 provides theory of this research. First a brief description of salt marshes is presented followed by the interaction of mud and sand. Then processes influencing salt marsh development are described. Chapter 3 provides the set up of a test model. In this chapter the model area, boundary conditions and input variables are described. Furthermore this chapter provides information of different processes which will be examined. The last paragraph of chapter 3 shows how simulation results are analysed.

Chapter 4 provides results and validation of simulations stepwise adding processes (sand-mud interaction and vegetation). Chapter 5 presents a sensitivity analysis of adapted processes (for example an increase in tidal amplitude or decrease in mud availability). Subsequently chapter 6 contains a first step towards modelling salt marsh development subject to storms. The last chapters (chapter 7 and 8) cover discussion and conclusion respectively.

2 SALT MARSH DYNAMICS

This chapter provides a definition of salt marshes and processes affecting marsh development. Also a description of sand-mud interaction is provided.

2.1 What are salt marshes?

Salt marshes are tidal-influenced ecosystems usually located at the seaward side of the dike. Salt marshes only occur at low-energy shorelines in temperate and high latitudes (Allen & Pye, 1992) and are formed on sheltered locations where fine sediments can settle (Fagherazzi et al., 2012). During high tide the marsh becomes inundated while during ebb tide the marsh remains dry. Therefore salt water enters the marsh during high tide and vegetation located on the marsh has to withstand salty inflow. This unique environment makes salt marshes one of the richest ecosystems in terms of productivity and species diversity (Tonelli et al., 2010). Typical locations of salt marshes are estuaries, shallow bays and landward sides of barrier islands. Salt marshes can also arise at large rivers and deltas, but only when enough sediment is available for formation and evolution.

Salt marshes consist of multiple sections with each their own characteristics considering inundation frequency and vegetation species. Lower marshes, located at the sea boundary inundate every flood tide and consist of other plants than high marshes, which only inundate during above average high tides. Figure 2 shows a cross-section with different sections of a salt marsh with their corresponding vegetation types.

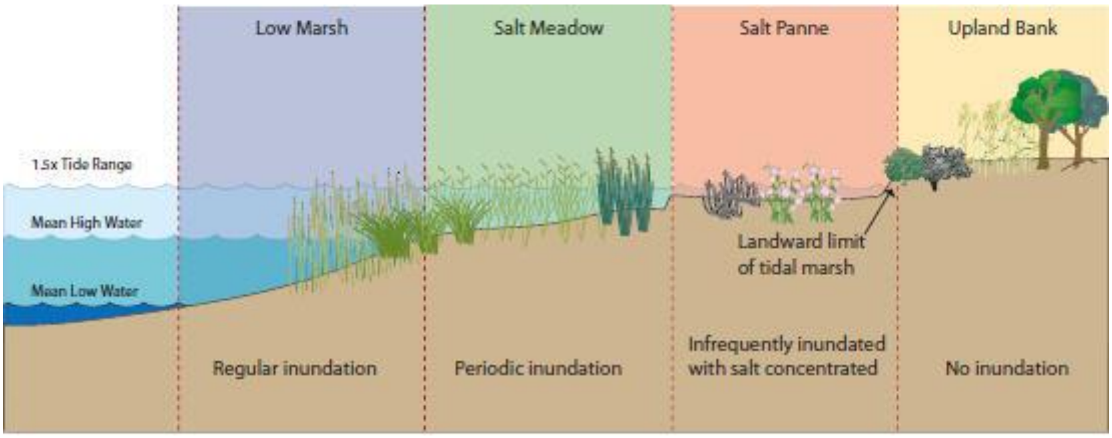

FIGURE 2 CROSS-SECTION SALT MARSH SHOWING DIFFERENT SECTIONS

The amount of plant species which are able to establish in salt marsh conditions is little (Rand, 2000). The most common marsh plants are the Salicornia Europaea and Spartina plants, commonly known as cord-grass. These plants are called pioneer species. Pioneer species are plants which are the first to establish on locations where no other has established yet. Pioneer plants stabilize sticky mud but also carry oxygen into the mud. Examples of plant species which establish after pioneer vegetation are lavenders and rushes. Therefore the lower marsh mainly consists of Spartina and Salicornia vegetation and heading landwards species like lavenders and rushes are more observed. All vegetation species mentioned in this paragraph are pictured in figure 3.

FIGURE 3 DIFFERENT SALT MARSH VEGETATION UPPER LEFT: SPARTINA ALTERNIFLORA. UPPER RIGHT: SALICORNIA. BOTTOM LEFT: LAVENDER. BOTTOM RIGHT: RUSHES

After pioneer vegetation has established, sedimentation occurs. Erosion of marsh edges are generally linked to erosion by wind waves (Van De Koppel et al., 2005; Möller, 2006; Möller et al., 1999). Most marshes have a steep scarp dividing salt marsh and tidal flat (Mariotti & Fagherazzi, 2010; Van De Koppel et al., 2005). Because salt marshes are constantly influenced by tides and wind waves they change depending on sedimentation rates and wave erosion (Fagherazzi et al., 2007). Equilibrium in bed levels for waves is reached when the energy generated by wind action equals dissipated energy. However, the most important factor in stability of a dynamic equilibrium is the availability of sediment (Fagherazzi et al., 2006). If sediment availability increases, more sediment is deposited resulting in higher bed levels.

2.2 Sand-mud interaction

Whether a particle is classified as mud or sand depends mostly on grain size. Grains are classified as sand when their size ranges between 2 mm and 62.5 μm. The grain size of mud particles is everything smaller than 62.5 μm. The influence of mud in combination with vegetation on a developing salt marsh is not extensively examined yet. However, the contribution of mud on the development of salt marshes is quite significant. Mud affects bed levels and thereby water levels and vegetation patterns. Before addressing how mud is introduced in the model, the contribution of mud in salt marsh development is qualitatively assessed.

In general, mud especially contributes to the upper marsh. This is because the settling velocity of particles increases with grain size. In tide-dominated areas coarse grain sizes are observed at the sea boundary while finer grain sizes are found more landward (Amos, 1995; Woodroffe, 2002). Sand is mostly deposited at the boundary because here flow velocities rapidly decrease and sand settles immediately while finer sediments need even smaller velocities and more time due to settling lag (De Groot et al., 2011; Détriché et al., 2011). Fine sediments require thus low flow velocities which occur on high bed levels. Because fine sediments are deposited on high locations and coarse grains on lower bed levels a sorting effect arises (Détriché et al., 2011).

Van Ledden (2003) analysed the grain size distribution of the Western Scheldt. The median grain size in the Western Scheldt is 157 μm. A grain size of 157 μm is classified as fine sand. Although the median grain size of the Western Scheldt corresponds with fine sand, there is a relative large percentage mud present in the soil (44.3%). Although these values differ locally it tells us at least that there is plenty of mud available which can influence salt marsh development.

A comprehensive process-based model in which mechanisms are brought together to explain large-scale sand-mud segregation did not exist until van Ledden (2003) developed a method in which the interaction between sand and mud is described. High percentages of mud have consequences on deposition and erosion. When 5% to 10% of clay (median grain size between 1 μm and 4 μm and therefore identified as mud) is present in the soil it becomes cohesive. A cohesive bed is more difficult to erode due to electrostatic forces between smaller mud particles. Sand can be “trapped” in such a cohesive bed. A cohesive bed leads to a higher critical bed shear stress and therefore larger velocities are needed for erosion. To determine whether the bed is cohesive or not Van Ledden (2003) developed a method based on a critical mud content. When a certain percentage of mud is present in the soil, the bed becomes cohesive. In the Netherlands generally 30% of mud is used as a transition value from a non-cohesive to cohesive bed (Van Ledden, 2003).

The cohesiveness of soils affects accretion rates because erosion is less likely to occur. The highest accretion rates are observed at the salt marsh boundary as here the frequency of inundation is largest (Détriché et al., 2011). Towards the upper marsh accretion rates decrease as this part of the marsh is less inundated than the boundary. Zwolsman et al. (1993) analysed the accretion rates for the Western Scheldt marshes and found values of approximately 1.3-1.7 cm/year for Land van Saeftinghe and for Emanuelpolder 0.84-0.90 cm/year. These salt marshes also experience cohesive behaviour of the soil. However, they did not quantify this effect. The implementation of sand-mud into FINEL2D is described in appendix 1.

2.3 Processes influencing salt marshes

In figure 4 different processes affecting salt marsh development are presented in a schematic way. The four main processes are hydrology, vegetation, waves and sediment transport plus bed level update. The interaction between sand and mud is classified as sediment transport. The arrows in the figure indicate that these processes, next to affecting salt marshes, also affect each other. In this chapter vegetation-related processes are described. The numbers in the figure indicate the paragraph in which the specific interaction is discussed.

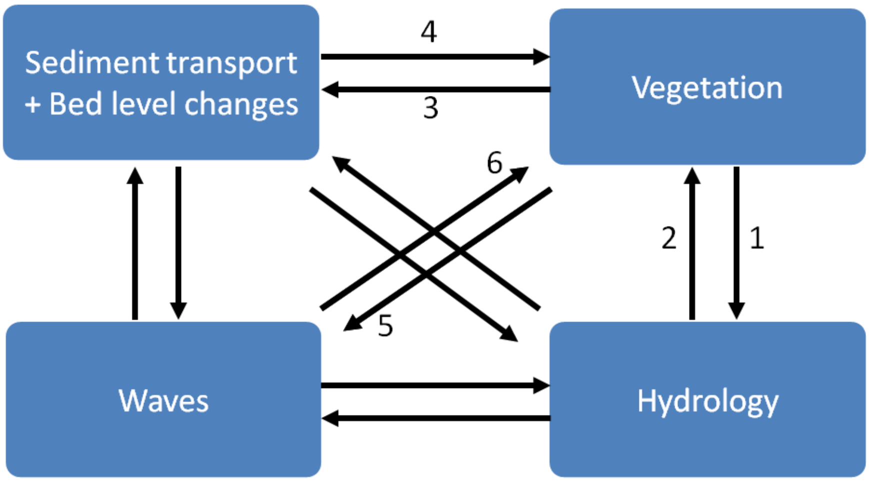

FIGURE 4 PROCESSES AFFECTING SALT MARSH DEVELOPMENT

2.3.1 Vegetation → hydrology

There has been a lot of research on the effect of vegetation on water-influenced ecosystems in the last few years. These studies resulted in the set up of different vegetation models. Vegetation influences the development of salt marshes in a few ways. One of these ways is the influence on flow velocities. Dense vegetation lets flow velocities decrease. This reduction in flow velocity depends on the density, height and stem diameter. The effect of plants on flow velocities is quantified in the hydraulic roughness. Figure 5 shows a representative situation of the effect of vegetation on velocities in the water column.

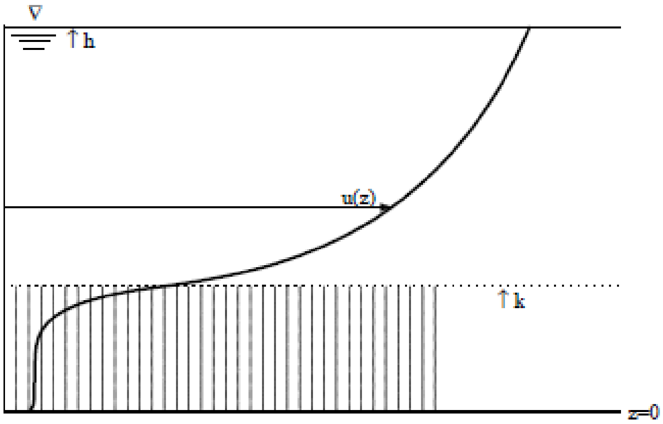

FIGURE 5 VELOCITY PROFILE OF SUBMERGED VEGETATION. K IS VEGETATION HEIGHT, U(Z) IS VELOCITY AND H IS WATER LEVEL

There are different methods which translate vegetation to a representative hydraulic roughness. In the Netherlands there are two methods which are used. The first method is developed by Klopstra et al. (1997). This method requires the following characteristics of vegetation to calculate the hydraulic roughness: stem diameter, stem density and vegetation height. The other method is set up by Baptist (2005). The method of Baptist requires the same vegetation characteristics but is a bit less complex. The main difference between the method of Klopstra and Baptist is that the method of Baptist is made dependent on the turbulence intensity near the bed. The underlying idea of this assumption is that the shear stress profile near the bed is not so much affected by drag forces of sediment particles alone, but by a combination of drag forces of sediment and vegetation. Although these methods differ from each other in calculating the hydraulic roughness, their principle is the same. When stem diameter increases, the incoming wave or current experiences a bigger friction surface. This leads to a larger wave or current energy dissipation. The stem density of plants influences waves and currents in the same way as the stem diameter. Vegetation height also affects the flow as velocity through and over vegetation differs from a normal velocity profile.

2.3.2 Hydrology → vegetation

Besides the effect of vegetation on hydrodynamics, there is also an effect reverse. This effect of hydrodynamics on vegetation is called “vegetation dynamics”. Hydrodynamic properties of a flow determine whether vegetation establishes or decays. In past recent years this effect got more attention which resulted in different methods. In this chapter two of these methods are discussed.

The first method is the so-called population dynamics method by Temmerman (2007). The principle of this method is that vegetation can grow everywhere but due to high flow velocities or long inundation periods plants could also decay. The establishment of plants is described by a possibility that favourable conditions exist. The possibility for these conditions to occur is based on soil conditions, temperature and the dispersal of seeds or rhizomes. Once established, stem density grows according to a logistic growth function depending on the current density and maximum plant density. The last stage is lateral expansion of vegetation. By lateral expansion of vegetation is meant that vegetation is able to expand to surrounding locations. The expansion rate depends on the difference in density between two adjacent locations and growth rate.

The other method is called the window of opportunity model by Balke et al. (2011). The biggest difference between the population dynamics model and the window of opportunity model is that vegetation in the window of opportunity model can only establish when favourable conditions are present while in the population dynamics model vegetation can establish everywhere and afterwards is analysed whether this location fulfils favourable conditions for vegetation to further develop.

Before vegetation establishes and develops into permanent vegetation in the window of opportunity model, it has to withstand three stages. The first stage requires an inundation free period. When this requirement is fulfilled, vegetation can establish based on a stochastical function. In the second stage the root system develops. For this stage to happen a relative calm inundation period is required. This stage is important for vegetation to develop their roots and thereby increase their resistance. After the root system reaches maturity, seedlings need to survive extreme energy events like spring tide or storms. When seedlings also survive this stage, stem density grows and vegetation expands according to the same principle as in the population dynamics model.

The window of opportunity model does not consider any decay processes, but monitors the conditions of existence of vegetation. These conditions are specified in terms of inundation period and bed shear stresses. When one of these conditions is not met, vegetation decays.

Attema (2014) compared these two vegetation dynamics methods and concluded that the outcome does not differ significantly. However, the window of opportunity model is better in describing the actual development of vegetation as in this model plants can only establish on locations where conditions are favourable whereas in the population dynamics model vegetation establishes everywhere and afterwards is analysed whether the conditions are favourable. Because the development of vegetation is better described by the window of opportunity model, this method is used in this research. The implementation of this model is described in appendix 1.

2.3.3 Vegetation → sediment transport + bed level update

Another aspect of vegetation is the ability to trap sediments. The amount of sediment that is trapped depends on the surface roughness of stems and leaves (Yang, 1998). When currents and waves flow through plants, part of the energy is dissipated by stems and leaves of vegetation. This results in a decrease in velocity and wave height. This decrease in velocity and wave height affects the capacity of water to carry sediment and thereby deposition rates.

In addition to stems and leaves, sediment entrapment also depends on suspended sediment concentrations and water depth (Li & Yang, 2009; Mudd et al., 2004). Suspended sediment concentrations determine the amount of sediment available for entrapment. Water level relative to the bed determines the frequency, duration and depth of submerged plants. A lower bed level leads to a higher frequency and duration of tidal submergence, which leads to an increasing amount of deposition. The relative importance of bed levels compared to the effect of vegetation properties in trapping sediments is already studied (Li & Yang, 2009). This study shows that the bed level is relatively more important for trapping sediments by vegetation than vegetation characteristics. The overall contribution of sediment trapping by vegetation to the total deposition rate differs throughout different studies. Some studies state that 50% of the deposition in salt marshes is explained by vegetation while other studies suggest contributions of 10% or less (Li & Yang, 2009). The overall contribution of vegetation is thus uncertain and depends on location specific characteristics

Vegetation influences the stability of the soil in two ways: through hydrological effects and mechanical effects (Chok et al., 2004). Hydrological effects involve evapotranspiration of water from the soil through plants. Evapotranspiration by plants reduces the amount of water in the soil resulting in higher soil shear strength. Shear stresses are also affected by mechanical effects of plants. The density and tensile strength of the roots contribute to the ability of the soil to resist shear stresses. The increasing stability of the soil is only indirectly modelled as the hydraulic roughness increases by plants and therefore the soil becomes more resistant for shear stresses. However, these equations do not include root density, tensile density by roots and change in porosity of the soil. The question remains how big the influence is of these processes. A new study has to be set-up in order to quantify this effect.

2.3.4 Sediment transport + bed level update → vegetation

Large erosion rates cause roots to be exposed to the surface. Exposure of roots leads to decreased plant stability (Osterkamp et al., 2012). In addition, erosion also leads to a decrease in water and nutrient uptake from plants and thereby reduces their vitality. This reduction in vitality is caused by dieback from a cellular plant tissue which is responsible for creating new cells (Carrara & Carroll, 1979).

This effect is not implemented in the model. However, large erosion rates most come hand in hand with high shear stresses. Decay by high shear stress is present in FINEL2D. Although low erosion rates over a long time span could cause roots to be exposed to the surface. This would lead to wash out of plants.

2.3.5 Vegetation → waves

Vegetation dissipates waves due to the morphology, stiffness and length of vegetation (Houwing et al., 2002). Not only the characteristics of plants determine the dissipation of wave energy, also wave properties are important. However, the density and height of plants contribute the most to wave dissipation.

2.3.6 Waves → vegetation

In the window of opportunity model, waves are not included. However, there is a model which includes the effect of waves on vegetation. Vegetation damage by waves is assumed to be a linear function of the slope in sediment elevation and a conversion constant (Koppel et al., 2005). The slope in sediment elevation is important for the damage by waves because the slope determines the length and height of exposure.

In this study, the effect of waves is implemented by adapting the window of opportunity model. In the current window of opportunity model only current-related bed shear stresses are considered. This is adapted in the model by adding the bed shear stress induced by waves. For the exact implementation of waves in FINEL2D is referred to chapter 4.5.

3 MODEL SET-UP

3.1 Model description

As already stated in the problem definition, the modelling software primarily used in this thesis is FINEL2D (FINite Element 2Dimensional). FINEL2D is able to simulate flows in rivers, estuaries, lakes and coastal waters. Because FINEL2D contains a robust procedure for drying and flooding of tidal flats, it is especially suited to model the interaction between flow and morphological characteristics in estuaries.

The biggest difference between other software packages and FINEL2D is that the model domain is divided into triangles instead of rectangles. These triangles are called elements. The element size can be specified beforehand. In this way modelling time can be adapted and more detail can be applied on specific locations of interest. The shallow water equations are then solved for each element.

In FINEL2D there are four sorts of model types. Each model type corresponds with a specific calculation. FINEL2D is able to compute flow, flow and mud, flow and sand and flow including the interaction between sand and mud. The latest development in FINEL2D is the introduction of vegetation effects. By turning on the plant switch the effect of vegetation on the hydraulic roughness can be analysed. Also the effect of vegetation dynamics (growth and decay) can be modelled.

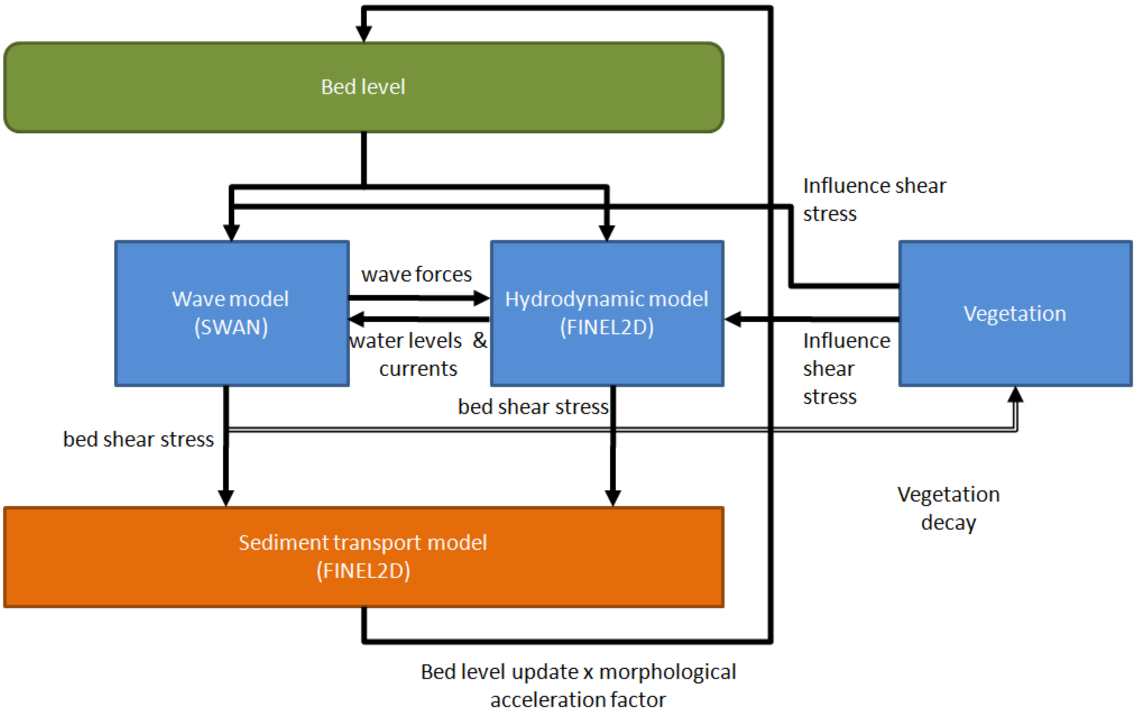

FIGURE 6 SCHEMATIC OVERVIEW OF FINEL2D

Figure 6 shows how FINEL2D is set-up. An initial bed level is used as input. Subsequently FINEL2D calculates hydrodynamic forces. The hydrodynamic model calculates flow velocities, water depths, roughness values etc. These values are converted into bed shear stresses. With the use of bed shear stresses sediment transport is calculated. In this module also the deposition and erosion rates are determined. Because plants affect flow velocities, a factor derived from a variety of vegetation characteristics influences the bed shear stress used in the sediment transport module. In addition, hydrodynamic conditions (inundation time and bed shear stress) are constantly monitored to assess whether conditions are favourable for plants to establish, develop or remain present. Once not favourable, vegetation decays.

To reduce simulation time, a morphological acceleration factor is used. The erosion and deposition rates calculated in the sediment transport mode are multiplied by this factor. This means that when for example a hydrological time step of 5 seconds is simulated, a morphological acceleration factor of 25 results in a bed level update of 125 seconds. This is an effective and simple way of decreasing simulation time.

After the deposition rates and erosion rates are multiplied by the morphological acceleration factor, the bed is updated and the cycle starts over again as the new bed has consequences for the hydrodynamic model. The implementation of sand-mud interaction, multiple layer mixing and vegetation are discussed in appendix 1.

When the effect of waves are analysed SWAN is used. SWAN is a wave model for obtaining realistic estimates of wave parameters in coastal seas, lakes and estuaries developed by Delft University of Technology. SWAN and FINEL2D are already linked to each other. The waves in SWAN are translated into wave forces. Wave forces then influence the hydrodynamic model of FINEL2D. FINEL2D influences waves by water levels and currents. FINEL2D as SWAN each deliver a shear stress for the sediment transport model of FINEL2D. These shear stresses are then added resulting in the total shear stress used as input for calculating sediment transport. The combined shear stress is also used for monitoring vegetation dynamics conditions. In the current model the shear stress induced by waves was not linked to vegetation. Therefore FINEL2D had to be adapted (see appendix 1).

3.1.1 Overview processes in FINEL2D

In table 1 the implementation of processes mentioned in chapter 2.3 in FINEL2D is presented

TABLE 1 IMPLEMENTATION OF PROCESSES INTO FINEL2D

Process	Implementation
Vegetation → hydrology	
- Flow hindrance	Method of Baptist (2005) with increased roughness
Vegetation → sedimentation + bed level update	
- Increased capture of fine sediment by stems and leaves	Not implemented
- Increased soil stability by evapotranspiration through plants	Not implemented
- Prevent erosion due to soil stabilization by roots	Not implemented,
Hydrology → vegetation	
- Vegetation dynamics	Window of opportunity model (Balke et al., 2011)
Sediment transport + bed level update → vegetation	
- Large erosion digging out roots	Not implemented, indirectly through high shear stresses in the window of opportunity model
Vegetation → waves	
- Wave attenuation	Not implemented
Waves → vegetation	
- Vegetation decay by wave damage	Window of opportunity model

3.2 Model area

A test case area is set-up to evaluate different processes. The area used in this test case is based on dimensions of Paulinaschor. Paulinaschor is a salt marsh located in the Scheldt estuary at the west of Terneuzen (see figure 7).

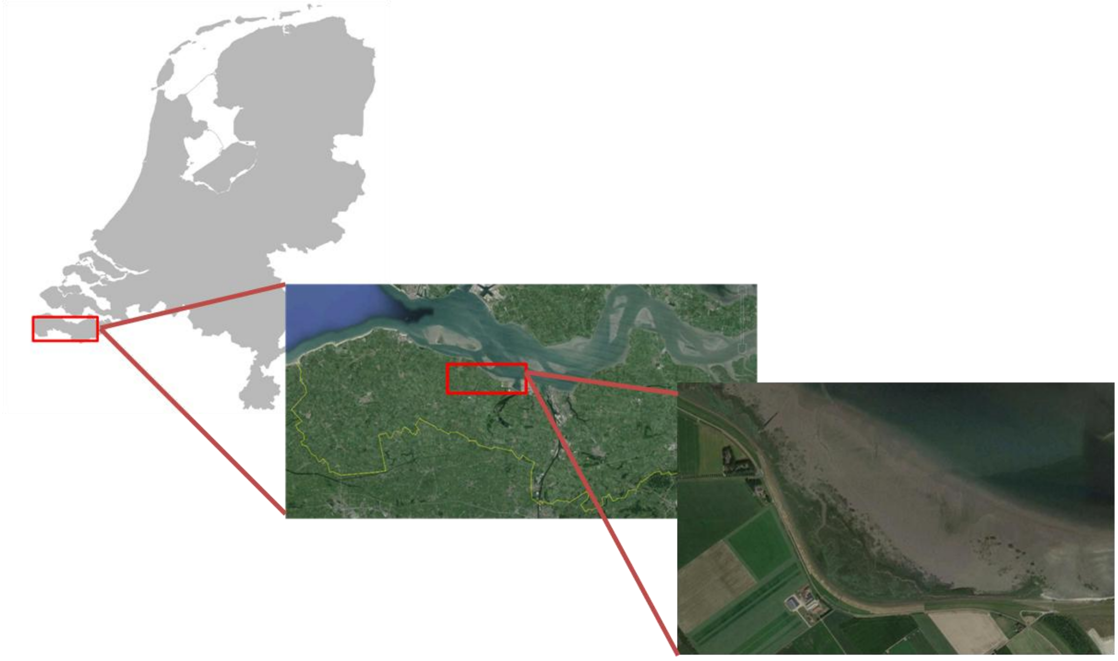

FIGURE 7 PAULINASCHOR, NETHERLANDS. THIS MARSH IS USED AS BASIS FOR THE TEST CASE

One of the reasons for choosing dimensions of Paulinaschor as test case is the size of this salt marsh. Paulinaschor is a relatively small salt marsh. The advantage of modelling a small salt marsh is the short modelling time. Another advantage is that applying proper boundary conditions, a salt marsh should arise. After all, this location also developed into a marsh.

The initial bed profile of the test case is presented in figure 8. The bed level of the channel flowing along the marsh (with marsh is meant the middle section of figure 8) is located five meters below mean sea level (hereafter referred as NAP which is approximately mean sea level in Dutch waters). In front of the marsh a 1:20 slope is applied. This seems a little steep, however simulations showed that this slope does not influence the outcome of the simulations. Another option would be to implement a cliff between the channel and the marsh, but a slope corresponds physically better with actual marshes. A slope of 1:20 implies that the marsh surface is at mean sea level in the beginning of the calculation. In this way the development from flat bed to a fully developed marsh can be modelled. The channel is relatively wide compared to the marsh. In this way the boundary conditions can adapt to the circumstances in the channel with a more realistic simulation as result. The channel area of the model is 4000 metres long and has a width of 1200 metres. The marsh located at sea level has a length of 300 metres and a maximum width of 1000 metres. The marsh has a minimum width of 200 metres.

The underlying grid of this bathymetry is presented in figure 9. The grid is coarse in the channel and finer on the marsh. By making the channel grid coarse, simulation time is reduced. The smallest elements are thus applied on the marsh. Hence, the processes on the marsh can be analysed in large detail.

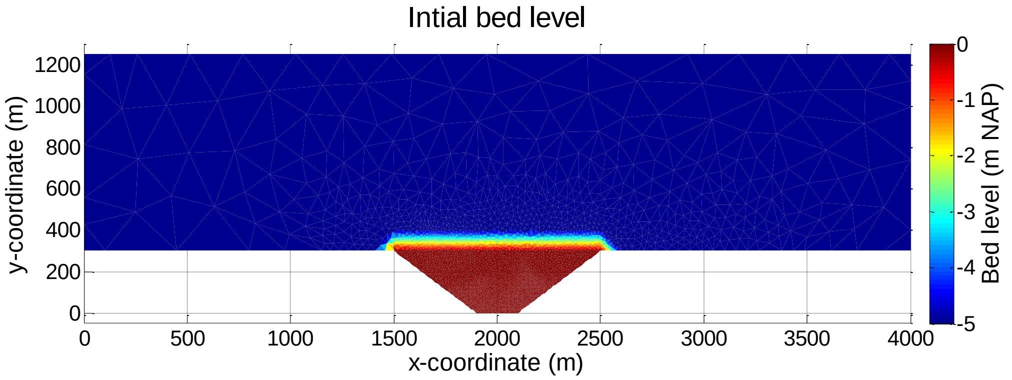

FIGURE 8 INITIAL BED PROFILE TEST CASE

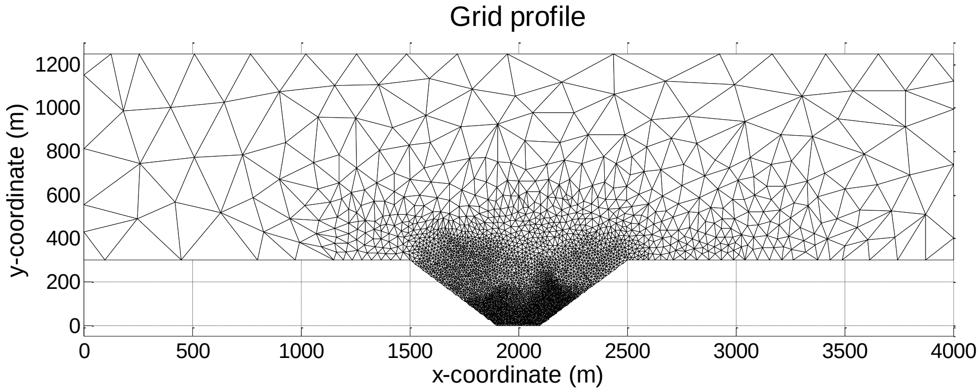

FIGURE 9 GRID PROFILE WITH MORE DETAIL ON THE MARSH THAN IN THE CHANNEL

3.3 Boundary conditions

Boundary conditions are imposed at the left, upper and right side of the channel. The hydrodynamic boundary consists of four tidal components: M2, S2, MN4 and S4. These components are chosen in such a way that together they show a spring-neap cycle (advised by Bram van Prooijen). The result is presented in figure 10. In this figure a month of water level variation is presented and the spring-neap cycle is clearly observed. Amplitudes corresponding the individual components are presented in table 2. The amplitude of the M2-tide is assumed to be two metres. By using a database with different tidal components the amplitude of the other three components are based on the relative amplitude in comparison to the M2-tide.

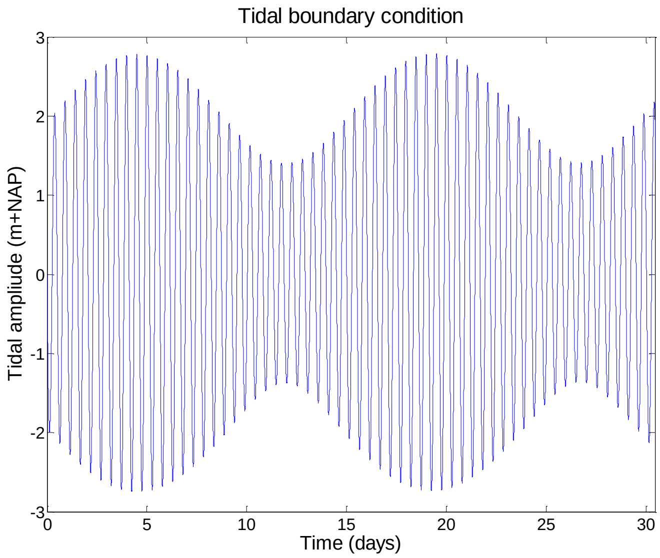

FIGURE 10 TIDAL BOUNDARY CONDITION

TABLE 2 AMPLITUDES OF TIDAL COMPONENTS

Tidal component	Amplitude (m)
M2	2.0
S2	0.69
MN4	0.01
S4	0.02

Novel in this study is that the tide does not propagate perpendicular but parallel to the shore, as is normally the case for salt marshes in the Scheldt. The right boundary of the area is located 4000 metres from the left boundary resulting in a phase difference. For calculating phase differences, wave velocities are needed. Tidal waves are shallow water waves in coastal waters Therefore wave-propagation velocities are calculated using $c = \sqrt{gh}$. In this equation h is water depth in meters, so in this case 5.00 metres, and g is the acceleration of gravity, which is equal to 9.81 m/s^2. This means that the wave propagation velocity has a value of 7.00 m/s. Dividing the distance from the left to the right boundary (4000m) by the wave propagation velocity (7.00 m/s) provides the time it takes for waves to flow from one end to the other. Dividing this time by the period of the tidal component results in a phase difference. Because FINEL2D requires a phase difference in radians, the outcome has to be multiplied by 2π. In the initial situation the phase on the left boundary is assumed to be zero and on the right boundary the calculated phase difference is imposed. Because waves move from left to right, the phase difference on the right is negative as it lags waves coming in from the left.

In table 3 each tidal component with their corresponding period and phase difference is presented.

TABLE 3 PHASE DIFFERENCE OF TIDAL COMPONENTS

Tidal component	Period (s)	Phase difference
M2	44700	-0.080
S2	43200	-0.083
MN4	22569	-0.159
S4	21600	-0.166

3.4 Input parameters

FINEL2D requires input parameters considering flowconstants, plants, morphology, time-related input and some general information. The input parameters will be explained in this paragraph.

3.4.1 Roughness

A spatial-varying bed roughness is implemented. Usually a Nikuradse roughness length of 2cm is used. However, at the left and right bottom grid boundaries a high roughness length of 10m is applied (see figure 11). This is done because test simulations showed that when using a Nikuradse length of 2cm for the whole domain, a spiral flow occurs at the boundaries (due to boundary effects) resulting in unrealistic bed level changes.

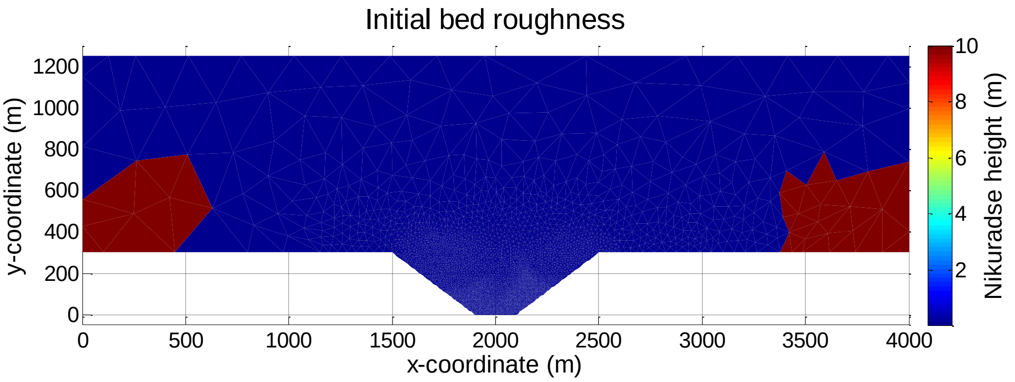

FIGURE 11 INITIAL ROUGHNESS OF THE GRID IN NIKURADSE LENGTH

3.4.2 Simulation time

A period of 100 years is used in the simulations. As will be seen in the upcoming results, 100 years is long enough for the simulations to reach or come close to equilibrium conditions. Because simulating 100 years takes a lot of time an acceleration factor of 100 is used. This means that every time step, morphological changes are multiplied with 100. Doing so, it takes about three days to simulate 100 years of morphological development.

3.4.3 Morphological active area

In FINEL2D an active morphological zone has to be determined. This means that morphological influences are only present within given boundaries resulting in a shorter simulation time. In this research the boundaries are set in such a way that only around the marsh, morphological changes occur. The values of the boundaries are presented in table 4.

On the boundaries of the morphological active area a mud concentration has to be implemented. According to Veheyen et al.(2013) mud concentrations are around 50 mg/l in the Scheldt estuary. Therefore the boundary concentration is put on this value. The effect of different boundary concentrations is analysed later in this thesis.

3.4.4 Morphological parameters

The values for the sand-, mud- and sand/mud variables in the reference case are based on a paper from Dam and Bliek (2013). Dam and Bliek studied the effect of sand and mud on sedimentation and erosion of a salt marsh located in the Scheldt estuary near Waarde. At Waarde a mud flat is located between two constructed groynes. This tidal mud flat is sensitive for deposition from sand as well as mud. The objective of this study was to assess the quality of the sand-mud module present in FINEL2D. Dam and Bliek conclude that after simulating 5 years, the model is able to produce bed level development. However, the performance of sand-mud interaction in combination with vegetation on a developing salt marsh has not been studied yet and thereby this research differs from the study by Dam and Bliek.

In table 4 the different input variables per module in FINEL2D are presented. For calculating sand-mud interaction the number of bed layers and layer thickness must be specified. The number of layers is set on 5 and layer thickness on 25 cm. For an extensive description of multiple layers in FINEL2D see appendix 1 chapter 1,2.

3.4.5 Vegetation parameters

The window of opportunity model is applied. The values of vegetation-related parameters are obtained from the thesis from Attema (2014). He based his values on papers from Temmerman (2007) and Van Hulzen (2007).

TABLE 4 INPUT VARIABLES

Variable	***Value***
Flowconstants	
Acceleration of gravity (g)	9.81 m/s^2
Density of water (ρ_{water})	1015 kg/m^3
Morphology	
Morphological acceleration factor (N_{acc})	100
morfstart[1]	12.000 s
x_{min}[2]	1200
x_{max}	2800
y_{min}	0
y_{max}	600
Mudconstants	
Fall velocity of mud ($w_{s,silt}$)	0.001 m/s
Critical erosion shear stress (τ_s)	0.5 N/m^2
Dry buklk density of mud (ρ_{silt})	750 kg/m^3
Sandconstants	
Formula	*Engelund & Hansen*
Median grain size (d_{50})	$200 * 10^{-6}$ m
Porosity (ϵ)	0.4
Dry bulk density sand (ρ_{sand})	2650 kg/m^3
Fall velocity of sand ($w_{s,sand}$)	0.015 m/s
Sand/mud interaction	
layer thickness (dz)	0.25 m
Numerical coefficient Cranck Nicholson scheme (θ)	0.55
Mixing coefficient (K_{m0})	0.0000025 m^2/s
Mud content non − active layer ($p_{m,sub}$)	0 %
Initial mud percentage of bed (*all layers*)	2%
Critical shear stress for cohesive bottom (τ_{ec})	0.75 N/m^2
Critical shear stress for non − cohesive bottom (τ_{enc})	0.2 N/m^2
Erosion coefficient for cohesive bottom (M_c)	0.0001 kg/m^2
Erosion coefficient for non − cohesive bottom (M_{nc})	0.001 kg/m^2
Plants	

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[1] Determines when FINEL2D becomes morphological active

[2] Coordinates of morphological active zone

Plant drag coefficient (C_d)	1.0
Plant height (k)	$0.4\ m$
plant stem diamerer (D)	$4.3\ mm$
Time needed for vegetation to establish ($T_{Ph:1}$)	$6\ hrs$
Max. water level under which vegetation could still establish	$0\ m$
Plant density of new − established plants ($n_{b,establishment}$)	$200\ m^{-2}$
Probability of plant establishment	0.05
Time needed to reach full strength and shear stress resistance $\left(T_{ph,2}\right)$	$3\ hrs$
Max shear stress resistance of new established vegetation (stage 3)	$0.20\ N/m^2$
critical shear stress for plant mortality $\left(\tau_{b,crit}\right)$	$0.26\ N/m^2$
Time for perserverance throughout high energy events $\left(T_{ph,3}\right)$	$4\ hrs$
Intrinsic growth rate of stem density (r)	$1\ yr^{-1}$
Maximum plant density $\left(n_{b,max}\right)$	$1200\ m^{-2}$
Diffusion coefficient for lateral growth (K)	0.2
Density threshold before vegetation influences hydrodynamics	$200\ m^{-2}$
Density threshold before vegetation expands laterally ($n_{b,crit\ diff}$)	$200\ m^{-2}$
Maximum % of time that vegetation can be submerged $\left(I_{\%,crit}\right)$	38%
Average time over which submergence of vegetation is computed	$12.42\ hrs$
Inundation relaxation time $\left(T_{I\%,avg}\right)$	$13\ hrs$

3.5 Analysis set up

3.5.1 Set up test cases

In order to assess the importance of different processes this paragraph describes the set-up of different test cases, each including different processes or change in input parameters. First a case is built which only considers changes in bed level by sand. In the subsequent case the interaction between sand and mud is added. Finally a test case is made which combines the effect of vegetation with sand-mud interaction.

Processes affecting salt marsh development are tidal amplitudes, boundary mud concentrations, storms, critical mud content, continuous deposition, settling velocity of mud and a maximum bottom slope. With continuous deposition is meant that the critical sedimentation shear stress is adapted in such a way that sedimentation occurs all the time. A more extensive description of these processes is presented in chapter 4. In figure 12 the set-up of test cases is shown in a more schematic way.

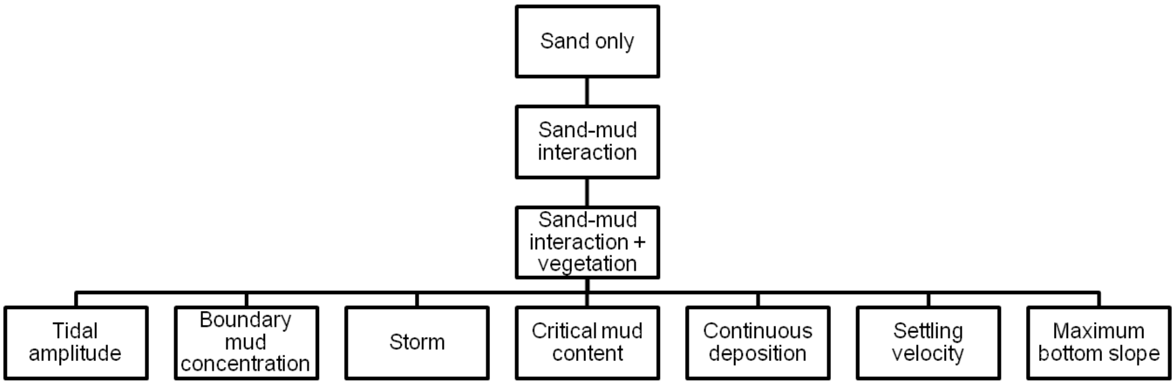

FIGURE 12 TEST CASE SET-UP

3.6 Evaluation methods

Evaluation methods are set-up to assess and compare results.

The first evaluation method consists of checking the bed level-, plant density- and mud percentage pattern. By analysing these patterns the influences of processes or adapted parameters can be observed in a qualitative way.

Secondly, the average bed level is plotted against time. This is not only useful to analyse differences in bed levels between processes but also to determine whether equilibrium conditions arise. When bed levels are constant at the end of the simulation period, it implies that no sedimentation or erosion occurs anymore and the bed is stable. For this graph only locations which are higher than 0m NAP at the end of the simulation period are considered. Also cross-sections in time are presented to show bed level development for individual simulations. Furthermore plant area development is analysed. This graph shows the area consisting of plants over time.

The number of creeks are quantified by taking the area of the creeks and divide this by the total area of the marsh[3]. In addition the average creek bed level is determined. The average bed levels of the marsh are also analysed. In this way the average creek depths are obtained.

Finally the simulation results are summarized by the average bed level, total marsh area, plant area and average mud content after 100 years.

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[3] Creeks are determined by clicking elements in Matlab which have a relative low bed level compared to the surrounding elements

4 RESULTS AND VALIDATION

This paragraph presents the stepwise adding of processes. This means that first a simulation which consists of only sand is presented. After this simulation the interaction between sand and mud is added followed by the implementation of vegetation.

4.1 Bed level

In figure 13 bed levels after 100 years of simulation are shown. The bed level in the upper figure is the result of simulating bed level changes by sand only. The middle figure shows the bed level with sand-mud interaction and the lowest figure shows the bed level of sand-mud interaction in combination with plants.

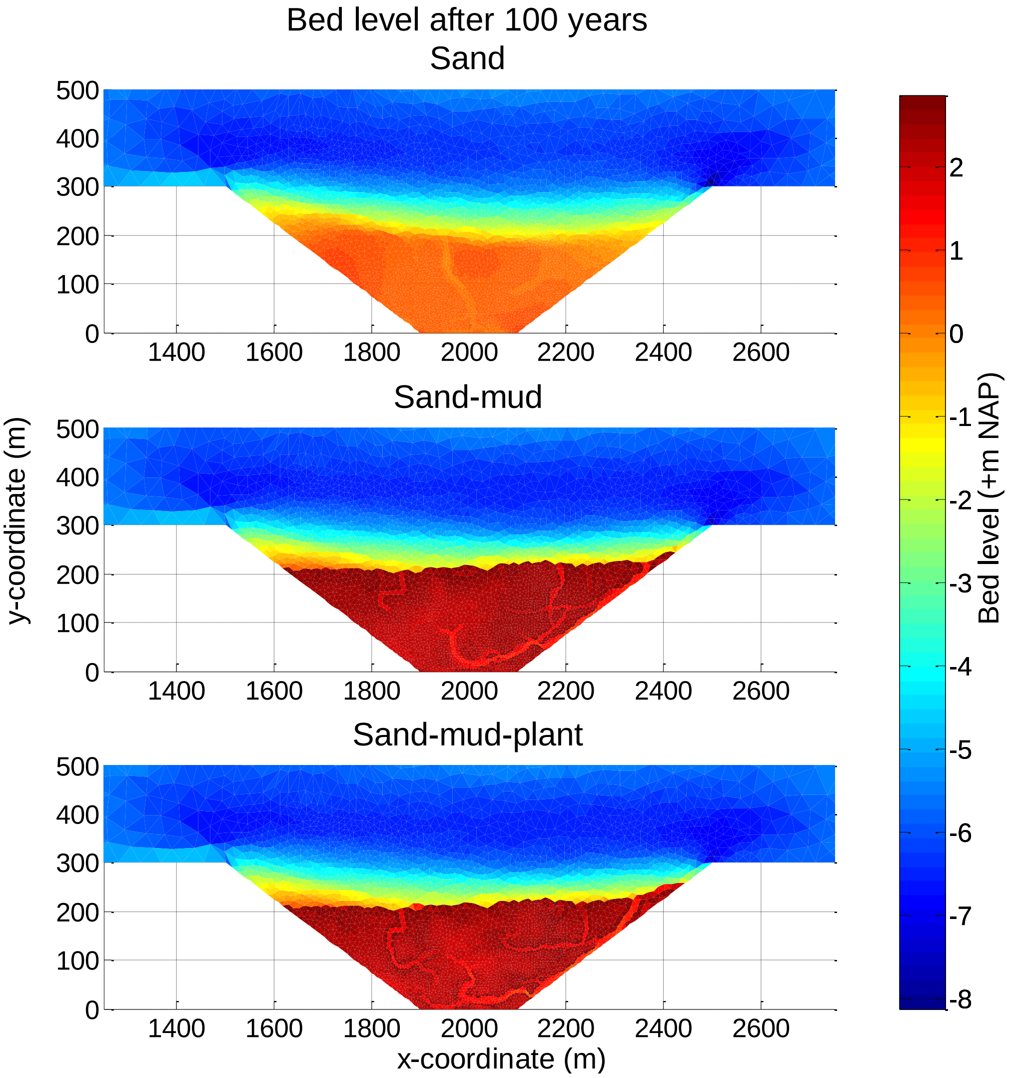

FIGURE 13 BED LEVEL AFTER 100 YEARS OF SIMULATING

The simulation with sand shows much lower bed levels than the other two simulations. The maximum bed level of the sand simulation is 0.76m. The maximum bed level of the simulation with sand-mud interaction is 2.87m and for the simulation including plants 2.83m. The introduction of mud leads to significant higher bed levels. This effect is also visible in figure 14.

The average bed level for the simulation with sand is significantly lower than the simulations with mud.

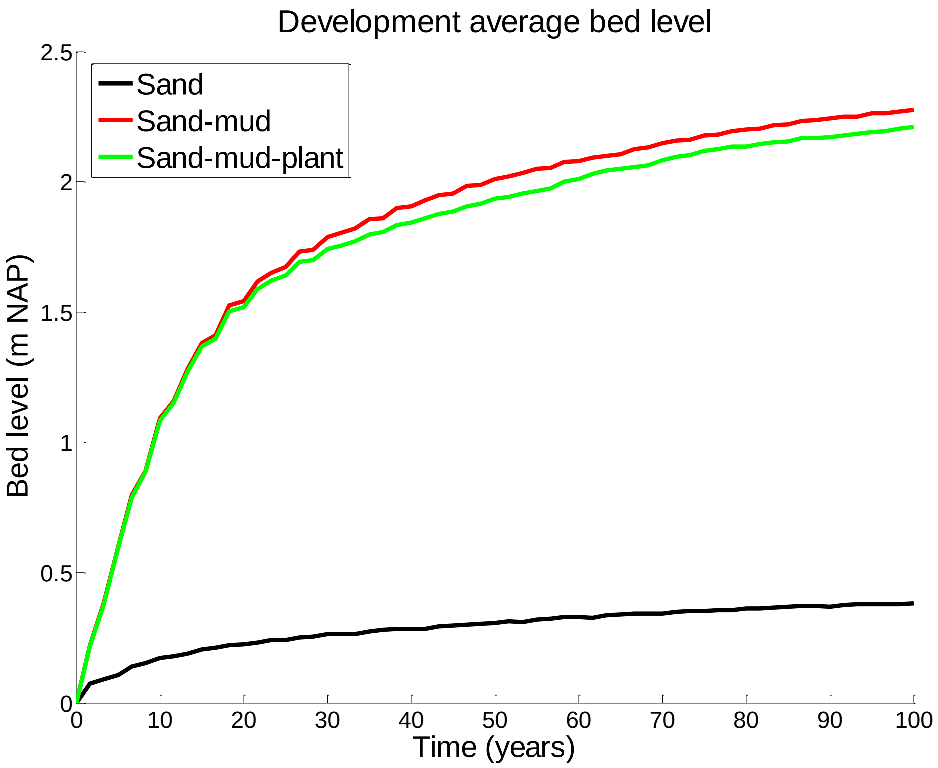

FIGURE 14 DEVELOPMENT AVERAGE BED LEVEL. THIS GRAPH ONLY CONSIDERS LOCATIONS WITH A BED LEVEL HIGHER THAN 0M IN THE END-SITUATION

The difference in bed level between a simulation with and without mud is explained by settling lag. Mud has a smaller particle size than sand and therefore it takes longer for mud to settle. The result is that mud can deposit particles on higher bed levels leading to a higher marsh. Settling lag also requires higher velocities to erode mud once settled. This effect is enhanced by cohesive properties of mud as when enough mud is available, it is able to trap sand and form a coherent mass.

Figure 14 also shows that after 100 years the simulations with mud are close to equilibrium as bed levels almost reach a constant value (which is below maximum spring tide). These lines fluctuate (especially at the beginning) from a large increase towards a smaller increase. These fluctuations are explained by the spring-neap cycle and the applied morphological acceleration factor of 100. When spring tides occur more sediments are deposited and higher bed levels are reached. For neap tides the opposite is true. The morphological acceleration factor enhances this effect. The simulation considering only sand still shows relative large bed level growth. To really determine when the sand simulation shows equilibrium conditions, simulation period has to be extended. This falls beyond the scope of this study.

Although maximum bed levels of the sand-mud and sand-mud-plant simulation are in the same order of magnitude, the bed pattern shows differences. The simulation with plants has more and smaller tidal creeks than the simulation without plants (see Table 5). When marsh is inundated, water is discharged through the creeks. The presence of plants cause velocities to decrease as water is discharged away from the marsh. Because flow velocities are reduced, more creeks arise to discharge all water away from the marsh platform (see also table 5).

TABLE 5 PERCENTAGE CREEKS AND AVERAGE DEPTH CREEKS AND BED LEVEL ON THE MARSH (BED LEVELS OF CREEKS ARE ECXCLUDED IN DETERMINING THE AVERAGE MARSH BED LEVEL)

Case	% Creeks on marsh	Average bed level creeks (m NAP)	Average bed level marsh (m NAP)	Average depth creeks (cm)	Number of tributaries
Sand-mud	10.5	1.54	2.34	80	8
Sand-mud-plant	12.6	1.50	2.29	79	12

Vegetation reduces erosion of tidal and fluvial channels (D'Alpaos et al., 2005). However, a study by Temmerman (2007) showed that this reduction of erosion is only a local effect. Dynamic vegetation patches have a larger scale off-site effect. They obstruct flow and therefore cause flow concentration and channel erosion between vegetation patches. This results in more channels. Figure 13 and table 5 show that the simulation with plants has more channels supporting the theory by Temmerman.

Figure 15 shows a cross-section after 100 years of modelling for a simulation with sand, sand-mud and sand-mud-plants. The location where the cross-section is taken is indicated in the smaller subplot on the right side of the same figure with a red solid line. Again the large difference between a simulation with and without mud is clearly visible. Simulations with mud show much higher bed levels than the simulation with only sand. In the figure large fluctuations on the marsh are observed. This is because creeks cause differences in bed level. Taking a cross section 100 meters further would show different fluctuations. Figure 15 is therefore meant to show the general trend of different simulations.

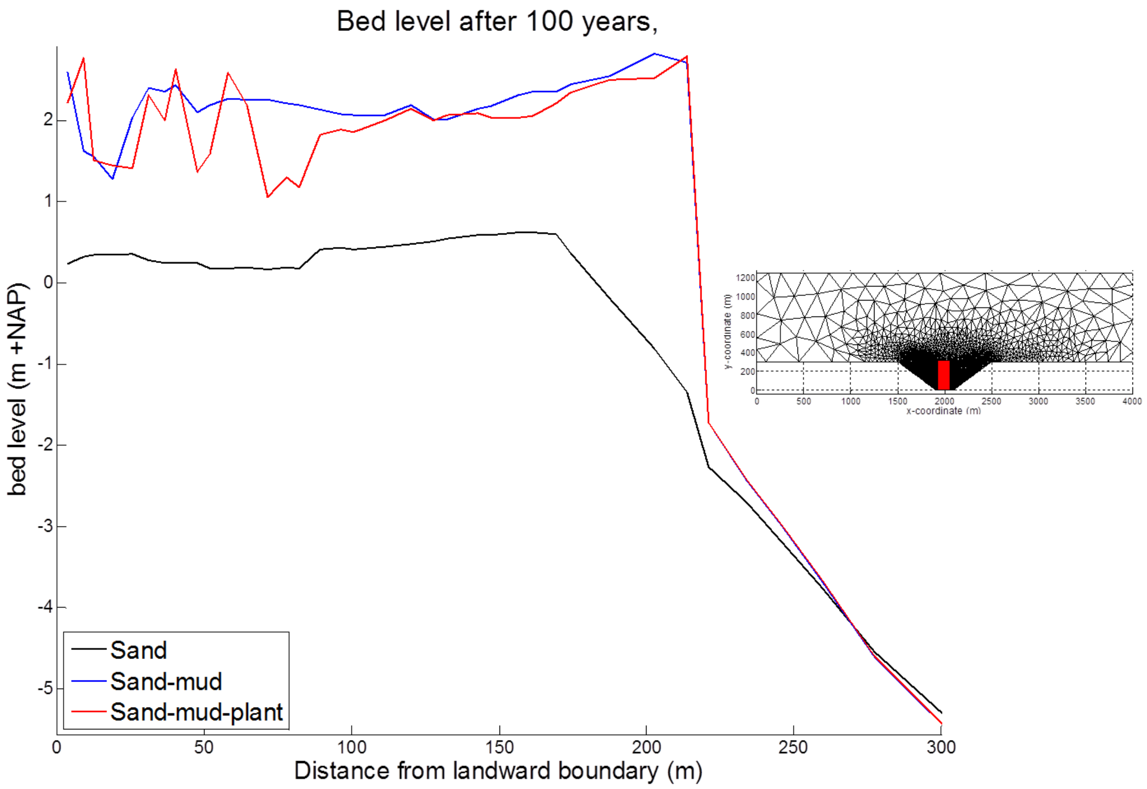

FIGURE 15 CROSS-SECTION S OF THE SIMULATIONS WITH SAND, SAND-MUD AND SAND-MUD-PLANTS. IN THE RIGHT CORNER IS INDICATED WITH A RED SOLID LINE WHERE THE CROSS-SECTION IS TAKEN.

Something else that stands out from figure 15 is that all simulations show the same slope from 200 to 300 meter from the landward boundary. Mud has a smaller settling velocity than sand due to its smaller grain size. Mud is therefore deposited further from the marsh edge (steep slope located around 200m from landward boundary in figure 15) on the marsh platform as here flow velocities are low enough for mud particles to settle. Vegetation and small water depths cause this decrease in velocity. Therefore the salt marsh edge consists of mainly sand resulting in the same slope in all simulations.

4.2 Plants

Figure 16 shows plant densities for the simulation with sand-mud and plants. On many locations on the marsh plants reach maximum plant density of 1200 stems/m^2. Where plants do not establish tidal creeks are present. High inundation periods and velocities make it unfavourable for vegetation to establish in creeks. In addition there are some locations where plants did establish but were not able to reach maximum plant density. Most of these locations are adjacent to creeks. Because the simulation ends with a neap tide (relative low water levels), vegetation is able to establish next to the creeks.

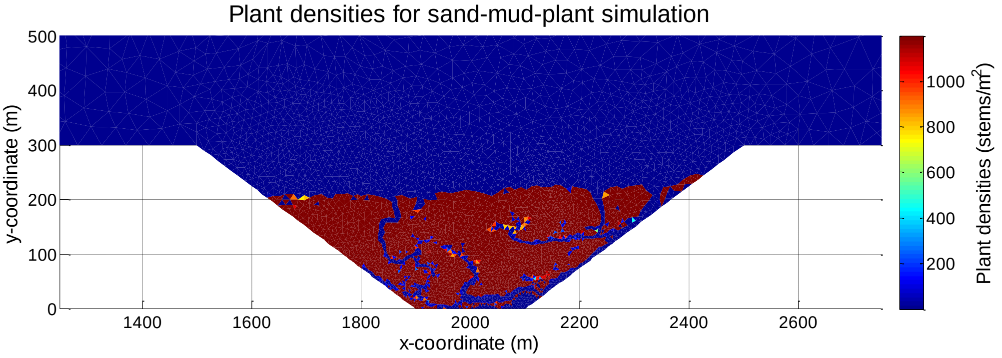

FIGURE 16 PLANT DENSITIES FOR SAND-MUD-PLANT SIMULATION

Figure 17 shows the area development consisting of plants. Plants seem to move towards a dynamic equilibrium, and it looks like it is close to equilibrium after 100 years. The small fluctuations are again caused by the spring/neap cycle.

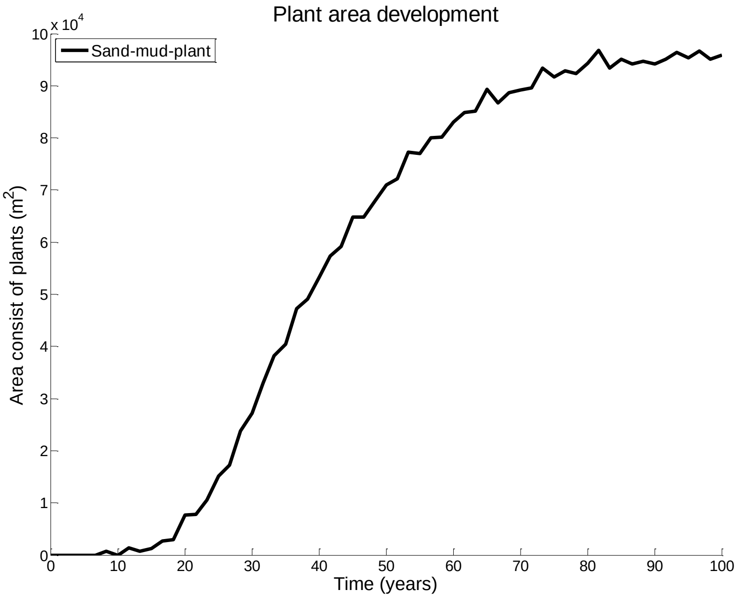

FIGURE 17 DEVELOPMENT OF AREA CONSISTING OF PLANTS

4.3 Mud content

In figure 18 the mud content for the simulation with and without plants is presented. The bed behaves cohesive when 30% of the bed consists of mud. Many locations reach this critical mud content. Nevertheless some locations on the marsh platform show a mud content around 0%. A part of these locations is clarified by the presence of tidal creeks. The flow velocities in tidal creeks withhold mud from settling. Furthermore, there are locations where no tidal creeks are present but still the mud content is around zero. This is explained by the bed becoming stable as no deposition or erosion occurs anymore. Due to vertical mixing, sand reaches the upper layer of the bed resulting in low mud percentages. This also explains why a decrease in mud content does not lead to a decrease in bed level.

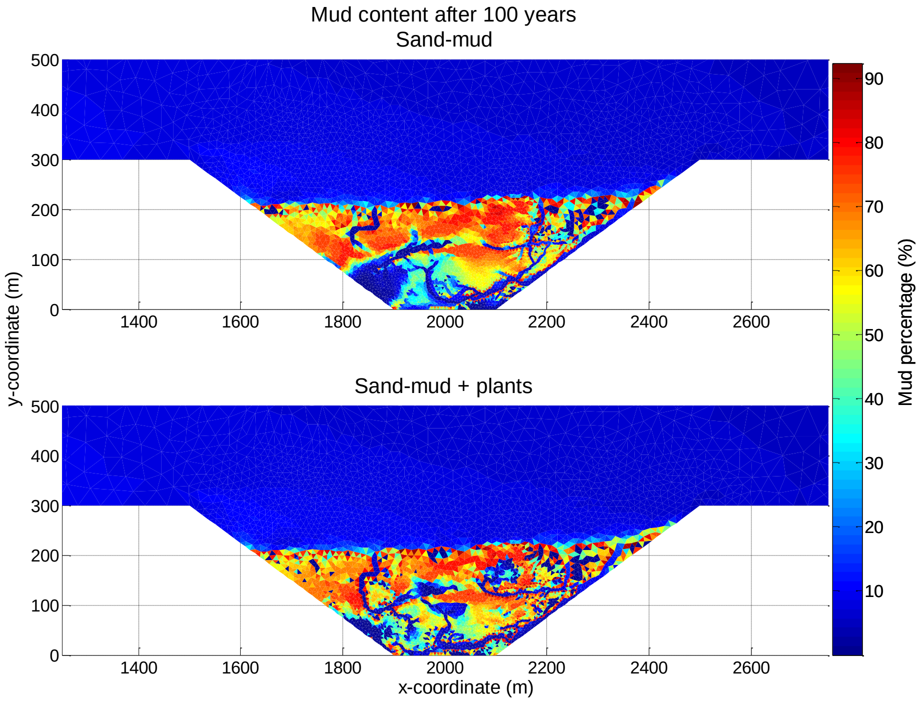

FIGURE 18 MUD CONTENT AFTER 100 YEARS FOR SIMULATIONS WITH SAND-MUD AND SAND-MUD AND PLANTS

The outcome shows that mud content increases with distance from creeks. When flow enters the platform, it takes time for velocities to decrease in such a way that mud is able to settle, resulting in a sorting effect around the creeks from low mud percentages along the creek to high mud percentages further away from the creeks. This effect is indeed observed in figure 18 and corresponds with actual marshes.

4.4 Validation

Validation of results is limited in this thesis because an idealized situation is simulated. Seasonal variations like winter storms are not implemented in the model causing differences between actual and simulated development of salt marshes. Nevertheless, the growth rate, final elevation-, mud content- and vegetation pattern of the simulation are evaluated based on characteristics of Paulinaschor.

Paulinaschor shows sedimentation rates of 4 to 19 mm per year (Stikvoort et al., 2003). At the end of the 100 year simulation the sedimentation rates are close to these values (between 2 and 8 mm/year). However, because there is no real event in the model which causes erosion or sedimentation on bed levels higher than the maximum tide (storm events), sedimentation/erosion rates will eventually fluctuate around zero depending on the spring/neap cycle and morphological acceleration factor.

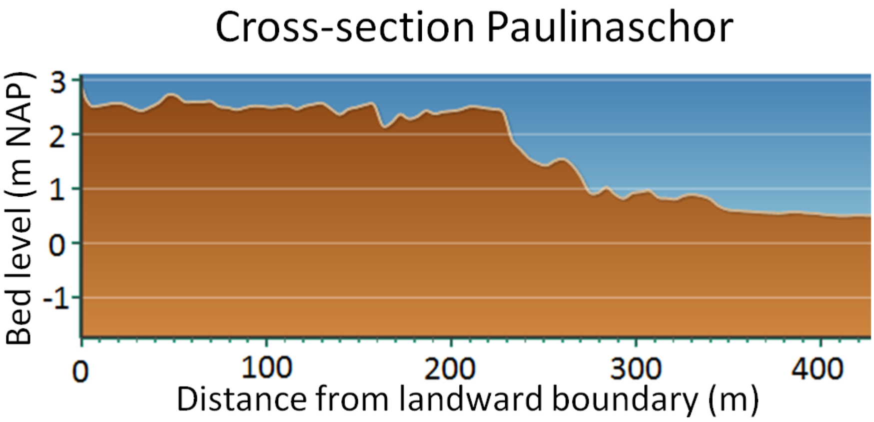

FIGURE 19 CROSS-SECTION OF PAULINASCHOR

From AHN (Actueel Hoogtebestand Nederland) a cross-section is made from Paulinaschor (figure 19). The bed levels on the marsh platform correspond really well with the simulation with plants and sand-mud interaction (figure 15). Also the location of the marsh edge at 200 meters distance from the landward boundary is in correspondence with the simulation. A difference between the simulation and the actual cross-section is the height of the edge. In the simulation the marsh edge is about 4 meters high while on Paulinaschor the edge is about 2 meters and not as steep as in the simulation. The model was not able to reproduce a mud flat in front of the marsh resulting in a marsh edge of 4 meters. Causes for this difference could be the lack of waves and multiple sediment fractions in the model. Waves cause erosion of the marsh edge and multiple sediment fractions improve the sorting effect on the marsh (from large particles at the sea towards small particles at the landward boundary). Both processes result in a more gentle slope.

The marsh platform shows a slightly positive slope while in the simulation a negative slope occurs. However, both slopes are more or less flat.

Analysing soil characteristics of Paulinaschor, the soil mainly consists of mud, sandy mud and fine sand as can be seen in figure 36 in appendix 2. This graph shows higher probabilities of mud at the landward boundary than at the marsh edge which is in correspondence with literature (De Groot et al., 2011). This does not correspond with the simulations where mud content increases from landward boundary towards the edge. Because mud deposits first at the landward boundary, this part of the marsh is stable in an earlier stage than the marsh edge. Vertical mixing then causes sand to reach the upper layer decreasing the mud content.

Based on the validation of Paulinaschor the model adequately reproduces bed levels, plant pattern and location of the marsh edge. The model does not predict a mud flat which may be due to the lack of wind waves. Because this thesis concerns salt marsh development (and not mudflat) the model is assumed to be suitable for application towards the goal of this study, evaluating the contribution of different processes on salt marsh development.

Furthermore the influence of the morphological acceleration factor and grid size is studied (see appendix 3). The results showed that the current acceleration factor and grid profile are suitable for analysing the influence of different processes.

5 SENSITIVITY ANALYSIS

In this chapter several processes are evaluated. The influence of tidal amplitude, boundary mud concentration, critical sedimentation shear stress, settling velocity for mud ,critical mud content and maximum bottom slope is checked. Before results are presented, each adaptation will be explained. When in this chapter “reference situation/simulation” is mentioned, the sand-mud-plant simulation is meant.

5.1 Process descriptions

5.1.1 Mud boundary condition of 100mg/L and 25 mg/L

In the initial situation the mud concentration is 50mg/L. These concentrations are imposed at the boundary of the morphological active zone meaning that tidal waves bring 50 mg/L of mud into the system. To evaluate the influence of mud availability, simulations are set-up which have a lower and higher mud concentration than the reference mud concentration. These concentrations are obtained from a paper by Verheyen et al. (2013). Verheyen determined the mud concentration for the whole Western Scheldt. He found low concentrations of about 25mg/L at the seaward side of the Scheldt, while more land inward, at Land van Saeftinghe, concentrations of 100 mg/L were observed. Therefore these values are used.

5.1.2 Tidal amplitude

The influence of tidal amplitudes is assessed by increasing and decreasing the amplitude of different tidal components. The amplitudes are based on one-year data of the tide observed at Terneuzen. The average daily high amplitude is 2.35m NAP. A maximum daily amplitude is found to be 2.96m NAP and a minimum of 1.44 m NAP. These values are slightly exaggerated to evaluate extreme conditions, however it has to be taken into consideration that 100 years of extreme conditions is not very realistic. Still it provides a good insight of the influence of tidal amplitudes. The values of the M2-tide are based on values obtained from data, other tidal components are calculated by taking the ratio with the M2-tide. The amplitudes are presented in table 6. One month of low and high amplitudes are presented in figure 20.

TABLE 6 TIDAL AMPLITUDES FOR THE SIMULATIONS WITH HIGH AND LOW TIDE

Tidal component	High Amplitudes (m NAP)	Low amplitudes (m NAP)
M2	3.00	1.00
S2	1.04	0.35
MN4	0.015	0.005
S4	0.030	0.010

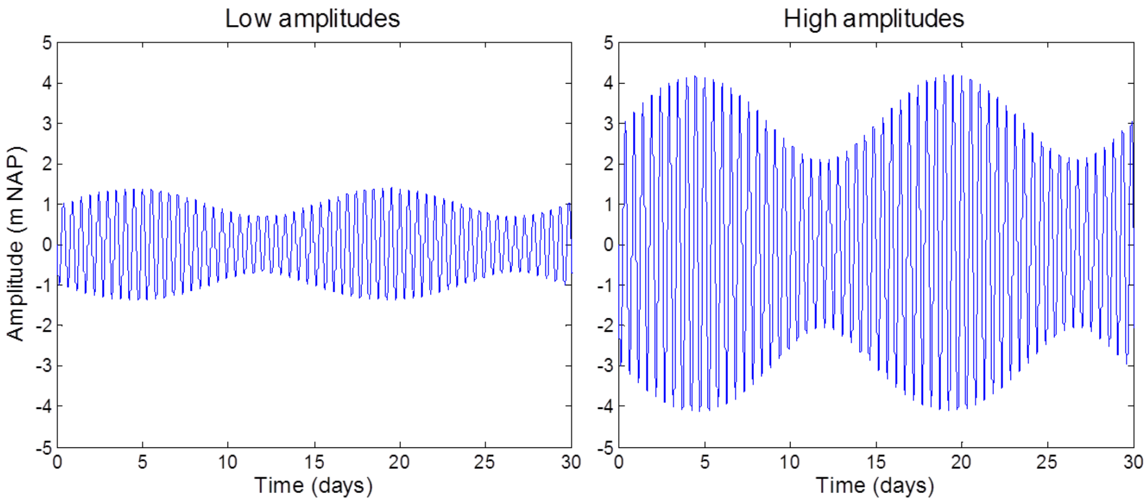

FIGURE 20 SIMULATION WITH LOW AND HIGH AMPLITUDE

5.1.3 Continuous deposition

Some studies suggest to apply continuous deposition in order to obtain realistic results (Sanford & Halka, 1993; Winterwerp, 2007). This means that the critical sedimentation shear stress must be set very high in order for deposition to occur all the time. This is done in FINEL2D by applying a critical sedimentation shear stress of 1000 N/m^2, while in the reference case the critical sedimentation shear stress is 0.5 N/m^2.

5.1.4 Low settling velocity of mud

In the reference situation a settling velocity for mud of 0.001 m/s is used. This value is obtained from a paper by Dam and Bliek (2013). A paper by Temmerman et al. (2003) suggests a ten times smaller settling velocity (0.0001 m/s). This value is implemented in the model.

5.1.5 Critical mud content of 20%

In the reference situation a critical mud content of 30% is applied. The critical mud content determines when the bed behaves cohesive. 30% of mud is suggested as the critical mud content in studies from Van Ledden (2003) and Mitchener and Torfs (1996). However, a study from Houwing (1999) found a critical mud content of 20% in the Dutch Wadden Sea. Although the Scheldt estuary is a different system, mud and sand should behave the same. Therefore it is interesting to analyse the effect of a critical mud content of 20%.

5.1.6 Maximum bottom slope of 0.5

In the simulation with sand-mud and sand-mud-plant a steep marsh edge arises. This edge is about 4 meters high. When analysing actual marshes, the slope should be more gentle. Therefore a simulation is done with a maximum bottom slope of 0.5. This means that when a bottom slope of 0.5 or less occurs in the simulation then erosion takes place according to an avalanche formulation.

Because now every process is described, results will be discussed.

5.2 Results

5.2.1 Bed level

In figure 21 and figure 22 on page 36 and 37 bed levels of all simulations after 100 years of modelling are presented. The results show that the availability of mud especially determines the lateral marsh expansion. The simulation with a boundary concentration of 100 mg/L shows significantly more expansion than the simulation with a boundary concentration of 25 mg/L. In contrast, bed levels are not really influenced by an increased mud concentration. The maximum bed level in the simulation with a concentration of 100 mg/L is 2.97 m NAP which is just slightly higher than the maximum bed level of the simulation with a concentration of 25 mg/L (2.79 m NAP). The simulation with low tidal amplitudes developed an error as the highest bed level is 7.32m NAP which is unrealistically higher than the rest of the marsh. Because flow velocities depend on water depth, the simulation with low tidal amplitudes has lower velocities than the simulation with high tidal amplitudes. The result is that in the simulation with low amplitudes deposition occurs on more locations leading to marsh expansion while the simulation with high amplitudes shows a relative small marsh.

The simulation with continuous deposition expands more laterally than the reference simulation. Mud now also deposits on locations where shear stresses are higher than 0.5 N/m^2 resulting in lateral marsh expansion. The creek occurring in the middle of the marsh in the continuous deposition simulation is much deeper than the rest of the creeks. This is caused by the fact that this creek has to empty most of the upper marsh after high tide.

For the simulation with a low settling velocity much lower bed levels arise in comparison to the other simulations. The settling velocity determines the deposition rate of mud. A smaller settling velocity implies that smaller flow velocities are required for mud to settle. Because boundary conditions do not change, flow velocities are the same as in the reference situation. Therefore less settlement of mud occurs. The result of the simulation with only sand and with a low settling velocity therefore look like each other as the bed in the situation with a low settling velocity also consists of mainly sand.

The simulation with a critical mud content of 20% shows a more laterally expanded marsh than the reference situation. When critical mud content is reached, the bed becomes cohesive. When cohesive, the bed is more difficult to erode. In this case the bed becomes cohesive in an earlier stage of the development resulting in less erosion. This leads to expansion of the marsh.

The difference between the simulation with a maximum bottom slope of 0.5 and the reference situation is small. When analysing a cross-section of both simulations can be seen that the simulation with a maximum bottom slope shows a slightly more gentle marsh edge (see figure 23 on page 38).

Figure 24 on page 39 shows bed level development for all simulations. Apart from the simulation with a low settling velocity for mud and low tidal amplitudes all simulation show a slope relatively close to horizontal after 100 years implying equilibrium conditions. The simulation with low settling velocity requires a longer period for reaching equilibrium as it takes longer for mud particles to deposit (for bed level development see figure 41 in appendix 4). The simulation with low tidal amplitudes is not close to equilibrium because it still expands (see figure 42 in appendix 4). This graph is based on bed level locations which are higher than 0 m NAP after 100 years. Because the marsh still expands, some locations have not reached their maximum bed level yet. Increasing simulation period will tackle this problem.

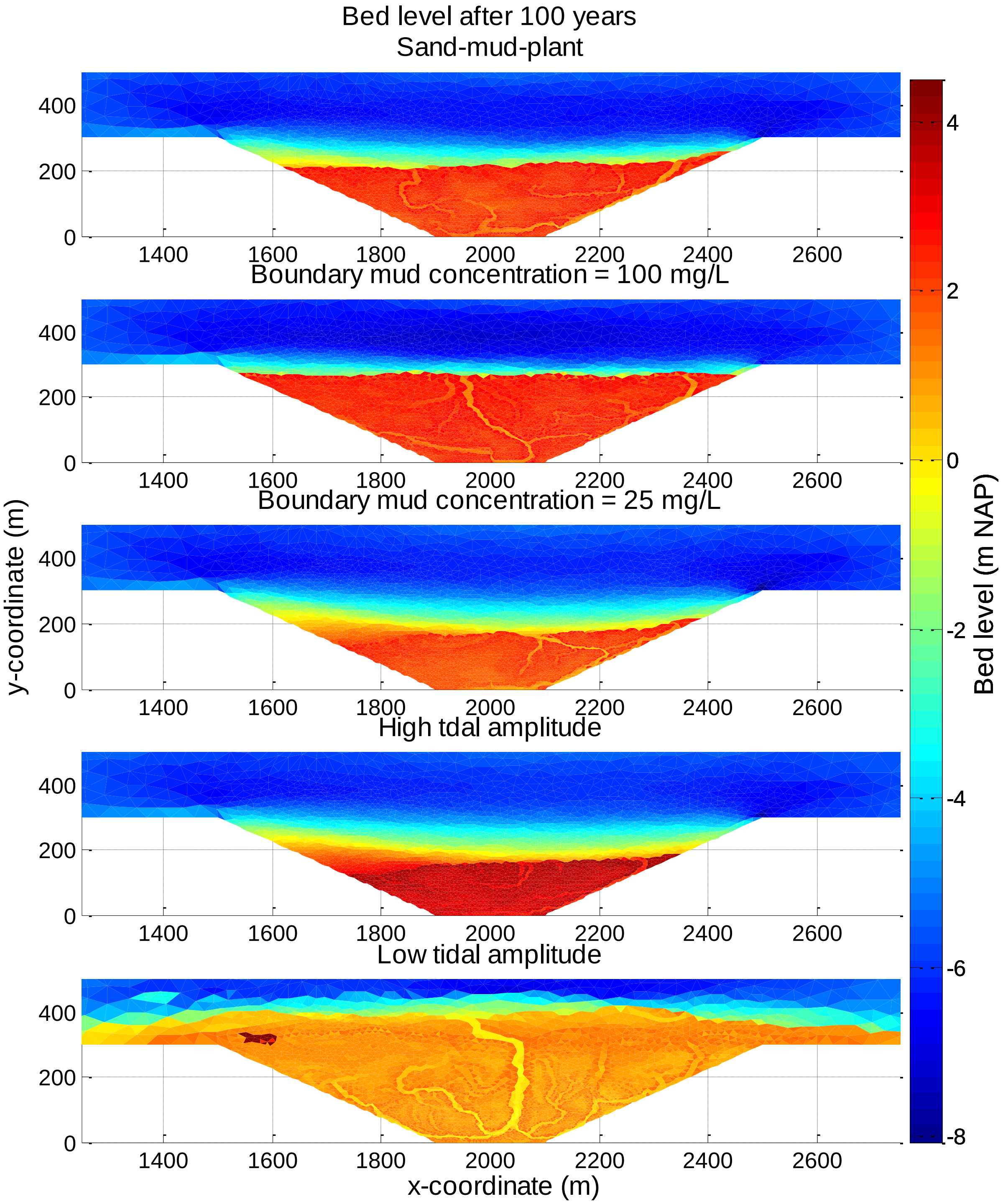

FIGURE 21 BED LEVELS AFTER 100 YEARS FOR SAND-MUD-PLANT,BOUNDARY MUD CONCENTRATIONS, AND TIDAL AMPLITUDES SIMULATIONS

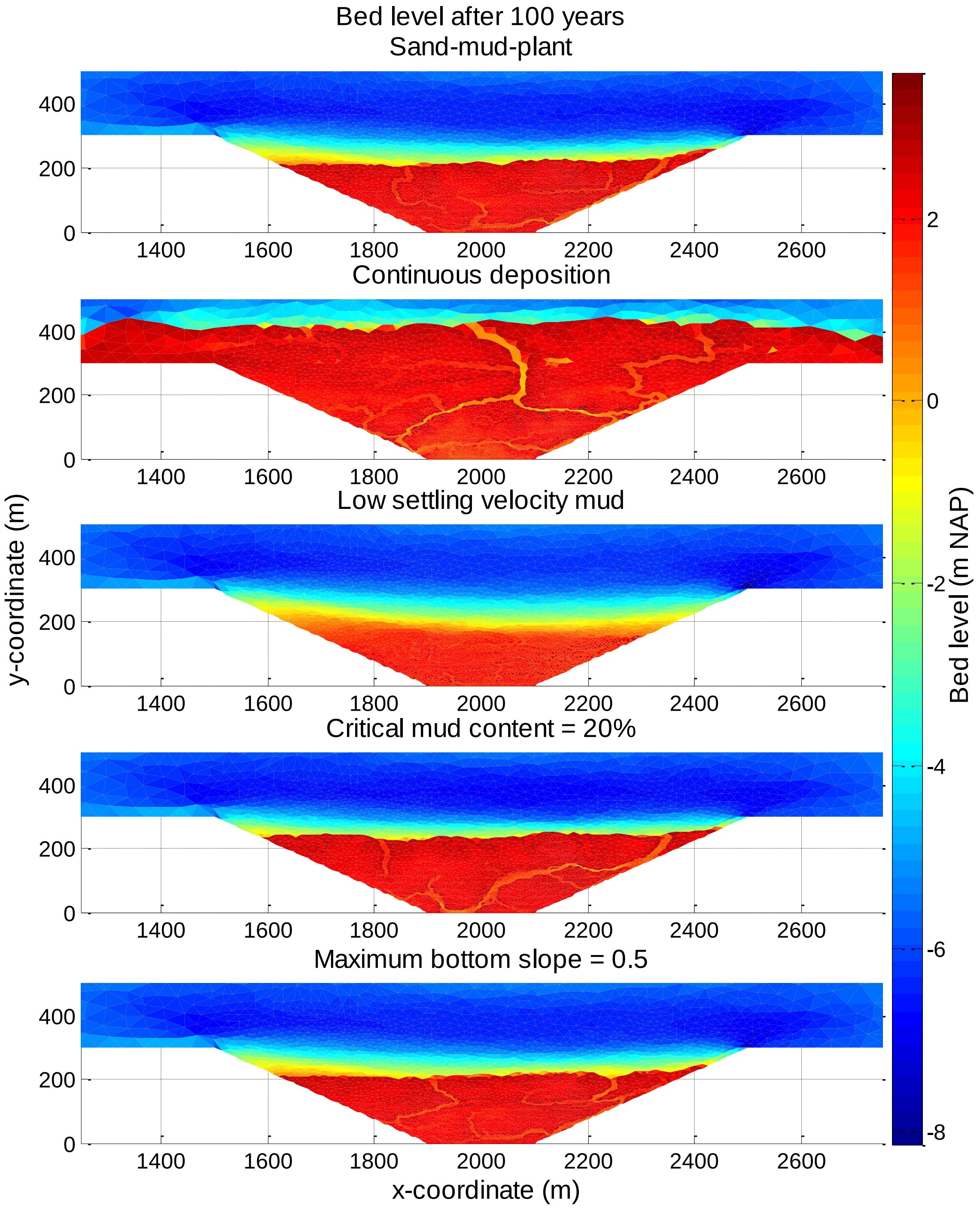

FIGURE 22 BED LEVELS AFTER 100 YEARS FOR THE REFERENCE SIMULATION, CONTINUOUS DEPOSITION, LOW SETTLING VELOCITY FOR MUD, CRITICAL MUD CONTENT OF 20% AND A MAXIMUM BOTTOM SLOPE OF 0.5

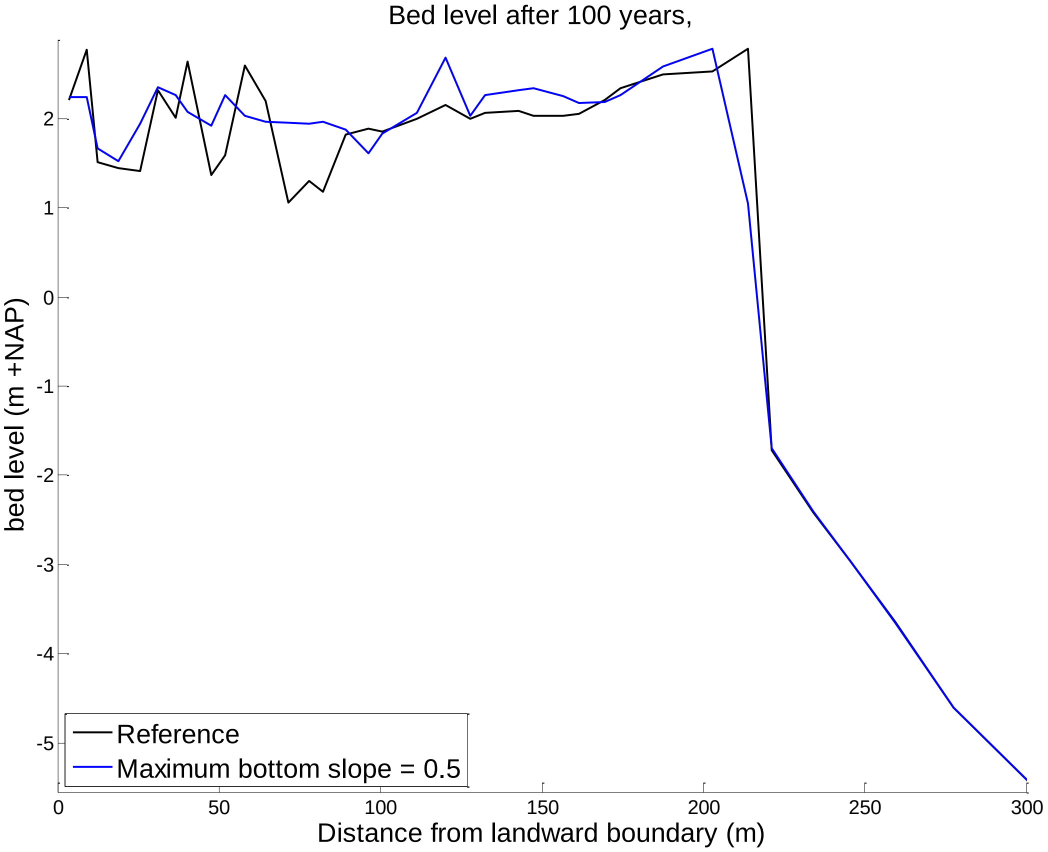

FIGURE 23 CROSS-SECTION AT THE SAME LOCATION AS FIGURE 15 FOR THE REFERENCE SIMULATION AND A SIMULATION WITH A MAXIMUM BOTTOM SLOPE OF 0.5

Most simulations in figure 24 start with an average bed level of 0 m NAP at the beginning of the simulation. However, the simulations with continuous deposition and low tidal amplitudes start with a bed level smaller than 0 m NAP. This figure only considers bed levels which are above 0m NAP at the end of the simulation. Because the simulation with continuous deposition and low tidal amplitudes expand, bed levels which are initially below 0 m NAP are also accounted for. The lower bed levels, where eventually a marsh will develop, are significantly lower than 0m NAP so when deposition occurs on these locations, it really influences the graph as the average bed level starts to increase substantially. The simulation with continuous deposition even shows a decrease in average bed level at the beginning. This is explained by erosion which occurs in front of the marsh at the beginning of the simulation. During the simulation the marsh expands and average bed levels increase (see figure 25).

The highest bed levels are found in the simulation with high tidal amplitudes. The large amplitudes cause sediments to reach high locations. For the opposite reason the lowest bed levels are achieved in the simulation with low tidal amplitudes.

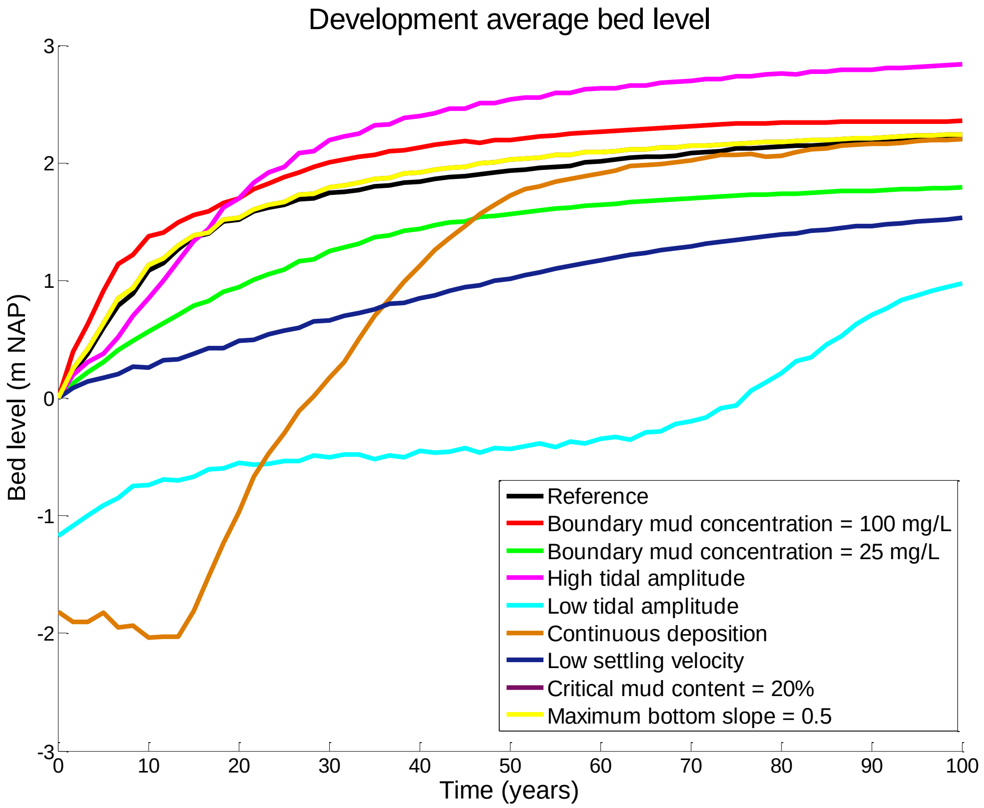

FIGURE 24 BED LEVEL DEVELOPMENT FOR THE DIFFERENT PROCESS SIMULATIONS

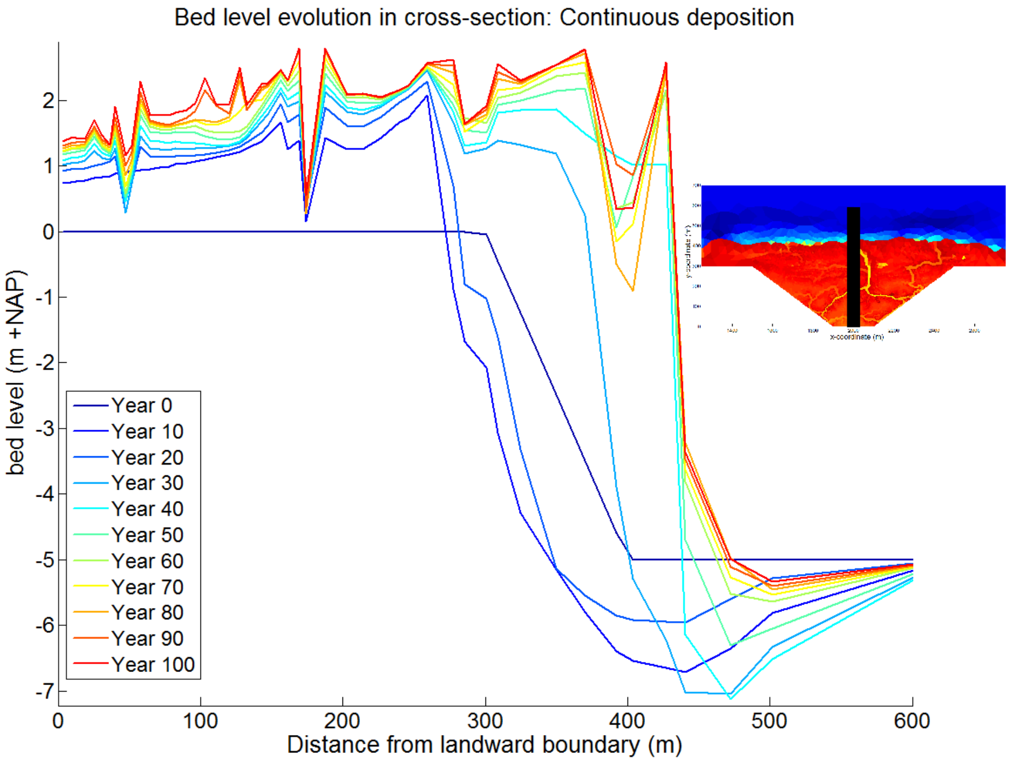

FIGURE 25 BED LEVEL DEVELOPMENT FOR SIMULATION WITH CONTINUOUS DEPOSITION. THE BLACK SOLID LINE IN THE SMALLER FIGURE REPRESENTS THE LOCATION OF THE CROSS-SECTION

Table 7 shows results regarding creeks. The dimensions of creeks depend on different characteristics like discharged volume, bed level and expansion of the marsh. The two simulations which showed lateral expansion (low tidal amplitudes and continuous deposition) have a relative lower percentage creeks than other simulations. The expansions at the sides (see figure 26) do not require creeks for water to be discharged and therefore the marsh area is larger while the area consisting of creeks remains the same.

TABLE 7 RESULTS CREEKS

Case	% Creeks on marsh	Average bed level creeks (m NAP)	Average bed level marsh (m NAP)	Average depth creeks (cm)	Number of tributaries
Sand-mud-plant	12.6	1.50	2.29	79	12
High tidal amplitudes	8.0	2.69	3.45	76	5
Low tidal amplitudes	9.3	0.24	1.03	79	7
High mud concentration	10.5	1.58	2.42	85	9
Low mud concentration	10.2	1.17	2.02	85	9
Critical mud content 20%	12.5	1.41	2.31	90	12
Continuous deposition	9.2	1.14	2.15	1.01	13
Maximum bottom slope	13.7	1.57	2.29	72	13

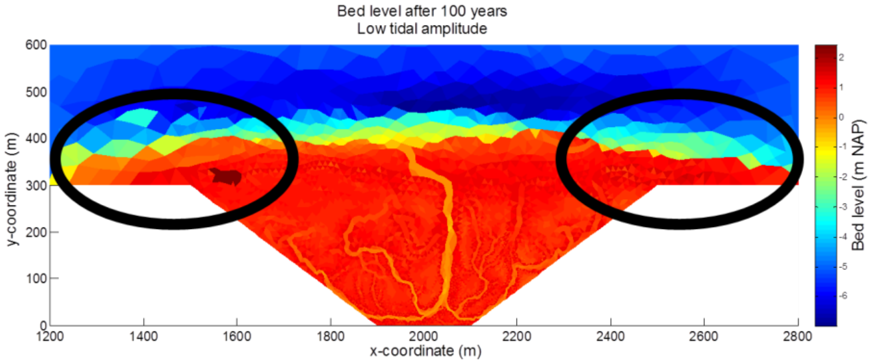

FIGURE 26 LOCATIONS WHERE NO CREEKS DEVELOP

In the simulation with a low settling velocity for mud no real distinction between creeks and marsh platform is observed. The simulation with low settling velocities for mud requires a longer simulation period for the marsh to fully develop. However the question is whether settling velocity is high enough to develop a marsh with creeks.

5.2.2 Plants

In appendix 5 plant densities for all simulations are presented. These patterns are again explained by the presence of creeks and inundation. More interesting is to analyse the total area consisting of plants (see figure 27). The simulations considering a high and low mud concentration, critical mud content of 20%, high tidal amplitudes and a maximum bottom slope of 0.5 are close towards reaching dynamic equilibrium as their slope is almost flat at the end of the simulation. It is a dynamic equilibrium as plants can establish during neap tides while at spring tide vegetation decays.

The simulations with continuous deposition and low tidal amplitudes still expand at the end of the simulation. This means that new land develops where vegetation is able to establish. This also explains the steep lines at the end of these two simulations. Low settling velocities make it difficult for mud to settle. Therefore marsh development goes slower. This also influences plant establishment as it takes longer before favourable conditions' arise.

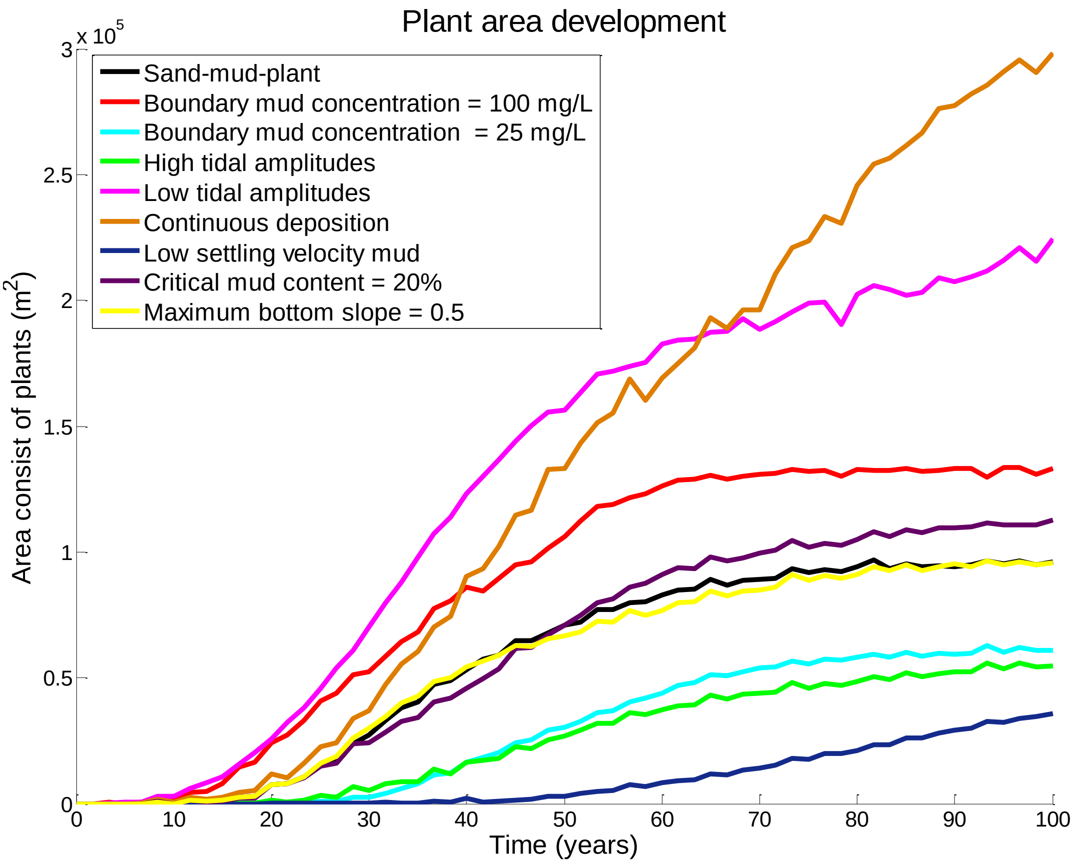

FIGURE 27 PLANT AREA DEVELOPMENT

5.2.3 Mud content

Appendix 6 shows mud concentrations after 100 years. Water levels on the marsh significantly influence the mud pattern. Locations where water is present in the form of creeks or where the bed is stable, mud content is relatively low. This explains the random pattern in the simulations with a high mud boundary concentration, low tidal amplitudes and continuous deposition. The simulations with low mud concentrations and a low settling velocity show good results with higher mud percentages at the landward boundary than at the edge. This implies that modelling with multiple sediment fractions would give better result regarding the sorting effect on the marsh.

All the simulations show that mud increases with distance from water. This corresponds with literature and is already explained in chapter 4.3.

5.3 Summary

In table 8 results are summarized in average marsh bed level, total marsh area, total area consisting of plants and average mud content. Because in the simulation with only sand no real marsh developed, this simulation is not included in the table. The simulation with a low settling velocity did not show a clear salt marsh pattern as the other simulations. Therefore is chosen to only present the total plant area.

The average bed level could be different from the average bed level presented in the figures about bed level development. This is because table 8 only considers bed levels on the marsh while the figures with bed level development are based on every location above 0 m NAP at the end of the simulation. The choice to use only bed levels above 0 m NAP in the figures is because defining marshes in the beginning of the simulation is difficult.

TABLE 8 SUMMARY RESULTS

Simulation	Average bed level (m NAP)	Total marsh area (ha)	Plant area (ha)	Average mud content (%)
Sand-mud	2.24	10.58	-	43.6
Sand-mud-plant	2.18	10.72	8.30	41.3
High tidal amplitudes	3.38	7.32	4.21	51.1
Low tidal amplitudes	0.93	29.32	18.66	32.6
High mud concentration	2.33	14.98	12.25	34.5
Low mud concentration	1.92	7.83	5.01	44.7
Critical mud content 20%	2.18	12.56	9.57	37.3
Continuous deposition	2.02	36.56	21.89	44.1
Maximum bottom slope	2.18	10.43	8.11	43.5
Low settling velocity mud	-	-	2.22	-

The simulation with continuous deposition consists of the largest marsh area followed by the simulation with low tidal amplitude. The smallest area is found in the simulation with high tidal amplitudes and low mud concentration.

Noteworthy is that mud concentration does not seem to influence the average mud content but does influence the total marsh area. An increased availability of mud leads to a larger marsh platform. Because a large part of the bed is not stable enough for sand to reach the upper layer (deposition of mud still occurs), expanding marshes show higher average mud percentages.

6 EXPLORING STORM EFFECTS

In this research an initial set-up of a model which combines the development of salt marshes in combination with wind waves is made, Wind waves are implemented using SWAN. How SWAN Is linked to FINEL2D is presented in paragraph 3.1.

6.1 Wave input

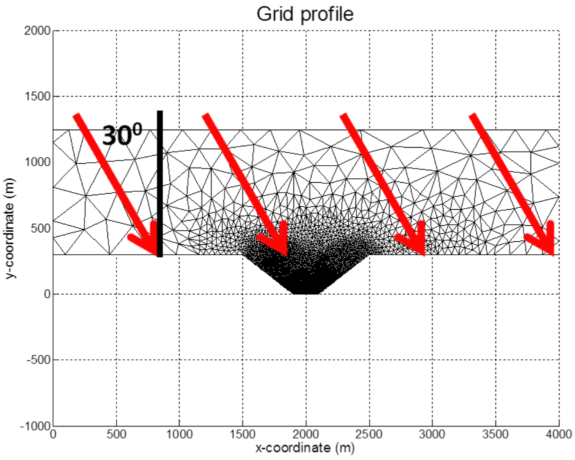

FIGURE 28 WAVE-DIRECTION

A study by Gautier and Van Den Boomgaard (2003) analysed field measurements of the Western Scheldt estuary between 1997 and 2002. On different locations measurements are done analysing wave height and period. At a measuring station close to Paulinapolder the highest wave height measured is 1.24m with a corresponding period of 2.8s. The wave direction is assumed to be 30 degrees (see figure 28). From the same study a wind velocity at 10m height is obtained. The maximum wind velocity found in this study close to Paulinapolder is 35.50 m/s. It is assumed that this wind velocity is a measuring error as at the same time at other stations in the Scheldt much lower values were observed. Therefore in the reference situation a wind velocity of 20m/s is assumed. These swan-related parameters are implemented as a one-day storm.

In the reference case some small adaptations are made. A maximum bottom slope of 0.5 is applied (see also chapter 5.1.6). Furthermore the amplitudes for zero frequency are set on 2m in each boundary point which results in a tide as presented in figure 29.

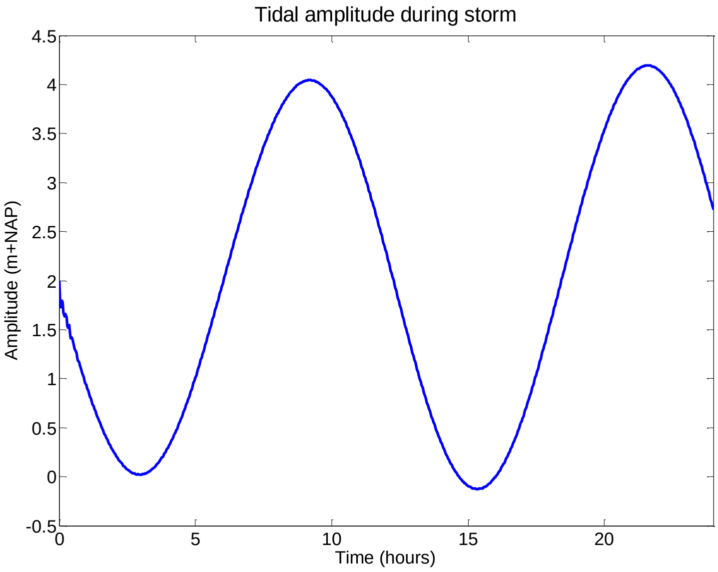

FIGURE 29 TIDAL AMPLITUDE FOR STORM EVENT

As already stated some variations are applied in the SWAN input in order to analyse the influence of different parameters. The first adaptation imposed is an arbitrarily large wave with a wave height of 3m and period of 8s. In another simulation the wind velocity is set on 30 m/s instead of 20 m/s. This is done because the 20m/s is an arbitrary value as the maximum wind velocity in the study by Gautier and Van Den Boomgaard (2003) turned out to be an error. Looking at other measuring stations values of 25 to 30 m/s also seem realistic. Also the wind-wave direction has been varied in such a way that waves are parallel to the marsh edge.

6.2 Results

In figure 30 cross-sections of different wave simulations are presented. On the marsh edge erosion occurs. High shear stresses from waves are the cause of erosion. Also waves cause flow velocities to increase and take away sediments. It turns out that the effect of a higher wind velocity and a different wind/wave direction is minimal. However, the effect of a higher wave period and significant wave height is much larger. This effect is more clearly observed in figure 31 where the difference in bed level between before and after the storm is presented. The simulation with an adapted significant wave height and wave period showed much more erosion at the marsh edge than the other simulations. In this figure negative values indicate erosion while positive values mean deposition.

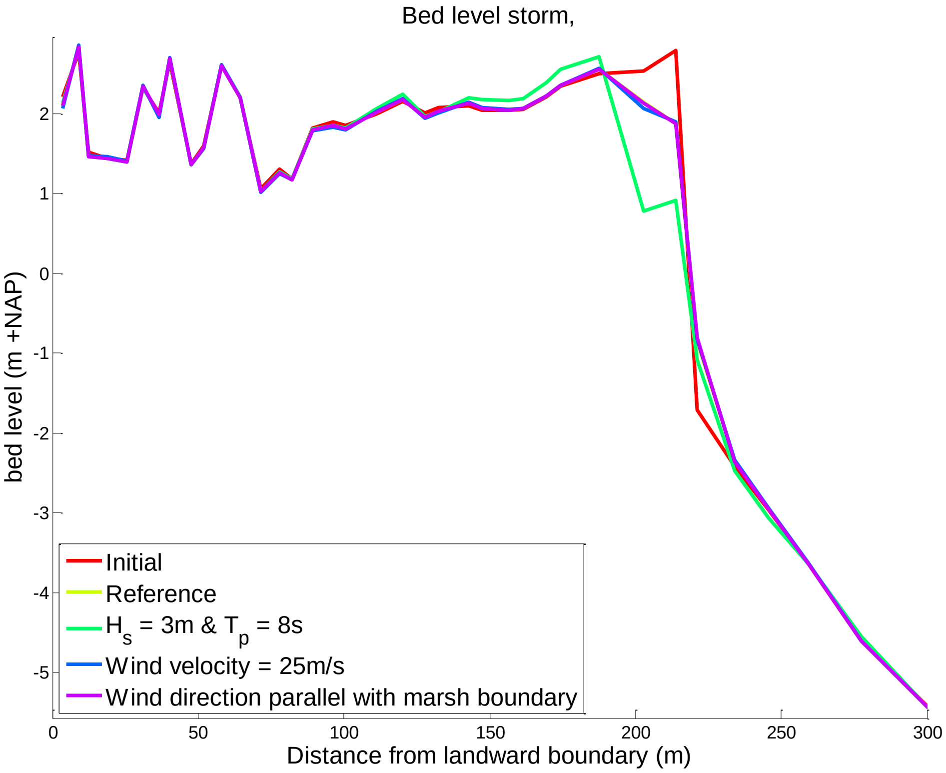

FIGURE 30 CROSS-SECTION BEFORE AND AFTER STORM FOR DIFFERENT VARIABLES

But not only bed levels change due to waves. The largest change occurs in the amount of plants. At the beginning of the simulation plants cover a large part of the marsh platform. Waves cause all plants to die off. The critical shear stress for plants is set on 0.26 N/m^2 (Temmerman et al., 2007). Because waves cause shear stresses higher than 0.26 N/m^2, plants decay.

When analysing the mud content, a small difference between before and after the reference storm is noticed (figure 32 on page 46).Small amounts of mud are eroded resulting in lower mud percentages. Especially close to the marsh edge most mud is eroded as here waves reach the marsh platform and break causing high shear stresses. Due to its smaller grain size than sand, mud erodes easier explaining lower mud percentages. As already stated n the chapter about validation is that waves cause erosion of the marsh edge. This statement corresponds with the outcome of these simulations.

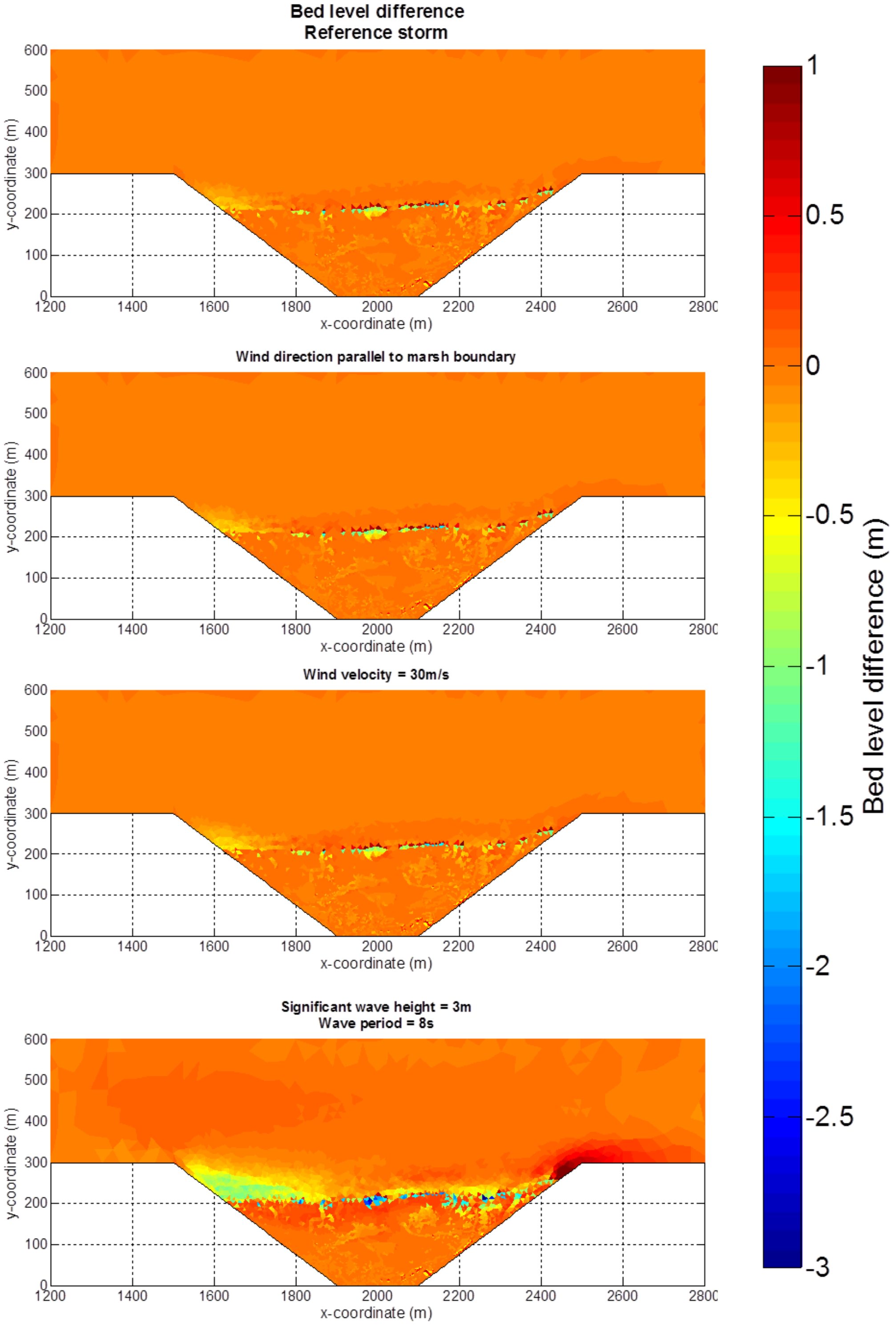

FIGURE 31 BED LEVEL DIFFERENCE BETWEEN SITUATION BEFORE STORM AND AFTER STORM FOR DIFFERENT SIMULATIONS. NEGATIVE VALUES INDICATE EROSION WHILE POSITIVE VALUES INDICATE DEPOSITION

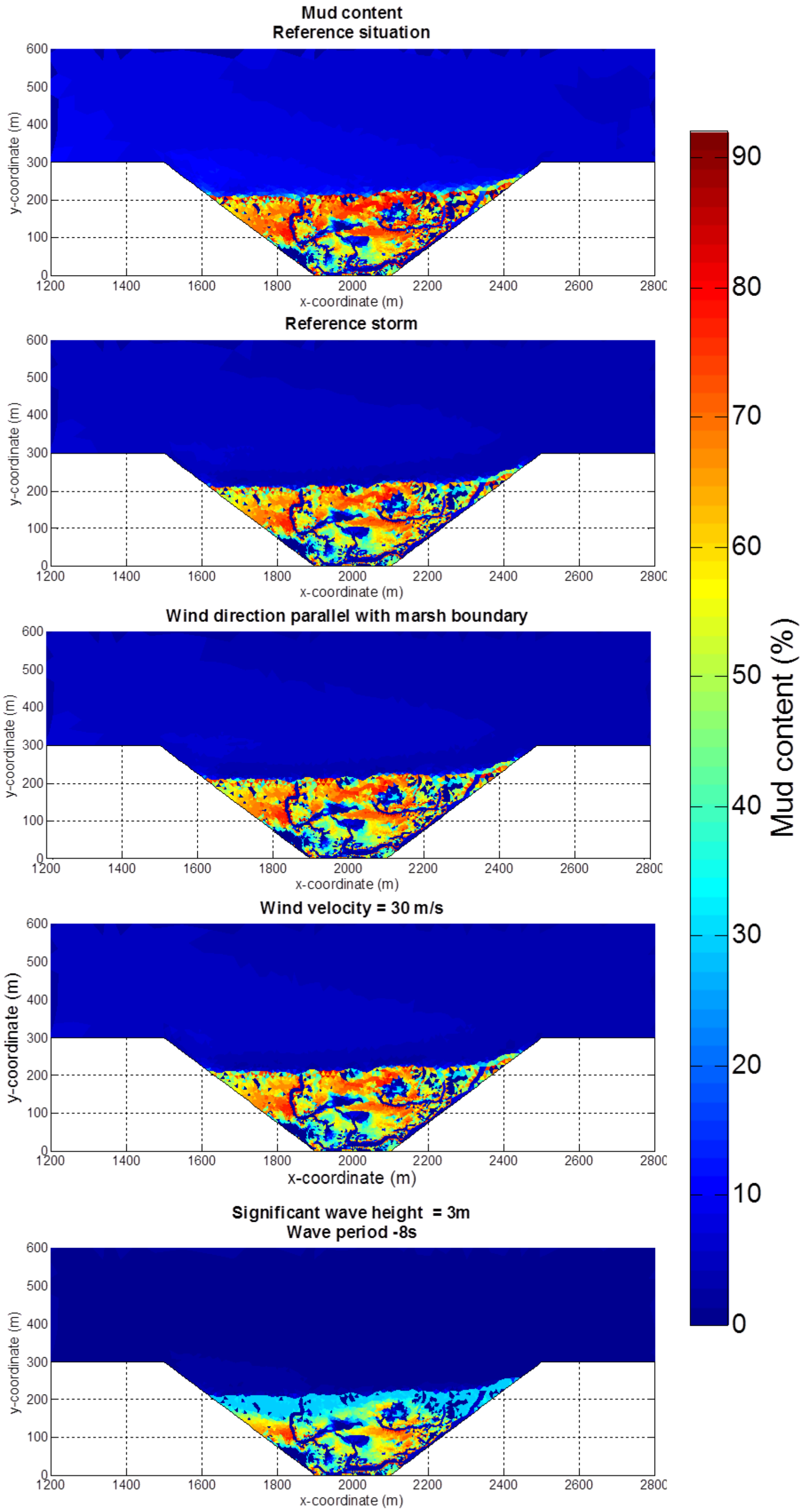

FIGURE 32 MUD CONTENT AFTER DIFFERENT STORMS. IN THE UPPER FIGURE, THE INITIAL MUD CONTENT BEFORE THE STORM IS PRESENTED

Figure 32 also shows that for the simulation with increased wave height and period the difference with the mud content in the reference simulation is largest. At some locations mud content decreases by as much as 62%. Because almost all locations on the marsh edge show mud percentages larger than the critical cohesive mud content and larger than 50% mud erodes faster than sand as the erosion rates are based on the available percentage in the bed. When the percentage of mud becomes equal to the percentage sand (50%), erosion has the same rate for sand as mud. Still the graph shows percentages lower than 50% of mud content. Therefore one of the conclusions could be that even under more difficult circumstances, sand is able to stay settled and apparently mud is not, or at least less than sand. Another explanation is that sand is more available in lower layers. This means that when layers exchange their mud and sand, sand increases in the upper layer and thereby decrease mud content.

An additional simulation is done with a significant wave height of 3m and wave period of 8s but now for a period of 5 days (figure 33). A 5 day-period storm is unrealistic but in order to explore whether multiple storms can influence the marsh further it is a simple assessment tool. It turns out that after 5 days of storm waves continue to erode the edge, resulting in a more gentle slope as is normal in salt marsh environments. Further from the landward boundary, the grid size increases leading to irregularities like the bed level at 214m from the landward boundary. However, this irregularity does not influence the general trend of wave erosion during multiple days. In conclusion a longer storm leads to more erosion.

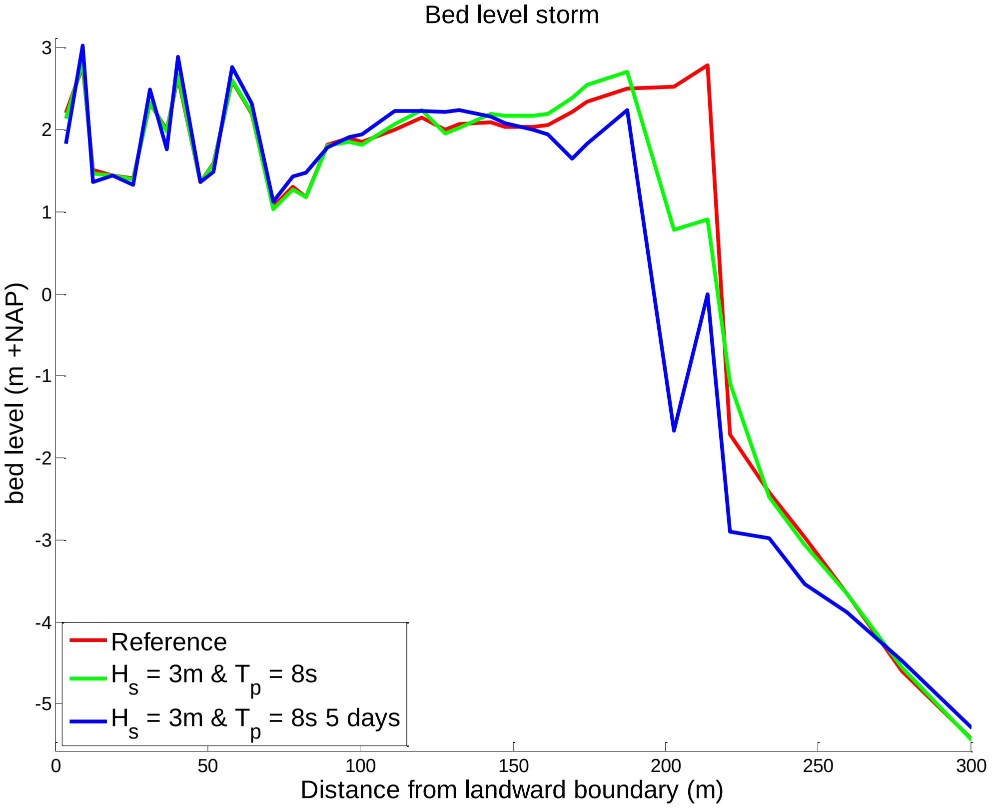

FIGURE 33 CROSS-SECTION BEFORE AND AFTER A STORM OF 1 DAY AND 5 DAYS WITH A SIGNIFICANT WAVE HEIGHT OF 3M AND A WAVE PERIOD OF 8S

6.2.1 Recovery

As already stated, after all test simulations no plants remained on the marsh platform. In order to assess how long it takes for plants to fully recover, some extra simulations are done. In figure 34 plant densities are presented. In the upper image of this figure, plant densities after 100 years of simulation without wind waves are presented. Here a fully developed plant pattern is observed. In the middle image can be seen that after a one-day storm, plants did not survive. To analyse how long it takes for plants to re-establish, the results obtained from the situation after the storm are used as input for another simulation. Mud content, bed level and plant density obtained from the simulation after the storm are therefore implemented in FINEL2D.

Results show that after 19 years of modelling, plants fully cover the marsh again. Because bed levels are higher than in the initial simulation ,where an initial bed level of 0m NAP is applied, plants are able to establish in a much earlier stage. The higher bed levels in the initial situation result in smaller inundation periods directly from the start of the simulation making it perfect conditions for vegetation to establish. Figure 35 shows the difference between the plant development before and after the storm even better.

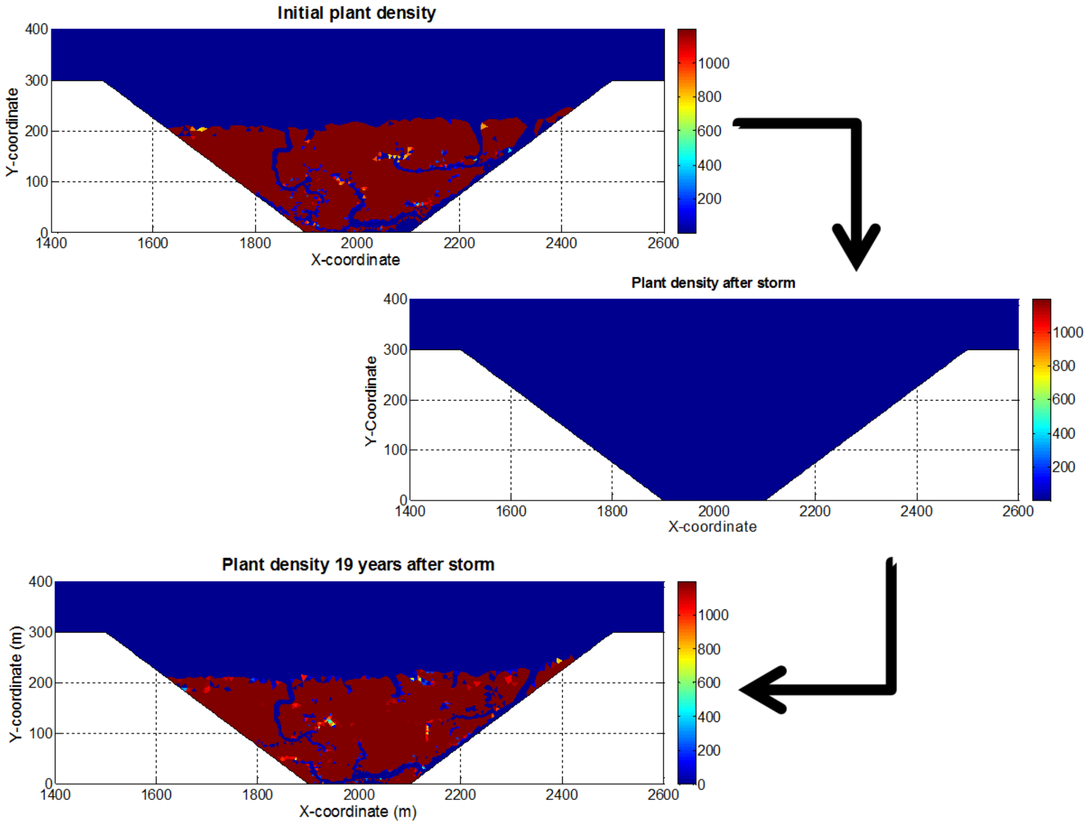

FIGURE 34 PLANT DENSITIES. UPPER FIGURE: PLANT DENSITIES AFTER 100 YEARS OF SIMULATION FOR THE SAND-MUD-PLANT CASE. MIDDLE FIDURE: PLANT DENSITIES AFTER A 1-DAY STORM. BOTTOM FIGURE: PLANT DENSITIES AFTER SIMULATING 19 YEARS AFTER STORM

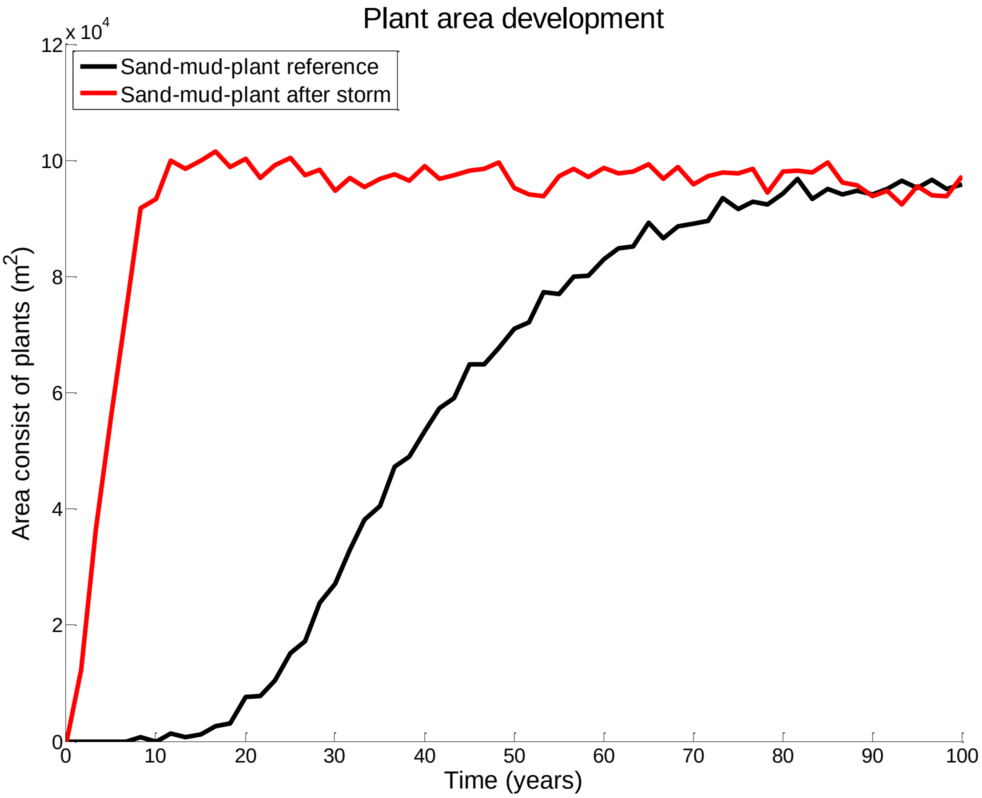

FIGURE 35 PLANT AREA DEVELOPMENT BETWEEN NORMAL SIMULATION AND SIMULATION AFTER STORM

7 DISCUSSION

This study presents a step forward towards modelling salt marsh development. A model has been set-up to quantify and evaluate processes to provide insight in this ecosystem. Finel2D is used for implementation of the interaction between sand-mud interaction and vegetation dynamics. Waves are implemented using SWAN.

7.1 Discussion of methodology

This research showed some good results in modelling the development of salt marshes. The main focus and success of this research was to set-up a model which combines sand-mud interaction with vegetation effects and waves. Nevertheless still some improvements can be made regarding salt marsh modelling.

7.1.1 Vertical mixing

Current simulations show very low mud percentages. When the bed becomes stable vertical mixing causes mud content to reduce as the influence of the lower non-active layer increases. The mud content in the lower layer has a value of 2%. So when equilibrium is reached, the mud content will eventually reach 2% on the entire marsh as there is no accretion of new mud particles. Applying location-specific mud content in the lower non-active layer based on measurements could improve results.

7.1.2 Multiple sediment fractions

Field studies have shown that mud particles settle especially at the landward boundary while sand settles at the edge. This may –in part be- explained by the smaller particle size of mud compared to sand.

A simulation with lower settling velocities for mud (meaning smaller particles) shows that at the landward boundary mud content is higher than at the edge. In addition, this simulation also shows that bed levels decrease from the landward boundary towards the marsh edge. These effects correspond with actual salt marshes. After all, highest mud percentages are found at the landward boundary and the same applies for high bed levels. For that reason the implementation of multiple sediment fractions could result in a better sorting of mud and distribution of bed levels.

7.1.3 Multiple vegetation species

Chapter 2.1 presented different vegetation species which can grow in marsh environments. Each of these plants have their own characteristics, which means that their influence on the flow is different. This study models vegetation according to constant parameters and is therefore independent of different species. An initial step towards a better model could be implementing a distinction between pioneer and normal vegetation. This would probably affect creek patterns on the marsh rather than bed levels. After all, vegetation does not seem to significantly influence marsh elevation on the long term.

7.1.4 Implementation of waves

An initial step towards implementation of waves is made. This is done by implementing waves on the end result of the reference simulation. A first improvement can be made by implementing wind waves during the whole simulation of 100 years. This can be done by using the exceedance probability of wind waves and defining a representative yearly maximum storm.

The implementation of waves in this research resulted in erosion of the marsh edge. Implementing wind waves during the whole simulation could therefore result in a more gentle positive slope from the high landward boundary towards the lower marsh edge. The implementation of waves could also result in the presence of a mudflat in front of the marsh.

The effect of waves on vegetation is another aspect which is not yet implemented in the model. Mariotti and Fagherazzi (2010) developed an equation which calculates the attenuation of waves by vegetation.

Already some papers are available which study the effect of vegetation on the attenuation of waves during storms (Borsje et al., 2011; Gedan et al., 2011; Lopez, 2009). All studies found significant contribution of vegetation in decreasing wave heights during storms. However, information on the effect of extreme events on ecological systems is lacking (Groffman et al., 2006). In this research all plants decayed as they did not survive the extreme stresses due to wind waves. Therefore is recommended to analyse the effect of vegetation decay during storms. When vegetation is able to withstand extreme conditions, it can be considered a good solution in attenuating waves.

7.1.5 Erosion digging out vegetation

Erosion can cause vegetation roots to reach upper surface. When this happens, vegetation is vulnerable to be taken away by waves. This effect is only indirectly modelled in FINEL2D. Vegetation roots reaching the upper surface go most of the time hand in hand with high erosion rates. High erosion rates are caused by high shear stresses. When these high shear stresses are higher than critical vegetation shear stresses, vegetation will decay.

Nevertheless in the present model vegetation will survive low erosion rates. When low erosion rates continue for a longer period, vegetation roots will eventually be revealed and waves will take away the plants. This effect is not included in the model yet. However, the question rises how often this happens in reality.

7.1.6 Pick up of sediment by stems and leaves

In addition to erosion digging out roots, the effect of stems and leaves picking up sediment as well as the effect of pioneer vegetation stabilizing mud flats is not implemented at the moment. First a formulation of these processes has to be developed before these processes can be implemented. The implementation of these kinds of processes contributes in assessing their influence.

7.1.7 Real test case

To really quantify the quality of the model an actual salt marsh has to be modelled. This brings some difficulties as there is not much information available about the long-term development of salt marshes from initial bed to fully developed marsh. Also boundary conditions have to be location-specific which requires measurements. The input of Attema (2014) could be used to evaluate this set-up and quantify the performance of the model on the development of Land van Saeftinghe. However, the set-up of a real test case is out of scope for this study.

7.2 Construction of artificial salt marshes

Salt marshes are an ecological solution in preventing floods. Some studies present experiences in the creation of artificial salt marshes. Groynes seem to create optimal conditions for sediment deposition enhancing the development of salt marshes (Bakker et al., 2002). Another option which enhances the development of marshes is digging of tidal creeks (Wolters et al., 2005).This improves drainage and enhances plant colonisation rates and species diversity/distribution. In addition sediment fences could protect the build-up from marshes as erosion is less likely to occur (Boumans et al., 1997; Scarton et al., 2000).

This thesis provides insight in which processes are important in the development of salt marshes, while the studies mentioned above improve the build-up of marshes. In other words this research gives an initial insight in which factors are important for salt marshes to be formed. For example salt marshes can only occur when enough mud is available as mud increases bed levels significantly. In addition tidal amplitudes determine bed levels and expansion of the marsh. Low tidal amplitudes result in lower bed levels making it more vulnerable for wind waves while high amplitude lead to high bed levels which prevent sediments from settling. The presence of vegetation is important in creating creeks.

In conclusion, this research has contributed in providing the external conditions (enough mud and sufficient amplitude) which favour the formation of salt marshes. When these conditions are present to a sufficient extent, the development of marshes can be enhanced by the construction of groynes, digging of tidal creeks and use of sediment fences.

8 CONCLUSION

In this chapter the research questions mentioned in chapter 1.3 will be answered.

8.1 Which processes contribute to salt marsh development according to literature?

The interplay between morphodynamics, hydrodynamics, vegetation dynamics and waves emerges salt marsh development. In addition, these processes also influence each other. It turns out that vegetation is able to influence bed levels because they increase friction. However, the establishment and decay of vegetation is determined by the other processes.

8.2 How can sand-mud interaction be taken into account when simulating salt marsh development?

The interaction between sand and mud is modelled using the method by Van Ledden (2003). Based on critical mud content is determined when the bed is cohesive resulting in higher critical erosion shear stress. It is assumed that when 30% of the bed consists of mud, electrostatic forces between particles arise which makes the bed more difficult to erode.

8.3 How can the influence of storms on salt marshes be modelled?

By using SWAN (a wind wave model developed by Delft University of Technology) different one day storm events are analysed. FINEL2D has been adapted so that the shear stress induced by waves now also influences vegetation. For this adaptation is assumed that vegetation is influenced in the same way by wind waves as by tidal flows.

8.4 How can the marsh model be validated?

Based on a cross-section, sedimentation rates and soil properties, simulation results are compared with characteristics of Paulinaschor. The bed levels of the marsh platform in the simulation showed large similarities with Paulinaschor. The relative flat marsh and the location of the marsh edge in the simulation also correspond well with Paulinaschor. Nevertheless, the reference simulation was not able to show a mud flat in front of the marsh. The lack of multiple sediment fractions and waves in the reference simulation is probably the explanation for the absence of a tidal mudflat.

8.5 What is the influence of the following processes on salt marsh development?

8.5.1 Sand-mud interaction and vegetation

Sand alone was not able to create a salt marsh environment due to settling lag. Once mud was added to the model, bed levels increased and creeks developed. Implementing vegetation mainly influences creek patterns on the marsh. Plants obstruct flow and therefore more creeks are needed to discharge all water from the marsh.

8.5.2 Tidal amplitude

Tidal amplitude is important for the expansion and height of the salt marsh. Higher amplitudes lead to higher bed levels but a smaller marsh, while lower amplitudes lead to lower bed levels but larger marsh. The height of the amplitude determines on which level sediments can be deposited explaining the difference in bed level. In addition, tidal amplitudes also determine flow velocities as these are dependent on the water depth. In the simulation with low tidal amplitudes flow velocities during high tide are lower than in the reference situation making it favourable for particles to settle. This explains the lateral expansion in the simulation with low tidal amplitudes and the small marsh in the simulation with high tidal amplitudes. However, such a low marsh in the simulation with low tidal amplitudes is more vulnerable to storm erosion. Therefore cannot be concluded that lower tidal amplitudes favour marsh development.

8.5.3 Mud availability

The availability of mud mainly affects the expansion of the marsh. When more mud is available, the marsh expands while the marsh decreases when less mud is available. The effect of mud availability on bed levels is relatively small, especially compared to the effect of tidal amplitudes. Nevertheless, the simulation with less mud resulted in a slightly lower average bed level than the simulation with a higher mud concentration.

8.5.4 Continuous deposition

A simulation is done where deposition is continuous. This means that sedimentation occurs all the time. In literature there is debate about critical sedimentation shear stresses. Some state that there is no such thing and therefore this simulation is done. Results show a large expansion of the marsh compared to the reference case as there is no threshold before particles settle.

8.5.5 Critical mud content

The simulation with a critical mud content of 20% showed a small expansion compared to the reference simulation. In this simulation the bed becomes cohesive earlier. This means that erosion is less likely to occur as the critical bed shear stress for erosion is influenced.

8.5.6 Settling velocity mud

The simulation with a low settling velocity for mud showed a very small salt marsh with low bed levels and without creeks. Despite the absence of creeks, this is the only simulation which shows higher mud concentration and bed levels at the landward boundary than the marsh edge which corresponds with literature. This implies that adding multiple mud fractions would result in a better representation of reality.

8.5.7 Maximum bottom slope

A maximum bottom slope of 0.5 is applied. This means that when a bottom slope of 0.5 is reached, erosion occurs according to avalanche formulations. Results show that the implementation of a maximum slope causes erosion of the marsh edge. This effect is however, relatively small.

8.5.8 Storms

Finally the influence of storm events is assessed. Storms caused the marsh edge to erode and mud to be distributed better in correspondence with actual marshes (high mud concentration at the landward boundary and lower at the edge). Vegetation completely decayed after the storm event. Whether this is a reasonable outcome is the question. The model can be improved in this respect, but initial results have been promising.

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1 APPENDIX: IMPLEMENTATION PROCESSES INTO FINEL2D

1.1 Sand-mud interaction

The method of Van Ledden (2003) is already present in FINEL2D, although – before this thesis - not used in combination with a developing salt marshes with inclusion of vegetation. The mathematical sand-mud interaction present in FINEL2D slightly differs from the method by Van Ledden. In this paragraph a mathematical description of sand-mud interaction is provided

In table 9 the formulas for erosion from sand and mud for a cohesive and non-cohesive bed are presented, Erosion only occurs when the actual bed shear stress (τ_b) is higher than the critical erosion shear stress (τ_c).So when $(\frac{\tau_b}{\tau_c} - 1)$ becomes negative, no erosion occurs.

TABLE 9 EROSION EQUATIONS FOR SAND AND MUD

	Cohesive ($pm < pm_{crit}$)	Non cohesive ($pm \geq pm_{crit}$)
Mud	$E_{mud} = p_m M_c(\frac{\tau_b}{\tau_c} - 1)$	$E_{mud} = p_m M_{nc}(\frac{\tau_b}{\tau_c} - 1)$
Sand	$E_{mud} = (1 - p_m)M_c(\frac{\tau_b}{\tau_c} - 1)$	Engelund-Hansen

In this formula E_{mud} is the erosion rate by mud in m/s, p_m is the mud content and M is the erosion coefficient (M_c when cohesive and M_{nc} when not cohesive).

For a cohesive bed, the only thing that changes in determining the erosion of mud particles is the erosion coefficient M. The cohesive erosion rate for sand particles is also calculated using the same formulation. It is exactly the same as for cohesive mud beds, apart from the mud content, which is now replaced by the sand content (equal to $1 - p_m$):

(1)

The deposition of sand and mud in the model is independent from whether the sand-mud mixture is cohesive or non-cohesive. Therefore the deposition formula for sand follows the more known sediment transport methods. The model which is used in this research is the sediment transport formula of Engelund and Hansen. This transport formula is used because it is the only method implemented in FINEL2D which works in combination with sand-mud interaction. In this method first the equilibrium concentration is calculated:

$$c_{eq} = \frac{0.05 * \rho_w^2}{(1 - \epsilon)\left(\frac{\rho_s}{\rho_w} - 1\right)^2 d_{50} g C^3} u^4 \tag{2}$$

In this formula ϵ is the porosity, ρ_w the density of water, ρ_s is the dry bulk density of sediment, d_{50} the median grain size, g is the acceleration of gravity, C is the Chézy-coefficient and u is the depth-averaged velocity. The following equation then determines the new sediment concentration:

$$\frac{dc}{dt} = \frac{c_{eq}(t) - c(t)}{T_A} \tag{3}$$

In which c is the concentration of the current time step and T_A is the adaptation time as sediment transport lags hydrodynamic forcing. The adaptation time is calculated as follows:

$$T_A = \frac{h}{w_s} \tag{4}$$

In which h is the water depth and w_s the settling velocity. When the actual concentration is lower than the equilibrium concentration erosion occurs (this formula is only applied when the bed is not cohesive), when the actual concentration is higher than the equilibrium concentration sedimentation takes place.

Mud deposition is calculated using the formula of Krone (1962). This formula is as follows:

$$D_{mud} = w_s * \frac{c}{h} * (1 - \frac{\tau}{\tau_s}) \qquad (5)$$

Wherein τ_s is the critical sedimentation shear stress, w_s is the fall velocity of mud, c is the potential silt layer in the water column and h is the water depth.

Because erosion and sedimentation of sand and mud are treated differently, in most studies only sedimentation or erosion occurs but not at the same time. However, actual measurements suggest that sedimentation can occur the same time as erosion. Therefore the critical shear stress for sedimentation was in some studies set on very large values resulting in continuous deposition (Sanford & Halka, 1993; Winterwerp, 2007). The results showed that with continuous deposition a more realistic picture arose. However, in this thesis, a lower critical sedimentation shear stress is used. In executing the effect of different processes, the effect of continuous deposition is included.

1.2 Multiple layer mixing

FINEL2D works with multiple bed layers. The reason for introducing multiple layers is twofold (Ribberink, 1987). Firstly, it is a more realistic representation of reality as the bed composition below the upper layer is not constant. Second, applying multiple layers increases model stability. In this study 5 active layers are used. These layers are called “active” because they can vary in mud content. A non-active layer is located below the lowest active layer. The non-active layer requires a constant mud percentage. The mud content in the other 5 active layers is then based on the lowest non-active layer and the deposition and erosion in the upper active layer.

The mud content in the active layers is based on a Cranck-Nicholson discretization scheme. The following equation is used to determine the bed composition of layer j on timestep $n + 1$.

$$\frac{p_j^{n+1} - p_j^n}{\Delta t} + \theta \frac{s_{j+1/2}^{n+1} - s_{j-1/2}^{n+1}}{\Delta z} + (1 - \theta) \frac{s_{j+1/2}^{n} - s_{j-1/2}^{n}}{\Delta z} = 0 \qquad (6)$$

In this equation p is the mud content, t is time ,z is bed level height, s is the sediment flux between layers and θ a numerical coefficient. The mud content of each layer is therefore determined by sediment fluxes from the layer above and below the specific layer of the current and previous time step. Furthermore the mud content is also dependent on its own mud content of the previous time step. Each sediment flux mentioned in equation 6 is determined by the same equation but with a slight difference in time step and layers. In equation 7 an example equation of the sediment flux is presented:

$$s_{j+1/2}^{n+1} = \frac{1}{2} u_z^{n+1/2} (p_{j+1}^{n+1} + p_j^{n+1} - \Xi_{j+1/2}^{n+1} \frac{p_{j+1}^{n+1} - p_j^{n+1}}{\Delta z} \qquad (7)$$

In this equation u_z is the propagation velocity of the bed level and Ξ is a mixing coefficient. The mixing coefficient represents the mixing between the different layers in the bed. It is argued that the mixing coefficient depends on water depth and flow velocity (Armanini, 1995). However, in this thesis the mixing coefficient is assumed constant.

From equation 7 can be derived the sediment flux of the layer below layer n depends on characteristics of layer n and one layer below. Approximately the same equation is used to determine sediment fluxes of the layer above layer n, but these then depend on the characteristics of layer n and the one above.

1.3 Vegetation

Vegetation affects hydraulic roughnesses and thereby velocities occurring on marsh platforms. The effect of vegetation on the hydraulic roughness is already present in FINEL2D. Furthermore, the effect of vegetation establishment, expansion and decay is also present in FINEL2D. In this paragraph the implementation of vegetation is described.

Vegetation only influences flow velocities when submerged. When submerged, vegetation causes resistance on the flow resulting in decreased flow velocities. The impact on the flow depends on the density of plants, drag coefficient of plants, plant height and stem diameter. Because vegetation is assumed to behave the same as small piles, the influence of vegetation is calculated the same as friction due to piles. More vegetation results in more resistance and thereby lower flow velocities. Because flow velocities affect shear stresses, indirectly sedimentation and erosion rates are also influenced by vegetation. The shear stress influenced by vegetation is calculated as follows:

$$\tau_b = \frac{1}{1 + \frac{1}{2} * C_{Dv} * k * \phi * n_b * C_{fb}} * \frac{\rho g u^2}{C^2} \tag{8}$$

In this equation τ_b is the bed shear stress, C_{Dv} is the plant drag coefficient, k is the stem height, ϕ is the stem diameter,n_b is the plant density, C_{fb} is a bed friction coefficient, ρ is the density of water, g is the acceleration of gravity, u is the depth-averaged velocity and C is the Chézy-coefficient without vegetation. This equation corresponds with the equation from Baptist (2005).

From this equation some characteristic behaviour from vegetation (as already presented in chapter 2.3) can be derived. For example, more plants means higher plant densities, and a higher density causes more friction. Because more friction is present, velocities decrease and therefore the shear stress decreases. Low velocities result in high sedimentation rates as particles‘ gravity forces are higher than the upward forces from the flow.

Besides the effect of vegetation on the hydraulic roughness, vegetation growth is also implemented in FINEL2D. In chapter 2.3 the window of opportunity model which is present in FINEL2D is described (Balke et al., 2011). This paragraph will provide some equations associated with this model.

For seedlings to establish an inundation free period ($T_{phase,1}$) is required. When this condition is met, seedlings establish as follows:

$$For\ T_t > T_{phase,1} \quad \left(\frac{dn_b}{dt}\right)_{seedling} = P_{est} * n_{b,establisment}$$

A stochastical function (P_{est}) determines whether seedlings establish, but only when the inundation-free period condition is fulfilled. Next the root system develops. This phase requires relative calm hydrodynamic conditions and is characterized by a linear function:

$$For\ T_{phase\ 2} > T_i > T_{phase\ 1} \qquad \tau_{b,crit,phase\ 2} = a_\tau * \left(T_i - T_{phase\ 1}\right) + \ b_\tau$$
$$\tau_{b,crit,phase\ 2} > \tau_b$$

In this equation $\tau_{b,crit,phase\ 2}$ is the critical bed shear stress for seedling resistance and τ_b is the actual critical bed shear stress.

In phase 3 high energy events must be survived for vegetation not to decay. This equation is as follows:

$$For\ T_{phase\ 3} > T_i > T_{phase\ 1} + T_{phase\ 2}: \qquad \tau_{b,crit} > \tau_b$$

In this equation $\tau_{b,crit}$ is the maximum shear stress resistance of mature vegetation.

After vegetation established and developed throughout the first three phases, the stem density starts to grow according to the following equation:

$$\left(\frac{dn_b}{dt}\right)_{growth} = r\left(1 - \frac{n_b}{n_{b,max}}\right)$$

In this equation r is the intrinsic growth rate and $n_{b,max}$ is the maximum stem density.

The last stage determines the lateral expansion of plants. This is implemented by the following equation:

$$\left(\frac{dn_b}{dt}\right)_{expansion} = K\frac{\nabla \mathrm{n_b}}{|\nabla \mathrm{n_b}|} * \nabla \mathrm{n_b}$$

In which ∇n_b is the difference in plant densities between two adjacent locations and K is a uniform radial growth rate.

An important remark is that morphological development is calculated using a morphological acceleration factor. Because this factor is also used as acceleration factor for determining the required inundation free period for vegetation to establish it means that during low tide, vegetation can easily establish because time steps are multiplied by the morphological acceleration factor and a relative calm period is easily reached. However, this effect is compensated at high tide when vegetation decays.

1.4 Storm events

First waves have to be implemented in FINEL2D before addressing the effect on the bed level. Because plants are not able to simulate in combination with waves, a small adaptation has to be done in the source code of FINEL2D. In the equation below the shear stress for plants as it is present in the initial model is presented:

$$\tau_b = \frac{1}{1 + \frac{1}{2} * C_{Dv} * k * \phi * n_b * C_{fb}} * \frac{\rho g u^2}{C^2} \tag{9}$$

Because waves also cause shear stress, the following adjustment is made:

$$\tau_b = \frac{1}{1 + \frac{1}{2} * C_{Dv} * k * \phi * n_b * C_{fb}}\left(\frac{\rho g u^2}{C^2} + \tau_{bw}\right) \tag{10}$$

In which τ_{bw} is the shear stress induced by waves. In this way the bed shear stress of currents and waves are influenced by vegetation. Because the total bed shear stress consists of shear stress by currents and waves, it seems plausible that the combined bed shear stress can also be multiplied by the vegetation factor

2 APPENDIX: SOIL CHARACTERISTICS PAULINASCHOR

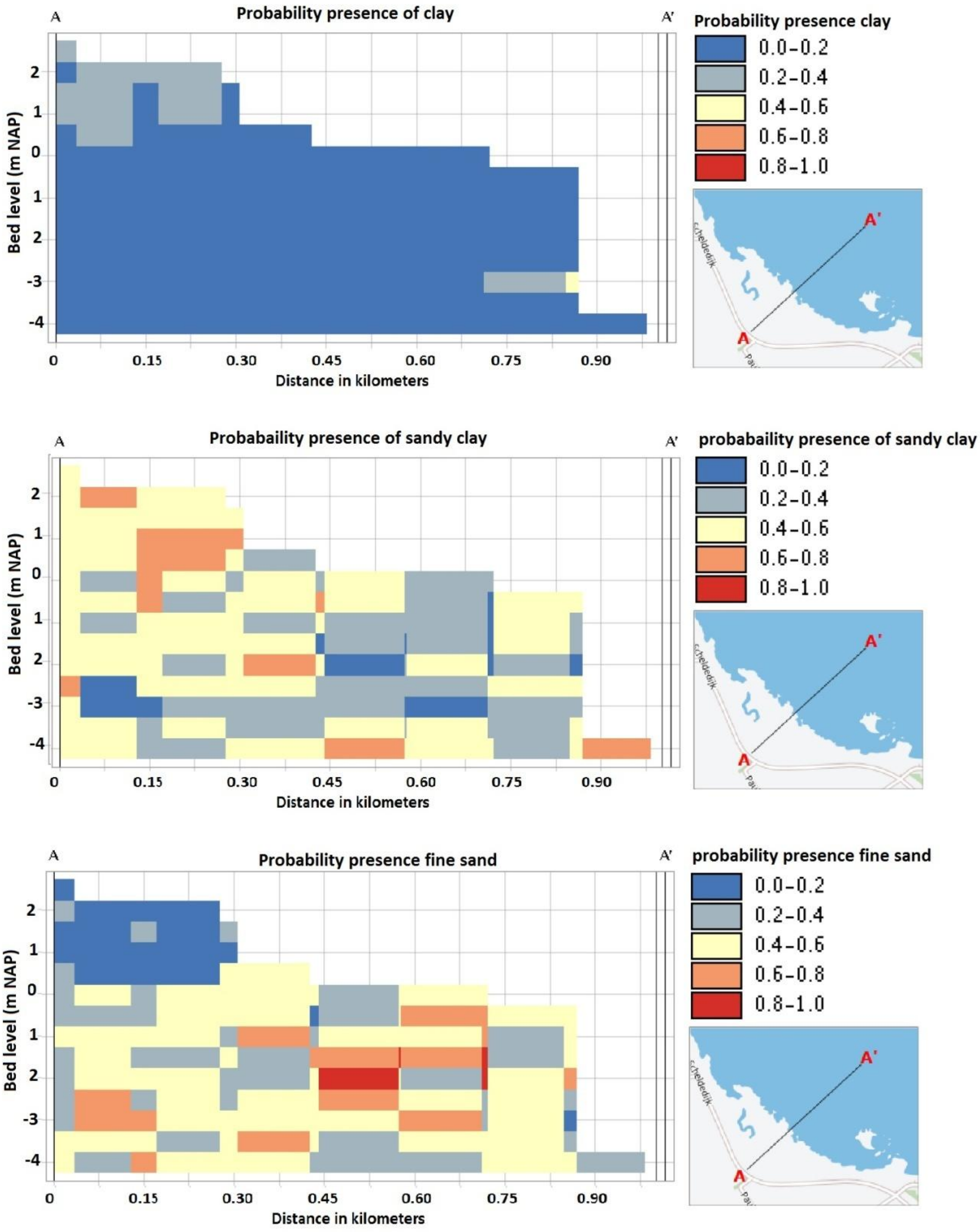

FIGURE 36 PROBABILITY PRESENCE SOIL TYPES, OBTAINED FROM THE REGIS II MODEL, DINLOKET.NL

3 SENSITIVITY MODEL

This paragraph will present results regarding changes in morphological acceleration factor and grid profile.

3.1.1 Morphological acceleration factor

In order to assess the importance of the morphological acceleration factor, simulations are done with an acceleration factor of 25 and 50. In general is assumed that a lower acceleration factor implies more robust results.

Figure 37 shows the average bed level development for different morphological acceleration factors. In this study a factor of 100 is used. A factor of 100 shows the most fluctuating line of the different simulations. A higher acceleration factor means that the effect of spring and neap tide is also larger as every time step is multiplied by 100. However, the difference is relatively small between a morphological factor of 100 and 25. All simulations will eventually result in about the same equilibrium average bed level as this is independent of the used morphological acceleration factor. Therefore the difference between the average bed levels of the different factors decreases towards the end of the simulation period (100 years).

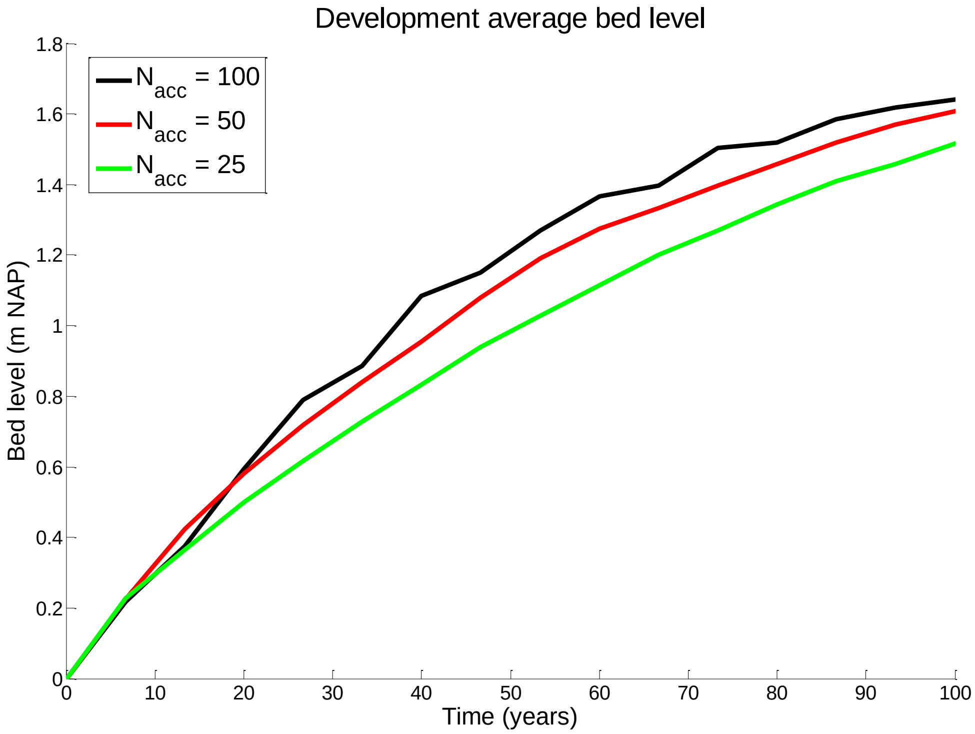

FIGURE 37 AVERAGE BED LEVEL DEVELOPMENT FOR DIFFERENT MORPHOLOGICAL ACCELERATION FACTORS

3.1.2 Grid size

In current simulations creeks are almost all one grid size wide. One coarser and one finer grid are used to determine the influence on the outcome of the model. This could also influence the width of creeks and thereby depth and length of creeks as the same volume has to be discharged. Figure 38 shows the coarse and fine grid used as input. The smallest element in the fine grid simulation is 3.46 m^2. The coarse grid has a smallest area of 54.4 m^2. Modelling time for the fine grid is much smaller than for the coarse grid. The coarse grid profile takes about 1 day for modelling 100 years. The fine grid profile takes about 15 days.

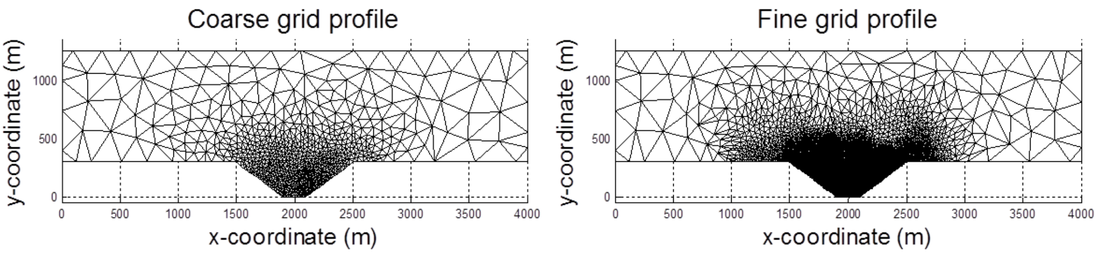

FIGURE 38 COARSE AND FINE GRID PROFILE

FIGURE 39 SHOWS BED LEVELS OF THE TWO GRIDS AFTER 100 YEARS OF MODELLING. THE COARSE GRID PROFILE SHOWS ONE LARGE CREEK WHILE THE SIMULATION WITH A FINE PROFILE SHOWS MULTIPLE SMALLER CREEKS (SEE ALSO
table 10table 10). The amount of creeks really depends on the grid size, as a smaller grid results in more tributaries (see table 10). Also the area percentage consisting of creeks in the simulation with a fine grid is larger. You would expect that this percentage stays relatively constant as the same amount of water has to be discharged in all simulations. Although the percentages slightly differ, the location of the creeks in the medium grid does not differ a lot from the fine grid. The location of these creeks is kind of the same. The only difference is that the simulation with a finer grid has more small tributaries.

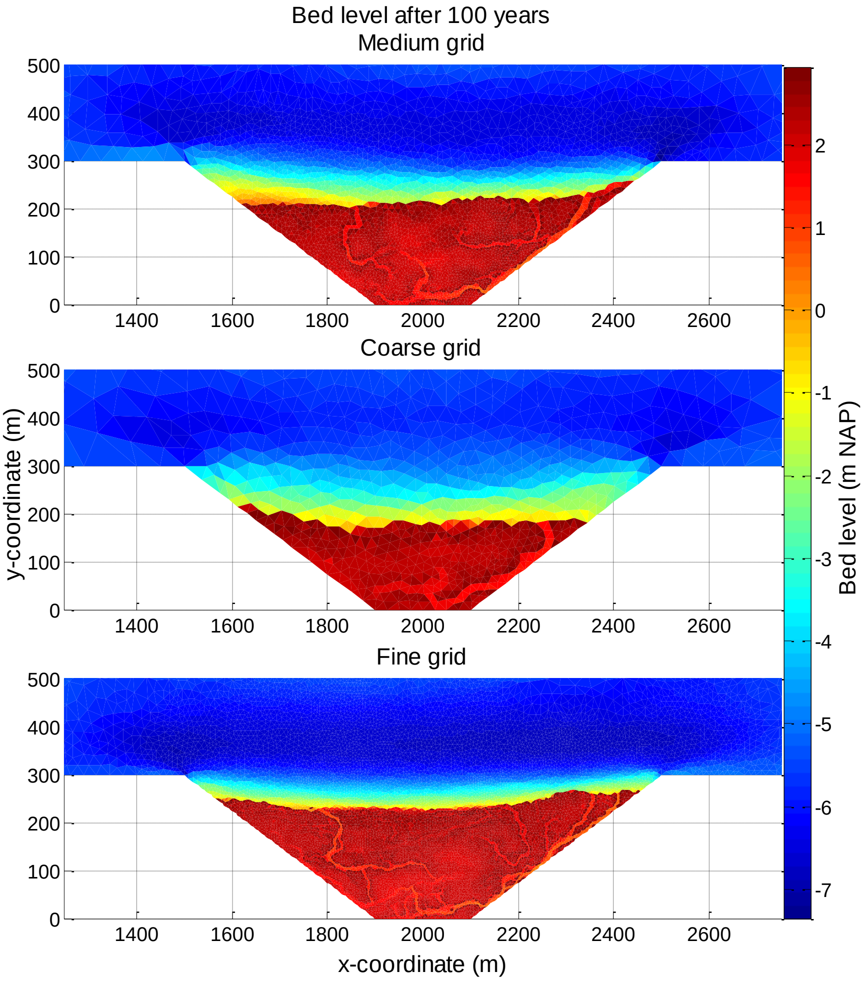

FIGURE 39 BED LEVEL MEDIUM, COARSE AND FINE GRID

TABLE 10 CREEK CHARACTERISTICS MEDIUM, COARSE AND FINE GRID

Case	% Creeks on marsh	Average bed level creeks (m NAP)	Average bed level marsh (m NAP)	Average depth creeks (cm)	Number of tributaries
Medium grid	12.6	1.50	2.29	79	12
Coarse grid	12.1	1.67	2.41	74	2
Fine grid	14.0	1.43	2.27	84	26

A relative large difference between marsh area is observed, the simulation with a fine grid shows a larger marsh area than the reference- and coarse grid simulation (see table 11). The areas will not grow largely anymore as all three simulations are close to reaching equilibrium (see figure 40). The large area in the fine grid is compensated by higher bed levels in the coarse grid simulation. This will eventually result in the same marsh volume.

TABLE 11 MARSH AREA DIFFERENT GRIDS

Simulation	Total marsh area (ha)
Medium grid	10.72
Coarse grid	8.25
Fine grid	12.58

The difference between average bed level development of the different simulations is small (figure 40). Even the simulation with a coarse grid shows the same order of magnitude bed levels as the other simulations. Therefore considering bed level, the model is quite robust.

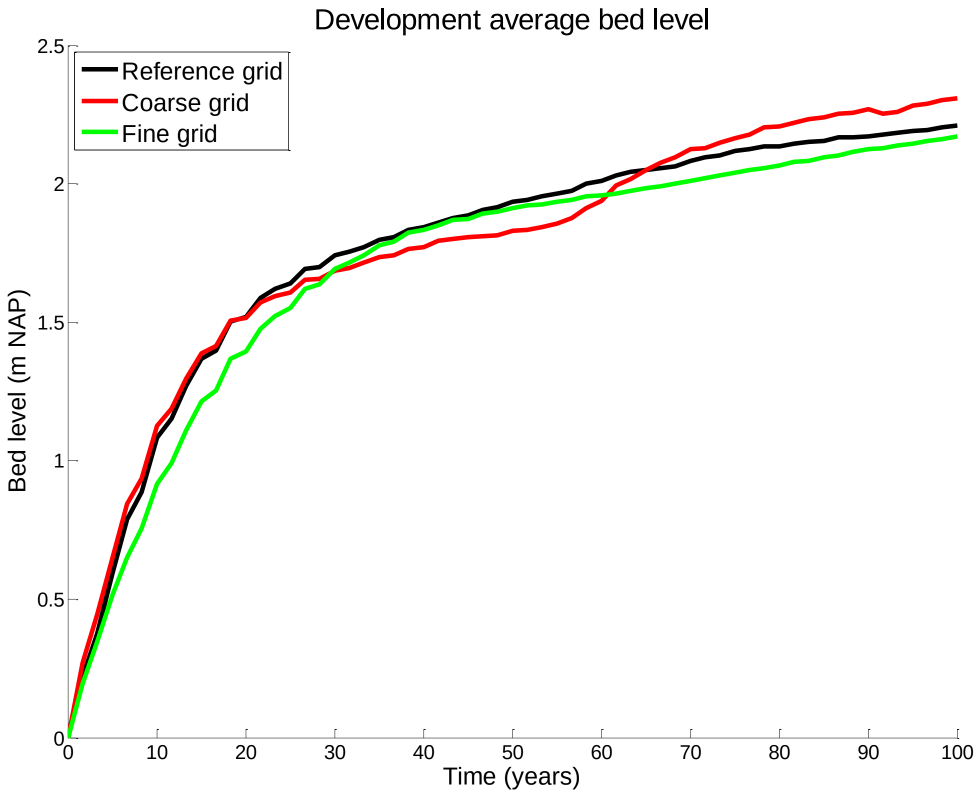

FIGURE 40 BED LEVEL DEVELOPMENT OF SIMULATIONS WITH DIFFERENT GRID

4 APPENDIX: BED LEVEL DEVELOPMENT

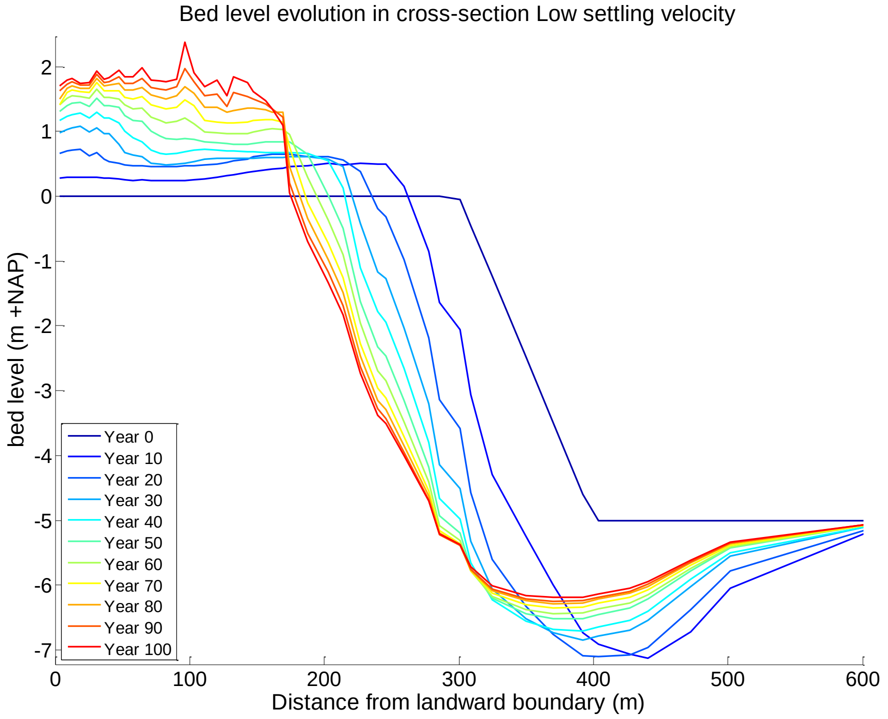

FIGURE 41 BED LEVEL DEVELOPMENT OF SIMULATION WITH LOW SETTLING VELOCITY

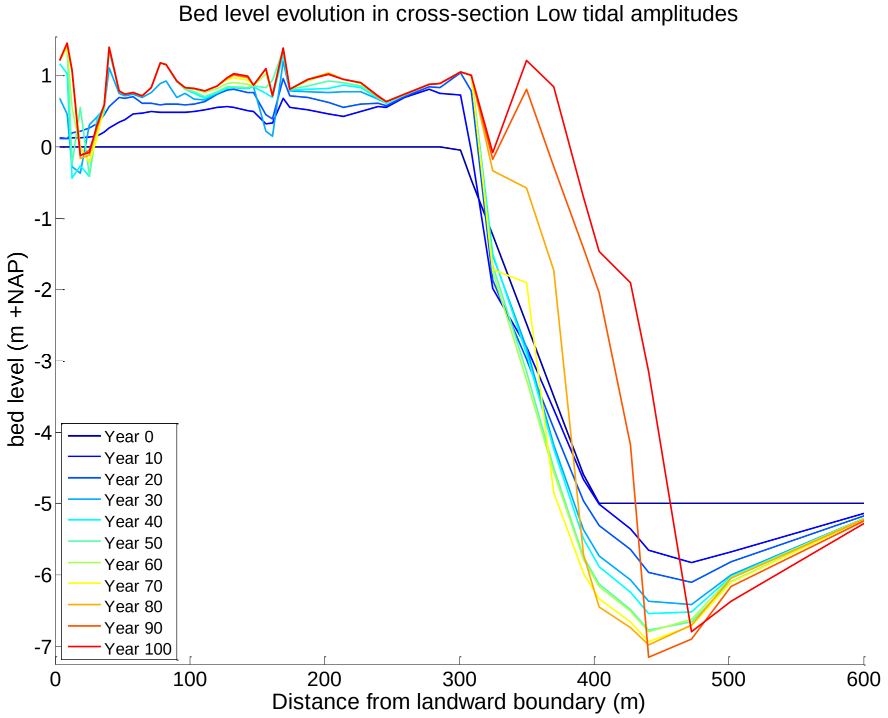

FIGURE 42 BED LEVEL DEVELOPMENT OF SIMULATION WITH LOW TIDAL AMPLITUDES

5 APPENDIX: PLANT DENSITIES

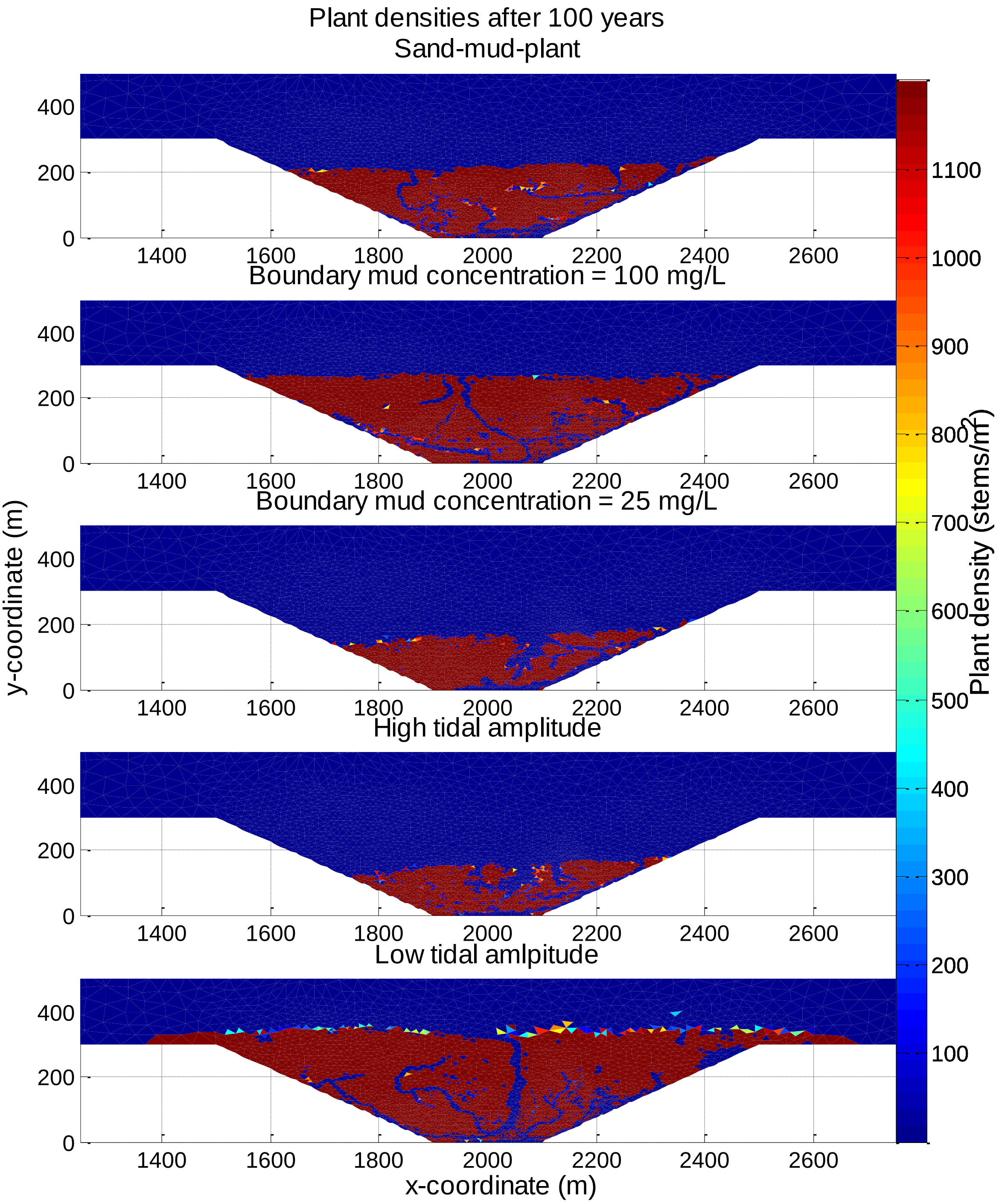

FIGURE 43 PLANT DENSITIES AFTER 100 YEARS FOR SAND-MUD-PLANT, BOUNDARY MUD CONCENTRATIONS AND TIDAL AMPLITUDES SIMULATIONS

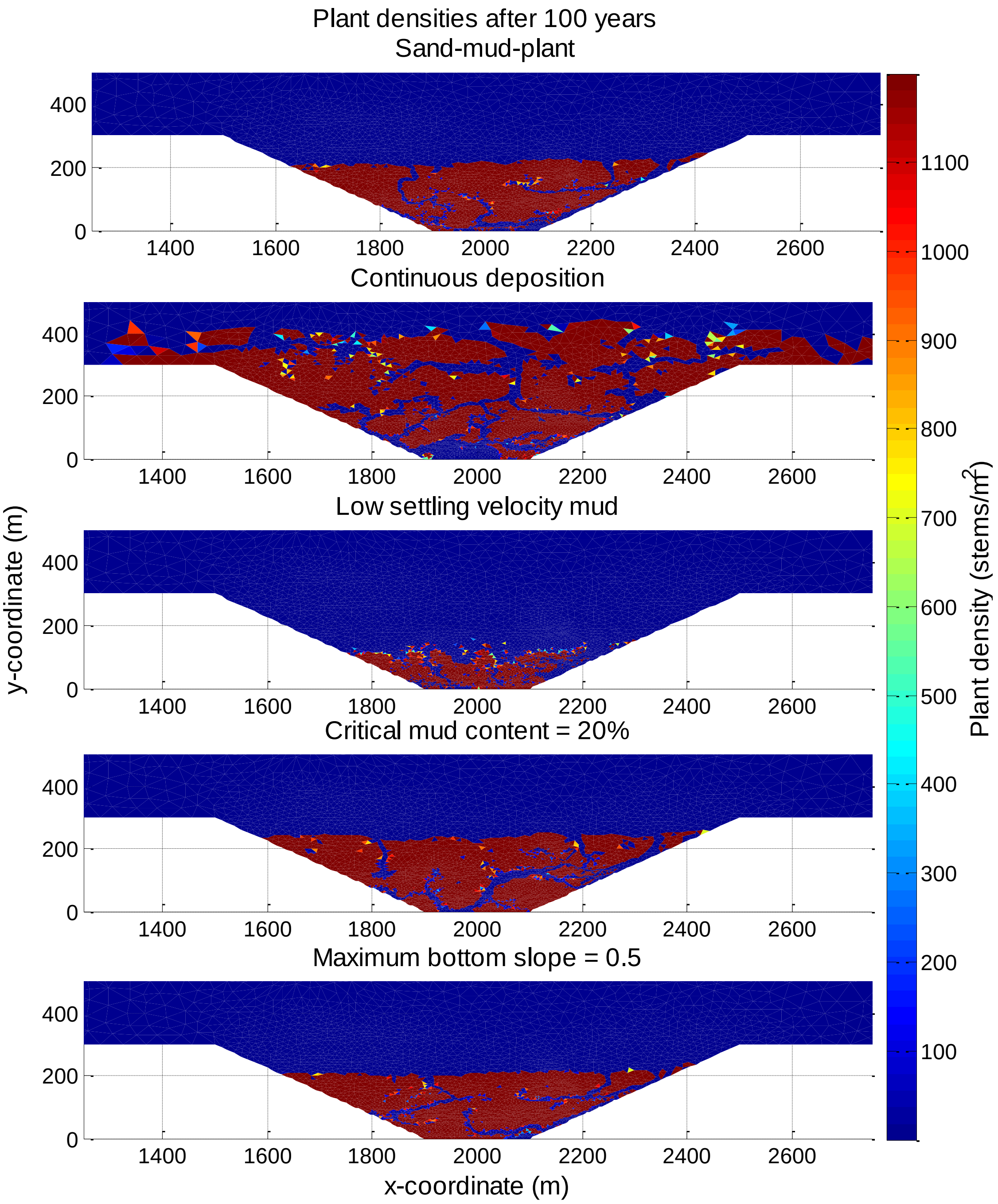

FIGURE 44 PLANT DENSITIES AFTER 100 YEARS FOR THE REFERENCE SIMULATION, CONTINUOUS DEPOSITION, LOW SETTLING VELOCITY FOR MUD, CRITICAL MUD CONTENT OF 20% AND A MAXIMUM BOTTOM SLOPE OF 0.5

6 APPENDIX: MUD CONTENT

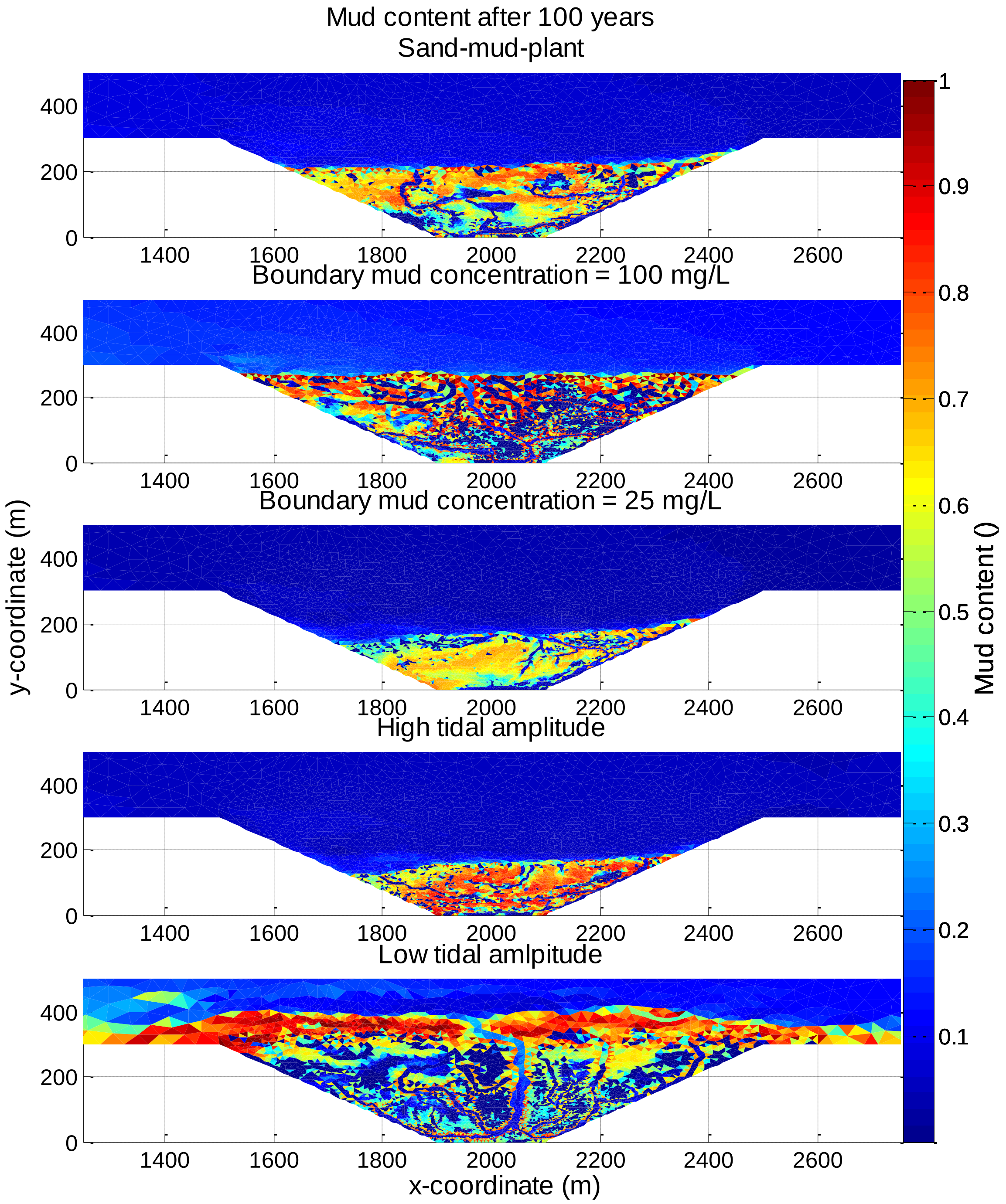

FIGURE 45 MUD CONTENT AFTER 100 YEARS FOR SAND-MUD-PLANT, BOUNDARY MUD CONCENTRATIONS AND TIDAL AMPLITUDES SIMULATIONS

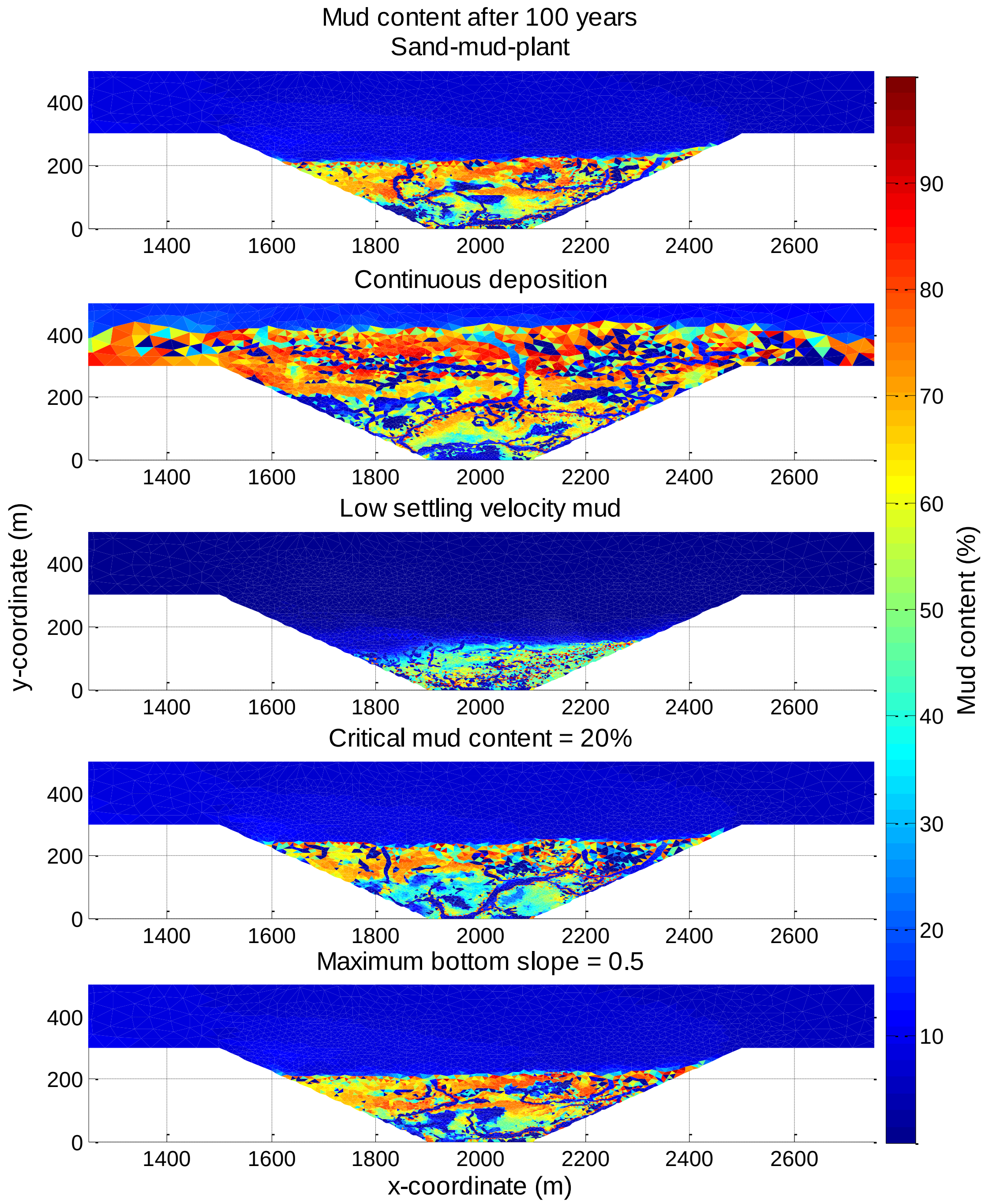

FIGURE 46 MUD CONTENT AFTER 100 YEARS FOR THE REFERENCE SIMULATION, CONTINUOUS DEPOSITION, LOW SETTLING VELOCITY FOR MUD, CRITICAL MUD CONTENT OF 20% AND A MAXIMUM BOTTOM SLOPE OF 0.5