Modeling the interaction between morphodynamics and vegetation in the Nisqually River estuary

MSc Thesis

Martijn Monden

1201423-000

Deltares

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Martijn Monden

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Department of Hydraulic Engineering

Graduation committee:

Prof. dr. ir. M.J.F. Stive	Delft University of Technology
Dr. ir. J.E.A. Storms	Delft University of Technology
Ir. D.J.R. Walstra	Delft University of Technology / Deltares
Ir. A.C.S. Mol	Deltares
Ir. M. van Ormondt	Deltares

Deltares

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Summary
In the last 150 years, there has been an 80% loss of salt marsh area in Puget Sound, mainly due to reclamation for agricultural purposes. In recent years there has been a growing recognition of their value as habitat for fish, birds and numerous species of plants and as coastal protection, which is why currently numerous restoration projects are being carried out or planned. One of the largest of these takes place in the Nisqually River estuary, in the southern end of Puget Sound. By removing a dike, built in the early 1900, an area of nearly 405 hectares was reintroduced to the salt water and tides of Puget Sound on November 12, 2009.

In this study a computational model was set up in Delft3D to describe the hydrological and morphological effects of this dike removal, with focus on the interaction with vegetation. It was concluded that the success of salt marsh restoration mainly depends on elevation. Due to subsidence during the period in which the area was diked, in its current state salt marsh vegetation will only be able to populate the eastern part of the estuary. However, sediment provided from the Nisqually River can increase the elevation, allowing the marsh to extend further. This effect could be accelerated by forcing the river to change its course into the restoration area, but further research into these effects is recommended.

References

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Preface

This thesis concludes my study Coastal Engineering at the faculty of Civil Engineering and Geosciences at Delft University of Technology. For this study a computational model was developed that looks into the effects of a wetland restoration project at the Nisqually River estuary in the northwest of the United States. The study was performed partly at Deltares in Delft, the Netherlands and partly at the U.S. Geological Survey in Menlo Park, California.

I am grateful to my supervising committee for their guidance and support. First I would like to thank Arjan Mol and Maarten van Ormondt for their daily guidance during my stay at Deltares. Furthermore I would like to thank Marcel Stive for being the chairman of my committee, and Dirk-Jan Walstra and Joep Storms for their feedback during the committee meetings.

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Martijn Monden

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Abstract

Due to growing human activity in coastal zones, there is an increasing stress on salt marshes all over the world. These intertidal wetlands were often seen as coastal 'wasteland' and large areas were reclaimed for urban development and agriculture. In Puget Sound, a system of interconnected marine waterways and basins in the northwest of the United States, this has lead to an 80% loss of marsh area in the last 150 years. In recent years however there has been a growing recognition of their value as habitat for fish, birds and numerous species of plants and as coastal protection. In many countries they are now protected areas and numerous restoration projects are being carried out or planned. One of the largest of these restoration projects takes place in the Nisqually River estuary, in the southern end of Puget Sound. By removing a dike, built in the early 1900s for farming purposes, an area of nearly 405 hectares was reintroduced to the salt water and tides of Puget Sound on November 12, 2009.

The goal of this study was to research how this dike removal will affect the estuary in the coming years. A computational model was set up in Delft3D to describe hydrological and morphological processes, with focus on the interaction with vegetation. The vegetation in Delft3D is schematized as cylindrical rods, which add extra source terms to the momentum equation. An external Matlab routine was used to calculate changes in the vegetation field based on the model results.

Because this type of vegetation modeling had not been done on this scale before and there were large uncertainties in the required parameters, first a sensitivity analysis was carried out with a schematized model. By doing different runs, changing one parameter at a time, the relative importance of each parameter was examined. The most important parameters were then researched further so that a detailed final model could be set up, with a discharge from the Nisqually River on the southern boundary and tidal forcing on the northern boundary. With the use of a morphological factor a period of 10 years was simulated.

Due to limitations in computation time and the lack of some important data, concessions had to be made in the setup of the model. These concessions, combined with the fact that the model could not be validated since there were no post-restoration measurements available at the moment of writing, make it hard to determine the accuracy of the model predictions. Therefore the results should not be seen as an exact prediction, but more as a qualitative impression of how the area is going to develop in the coming years.

It was concluded that success of salt marsh restoration mainly depends on elevation. Higher areas are inundated for a shorter amount of time, which makes it easier for pioneer vegetation to establish. During the period in which the restoration area was diked no sediment was brought in, which caused subsidence. As a result, a salt marsh can develop in the eastern part of the estuary but the western part of the estuary is too low to be colonized. However, the dike removal will allow sediment from the Nisqually River to enter the area again, so if enough sediment is provided the elevation will increase, allowing the marsh to

expand further. This suggests that sediment discharge from the river is a key factor, and it is therefore recommended to measure this in the future.

An alternative scenario, in which the river is forced to flow through the restoration area, was also examined, based on expectations for high river discharges. This increases the amount of sediment that is imported into the area, and could therefore have a positive effect on the salt marsh development. It does however also influence the salinity, which has a large impact on the distribution of vegetation. Further research into these effects is recommended if forcing this change is considered.

Finally, a secondary objective of this thesis was to examine the method of vegetation modeling in Delft3D and see if this can be improved. The current method of using an external Matlab routine was found to be relatively complicated. Support for multiple vegetation types and salinity was added, and an attempt was made to make the routine more generally applicable. Still, for the future it is recommended to build the routine into the code of Delft3D.

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1 Introduction

1.1 Background

Salt marshes are areas that can be found along sheltered coasts with tidal influence, where silt and mud can accumulate. They typically consist of dense patches of salt resistant vegetation, dissected by tidal creeks and bare mud flats. These intertidal wetlands are some of the most biologically productive ecosystems on earth and play an important role as habitat for fish, birds and numerous species of plants. They also filter contaminants from the water and offer coastal protection.

They are however also very vulnerable areas and growing human activity in coastal zones, as a result of population growth and economic development, has led to an increasing pressure on salt marshes all over the world. In the past, they were often seen as coastal ‘wasteland’ and large areas were diked for urban development and agriculture. Other parts were affected by nitrogen from sewage and agricultural and industrial waste, causing shifts in vegetation structure and the invasion of non-native species. In addition, global sea level rise as a result of climate change causes landward migration of the marshes. When inland obstacles like dikes or sea walls prevent this migration this also results in loss of salt marsh area.

In recent years there has been a growing recognition of the value of these ecosystems, and in many countries they are now protected areas. Along with this there has also been an increasing interest in salt marsh restoration. At numerous locations around the world there have been attempts at restoration by reintroducing tides to formerly diked areas, however not all of these have been successful. Re-establishment of the marsh vegetation is a slow and delicate process and its success depends on a large number of factors, not all of which are completely understood yet.

One of the locations where salt marsh restoration projects are currently being carried out is Puget Sound. Puget Sound is a large system of interconnected marine waterways and basins in the northwest of the United States. It is connected to the Pacific Ocean in the north and fed freshwater by a large number of rivers. The estuaries of these rivers, combined with the large tidal range and sheltered waters of the sound, are an ideal location for salt marshes.

Unfortunately in the last 150 years nearly 80% of Puget Sound’s intertidal wetlands have been lost, mainly due to land reclamation (*U.S. Fish and Wildlife Service 2005*). Nowadays efforts are being made to restore some of these areas to their original state. By removing or breaching dikes, natural tidal, fluvial and estuarine processes are reintroduced into the area. One of the largest of these projects takes place in the Nisqually Delta, in the southern end of Puget Sound.

Before the area was affected by human activity, the transition between the Nisqually River and Puget Sound consisted of an estuary populated with salt marsh vegetation. In the early 1900s a part of nearly 405 hectares of the estuary was reclaimed as farmland. The area was appointed as a National Wildlife Refuge in 1974, because of its importance for migratory birds and its unique fish and wildlife resources, and since then it has been maintained as freshwater wetlands by the U.S. Fish and Wildlife Service. In 2005, they released a Comprehensive Conservation Plan in which they decided to reopen part of the area to tidal influence, in the hope that a salt marsh will develop. Work on this began at the end of 2008 and was completed on November 12, 2009, when the first tide in more than 100 years entered the Nisqually estuary.

The goal of this thesis is to predict how this restoration will affect the Nisqually estuary in the coming years. This will be done by means of numerical modeling using the modeling software Delft 3D.

1.2 Site description

1.2.1 Puget Sound

Puget Sound is located between the Cascade and Olympic mountains, in the state of Washington in the northwest of the United States. It got its present form between 10,000 and 15,000 years ago by scouring and till deposition of the Wisconsin Glaciation, the last major advance of continental glaciers in North America. This process created a system of deep and narrow channels divided by islands and peninsulas. The sound covers an area of approximately 160 by 80 kilometers and consists of four deep basins separated by shallow sills. The average depth is 62 m and the maximum depth, just north of Seattle, is 280 m.

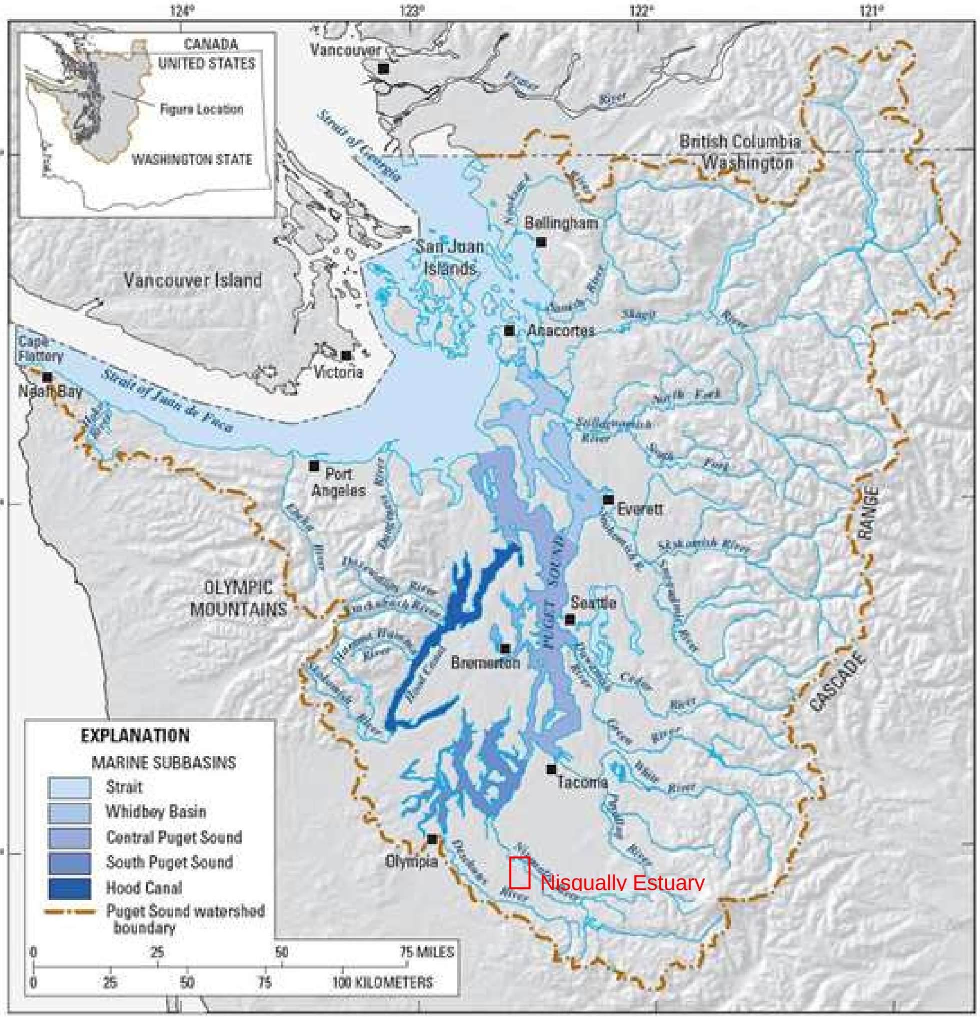

Figure 1-1: Basins of Puget Sound (Gelfenbaum et al 2006)

Puget Sound is connected with the Strait of Juan de Fuca (which in its turn is connected with the Pacific Ocean) in the north via a major and a minor connection: Admiralty Inlet and Deception Pass. It is essentially a very large salt water estuary that is fed with freshwater from the Cascade and Olympic Mountains watershed via a large number of rivers and streams. The mean annual average discharge into Puget Sound is 1,200 m^3/s.

Tides in Puget Sound are of the mixed type, with two high and two low tides per day. The configuration of basins and sills causes the tidal range to increase when propagating through the sound. Mean High Water (MHW) increases from 2.36 m (above MLLW) at Admiralty Inlet to 4.13 m at Olympia, while Mean Low Water (MLW) increases from 0.78 m to 0.93 m. The average volume of water flowing in and out of Puget Sound during each tide is 5.3 km^3, approximately 5% of the total volume of the sound. This large tidal influence combined with the shallow sills and narrow passages leads locally to large velocities, up until 9 or 10 knots at Deception Pass. The sills also have a large influence on the water movement through the basin. Combined with differences in density between salt and fresh water they cause circulation patterns, which draw down outflowing water at one end of the basin and pump it up at the other end. This also affects the sediment transport in the estuary, and makes that only a small amount of sediment can leave the basin.

1.2.2 Nisqually River

The Nisqually River drains the southern slope of Mount Rainier, part of the Cascade mountain range. It flows approximately 130 km, west-northwest, to the Nisqually Estuary where it flows into the southern end of Puget Sound, near Olympia. The watershed covers an area of approximately 1970 km^2. Flows in the lower reaches are regulated in part by two dams (La Grande and Alder) about halfway down the river, which also divide the watershed into two distinct physiographic areas. Upstream the area is dominated by volcanic rock and steeper mountainous terrain, while the downstream part consists of low hills and prairie plains of glacial outwash. The Nisqually River has an average discharge of approximately 60 m^3/s in winter and 30 m^3/s in summer. Peak discharges can be as high as 600 m^3/s for a 10 year return period (*Puget Sound Partnership 2008*).

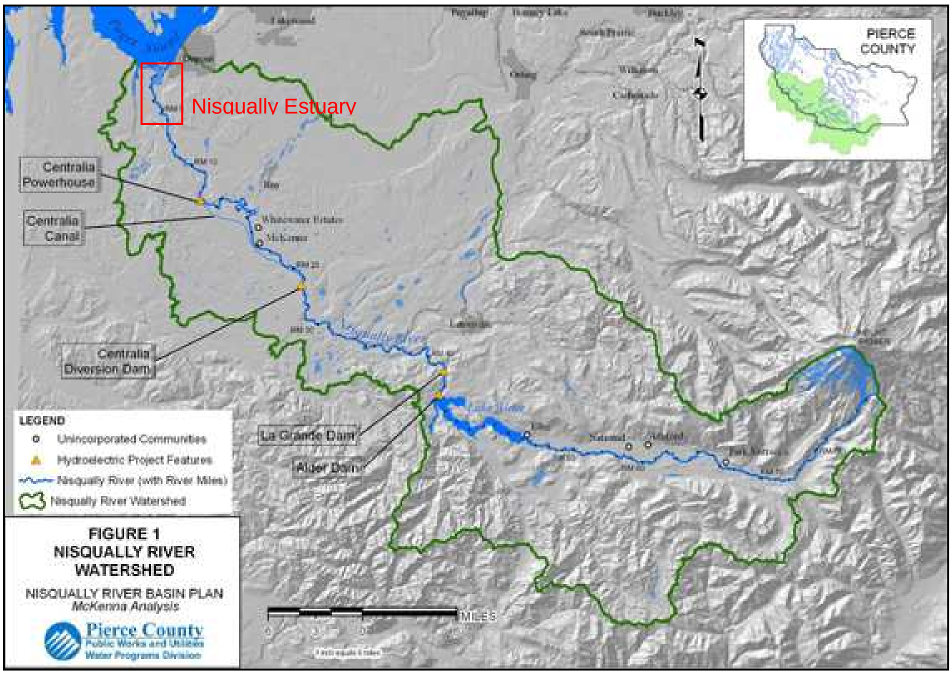

Figure 1-2: Nisqually watershed (Pierce County Public Works and Utilities Water Programs Division 2008)

1.2.3 Nisqually estuary

The mouth of the Nisqually River is located on the border of Thurston and Pierce Counties, 16 km northeast of Olympia, Washington. East of the river there have already been two smaller restoration projects: tidal inundation has been restored to an area of approximately 16 hectares in 2002 and an additional 40 hectares in 2006. The main restoration project however lies just west of the river. The old Brown Farm Dike enclosed a rectangular area of approximately 2.5 by 2 kilometers. On the north it is bordered by Puget Sound, on the west by a small stream called McAllister Creek and on the south by the Highway I-5.

Figure 1-3: Nisqually estuary seen from the west (Microsoft Bing Maps)

Even after a century of being shut off from tidal influence the old channels were still visible before the restoration. Though they are partly covered with vegetation, four major channels can be distinguished: three along the northern dike and one along the western dike next to McAllister Creek. The majority of the area was covered with grasslands, with some riparian and mixed forest habitats in the slightly higher eastern part. Along the western dike was a part with lower elevation which was submerged most of the time. Over 50% of the area was covered with the tall reed canary grass (Phalaris arundinacea), an invasive species that suppresses native vegetation and reduces diversity (*Woo et al 2010*).

Outside of the dike some patches of salt marsh remained. The tidal channels were still in line with the channel remains inside the dike, which suggests that the system was more or less in equilibrium. Some of the dominant salt marsh vegetation species are seashore saltgrass (Distichlis spicata), pickleweed (Salicornia virginica), tufted hair-grass (Deschampsia cespitosa), perennial rye grass (Lolium perenne) and Lyngbye’s sedge (Carex Lyngbyei) (*Burg et al 1980*, *Woo et al 2010*).

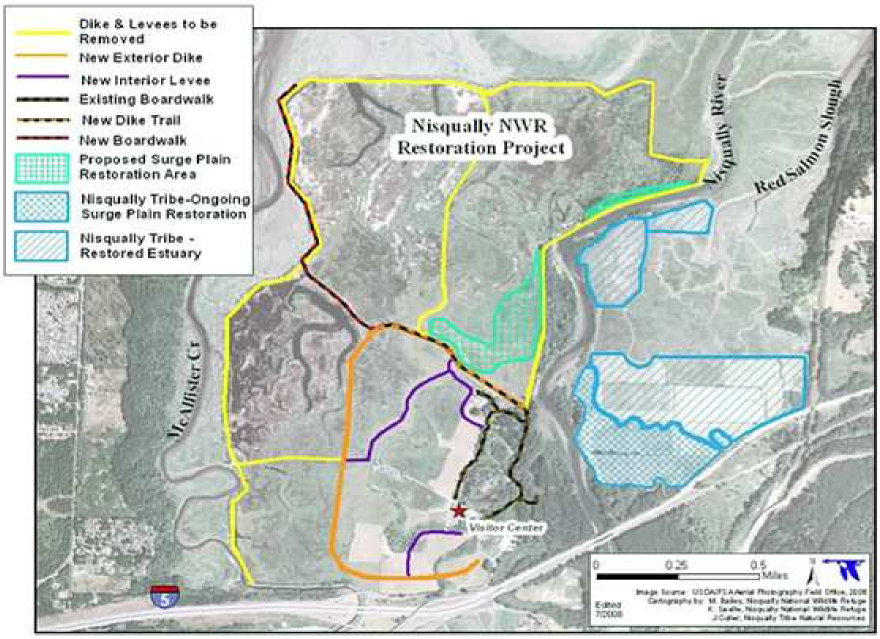

Figure 1-4: Nisqually NWR Restoration Project

Figure 1-4 shows the plans for the restoration project. The design was selected based on an eight year planning process that included input from numerous organizations and institutions. A new dike was designed to protect a small part of the area in the southeast, which contains a visitor centre and some other buildings. After this dike was completed the original dike was removed, exposing an area of 308 ha to the tides of Puget Sound. The effect of this became visible very soon (Figure 1-5). Almost all of the freshwater vegetation died off, including all of the invasive reed canary grass. The old channels got inundated again and most of the vegetation got flushed out. The channels also seem to be expanding further into the area. All of this makes it clear that the area is in a state of transition at the moment, and that it will keep changing considerably in the coming years.

Figure 1-5: Nisqually estuary before (left) and 7 months after dike removal (right) (Google Earth)

1.3 Objectives and research questions

As stated above, the main objective of this research is to predict how the Nisqually Delta Restoration Project will affect the Nisqually estuary. This is done by means of a numerical model, Delft3D, that looks not only at the hydrology and morphology but also at the development of salt marsh vegetation, and the interaction between these three. Since the modeling of this interaction in Delft3D is a relatively new application and there are still a lot of uncertainties, the goal is not to predict vegetation and channel patterns in detail, but more to give a qualitative impression of how the area will develop. To be able to say something about the extent of these uncertainties, first a sensitivity analysis is carried out.

The modeling of vegetation has not been built into the program code yet and the aforementioned interaction is calculated externally using a routine in Matlab. A secondary objective of this thesis is to look at the possibilities and limitations of this method and to see if any improvements can be made. Finally the influence of the path of the Nisqually River has been investigated. In the present situation it flows along the edge of the restored area, but there are expectations that at some point in the future with high discharges it will break through the remains of the dike and flow through the area. It is investigated how such a change would influence the development of the area, to see if this is desired.

Summarizing, this leads to the following research questions:

- How will reconnection with Puget Sound affect the morphology of the Nisqually River estuary?
- Will salt marsh vegetation be able to populate the restored area?
- Is changing the course of the river to go through the restoration area beneficial for the evolution of the estuary?
- How can the modeling of vegetation in Delft3D be improved?

1.4 Research approach

In order to answer the research questions the report is built up in the following way. Chapter 2, which follows after this introduction, gives some theoretical background on the processes and methods used in this research. First an explanation will be given about salt marshes and the processes that shape them. After that some reference projects are discussed. These are mainly other marsh restoration projects which have lead to conclusions possibly relevant to the Nisqually project. Finally an overview of the available data is given. In chapter 3, a description of the model that is used in this thesis is given. A short introduction to the modeling software Delft3D is given, while the modeling of vegetation is discussed in more detail, including the method used to update vegetation fields during a simulation, using a Matlab script. Chapter 4 describes the setup of the sensitivity analysis model. This model is based on the situation in the Nisqually estuary, but highly schematized in order to keep computation times low. Different runs have been carried out, varying one parameter at a time, in order to determine the influence of each parameter on the end result. This will help with getting more insight into the reliability of the final model, in which many factors are uncertain. This final model is described in chapter 5. It includes the influence of the river, as well as more detailed bathymetry, sediment properties, boundary conditions etc. The effect of incoming sediment from the river will be studied for the current situation and for a scenario where the river flows through the restoration area. Its goal is to predict how the estuary will evolve in the coming 10 years. This will be a qualitative study since the level of detail is limited and sediment data is only scarcely available. The last chapter summarizes the conclusions of previous chapters, answers the research questions and gives some recommendations for additional research and possible similar projects in the future.

2 Literature review

2.1 Salt marshes

As mentioned in the introduction, salt marshes can form on coasts where there is a relatively large tidal influence and small influence of waves. The development starts with the establishment of a pioneer species on a bare tidal flat. The chance of success of this establishment depends on a number of factors like inundation time, wave action, salinity and sediment properties. Once rooted, most pioneer species spread by means of vegetative reproduction from rhizomes, horizontal underground stems that send out roots from their nodes. This lets the vegetation expand in circular patches, until they coalesce and form closed fields. These vegetation fields affect the hydrodynamic forces from waves and currents, causing extra friction and turbulence and thus trapping sediment (*Van der Wal et al 2005*).This causes a positive feedback: the elevation of the patches increases, which makes that they are flooded for a shorter period of time, which gives better conditions for the plants to grow. This increasing geomorphic heterogeneity also causes flowing water to converge between the patches, locally leading to increasing shear stresses and possibly erosion, which further increases the difference in elevation (*Temmerman et al 2007*). This leads to the conclusion that, in tidal landscapes which are colonized by denser vegetation, channels are formed with a higher channel drainage density. This is in contrast with traditional insights in which vegetation was thought to reduce channel erosion due to the strengthening of the soil. The described feedback system eventually leads to an equilibrium situation where dense fields of vegetation are dissected by tidal creeks.

The long-term geomorphic development of tidal marsh landforms is thus determined by the flow paths of water and its constituents (sediments, nutrients, contaminants). These flow paths are determined by the topography of the area, the water level fluctuations and vegetation cover. *Temmerman et al (2005)* shows that in a tidal marsh with small topographic gradients like the Nisqually area, the vegetation has the largest influence on flow routing during single inundation events, while the influence of the micro-topography is negligible. This implies that the presence or absence of a vegetation cover is determinant for the long-term geomorphology of tidal marshes. Their simulations also show that spatial sedimentation patterns are related to three topographic variables: sedimentation rates decrease with increasing marsh surface elevation, increasing distance from the seaward marsh edge and increasing distance from tidal channels.

2.2 Reference projects

In the last two decades the de-embankment of historically reclaimed salt marshes became a popular method for restoring them into their original state. The success of this type of projects in north-west Europe was evaluated in *Wolters et al (2004)*, in which success was defined as the presence of target plant species, expressed as a percentage of a regional target species pool. It was found that most sites contained less than 50% of the regional target species, especially for sites smaller than 30 ha. Higher diversity was found for sites larger than 100 ha and for sites with a large elevational range. Another finding was that the diversity was highest for the youngest projects, with a rapid decrease setting in 15 years after restoration. This is likely to be the result of dominance of a single or a few tall growing species, which results in the suppression or disappearance of shorter species. For future restoration projects they recommend that clear targets are set from the start and monitoring will be carried out, so that adaptive management of the site becomes possible.

A restoration project close to the Nisqually project, with similar types of vegetation present, was carried out in Elk River Estuarine Marsh in Grays Harbor, Washington. In 1987 an area of 23 ha was reintroduced to tidal influence after having been diked for approximately 70 years. The development of vegetation in the area was monitored for 11 years and compared to a reference marsh next to it, and the results are described in *Thom et al (2002)*. Before the restoration, the freshwater pasture was dominated by reed canary grass (Phalaris Arundinacea). This was converted to low salt marsh vegetation within 5 years, yet the system continued to develop and even after 11 years still seemed to change considerably every year. Dominant vegetation species are Distichlis spicata and Salicornia virginica, unlike the reference marsh which is dominated by Deschampsia cespitosa. This is probably because of the elevation difference, caused by the subsidence of the system during the period the area was diked (in the order of a meter). Elevation is thought to be the main factor controlling vegetation structure within this localized area. Based on the measured accretion in the reference marsh between 1963 and 1991 they predict it will take 75 to 150 years for the marsh to reach an elevation (and thus vegetation cover) comparable to the reference marsh.

Another wetland restoration project in Puget Sound took place at the Gog-Le-Hi-Te wetland, in the Puyallup River estuary. *Simenstad and Thom (1996)* evaluated the first 7 years of its development after the reconnection. Before the restoration, culms of the pioneer vegetation Carex Lyngbyei were planted onto unvegetated intertidal areas. The authors observed a rapid retreat of planted Carex lyngbyei from lower intertidal elevations, expansion of naturally colonized, brackish emergent wetland species along upper edges of the intertidal flats, and sedimentation of the created tidal channels and basin. The unexpected retreat of Carex is thought to be the result of a combination of multiple factors, suggesting an extremely tight coupling among estuarine hydrogeomorphology, soil development, physicochemical and biological disturbance, and plant physiology and survival. These are all factors which tend to be unappreciated or unevaluated in most wetland restoration monitoring, which leads to the conclusion that the final outcome of restoration projects like this may be impossible to predict, even from a 5-10 year time series of measurements.

2.3 Available data

In order to set up a reliable model reliable data is required. In this paragraph an overview is given of the data that is available.

2.3.1 Bathymetry

In order to create a bathymetry file that can be used in a model bathymetry data is needed. A number of different datasets is available:

<u>Finlayson</u>

In 2005 a Digital Elevation Map was made by David Finlayson for the entire Puget Sound, compiled from multiple sources, with a resolution of 9.144 meters (30 feet). The used version was converted from State Plane coordinates (Washington North, NAD83) in feet to geographic coordinates (lon,lat) and the heights relative to NAVD88 were converted from units of feet to meters. The DEM was made mainly for the deep waters of Puget Sound, so the level of detail is not very large, elevations are in whole feet.

Multibeam data
Echo sounding is a way of measuring the distance to the bottom by means of sound pulses. By using multiple echo sounders on a beam large underwater areas can be mapped in a short amount of time. In 2009 part the Nisqually reach was mapped in this way, but not the restoration area itself. Measurements with a resolution of 5 meters are available.

Ground based LIDAR
LIDAR (Light Detection And Ranging) is an optical remote sensing technology that measures properties of scattered light to find the range of a distant target. LIDAR has a very high resolution compared to radar, which makes it possible to accurately measure changes in elevation. By attaching such a measuring device to a pole data can be collected from the ground.
Before the removal of the dike, a strip of land around the north part of the dike was mapped using ground based LIDAR, and it is planned to do this again in the future to keep track of morphological evolution. The data have a very high resolution (in the order of 1 meter) but it seems like in some places the top of the vegetation was measured instead of the ground level.

Nisqually River and McAllister Creek
There is some data available from a small boat with echo sounder that went up and down both the river and the creek that border the restoration area once. Since there is only a small overlap with the other datasets and the exact conditions at the time of measurement is not exactly known this information is not very reliable and should only be used for a rough approximation.

Field trip
Some additional data were collected during a field trip to the project area on May 24 and 25, 2010. At low tide this was done by means of Real Time Kinematic GPS. This is a technique used in land- and hydrographic survey based on GPS signals, but with a reference station providing real-time corrections. This way accuracy in the order of centimeters can be achieved. A base station was set up in the south part of the restoration area, after which some channel profiles were measured by walking through them with GPS backpacks.
At high tide some extra echo soundings were carried out at the main tidal channels and the mouth of the river.

2.3.2 Tide
The nearest tidal station is at Dupont Wharf in Nisqually Reach. This station is located approximately 3 kilometers northeast of the project area (Figure 2-3). This station is not active anymore but tide predictions are still being done, and can be found on the website of NOAA. The tidal signal for two days is shown in Figure 2-1 and the tidal datums are found in Table 2-1.

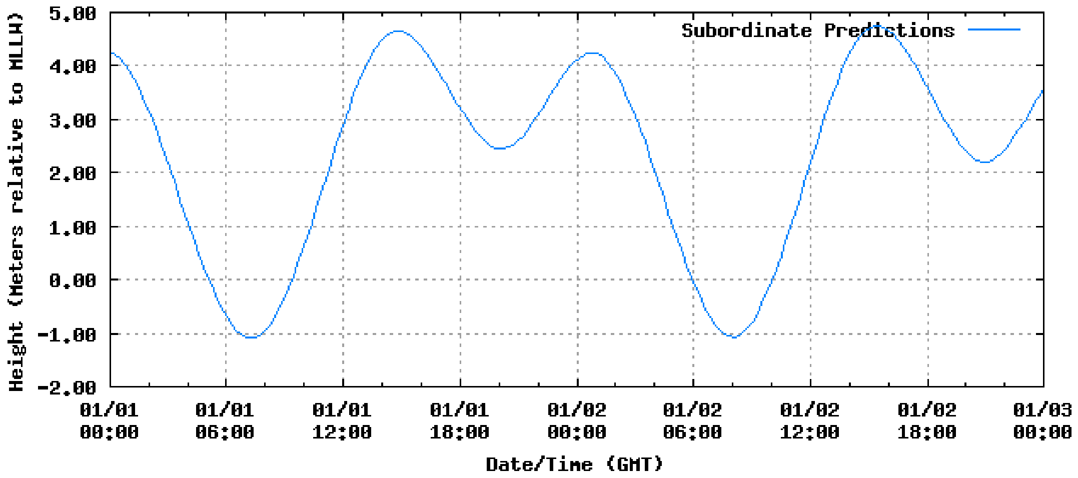

Figure 2-1: Tide at Dupont Wharf (http://tidesandcurrents.noaa.gov)

Datum	Observed height (m)
MHHW	4.12
MHW	3.83
MTL	2.37
MLW	0.90
MLLW	0.00
NAVD88	1.12

Table 2-1: Tidal datums for Dupont Wharf, relative to MLLW (Mojfeld et al 2002)

Another source is a tide model for the whole of Puget Sound developed by USGS. By the use of 'nesting' boundary conditions for a Nisqually estuary model can be generated.

2.3.3 River

Discharge data for the Nisqually River are available at http://waterdata.usgs.gov for multiple flow gauges (Figure 2-2). The station furthest downstream is 'Nisqually River at McKenna, WA', with site number 12089500. It has been active from 1947. Apart from real time data, also peak values and statistics are available.

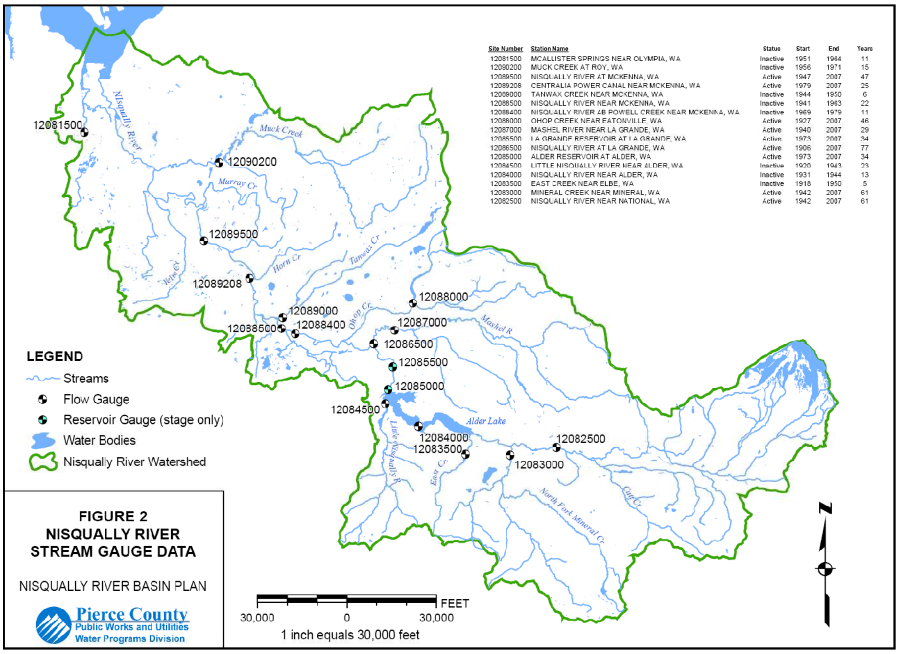

Figure 2-2: Measurement stations in Nisqually River (Pierce County Public Works and Utilities Water Programs Division 2008)

At the moment of writing, no information was available on sediment concentrations in the river. Data for the Deschutes River, a nearby river with a comparable average discharge are available from *George et al (2006)*.

2.3.4 Sediment

A number of sediment samples is available from the shallow area north of the restoration project. An overview is given in Figure 2-3. For the restoration area no data are available.

Figure 2-3: Sediment samples and tide station

2.3.5 Vegetation

An important part of the Nisqually Delta Restoration Project is an extensive vegetation survey. Vegetation sampling is conducted every year during summer, when vegetative cover is at its maximum. Multiple transects are established to determine the composition, height, and percent cover of plant species and to detect changes in vegetation through time. Data from the last survey prior to the dike removal are available in *Woo et al (2010)*.

The vegetation outside of the dike was studied extensively by *Burg et al (1980)*. This study identified twelve salt marsh plant associations and includes a detailed map with the spatial distribution of these associations.

The modeling of vegetation requires a number of parameters for each vegetation species. Exact numbers are not available because they are very specific, but http://plants.usda.gov/ provides a lot of qualitative characteristics of plants found in the area. With the help of these characteristics and the parameters used in earlier models for other species an estimation is made.

3 Model description

3.1 Introduction

The computational model used in this research is Delft3D. Delft3D is a software suite for a multi-disciplinary approach and 3D computations for coastal, river and estuarine areas. It is composed of a set of modules (components) that can carry out simulations of flows, sediment transports, waves, water quality, morphological developments and ecology. The main module used for this research, Delft3D-FLOW, is a multi-dimensional (2D or 3D) hydrodynamic and transport simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. Furthermore the sediment transport module is used, which supports both bed-load and suspended load transport of non-cohesive sediment and suspended load transport of cohesive sediment. Exchange of sediment with the sediment bed causes changes in bed level in the form of erosion or accretion. Because these morphological processes take place on a larger time scale than the flow, a morphological factor can be applied. The bed level change is then multiplied with this factor for every time step. For a more detailed description reference is made to the Delft3D User Manual (*Deltares 2009*).

An important aspect in the model used in this thesis is the interaction between the aforementioned flow, morphology and vegetation. The modeling of vegetation in Delft3D is a relatively new application and will therefore be treated in more detail in this chapter.

3.2 Vegetation module

3.2.1 Introduction

The influence of vegetation on hydrodynamics in Delft3D-FLOW can be modeled with a vegetation module. This module is based on a model developed by *Uittenbogaard (2003)*, in which vegetation is represented by a number of rigid cylindrical rods. These rods influence the momentum and turbulence equations by adding extra source terms for drag and turbulence. The vegetation is characterized by a number of parameters: the number of stems per unit area (stem density), the stem diameter and the stem height.

3.2.2 Equations

As mentioned in the introduction, the influence of the vegetation on drag leads to an extra source term of friction force, F(z) [N m^{-3}], in the momentum equations:

$$F(z) = \tfrac{1}{2}\rho_0 C_D \phi(z) n(z) \left|u(z)\right| u(z) \qquad (3.1)$$

Where:
ρ_0 = the fluid density [kg m^{-3}]
C_D = the drag coefficient [-]
φ(z) = the diameter of the plant structure [m] at height z [m] above the bottom
n(z) = the number of plant structures per unit area [m^{-2}] at height z
u(z) = the horizontal flow velocity [m/s] at height z.

The vegetation module uses the k-ε turbulence closure model (*Rodi 1984*). In this model, transport equations must be solved for both the turbulent kinetic energy k and for the energy dissipation ε. The mixing length L is then determined from ε and k according to:

$$L = C_D \frac{k\sqrt{k}}{\varepsilon} \tag{3.2}$$

For 3D models, the influence of vegetation on turbulence leads to an extra source term in the kinetic turbulent energy equation:

$$\frac{\partial k}{\partial t} = \frac{1}{1-A_p}\frac{\partial}{\partial z}\left\{\left(1-A_p\right)\left(\nu+\nu_T/\sigma_k\right)\frac{\partial k}{\partial z}\right\} + T(z) \tag{3.3}$$

with $$A_p(z) = \frac{\pi}{4}\phi^2(z)n(z) \tag{3.4}$$

and $$T(z) = F(z)u(z) \tag{3.5}$$

Where:
A_p = the horizontal cross-sectional plant area per unit area [m^2] at height z
v = the molecular fluid viscosity [m^2 s^{-1}]
v_T = the eddy viscosity [m^2 s^{-1}]
σ_k = the turbulent Prandtl-Schmidt number for self-mixing of turbulence [-]
T(z) = the work spent by the fluid [m^2 s^{-3}] at height z.

For the energy dissipation equation, the vegetation also leads to an extra source term:

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{1-A_p}\frac{\partial}{\partial z}\left\{\left(1-A_p\right)\left(\nu+\nu_T/\sigma_\varepsilon\right)\frac{\partial \varepsilon}{\partial z}\right\} + T\tau^{-1} \tag{3.6}$$

Where:
σ_ε = the turbulent Prandtl-Schmidt number of mixing of small-scale vorticity [-]
τ_ε = the minimum of the dissipation timescale of free turbulence (τ_{free}) and the dissipation timescale of eddies in between the plants (τ_{veg}):

$$\tau_{free} = \frac{1}{c_{2\varepsilon}}\left(\frac{k}{\varepsilon}\right) \tag{3.7}$$

$$\tau_{veg} = \frac{1}{c_{2\varepsilon}\sqrt{c_\mu}}\left(\frac{L^2}{T}\right)^{1/3} \quad \text{with} \quad L(z) = C_l\left\{\frac{1-A_p(z)}{n(z)}\right\}^{\frac{1}{2}} \tag{3.8}$$

Here $c_{2\varepsilon}$ is a coefficient to be determined from calibration [-] and C_l is a coefficient reducing the geometrical length scale to the typical volume averaged turbulence length scale [-]. For vegetation a value of 0.8 was found to be applicable for C_l. Other values are σ_ε = 1.3 and $c_{2\varepsilon}$ = 1.92. (*Uittenbogaard 2003*). When modeling in 2DH (depth-averaged) instead of 3D the k-ε turbulence closure model is not used, meaning that the influence of the vegetation is accounted for only by the extra term in the momentum equation (3.1).

3.2.3 Input in Delft3D-FLOW

The use of the vegetation module has not been built into the interface of Delft3D yet. In order to include vegetation in Delft3D-FLOW, the keyword ‘Filpla’ must be filled in in the tab ‘Additional Parameters’. The accompanying value must refer to a plant input file in the model folder. In this file multiple plant types may be specified, each with its own vertical plant structure and horizontal spatial distribution.

The vertical plant structure describes the number of stems per unit area and the stem diameter as a function of the height. The horizontal spatial distribution of the number of plants can be specified in two ways:

- The keyword ‘Polygon’ refers to a polygon in the polygon-file. The keyword ‘NPlants’ denotes the number of plants per square meter for each cell whose centre is inside the polygon.
- The keyword ‘NPlantsFile’ refers to an existing file in depth-format, corresponding to the used grid. Each positive value in this file is interpreted as the number of plants per square meter in the corresponding cell. This is the method used in this thesis.

If more types of plants are present in the same grid cell, the average stem density and diameter are combined in such a way that the combination gives the total resistance and total occupied plant areas.

3.3 Matlab routine

3.3.1 Introduction

In the vegetation module that is described above the vegetation field is defined at the beginning of the simulation and then is kept the same during the whole simulation period. *Temmerman et al (2007)* suggests a way of taking into account the growth and erosion of vegetation by coupling the Delft3D model to a Matlab routine.

This routine does multiple short simulations instead of one. It runs Delft3D-FLOW via a batch file and then takes the results and calculates the effect of water levels, currents and erosion on the vegetation density, and will then calculate possible expansion due to growth, diffusion and establishment of new seedlings. The new vegetation field is then automatically used as input for the next simulation. This way the interaction between flow, vegetation and morphology can be modeled. This is shown schematically in Figure 3-1.

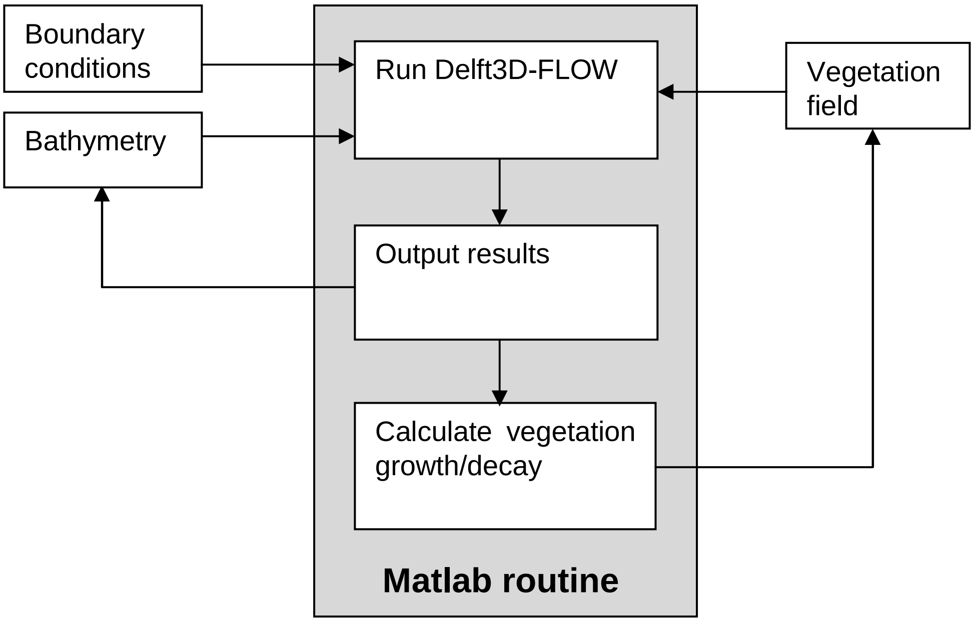

Figure 3-1: Flow diagram of vegetation modeling with the Matlab routine

3.3.2 Equations

As mentioned above, the horizontal distribution of plants is defined in a depth file, with the number of plants per square meter specified for every grid cell. The Matlab routine reads this file and the results from the Delft3D-FLOW simulation, and then calculates the change in density for every cell using a number of terms:

<u>General growth</u>

The stem density in a cell grows logarithmically up to its maximum carrying capacity:

$$dP_{growth} = r(1 - \frac{P}{K})P \times dt \quad [\mathrm{m}^{-2}] \tag{3.9}$$

Where:
r = the intrinsic growth rate [yr^{-1}]
P = the stem density [m^{-2}]
K = the maximum carrying capacity of stem density [m^{-2}]
dt = the time resolution [yr]

<u>Diffusion</u>

Rhizomous plants expand in lateral direction to neighboring cells:

$$dP_{diffx} = D\left\{\frac{P_{x-1} - 2P + P_{x+1}}{dx^2}\right\} \times dt \quad [\mathrm{m}^{-2}] \tag{3.10}$$

$$dP_{diffy} = D\left\{\frac{P_{y-1} - 2P + P_{y+1}}{dy^2}\right\} \times dt \quad [\mathrm{m}^{-2}] \tag{3.11}$$

Where:
D = the plant diffusion coefficient [m^2 yr^{-1}]

P_{x-1},P_{x+1}, P_{y-1} and P_{y+1} = the stem density in neighboring cells [m^{-2}]
dx and dy = the cell resolution in x and y direction [m]

Establishment of new seedlings
New patches of vegetation can appear in bare grid cells randomly through the whole model area:

$$dP_{seed} = rand(ny, nx) < Seed \times P0 \times dt \quad [m^{-2}] \tag{3.12}$$

Where:
Seed = the chance that a bare cell gets colonized [yr^{-1}]
P0 = the initial stem density in the new vegetation patch [m^{-2}]

Bed shear stress
When high flow velocities occur and the bed shear stress exceeds a critical value the vegetation will disappear:

$$dP_{erostau} = C_{\tau} \times (\tau - \tau_{cr}) \quad [m^{-2}] \tag{3.13}$$

Where:
C_{τ} = a plant mortality coefficient related to flow stress [m^{-2} / (N m^{-2})]
τ = the bottom shear stress [N m^{-2})
τ_{cr} = the critical bottom shear stress for plant mortality [N m^{-2}]

Inundation
The vegetation will die when it is inundated above a certain inundation height:

$$dP_{inund} = C_{inund} \times (H - H_{cr}) \quad [m^{-2}] \tag{3.14}$$

Where:
C_{inund} = a plant mortality coefficient related to inundation height [m^{-2} / m]
H = the inundation height [m]
H_{cr} = the critical inundation height for plant mortality [m]

Net result
The total change in stem density is found by adding all the above terms:

$$dP = (dP_{growth} + dP_{diffx} + dP_{diffy} + dP_{seed}) - (dP_{erostau} + dP_{inund}) \quad [m^{-2}] \tag{3.15}$$

This is then added to the old stem density (P) and saved to a new depth file.

3.3.3 Alterations

The used Matlab routine is based on the one developed by *Temmerman et al (2007).* This was made for a specific site with a specific type of vegetation, in the Westerscheldt Area in the Netherlands. For this research some changes were made to make it more generally applicable and add some functionalities:

<u>Split into different .m files</u>
In the original version of the routine all the code was written in one script. To make it more orderly this was split up into a general script and two functions: the first one to read in the results file from Delft3D-FLOW and the second one to calculate the changes in vegetation.

<u>Folder structure</u>
Originally both input and output files, were in the same folder. This could lead to confusion as the output file for a certain cycle is used as input for the next one. Therefore some lines were added to the script which move the files to different folders. The initial input files now have to be placed in a separate folder called ‘input’. At the start of each cycle, the necessary files are copied to the folder ‘run’, from where the simulation is carried out. After each cycle the results are moved to an ‘output’ folder, and they are used again as input for the next cycle.

<u>Combining result files</u>
In the original version of the script graphs were created, but the Delft3D result files were overwritten after every cycle. This makes it hard to examine the results afterwards, for example when the model crashes. Therefore a method was developed to save all the different result files and combine them into one file at the end. To make it easier to analyze the result the start and stop times of the different simulations have to match. For this the time values in the Delft3D input file were replaced by keywords, which can be updated by a function called ‘findreplace’. The Delft3D result files get saved in different folders and in the end they are all combined into one file with the function ‘combine_trim’, so that they can easily be used to analyze the results.

<u>Multiple vegetation species</u>
Support was added for multiple types of vegetation. They have to be defined in the plants.pla file, and for each type a text file with parameters has to be made. The order in which they are defined determines the order of ‘dominance’. Multiple species can grow in one grid cell, but only until the total carrying capacity is reached. For each species the ‘relative density’ is calculated by dividing the calculated density by the carrying capacity. These are then added up, and when the total is larger than 1 the densities of the species of lower order of dominance are decreased.

<u>Salinity</u>
An extra term due to which vegetation can die is added in the form of salinity. It works the same as the terms for shear stress and inundation: when the salinity in a cell exceeds a specified critical value the vegetation dies off with a certain speed, defined by a mortality coefficient:

$$dP_{sal} = C_{sal} \times (S - S_{cr}) \quad [\mathrm{m}^{-2}] \qquad (3.16)$$

Where:
C_{sal} = a plant mortality coefficient related to salinity [m^{-2} / ppt]
S = the salinity [ppt]
S_{cr} = the critical salinity for plant mortality [ppt]

4 Sensitivity Analysis

4.1 Introduction

The purpose of this thesis is, as mentioned in the introduction, to predict how the Nisqually Delta Restoration Project will affect the Nisqually estuary. This will be done by means of a numerical model which tries to model flow and morphology as well as the vegetation. Because the coupling of these functions is a relatively new application and there are a lot of vegetation parameters which are hard to determine there are quite some uncertainties. That is why a sensitivity analysis was carried out to get some insight into the relative importance of these parameters.

Because a sensitivity analysis requires a lot of different runs the runtime has to be limited. That is why a schematized model is used, based on the conditions in the project area. A slice was ‘cut’ out of the project area and treated as a standalone model with one open and three closed boundaries. Boundary conditions and model parameters were based on the local conditions but simplified.

Tested parameters were, among others, sediment particle size, mean water level and tidal amplitude. For the vegetation the initial vegetation density, critical inundation height and critical shear stress were varied. A list of the compared parameters is shown in Table 4-1. A complete overview of the simulations is given in appendix A For every run one parameter is changed and the results are all compared to the same run. Paragraph 4.2 describes these settings. In paragraph 4.3 first the results of the base run are described, after which the results of the other runs are compared to these.

They are compared on the morphologic changes and the vegetation growth after a simulation period of 5 years. Erosion, sedimentation and vegetation development are analyzed both qualitatively and quantitatively. Based on these comparisons a number of conclusions is drawn that are used for setting up the final model.

Variation	Run numbers	Paragraph
- (base run)	1	4.3.2
Type of sediment	1, 5, 19, 20	4.3.3
Initial vegetation density	1, 3, 4, 15	4.3.4
Critical inundation height	3, 13, 14	4.3.5
Critical shear stress	3, 11, 12	4.3.6
Plant stem diameter	3, 27, 28	4.3.7
Tidal amplitude	1, 6, 7	4.3.8
Mean sea level	1, 8, 9	4.3.9
Chezy coefficient	1, 16, 17	4.3.10
Method of dike removal	1, 18	4.3.11
Cell size	1, 10	4.3.12
Inclusion of waves	1, 25	4.3.13
Width of area	1, 29	4.3.14

Table 4-1: Sensitivity Analysis overview

4.2 Model settings

In this paragraph the setup of the base model will be described.

4.2.1 Grid

Because a lot of different simulations are carried out, the computation time must be limited. The best way to do this is to limit the number of grid cells. However, this leads to less detail, which may cause some processes not being captured correctly. To get a good balance between detail and computation time the number of grid cells was limited to 10,000.

To make sure that the results can be used to set up a detailed model for the Nisqually estuary, the sensitivity analysis is set up to have similar conditions as are present in that area. This was realized by taking a slice of the area and treating it as a standalone model. It has tide coming in from deep waters on the northern boundary and extends to a shallow part in the south, requiring a length of 4 km. A width of 1 km was chosen to make sure that channels have enough space to form and migrate. Together with the chosen number of grid cells this lead to cells of 20x20 m. The location of the grid is shown in Figure 4-1 below.

Figure 4-1: Grid for sensitivity analysis

4.2.2 Bathymetry

For the creation of the bathymetry the dataset by Finlayson was used. The elevations in this dataset are not very detailed, it was however the only data available at that moment. The bathymetry was created by grid cell averaging the samples from the Finlayson dataset. Since the dataset is from 2005 the profile of the dike is still in it. This dike was removed from the bathymetry by hand by interpolating between the values on both sides of it.

4.2.3 Time settings

From the literature review it became clear that a salt marsh can take a long time to fully restore, in the order of decades. However, most change happens in the first few years. Because of this, and to limit the computation time a simulation time of 5 years was chosen.

This is long enough to get a good impression of how the vegetation will develop while the total simulation time is still small enough to do a lot of different runs.
In order to be able to do such a long term simulation a morphological factor of 72 is applied. This means that for every day that is simulated in Delft3D the morphological change of 72 days is calculated. So in order to calculate the morphological change in 5 years a period of 25 days has to be simulated in the model. These 25 days are divided in 50 small simulations of 12 hours (or 36 days), after each of which the Matlab routine calculates the changes in the vegetation field. A time step of 30 seconds is used.

4.2.4 Boundary conditions

The project area is more or less a rectangle with the connection with Puget Sound in the north. That's why it was chosen to use the northern boundary as open boundary, while the other three are closed. Based on tidal data from Dupont Wharf, a measurement point approximately 3 kilometers northeast from the estuary, a simplified sinusoidal tide with an amplitude of 2 meters was used.

4.2.5 Sediment

At the moment of the sensitivity analysis no sediment data were available yet. That is why the default values Delft3D were used for the sediment. A uniform layer of 5 meters is used for the entire area, with non-cohesive sediment with a d50 of 0.2 mm.

4.2.6 Vegetation

Even though the vegetation community in the Nisqually estuary is a complex mix of species, for the sensitivity analysis only one type of vegetation is used. This makes it easier to see how the model reacts to a change in the parameters. Parameters for Spartina Anglica were adopted from *Temmerman et al (2007)*, even though it does not occur locally, because no data were available for any other species. These parameters are as follows:

Parameter	Unit	Value
Seed	yr^{-1}	0.01
P0	m^{-2}	200
r	yr^{-1}	1
K	m^{-2}	1200
D	$m^2\ yr^{-1}$	0.2
C_τ	N^{-1}	30
τ_{cr}	$N\ m^{-2}$	0.26
C_{inund}	m^{-1}	3000
H_{cr}	m	1.1

Table 4-2: Vegetation parameters

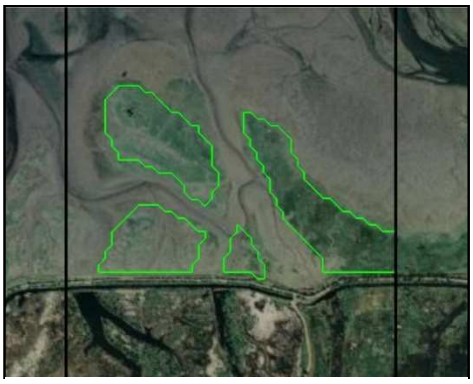

Figure 4-2: Initial vegetation patches

In the base run there is no vegetation at the start of the simulation. To see how initial vegetation would affect the results a vegetation map file is prepared with some patches outside of the original dike. These were based on the salt marsh vegetation that was already growing there before the restoration, as shown in Figure 4-2. They were given a constant plant density of 100 stems/m^2 for run 3 and 500 stems/m^2 for run 4, roughly based on information found in *Woo et al (2010)*.

4.3 Results

4.3.1 Introduction

In section 4.3.2 the base run is described. From section 4.3.3 to 4.3.14 the results of the sensitivity analysis are described per varied parameter, by comparing them to the base run. First it is explained how these runs differ and why they were chosen, and then a comparison is made based on 4 figures. The first figure shows the erosion/sedimentation pattern for the different runs. This shows how the area evolves in 5 years time. Next to that is a graph that shows the evolution of the tidal channels in time. This is calculated by counting the cells of which the bed level has decreased more than 1 meter and multiplying this with the cell area. A threshold value of 1 meter was chosen so that only the erosion in channels is taken into account.

To look at the development of vegetation, the vegetation patterns at the end of the simulation are plotted over the bathymetry. Because of the way in which the vegetation file is saved it was not possible to show the vegetation density in the same figure as the bathymetry. That is why the patches are represented by contour lines. This is mainly noticeable at the larger patches of initial vegetation in some of the runs. Finally, a graph is shown in which the total number of plants (the plant density times the cell area summed for every cell) is plotted against time.

4.3.2 Base run

Before comparing the different runs, some general results of the base run are described. Results after 5 years are used for comparison with the other simulations, but to get an idea of how much change is still going on after that the base run is continued for 30 years. Results are shown after 5, 10, 20 and 30 years in Figure 4-3.

<u>Conclusions</u>

- The main morphological change is the formation of tidal channels. No channels are present in the initial bathymetry but there are small elevation differences, and immediately in the first time step the incoming tide flows through the lowest part forming a channel. Sediment that is eroded from these channels is transported mainly with ebb-tidal flow, and deposited out of the area on the sides of the channel.
- After the initial changes the erosion continues more gradually, with the channels penetrating further inland.
- The development of the vegetation starts with small individual patches. After a long period they coalesce until the whole area except for the tidal channel is covered.

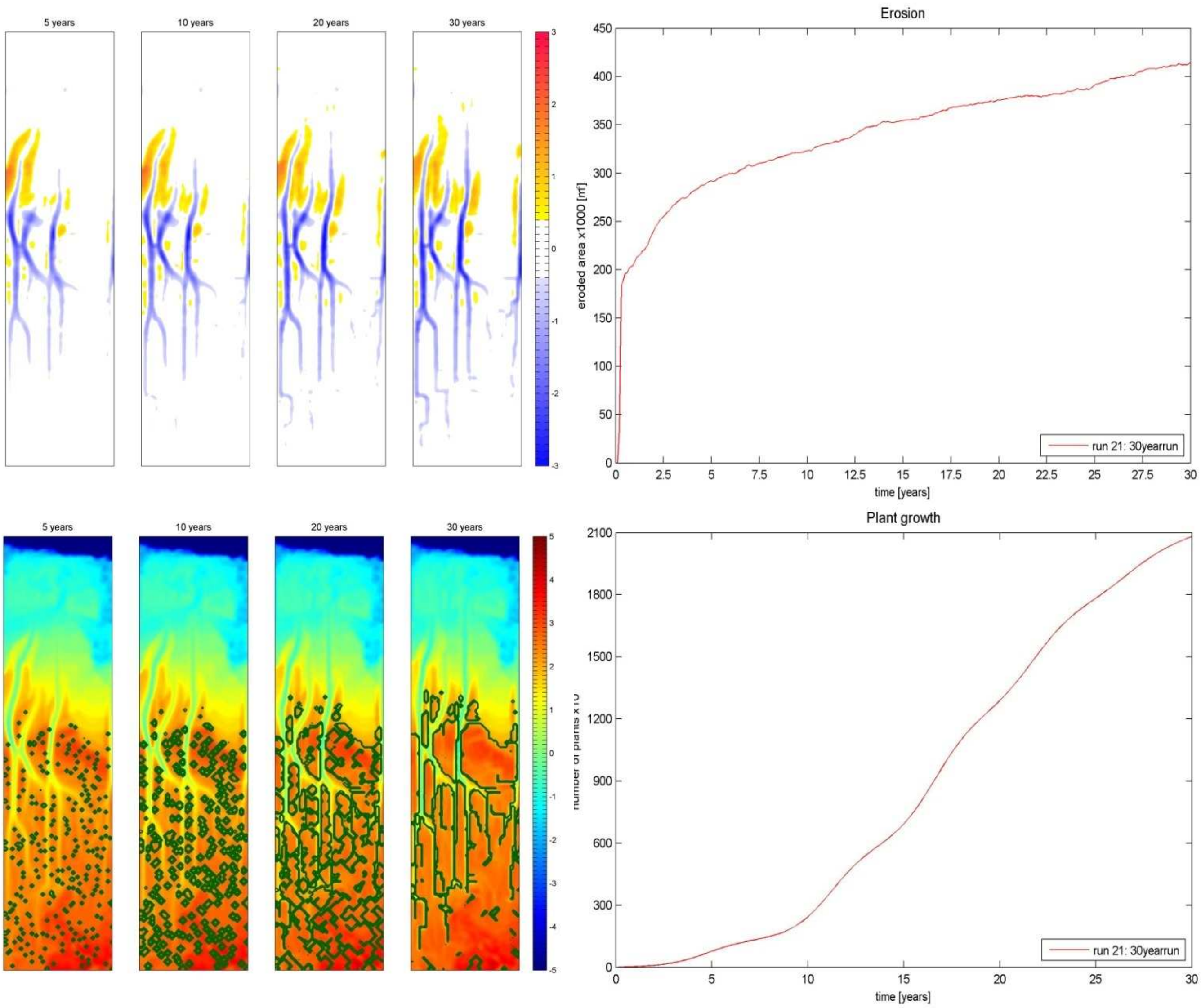

Figure 4-3: Results base run

4.3.3 Sediment

At the moment of the sensitivity analysis no information was available on the bottom material in the area. To see how sensitive the model is to different types of material, four different runs were carried out. As described above, for the base run a uniform layer of sand with a default median grain diameter of 0.2 mm was used. In another run (run 5) this was replaced with silt with a (default) fall velocity of 0.25 mm/s. Also two runs were carried out with 2 types of sediment. Run 19 uses two sand layers of 2.5 m, with median grain diameters of 0.1 and 0.3 millimeters, while run 20 uses a sand and a silt layer, both with the default values used in run 1 and 5.

<u>Conclusions</u>

- For sand and silt there is hardly any difference in the amount of the eroded area but a significant difference in channel and sedimentation patterns. The channels for sand look unrealistically straight while those for silt are more curved.
- Using two sand layers increases the amount of erosion, mainly due to the more easily erodible fraction of 0.1 mm.
- The run for sand and silt leads to less erosion. This might be due to bed armoring.
- There is hardly any difference in plant growth. There is slightly more vegetation for run 20, this could be caused by the decreased erosion, which leaves more room for plants to grow.

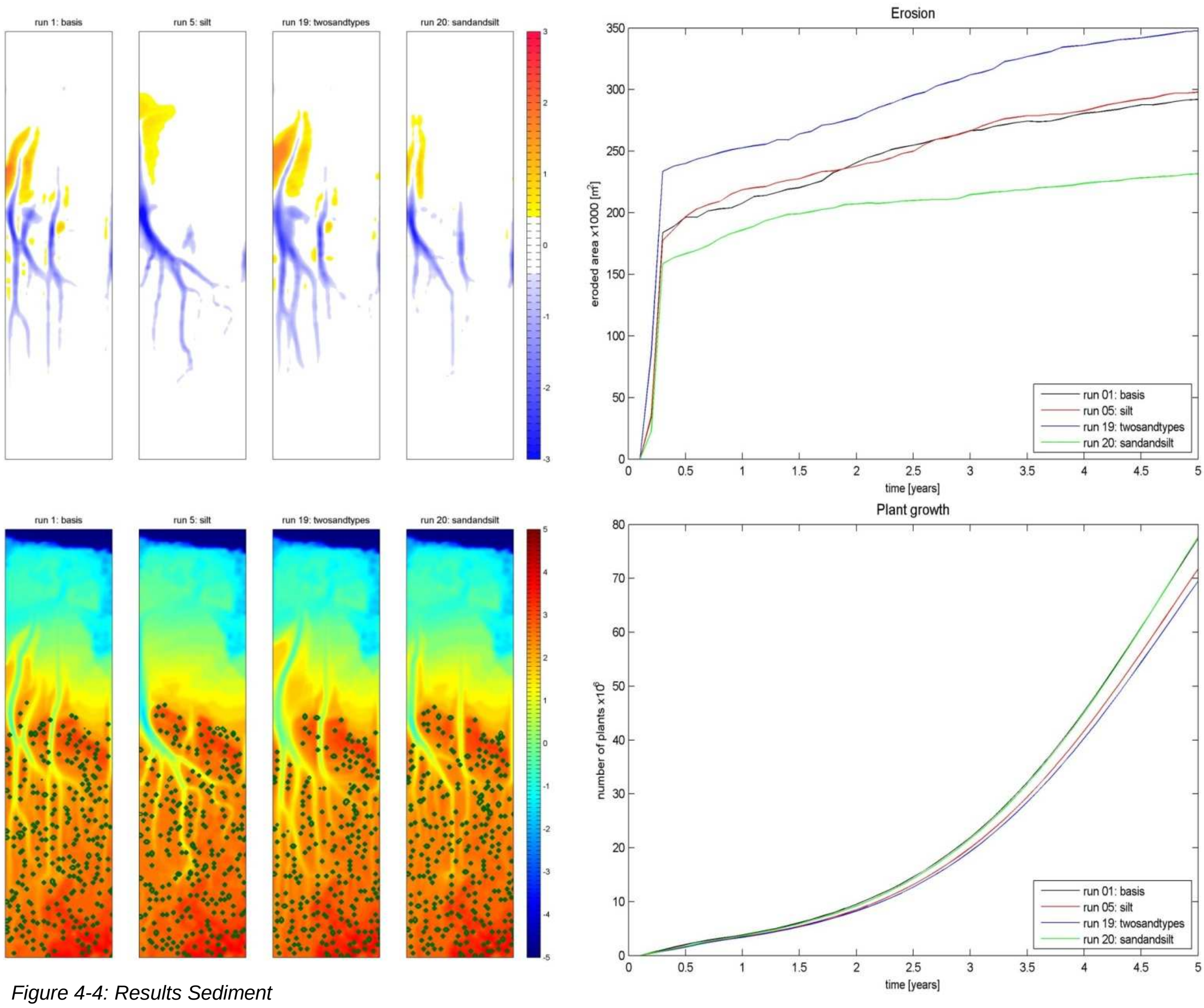

Figure 4-4: Results Sediment

4.3.4 Vegetation

From satellite photos, it can be seen that there is already some salt marsh vegetation present before the dike removal, just outside of the dike. To see if this initial vegetation influences the morphology, some patches of vegetation were created in the model, based on these photos. Two runs were carried out with this initial vegetation, one (run 3) with a low density of 100 stems/m^2 and one (run 4) with a high density of 500 stems/m^2. In another case (run 15) the model was run without the vegetation module.

<u>Conclusions</u>

- Initial vegetation 'focuses' flow, resulting in narrower but deeper channels
- This focusing leads to more erosion in the first time step, but in the long run the amount of eroded area is the same as for the runs without initial vegetation.
- Flow erodes part of the initial vegetation field for the low density, but not for the high density. This also leads to slightly different channel patterns.
- The amount of vegetation grows faster if initial vegetation is present, but seems to be going to the same equilibrium value for the different runs in the long run.

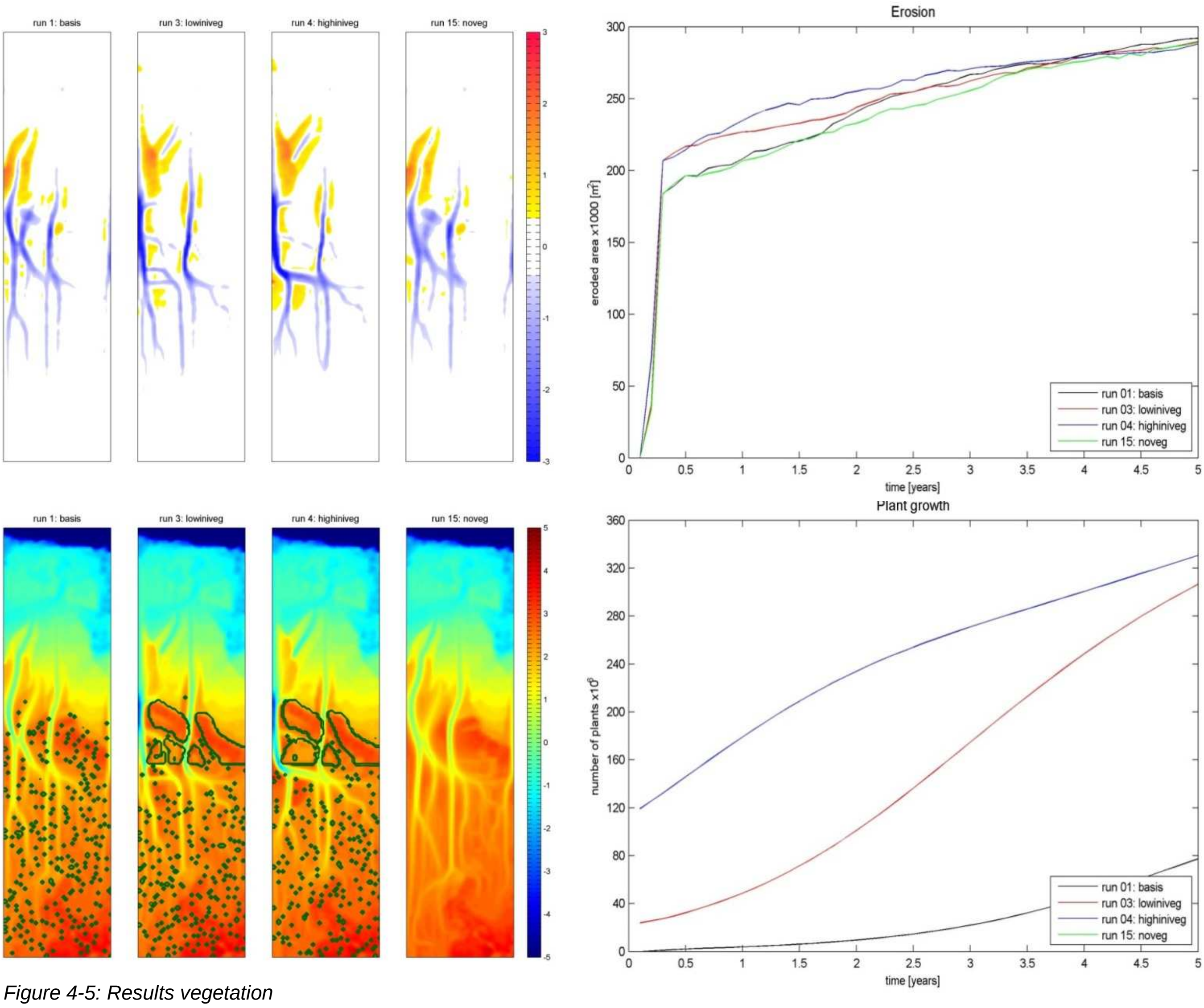

Figure 4-5: Results vegetation

4.3.5 Critical inundation height

One of the parameters in the Matlab script that determines the growth and death of the plants is the critical inundation height. If the maximum waterdepth exceeds this value in a certain cell during the simulation the number of plants in this cell will decrease. The default value for Spartina Anglica for this parameter is 1.1 m, this was changed into 0.6 m and 1.6 m for run 13 and run 14. In order to see how this affects already established patches of vegetation the initial vegetation fields of run 3 were used in these runs.

<u>Conclusions</u>

- The critical inundation height has a large effect on the plant growth in the area. If the value is lowered, parts of the initial vegetation die, and plants will only grow in the higher southern part of the area.
- These differences in plant growth do not have a large effect on the bathymetry. Although the erosion patterns differ slightly, the total eroded area is almost the same for the three runs.

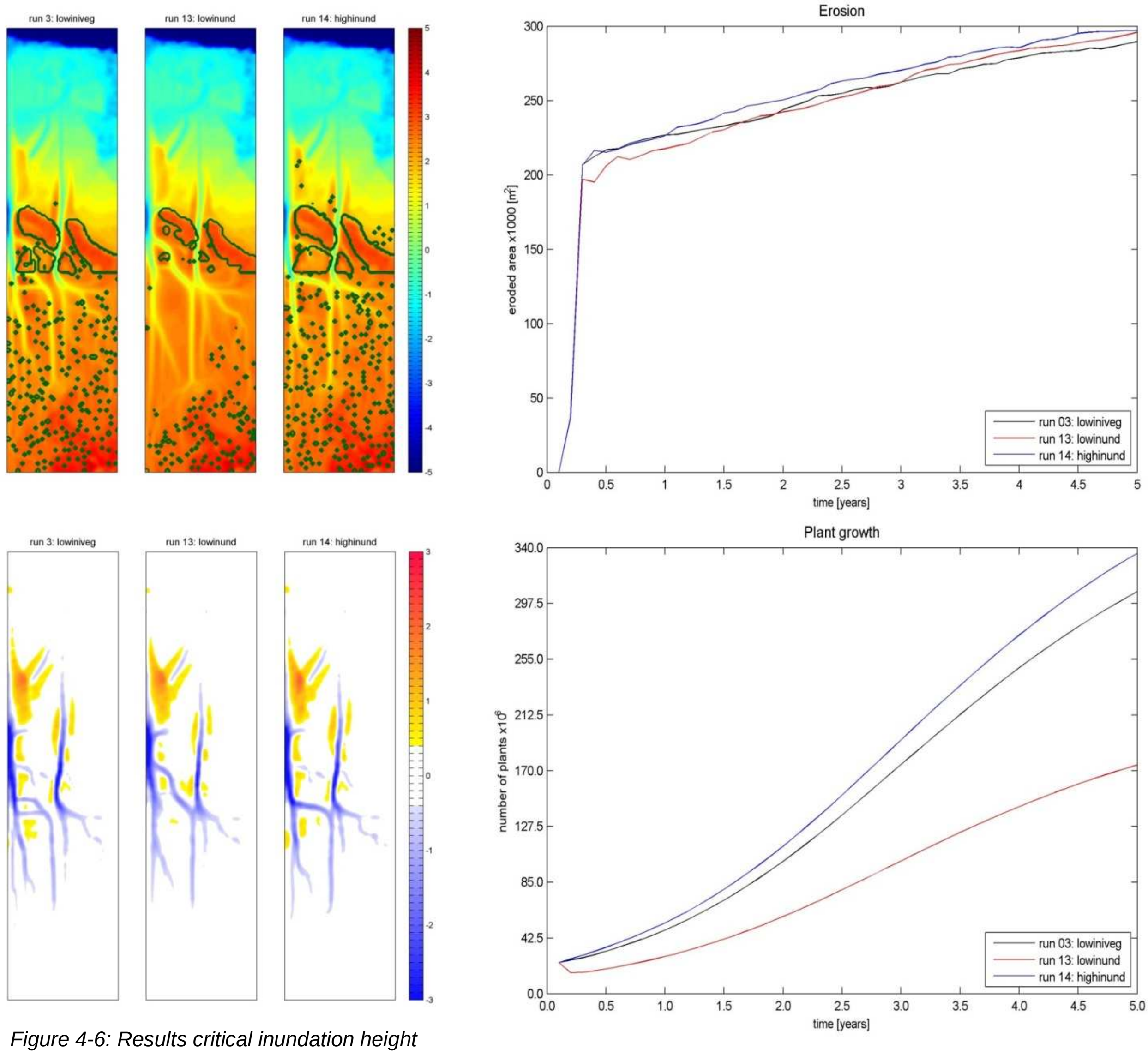

Figure 4-6: Results critical inundation height

4.3.6 Critical shear stress

High shear stresses are another reason vegetation that can cause the vegetation to die off in the Matlab script. The critical shear stress in the base run is 0.26 N/m^2, for the sensitivity analysis this is changed into 0.052 N/m^2 and 1.30 N/m^2 (multiplied/divided by a factor of 5) in run 11 and 12. The same initial vegetation as for the inundation height was used.

<u>Conclusions</u>

- Contrary to the runs for the inundation height these runs show little difference in the plant growth.
- The erosion is almost the same for the three different runs and does not seem to be significantly influenced by the critical shear stress.

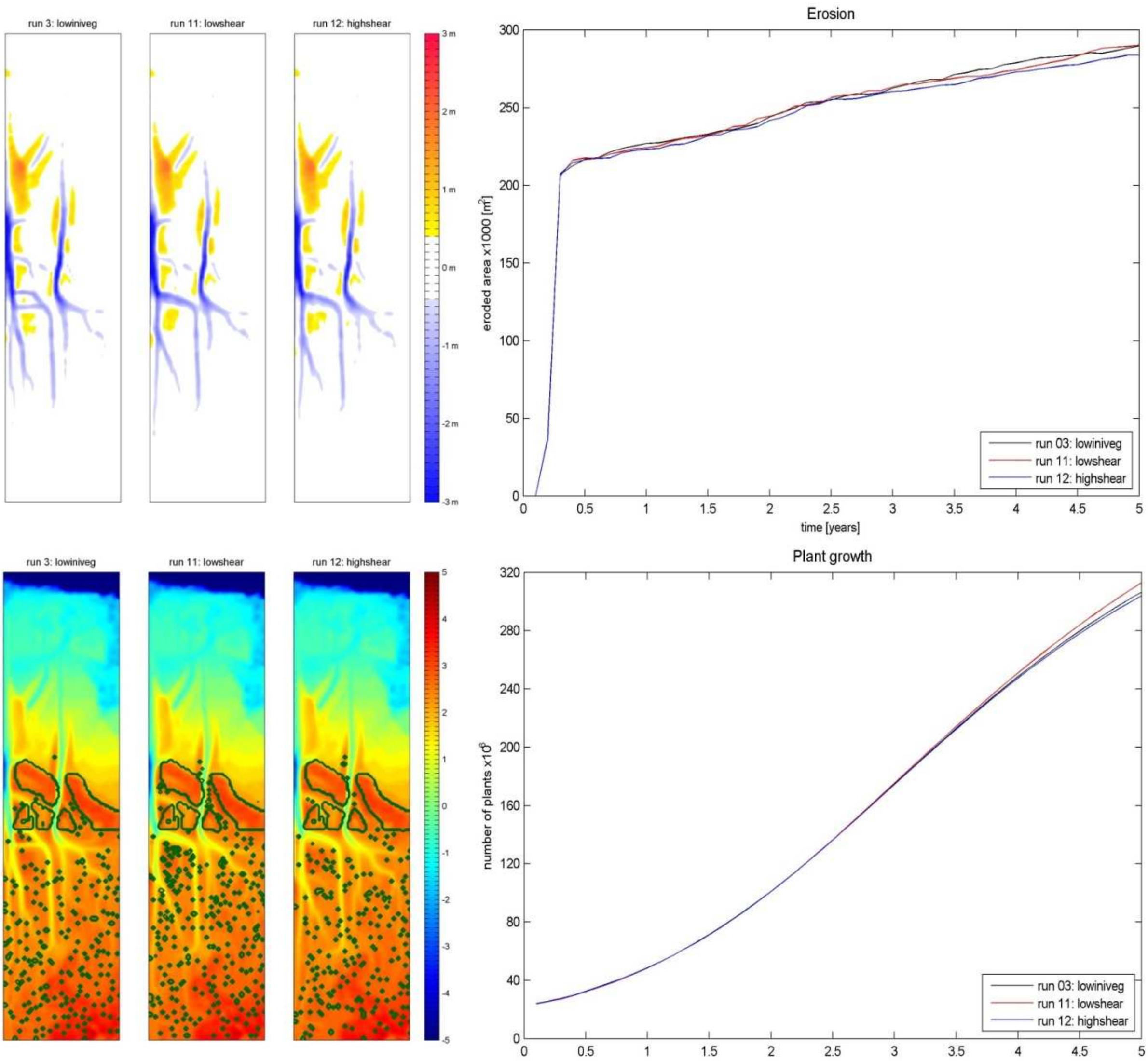

Figure 4-7: Results critical shear stress

4.3.7 Stem diameter

As described earlier, the vegetation is represented in Delft3D by cylindrical rods. The diameter of these rods is varied to see how this influences the model results. Values of 1 mm and 3 mm were used for run 27 and 28, again with the initial vegetation fields of run 3.

<u>Conclusions</u>

- The initial vegetation gets ‘eroded’ more easily when then stem diameter is decreased. Because of this the total number of plants is slightly smaller than for the base run.
- At the place where the initial vegetation disappears in run 27 a small channel is formed. This alters the channel pattern but the total amount of erosion is practically the same.

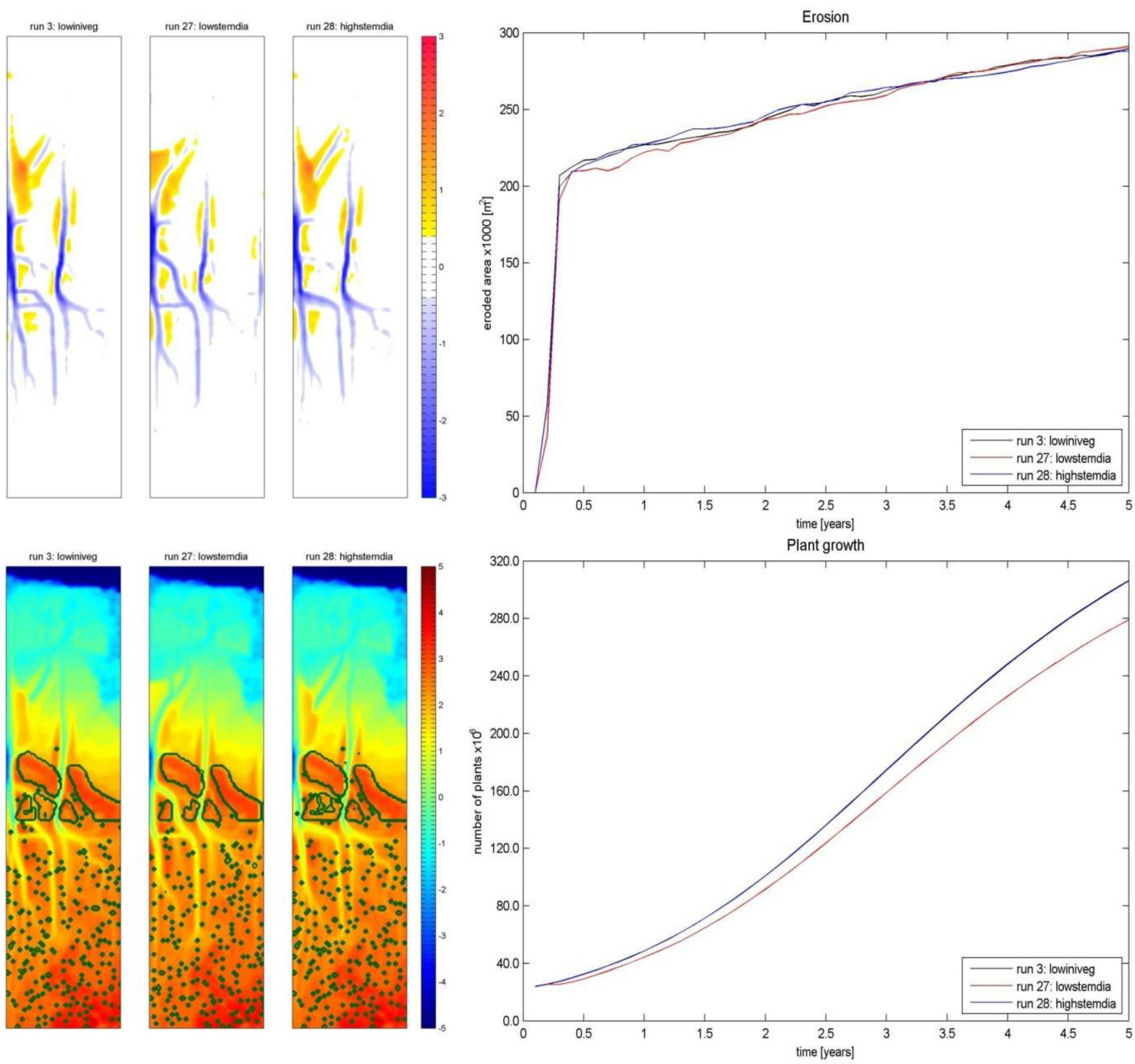

Figure 4-8: Results stem diameter

4.3.8 Tidal amplitude

For all of the sensitivity runs a simple sinusoidal tide is used, with an amplitude of 2. In reality the tide is more complex due to spring-neap variations; therefore it is important to see how sensitive the model is to changes in the amplitude. Additional runs are carried out with amplitudes of 1 m (run 6) and 3 m (run 7).

<u>Conclusions</u>

- The tidal amplitude has a large influence on both the erosion and the plant growth. A larger amplitude leads to a larger tidal prism, deepening the channels and making them penetrate further into the area. For run 7 an equilibrium is already reached after a few time steps, after this the erosion is stopped.
- Because of the higher inundation height in the run with the high amplitude plants can no longer grow in the area, except for a small part in the south. For the lower amplitude of run 7 the opposite is true, the total number of plants increases and vegetation can also grow outside of the original dike.

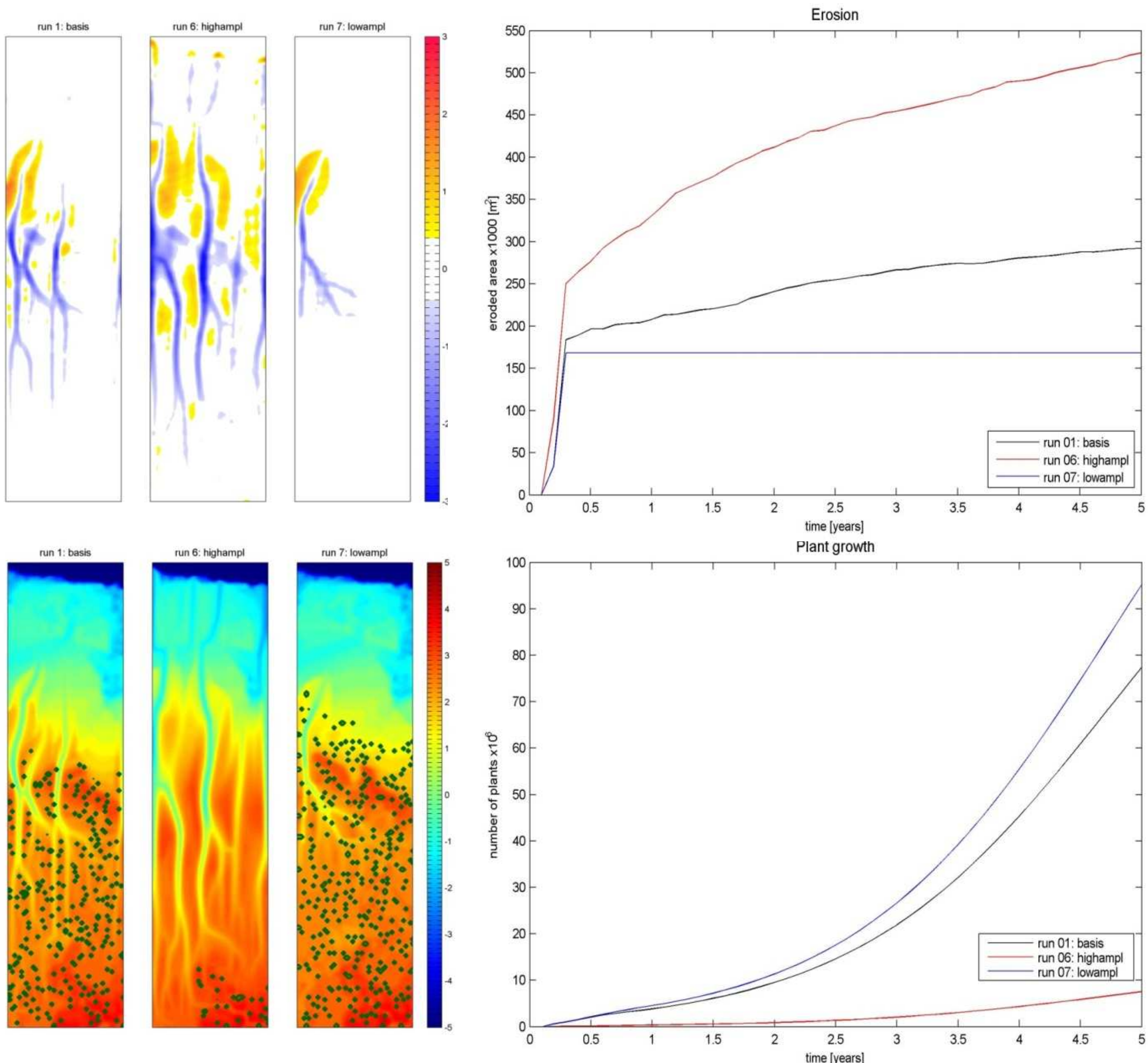

Figure 4-9: Results tidal amplitude

4.3.9 Mean sea level

In the introduction it was explained how sea level rise leads to increased stresses on salt marshes. Therefore it is investigated how the model reacts to an increase of the mean water level. In run 8 it is increased with 0.5 m, while in run 9 it is decreased with 0.5 m.

<u>Conclusions</u>

- Increasing the mean sea level leads to more erosion, because the water penetrates further into the area. A decrease then logically leads to less erosion.
- With the decrease of the mean sea level the channel pattern changes completely. Instead of multiple channels there is now only one very deep channel. This shows that the mean water level has a large influence on the channel evolution.
- Similar to the run with increased tidal amplitude, a higher water level leads to less plant growth because the inundation height increases.

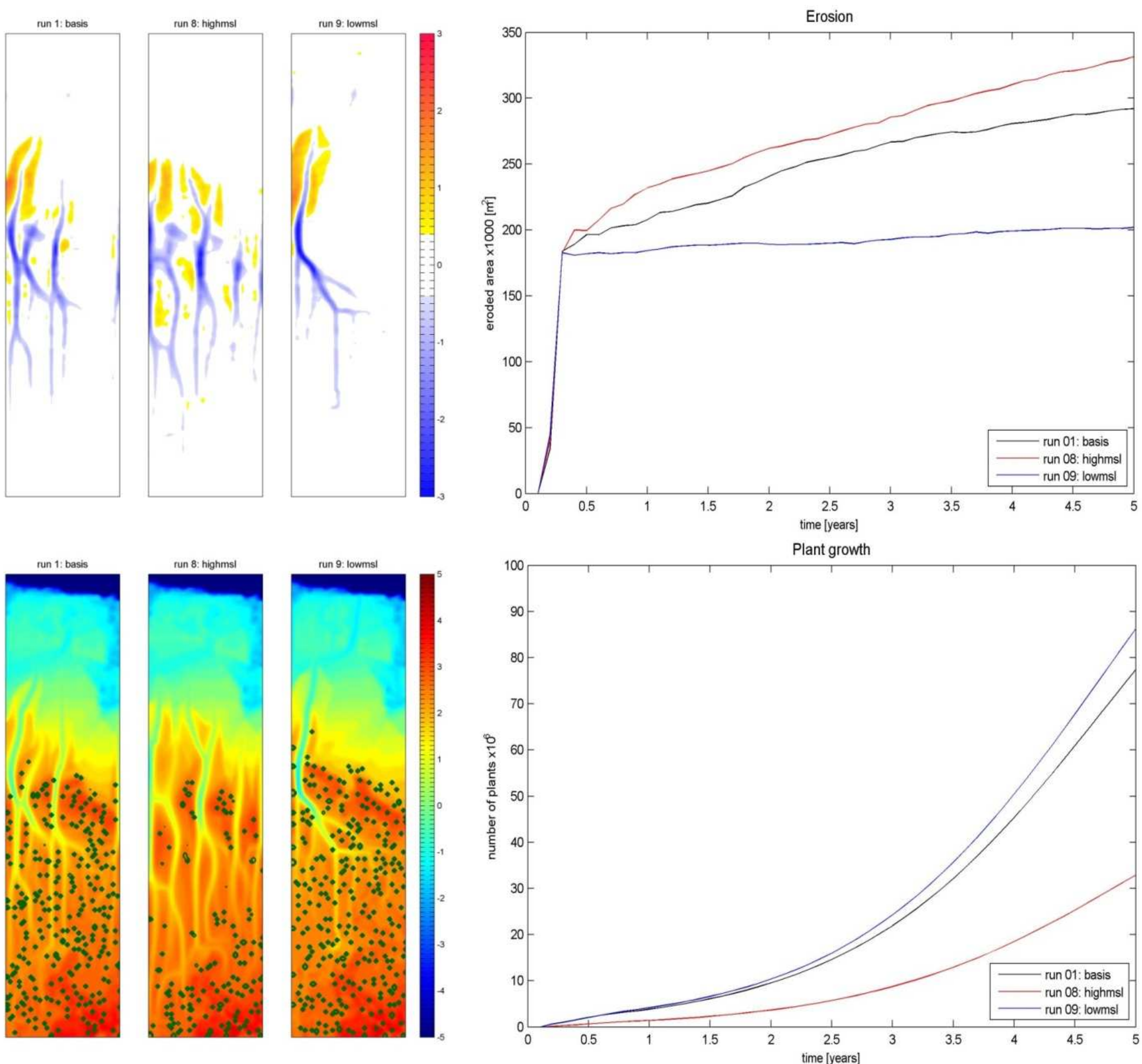

Figure 4-10: Results mean sea level

4.3.10 Chézy coefficient

The Chézy coefficient is used to define the roughness of the area, where a lower value implies a higher roughness. For the base run the default coefficient of C = 65 $m^{½}/s$ was used. Since there are large variations and uncertainties in roughness over the area, due to for example the different types of vegetation, it was examined how sensitive the model is to changes in this roughness. For run 16 the roughness was increased, with C = 50 $m^{½}/s$, and for run 17 decreased, with C = 80 $m^{½}/s$.

<u>Conclusions</u>

- As the roughness increases the flow gets more focused, leading to narrower and deeper channels, comparable to what happens with dense initial vegetation. This leads to an a decrease of the eroded area, but the eroded volume is likely to be approximately the same.
- Plant growth decreases with decreased roughness. This is probably because there is more erosion, so less available area for the vegetation.

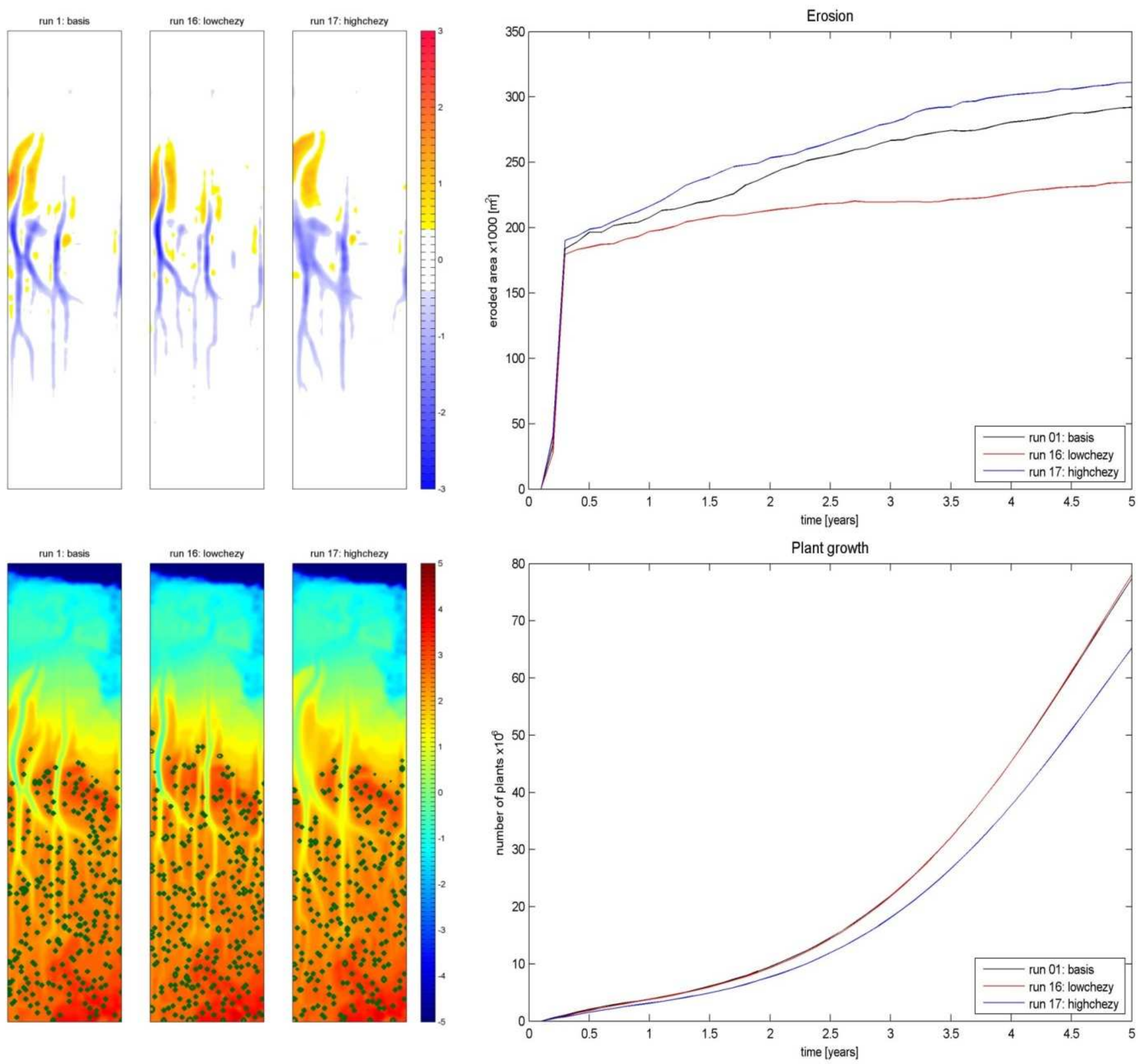

Figure 4-11: Results Chézy coefficient

4.3.11 Dike removal

For the Nisqually project the whole dike was removed at once. In the past there have been restoration projects where only a part of a dike was removed. To see if this influences the results an additional simulation (run 18) was done where only a part of approximately 100 m wide of the original dike was removed.

<u>Conclusions</u>

- All the water is forced to go through a small opening. This creates one large channel locally instead of two or three smaller ones. On both sides of the opening this is divided into two smaller channels.
- The total erosion slightly increases, and the total number of plants is slightly smaller because of this, but the difference is very small. This leads to the conclusion that the method does influence the channel patterns but not the effect of marsh restoration.

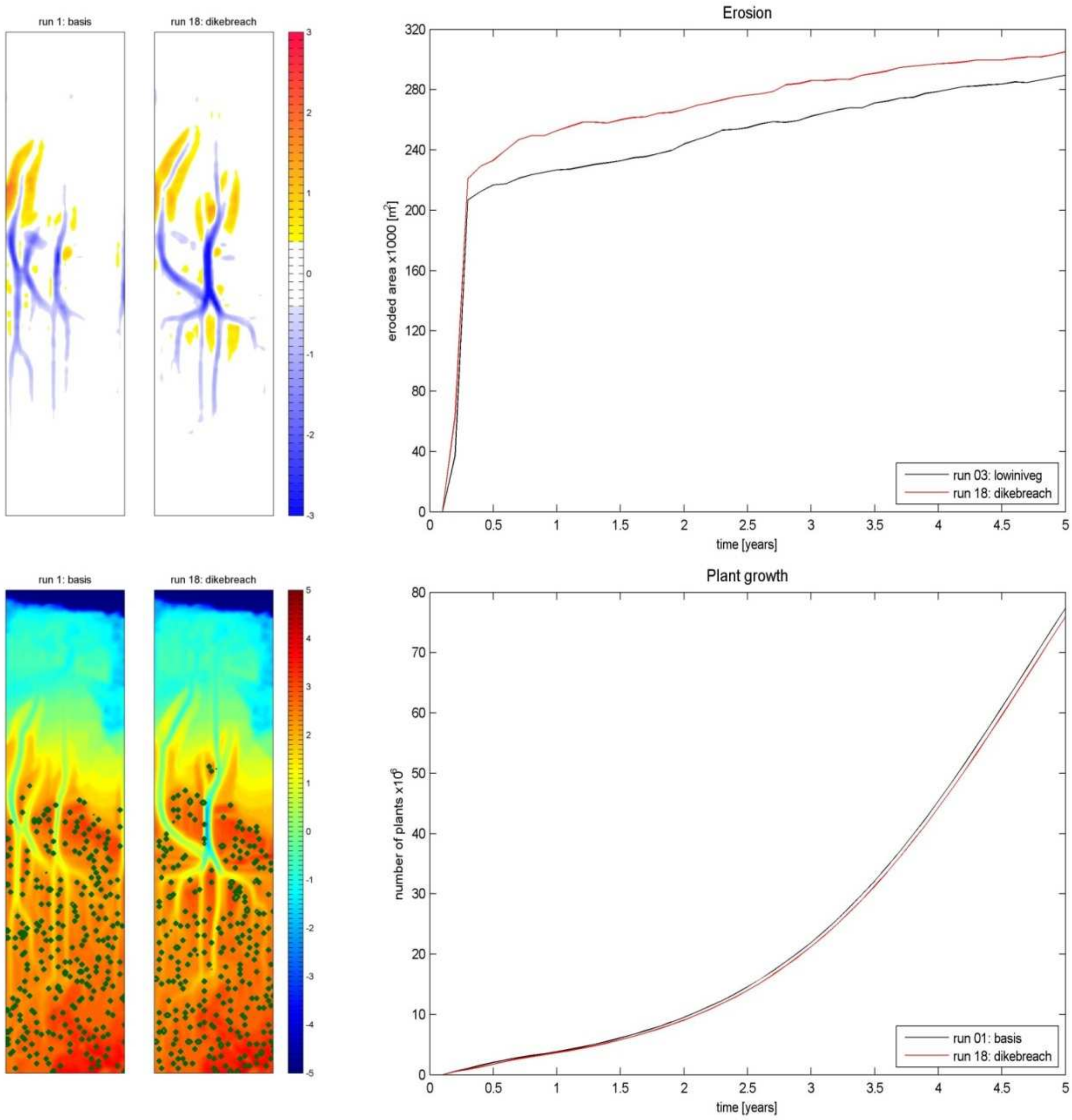

Figure 4-12: Results dike removal

4.3.12 Cell size

The cell size that is used in the base run in order to limit the computation time is 20x20 m. It is expected that this is too large to capture some of the channels in a realistic way. That is why an additional run (run 10) was carried out with cells of 10x10 m. In order to keep the model stable both the morphological factor and the timestep had to be halved as well, so the total run consisted of 100 cycles of 12 hours with a morphological factor of 36 (leading to an increase of computation time with a factor 16). To check if differences are not caused by the change in morfac, another run (run 26) is carried out with a morfac of 36.

<u>Conclusions</u>

- For the smaller grid cells the channels look more realistic (i.e. less straight).
- Channels are narrower for the smaller cell size. Large parts of the channels in both runs are only one cell wide, which implies that the channel width gets overestimated. It also explains why there is less eroded area for run 10.
- For run 10 the channels get narrower but also deeper, so the eroded volume differs less than the eroded area.
- Because the plant growth is calculated per cell the vegetation pattern changes from a few large spots to a lot of small ones. Run 26 shows that the difference in the number of plants is caused by the adjusted timestep and not by the cell size.

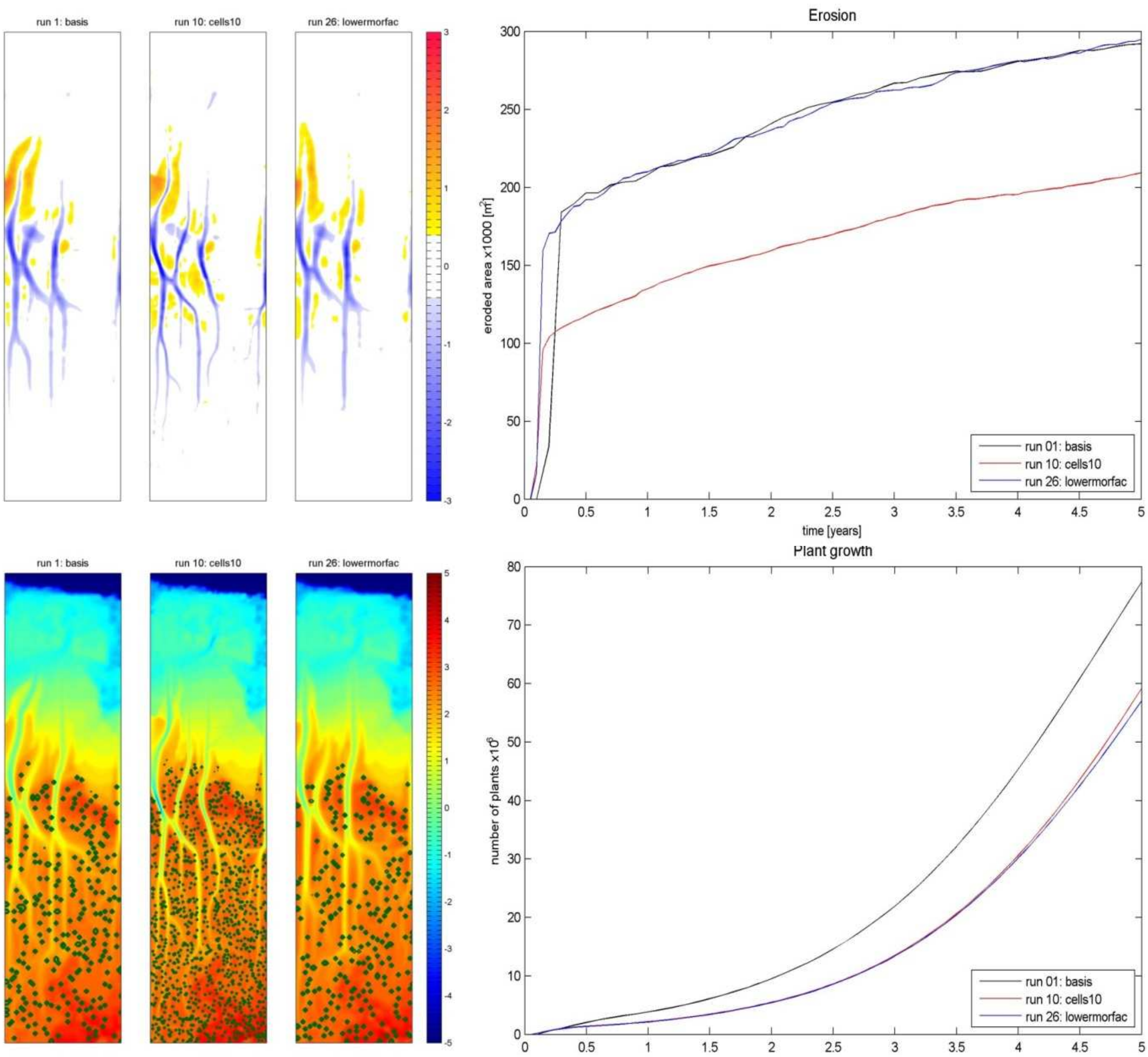

Figure 4-13: Results cell size

4.3.13 Waves

Because of the sheltering effect of Puget Sound no big waves are expected in the Nisqually estuary. That is why no waves were included in the simulation. Still, there will be some small waves that could have effect in shallow waters. Therefore a run (run 25) is carried out to see how the results would change with small incoming waves coming in from the northern boundary. A significant wave height of 0.5 m with a wave period of 3.0 s were chosen (wave data were not available).

<u>Conclusions</u>

- Even though the waves are relatively small, they have a large influence on the erosion. The majority of this change is caused by the erosion of a shallow area in the north; this sediment gets 'pushed' towards the south where it is deposited just north of the restoration area.The tidal channels that are formed are smaller and shallower than for the base run. This might be because the erosion caused by tidal flow is compensated by the sedimentation by the waves.

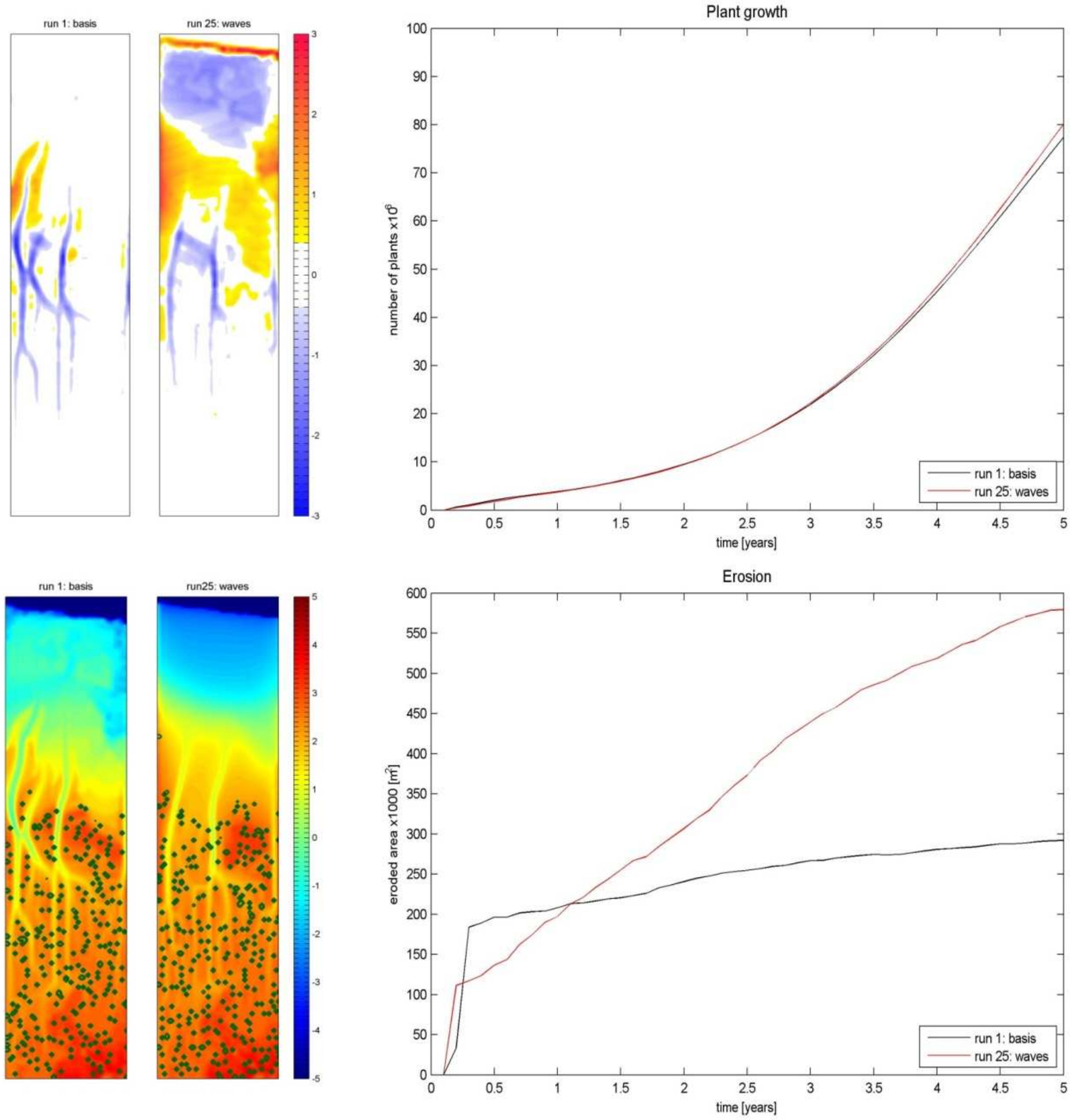

Figure 4-14: Results waves

4.3.14 Area

For some of the previous runs channels are formed along one of the closed boundaries. This raises the question if these boundaries, which can be seen as solid walls, influence the channel formation. To answer this, run 29 was carried out in which the area was widened. On both sides the model was extended with 300 m, increasing the total width from 1 km to 1,6 km. For easier comparison, the boundaries of the base model are indicated with a dashed line in the area plots of the extended area. The eroded area and the number of plants were divided by 1.6 to compensate for the extra area.

Conclusions

- There are some differences in the channel- and vegetation patterns, mainly caused by the initial bathymetry of the area outside of the original boundaries.
- Although the patterns are different, the boundaries do not cause a significant change in eroded area or amount of vegetation.

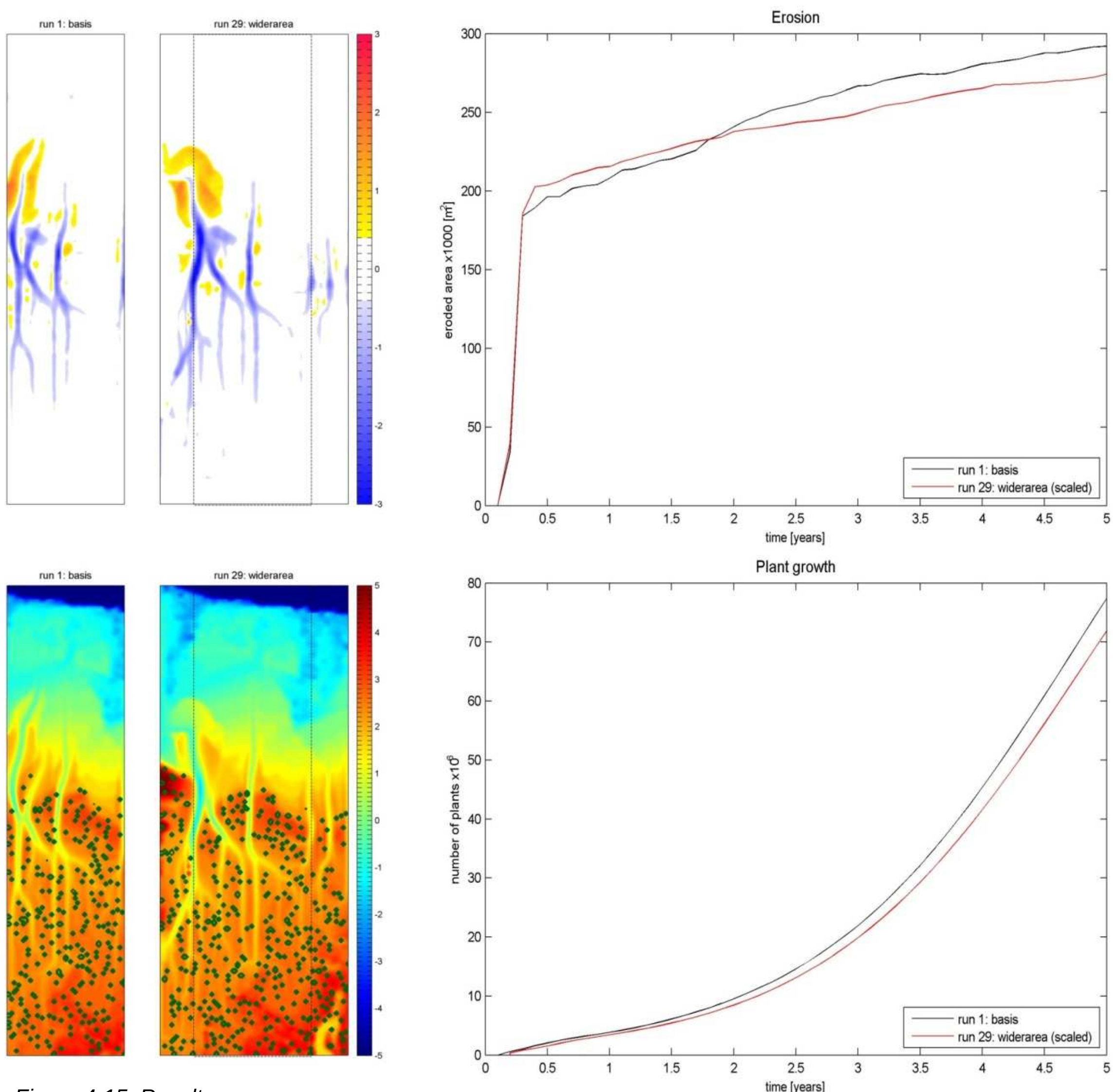

Figure 4-15: Results area

4.4 Conclusions

- Erosion takes place in 2 phases: A large initial erosion in the first few time steps forming the tidal channels, and after that a steady increase of eroded area due to gradual penetration of channels further inland.
- The channel patterns are influenced by initial vegetation but not by new vegetation because of the different time scales, the channels are already more or less in equilibrium before the vegetation expands.
- The type of bottom material has a large influence on the morphology, therefore more information on this should be gathered.
- More detail should be used in the input of the tide, since the tidal amplitude has a large effect on the results.
- The dying of the vegetation is mainly caused by the inundation height. Shear stress seems less important in this situation (with only the tide coming in there are no large flow velocities).
- With grid cells of 20x20 m the erosion is overestimated. If the computation time allows it a more detailed grid should be used to get better and more detailed results.
- Further investigation into the importance of waves in the area should be carried out.

5 Final model

5.1 Introduction

The sensitivity analysis of Chapter 4 gave some insight into the relative importance of the different parameters relevant in the Nisqually estuary. Now this is known, a more detailed model can be set up to see how the dike removal affects the estuary. Different approaches were tried that in the end were not practicable due to a number of reasons. A short summary of these attempts is given appendix D . to possibly save trouble for future modelers.

The final model that was used consists of one domain that extends from the restoration area to the deep part of Puget Sound and has two open boundaries. In the north there is the tidal influence from the sound and in the south the Nisqually River flows into the area. The goal is to get an impression of how the estuary will change over a long period of time and to predict if a salt marsh will be able to develop.

Two different scenarios are examined. The first is the normal situation in which the river keeps following the route it did before the dike removal. The second scenario is based on expectations from people involved with the restoration, that the river will overflow at high discharges and change its route at the bend halfway along the estuary (Figure 5-1). It is hypothesized that this will increase the amount of sediment delivered to the area, which might be beneficial to salt marsh evolution.

le change of river course

First, a base run (run 1) is carried out, simulating a period of 10 years. Since some important data were not available at the time of the modeling a number of assumptions had to be made. To gain some insight in the effect of these assumptions on the results, additional runs are carried out looking at the effects of the sediment discharge and the presence of vegetation (run 2 and 7). For the alternative scenario the river was forced to change its path by adjusting the bathymetry locally. Runs are carried out both with and without sediment discharge (runs 5 and 6). An overview of the runs is given in Table 5-1. Numbers 3 and 4 are missing because these were test runs.

Run number	Description	Goal
1	Base	To Predict how dike removal affects the Nisqually estuary.
2	No sediment from river	To determine the effect of the sediment coming from the river on the evolution of the estuary (compared to run 1).
5	Changed river course	To see if changing the river course is beneficial to the evolution of the estuary (compared to run 1).
6	Changed river without sediment	To determine the effect of the sediment coming from the river on the evolution of the estuary (compared to run 5).
7	No vegetation	Determine the effect of the vegetation on the evolution of the estuary (compared to run 1).

Table 5-1: Runs final model

5.2 Model settings

5.2.1 Grid

The project area is orientated almost exactly in line with the main compass directions, with the Puget Sound in the north and the river coming in from the south. The grid, with square cells of 15 times 15 meters was aligned with these directions. Since the interest area takes up a large part of the model area it was found not to pay off to increase the grid size towards the boundaries, which is why a constant resolution was used. To keep a reasonable computation time the size of the grid cells could not be smaller than 15 meters. This is too large to be able to model the smaller tidal channels. The grid was extended from the restoration area in the south to the deep part of Puget Sound in the north. McAllister Creek in the west was not included in the grid, because no good bathymetry or discharge data for it were available.

Figure 5-2: Grid for final model

5.2.2 Bathymetry

In order to create a bathymetry file for the entire grid, a combination of different datasets had to be used. The deepest part in the north was created by using the multibeam data. For the area just north of the dike the Ground Based LIDAR was used, with some manual corrections for places where the LIDAR seemed to have reflected on the vegetation instead of the bottom. The profiles of the river and the tidal channels were measured in a few locations during a fieldtrip. With these data and some interpolation the bathymetry of the channels could be created. For the remaining area the dataset of Finlayson was used. Finally, the old dike was again removed by hand, and the new dike in the south was put in with help of the plans in Figure 1-4.

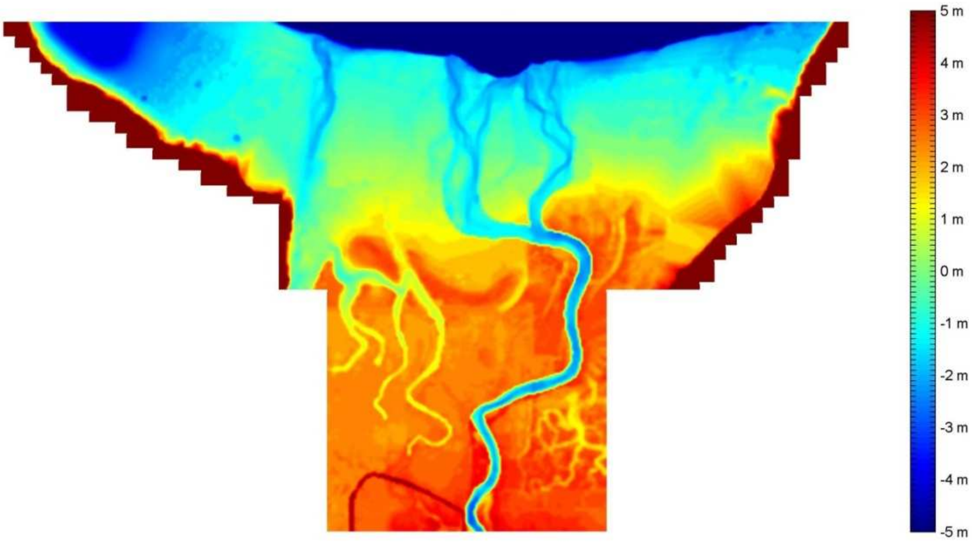

Figure 5-3: Bathymetry for final model

To make the river change its course and flow through the restoration area in the alternative scenario, the bathymetry was changed. The river was blocked after the bend and a gap in the bank was made so that the water flows directly into the restoration area (Figure 5-4).

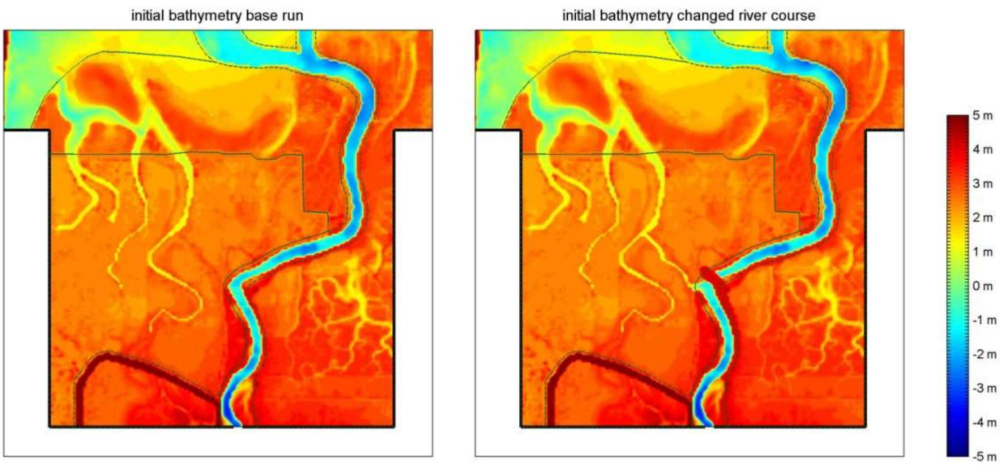

Figure 5-4: Initial bathymetry for base run (left) and changed river course right)

5.2.3 Time settings

A total period of 10 years is simulated for each run. Like with the sensitivity analysis, a morphological factor of 72 is used, which means that the hydrodynamic model time is approximately 50 days. The vegetation field is updated every 12 hours (or 36 days), so a total of 100 cycles is applied. A timestep of 15 seconds is used.

5.2.4 Boundary conditions

<u>Tide</u>

The main forcing comes from the tide along the entire northern boundary. Boundary conditions in the form of astronomical constituents were generated with a tide model for the southern part of Puget Sound, provided by USGS. The domain of this model is shown in Figure 5-5. The model was run for two weeks, and output was generated for both ends of the boundary of the fine model. With a tidal analysis the harmonic constituents were determined, and these are used as input. The main components are listed in Table 5-2.

	Left end		Right end	
Component	Amplitude [m]	Phase [°]	Amplitude [m]	Phase [°]
M2	1.3686621	23.5107787	1.3686743	23.5103837
K1	1.0652021	288.584921	1.0651773	288.585803
O1	0.4674312	260.470550	0.4674151	260.472223
S2	0.3019271	65.7269567	0.3019214	65.7292597
N2	0.2865675	4.0516227	0.2865694	4.0520937

Table 5-2: Main tidal constituents

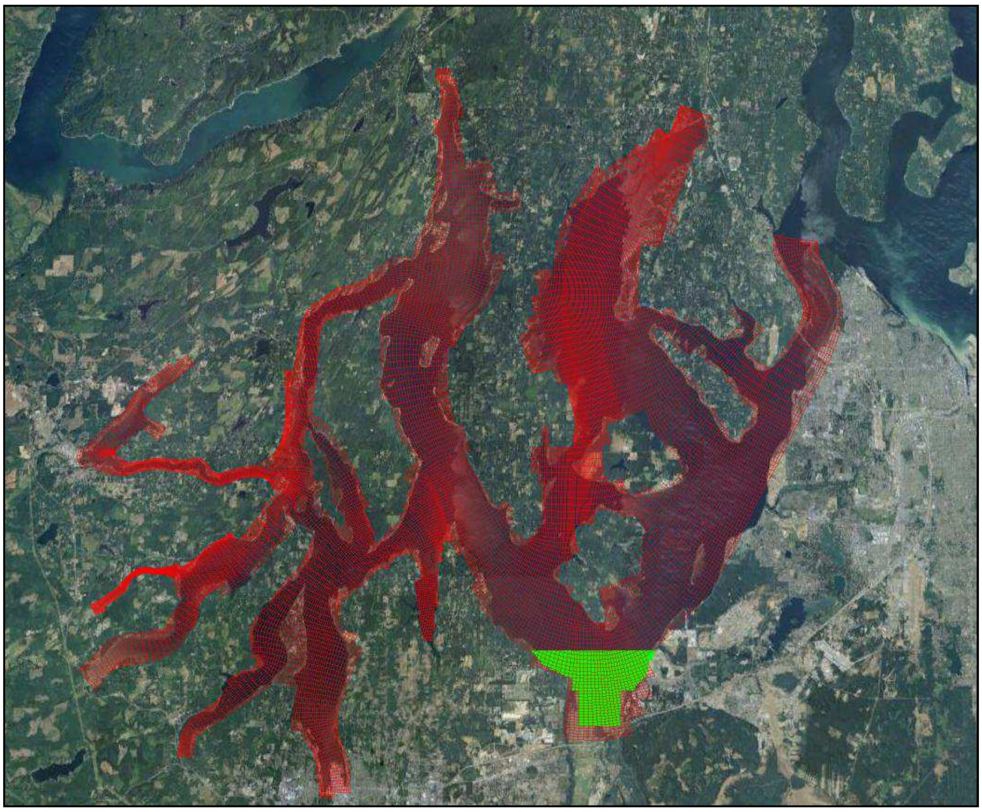

Figure 5-5: Tidal model used to generate boundary conditions

River

The second open boundary lies on the southern boundary and represents the Nisqually River. A time-varying discharge boundary condition is used over a width of 5 grid cells. The discharge was schematized by averaging the mean of daily values for the period of 1947-2009 for every month. This way one representative discharge is found for each month, so that the difference between summer and winter discharges is captured. The morphological timescale is used, so that the discharge cycle is used ten times over the course of the ten-year simulation. The schematized yearly discharge is shown in Figure 5-6.

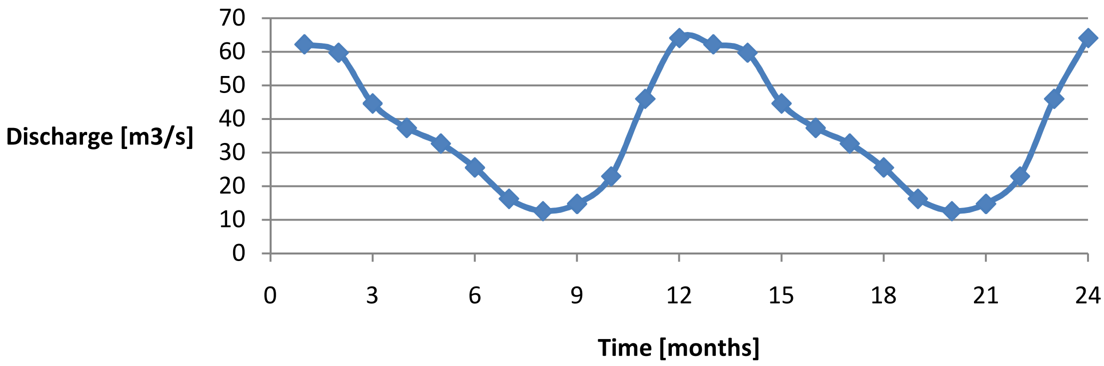

Figure 5-6: Schematized river discharge

Sediment discharge

As mentioned in the introduction, no information was available on the transport of sediment by the Nisqually River. For lack of a better option, discharge data were used from the Deschutes River, a nearby river with comparable discharge and dimensions. Data were taken from *George et al (2006)* and are shown in Table 5-3. These values were interpolated to fit with the sediment fractions and discharges used in this model. Since the occurring flow velocities are too low to transport the larger fractions, only the two smallest fractions were used as discharge. Sediment discharge was set to zero for run 2 and 6.

river flow (m^3/s)	total concentration (kg/m^3)	2 μm concentration (kg/m^3)	31μm concentration (kg/m^3)	200 μm concentration (kg/m^3)	2000 μm concentration (kg/m^3)
146	1.20	0.34	0.49	0.34	0.04
95	0.52	0.15	0.21	0.15	0.02
66	0.26	0.07	0.11	0.07	0.01
42	0.11	0.03	0.04	0.03	0.00
13	0.01	0.003	0.005	0.003	0.00

* component concentrations may not sum to total concentrations because of rounding

Table 5-3: Sediment concentrations at Deschutes River (George et al 2006)

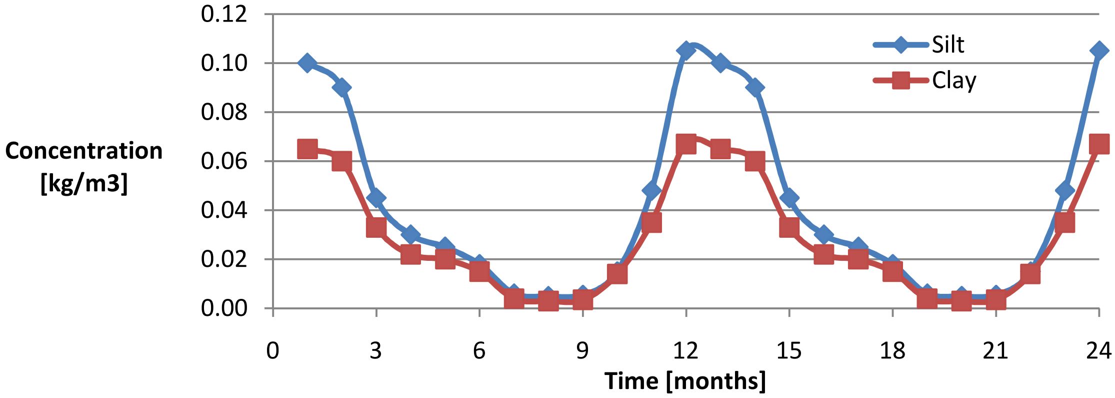

Figure 5-7: Schematized sediment concentrations

5.2.5 Sediment

Based on sediment samples taken in the shallow area north of the restoration area three representative fractions were determined: A non-cohesive sand fraction with d_{50} = 160 μm, a cohesive silt fraction with d_{50} = 28 μm and a cohesive clay fraction with d_{50} = 1.6 μm. For the cohesive fractions this translates to settling velocities of respectively 1.4 mm/s and 0.0046 mm/s. The settling velocity for silt was later changed to 0.25 mm/s since the sediment from the river seemed to settle too fast. The layer thicknesses were also chosen in accordance with the sediment samples: 4 meters of silt and 1 meter of both sand and clay. A more detailed explanation is given in appendix 1)a)i)(1)(a)(i)C C

5.2.6 Vegetation

A lot of different vegetation species are found in the Nisqually estuary. In *Burg et al 1980* the plant communities outside of the diked area are described in great detail. Because of the level of detail of the model it is of no use to try to reproduce this. Therefore a few species are selected that are believed, based on this and other researches (*Seto et al 2000*, *Woo et al 2010*) to be dominant in the restored salt marsh. One fresh water species was also used to represent the vegetation before the dike removal. Parameters were determined with the help of multiple sources (mostly the website http://plants.usda.gov/characteristics.html) which gave mainly qualitative information about characteristics such as density and growth rate. The parameters from the sensitivity analysis were used as starting point, and then changed where needed according to the available information. An overview of the used parameters is found in Table 5-4.

<u>Carex Lyngbyei (Lyngbye's sedge)</u>

Carex Lyngbyei is a species of sedge that is native to the west coast of North America. It is a pioneer species, one of the first plants to colonize the mud of tidal flats. It usually has a height of approximately 30 cm and grows from a network of long rhizomes. It has a moderate spreading rate and a medium salinity tolerance, but can grow at relatively low elevations.

<u>Distichlis Spicata (saltgrass)</u>

Distichlis Spicata is a species of grass that thrives along coastlines and on salt flats. It grows from rhizomes and can form dense monotypic stands. It has a high salinity tolerance and can reach heights of half a meter, but is generally slightly shorter.

<u>Salicornia Virginica (pickleweed)</u>

Salicornia species are small, succulent herbs that have a horizontal main stem and erect lateral branches. They have a very high salinity tolerance but spread slowly.

Phalaris Arundinacea (reed canary grass)

Phalaris Arundinacea is a tall grass that is widely distributed over most of the world. Particularly in wetlands it is considered an invasive species because it suppresses native vegetation and reduces diversity. Before the dike removal it covered almost the whole restoration area, but since it is intolerant to salt water it is expected to disappear quickly.

Parameter	Unit	PHAR	CALY	DISP	SAVI
Stem diameter	m	0.001	0.001	0.001	0.001
Stem height	m	1.18	0.30	0.34	0.30
Seed	yr^{-1}	0.00	0.02	0.02	0.01
P0	m^{-2}	200	200	200	300
r	yr^{-1}	1	1	1	1
K	m^{-2}	600	600	1000	800
D	$m^2\ yr^{-1}$	0	0	0	0
C_τ	N^{-1}	30	30	30	30
τ_{cr}	$N\ m^{-2}$	0.26	0.26	0.26	0.26
C_{inund}	m^{-3}	3000	3000	3000	3000
H_{cr}	m	1.1	1.44	0.72	1.18
C_{sal}	$m^{-2}\ ppt^{-1}$	100	100	100	100
Sal_{cr}	ppt	3	20	31	31

Table 5-4: Vegetation parameters

Initial vegetation fields

Based on the detailed vegetation research that has been done both in- and outside the old dike initial patches of vegetation were put into the model (Figure 5-8). It was assumed that reed canary grass was uniformly spread over the entire restoration area except for the tidal channels. The different patches outside of the dike were given one type of vegetation, except for the curved patch in the middle which consists of both saltgrass and pickleweed (due to the method of displaying only saltgrass is shown in the figure).

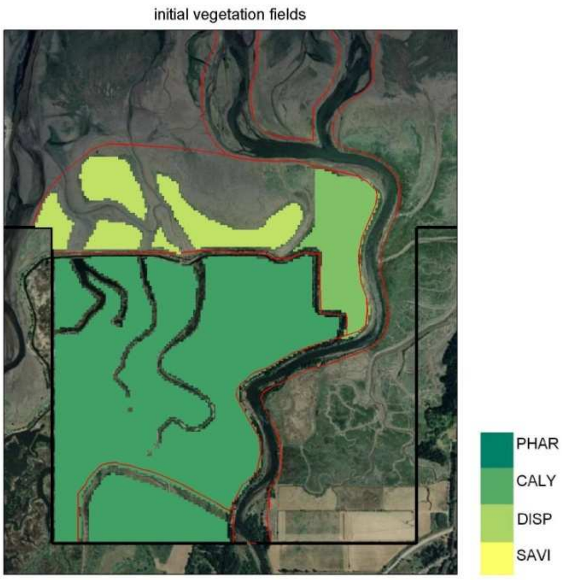

Figure 5-8: Initial vegetation fields

5.2.7 Calibration

Since no post-restoration data were available at the time of modeling, no real calibration could be carried out. However, the plant parameters were tried to be calibrated in the following way:

From a map from 1980 and a number of satellite photos dating back to 1990 it is seen that the patches of existing salt marsh outside of the old dike do not expand or retreat. From this it can be concluded that they are more or less in equilibrium at the current conditions. When running the Matlab routine for vegetation with the initial fields of Figure 5-8 these patches should be stable. Critical inundation heights of saltgrass and pickleweed were originally chosen to be 0.22 m and 0.68 m, based on *Seto et al 2000*. In this research elevation ranges of vegetation types were estimated based on tidal datums. Since these do not correspond exactly with inundation heights, which are different for every tidal cycle, some adjustments had to be made. With the used values the patches largely disappeared, so different values were tried. Eventually it was found that by increasing the parameters to 0.72 m and 1.18 m respectively the patches of marsh vegetation are largely stable.

From the one post-restoration satellite photo available and a site visit half a year after the dike-removal, it was clear that in a few months almost all of the freshwater vegetation had died. With this information the salinity parameters were calibrated so that the model corresponded with this.

5.3 Results

5.3.1 Introduction

As described in the beginning of this chapter, 7 different runs were carried out. Here the results of those runs are described and compared to each other. For each run, plots are shown for the cumulative erosion and sedimentation and for the vegetation patterns after ten years. To quantify these results the model area was divided into 4 parts by polygons. Polygon 1 represents the restoration area, polygon 2 the river bed, polygon 3 the marsh area outside of the dike and polygon 4 the remaining area (Figure 5-9). For each polygon the amount of vegetation and the change in sediment volume is determined from the model results. Since the goal of the restoration project is the restoration of salt marsh, it is strived for to maximize the amount of marsh vegetation and the import of sediment in areas 1 and 3.

Furthermore the elevation of every cell is determined and then the percentage of area between certain elevations is calculated. Since the distribution of vegetation mainly depends on elevation, this gives an impression of the possible expansion of vegetation. By basing the used elevations on the parameters found earlier this can be done per species. It is assumed that for elevations lower than +1.56 m (in reference to NAVD88) no vegetation can establish. Carex Lyngbyei can establish at an elevation higher than +1.56 m, Salicornia Virginica higher than +2.32 m and Distichlis Spicata higher than +2.78 m. To get an impression of the variation in water level and salinity, some extra plots are shown in appendix E.

In section 5.3.2, first the results of the base run are described. In the following sections these are compared to the other runs, and from these results conclusions are drawn.

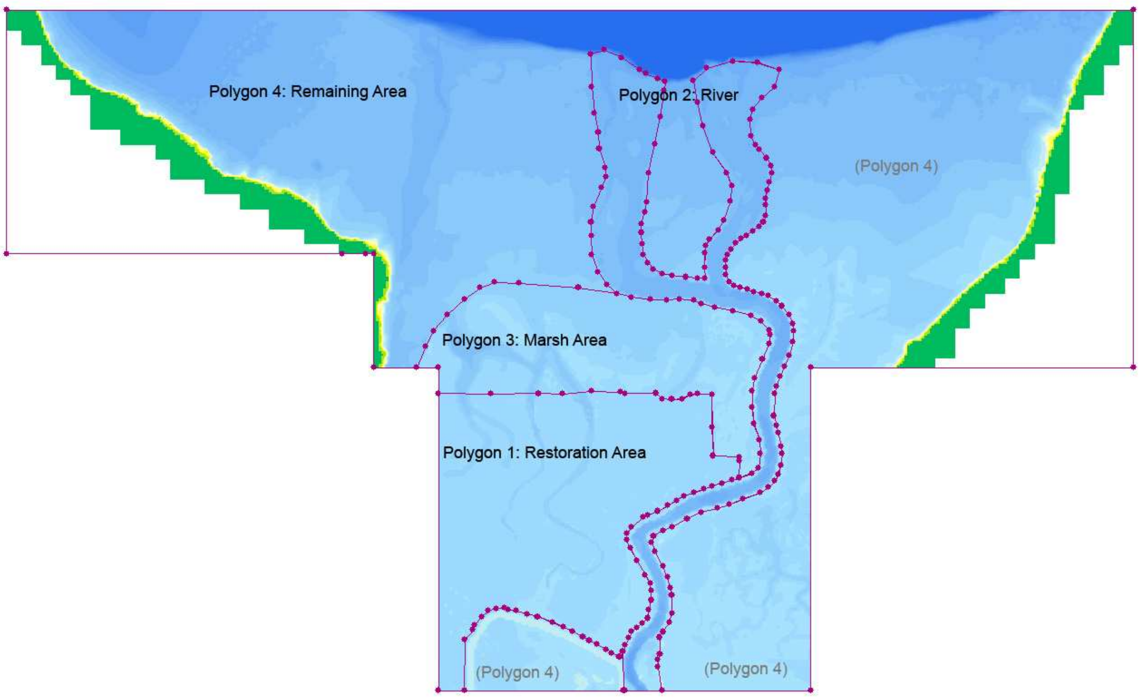

Figure 5-9: Polygons

5.3.2 Base run

<u>Morphology</u>
As can be seen from the results on the next page, a large amount of the sediment coming in from the river boundary is already deposited in the river itself. In the initial bathymetry the river had a width of 4 or 5 grid cells, but this quickly decreases because sediment is deposited on the sides, until a width of only one cell remains. This is obviously not realistic, and could be caused by one of the following reasons:

- The river discharge in the model is based on monthly averages, which excludes incidental peak discharges. It could be that these are required to 'flush' the river bed.
- The initial river profile was created based on limited data, and was largely constant over the width, so on the sides it was possibly deeper than in reality.
- It could be that the sediment fractions were not set up correctly. Only two sediment fractions were used for the discharge from the river. A large part of the silt settles in the river (initially for the silt fraction a settling velocity of 1.4 mm/s was used and for that an even larger amount of sediment was deposited in the river), while most of the clay sediment never settles. In reality there is a range of sediment sizes so the transition would be more gradual when more fractions are used.

In the restoration area, the morphological change for the tidal channels is limited. There is some alternating erosion and sedimentation but they do not expand like in the sensitivity analysis runs. This makes sense when it is assumed that there was already an equilibrium before the diking of the area, and since then the channels have barely changed. The initial bathymetry of the channels used in the model might not have been very accurate (measurements were only available for a few cross-sections, at other places an estimation had to be made), which is probably the reason for some erosion and sedimentation taking place. Outside of the channels there is deposition of sediment from the river, mainly in the eastern part. On the existing salt marsh patches there is not a lot of morphological change, while it was expected that vegetation would trap sediment, increasing the elevation locally. This could have to do with the fact that the vegetated patches, mainly outside of the old dike, only get flooded occasionally with the highest tides. Another possible explanation is that a 2D depth averaged model is used, so some 3D effects are ignored.

In total there is an amount of 1.09 million m^3 of sediment coming into the model from the river. Almost 60% of this is deposited in the river and only 8.5% makes it into the restoration area. The sediment that does make it there leads to an increase of area that has a suitable elevation for salt marsh vegetation. The existing marshes north of the old dike lose sediment but still gain a small amount of 'salt marsh suitable area'. This seems to be because part of the sediment that gets eroded in the center of the channels gets deposited on the sides. It should be noted that there is also some sediment deposited in the area directly from the river (near the bend) at high water.

<u>Vegetation</u>
As expected, almost all of the salt-intolerant Phalaris arundinacea dies off quickly after the saline water of Puget Sound enters the restoration area. The salt marsh species, initially present only north of the old dike start expanding southward. After 10 years, mainly the higher laying eastern part is covered. It is covered with mainly Carex Lyngbyei, a pioneer species that does not have a very high salt tolerance, but can thrive due to the fresh water from the river.

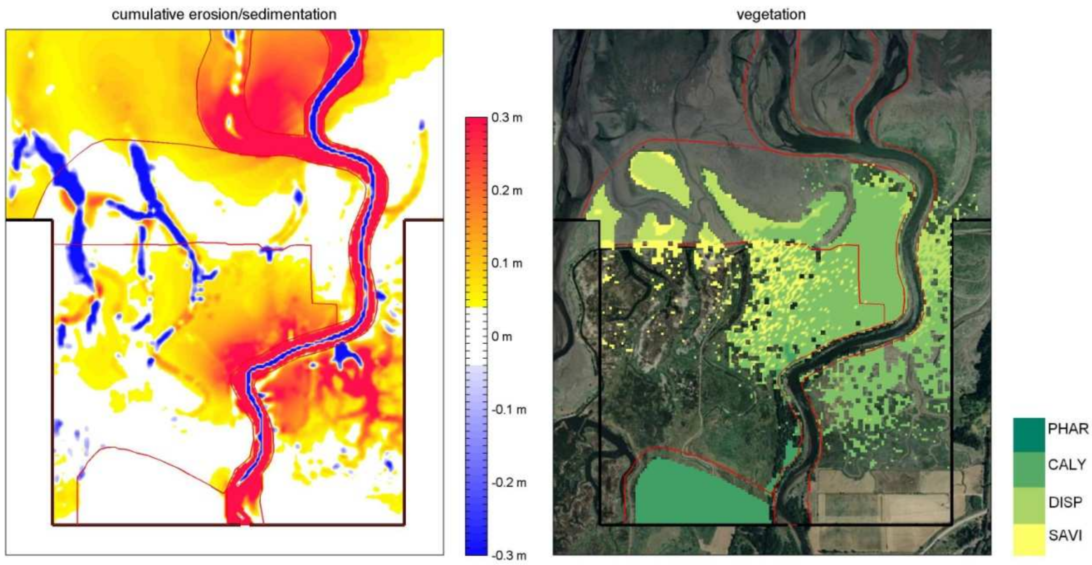

Figure 5-10: Results for base run

	Initial	Run 1
Volume change [m^3]	-	+9.32E+04
Percentage of area with elevation <-1.12 m	0.0	0.0
Percentage of area with elevation -1.12 – 1.56 m	8.3	7.8
Percentage of area with elevation 1.56 - 2.32 m	18.1	15.8
Percentage of area with elevation 2.32 – 2.78 m	65.3	63.1
Percentage of area with elevation >2.78 m	8.3	13.3
Amount of vegetation (PHAR) [no. of stems * 10^6]	733	22.7
Amount of vegetation (CALY) [no. of stems * 10^6]	4.86	236
Amount of vegetation (DISP) [no. of stems * 10^6]	0.68	8.85
Amount of vegetation (SAVI) [no. of stems * 10^6]	0.54	97.6

Table 5-5: Results for base run - polygon 1

	Initial	Run 1
Volume change [m^3]	-	-2.77E4
Percentage of area with elevation <-1.12 m	0.0	0.4
Percentage of area with elevation -1.12 – 1.56 m	25.2	18.1
Percentage of area with elevation 1.56 - 2.32 m	26.9	32.7
Percentage of area with elevation 2.32 – 2.78 m	22.8	22.6
Percentage of area with elevation >2.78 m	25.0	26.1
Amount of vegetation (PHAR) [no. of stems * 10^6]	0.00	0.00
Amount of vegetation (CALY) [no. of stems * 10^6]	225	201
Amount of vegetation (DISP) [no. of stems * 10^6]	200	239
Amount of vegetation (SAVI) [no. of stems * 10^6]	91.7	46.1

Table 5-6: Results for base run - polygon 3

5.3.3 Influence of sediment discharge

Morphology
For the run without sediment discharge a large difference lies near the river. There is still some sedimentation on the banks but the remaining channel is wider. The main difference however is the lack of sedimentation near the mouth of the river and inside the restoration area. There is still some sediment imported, but the amount decreases from 93,200 m^3 to 9,400 m^3. This shows that sediment coming from the river does reach the restoration area. It increases the elevation (5% more area with elevation higher than 2.78 m in the base run compared to the run without sediment discharge), which allows the salt marsh to expand further in the long term.

Vegetation
Although the vegetation fields in Figure 5-12 look very similar there are some differences in the amount of vegetation. The increase in elevation due to the incoming sediment makes it possible for more pickleweed (SAVI) and saltgrass (DISP) to grow. This is at the expense of the other salt marsh species, Lyngbyei's sedge, which grows at lower elevations.

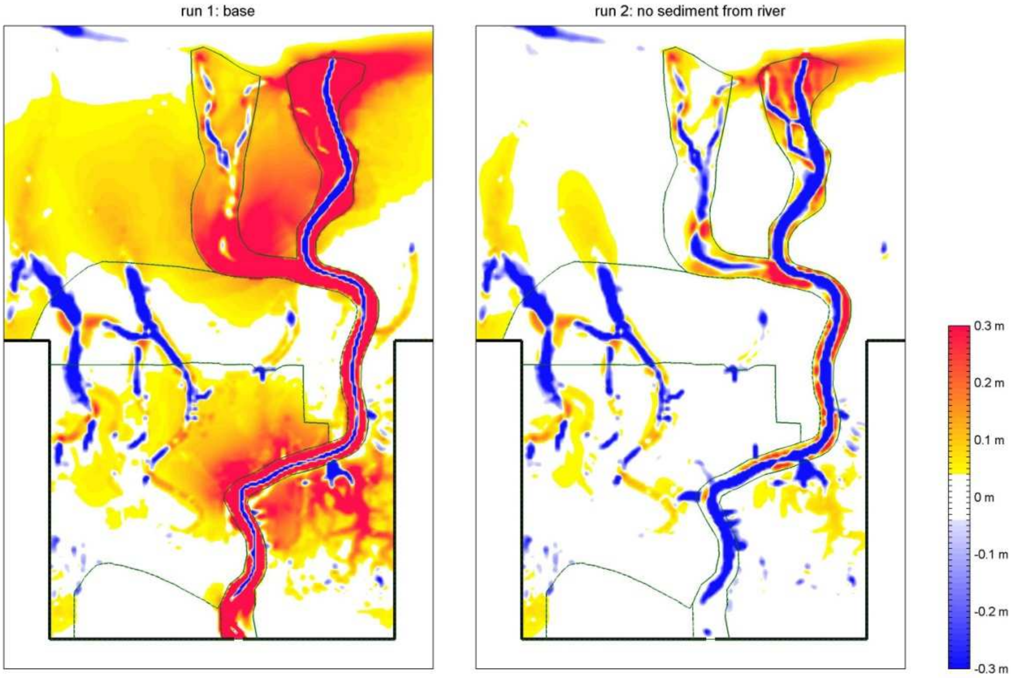

Figure 5-11: Erosion/sedimentation for run without sediment

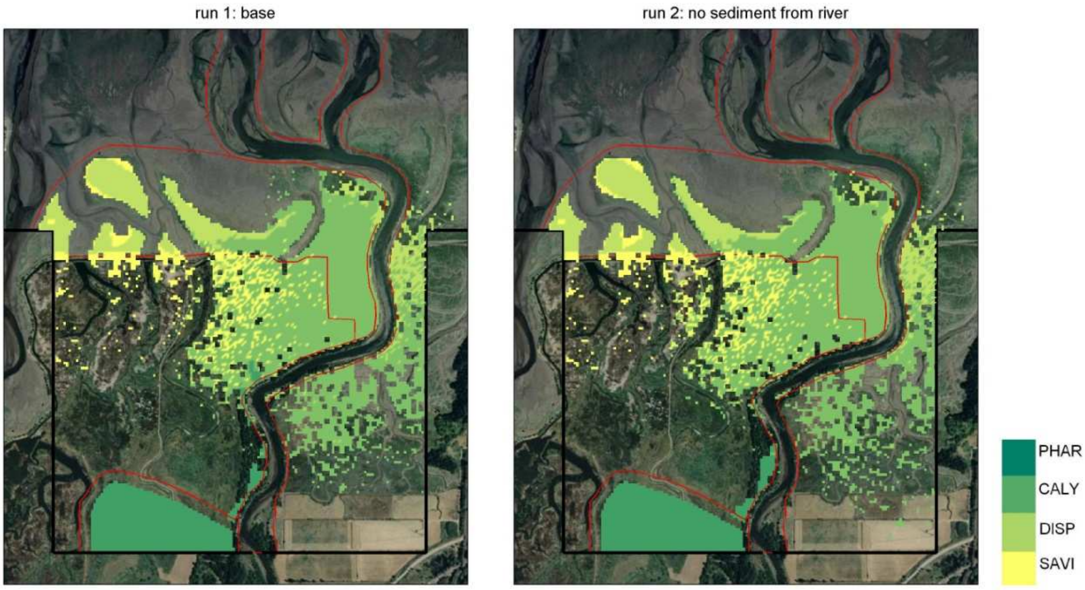

Figure 5-12: Vegetation for run without sediment

	Run 1	Run 2
Volume change [m^3]	+9.32E+04	+9.40E3
Percentage of area with elevation <-1.12 m	0.0	0.0
Percentage of area with elevation -1.12 – 1.56 m	7.8	8.1
Percentage of area with elevation 1.56 - 2.32 m	15.8	18.4
Percentage of area with elevation 2.32 – 2.78 m	63.1	65.3
Percentage of area with elevation >2.78 m	13.3	8.3
Amount of vegetation (PHAR) [no. of stems * 10^6]	22.7	21.6
Amount of vegetation (CALY) [no. of stems * 10^6]	236	266
Amount of vegetation (DISP) [no. of stems * 10^6]	8.85	4.13
Amount of vegetation (SAVI) [no. of stems * 10^6]	97.6	89.8

Table 5-7: Results for run without sediment - polygon 1

	Run 1	Run 2
Volume change [m^3]	-2.77E4	-5.69E4
Percentage of area with elevation <-1.12 m	0.4	0.4
Percentage of area with elevation -1.12 – 1.56 m	18.1	24.5
Percentage of area with elevation 1.56 - 2.32 m	32.7	27.0
Percentage of area with elevation 2.32 – 2.78 m	22.6	22.7
Percentage of area with elevation >2.78 m	26.1	25.3
Amount of vegetation (PHAR) [no. of stems * 10^6]	0.00	0.00
Amount of vegetation (CALY) [no. of stems * 10^6]	201	190
Amount of vegetation (DISP) [no. of stems * 10^6]	239	237
Amount of vegetation (SAVI) [no. of stems * 10^6]	46.1	45.6

Table 5-8: Results for run without sediment - polygon 3

5.3.4 Influence of vegetation

Morphology

To see how the vegetation influences the morphological results a run was carried out without vegetation. One of the differences that can be seen in Figure 5-13 is that there seems to be less erosion in the tidal channels. An explanation for this is that the flow is less 'focused', since there is no vegetation on the sides. This leads to lower flow velocities and therefore less erosion. Another important difference is that the amount of sediment imported into the restoration area increases, from 93,000 m^3 to 136,000 m^3, which also leads to more area with an elevation higher than 2.78 m.

These results seem to be in contradiction with the theory that vegetation 'traps' sediment. A possible explanation could be the aforementioned sediment characteristics. When for example the fall velocity is set too high the sediment gets deposited too soon and does not get a chance to reach the restoration area.

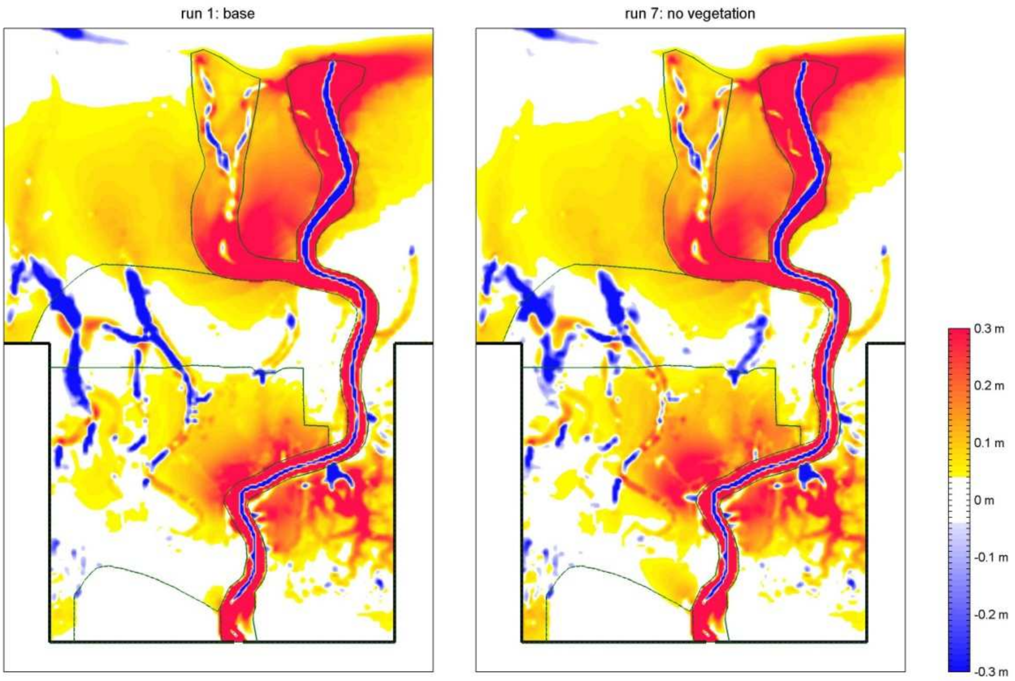

Figure 5-13: Erosion/sedimentation for vegetation runs

	Run 1	Run 7
Volume change [m^3]	+9.32E+04	+1.36E5
Percentage of area with elevation <-1.12 m	0.0	0.0
Percentage of area with elevation -1.12 – 1.56 m	7.8	7.6
Percentage of area with elevation 1.56 - 2.32 m	15.8	16.1
Percentage of area with elevation 2.32 – 2.78 m	63.1	59.1
Percentage of area with elevation >2.78 m	13.3	17.2

Table 5-9: Results for vegetation runs - polygon 1

	Run 1	Run 7
Volume change [m^3]	-2.77E4	-1.49E4
Percentage of area with elevation <-1.12 m	0.4	0.1
Percentage of area with elevation -1.12 – 1.56 m	18.1	19.4
Percentage of area with elevation 1.56 - 2.32 m	32.7	32.7
Percentage of area with elevation 2.32 – 2.78 m	22.6	22.2
Percentage of area with elevation >2.78 m	26.1	25.7

Table 5-10: Results for vegetation runs - polygon 3

5.3.5 Changed river course

Morphology
The change of the path of the river is the most noticeable difference with the base run. A new path forms, narrow but deep. It leads through the area to one of the existing tidal channels, which gets deepened considerably. The sediment that is taken along mostly gets deposited on the shallows north of the existing marsh, but a part also is deposited in the area of interest. Compared with the base run, the volume change inside the restoration area increases from 93,200 m^3 to 141,000 m^3. In the existing salt marsh area there is now sedimentation instead of erosion. In both areas this leads to an increase of area suited for salt marsh vegetation.

Vegetation
The main difference with the base run when looking at the vegetation is the presence of Phalaris arundinacae. Because the river flows directly into the restoration area, the average salinity there is much lower, which enables the reed grass to survive (except in the western part furthest from the river). In reality almost all the reed grass already died off, but it could return when conditions are favorable. The amount of salt marsh vegetation does not change considerably but in total there is slightly less vegetation than in the base run, possibly because it is replaced by the fresh water vegetation. However the system still seems to be developing after 10 years and the area where salt marsh vegetation can develop is slightly larger. Therefore it is expected that in the long run the amount of salt marsh vegetation will be larger than for the base run.

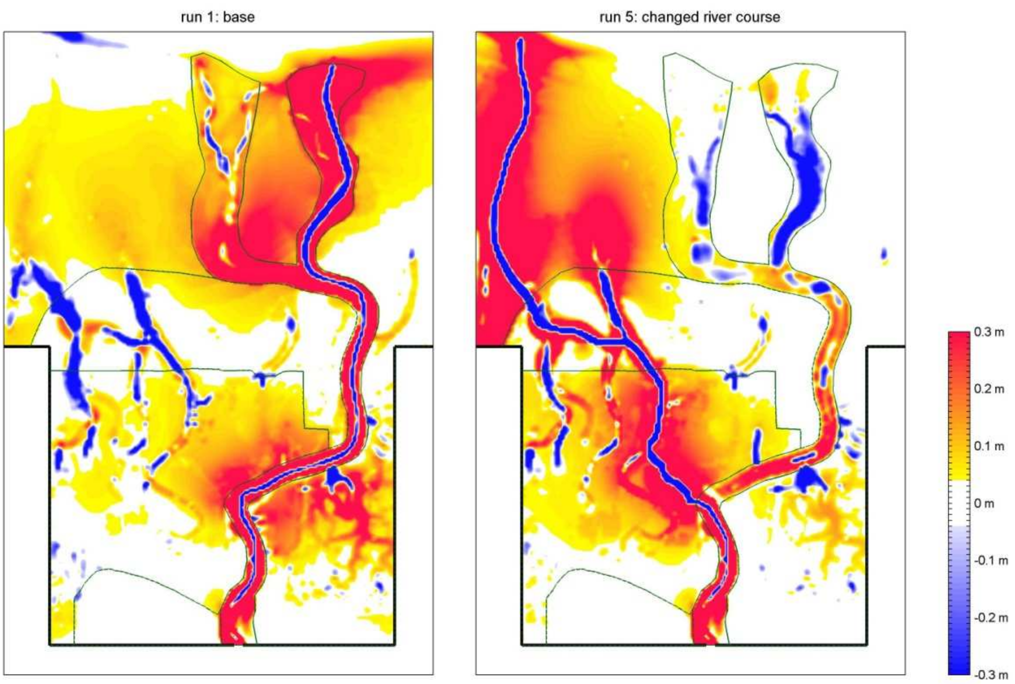

Figure 5-14: Erosion/sedimentation for run with changed river course

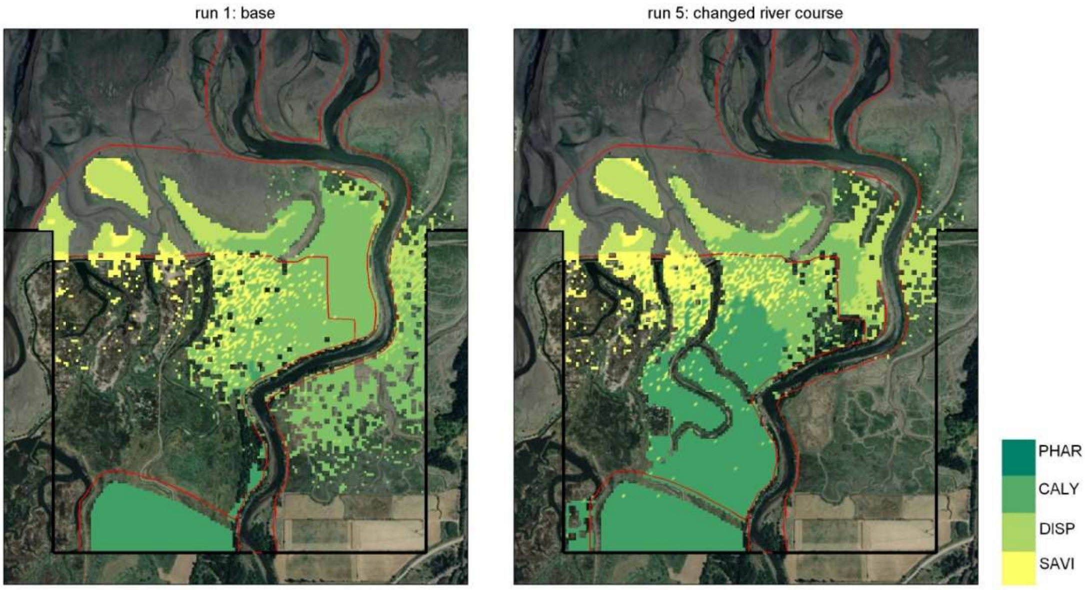

Figure 5-15: Vegetation for run with changed river course

	Run 1	Run 5
Volume change [m^3]	+9.32E+04	+1.41E5
Percentage of area with elevation <-1.12 m	0.0	1.2
Percentage of area with elevation -1.12 – 1.56 m	7.8	5.5
Percentage of area with elevation 1.56 - 2.32 m	15.8	13.1
Percentage of area with elevation 2.32 – 2.78 m	63.1	62.1
Percentage of area with elevation >2.78 m	13.3	18.2
Amount of vegetation (PHAR) [no. of stems * 10^6]	22.7	421
Amount of vegetation (CALY) [no. of stems * 10^6]	236	195
Amount of vegetation (DISP) [no. of stems * 10^6]	8.85	8.60
Amount of vegetation (SAVI) [no. of stems * 10^6]	97.6	80.3

Table 5-11: Results for run with changed river course - polygon 1

	Run 1	Run 5
Volume change [m^3]	-2.77E4	+4.33E4
Percentage of area with elevation <-1.12 m	0.4	2.4
Percentage of area with elevation -1.12 – 1.56 m	18.1	14.8
Percentage of area with elevation 1.56 - 2.32 m	32.7	33.8
Percentage of area with elevation 2.32 – 2.78 m	22.6	23.1
Percentage of area with elevation >2.78 m	26.1	25.9
Amount of vegetation (PHAR) [no. of stems * 10^6]	0.00	0.00
Amount of vegetation (CALY) [no. of stems * 10^6]	201	116
Amount of vegetation (DISP) [no. of stems * 10^6]	239	296
Amount of vegetation (SAVI) [no. of stems * 10^6]	46.1	42.3

Table 5-12: Results for run with changed river course - polygon 3

5.3.6 Influence of sediment discharge for changed river course

Morphology
Also for the scenario with a changed river course a run was carried out where no sediment is coming in from the river. Here it can be seen that a new channel forms in the same way, but no sedimentation takes place on the sides of the channel. This shows in the volume change for both the restoration area and the marsh, both suffer large erosion and loss of area with higher elevation. Again this shows that the sediment discharge from the river is important for the evolution of the restoration area.

Vegetation
Vegetation patterns do not differ considerably, except for the bottom left corner of the area where less fresh water vegetation is present, presumably because of changed salinity. The amount of vegetation decreases for all species when no sediment is transported down the river.

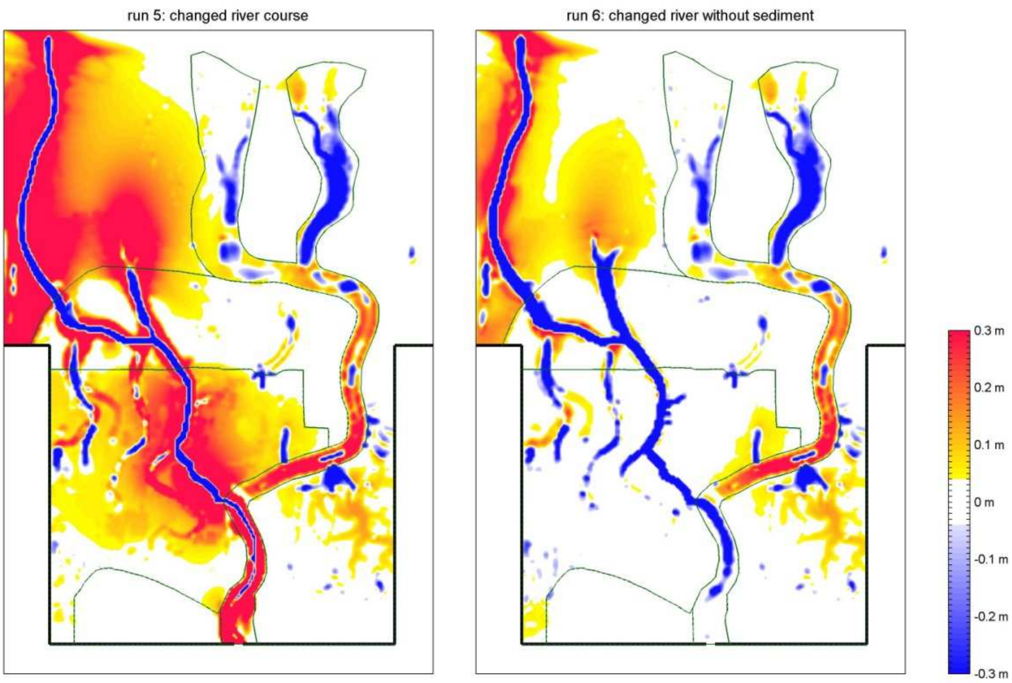

Figure 5-16: Erosion/sedimentation for run without sediment for changed river course

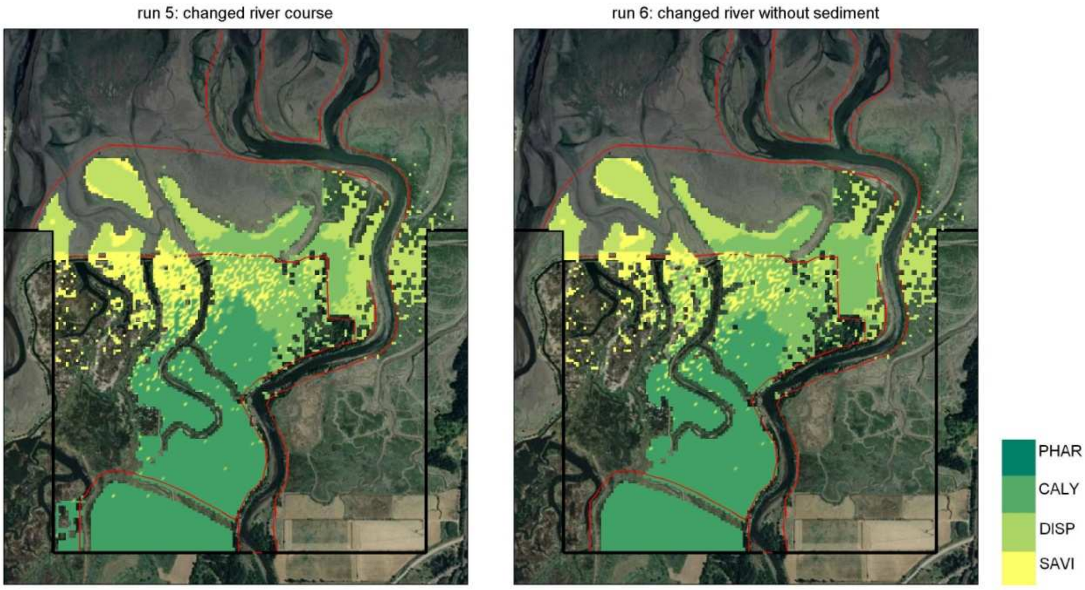

Figure 5-17: Vegetation for run without sediment for changed river course

	Run 5	Run 6
Volume change [m^3]	+1.41E5	-1.31E5
Percentage of area with elevation <-1.12 m	1.2	1.7
Percentage of area with elevation -1.12 – 1.56 m	5.5	7.7
Percentage of area with elevation 1.56 - 2.32 m	13.1	18.7
Percentage of area with elevation 2.32 – 2.78 m	62.1	63.3
Percentage of area with elevation >2.78 m	18.2	8.7
Amount of vegetation (PHAR) [no. of stems * 10^6]	421	346
Amount of vegetation (CALY) [no. of stems * 10^6]	195	187
Amount of vegetation (DISP) [no. of stems * 10^6]	8.60	7.81
Amount of vegetation (SAVI) [no. of stems * 10^6]	80.3	73.6

Table 5-13: Results for run without sediment for changed river course - polygon 1

	Run 5	Run 6
Volume change [m^3]	+4.33E4	-1.40E5
Percentage of area with elevation <-1.12 m	2.4	3.7
Percentage of area with elevation -1.12 – 1.56 m	14.8	20.8
Percentage of area with elevation 1.56 - 2.32 m	33.8	27.5
Percentage of area with elevation 2.32 – 2.78 m	23.1	22.6
Percentage of area with elevation >2.78 m	25.9	25.4
Amount of vegetation (PHAR) [no. of stems * 10^6]	0.00	0.00
Amount of vegetation (CALY) [no. of stems * 10^6]	116	124
Amount of vegetation (DISP) [no. of stems * 10^6]	296	285
Amount of vegetation (SAVI) [no. of stems * 10^6]	42.3	117

Table 5-14: Results for run without sediment for changed river course - polygon 3

6 Conclusions and recommendations

6.1 Discussion

When starting out with this thesis, the goal was to make a numerical model which would predict the longterm morphodynamic evolution of the Nisqually River estuary, with focus on the influence of vegetation. During the course of time however it became clear that this was more complicated than anticipated, due to a number of reasons:

- The estuary is a relatively large area compared to the scale on which the relevant processes take place. The level of detail required to accurately model these processes on this scale leads to very large computation times.
- The interaction between flow, morphodynamics and vegetation is a complicated process. The modeling of this interaction is a relatively new application and has (to our knowledge) not yet been done on this scale.
- The situation in the estuary is quite complex. There is a combination of both tidal and fluvial influence and a mixing of saline and fresh water. Furthermore there is a large number of different plant communities, each with their own characteristics.
- Some important data required for a reliable model were not (yet) available at the moment of this research. This includes sediment discharge data for the river, vegetation parameters for the local species, and any post-restoration data to be used for model validation.

Because of these limitations a number of concessions had to be made:

- A constant grid resolution of 15x15 m was chosen to limit the computation time. This is too large for the smaller tidal channels to be present in the model.
- Also because of limitations of the computation time it was not possible to model in 3D. Instead, a 2D depth averaged model was used, which might not be able to capture the mixing of fresh river water and the saline Puget Sound correctly. It also neglects the effect of the vegetation on the turbulence, which can influence the erosion and sedimentation locally.
- Because of the complexity of the vegetation communities and the lack of data on most of the species, as well as the sediment discharge, some crude simplifications and assumptions had to be made.
- Since there were no bathymetry data available for McAlister Creek and the channel east of the Nisqually River they were not included in the model. The discharge from the creek is negligible but it is realised that excluding this creek and channel influences the tidal prism and the way that the western part of the restoration area is flooded.

These factors, combined with the fact that the model could not be validated since there were no post-restoration measurements available at the moment of writing, make it hard to determine the accuracy of the model predictions. That is why the results should not be interpreted as an exact prediction of the location of channels and plant communities, but more as a qualitative impression of how the area is going to develop in the coming years and what the effect is of possible human interventions.

6.2 Conclusions

Based on the research questions a number of conclusions is drawn:

How will reconnection with Puget Sound affect the morphology of the Nisqually River estuary?

- The tidal channels that existed in the original situation were still in place after a century of being shut off from tidal influence, but were partly filled up with sediment and vegetation. After the reconnection these channels will reopen and return more or less to their old state. Some erosion may take place but the channels will not expand or migrate considerably.
- During the period of being shut off no new sediment was brought into the area, which caused the system to subside. The dike removal will allow sediment from the Nisqually River to enter the area again so the elevation is likely to increase, although it is unclear at what rate.

Will salt marsh vegetation be able to populate the restored area?

- The success of salt marsh restoration mainly depends on the elevation. Higher areas are inundated for a shorter amount of time, which makes it easier for pioneer vegetation to establish.
- In the first few years after reconnection the system will undergo large changes. Existing fresh water vegetation will die off and salt marsh vegetation will colonize the high lying eastern part of the estuary from the existing communities outside of the old dike. The area along the western dike seems to be too low for this.
- On the condition that enough sediment is provided, the elevation will increase and the marsh can develop further. After a long period of time (in the order of decades), the system will grow to some kind of equilibrium, with dense fields of vegetation dissected by tidal creeks. Distribution of the different plant species will depend mainly on elevation and salinity.

Is changing the course of the river to go through the restoration area beneficial for the evolution of the estuary?

- Changing the course of the river will increase the amount of sediment deposition in the restoration area and thus speed up the increase of elevation. This has a positive effect on the development of a salt marsh.
- It does however also influence the salinity, which has a large impact on the distribution of vegetation. If salinity gets too low the invasive canary reed grass may return.
- Further research into these effects is required, with better river and sediment discharge and if possible 3D modeling.

How can the modeling of vegetation in Delft 3D be improved?

- The implementation of vegetation in Delft3D is still in an early stage. It is not documented clearly and the use of ‘interactive’ vegetation is very laborious. An external Matlab routine has to be used to determine changes in vegetation and the processing of the results is a complicated process.

- The existing Matlab routine was developed for a specific situation. In this thesis an effort was made to make it more generally applicable. Support was added for multiple types of vegetation and the use of Domain Decomposition. By automatically updating the time parameters and coupling the result-files it is now easier to process the model results. An extra term was added for plant decay due to salinity, although without much of a scientific basis.
- The main problem with using the Matlab routine at this moment is the lack of availability of the parameters required for the vegetation. The applied parameters were based, without much ecological knowledge, on mainly qualitative descriptions, and require validation before further use.

Outside of the answers to the research questions, some other conclusions were found as a result of the modeling process:

- The use of Domain Decomposition in combination with vegetation on flooding and drying flats gives a lot of model instabilities.
- The ‘trapping’ of sediment by vegetation patches (described in chapter 2) is not captured very well in the model. This could be due to either the grid resolution being too large or the depth averaged 2D modeling instead of 3D.

6.3 Recommendations

As discussed above the model that was used in this research has a number of limitations. Some recommendations are made here for further research:

- The main factor determining the success of salt marsh restoration is the elevation. It is therefore advised to keep track of the erosion and sedimentation rates in the area. Since this is influenced by sediment transported by the Nisqually River, the sediment discharge should also be measured.
- Changing the course of the river brings more sediment to the restoration area. It should be investigated how large this effect is and if forcing the course to change is an option.
- The issue of a large amount of the sediment discharge depositing in the river should be solved. Possible solutions are introducing peak flows or further research of the sediment characteristics.
- The effect of waves was not investigated in the final model, since the Nisqually estuary is a relatively sheltered area. In shallow water however even small waves could have an effect on the sediment transport, so it could be worthwhile to do a model run in which waves are included.
- If long-term simulations are carried out sea-level rise should be accounted for.
- From multiple reference projects it becomes clear that even after a long period of time the vegetation communities can undergo large changes. Unfortunately most monitoring programs are stopped after a number of years. If possible it would be interesting to keep monitoring for as long as possible to get better insight into the long term effects of salt marsh restoration.

Finally, some recommendations are given to improve the modeling of vegetation in Delft3D:

- The routine for 'interactive' vegetation should be built into the code of Delft3D instead of using an external program. (Work on implementing a similar vegetation module in Delft3D-WAQ is currently already being carried out within Deltares.)
- At this moment the parameters required for the vegetation modeling are only known for a few plant species. To gain more insight into these parameters and increase the applicability of the model there should be a closer collaboration with ecologists.
- The use of Domain Decomposition in combination with vegetation on flooding and frying flats should be avoided until stability problems are solved.
- If computation time allows, it is advised to model in 3D, since this better captures the processes that play a role in the interaction between flow, morphology and vegetation.
- The situation in the Nisqually River estuary is a relatively complicated one, with a large area and a lot of changes in a short period of time. To gain better insight into the separate processes and how to model them, it could be interesting to use the model on a natural situation where changes happen more gradually.

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Appendices

A Sensitivity analysis run overview

Run nr.	Run name	Type	Variation	Notes
1	Basis	-	-	(dt=0.25 s) no his file
2	diffusion	Vegetation	Different formula for random plant growth	(dt=0.25 s) no his file
3	lowiniveg	Vegetation growth	Initial veg. outside of old dike (100 stems/m2)	no his file
4	highiniveg	Vegetation growth	Initial veg. outside of old dike (500 stems/m2)	no his file
5	silt	Sediment	Silt (uniform 5 m. layer)	
6	highampl	Water level	Tidal amplitude of 3 m.	
7	lowampl	Water level	Tidal amplitude of 1 m.	
8	highmsl	Water level	Mean sea level +0.5 m	
9	lowmsl	Water level	Mean sea level -0.5 m	
10	cells10	Other	Cell size of 10x10 m	morfac 36, dt 0.25
11	lowshear	Vegetation	Critical shear stress for plants tau_crp = 0.052 N/m^2	with low density ini veg
12	highshear	Vegetation	Critical shear stress for plants tau_crp = 1.30 N/m^2	with low density ini veg
13	lowinund	Vegetation	Critical inundation height inund_crp = 0.6 m	with low density ini veg
14	highinund	Vegetation	Critical inundation height inund_crp = 1.6 m	with low density ini veg
15	noveg	Vegetation growth	No vegetation growth	
16	lowchezy	Other	C = 50 [m$^{1/2}$/s]	
17	highchezy	Other	C = 80 [m$^{1/2}$/s]	
18	dikebreach	Other	part of dike removed instead of whole dike	
19	twosandtypes	Sediment	two sand layers of 2.5 m each with d50 = 0.1 mm and 0.3 mm	
20	sandandsilt	Sediment	sand layer with d50 = 0.2 mm and silt layer with ws = 0.06 m/s	

Run nr.	Run name	Type	Variation	Notes
21	Basis	-	30 year run	
23	fulliniveg	Vegetation growth	Initial veg. inside of old dike (500 stems/m2)	
24	higheriniveg	Vegetation growth	Initial veg. outside of old dike (1000 stems/m2)	
25	waves	Waves	Waves coming from the north, Hs = 0.5 m	
26	lowermorfac	Morphological factor	100 cycles with morfac of 36	
27	lowstemdia	Vegetation	Stem diameter of 1 mm.	with low density ini veg
28	highstemdia	Vegetation	Stem diameter of 3 mm.	with low density ini veg
29	widerarea	Water level	Area widened with 300 m on both sides	

B Bathymetry datasets

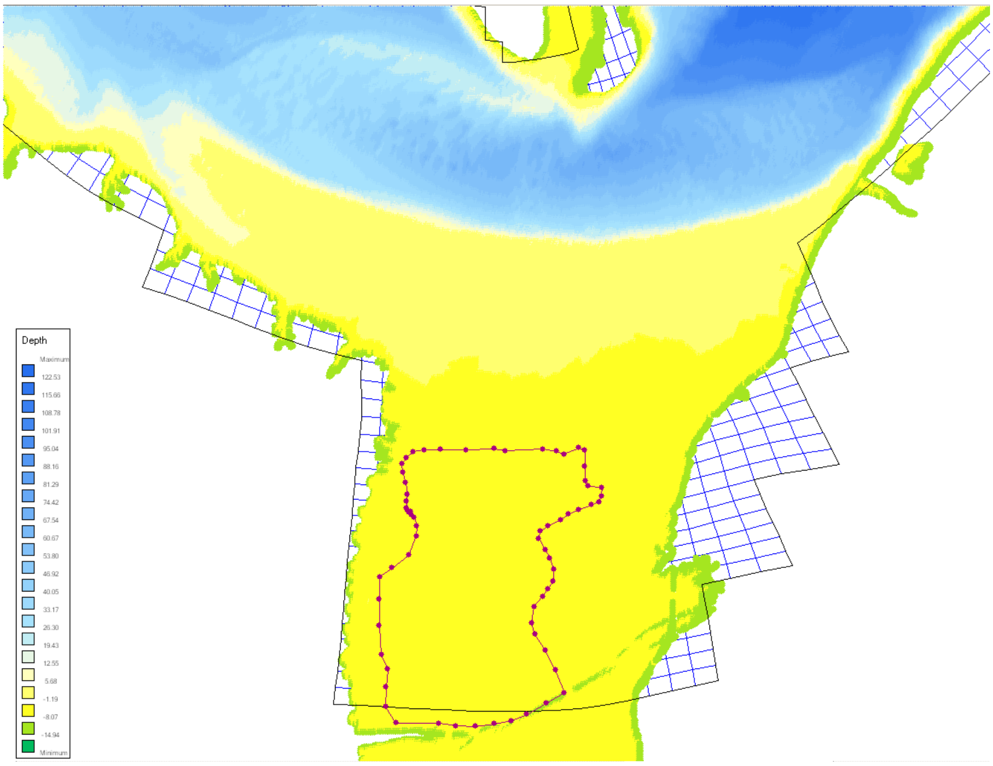

Figure B-1: Finlayson

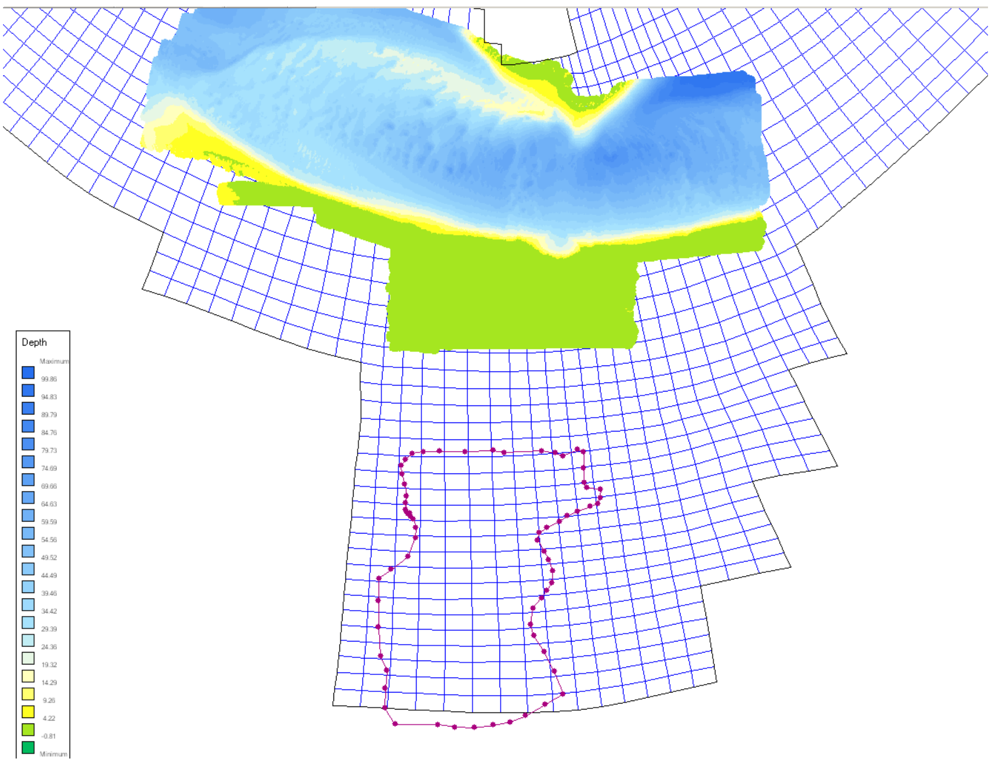

Figure B-2: Multibeam

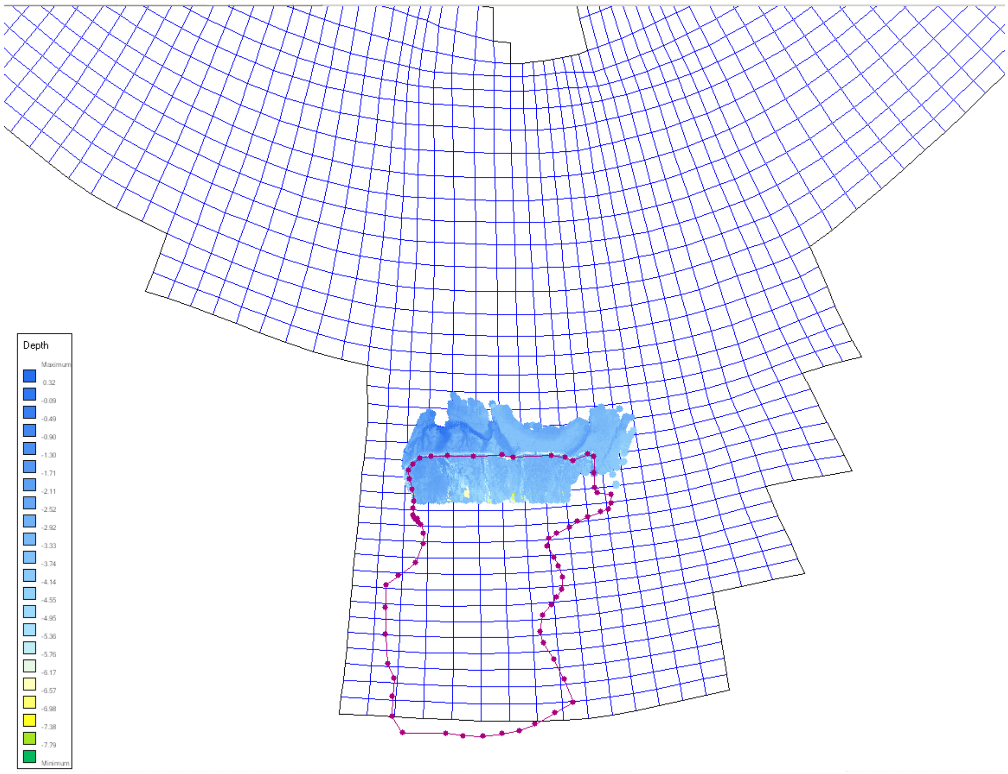

Figure B-3: Ground based LIDAR

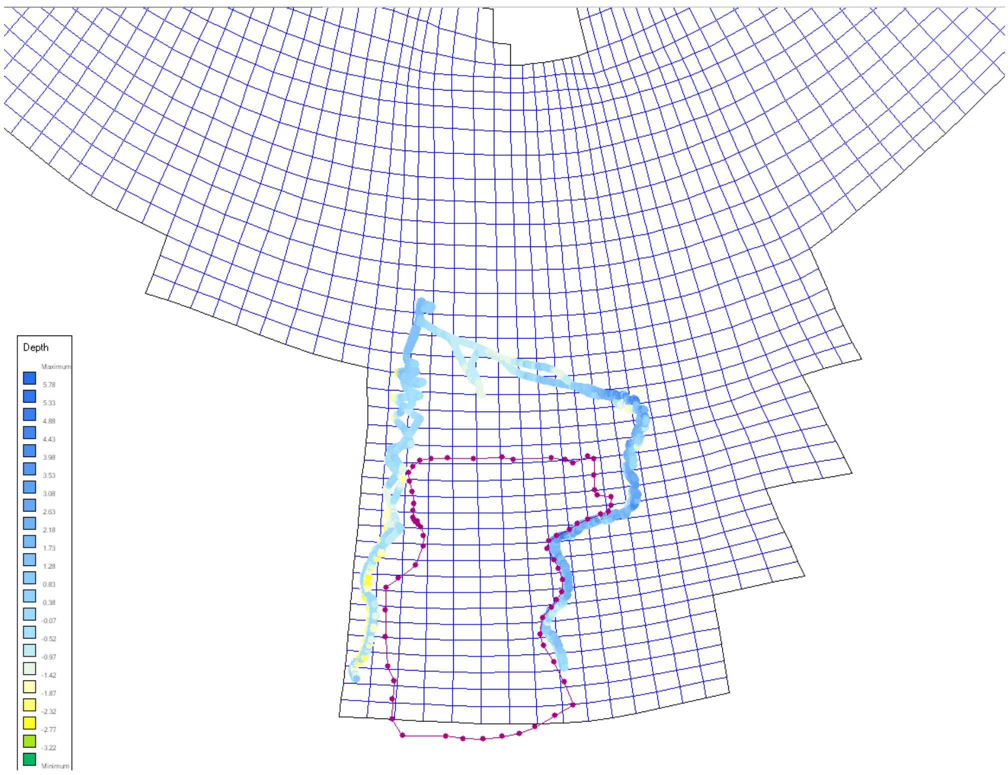

Figure B-4: Nisqually River and McAlister Creek

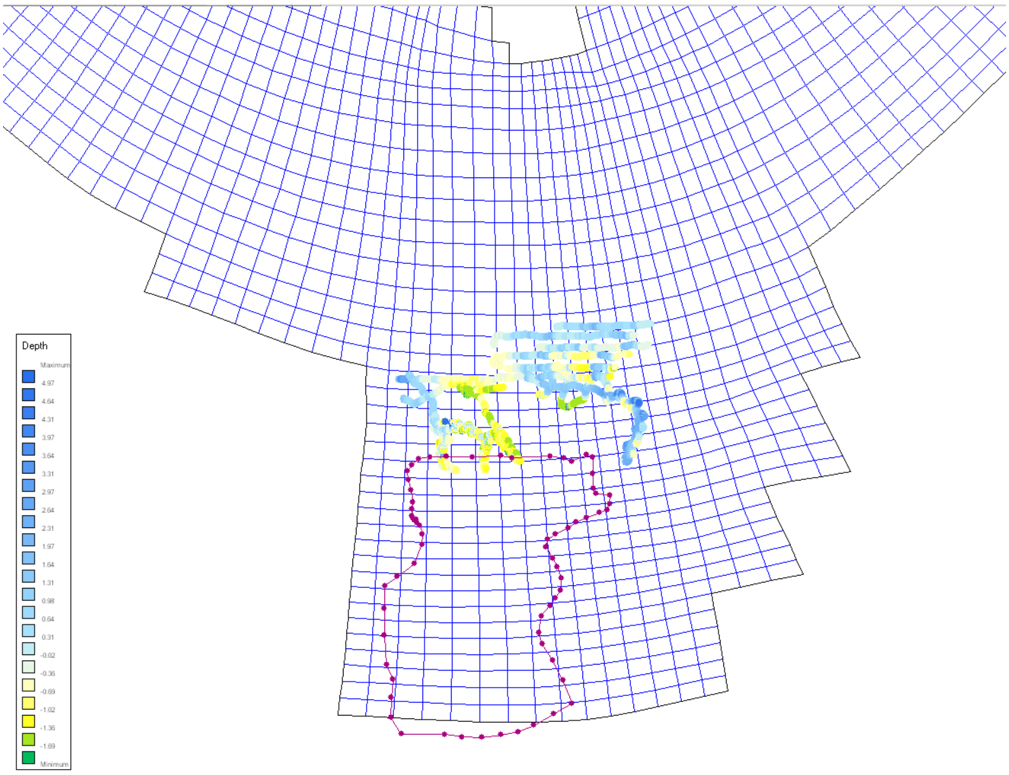

Figure B-5: Field trip: Echo sounder

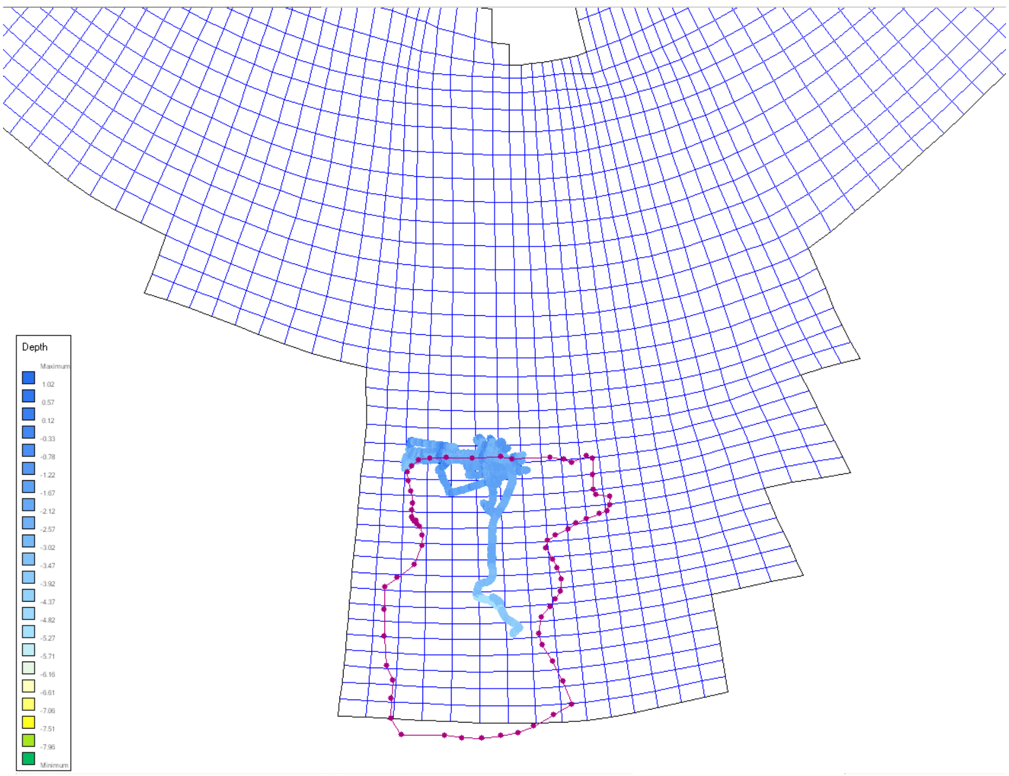

Figure B-6: Field trip: RTK-GPS

C Sediment

The data available was a number of sediment samples outside of the restoration area. For each of these samples sieve curves were made to determine the median grain diameter d50 for sand (63 µm to 2 mm), silt (3.3 µm to 63 µm) and clay (0.1 µm to 3.3 µm). These sieve curves are shown below. For each sediment type an average d50 was then determined: $d50_{sand}$ = 160 µm, $d50_{silt}$ = 28 µm and $d50_{clay}$ = 1.6 µm.

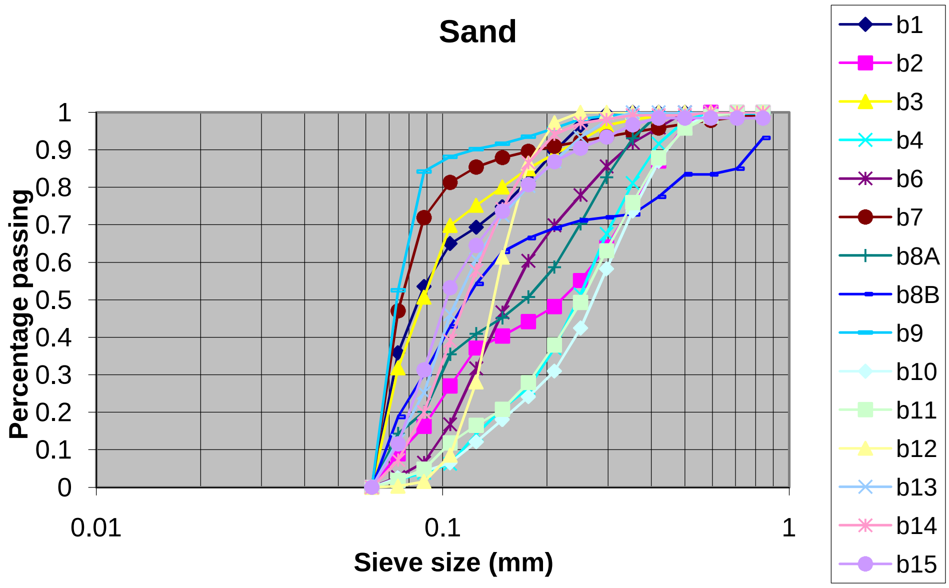

Figure C-1: Sieve curve for sand

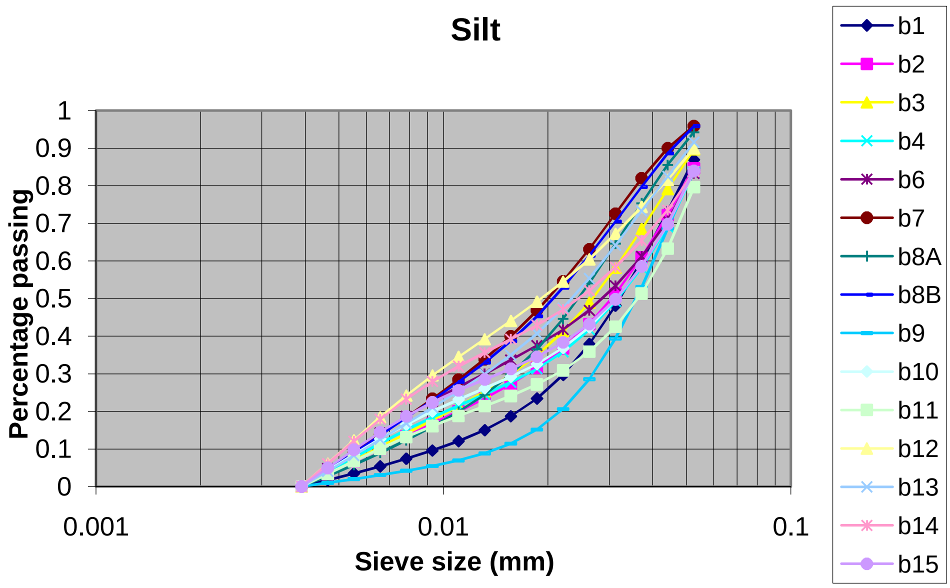

Figure C-2: Sieve curve for silt

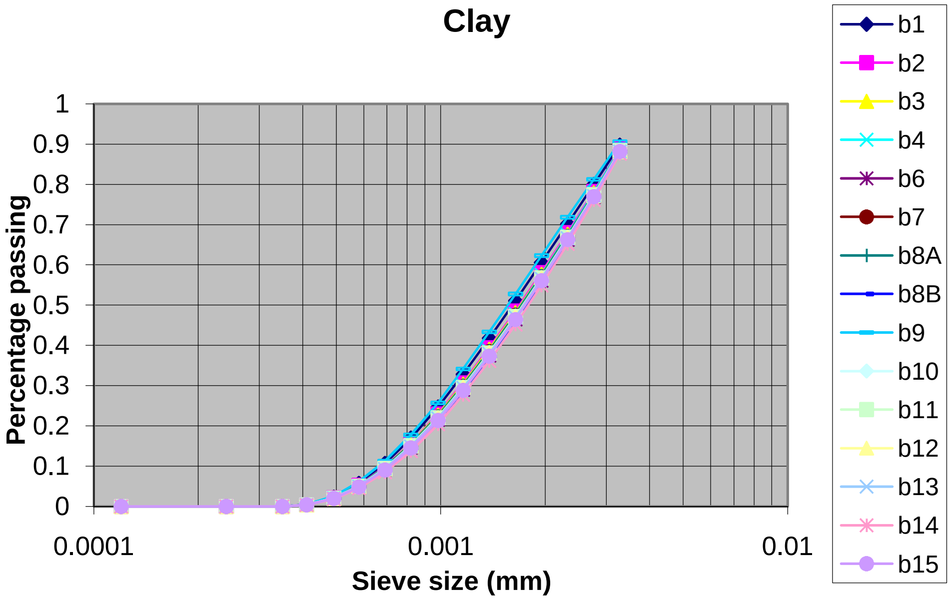

Figure C-3: Sieve curve for clay

For the cohesive fractions these grain sizes were translated into a settling velocity with $v_s=(2/9)*(\rho_p-\rho_f)/\mu*g*R\text{^}2$, which resulted in settling velocities of respectively 1.4 mm/s for silt and 0.0046 mm/s for clay. Due to the silt settling too fast, its settling velocity was later changed to 0.25 mm/s.

For a number of samples closest to the restoration area the percentage of each sediment was determined. The layer thickness in the model was then based on the average of these percentages (Table C-1).

Sample	**% Gravel**	**% Sand**	**% Silt**	**% Clay**
b1	0	19.78595	68.82396	11.3901
b2	0	55.73547	34.37311	9.891415
b3	0	15.99645	65.09853	18.90502
b7	0	4.162026	70.41744	25.42054
b8A	0	11.71034	71.47191	16.81775
b8B	0	5.561986	69.5719	24.86611
b9	0	14.89371	76.90032	8.20597
	Average	18.2637	65.23674	16.49956
	Layer thickness (m)	1	4	1

Table C-1: Layer thickness

D Failed model setups

<u>Including Nisqually Reach</u>

To be able to model the effect of cross-currents on the plume of the Nisqually River, at first the idea was to include a larger area in the model. A varying grid cell size was chosen to limit the number of cells. Because of the island north of the restoration area the northern boundary was divided into two parts. Different tests were carried out with different configurations for the boundary conditions (water levels, currents, discharges etc.) but with all of these the same problem occurred. After a certain amount of time large velocities occurred in one row of cells near one of the boundaries, which then caused the morphological changes to explode and the model to crash. On top of that computation times became very large, so it was decided to decrease the modelled area.

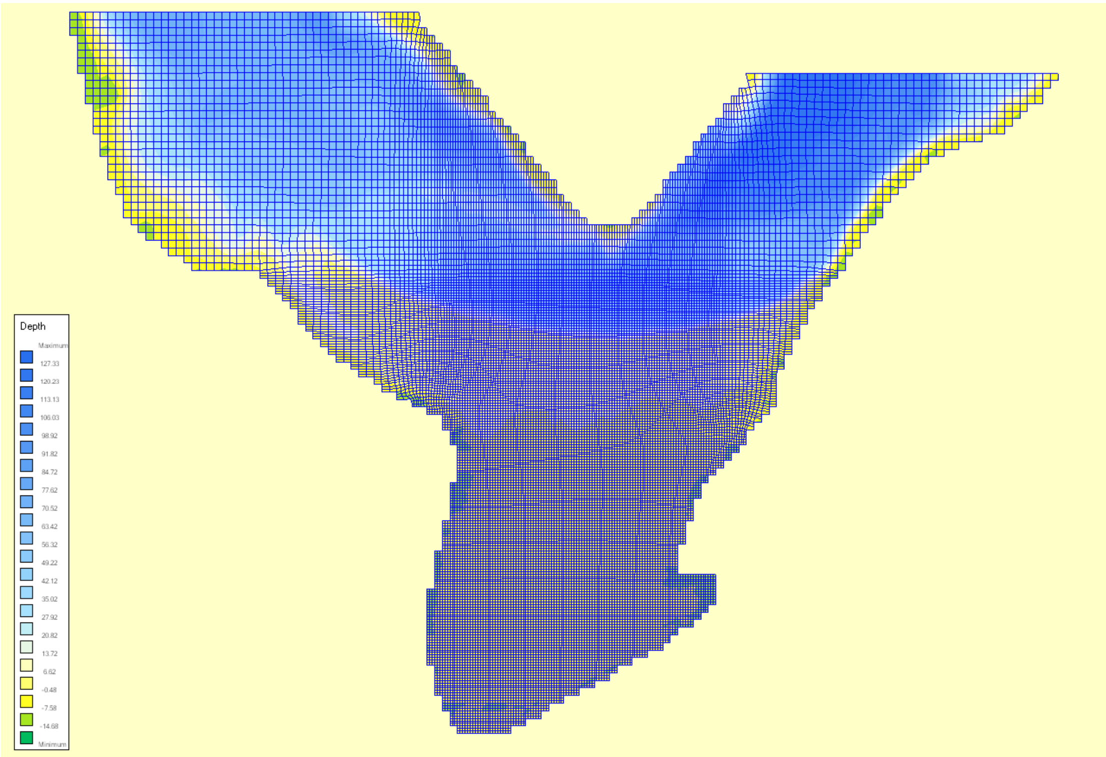

Figure D-1: Model setup with inclusion of the Nisqually Reach

Domain Decomposition

When it was decided to go back to a smaller model area, it was decided to start with the grid from the sensitivity analysis and expand it to include the effect of the Nisqually River. The northern part of the grid was widened so it included the river mouth, but to capture the cross-currents the area needed to be increased even more. In order to not let the computation time grow too large, Domain Decomposition (DD) was introduced. This is a technique in Delft3D with which the model is divided into several smaller domains. Computations can then be carried out separately on these domains, with communication taking place along the boundaries. By using a larger resolution on the outer domain the computation time can be decreased without losing detail in the inner domain. The used setup is shown in Figure D-2, with the outer domain in dark blue and the inner domain in light blue.

Again, multiple configurations were tried but the same problem kept occurring. On the DD boundary differences in bed level occurred after a number of time steps, after which the whole model crashed. It is assumed that this has to do with flooding and drying flats near the boundary in combination with the vegetation module. Because none of the people involved knew a solution, in the end the domains were combined into one large domain, with very large computation times as a result.

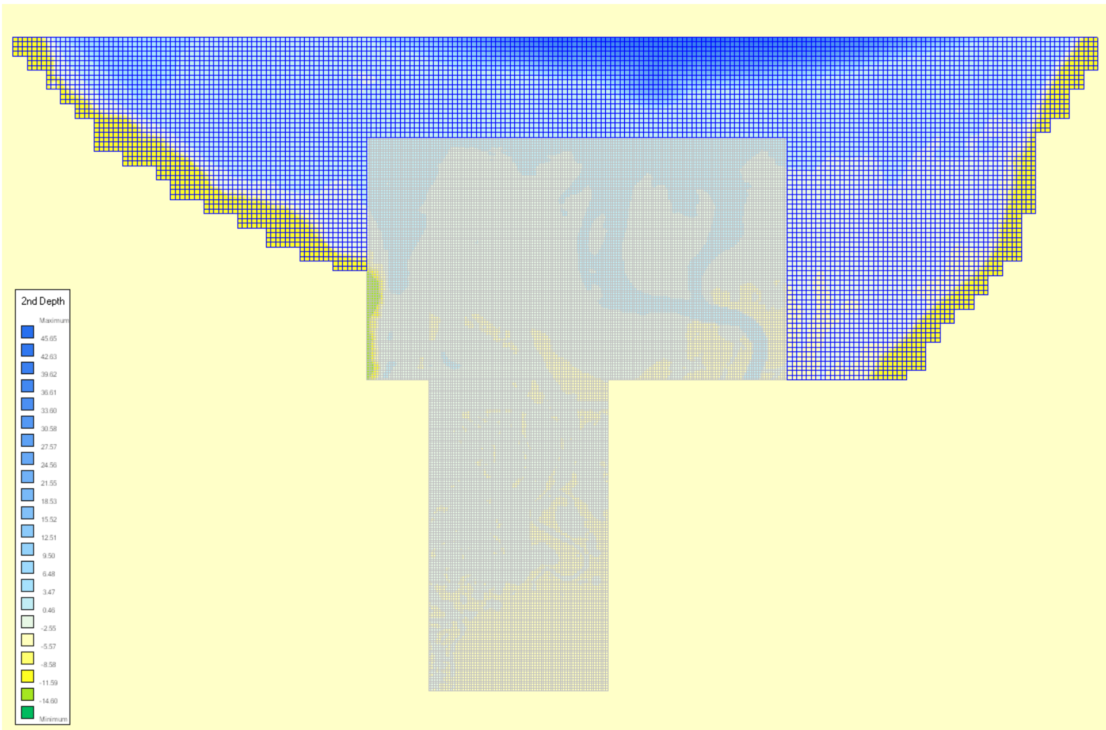

Figure D-2: Model setup with Domain Decomposition

E Water levels and salinity

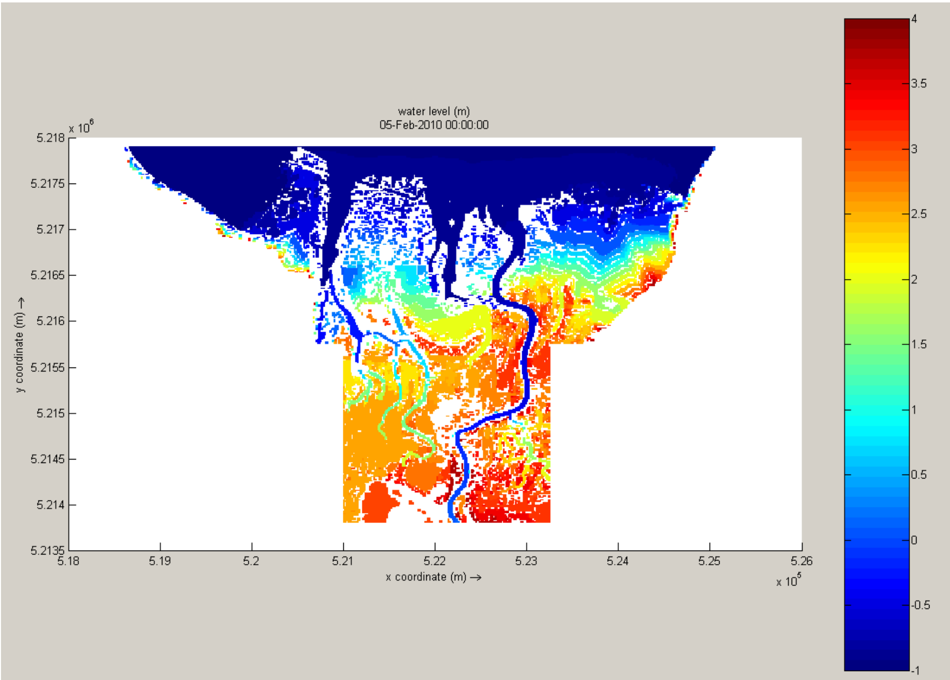

Figure E-1:Lowest water level during simulated period

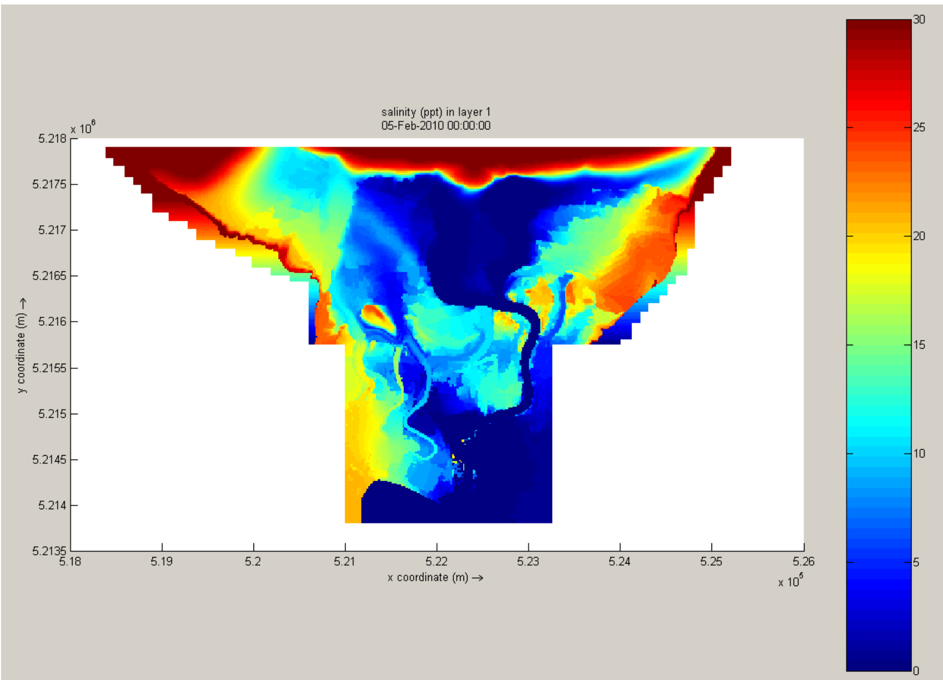

Figure E-2: Salinity for lowest water level during simulated period

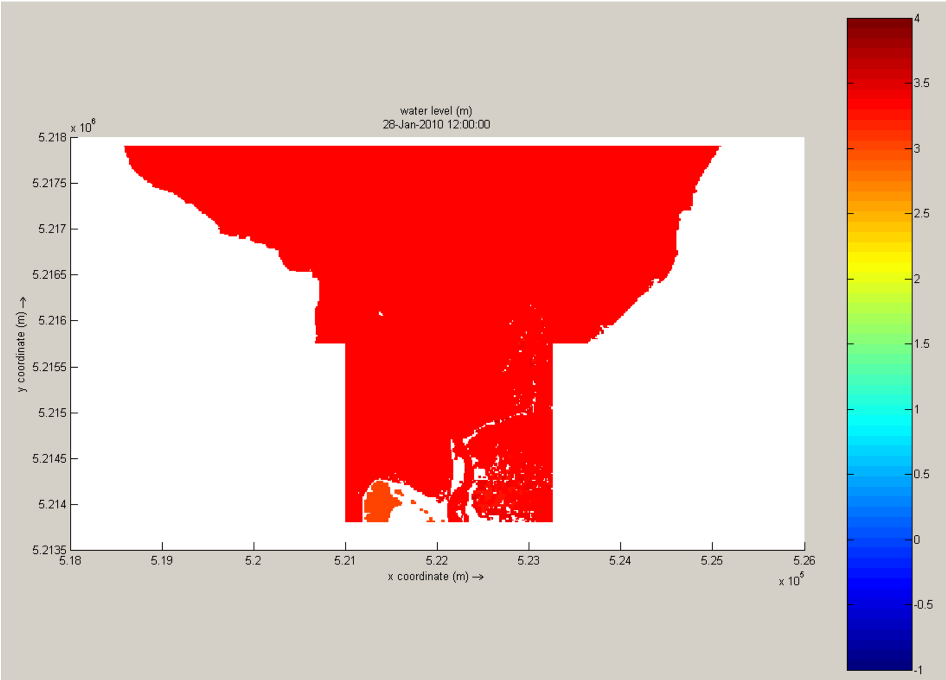

Figure E-3: Highest water level during simulated period

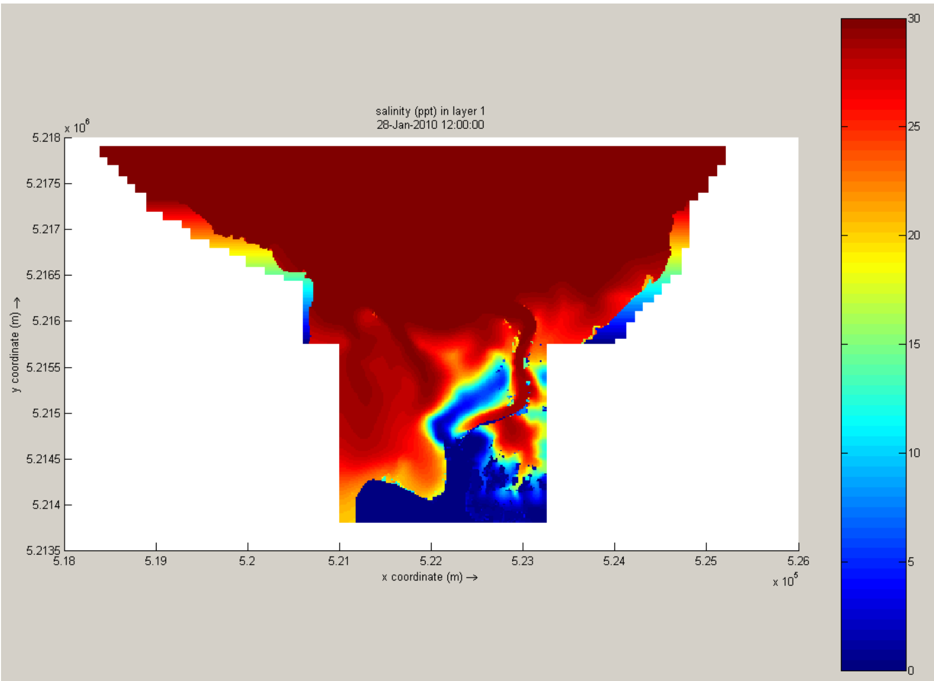

Figure E-4: Salinity for highest water level during simulation period