Validation of the ASMITA-marshes model

An application to the Langstone Harbour estuary

Final version
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Preface

This report forms my Bachelor thesis within my study of Civil Engineering and Management at the University of Twente. This research is carried out from the 20th of April till the 3rd of July at HR Wallingford Ltd.

I would like to thank my supervisors M.A.F. Knaapen (HR Wallingford) and P.C. Roos (University of Twente) for their feedback and their advice. Furthermore I want to thank S.K. Rossington (HR Wallingford) and I.H. Townend (HR Wallingford) for their advice and helping me out when I was facing problems.
In the end, I want to thank my temporary colleagues at HR Wallingford for making it a fantastic stay in the United Kingdom.

Jasper Middelkamp,
Enschede, September 09

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Summary

Tidal inlets form an important part of coastlines in the world. These inlets are a very interesting site for research due to all the processes in these inlets. One of the most important processes is the exchange of sediment within the inlet. This sediment exchange determines the long-term development of the tidal inlet. The ASMITA model predicts this long-term development. Many tidal inlets form a habitat for salt marshes. ASMITA has been extended to represent estuaries with salt marshes.

The objective of this study is to validate the ASMITA salt marsh application to test how the prediction corresponds to observed estuaries. This objective is satisfied by answering the following main research question:

How are the parameters used in the ASMITA salt marsh model related to each other and how reliable are the model predictions compared with measured data?

In order to answer this main question, the following sub-research questions are formulated:

- How do the vegetation parameters affect the ASMITA-salt marsh model?
- To which parameters is the model most sensitive?
- What are the differences between the model predictions and the real behaviour of the salt marsh and, if necessary, how can the model be improved to give a better result?
- How do regional differences affect the vegetation parameters and the model prediction?

In this research the ASMITA-salt marsh model was applied to the Langstone Harbour tidal inlet (UK). There was also data retrieved for marshes in the Western Scheldt (Netherlands), but due to a lack of time these data could not be tested.

There was very little information available for the vegetation parameters used in the model. This is the reason why two scenarios were tested in the model: one scenario with standard vegetation parameters and another scenario with estimated vegetation parameters.

The prediction of the scenario with estimated parameters showed a satisfying prediction. For the marsh the volume prediction was very good. The predictions for the other elements were worse than in the scenario with standard parameters.

The Langstone Harbour estuary showed a massive dying of *Spartina Anglica*, a marsh species. Due to this the marsh erodes very fast. The recommendation is made to test the ASMITA-salt marsh model to an estuary were this is not the case, for example the Western Scheldt.

1 Introduction

An estuary is a very interesting environment. Due to its transition between a river and the coastal environment a lot of processes are going on. These processes can be described in hydrodynamic and morphological changes. Hydrodynamic processes deal with the characteristics of the flow within the estuary, like changes considering waves or the salinity of the estuary. Morphological processes deal with the form of the estuary, affected by the transport of sediment. At the moment these processes are under pressure due to human influence. An increasing sea level due to the greenhouse effect causes the coastal morphology to change. This is not the only way of changing the coastal environment, human activities like dredging also cause the morphology to change. In order to predict changes on the long term (10-100 years), several models are formulated. One of these models is the ASMITA model. In this chapter a brief description of this model will be given. In order to understand the model a brief introduction of estuaries will be given first. After this the ASMITA model will be discussed, followed by a subsection considering salt marshes and their influence on morphology. These subsections will lead to the objective of this thesis.

1.1 Estuaries

Estuaries form the transition between a coastal environment and the river environment. This means that estuaries are influenced by both marine characteristics like tides and waves, but also river characteristics like the river inflow and the water quality of this river. The combination of these environments makes estuaries very interesting from a biological point of view. From a ecological point of view estuaries form a very good environment for species. It is one of the most productive environments in the biological world.

However, due to its location between river and sea, it is also a very attractive area for human settlement. It gives very good opportunities for trade and recreation. Due to human settlement the area also suffers from an increase for water demand. Drinking water is often taken from rivers, while pollution is discharged in the same river. Need for agriculture and space for new settlement leads to reclamation. In the meantime, dredging is needed to maintain the channel depth for ports.

These human activities change the morphological condition of the estuary and modify the processes within the estuary. This increases the pressure on the wildlife and the opportunity for recreation. The modifications of these processes are mostly not directly noticeable. To look at the effect of human activities in an estuary it is necessary to predict the effect on the long-term. In order to do this, morphological models are developed and applied. One of these models is the ASMITA model, which will be explained in the next subsection.

1.2 Description ASMITA model

In order to describe the morphological change in an estuary, Stive et al (1998) present a model that copes with these changes, named ASMITA. This abbreviation is short for Aggregated-Scale behaviour-model for Morphological Interaction between a Tidal lagoon and its Adjacent coast. ASMITA can be seen as an aggregation and extension of the ESTMORF model, formulated by Wang et al (1996). The aggregation copes with the fact that all elements are described in one variable, namely the water volume. The extension handles the incorporation of the ebb-tidal delta and the adjacent coast (Kragtwijk, 2001).

The name ASMITA indicates a few characteristics of the model. The model is an Aggregated-Scale behaviour-model. This implies that the model is based on a combination of empirical relations and aggregated descriptions of physical processes, making it a semi-empirical model (Wang et al, 2007). The second characteristic follows from the

Morphological Interaction. There must be an interaction between certain elements that concerns a morphological change. In this case, morphology is the field of sciences that investigates the forms of water bodies. These forms are modified by processes as erosion, transport and deposition of sediment. The last part of the abbreviation gives the scope of the model. The model is only applicable for tidal lagoons and their adjacent coast. Furthermore Stive et al. (1998) state that general sediment transport equations and the assumption that the equilibrium state of the model is known or can be defined. The equations used in the model are given in Appendix A. In the same Appendix the definitions of the various output parameters are given.

Since the introduction of ASMITA in 1998, it has been applied for several cases. ASMITA is used to study the effect of sea level rise on the morphological equilibrium (Van Goor et al., 2003). Another application is the morphological response of tidal basins to human interventions (Kragtwijk, 2004). This study investigates the morphological consequences of the closure of the Zuiderzee in the Netherlands. Townend et al. (2007) investigated the combined influence of sea level rise, changes in tidal range and the nodal tide with ASMITA. Rossington (2008) applied ASMITA for several UK estuaries in order to predict their response on climate change and anthropogenic disturbance by using historical data. A very recent use of ASMITA is the morphological impact of a barrage in the Severn (HR Wallingford, 2009a). This application extended the model with an application for tidal pumping. Tidal asymmetry can occur in estuaries and when this favours landward sediment transport, it is possible for sediment to move into the estuary, even though diffusion is in the seaward direction.

HR Wallingford (2009a) suggests in their research that the application of a marsh element will give a better prediction. In order to predict morphological changes in estuaries including salt marshes some definitions of the volumes had to be changed. The marshes represent the part between Mean High Water Springs (MHWS) and Mean High Water (MHW). This implicates that they are not constantly flooded, but only during spring tides. Salt marshes have a big influence on erodibility and the deposition rate of sediment. They are also essential for lateral expansion or contraction of the estuary (Knaapen et al., 2009). In subsection 1.3 more background information on salt marshes is given.

As mentioned there is an interaction between elements in the model. The original model only describes the exchange between the channel, the intertidal flat and the ebb-tidal delta. Townend et al. (2008) extended ASMITA to allow the surface areas of models to vary. Because of this the model can vary its boundaries and transgression/regression can be modelled more exactly. Knaapen et al (2009) on their turn extended ASMITA with an element that represents salt marshes. Due to this extension, some elements had to be defined in another way than in the original model. The channel element is represented by the volume of water under Mean Low Water (MLW). The flats are represented as the water volume over the tidal flats between MHW and MLW, instead of the sand volume of the flats in the former ASMITA version. The marshes are represented as the water volume over the marshes at MHW.

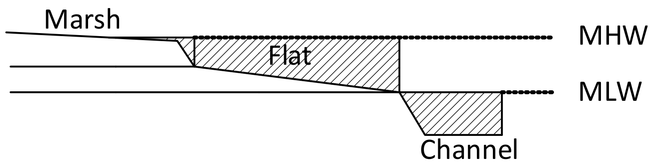

Figure 1: Cross-section estuary with element volumes

In Figure 1 these volumes are shown in a cross section of an estuary. The ebb-tidal delta element is given by the water volume over the delta area in contrast to the first version, where it was defined as the sand volume above an imaginary sea bottom when there was no inlet. In the end there is also the outside world. This element represents the boundary of the model and can supply the inlet with unlimited sand (Kragtwijk, 2001).

The ASMITA-marshes model focuses on the relationship between depth, vegetation (density) and sedimentation. Vegetation located on the marsh will increase sedimentation. This leads to shallower water and a decrease of the tidal prism (the volume of water exchanged in a tidal cycle). This decrease leads to lower flow velocities and less erosion what makes the circle go round.

The calculations used in ASMITA-marshes are mostly based on equations stated by Morris et al. (2002) to describe the interaction between vegetation and sediment transport and morphology. These equations are presented in Appendix A.

1.3 Salt marshes

In order to understand the importance of marshes a closer look to the marsh system is needed. A salt marsh is a wetland that is frequently inundated with water. The marsh is vegetated by species that are adapted to the conditions.

Salt marshes arise at locations where the sedimentation is at least equal to the lowering of the ground and on places were they are protected against wave attacks. Grounds with a lot of silt in calm waters are very suitable for marshes. Due to the sedimentation the height of the flat will rise, which gives pioneering species the chance to live on the beginning marsh. These species will increase sedimentation, causing the beginning marsh to rise further. The marsh will inundate less often, leading to more species on the marsh. These species are the lower marsh-species. Due to these species, sedimentation will keep on going, what will lead to the middle marsh-species (Effing, 2005). This process keeps on going and the marsh will become higher and higher. According to this principle the marsh only grows. In Figure 2 the distinction of the several types of salt marsh and some common species of that type of marsh are given.

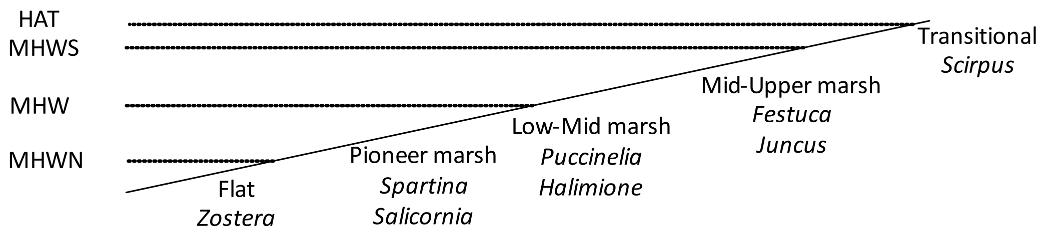

Figure 2: Salt marsh type in relation to tide (partly after Effing, 2005 and NRA, 1995)

In reality this is not true. According to observations, salt marshes suffer a lot of erosion (Royal Haskoning, 2004). A main reason for this behaviour is sea level rise (SLR). As mentioned earlier, one of the conditions for the rising of salt marshes are calm waters were it is situated. Due to SLR the marsh will inundate more often, what causes species to die because of the higher salinity of the ground. SLR also causes increasing wave action from deeper water. The result of this is higher wave energy, which encourages erosion of the marsh. In an unconstrained habitat, the marsh will react to this by moving inland. However, to prevent flooding a lot of coastal areas are protected by dykes. This makes it impossible for the marsh to move inland and eventually causes it to disappear (National Rivers Authority, 1995). This phenomenon is called coastal squeeze. The marshes are also vulnerable to land reclamation and dredging activities. The dredging changes the morphological equilibrium in the estuary and mostly this change encourages erosion of the salt marsh. According to Cox et al. (2003) the extension and retreat of marshes is also a natural cycle.

There are several reasons to maintain salt marshes. From an ecological perspective they are very important. The salt marsh environment is a very productive environment. It is a unique environment with a big variety of (rare) plant species. It also forms a habitat for invertebrates, especially the lower – mid marsh area. The marsh also forms a place for breeding and wintering birds and some small mammals (NRA, 1995). From another point of interest, salt marshes form a very effective coastal defence. The vegetation on the marsh dampens wave action against the defence and the weight of the marsh provides some support for the toe of the defence. Taken this in mind, the appearance of a marsh will reduce the requirements for the sea defence due to its beneficial characteristics.

Because of its environmental and indirect economical benefits it is important to take measurements against coastal squeeze and reduce the negative effects of dredging in the estuary.

1.4 Objective

The objective of this study is to validate the ASMITA salt marsh application to test how the prediction corresponds to observed estuaries. The results of these calculations can be used in to help maintain salt marshes. The model can be applied to predict the reaction of estuaries on human interventions as dredging. It can also be used to analyse several measurements to sustain the salt marsh area or to expand this.

The objective can be satisfied by answering the following research questions:

How are the parameters used in the ASMITA salt marsh model related to each other and how reliable are the model predictions compared with measured data?

The parameters are the physical input parameters of the model. These are for example the rate of SLR and the parameters that describe the vegetation on the marsh. The measured data that is mentioned is information of the surface area of marshes through time. With these data, a representation of the estuary can be modelled and the output can be compared with the measured behaviour of the salt marsh.

In order to answer the main question the following sub-research questions are formulated:

- How do the vegetation parameters affect the ASMITA-salt marsh model?
- To which parameters is the model most sensitive?
- What are the differences between the model predictions and the real behaviour of the salt marsh and, if necessary, how can the model give a better result?
- How do regional differences affect the vegetation parameters and the model prediction?

The first two sub-research questions will be answered by doing a sensitivity analysis of the model. In this way an indication of the reaction of the model to various parameters can be made and more insight is acquired in the model. This sensitivity analysis also makes clear which data must be measured most accurately.

The third question will be answered by validating the model. By setting up various model runs of estuaries and comparing the different results an indication can be given of the reliability of the model.

The fourth question will be answered by looking closely to the results of the sensitivity analysis and the differences between the models for different estuaries.

1.5 Outline of the thesis

Chapter 2 will give the results of the sensitivity analysis. Chapter 3 describes the retrieved data. In the fourth chapter the Langstone Harbour estuary will be discussed more detailed. Chapter 5 considers the parameterisation of ASMITA and the uncertainties in these parameters. In Chapter 6 the calibration and the problems during this process is talked through. This is followed by the results of the model and the conclusion for the research questions. Chapter 9 gives some recommendations for further extension of the ASMITA model.

2 Sensitivity analysis

As an introduction to the model, the research was started by carrying out a sensitivity analysis. By doing this the knowledge of the model increased and it will become clear how the different parameters influence the model.

The sensitivity analysis is divided into model runs with three scenarios. The reference scenario represents an estuary without salt marshes. To investigate the inclusion of a salt marsh, the second scenario will extend the first model with a salt marsh area. The third and last scenario deals with changes in the vegetation parameters of the salt marsh. The model is based on the model used by Knaapen et al (2009) for the Humber estuary in the northeast of England. However, the model is not intended to give an exact representation of the estuary. It represents an imaginary estuary and uses the Humber parameters to get an indication for the vegetation parameters.

Firstly the methodology of the sensitivity analysis will be given. After this the various results are presented for each different model. In Figure 3 the base model investigated is given. Appendix A explains the equations and parameters of the ASMITA model. In Appendix B the properties for the scenarios are given.

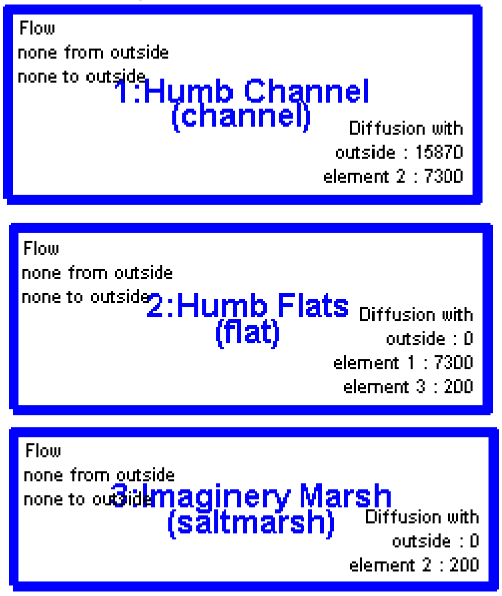

Figure 3: Base model sensitivity analysis

2.1 Methodology

In order to get a good view on the influence of the parameters on the model, the other parameters must be kept equal. It can be that a parameter is not sensitive for small changes, but very sensitive for big changes. Therefore the parameter is changed for various percentages, positive and negative.

The rate of sensitivity is calculated as the difference between the actual run and the base run. This difference is converted into a percentage of the original value. Big changes are converted to a percentage for one per cent to compare them with small changes. A value of 0.007% represents how the model respects to a change of 1% in the input value. The sensitivity value mentioned is an average for all outcome parameters. All the values are measured in a reference year, in this case 2000.

The sensitivity is measured by comparing the moving volume and surface and the accompanying equilibrium values. This because the equilibrium value affects the way the moving value behaves. The moving parameter is chosen because it takes also external effects into account (see Appendix A). In the case of sea level rise the fixed volume is also observed to look at the effect of sea level rise on the morphology.

2.2 Exchange parameters

In this subsection the sensitivity of the exchange parameters will be discussed. In this research the diffusion is the most important way of sediment exchange between the elements. Therefore the diffusion was the only process to be looked at for the sensitivity. The diffusion can be separated in three different cases: diffusion between the outside world and the channel, between the channel and the flats and between the marsh and the flats. The model responds differently to the various processes so they will be discussed separately. In Appendix C the sensitivity of the various parameters per scenario is given. Because of the importance for this research this is only done for the parameters including a salt marsh. The case of two marsh species is not investigated for these parameters because the focus was on the reaction of the model on the inclusion of a marsh, independent of its characteristics.

2.2.1 Diffusion Channel → Outside World

The first diffusion process is between the outside world and the channel. A lower diffusion coefficient leads to a higher water volume. This can be explained by the fact that the model uses the outside world for the supply of sediment. A lower diffusion coefficient represents less input of sediment, keeping the volume of the channel high. The model is not sensitive for the diffusion between the channel and the outside world. The inclusion of a marsh makes the model more sensitive. However, the sensitivity is still low. The values of the sensitivity of Scenarios I and II are shown in Table 1.

Element	Sensitivity without marsh (%)	Sensitivity with marsh (%)
Channel	0.0079±0.0004	0.1639±0.0029
Flat	0.0077±0.0005	0.1621±0.0036
Marsh	-	0.1613±0.0565

Table 1: sensitivity diffusion outside world → channel

As can be seen, including a marsh raises the sensitivity more than 20 times for the channel and flat element. Remarkable is that the moving surface of the marsh element is most sensitive parameter. This is compensated with a low sensitivity for the moving volume (See Appendix C). This is represented by the higher deviance number of the marsh element.

2.2.2 Diffusion Flat→Channel

The second diffusion process looked at is the diffusion between the flats and the channel. A high diffusion coefficient will increase both flat and channel volume. The decrease of the flat element will increase the volume of the tidal prism, leading to a higher flow velocity. A higher flow velocity will transport more sediment to the outside world, lowering the channel and increasing the channel volume. In Figure 4 the graph of the reaction of the moving channel volume is given.

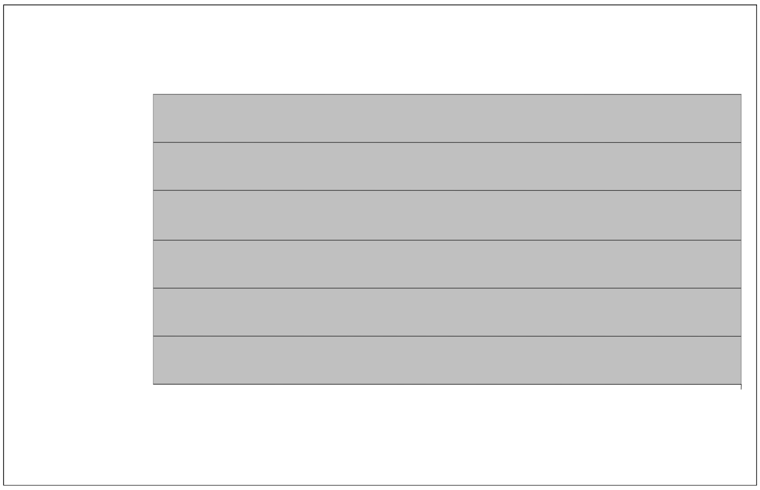

Figure 4: Graph channel volume diffusion channel → flat

This graph shows the same behaviour as the graph presented in Figure 4 of Gao and Collins (1992) considering the basin area and the elevation of Langstone Harbour. This can be explained with the fact that a higher diffusion coefficient will be obtained with a higher volume or a lower surface. A higher volume will lead to a higher elevation, what is represented in the graph of Gao & Collins (1992). The sensitivities of the model for change in this parameter are given in Table 2.

Element	Sensitivity without marsh (%)	Sensitivity with marsh (%)
Channel	0.0083±0.0002	0.1567±0.0007
Flat	0.0081±0.0012	0.1537±0.0090
Marsh	-	0.1526±0.0816

Table 2: Sensitivity diffusion Flat→Channel

Again the inclusion of the marsh makes the total sensitivity of the model higher. However, in this case the increase is smaller than in the case with the diffusion between the channel and the outside world. Again the marsh is least sensitive, and again the deviation of the marsh is the highest. This is caused by the high sensitivity of the moving surface and the low level of change of the moving volume, just as in the previous case.

2.2.3 Diffusion Marsh → Flat

The last diffusion process is between the marsh and flat elements. This diffusion coefficient is very small compared to the other coefficients. Reason for this is the assumption in the model that there is hardly any diffusion between the marsh and flat element. A high coefficient causes more sediment transport from the marsh to the flat, increasing the marsh volume. More sediment transport from the marsh to the flat will decrease the water volume of the flat. This decrease lowers the tidal prism. This on its time reduces flow velocity and less sediment transport from the channel to the outside world.

The sensitivity of the flat and channel volume show a different graph than in the previous runs. The previous runs all showed sensitivity in a form similar to the graph presented in Figure 4. The only difference was that it could have a declining behaviour instead of growth. The Figure below gives the result found in this run.

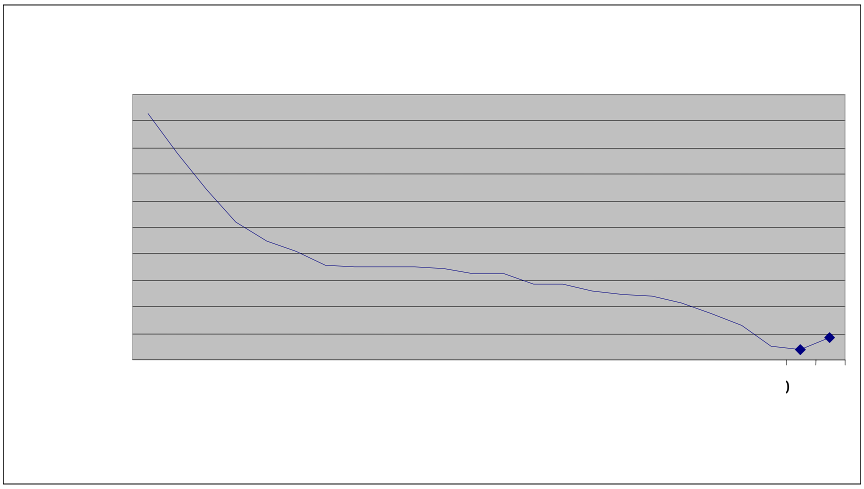

Figure 5: Sensitivity Channel element diffusion marsh→ flat = 200

In order to understand the behaviour the model run was extended with more data points. However this could not explain the different behaviour. As mentioned before the assumption is made that there cannot be a lot of diffusion between the marsh and flat elements. The reason for the strange behaviour could be that the diffusion coefficient was set too high. Therefore the same run was done with a diffusion coefficient of 100 (instead of 200). The graph of this run is seen in Figure 6.

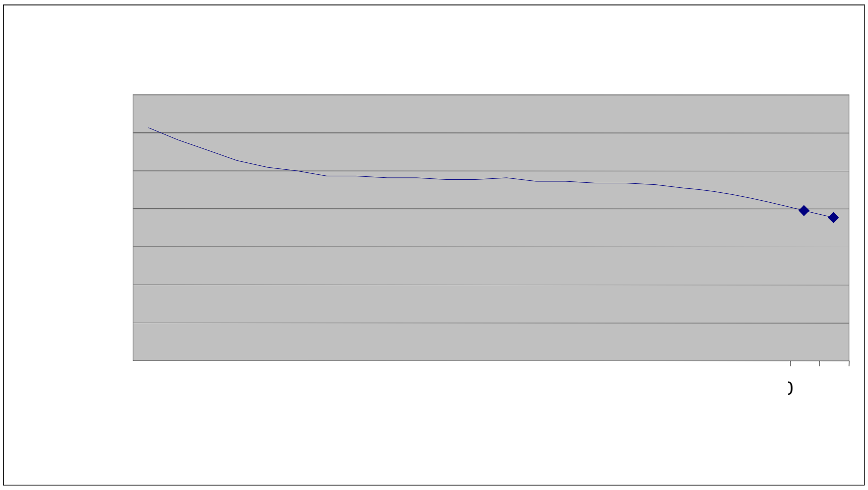

Figure 6: Sensitivity Channel element diffusion marsh→ flat = 100

The behaviour of this graph looks more like the declining version of Figure 4. However, with a smaller diffusion coefficient the channel and flat elements react more sensitively. Nevertheless the differences are relatively small. In Table 3 the differences in sensitivity are shown.

Element	Sensitivity diff. coeff. = 100 (%)	Sensitivity diff. coeff. = 200 (%)
Channel	0.0480±0.0008	0.0067±0.0009
Flat	0.0471±0.0036	0.0066±0.0026
Marsh	0.1001±0.0871	0.1413±0.1678

Table 3: Sensitivity diffusion coefficients marsh → flat

As expected the marsh suffers the biggest change. Looking at the various parameters of the marsh area it is especially the moving volume that has changed a lot. The sensitivity of this element is on average 0.2228±0.0123 %. The equilibrium parameters lower the total average change. This only holds for the run with a coefficient of 100. In the model with a diffusion of 200 the moving surface is sensitive (0.3591±0.0022). This is also the reason for the high deviation of the marsh element.

2.3 System Properties

System properties are the parameters that account for all elements. In this sensitivity analysis only the rate of sea level rise will be analyzed. The global equilibrium concentration should be used to calibrate the model (Wang et al., 2007). From this it can be concluded that the model is very sensitive to this parameter. The global equilibrium concentration indicates the morphological activity within the area. A high value represents a quick infill of the estuary.

Sea level rise is another parameter that counts for the whole system. It is expected that the model will react different on sea level rise when a marsh is included. Adding an extra species may influence the sensitivity too. Therefore all three scenarios are used for the reaction on sea level rise. In contrast to all the other runs the fixed volume is also examined. Reason for this is that with the fixed volume the morphological reaction of the model can be taken into account.

The first scenario without the marsh shows little sensitivity for the channel area. A lower rate of sea level rise leads to a higher fixed channel volume and a lower fixed flat volume. In a morphological perspective a higher sea level rate encourages the exchange of sediment from the flat to the channel. This is caused by the higher flow velocity that comes along with the higher sea level. A higher rate of sea level rise raises the moving volume of both areas. This is logical because a higher sea level increases the height of the water volume. The sensitivity hardly changes and shows a slightly linear behaviour. What is more important is that the graph of the moving volume shows a different behaviour that the graph represented in Figure 4. The graph shows a steeper and shorter middle area. At the same time the ends are more linear. This implies that the basin fills quicker. This graph is shown in Figure 7.

Figure 7: Sensitivity rate of sea level rise

The scenario with a marsh (one species) does not change a lot. In increases the total sensitivity of the model, but that behaviour is also noticed in the other cases. The fixed volume of the marsh decreases when the rate of sea level rise increases. A higher rate of sea level rise will transport sediment from the upper areas of the marsh to the lower areas. This will fill the initial area of the fixed volume.

In Table 4 the different sensitivities for each scenario are given. A higher amount of salt marsh species lowers the average sensitivity for the salt marsh element as well as the standard deviation. The sensitivity for the channel and flat elements is highest in the scenario without a marsh.

Element	Sensitivity without marsh (%)	Sensitivity with one species (%)	Sensitivity with two species (%)
Channel	0.0518±0.0251	0.0417±0.0064	0.0433±0.0043
Flat	0.0869±0.0332	0.0652±0.0452	0.0704±0.0503
Marsh	-	0.0746±0.0474	0.0639±0.0330

Table 4: Sensitivity rate of sea level rise (including fixed volume & surface)

In these runs the estuary is unconstrained. This can be the reason why the sensitivity is quite low. It can be interesting to look at the sensitivities when the estuary is constrained. It is probably that the marsh will show the highest sensitivity in this case. Normally it will be the first element to drown due to coastal squeeze.

2.4 Vegetation

The last parameters investigated for this sensitivity analysis consider the vegetation on the salt marsh. The parameters were changed in a one-species marsh and in a two-species marsh. The parameters are divided into the area of the marsh they describe. This is divided into parameters defining the boundary of the element, the growth of the marsh and the scaling coefficients.

The only parameter that could not be fit into one of the subjects was the amount of species. To analyze this parameter an extra species was implemented in the model with exactly the same parameters. Logically this does not influence the model. This implies that the model only reacts on the different parameters of another kind of species.

2.4.1 Boundaries

The first vegetation parameters changed consider the boundaries of the marsh. These boundaries are set according the minimum and maximum depth below MHW of the marsh species. In the case for only one species the model was independent for an increase in minimum depth. After further investigation this can be blamed to the settings of the model. The marsh is a lot bigger than it would be in a normal case. Therefore the same run was made but now with a lower marsh volume. This resulted in a more logical result. A lower minimum depth gives a higher moving volume. The minimum depth is the top of the vertical boundary for the marsh element. Still remarkable is the little change that can be noticed in an increase of the minimum depth (see Figure 8).

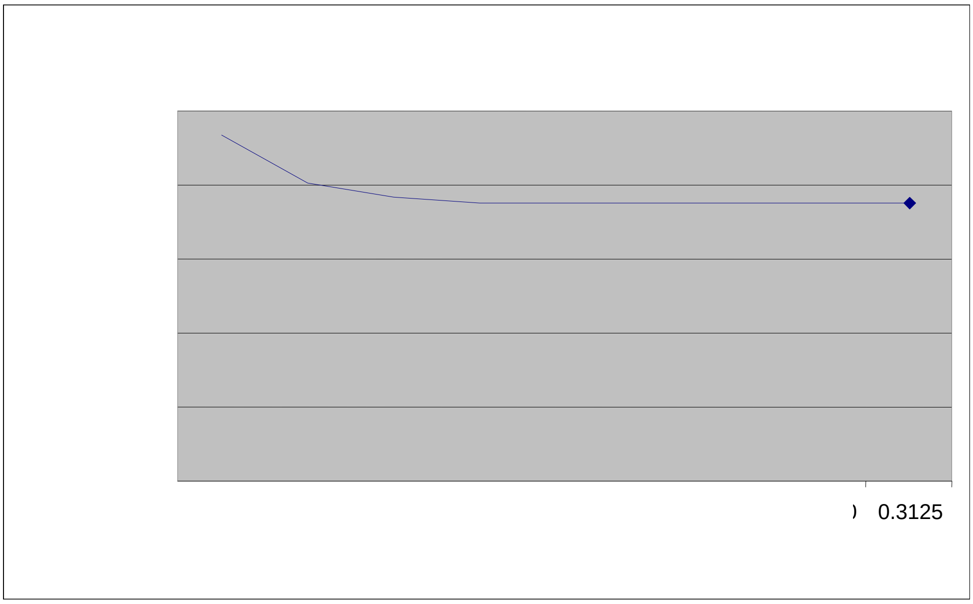

Figure 8: Moving volume marsh minimum depth

In the case of two marsh species the lowest minimal depth (from MHW) is the most important. This is according the fact that the minimal depth forms the vertical boundary of the marsh.

Element	Sensitivity min. depth one species (%)	Sensitivity two species lowest min. depth (%)	Sensitivity two species highest min. depth (%)
Channel	0.0190±0.0002	0.2180±0.0016	0.0019±1.36e^{-5}
Flat	0.0189±0.0008	0.2174±0.0061	0.0019±5.30e^{-5}
Marsh	0.2853±0.3163	0.4542±0.2281	0.0040±0.0020

Table 5: Sensitivities minimal depth

As seen in Appendix C especially the volume parameters act very heavy on changes in the minimal depth. The marsh element is very sensitive for changes in the lowest minimal depth in the species.

The maximum depth forms the horizontal boundary of the marsh element as shown in Figure 9. This Figure also implicates that there is a relation between the rate of change in volume and surface and the slope of the element.

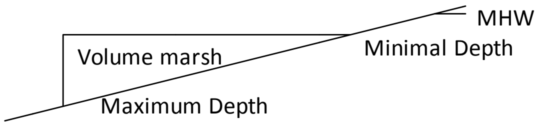

Figure 9: Boundaries marsh element

As mentioned the maximum depth gives the point where the marsh will start to elevate. A lower maximum depth will allow a higher elevation of the marsh, which decreases the total water volume of the element. This decrease is higher than the volume gained by a higher depth. In the scenario with only one marsh species the sensitivity is extremely high. Again the volume parameters show a big sensitivity on the changes (see Appendix C). The equilibrium volumes changes even more than the actual change. Two species will decrease the total sensitivity of the model with almost 50%. As expected the model reacts most on the deepest depth (highest max depth from MHW). In Table 6 the sensitivities in both scenarios are presented.

Element	Sensitivity max. depth one species (%)	Sensitivity two species lowest max. depth (%)	Sensitivity two species highest max. depth (%)
Channel	0.2571±0.0024	0.0157±0.0001	0.1672±0.0012
Flat	0.2559±0.0093	0.0157±0.0004	0.1677±0.0047
Marsh	0.6761±0.4248	0.0327±0.0165	0.3390±0.1654

Table 6: Sensitivities maximum depth

2.4.2 Growth of marsh

The second set of parameters describes the rate of growth of the marsh: the biomass and production rate. In the scenario with one species the sensitivity analysis showed that there is no change at all. This can be caused by the fact that the model estimates a fully grown marsh. The biomass will determine the rate of growth of the marsh (see Equation 27 Appendix A). In the case of two species there is other behaviour noticeable. It does not matter if the change in biomass is positive or negative, it gives the same average. However, the sensitivity for the parameter is so small that it can be neglected. The highest biomass gives more sensitivity, even though it is still a small change. A higher value increases the moving volume of the element. As mentioned before the model assumes a fully grown marsh. Therefore the model has already adapted to the changes and the growth is caused by sea level rise. This can also explain the low sensitivity for the parameter (see Table 7). Normally a higher biomass will decrease moving volume because it traps more sediment. The moving volume of the flat element decreases with a higher biomass. This can confirm the hypothesis that the marsh traps more sediment with a higher biomass. When changes are implemented in the model, these parameters will affect the outcome more.

Element	Sensitivity biomass one species (%)	Sensitivity two species lowest biomass (%)	Sensitivity two species highest biomass (%)
Channel	0	$1.9650e^{-11}\pm7.37e^{-13}$	0.0125±0.0001
Flat	0	$1.8916e^{-11}\pm1.33e^{-12}$	0.0124±0.0004
Marsh	0	$1.6980e^{-11}\pm1.37e^{-11}$	0.0260±0.0131

Table 7: Sensitivities biomass

The lowest production also determines the rate of growth of the marsh. As explained before the marsh is modelled as a fully grown marsh. Therefore the rate of growth does not matter. In a one species model this causes insensibility for any change in productivity. In a two species model the lowest production is the most sensitive parameter. It shows the same behaviour as the maximum biomass. The reason for this is the same as for the behaviour of the biomass. The marsh is already fully grown and therefore the sea level rise plays an important role and increases the moving volume. The model is a bit more sensitive for the lowest production than the highest biomass. The lowest production determines the lowest rate of marsh growth and therefore plays a bigger role for sediment trapping. The succeeding table gives the sensitivities for the production.

Element	Sensitivity productivity one species (%)	Sensitivity two species lowest productivity (%)	Sensitivity two species highest productivity (%)
Channel	0	0.0127±0.0001	0
Flat	0	0.0127±0.0004	0
Marsh	0	0.0265±0.0134	0

Table 8: sensitivities productivity

2.4.3 Scaling Coefficients

The last parameters are scaling coefficients for the relative biomass. This is done in order to give an appropriate variation in enhanced settling rate (Knaapen et al., 2009). The alpha coefficient is a multiplication coefficient and beta is a power-coefficient (see Equation 26 in Appendix A). In the case of one species both parameters do not affect the outcome of the model. This is because the coefficients give a variation in settling rate. This variation is only needed in the case of more species. In the case of two species the model still shows very little change. The graph of the alpha parameter shows a very slight linear behaviour, what can be expected because the alpha is a multiplication coefficient. The beta coefficient shows a behaviour that can be expected when dealing with a power function. A higher negative change gives a bigger sensitivity and a lower moving volume of the channel. For the marsh volume a lower coefficient gives a higher volume. The graph has an exponential behaviour, as can be seen in Figure 10. In this sensitivity analysis a beta value higher than one is not taken into account.

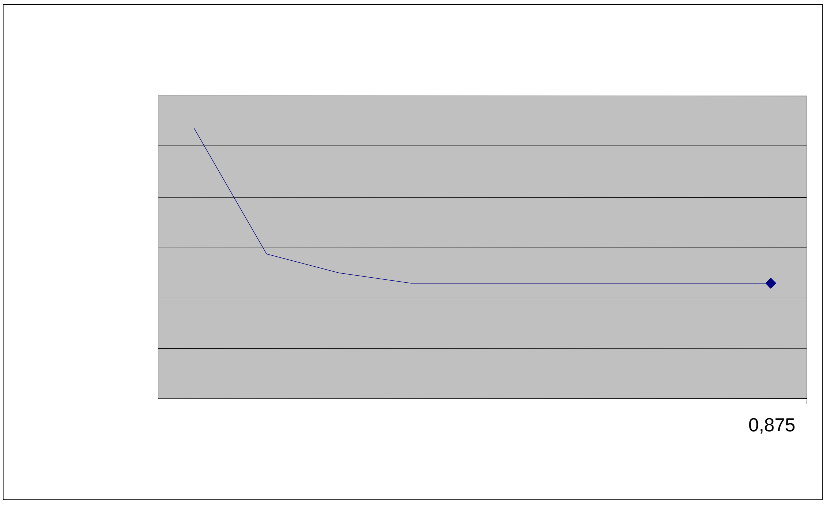

Figure 10: Moving Volume marsh beta coefficient

The sensitivity for both scaling coefficients is only represented for the case with two marsh species. As mentioned before, in the case of one species the model does not change.

Element	Sensitivity two species alpha (%)	Sensitivity two species beta (%)
Channel	$1.81e^{-10} \pm 1.31e^{-12}$	$1.44e^{-7} \pm 1.02e^{-9}$
Flat	$1.81e^{-10} \pm 4.86e^{-12}$	$1.44e^{-7} \pm 3.86e^{-9}$
Marsh	$3.74e^{-10} \pm 1.68e^{-10}$	$2.99e^{-7} \pm 1.49e^{-7}$

Table 9: Sensitivities scaling coefficients

Looking at this table it can be concluded that the marsh area is most affected by these coefficients. However, the sensitivity is very low. The marsh is also most vulnerable for changes in the beta coefficient.

2.5 Conclusion

In most cases it can be concluded that the marsh area is the element that is most affected by changes. Exception is the case of diffusion. In this case the element that is located most far away from the diffused elements is least sensitive.

When looked at the various parameters the volume parameters show the most sensitivity. This can be explained with the fact that the model is calculating the volume area. In the original model the volume was the only output parameter. Due to this, it is still the parameter that is most affected.

In the case of sea-level rise the model without the marsh shows the most sensitive values for the channel and flat elements. Including more salt marsh species decreases the sensitivity for the marsh element, but increases the sensitivity for the other two elements.

The vegetation parameters have most influence on the marsh element. Especially the parameters describing the depth have a big effect. This is because these parameters represent the boundary of the marsh element. Other parameters describe the rate of growth of the marsh. In this sensitivity analysis these parameters did not affect the outcome. The rate of growth is most of importance after implied changes in the estuary.

The equilibrium values are always equally sensitive. This confirms that the parameters are defined in the same way. A bigger change also increases the sensitivity in a positive or negative way. The cause of this is that there is an error in every percentage change. Increasing the change sums all these error, leading to a bigger error in absolute numbers. This is due to the incretion of more or less error. The equilibrium surface value of the marsh element is often just as sensitive as the moving surface of the flat element.

The relation between the parameters and elements describes how the estuary gets filled with water. This is characteristic for each estuary. It is dependent on the composition of the estuary. An estuary with a very steep channel element will fill quicker, but its total channel volume will be less. For a more detailed description is referred to Gao & Collins (1992).

3 Data

In this chapter the various datasets will be discussed. The first dataset retrieved considered the Langstone Harbour tidal inlet located in the southern part of England. The second dataset deals with salt marshes in the Western Scheldt estuary in the south western part of the Netherlands. This dataset considers three different marsh areas that will be discussed separately. However, due to a lack of time the only dataset that could be investigated is the dataset considering Langstone Harbour.

3.1 Langstone Harbour

The first dataset is situated within the Langstone Harbour estuary. The data exists of salt marsh areas of 1955, 1971 and 2001. This is the same data used by Royal Haskoning (2004). In this area a lot of erosion is noticeable. Between 1955 and 2001 the marsh area decreased from 273 ha to 75 ha. In Figure 11 the location of the marshes is shown, as well as the differences between the estuary area (1955 green, 2001 blue) and the 1955 (green) and 2001 (orange) data.

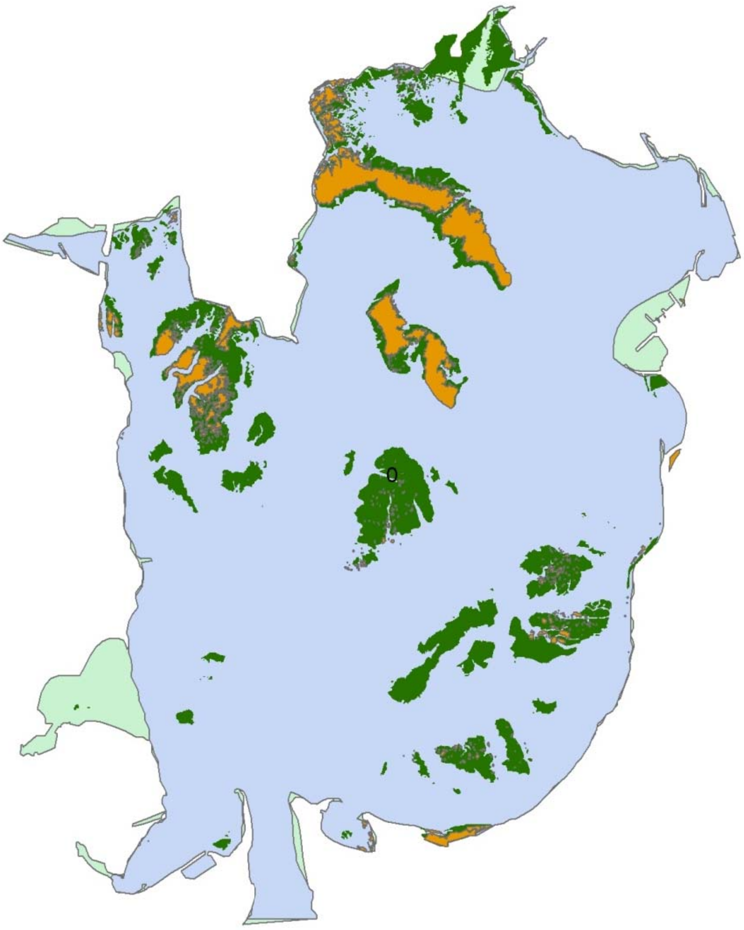

Figure 11: Langstone Harbour salt marsh area 1955 (green) & 2001 (orange)

It can be noticed that there are several areas reclaimed between 1955 and 2001. The northern part is reclaimed after the marsh area disappeared. The others areas only reclaimed flats. Erosion took place mostly in the centre and south eastern part of the estuary. The reason for this will be discussed in Chapter 4. The estuary could be modelled according the elevation used by Rossington (2007). The estuary will be discussed more in Chapter 4.

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3.2 Western Scheldt

The second dataset concerned the Western Scheldt estuary in the Netherlands. This estuary is the only remaining estuary that is fully connected with the sea in this part of the Netherlands. In Figure 12 the location of the various salt marsh areas are presented. Number 1 represents a marsh situated in the harbour of Vlissingen (Flushing). This marsh will be referred as the Ritthem marsh. The second marsh is the Zuidgors, situated near the village of Ellewoutsdijk. The last marsh area is the Waarde marsh, located at number 3. These datasets are retrieved from Cox et al (2003), the vegetation data is retrieved from Rijkswaterstaat (2006).

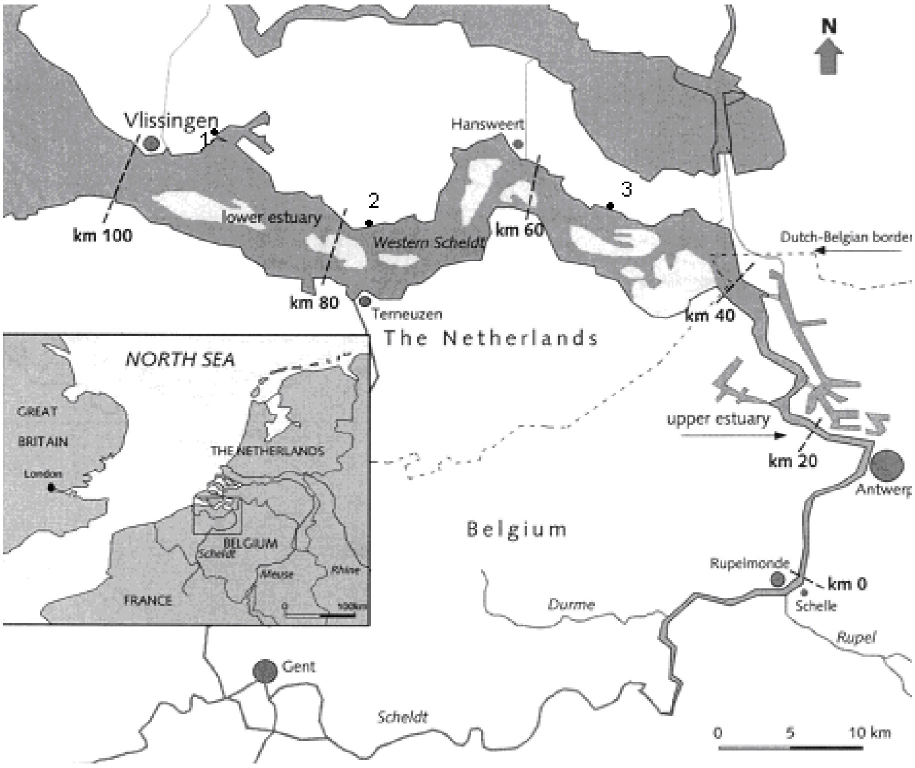

Figure 12: Location salt marshes Western Scheldt

3.2.1 Ritthem

The first marsh considered is the Ritthem marsh. This marsh is situated in the harbour of Flushing. This makes that the marsh suffered from human involvement in the past. In 1965 the harbour was developed, what decreased the marsh area from 24 ha to 10.6 ha. The data for this marsh was quite difficult to measure because of the many changes made and the lack of maps for all years. The marsh experienced mostly growth because it is situated in an enclosed area of the harbour as can be seen in Figure 13. In this Figure the 1970 (green) and 1998 (orange) marsh areas are represented. The accompanying areas are given in Table 10.

Year	Area (ha)	Change (m/yr)
1944	11.9	
1959	24.0	0.81
1970	10.6	-1.22
1981	18.3	0.70
1992	8.5	-0.89
1996	17.4	2.23
1998	25.6	4.10

Table 10: Marsh area Ritthem

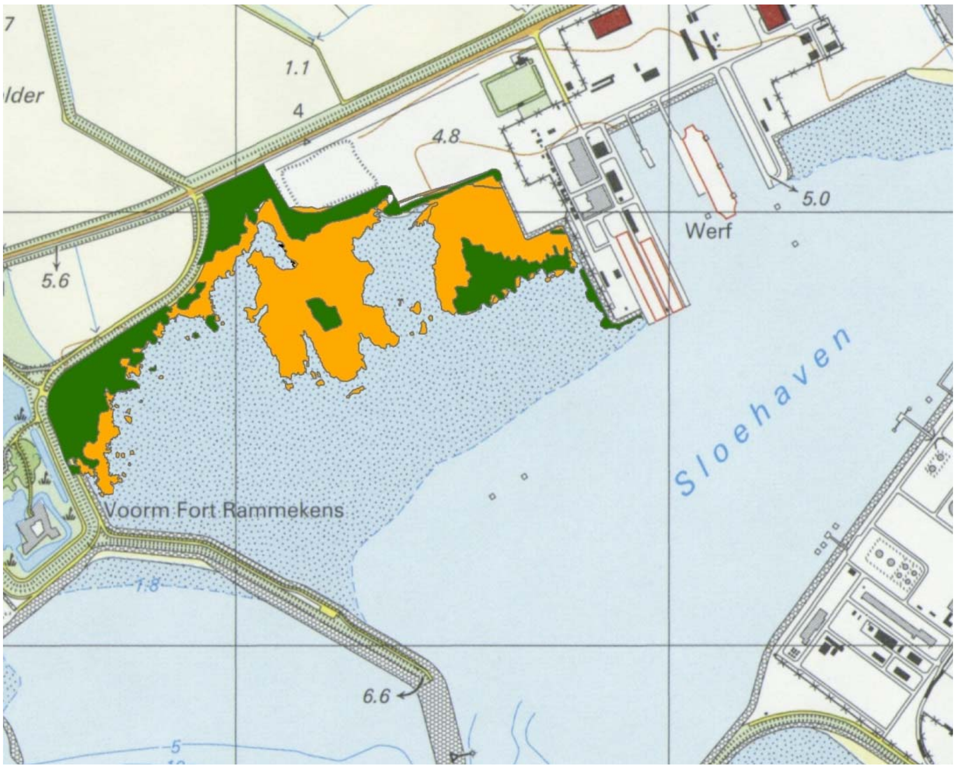

Figure 13: Marsh area Ritthem 1970 (green) & 1998 (orange)

Because its location within a harbour it is very interesting to investigate the reaction of the marsh on the maintenance dredging. Therefore there is also data retrieved considering the channel depth. The vegetation consists of mid-upper marsh areas near the dyke, protected by *Spartina* and *Zostera* areas (Rijkswaterstaat, 2006).

3.2.2 Zuidgors

The second marsh that was investigated in the Western Scheldt is the Zuidgors. The dataset lasted from 1944 until 1998. The marsh is constrained on the landward boundary by a dyke.

Figure 14: Marsh area Zuidgors 1944 (light green), 1981 (green) & 1998 (orange)

As seen in Figure 14 the marsh increased quickly from 1944 to 1981 with a maximum rate of 6.04±0.09 m/yr between 1944 and 1959. Between 1992 and 1996 it suffered a maximum erosion of 4.91±0.07 m/yr (Cox et al., 2003). Vegetation on this marsh consists mostly of upper and mid-upper marsh. In the eastern part more pioneering marsh is present. Especially the western part of the marsh suffers erosion (Rijkswaterstaat 2006). In Table 11 the marsh areas are shown.

Year	Area (ha)	Change (m/yr)
1944	32.3	
1959	53.8	1.43
1970	54.0	0.02
1981	62.0	0.73
1986	59.5	-0.50
1990	57.0	-0.63
1992	54.5	-1.25
1996	49.0	-1.38
1998	46.8	-1.10

Table 11: Marsh Area Zuidgors

3.2.3 Waarde

The last marsh investigated in the Western Scheldt is the Waarde marsh. This marsh is also constrained by a dyke on the landward boundary. The behaviour of this marsh is different on the western and eastern side of the marsh. Between 1944 and 1957 the western half retreated at a rate of 1.51±0.05 m/yr, while the eastern part grew with a rate of 4.91±0.08 m/yr. The marsh front was relatively stable until 1985. Since then fluctuations have been noticed between extension and retreat, especially in the western part of the marsh. Between 1996 and 1998 the western part suffered a retreat of 7.92±0.10 m/yr (Cox et al., 2003).

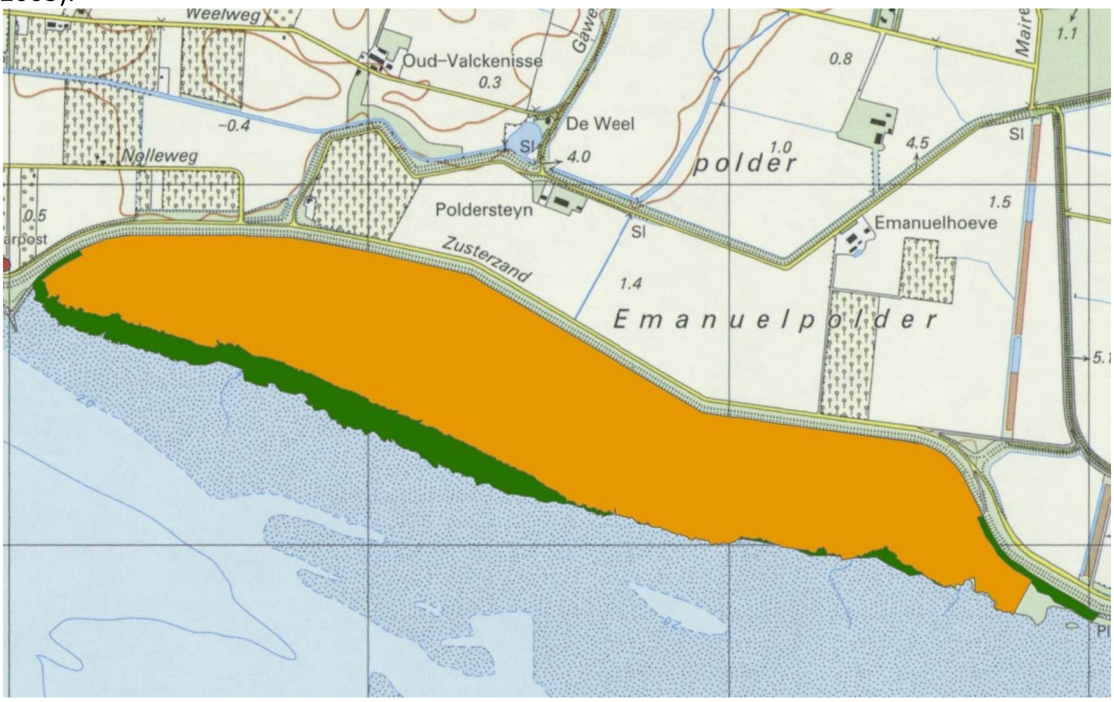

Figure 15: Waarde marsh 1957 (green) and 1998 (orange)

Unfortunately in Figure 15 the rate of extension of the marsh in the eastern part is not noticeable.

Just like the other marshes the vegetation on this marsh is mostly upper and mid-upper marsh. In the eastern part there is more pioneering marsh, what causes the extension of the marsh in this area. The total marsh area is given in Table 12. As can be seen, the total marsh area does not change a lot.

Year	Area (ha)	Change (m/yr)
1944	99.2	
1959	104.8	0.37
1965	104.4	-0.07
1975	102.7	-0.17
1985	104.2	0.15
1989	95.9	-2.08
1992	98.9	1.00
1996	97.9	-0.25
1998	93.5	-2.20

Table 12: Marsh Area Waarde

4 Description Langstone Harbour

In order to validate the ASMITA-marshes model a comparison had to be made between the output predicted by the model and the measured values. In this report ASMITA-marshes is applied to the Langstone Harbour estuary. Firstly a description of the Langstone Harbour estuary will be given, followed by the methodology used to calculate the parameters needed for ASMITA.

4.1 Description Langstone Harbour

Langstone Harbour is situated in Hampshire, southern England, East of the city of Portsmouth (See Figure 16).

Figure 16: Location Langstone Harbour in the United Kingdom

In Figure 17 an aerial photograph of the harbour is shown. It is the middle of a total of three tidal inlets, to the west Portsmouth Harbour is situated and to the east Chichester Harbour. It is connected to these harbours via channels in the north, with a flow going from east to west. Because of this, Langstone Harbour receives an import of approximately $3.5\cdot10^{6}$ m^{3} on spring tides from Chichester Harbour and has an export of $0.73\cdot10^{6}$ m^{3} to Portsmouth Harbour (Gao & Collins, 1992).

Figure 17: Aerial photograph Langstone Harbour (Google Earth)

The harbour is mostly used by commercial fishermen and for recreational activities. Due to the marshes is also has an environmental function. The land use around the estuary is quite diverse. On Portsea Island (western bank) is the city of Portsmouth with mostly residential land use. On Hayling Island there are also some residential areas, varied with more grazing or arable land. Industry is situated in the north and there are some marinas on the western bank. The estuary is largely constrained by flooding defences (HR Wallingford, 1997).

The harbour is connected with the eastern part of the Solent and protected against wave attacks from the southwest due to the narrow estuary mouth. In the East Solent region wave climate and tidal regime are relatively complex compared to other parts of the UK. This is mostly due to the presence of the Isle of Wight and the constricted harbour entrances. Especially the tides are complex, with a rapidly changing tidal range, extended high waters and complex patterns of tidal flow. This tidal flow includes strong ebb and flood currents through the harbour entrance channels. An increase in tidal range and high water is noticeable from west to east, while an increase in wave height is noticeable from east to west (HR Wallingford, 1997; Mark, 2007). The East Solent is also a busy shipping route due to Portsmouth Harbour and the possibility to reach Southampton Harbour via the Southampton Water. An important part of the coastline in the Solent is protected by salt marsh.

The harbour is classified as a (macro)tidal inlet and has a shoreline length of about 43 km. The total area of the estuary is 1925 ha, with a big intertidal area of 1513 ha (79%). As seen in the aerial photograph, most marshes are situated in the northern part of the harbour. The tidal range of the harbour is 4.2 m (Estuary Guide, 2008). Within the harbour the strongest currents are situated in the entrance channel, with a 0.9 m/s flood velocity at maximum spring tide and an ebb velocity of 1.8 m/s (SCOPAC, 2006). Within the channel ebb currents are most important, while the flood currents are stronger in the upper channel parts. Storm surge conditions within the harbour are not significantly stronger than spring tide currents (HR Wallingford, 1997).

Sediment within the estuary consists mostly of fine silts and clay, while gravel and sands are more common near the harbour entrance. Due to the higher ebb-velocity coarse sand and gravel tend to be transported seaward, causing erosion within the estuary. This also leads to the forming of extensive coarse sand and gravel deposits just outside the estuary. However, the transport rates are rather small according to Gao & Collins (1992), while this process might explain the appearance of a delta just outside the estuary. Waves will transport more coarse material, but as mentioned before, the estuary is dominated by tidal currents. The estuary has asymmetrical tide with flood duration of 7.1 hours and ebb duration of 5.7 (SCOPAC, 2006). Sediment is transported into the estuary by tidal currents, so there is a net sediment transport to the inlet. Within the estuary it tends to accumulate. Sediment is also imported into the estuary due to erosion of the coastline.

The underlying geology consists mostly of easily eroded Tertiary strata namely London Clay, Reading Beds, Brackleham Beds and Bagshot Beds. These grounds mostly consist of clay and sand. There is an exception in the north were the more resistant Upper Chalk can be found. Because of these easily eroded grounds the rate of suspended sediment will be quite high (HR Wallingford, 1997).

There has been a lot of human interference in Langstone Harbour, especially reclamation and dredging. The biggest change in the estuary was the reclamation of Farlington Marshes in the northern part in the 1700s. Another big reclamation was the reclamation of Milton Common on Portsea Island on the western bank in 1968. In total approximately 9%of the total area has been reclaimed. Dredging took place mostly at the ebb-tidal delta outside the harbour (Rossington, 2007).

4.2 Salt marshes

At the beginning of the 20th century the salt marsh area in the estuary was quite low (Figure 18). There were some areas with upper salt marsh, but these were mostly reclaimed for agricultural use. In this period the *Spartina Anglica* (Common Cordgrass) was introduced in the area. This is a species common in the pioneering areas of the marsh with a high capability to trap sediment. This increased the marsh area till the 1950s. In the mid 20th century it began to die-back, reducing the area of coverage. This dying also made the marsh more susceptible to wave action. This caused a vicious circle; greater wave energy damaged the species, which caused the plant to reduce its capability of dissipating wave energy, leading to greater wave energy again. At this moment there is only active *Spartina* in the northwest and *Spartina* in the southeast is degenerating. Upper salt marsh can only be found in the north near the reclaimed Farlington Marshes (HR Wallingford, 1997; Rossington, 2007). The decline of *Spartina* cannot be explained. On the mudflats there is now a growth and colonization of *Zostera* noticeable. Reason for this can be that the *Zostera* provides a habitat that is of greater value to wildlife (Adam, 1993).

As mentioned in Chapter 3 a large decline of marsh was noticeable. The main reason for this decrease is the dying of *Spartina Anglica*. Next to this process, sea level rise also decreases the marsh area. Because the boundaries of the estuary are largely constrained the salt marsh cannot respond by moving landward and coastal squeeze is occurring.

It is predicted that erosion of the marsh will go on the next 100 years (Royal Haskoning, 2004). They predict a total loss of 327 ha for both Chichester and Langstone Harbours, with a total loss of 52 ha for Langstone Harbour. This prediction leads to an estimation of only 23 ha of marsh in 2101.

As seen in Appendix D the dying of vegetation in the southeast and in the middle of the estuary is mostly due to the dying of *Spartina Anglica*. The northern parts are mostly upper marsh species which only occur around MHWS. The steeper slope in this area makes it vulnerable to cliff erosion. In the northwest of the estuary there is still some active *Spartina Anglica* found, suggesting that wave energy must be lower in this part of the estuary.

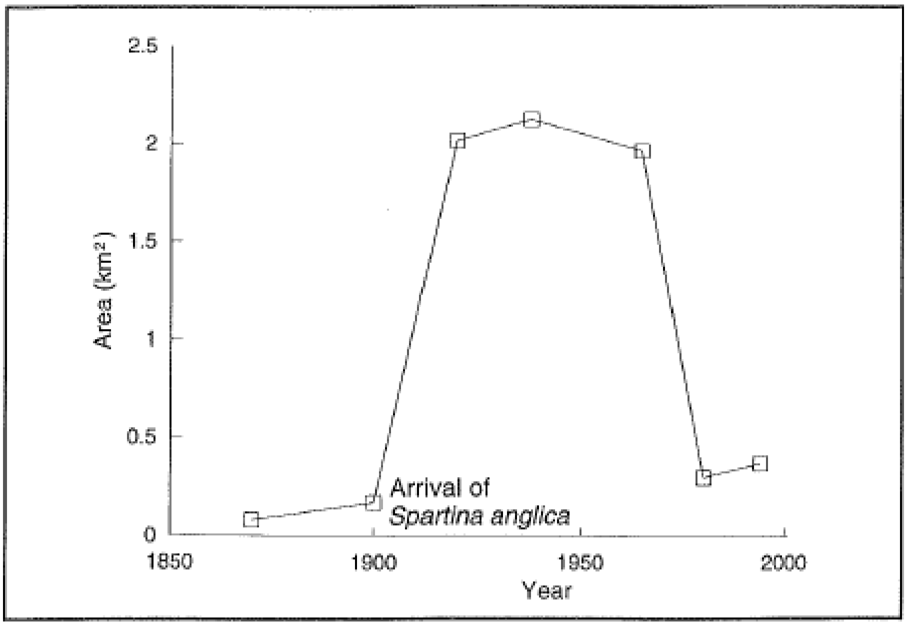

Figure 18: Change in area occupied by *Spartina Anglica* (HR Wallingford, 1997)

In Figure 18 is shown how the area occupied by *Spartina Anglica* has changed in time. Remarkable is that when the linear part from 1900 is interpolated to 2000, there will be little difference.

5 Parameterisation ASMITA

After the brief description of Langstone Harbour in the previous chapter, the estuary will be applied to validate the ASMITA-marshes model. In this chapter the methodology used will be discussed and the parameter setting will be given. The uncertainties in the parameter estimation are also included in this chapter.

ASMITA is a semi-empirical model. The computational procedure to calculate the output is given in Figure 19. The base for the calculation is the bathymetry of the estuary. This is used as input in the model, together with the hydrodynamic conditions. With these parameters the model is able to calculate the morphological equilibrium and the equilibrium concentration. This leads to a concentration field. With this field the morphological change can be calculated. This leads to a different bathymetry, which starts the whole cycle.

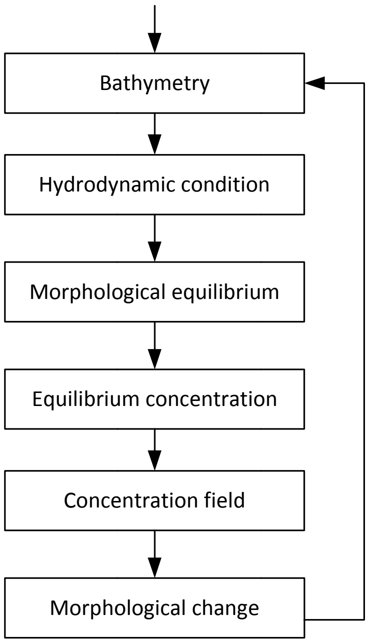

Figure 19: computational procedure semi-empirical models (Wang et al, 2007)

The model for Langstone Harbour is set up by using the dataset of the Royal Haskoning (2004). Other data was received from Rossington (2007). The bathymetry was loaded into ArcGIS, a programme that can be used for displaying and analyzing geographically referenced information. In this way the surface areas of the elements are measured and the volume can be calculated. The various geo-referenced data can be displayed in a database that consists of several layers. These layers display different information, which can be combined to get new data. Hydrodynamic parameters are calculated or assumed by using available literature. This subsection will divide the needed parameters according to the different classes used in Figure 19. The vegetation parameters are also applied, even though there are not mentioned in the Figure. All the parameter values can be found in Appendix F.

5.1 Bathymetry

The bathymetry determines the initial volumes and surfaces, as well as the slopes and flow axis of the elements. In order to obtain the initial volumes and surfaces of all the elements some adjustments had to be made. The initial values of 1956 were estimated by using bathymetry data of 1955 (Rossington, 2007). There is no reason to assume that big changes have occurred in this short period. Using the 3D-Specialist extension of ArcGIS the volumes and surfaces of the elements could be calculated. To do so, information about the tides was needed. The base map used for the 1955 bathymetry was available, which displayed the spring and neap levels. In Appendix E the several tidal levels are represented.

For 1955 a raster representing the bathymetry at Ordnance Level (Newlyn) was available. However to get a good comparison the data of 1971 and 2001 also had to be determined. In order to do this a raster was made for the 1974 and 1997 base maps. This was done with the help of digitized maps of the surface of the estuary. By adding point depths, depth contours in the area, new rasters could be made. This provided the volume and surface of the areas.

Where there are clear definitions within ASMITA for Channel and Flat areas, this definition is unclear for deltas. The delta volume is chosen at MLW. Reason for this is that it is only connected to the channel element, what is also calculated at MLW. Another problem that occurs with the delta area is the area coverage. In this case is chosen for an area that is also used by Rossington (2007). This area is an area of approximately 5 km wide and 4 km long (measured from the estuary mouth).

Next to the surface and area volumes the GIS data of 1955 was used to calculate the length between the elements and the slope of the elements. The slopes of the elements are taken as an average of the element. Unfortunately, this assumption neglects the appearance of cliffs at the boundary of the marsh and the flat element.

The lengths of the channel and delta elements were hard to measure. The boundary between the delta and the channel is very hard to recognize. To get a representative value the slope was used to distinguish the boundaries. However it has to be accounted that some errors could be made during this process. The used depths in the 1955 and 1974 cases were only available for the channel area. In order to get a better representation of the estuary the marsh boundaries were used as contours. For areas mostly considering pioneering species the average between MHWN and MHW was used as the contour. For upper marsh areas this contour was set between MHW and MHWS. These estimations give a better representation of the estuary, but will also include errors.

5.2 Hydrodynamics

For the ASMITA-marshes model there are also some hydrodynamic parameters needed in order to calculate diffusion and flow between the elements. These parameters are mostly assumed according literature or otherwise they are estimated using calculations. The tidal range in the harbour is 4.2 m (EstuaryGuide, 2008).

For the calculation of the diffusion there is a difference made between the calculation for the channel and delta element and the flat and marsh areas. This is done because of different dominating processes determining the diffusion.

For the calculation of the diffusion of the channel and delta element the following formula is used: $D = \frac{u^2 H}{w_s}$ [1]

In this formula

D = dispersion coefficient [m^2/s];

u = velocity between the elements [m/s];

H = hydraulic depth at mtl [m];

W_s = vertical exchange [m/s].

The background of this equation is explained in Wang et al (2007). With the help of this equation it is also possible to convert the dispersion coefficient used in the ESTMORF model to the diffusion coefficient used by ASMITA. This is done according to

$$\delta = \frac{D \cdot A}{L_x} \quad [2]$$

Where,

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δ = diffusion coefficient [m^3/s];
A = cross-section area between the elements [m^2];
L_x = distance between the elements [m].

However, using L_x is very sensitive to the definition of the element. In order to counteract this, it is better to use the tidal excursion distance, given by $L_x = \frac{u_p \cdot T_p}{2}$ [3]

Were u_p = peak velocity [m/s],
T_p = tidal period [s].

This distance assumes a triangular variation in velocity over the tidal cycle (HR Wallingford, 2009b).

The exchange between the flat and the channel and the marsh and the flat is described different. The base is Equation [2]. A is replaced by A_{int} which is given by

$$A_{\text{int}} = \frac{L_r \cdot tr}{2} \qquad [4]$$

L_r = length of the element boundary[m],
tr = tidal range [m].

This area is an average value based on the tidal variations.

The second step to be taken for the diffusion coefficient between the flat and the channel is to replace the hydraulic depth at Mean Tidal Level (MTL) with a new hydraulic depth. This new depth can be estimated with $H = \frac{V}{S}$. [5]

In this calculation V = Volume of the element [m^3],
S = Surface of the element [m^2].

The velocity mentioned in Equation [1] has to be replaced with the transverse speed over the flat or the marsh. This speed is described as $u = \frac{2 \cdot W}{T_p}$, where [6]

W = average width of the element, estimated by $W = \frac{S}{L_r}$, [7]

Equations [5] and [6] can be used to calculate a new value for D from equation [1]. With this new value for the dispersion coefficient and the A obtained from equation [4] the diffusion coefficient for the marsh and flat elements can be calculated.

As can be concluded from the above mentioned, the bathymetry defines a lot of the diffusion parameters. However, there are still some parameters left to be defined.

The hydraulic depth for the delta and channel elements needs to be at MTL. The elements are defined as the areas below MLW, so the depth at MTL can be estimated by adding half the tidal range to the hydraulic depth of the element.

The cross-sectional area is estimated according $A = \frac{V}{L_r}$. However, as mentioned there is an uncertainty in the estimation of V and L_r. This increases the inclusion of error in the diffusion number. This only accounts for the delta and channel element. The other elements are calculated with A_{int}.

The last parameter that needs to be estimated is the velocity in the delta and channel elements. For the delta element a velocity of 1.5 m/s is estimated. For the channel element a velocity of 1.1 m/s is used (HR Wallingford, 1997; Rossington, 2007).

In the model the inflow of rivers is neglected. There is a maximum daily inflow of 40.6 x 10^4 m^3 and a minimum of 10.3 x 10^3 m^3. Together with the inflow of the Portsmouth and Chichester Harbours inflow the discharge in the harbour is 45 m^3/s. This is much smaller than the water volume that enters the harbour through the channel entrance (Gao & Collins, 1992).

The vertical exchange coefficient was adjusted from 0.003 m/s to 0.0003 m/s (Rossington, 2007). This is done to represent the muddy sediment and the preference for fine sediments in the estuary.

5.3 Salt marsh Vegetation

There was little literature available that could be used for the vegetation parameters. Due to this the vegetation had to be characterized with only assumptions. The first assumption was the amount of species available. As mentioned in subsection 3.2 the change in the estuary was caused by the dying of *Spartina Anglica*. In the initial case this was the most common species. Next to the *Spartina* there is a big amount of upper salt marsh species located in the northern part of the estuary. These species together are the most common in the estuary and therefore the vegetation is characterized by these two species.

The species can be divided into various types of salt marsh. The *Spartina* is a typical species for the pioneering area of the marsh, while the upper marsh is a type of its own. With Figure 2 the depth of both species could be assumed. For the *Spartina* the assumption is made that is occurs in the whole area from MHWN to MHW. Here the transition to the upper marsh area is visible. The assumption is made that both species will occupy the area around MHW.

The biomass of the species was a lot harder to assume. The biomass depends highly on the availability of nutrients in the estuary and therefore there is no fixed number for the biomass of every species. There is no literature found that describes the biomass according to tidal levels, so this cannot be used to estimate the parameter. Therefore the estimation made by Knaapen et al (2009) is used. This estimation is representative for the Humber estuary in the northeast of England, but is not intended to represent the Humber.

Another parameter that could not be described is the production rate of the vegetation species. This parameter also depends on the availability of nutrients and little literature was available for this subject too. Therefore the values that are used by Knaapen et al (2009) are also applied to Langstone Harbour.

The alpha and beta coefficient are used to scale the relative biomass to give the variation in settling rate. The sensitivity analysis showed that these values have a little effect on the outcome of the model. Therefore the same values are applied that were used by Knaapen et al (2009).

5.4 System Properties

The most important parameters concerning the external influence are the rate of sea-level rise and the option to implement changes that are made in the estuary.

Literature pointed out various amounts of the rate of sea level rise. Shennan (1989) applies a rate of 1.5 mm/yr. Woodworth et al (1999) however calculated an amount of 1.45 ± 0.6 mm/yr at Portsmouth and Mark (2007) uses a rate of 1.37 mm/yr. The most recent value is used in this model.

When adapting sea level rise in the model an initial spin-up occurs. This is because of the reaction of the estuary. In order to get a good prediction the model must reach equilibrium again. The time the estuary needs to reach equilibrium again is called the morphological timescale. The closer the element is to the outside world, the quicker it will reach its new equilibrium (Kragtwijk, 2001). This also accounts for ASMITA with the implementation of marshes. The timescale of the model has to be extended with its morphological timescale. The values can be calculated by distracting the difference in volume at the starting year from the predicted results in the new equilibrium.

Another parameter considering the external influence on the estuary is the ability to include changes. In this way the influence of dredging and reclamations can be taken into account. The volumes and surfaces that suffered any change are represented in Table 13. These data was retrieved from Rossington (2007). These values are calculated for the old version of the model. The new values were calculated using the difference between the hydraulic depth of the removed area and the hydraulic depth of the wet volume. The change in flat volume and area remains negative because the area is reclaimed and not dredged like the delta volume.

Year	V_{marsh}	V_{flat}	$V_{channel}$	V_{delta}	A_{marsh}	A_{flat}	$A_{channel}$	A_{delta}
1968	0	-64350	343700	0	0	-17500	250000	0
1976	0	-377600	0	0	0	-95000	0	0
1984	0	-439000	0	0	0	-115000	0	0
1987	0	0	0	120000	0	0	0	0
1988	0	0	0	120000	0	0	0	0
1989	0	0	0	120000	0	0	0	0
1990	0	0	0	120000	0	0	0	0
1991	0	0	0	120000	0	0	0	0
1992	0	0	0	120000	0	0	0	0
1993	0	0	0	120000	0	0	0	0
1994	0	0	0	120000	0	0	0	0
1995	0	0	0	120000	0	0	0	0
1996	0	0	0	120000	0	0	0	0
1997	0	0	0	120000	0	0	0	0

Table 13: Disturbance data, after Rossington (2007)

Next to the possibility to include changes there is also an option to represent the constraint of the estuary. In the Langstone Harbour case, the estuary is largely constrained by flood defences (HR Wallingford, 1997). This option can be used to simulate coastal squeeze.

5.5 Uncertainties

In the parameterisation there is a risk of making errors. These errors will influence the outcome of the model. In this subsection the parameters with the highest possibility of error will be discussed.

The bathymetry is one of the most important aspects of the model. Bathymetry errors made have a big impact on the model. As mentioned in subsection 5.1 there was no base map available for the 1971 and 2001 data points. To get a raster for these data points, base maps of 1974 and 1997 were used. In the time between the data points and the base maps the estuary keeps on changing. This means that the actual values in 1971 are different than the measured values. To counteract this, the output parameters are measured in the year of the base map.

In order to get a raster that is accurate, some assumptions had to be made. The coastline was set as a contour at MHW. This gave a more representative raster. However, this assumption is quite doubtful. It implies that the sediment is situated at MHW. This assumption was needed to compensate the lack of data points outside the channel area in the 1956 and 1974 base maps. Because of consistency this assumption was also used in the 1997 base map. Another measurement taken to improve the raster was the use of the marsh edges as a contour. These assumptions increase the risk on error. Rossington (2007) measures a Mean Square Error (MSE) of the various elements between 13 and 19%. This is only the error for digitizing and converted map data. These numbers are a worst case scenario. The highest risk is within the chart compilation. The volume is most subjected to error.

Next to the difficulties considering the various rasters, the model also needs the length of the element. This is very dependent on the definition of the element. In the case of the delta this gives some problems. There is no clear definition for the delta element and therefore it is difficult to get the length of this element. The length of the delta is measured by looking at the slope of the area.

For the hydrodynamics there are some variables needed to calculate the diffusion coefficient. The marsh and flat elements are less vulnerable for these variables. Because of this, their risk on error is also lower. The channel and delta elements are more vulnerable to error. The assumptions made for A, H (at mtl), u and w_s are all used to calculate the diffusion coefficients of these two elements. These values depend on the initial volume, the area and available literature.

As mentioned earlier there was no literature available for the vegetation parameters. Because of this there were only assumptions made to set these parameters. The only available data was used by Knaapen et al. (2009) for the making of the model. These parameters had to be applied but it increases the risk on error.

The external changes are little subjected to error. There can be an error in measuring the areas and volumes for the reclaimed areas. However, these areas are mostly quite small. The error in these areas will be so small that they hardly have any influence. For the estimation of the global equilibrium coefficient Van Goor et al. (2003) suggest that the uncertainty associated with the sediment exchange parameters is approximately ± 50%.

6 Calibration Process

For calibration of the model various parameters can be used. Wang et al. (2007) mention that for the old model the global equilibrium concentration C_E and the transport coefficient n can be used for calibration. This still accounts for the newer version of the model.

A higher C_E represents a quicker infill of the estuary. For the East Solent C_E can be varied between 20-80 ppm. Rossington (2007) uses a value of 0.00003. This has to be converted to kg/m^3 by multiplying the value with the density of the sediment (2650 kg/m^3). This gives a value of 0.0795 kg/m^3. The value used for calibrating the model to the Langstone Harbour scenario was set to 0.08 kg/m^3, what is equal to 80 ppm. It is also very similar to the value for Rossington (2007).

The second parameter that can be used to calibrate the model is the transport coefficient *n*. Together with C_E it determines the order of magnitude of the morphological timescale (Wang et al., 2007). The default transport coefficient is set at 2. By adjusting *n* the morphological timescale can be changed. A lower product of $n \cdot C_E$ gives a lower morphological timescale, thus a quicker infill of the estuary.

Because the lack of data for the vegetation parameters the biomass and the production are also used to calibrate the model. The assumption was made that upper marsh species have a higher biomass. This assumption is made because the upper marsh species are bigger and taller than the pioneering species. This can be projected into a higher biomass. For the pioneering species the production normally is very high. However, because the *Spartina Anglica* suffers a high death rate, the production is set to 0. These parameters can be used as calibration parameters because they control the rate of growth of the marsh.

6.1 Problems

During the whole process several problems occurred. These problems will be discussed in this subsection. Next to these problems also other remarkable outcomes will be reviewed.

In order to get a good prediction of the reality the nodal tide cycle of 18.6 yr needs to be included. However, when the nodal tide was included in the model it crashed over and over again. Due to this it was necessary to run the model without the inclusion of the nodal tide. The most plausible reason for these problems is in the slope of the marsh area. The nodal tide will influence the water volume over the marsh area. Because the slope of the marsh element is very low (1:453) an increase in moving volume has a big effect. A steeper slope of the element causes the model to fulfil the entire run. The amplitude of the nodal tide is 3.8% of the tidal range, so 0.16 m. This small amplitude causes the entire marsh area to drown when the slope is very low. In reality there will be marsh cliffs. These cliffs will have a steep slope, which makes it possible to include the effect of the nodal tide.

The output of the marsh volume has a negative value. This implies that the water volume is turned into a dry volume of the marsh area. Normally it would be logical that this area will become zero. Reason for the negative value could be that the upper marsh species is defined with a negative value for the minimum depth of this species. This implies that the volume of the marsh is higher than it is predicted in the model. Another reason for this behaviour is that the volume is adapted with the rate of sea level rise. In the actual model with the new equilibrium the volume remains positive.

As mentioned in the chapter considering parameterisation there were some problems with the bathymetric data. For the 1956 and 1974 bathymetry the elevation data was only retrieved for the channel area. ArcGIS uses interpolation to form a raster. Because the data was only available for the channel element ArcGIS calculates a flat area that rises gradually. In reality there will be big differences within this element. This is counteracted by adding the marsh boundaries. However, in ArcGIS the contours have to be at an equal height. In reality the marsh edge will fluctuate. The eroded marsh areas are not taken into account. These areas will be higher than the areas were no marsh has grown. In reality the volume of the estuary will be lower than the measured volume. The problems with the bathymetry data have a big effect on the outcome of the model.

A problem that is mentioned before is the lack of data for the vegetation parameters. The parameters differ per area because of the tidal behaviour in the estuary. The only estimation that can be made is to divide the species in a type of marsh (i.e. pioneer marsh) and use the boundaries of this type (see Figure 2). The biomass and production parameters depend on the environment of the species. When an estuary can provide a lot of nutrition and favourable circumstances it can grow faster. However, this information lacks for most estuaries.

It is doubtful if the estuary can be assumed to be in equilibrium. Looked at a short timescale it can be assumed that it was in equilibrium during the 1950s. It did not suffer big changes since the beginning of the 20th century. However, when there is looked at a longer timescale it can be said that the estuary suffers a perturbation because of the introduction of *Spartina*.

7 Results

In this chapter the results for the model are presented. Firstly the Brier's Skill Score (BSS) will be explained. This Score is used to discuss the results of the model. After this the results of the model will be given. The results are divided in two scenarios. The first scenario deals with the model without changing the vegetation parameters (Scenario 1). The second scenario (Scenario 2) includes a change in the vegetation parameters. This is done to simulate the specific behaviour of the Langstone Harbour estuary. The error bars in the graphs are set at 25%. This is because the high uncertainties in the bathymetry data. The error of the delta element is set at 2% because the big area. The 1955 values are used for the initial volume and surface. Because of this there is no BSS or difference in percentage for these values. The focus will be on the volume parameter, because this is the most accurate output parameter. In Appendix G the original MATLAB graphs are given.

7.1 Brier's Skill Score

For the results two different scenarios were investigated. The first scenario is the model calibrated only with the same parameters used in the older version of the model (n and C_E). The vegetation parameters are not changed in this scenario. The second scenario is calibrated with the assumptions made for the vegetation parameters. The suitability of the model is calculated according the Brier's Skill Score. This score is given by:

$$BSS = 1 - \frac{\left[(Y - X)^2\right]}{\left[(B - X)^2\right]} \qquad [8]$$

Where;
B = a set of N initial observed depths;
X = a set of N observed final depths;
Y = a set of N predicted final depths.
The BSS compares the mean square difference between the forecast and observation with the mean square difference between baseline and observation. The score itself is the ratio of improvement in accuracy of the forecast over the baseline prediction, compared to the total possible improvement in accuracy. Perfect agreement gives a BSS of 1, where the baseline condition gives a score of 0. A negative value indicates that the predicted value is further away from the observed value than the baseline (Sutherland & Soulsby, 2003).

Disadvantage of the BSS is that the it is unbound at the lower limit. This means that it can be extremely sensitive to small changes when the denominator is low. Due to this large negative values can be obtained from models which predict a small change, when the measured change is very small (Sutherland & Soulsby, 2003).

The main output parameter is the volume of the elements. Due to this, the choice was made to carry on with the parameters that gave the best BSS for the volume. The baseline used is the initial value.

7.2 Marsh

The first element is the marsh. A slight increase in moving volume is noticeable in the beginning. This is due to sea level rise. For Scenario 2 the rise of moving volume is higher. The model with the production of the pioneering marsh causes a quicker decline of the moving volume because of growth.

The volume of the marsh increases due to the changes. This implies that the marsh disappears. There is also a big decrease of volume noticeable. This can be caused by two processes: a decrease in marsh surface or growth of the marsh. As can be seen in Appendix G the surface suffers an increase. Therefore the declining behaviour must be a result of a growing marsh element. The negative volume can be explained by the fact that the volume is calculated with the morphological timescale. In reality the volume would be zero.

Figure 20: Comparison moving volumes marsh

The error is hardly noticeable. This is because the percentages represent a very low number. This model gives a good prediction for the 1971 values, especially in Scenario 1. For the 2001 value it gives a very bad prediction in percentage. However, the BSS for Scenario 2 gives a very good value. The prediction gives a higher value for 1971 and a lower value in 2001.

Year	Observed V_{marsh} (m^3)	Predicted V_{marsh} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	300296	332187	10.62	0.999
2001 (1997 bathymetry)	97238	-1667209	-1814.57	-1.195

Table 14: Prediction Marsh Volume no vegetation change

Year	Observed V_{marsh} (m^3)	Predicted V_{marsh} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	300296	1052815	250.59	0.420
2001 (1997 bathymetry)	97238	-58093	-159.74	0.983

Table 15: Prediction Marsh volume with vegetation change

In Tables 14 and 15 the different results for the predictions are given. The high percentage difference number is caused by the low volume. Therefore the BSS gives a better representation for the prediction of the model. The average prediction for Scenario 1 is -0.098 and therefore worse than the baseline prediction. Main cause of this is the bad prediction for 2001. Scenario 2 gives a BSS score of 0.701. This scenario gives a very good prediction for the behaviour of the marsh.

7.3 Flat

The influence of the sea level rise is less noticeable because the higher volume of the flat.
In the end of the model runs the element is almost in equilibrium again. There is hardly any difference noticeable between both scenarios. Scenario 2 gives a slightly lower volume. Within the observed volume there is a big change from 1955 to 1974. The flat element is most influenced by the uncertainties in the raster. This leads to more uncertainty in the

observed volume. Figure 21 shows the behaviour of the model. The implemented changes do not influence the element very much. Remarkable is that the flat element is the only element were the graph for the surface shows exactly the same behaviour as the volume (see Appendix G).

Figure 21: Comparison moving volumes flat

The value of the error is quite high because the high volume of the flat element. For both values the difference with the observed volume is quite high. One of the reasons can be that the depth of the flat is too low in the GIS-raster. For 1974 both scenarios give a volume that is lower than the error. For the 2001 value the model runs are within the error. This is because of the decline in the observed volume instead of a better model prediction.

Year	Observed V_{flat} (m^3)	Predicted V_{flat} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	40655940	30177419	-25.77	-0.088
2001 (1997 bathymetry)	37993022	30372525	-20.06	-0.065

Table 16: Prediction Flat volume no vegetation change

Year	Observed V_{flat} (m^3)	Predicted V_{flat} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	40655940	30054002	-26.08	-0.113
2001 (1997 bathymetry)	37993022	30225714	-20.44	-0.106

Table 17: Prediction Flat volume with vegetation change

In Tables 16 and 17 the BSS and percentage scores are given of both scenarios. Scenario 1 gives slightly better results. In both cases the baseline gives a better prediction than the model does. For Scenario 1 the average BSS is -0.076, for Scenario 2 it is -0.110. The model does not give a good representation of the actual behaviour of the estuary. The comment has to be made that the GIS-raster has a big influence on these values. In reality the estuary will be less deep than is assumed in the GIS raster. The disappeared marsh area will be higher than the average depth of the flat. This is not taken into account in the GIS-raster. The 1997 raster also has depth points of the flat. For this raster the difference is lower.

7.4 Channel

The third element is the channel element. During the observation time the channel has been deepened once. In the graph of Figure 22 is shown that there is hardly any difference between both scenarios. The observed volume shows equal behaviour as the volume in the flat element. However, there was more information available for the channel element in the bathymetry. In the end of the model run the channel element is in equilibrium again.

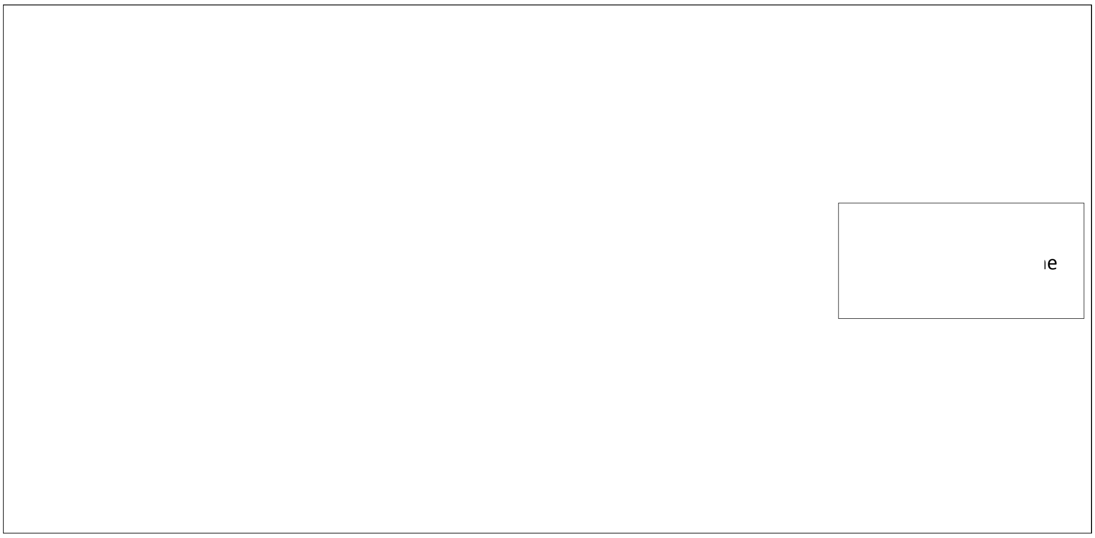

Figure 22: Comparison moving volumes channel

Just as in the Flat element the 1974 predictions are just outside the error bar of 25%. For the 1997 value both predictions are within the error bar. In this graph there is hardly any reaction visible on the changes made in the flat element. However, in Appendix G it is shown that the volume in Scenario 1 is affected by the changes in the flat. In the other scenario this is not the case. This implies that in this scenario the flat element only uses the marsh element to get in equilibrium again.

Year	Observed $V_{channel}$ (m^3)	Predicted $V_{channel}$ (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	14598178	10897223	-25.35	0.036
2001 (1997 bathymetry)	12554698	10812610	-13.88	-0.019

Table 18: Prediction Channel volume no vegetation change

Year	Observed $V_{channel}$ (m^3)	Predicted $V_{channel}$ (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	14598178	10890330	-25.40	0.032
2001 (1997 bathymetry)	12554698	10762937	-14.27	-0.078

Table 19: Prediction Channel volume with vegetation change

In Tables 18 and 19 the scores of the channel element are given. For this element it also counts that Scenario 2 gives a worse prediction than Scenario 1. The 1974 values give a worse prediction in percentage, but a better result with the BSS. For the scenario without change the average BSS is 0.009, for the other scenario it is -0.023.

7.5 Delta

The last element that is discussed is the delta. In Figure 23 there is a difference noticeable between both scenarios. Between 1987 and 1997 there was maintenance dredging, which causes the variations in the volume. The changes in 1976 and 1984 in the flat element decrease the delta volume. The deepening of the channel increases the delta volume because sediment is transported back to the channel.

Figure 23: Comparison moving volumes delta

The delta area was set very large. This will decrease the effect of any effects. Because this big area the error bars are set at 2%. Figure 23 shows that both scenarios give values within this error. The scenario with no vegetation change gives a higher volume than the scenario with vegetation change. The scenario with vegetation needs less sediment to get the estuary in equilibrium. The sediment needed by the flat and channel area is partly supplied by the erosion of the marsh.

Year	Observed V_{delta} (m^3)	Predicted V_{delta} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	80590502	81344145	0.94	-1.892
2001 (1997 bathymetry)	81670157	81644055	-0.03	0.998

Table 20: Prediction Delta volume no vegetation change

Year	Observed V_{delta} (m^3)	Predicted V_{delta} (m^3)	Difference (%)	BSS
1971 (1974 bathymetry)	80590502	81137773	0.68	-0.525
2001 (1997 bathymetry)	81670157	81316843	-0.43	0.692

Table 21: Prediction Delta volume with vegetation change

The predictions for the 1974 values are bad. For the percentage the differences are very low. This is caused by the big area of the delta. Therefore the BSS gives a more reliable result. In both cases the 1974 value give a bad prediction. This is compensated with the 1997 values. For both scenarios the BSS is very good, especially the scenario without vegetation change. The average BSS for the first scenario is -0.447, the second scenario gives an average BSS of 0.083.

7.6 Total estuary

The model is applied to the whole estuary. Therefore a comparison is made between the several elements and an average BSS is given for both the volume and the surface area.

Element	BSS Volume (no veg. change)	BSS Volume (veg. change)	BSS Surface (no veg. change)	BSS Surface (veg. change)
Marsh	-0.098	0.701	0.025	-0.034
Flat	-0.076	-0.110	-0.490	-1.101
Channel	0.009	-0.023	0.103	0.086
Delta	-0.447	0.083	-0.547	0.119
Total	-0.153	0.163	-0.227	-0.233

Table 22: BSS volume and surface both scenarios

Table 22 gives the average BSS for the volume and surface parameters and both scenarios. The flat element is the worst prediction. As discussed earlier this is possibly due to the bad data available for the flat element. The ASMITA prediction for the scenario with change gives a positive BSS for the total estuary. This number is still low so there are some expansions needed for the model. The recommendations are found in Chapter 9. The positive value for Scenario 2 is mostly caused by the good prediction of the marsh and the increase in the delta element.

A remarkable thing is that the surface of the marsh element reacts exactly the opposite of the volume. A better prediction of the volume leads to a worse prediction of the surface. The reaction of the marsh surface on the changes in the flat is also remarkable. According to the prediction a decline of the flat will cause a growth of salt marsh in the estuary. In reality a decline of flat will have a small, but declining effect on salt marsh.

The declining behaviour of the marsh area is a result of growth of the marsh and not of a decline of surface area. Thus the model has to much a focus on accretion of the marsh. In reality there will be more factors that cause the marsh to erode, like wave attacks.

8 Conclusion

In the Introduction chapter the objective of this research is mentioned. This objective has been translated into the following research question:

How are the parameters used in the ASMITA salt marsh model related to each other and how reliable are the model predictions compared with measured data?

In this chapter this research question will be answered with the help of the sub-research questions.

- *How do the vegetation parameters affect the ASMITA-salt marsh model?*

The vegetation parameters affect, logically, mostly the marsh element. The parameters can be divided into three categories: the boundaries, the rate of growth and the scaling coefficients. Every category has its own effect on the model. The amount of species determines how the model reacts. In reality marshes will be populated by more than one species.

The minimum and maximum depths determine the boundary of the marsh element. A deeper maximum depth will increase both moving volume and surface of the marsh area. A minimum depth closer to MHW will have the same effect. A lower maximum depth decreases the flat area. For the channel element it hardly has any low effect. This is also represented in Figure 9. In a case of more species the lowest maximum depth and the highest minimum depth are most important.

The biomass and production parameters determine the rate of growth of the model. A high production and biomass will increase the rate of growth of the marsh. A higher rate of growth will give a higher marsh, so it decreases the moving volume. In the sensitivity analysis this effect is overruled by the effect of sea level rise. However, in the validated model this effect is taken into account. Cause of this is the implementation of change due to human interference in this model run.

The scaling coefficients have little effect on the outcome. There are some changes but these changes are very low, which makes them hardly recognisable. A higher alpha gives a higher moving volume, while this accounts for a lower value of beta. This can also be caused by the sea level rise. Looking at Equation 26 in Appendix A it is noticeable that a higher value of beta will give a higher volume.

- *To which parameters is the model most sensitive?*

In order to answer this question the sensitivity of the model is divided up in the several elements. A model without a marsh element reacts less sensitively to diffusion between the elements. The same model shows the highest sensitivity for unconstrained sea level rise. In this analysis the delta element is neglected. This is done because there is no data available from the sensitivity analysis of this element.

The channel element is most sensitive to diffusive processes in which it is involved and the boundary parameters for the marsh. The channel element has the least deviation. The cause of this is that the element is located furthest away from the marsh element. The marsh element suffers the most changes and is the element that is adjusted most. The element located most far is in all cases least affected.

The flat element shows little less sensitivity than the channel element, but has a higher deviation. For the vegetation parameters it shows equal sensitivity as the channel element. For the rate of sea level rise it suffers a bigger change than the channel element. This can be explained that the sea level rise also increases the upper boundary of the flat element.

The marsh element is very sensitive to the boundary vegetation parameters. The equilibrium volume of the marsh shows a change of more than 1% when a change of 1% is induced. The other vegetation parameters give little sensitivity for the marsh element. The diffusion parameters have a considerable effect for the marsh element.

In general the moving volume is most affected by changes. The vegetation parameters have the most effect on the equilibrium volume of the marsh. These parameters have little effect on the other elements. For the channel element sea level rise has more effect on the volume. For the other two elements the rate of sea level rise affects mostly the surface.

- *What are the differences between the model predictions and the real behaviour of the salt marsh and if necessary how can the model give a better result?*

In the model there are few erosion factors taken into account for the marsh area. In reality there is a big decrease in marsh area. This is caused by massive dying of *Spartina Anglica*. The model cannot cope with this scenario. With some changes in the vegetation parameters it is possible to imitate reality. This shows a representative result for the moving volume of the marsh and for the other elements. For the surface this gives a result that is not representative.

The surface area of the marsh element shows growth of the marsh element. In reality this element declines and is the most important factor that causes the volume to decrease. In order to get a more realistic prediction the surface has to have a declining behaviour. In reality the nodal tide influences the marsh volume and surface. In these predictions the nodal tide is not taken into account. In order to get a more realistic prediction this tide needs to be included.

The comment has to be made that the measured behaviour of the marsh is quite awkward. The massive dying of *Spartina Anglica* occurs only on the Southern coast of the UK. How the model can be improved is mentioned in Chapter 9.

- *How do regional differences affect the vegetation parameters and the model prediction?*

The vegetation parameters differ per estuary. The depth of the marsh species depends on the tide. This information is widely available. Because these parameters determine the boundary of the marsh element they have a big impact on the prediction. This is already shown in the sensitivity analysis described in Chapter 2.

The parameters that control the rate of growth of the marsh also differ per estuary. The cause can be found in the environment. The marsh can only grow when enough nutrition is available. Therefore the production rate depends on the availability of nutrition in the estuary. More nutrition leads to a higher biomass. The amount of solar hours in the estuary will play a role in the photosynthesis process. A higher biomass and production parameter will give a lower wet volume of the marsh, but a higher surface.

The scaling coefficients for the enhanced settling rate will be quite equal in several estuaries. However, these coefficients cannot be measured. It is difficult to mention how these parameters will react in different estuaries. However, the scaling coefficients have little effect on the outcome of the model. Therefore it is not very important to measure these coefficients very accurately.

Concluding it can be said that the regional environment has a big influence on the model. Therefore parameters used in other estuaries cannot be used without any check. The tidal circumstances play an important role. When dividing an estuary in several marsh elements these circumstances also have to be taken into account.

9 Recommendations

During the research some problems occurred. In this chapter some recommendations are mentioned and the reason why it is seen as an improvement of the current model. The recommendations are ordered in priority.

1) The model needs to be tested in another estuary. Because of the dying of the *Spartina Anglica* a disturbance occurs in the estuary. It is recommended to set up a model with the Western Scheldt data. In this estuary the behaviour of the marshes is more natural and therefore it gives a more reliable comparison with the model.
2) Include a tool to implement the cliffs that form the edge between the marsh and flat. This gives a better representation of the exchange between these elements. Including these cliffs makes it also easier to implement the nodal tide in the model runs. The cliffs are most liable to erosion.
3) Design and implement a tool for the influence of wave attacks on the marsh. These wave attacks play an important role in the erosion of salt marsh. These wave attacks also improve the prediction for the reaction on sea level rise. This rise will also influence the wave attacks on the marshes. In the Langstone Harbour estuary these wave attacks are not very important, but in the Western Scheldt marshes this will have a significant influence on erosion.
4) Replace the marsh species with marsh types. For every marsh species is known in which marsh type it can be divided. There is a lack of literature for the parameters for most marsh species. By dividing species into marsh types it increases the amount of literature available. For every type the boundaries are known (see Figure 2). For the growth parameters it is easier to estimate a value when there is no literature available. A pioneering marsh will have a high production rate but a low biomass. For upper marsh the opposite occurs. In order to include the upper marsh area it will be better to define the marsh not at MHW but at MHWS.
5) Introducing a clear definition for the delta area. In this research the prediction for the delta was not very reliable because the delta area was taken too big. In the GIS data a difference was noticeable in the slope between the delta and the surrounding bed level. For the volume it is also important which water level is needed (MLW or MHW). The recommendation is made to define the delta as the water volume below MLW where a clear difference in slope is noticeable between the delta and the surrounding bed.

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Appendix A Equations and output of the ASMITA-model

In order to get a clear view of the calculations of ASMITA the most important equations are given in this Appendix. Firstly the equations for a single element (the channel) are discussed, which forms the base of the model. Afterwards the interaction between the elements and the accompanying extensions are shown. This chapter is mostly based on the information in Wright et al (2008). The information of the salt marsh model is retrieved from Knaapen et al. (2009). In order to understand these equations the definition of the output parameters are given first.

A.1 Definitions output parameters

The most important output of the ASMITA salt marsh model is divided into the surface and the volume of the elements. In this subsection the definition of the most important output parameters are given.

Moving Surface Volume: This parameter describes the water volume of the element that is affected by morphological changes as well as water level change.

Equilibrium Volume: This volume describes the wet volume the element will try to adjust towards. This value is mostly described as a function of the tidal prism, but it can also be described as a function of the hypsometry.

Fixed Surface Volume: This parameter represents a water volume below a certain water height. This height is the water level at the start of the simulation. This volume represents the morphological change in the element.

The Area parameters represent the area that belongs to the volume.

A.2 ASMITA equations

In ASMITA the assumption is made that the equilibrium volume can be described as a (linear) function of the tidal prism:

$$V_{ce} = f(P) \qquad [9]$$

In this formula, V_{ce} represents the equilibrium volume and P the tidal prism.

The second assumption made is that the ratio of the actual flow velocity to the equilibrium condition is proportional to the ratio of the equilibrium and actual volume. Therefore, the local equilibrium concentration can be written in terms of the actual and equilibrium volume: $c_{ce} = c_E \left(\frac{V_{ce}}{V} \right)^n$ [10]

Where,
C_{ce} = local equilibrium concentration [kg/m^3]
C_E = global equilibrium concentration [kg/m^3]
V_{ce} = local equilibrium volume [m^3]
V = actual volume[m^3]
N = concentration transport coefficient [-]

This formula leads to morphological change that is governed according

$$\frac{dV}{dt} = wS\left(c_{ce} - c\right) = \delta_{co}\left(c - c_E\right). \qquad [11]$$

In this formula w is the vertical exchange coefficient [m/s], S represents the surface of the element [m^2] and the part between the brackets gives the difference between the actual concentration and the equilibrium concentration.

When the sediment transport is considered to be purely diffusive the right hand side of the previous equation can be considered as the horizontal exchange between the, in this case, channel and the outside world and is represented by diffusion coefficient δ [m^3/s].

A combination of these equations and the extension with it for a term that gives the change of volume due to sea level rise and a tidal cycle gives the moving volume of the element:

$$\frac{dV_m}{dt} = \frac{w\delta C_E S}{\delta + wS}\left[\left(\frac{V_e(t)}{V_m(t)}\right)^n - 1\right] + \frac{d\zeta}{dt}\cdot S + i\omega\frac{\eta}{2}e^{i\omega t}\cdot S \qquad [12]$$

In this equation ζ stands for the vertical sea level movement [m], ω gives the angular frequency of the nodal tide [s^{-1}] and η gives the amplitude [m] for this tide.

The other important volume output is calculated according the following formulas:

$$V_e(t) = \alpha\cdot P = V_0 + \alpha\Delta P \qquad [13]$$

$$\Delta P = \eta\cdot e^{i\omega t}\cdot S \rightarrow$$
$$V_e(t) = \alpha\cdot P = V_0 + \alpha\cdot\eta\cdot e^{i\omega t}\cdot S \qquad [14]$$

As mentioned before, the equilibrium volume can be described as a function of P. α represents an empirical coefficient [-]. As seen from this equation, the equilibrium volume is also dependent on the amplitude of the nodal tide and the surface. Without the nodal tide the equilibrium volume is the initial volume (V_0).

The fixed volume is the volume that is only affected by morphological changes. When this is written as a function of V_m the next equation can be expressed:

$$V_f(t) = V_m(t) - \frac{d\zeta}{dt}\cdot S\cdot t - \frac{\eta}{2}e^{i\omega t}\cdot S \rightarrow$$
$$V_f(t) = \frac{w\delta C_E S}{\delta + wS}\left[\left(\frac{V_e(t)}{V_m(t)}\right)^n - 1\right]\cdot t \qquad [15]$$

The morphological timescale in this model is determined by n and c_e, as can be seen in equation 10. The horizontal exchange is related to the vertical change as a function of hydraulic depth and velocity. The horizontal exchange coefficient can be used to calibrate the model. This can be done with the help of the vertical exchange (w), the sediment transport exponent (n) that is based on the sediment characteristics and the global equilibrium concentration (c_E) that handles the morphological time-scale (Wang et al., 2007).

In order to allow a variable surface area, the model also accounts for this parameter. The equations for the moving and fixed surfaces are equal to those of the volume with the exception of the appearance of S. Instead of S the equation deal with a parameter R, represented as $R = kLm_b$ and expresses the change in area for a unit change in water level. K is the number of banks in the estuary [-], L the length of the element [m] and m_b the transverse bed slope [-] (slope is given as 1:m_b) between both elements.
The equilibrium surface is slightly different

$$S_e(t) = \hat{\alpha}\cdot\frac{P}{tr} = S_0 + \hat{\alpha}\cdot\frac{\Delta P}{tr} \qquad [16]$$

In this equation $\hat{\alpha}$ is also an empirical coefficient [-], but now for the surface area. The second part shows that the surface is also influenced by the tidal range (tr) [m].

A.3 Multi-element model

For more elements things get a little bit more difficult, due to the interaction between the elements. In order to calculate this interaction and the result for the volume of the element the ASMITA model turns into a matrix. In this case the volume change of an element is described as

$$\frac{dV_i}{dt} = \sum_j J_{i,j} + S_i \frac{d\zeta}{dt} + S_i \frac{d(tr)}{dt} \qquad [17]$$

Where i is the element and J represents the sediment flux between elements i and j [m^3/s]. This sediment flux is not only diffusive, but also is affected by advection. This leads to

$$J_{i,j} = q_{i,j} \cdot c_i - q_{j,i} \cdot c_j + D_{i,j} A_{i,j} \frac{\partial c}{\partial x} \qquad [18]$$

in which $q_{i,j}$ (m^3s^{-1}) is the residual discharge from element i to element j and vice versa ($q_{i,j} \neq q_{j,i}$). $D_{i,j}$ represents the diffusion coefficient [m^2s^{-1}] between both elements and A [m^2] is de cross-sectional area between the elements. This equation can be written in a form that is similar as equation 11.

$$J_{i,j} = q_{i,j} \cdot c_i - q_{j,i} \cdot c_j + \delta_{i,j} \cdot (c_i - c_j) \qquad [19]$$

This equation can be used to calculate the sediment flux between the elements in a matrix. The matrices that are used are:

- **W** for the vertical exchange coefficient;
- **S** for the surface areas;
- **I** represents the unit or identity matrix;
- **M** is the unit matrix with sign of n;
- **D** is the matrix that reflects the structure of the horizontal exchange between elements and the outside world;
- **Q** is the matrix that calculates the residual discharge.

With the help of all these matrices Wright et al (2008) come to the following expression of the volume change in time

$$\frac{d\underline{V}}{dt} = \mathbf{B}\underline{\gamma} - \underline{d} + \underline{S}\frac{d\zeta}{dt} + \underline{S}.\times \underline{trs}\frac{d(tr)}{dt} + \Delta\underline{V} \qquad [20]$$

Where

$$\mathbf{B} = c_E \mathbf{MWS}\left(\mathbf{I} - (\mathbf{D} + \mathbf{Q}^T + \mathbf{WS})^{-1}\mathbf{WS}\right)$$
$$\underline{d} = c_E \mathbf{MWS}(\mathbf{D} + \mathbf{Q}^T + \mathbf{WS})^{-1}\left(\underline{\delta_{ext}} + \underline{k_c} \cdot \underline{q_{ext}}\right) \qquad [21]$$

The underlined parameters represent vectors. The number of $\underline{\gamma}$ represents the volume ratios $\left(\frac{V_{ke}}{V_k}\right)^n$ and $.\times\underline{trs}$ refers to element by element multiplication by ½ with a sign that reflects whether the element is influenced by high or low water. δ_{ext} and q_{ext} are respectively the diffusion and discharge from the external environment, while $k_c = \frac{c_{ext}}{c_E}$.

The power T is the transport coefficient, normally represented as n.

The equilibrium volume remains equal to its single element equation. The only difference that occurs in the equilibrium volume is the appearance of vectors. The equation for the fixed volume turns into

$$\underline{V_f} = \underline{V_m} - \zeta \cdot \underline{S} - \underline{S}.\times \underline{trs} \cdot \delta tr\,. \qquad [22]$$

The last term represents the variation in the tidal range from its mean value.

A.4 Equations salt marsh

In order to expand the ASMITA model with a salt marsh element, this element has to be fit into the original equations. The base for this subsection is found in Knaapen et al (2009). In the marsh application equation 20 is expanded with $\mathbf{Bm}k_{\underline{bm}}\underline{V}$. This addition only applies to marsh areas and represents the additional settling due to enhanced settlement and trapping caused by vegetation growth. **Bm** represents the species biomass [kg/m], k_{bm} the rate of production of settled organic material per kg biomass [m^2/kg/yr] and $\underline{\Delta V}$ additional changes, for example dredging or land reclamation. The vertical exchange rate is also influenced by the vegetation and because of this it needs to be calculated every time step. The equations for the equilibrium and fixed surface remain the same.

In order to calculate the changes in the surface area some extra depth averaged variables need to be added:

$$\hat{q} = \frac{q}{h}; \qquad \hat{\delta} = \frac{\delta}{h}; \qquad \text{and } \hat{w} = \frac{w}{h} \qquad [23]$$

With these extra parameters the rate of change for the surface can be described as

$$\frac{d\underline{S}}{dt} = \mathbf{F}\underline{\sigma} - \underline{e} + \underline{R}\frac{d\zeta}{dt} + \underline{R}.\times \underline{trs}\frac{d(tr)}{dt} + \underline{\Delta S}; \qquad [24]$$

where **F** and e are equal as **B** and d, but now with the usage of the depth average variables in **Q**, **D**, δ_{ext} and **W**. Just like in the volume description, ΔS is an additional variable for other changes in the surface area. Knaapen et al (2009) also mention another way of calculating the equilibrium form, the equilibrium hypsometry relationships for channels and tidal flats.

The salt marsh application makes use of the equation proposed by Morris (2006) that describes the rate of change of the marsh surface elevation as.

$$\frac{dz}{dt} = (q_m + k_{bm}B_m)D = (q_m + k_{bm}B_m)\cdot(mhw - z) \qquad [25]$$

Where,
Z = elevation of the marsh [m]
Mhw = Mean High Water [m]
Morris (2006) defines *q* proportional to the rate of sediment loading and k_{bm} proportional to the efficiency of the vegetation as a sediment trap.
In order to take the effect of biology into account the settling velocity needs to be adjusted. This is done according,

$$w_s^{'} = w_s + \alpha\frac{B^{\beta}}{B_{\max}} \qquad [26]$$

In this formula
w_s equals the settling velocity,
α and β are coefficients that scale the relative biomass to give the appropriate variation in enhanced settling rate.

In the end the change of volume in time is described as

$$\frac{dV}{dt} = S\cdot w_s^{'}\cdot(c_e - c) - k_{bm}B_mV \qquad [27]$$

Appendix B Input parameters sensitivity analysis

Element parameters:

	Channel	Flat	Marsh
Initial Volume [m3]	1.079E+09	3.977E+08	2.346E+08
Initial Area [m2]	1.867E+08	9.850E+07	7.235E+07
Tidal Range [m]	5.84	5.84	5.84
Bed Slope [1:mb]	80	220	150
Element Length [m]	134000	134000	134000
Import Density [kg/m3]	0	0	0
Bulk Bed Density [kg/m3]	1350	1350	1350
Transport Coefficient [-]	2	2	2
Vertical Exchange [m/s]	0.003	0.003	0.003
Coefficient k(Vp) [-]	1	1	1
Coefficient k(Sp) [-]	1	1	1

Table 23: Element properties sensitivity analysis

System properties:
Global equilibrium concentration: 0.72 kg/m^3
Upstream element: 1
Sea level rise: 0.0018 m/yr

Exchange:
Diffusion Outside world→Channel: 15870 [m^3/s]
Diffusion Channel→Flat: 7300 [m^3/s]
Diffusion Flat→ Marsh: 200 [m^3/s]
No flow

Vegetation parameters:

	Specie 1	Specie 2
Minimum Depth [m -MHW]	0.25	0.15
Maximum Depth [m -MHW]	0.55	0.45
Maximum Biomass [kg/m2]	0.5	1.4
Species productivity [m2/kg/yr]	0.015	0.012

Table 24: Vegetation parameters sensitivity analysis

Alpha: 9.2e-5 m/s
Beta: 0.5

Appendix C Tables sensitivity analysis

Sensitivity Diffusion Channel → Outside World:

	Channel	Flat
Moving volume [m^3]	0.0074	0.0071
Equilibrium volume [m^3]	0.0080	0.0080
Moving surface[m^2]	0.0083	0.0079
Equilibrium surface [m^2]	0.0080	0.0080

Table 25: Sensitivity diffusion channel outside world without marsh

	Channel	Flat	Marsh
Moving volume [m^3]	0.1600	0.1569	0.0897
Equilibrium volume [m^3]	0.1643	0.1643	0.1646
Moving surface[m^2]	0.1670	0.1631	0.2280
Equilibrium surface [m^2]	0.1643	0.1643	0.1631

Table 26: sensitivity diffusion channel outside world one marsh species

Sensitivity Diffusion Flat → Channel:

	Channel	Flat
Moving volume [m^3]	0.0082	0.0092
Equilibrium volume [m^3]	0.0084	0.0084
Moving surface[m^2]	0.0081	0.0063
Equilibrium surface [m^2]	0.0084	0.0084

Table 27: sensitivity diffusion flat channel without marsh

	Channel	Flat	Marsh
Moving volume [m^3]	0.1578	0.1600	0.0653
Equilibrium volume [m^3]	0.1573	0.1573	0.1420
Moving surface[m^2]	0.1563	0.1404	0.2627
Equilibrium surface [m^2]	0.1573	0.1573	0.1526

Table 28: sensitivity diffusion flat channel one marsh species

Sensitivity Diffusion Marsh → Flat 200:

	Channel	Flat	Marsh
Moving volume [m^3]	0.0080	0.0098	0.1876
Equilibrium volume [m^3]	0.0067	0.0067	0.0151
Moving surface[m^2]	0.0057	0.0034	0.3590
Equilibrium surface [m^2]	0.0067	0.0067	0.0034

Table 29: sensitivity per parameter diffusion marsh --> flat 200

Sensitivity Diffusion Marsh → Flat 100:

	Channel	Flat	Marsh
Moving volume [m^3]	0.0490	0.0506	0.2228
Equilibrium volume [m^3]	0.0479	0.0479	0.0340
Moving surface[m^2]	0.0470	0.0421	0.1018
Equilibrium surface [m^2]	0.0479	0.0479	0.0421

Table 30: sensitivity per parameter diffusion marsh --> flat 200

Sensitivity Sea level rise

	Channel	Flat
Moving volume [m^3]	0.0673	0.0660
Equilibrium volume [m^3]	0.0675	0.0675
Moving surface[m^2]	0.0681	0.0695
Equilibrium surface [m^2]	0.0675	0.0675
Fixed volume [m^3]	0.0289	0.1026
Fixed surface [m^3]	0.0115	0.1483

Table 31: Sensitivity Sea level rise without marsh

	Channel	Flat	Marsh
Moving volume [m^3]	0.0411	0.0408	0.0310
Equilibrium volume [m^3]	0.0406	0.0406	0.0376
Moving surface[m^2]	0.0406	0.0390	0.1007
Equilibrium surface [m^2]	0.0406	0.0406	0.0390
Fixed volume [m^3]	0.0534	0.0780	0.0889
Fixed surface [m^3]	0.0338	0.1522	0.1507

Table 32: Sensitivity Sea level rise with one marsh species

	Channel	Flat	Marsh
Moving volume [m^3]	0.0419	0.0415	0.0327
Equilibrium volume [m^3]	0.0414	0.0414	0.0381
Moving surface[m^2]	0.0414	0.0396	0.0990
Equilibrium surface [m^2]	0.0414	0.0414	0.0396
Fixed volume [m^3]	0.0520	0.0952	0.0658
Fixed surface [m^3]	0.0417	0.1630	0.1083

Table 33: Sensitivity Sea level rise with two marsh species

Sensitivity Vegetation:

	Channel	Flat	Marsh
Moving volume [m^3]	0.0192	0.0197	0.5454
Equilibrium volume [m^3]	0.0190	0.0190	0.5727
Moving surface[m^2]	0.0188	0.0179	0.0052
Equilibrium surface [m^2]	0.0190	0.0190	0.0179

Table 34: Sensitivity Minimum depth one species

	Channel	Flat	Marsh
Moving volume [m^3]	0.2199	0.2240	0.5826
Equilibrium volume [m^3]	0.2181	0.2181	0.7033
Moving surface[m^2]	0.2160	0.2093	0.3216
Equilibrium surface [m^2]	0.2181	0.2181	0.2093

Table 35: Sensitivity lowest minimal depth two species

	Channel	Flat	Marsh
Moving volume [m^3]	0.0020	0.0020	0.0052
Equilibrium volume [m^3]	0.0019	0.0019	0.0063
Moving surface[m^2]	0.0019	0.0019	0.0028
Equilibrium surface [m^2]	0.0019	0.0019	0.0019

Table 36: Sensitivity highest minimal depth two species

	Channel	Flat	Marsh
Moving volume [m^3]	0.2599	0.2659	0.9387
Equilibrium volume [m^3]	0.2572	0.2572	1.1291
Moving surface[m^2]	0.2541	0.2435	0.3933
Equilibrium surface [m^2]	0.2572	0.2572	0.2435

Table 37: Sensitivity maximum depth one species

	Channel	Flat	Marsh
Moving volume [m^3]	0.0158	0.0162	0.0416
Equilibrium volume [m^3]	0.0157	0.0157	0.0510
Moving surface[m^2]	0.0156	0.0151	0.0231
Equilibrium surface [m^2]	0.0157	0.0157	0.0151

Table 38: Sensitivity lowest maximum depth two species

	Channel	Flat	Marsh
Moving volume [m^3]	0.1687	0.1719	0.4309
Equilibrium volume [m^3]	0.1673	0.1673	0.5200
Moving surface[m^2]	0.1656	0.1604	0.2443
Equilibrium surface [m^2]	0.1673	0.1673	0.1604

Table 39: Sensitivity highest maximum depth two species

	Channel	Flat	Marsh
Moving volume [m^3]	$1.8771e^{-11}$	$1.7254e^{-11}$	$4.1957e^{-12}$
Equilibrium volume [m^3]	$1.9323e^{-11}$	$1.9266e^{-11}$	$1.8087e^{-11}$
Moving surface[m^2]	$2.0099e^{-11}$	$1.8691e^{-11}$	$3.5698e^{-11}$
Equilibrium surface [m^2]	$2.0392e^{-11}$	$2.0455e^{-11}$	$9.9259e^{-12}$

Table 40: Sensitivity lowest biomass two species

	Channel	Flat	Marsh
Moving volume [m^3]	0.0126	0.0128	0.0330
Equilibrium volume [m^3]	0.0125	0.0125	0.0405
Moving surface[m^2]	0.0124	0.0120	0.0184
Equilibrium surface [m^2]	0.0125	0.0125	0.0120

Table 41: Sensitivity highest biomass two species

	Channel	Flat	Marsh
Moving volume [m^3]	0.0128	0.0131	0.0337
Equilibrium volume [m^3]	0.0127	0.0127	0.0413
Moving surface[m^2]	0.0126	0.0122	0.0187
Equilibrium surface [m^2]	0.0127	0.0127	0.0122

Table 42: Sensitivity lowest production two species

	Channel	Flat	Marsh
Moving volume [m^3]	$1.8258e^{-10}$	$1.8582e^{-10}$	$4.8303e^{-10}$
Equilibrium volume [m^3]	$1.8108e^{-10}$	$1.8108e^{-10}$	$5.7486e^{-10}$
Moving surface[m^2]	$1.7937e^{-10}$	$1.7402e^{-10}$	$2.6524e^{-10}$
Equilibrium surface [m^2]	$1.8108e^{-10}$	$1.8108e^{-10}$	$1.7402e^{-10}$

Table 43: Sensitivity Alpha coefficient two species

	Channel	Flat	Marsh
Moving volume [m^3]	$1.4533e^{-7}$	$1.4791e^{-7}$	$3.8582e^{-7}$
Equilibrium volume [m^3]	$1.4418e^{-7}$	$1.4418e^{-7}$	$4.5871e^{-7}$
Moving surface[m^2]	$1.4284e^{-7}$	$1.3854e^{-7}$	$2.1126e^{-7}$
Equilibrium surface [m^2]	$1.4418e^{-7}$	$1.4418e^{-7}$	$1.3854e^{-7}$

Table 44: Sensitivity Beta coefficient two species

Appendix D Vegetation Map Langstone Harbour 1994

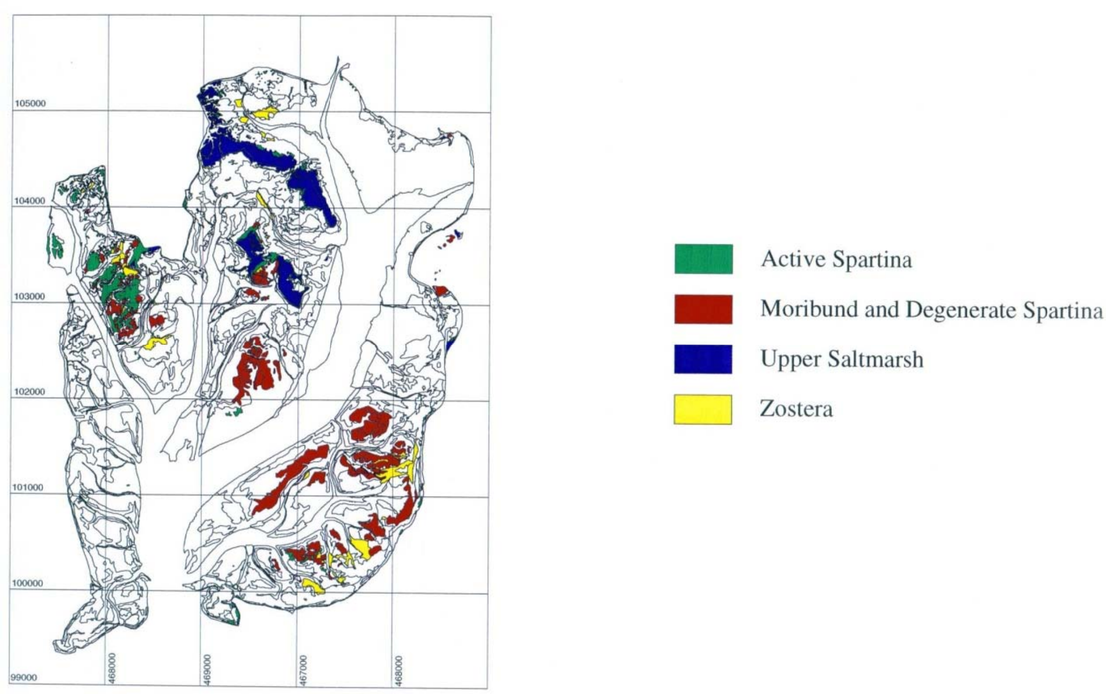

Figure 24: Vegetation Map 1994 (HR Wallingford, 1997)

Appendix E Tide Information

In this Appendix the tide information is given. The tidal levels were given in the original data. For 1955 the data had to be calculated to metres and in Newlyn Ordnance Date. Only the 1955 data was available for Langstone Harbour. For the other years the data was calculated using information of Portsmouth and Chichester Harbours. MHW and MLW were calculated as the mean between MHWS and MHWN and LHWS and LWHN respectively. MSL was calculated as the mean between MHW and MLW.

1955:

	Converted Data (m Newlyn)
MHWS	1.98
MHW	1.60
MHWN	1.22
MSL	0.32
MLWN	-0.85
MLW	-1.48
MLWS	-2.1

Table 45: Tide information 1955

1974:

	Converted Data (m Newlyn)
MHWS	2.10
MHW	1.74
MHWN	1.38
MSL	0.13
MLWN	-0.94
MLW	-1.49
MLWS	-2.04

Table 46: Tide information 1974

1997:

	Converted Data (m Newlyn)
MHWS	2.10
MHW	1.74
MHWN	1.38
MSL	0.19
MLWN	-0.88
MLW	-1.36
MLWS	-1.83

Table 47: Tide information 1997

Appendix F Parameter setting

	Delta	Channel	Flat	Marsh
Initial Volume [m3]	8.103E+07	1.083E+07	3.061E+07	1.288E+06
Initial Area [m2]	2.176E+07	5.390E+06	1.198E+07	2.730E+06
Tidal Range [m]	4.2	4.2	4.2	4.2
Bed Slope [1:mb]	190	64	215	453
Element Length [m]	10537	5278	35212	84826
Import Density [kg/m3]	0	0	0	0
Bulk Bed Density [kg/m3]	1350	1350	1350	1350
Transport Coefficient [-]	2	2	2	2
Vertical Exchange [m/s]	0.0003	0.0003	0.0003	0.0003
Coefficient k(Vp) [-]	1	1	1	1
Coefficient k(Sp) [-]	1	1	1	1

Table 48: Element properties validation run

System properties:
Global equilibrium concentration: 0.08 kg/m^3
Upstream element: 1
Sea level rise: 0.00137 m/yr

Exchange:
Diffusion Outside world→Delta: 15761 [m^3/s]
Diffusion Delta→Channel: 2175 [m^3/s]
Diffusion Channel→ Flat: 1061 [m^3/s]
Diffusion Flat → Marsh: 45 [m^3/s]
No flow

Vegetation parameters without change:

	Specie 1	Specie 2
Minimum Depth [m -MHW]	-0.05	-0.38
Maximum Depth [m -MHW]	0.38	0.05
Maximum Biomass [kg/m2]	0.5	1.4
Species productivity [m2/kg/yr]	0.015	0.012

Table 49: original vegetation parameters

Alpha: 9.2e-5 m/s
Beta: 0.5

Vegetation parameters with change:

	Specie 1	Specie 2
Minimum Depth [m -MHW]	-0.05	-0.38
Maximum Depth [m -MHW]	0.38	0.05
Maximum Biomass [kg/m2]	0.5	2.5
Species productivity [m2/kg/yr]	0	0.012

Table 50: changed vegetation parameters

Alpha: 9.2e-5 m/s
Beta: 0.5

Appendix G MATLAB plots

Scenario without vegetation change:

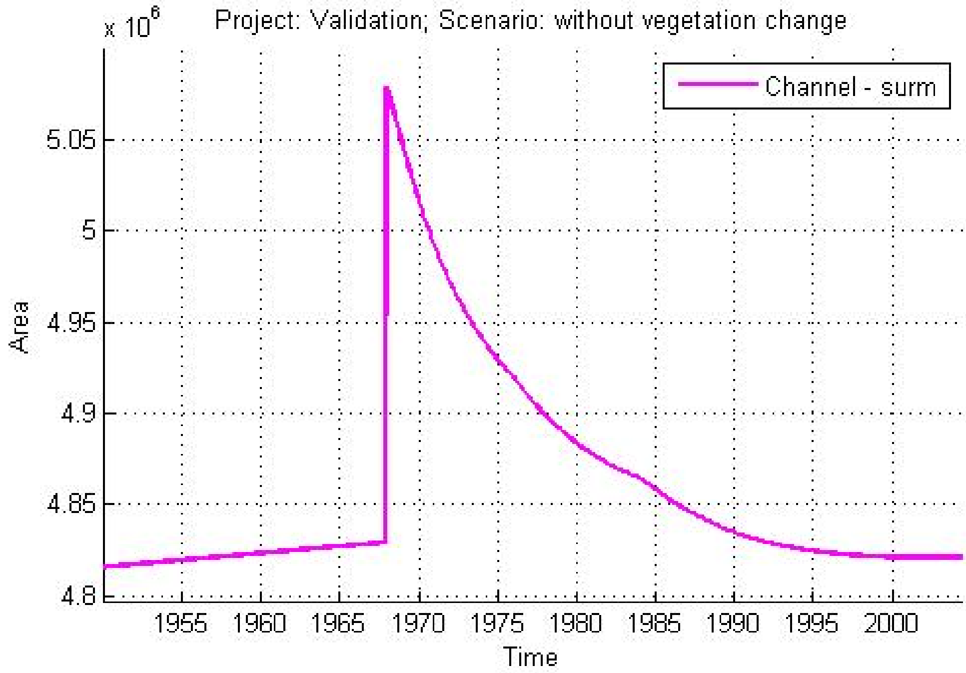

Figure 25: Moving surface Channel no vegetation change

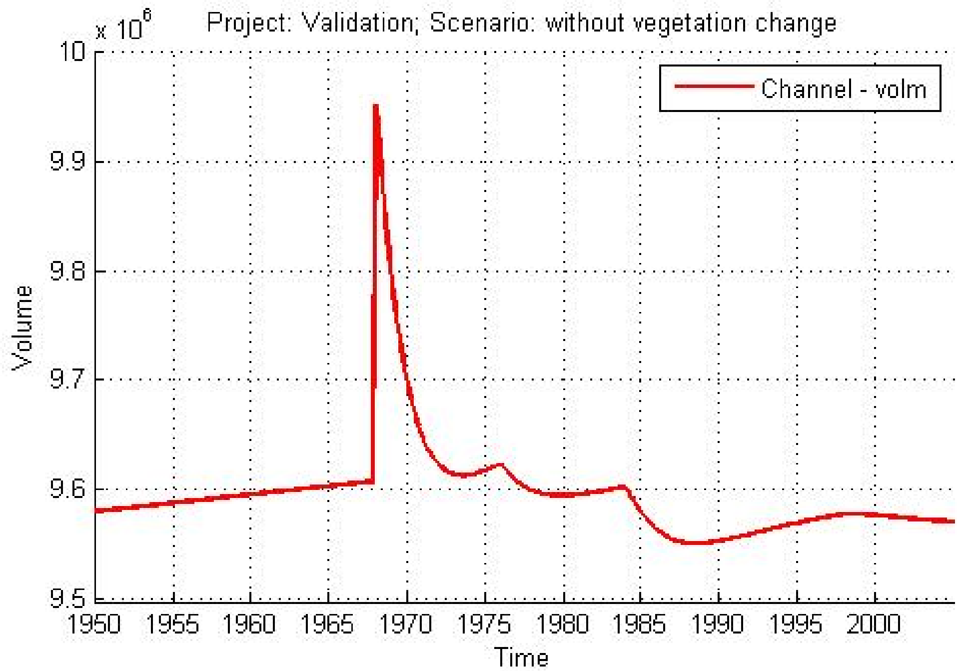

Figure 26: Moving volume channel no vegetation change

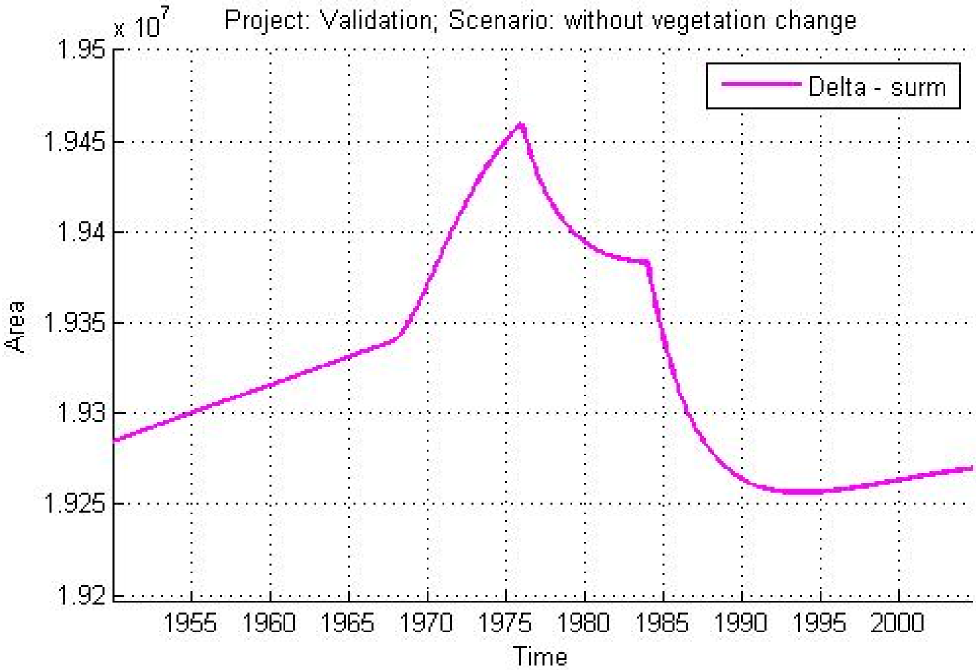

Figure 27: Moving surface delta no vegetation change

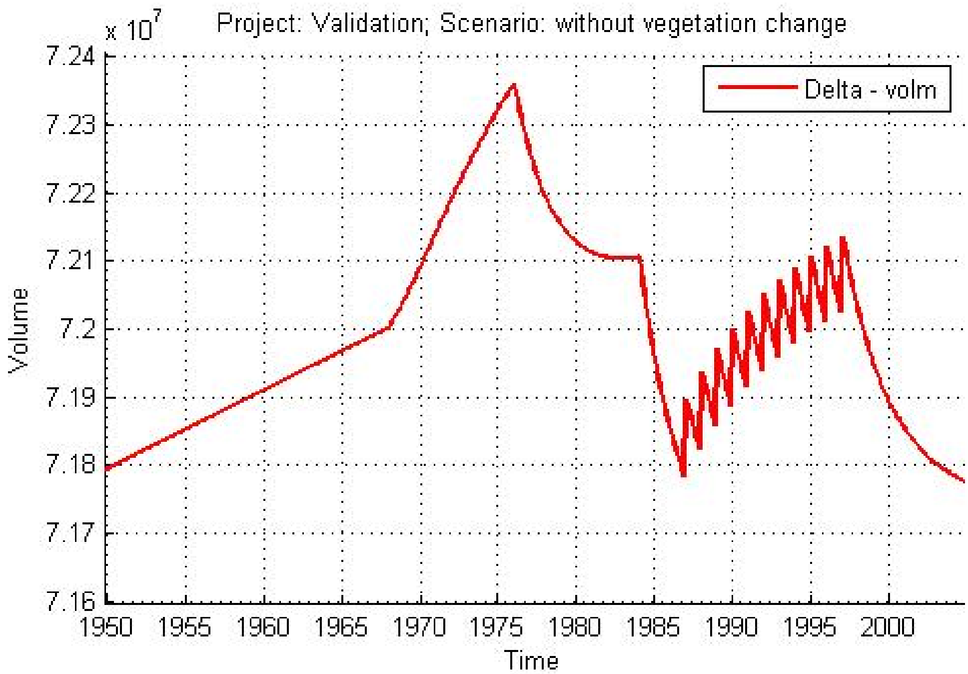

Figure 28: Moving volume delta no vegetation change

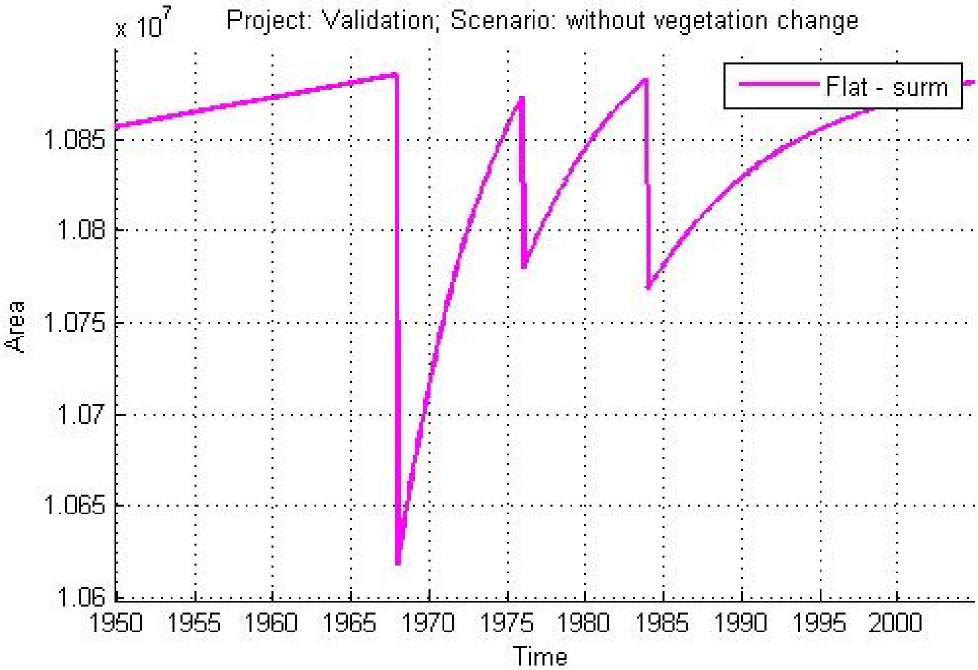

Figure 29: Moving surface flat no vegetation change

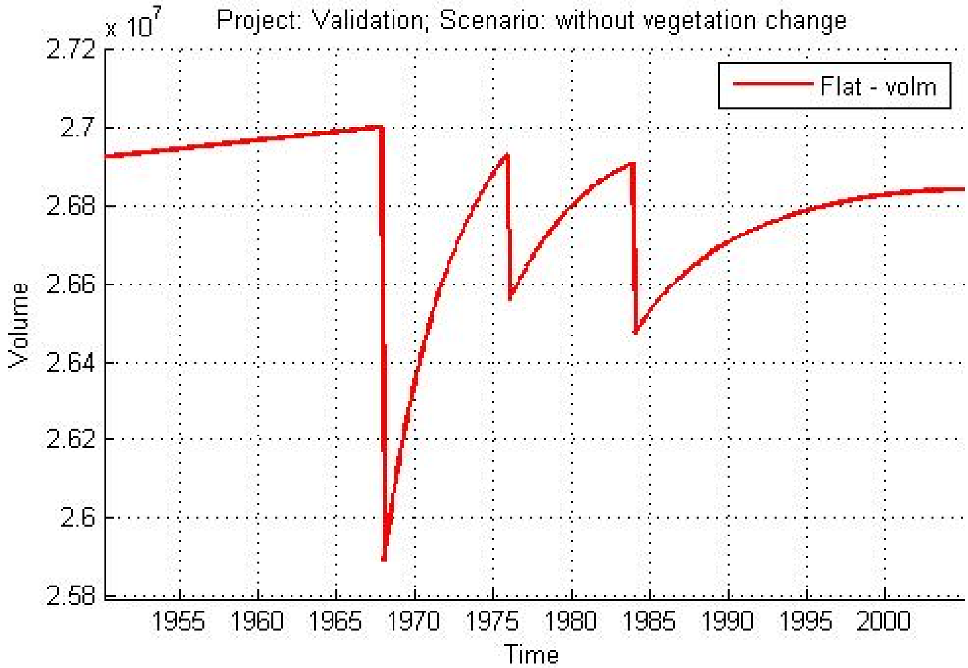

Figure 30: Moving volume flat no vegetation change

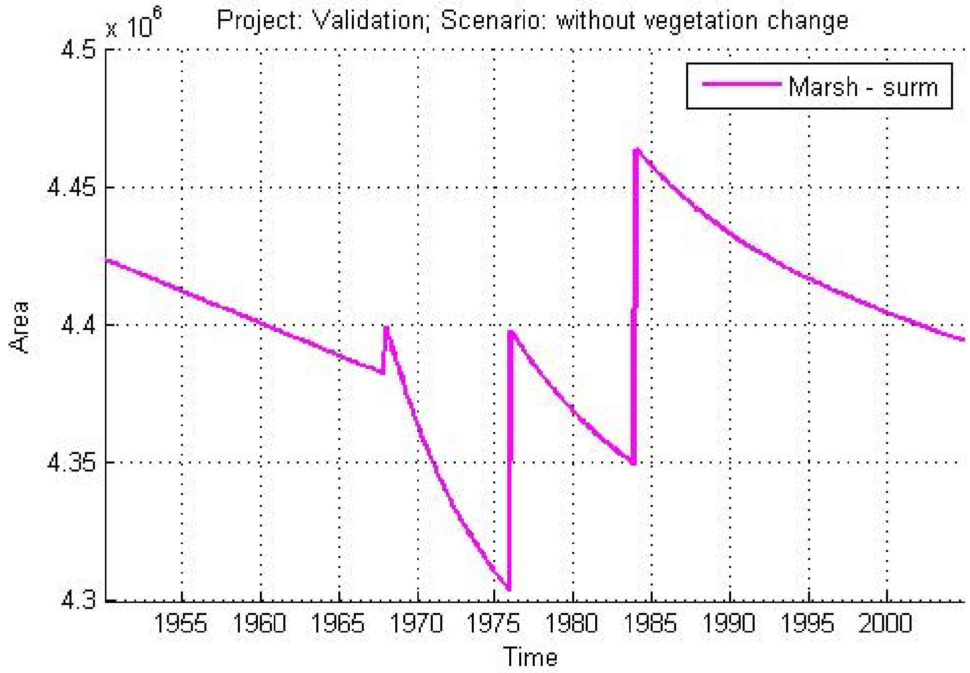

Figure 31: Moving surface marsh no vegetation change

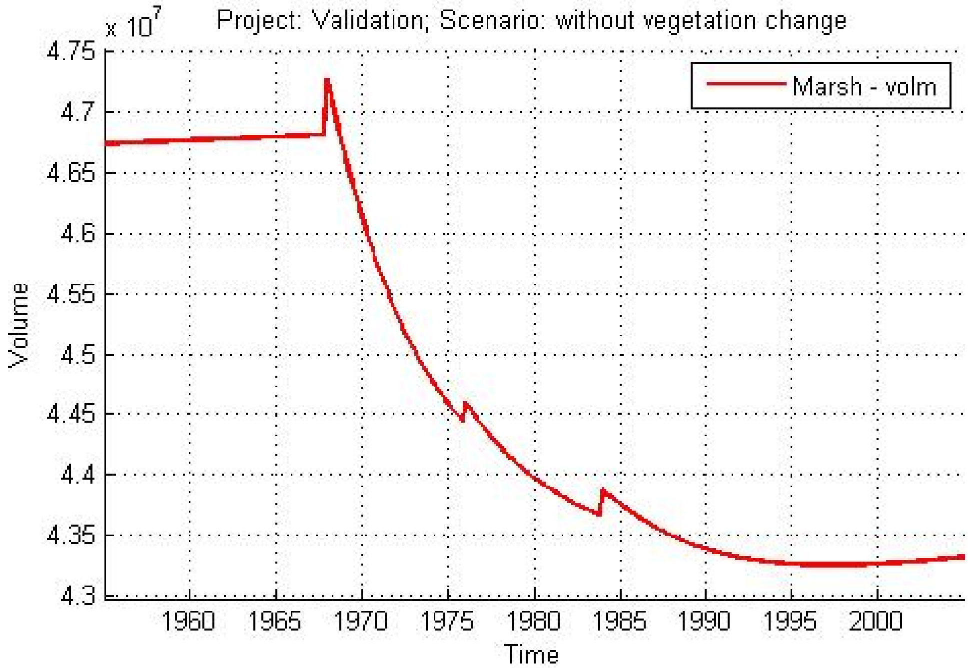

Figure 32: Moving volume marsh no vegetation change

With vegetation change:

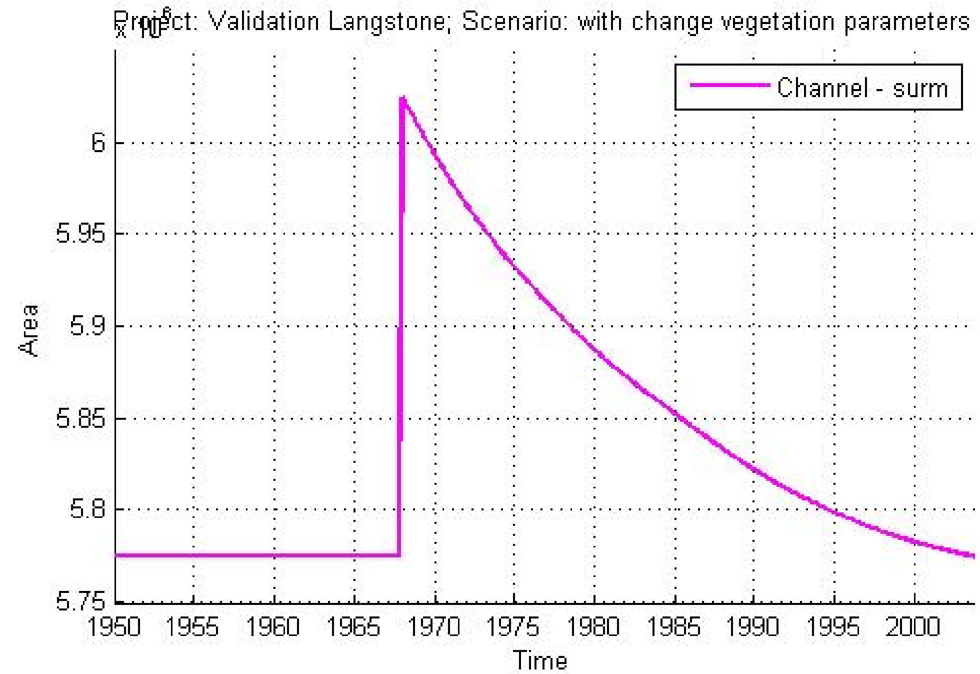

Figure 33: Moving surface channel with vegetation change

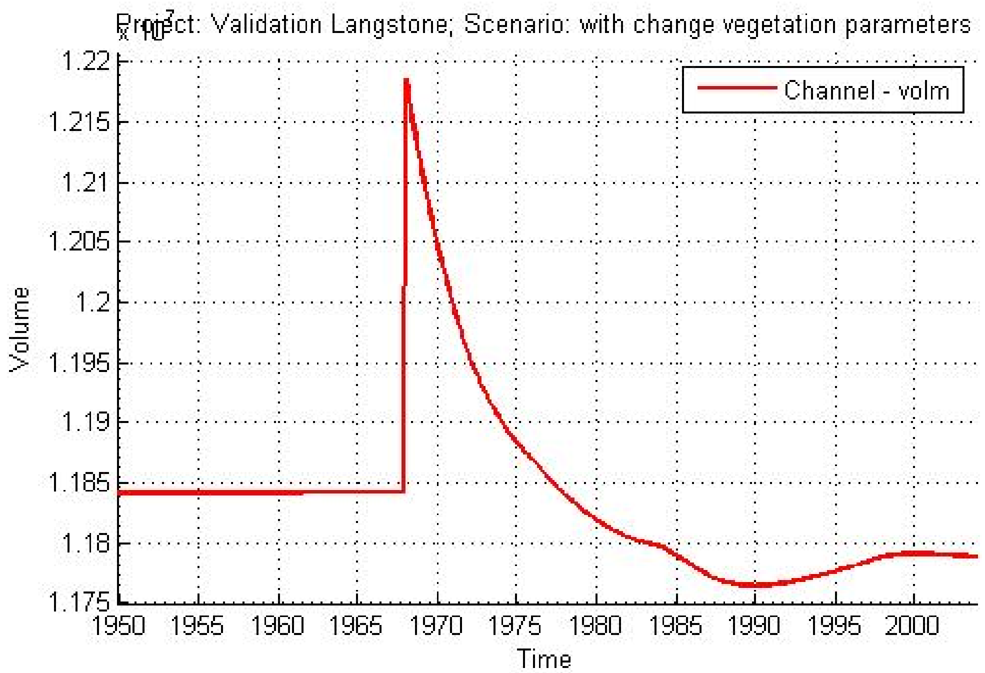

Figure 34: Moving volume channel with vegetation change

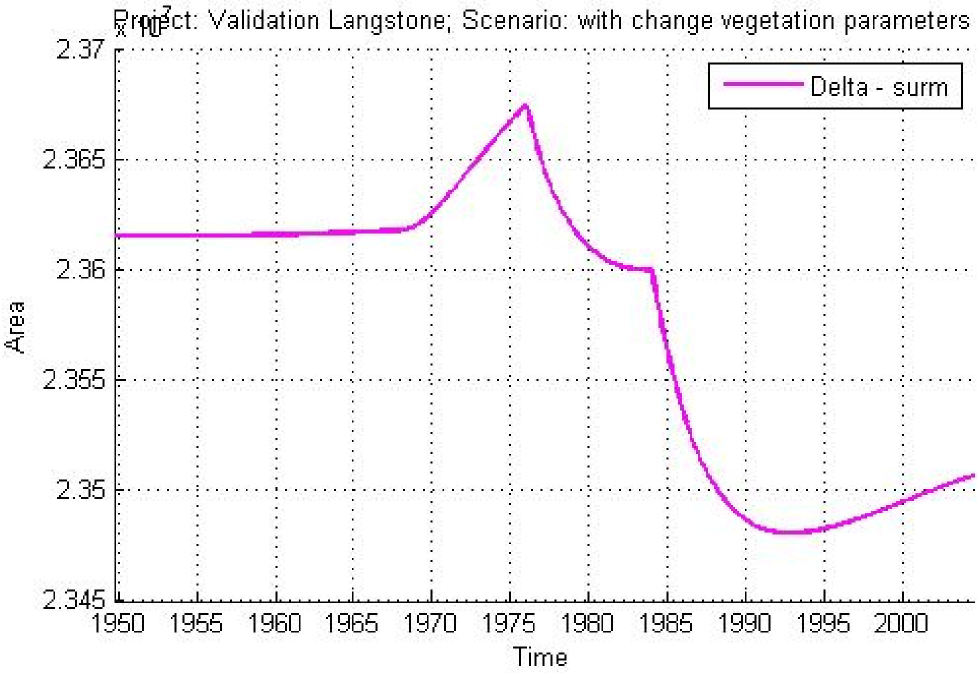

Figure 35: Moving surface delta with vegetation change

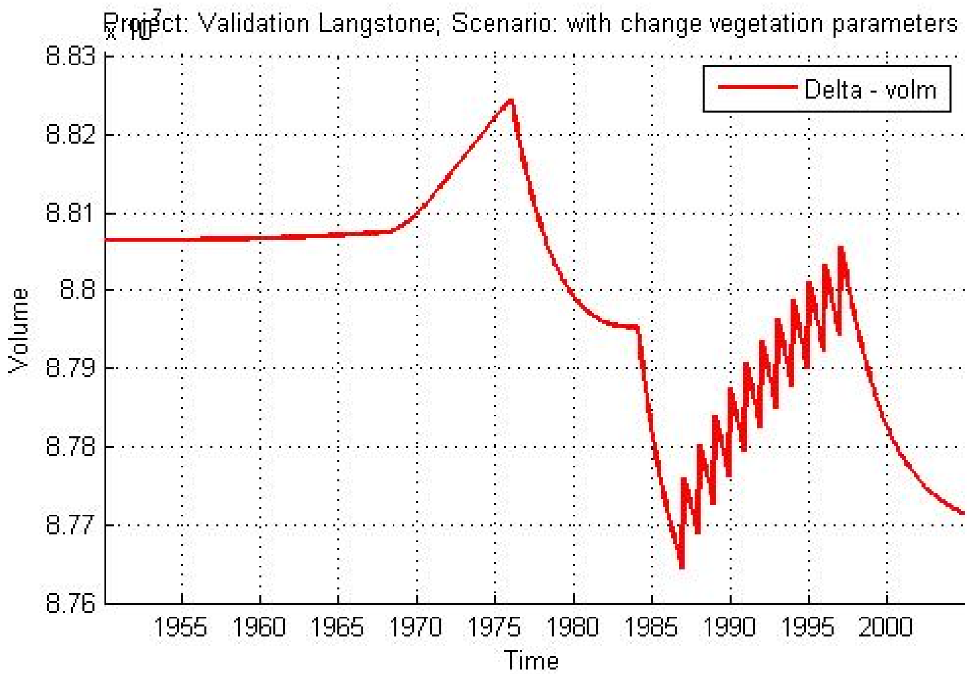

Figure 36: Moving volume delta with vegetation change

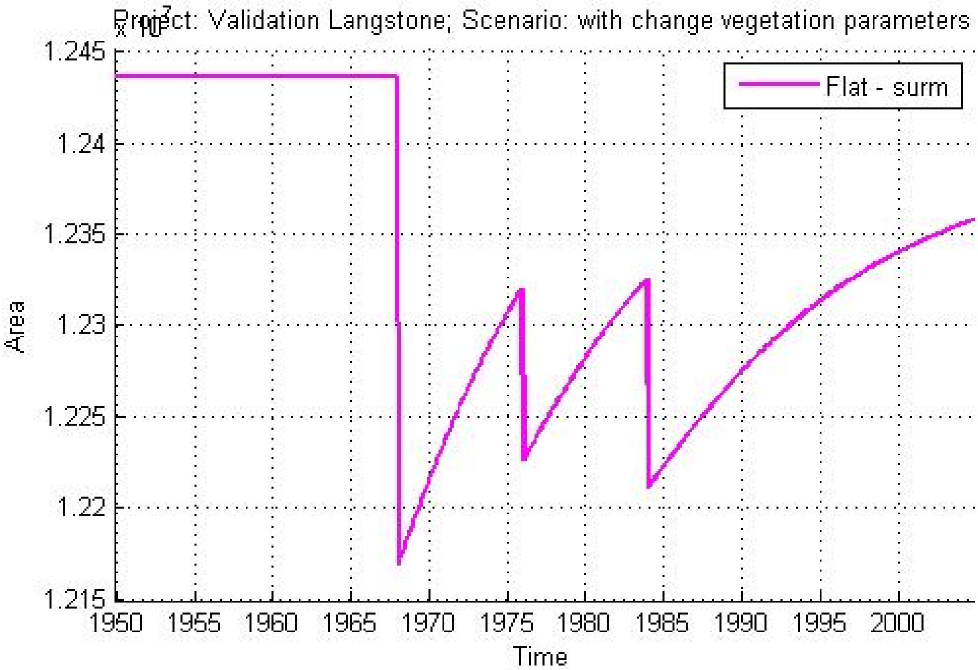

Figure 37: Moving surface flat with vegetation change

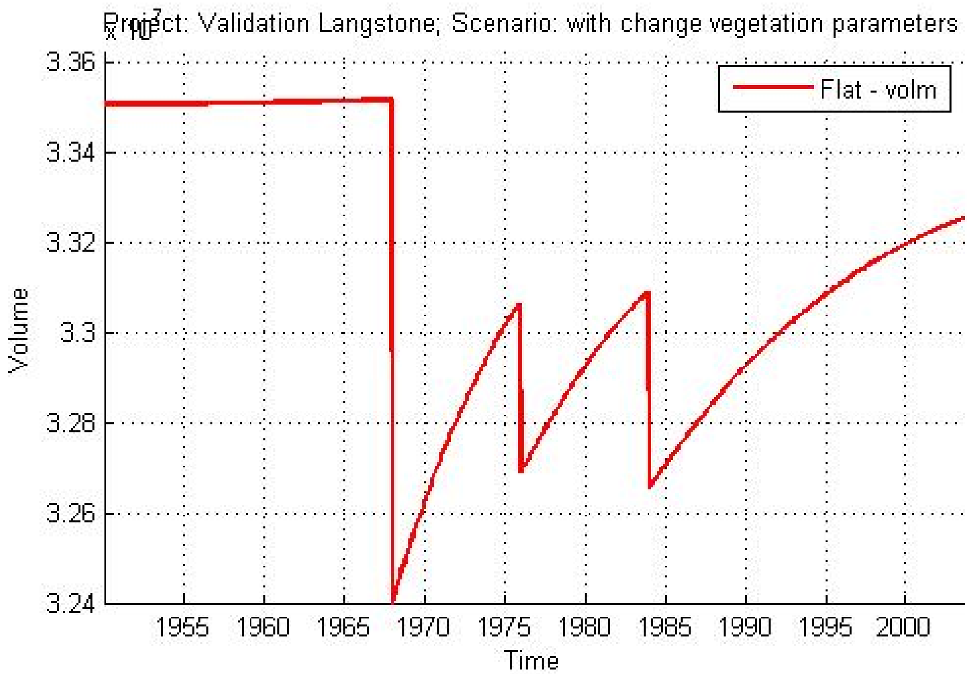

Figure 38: Moving volume flat with vegetation change

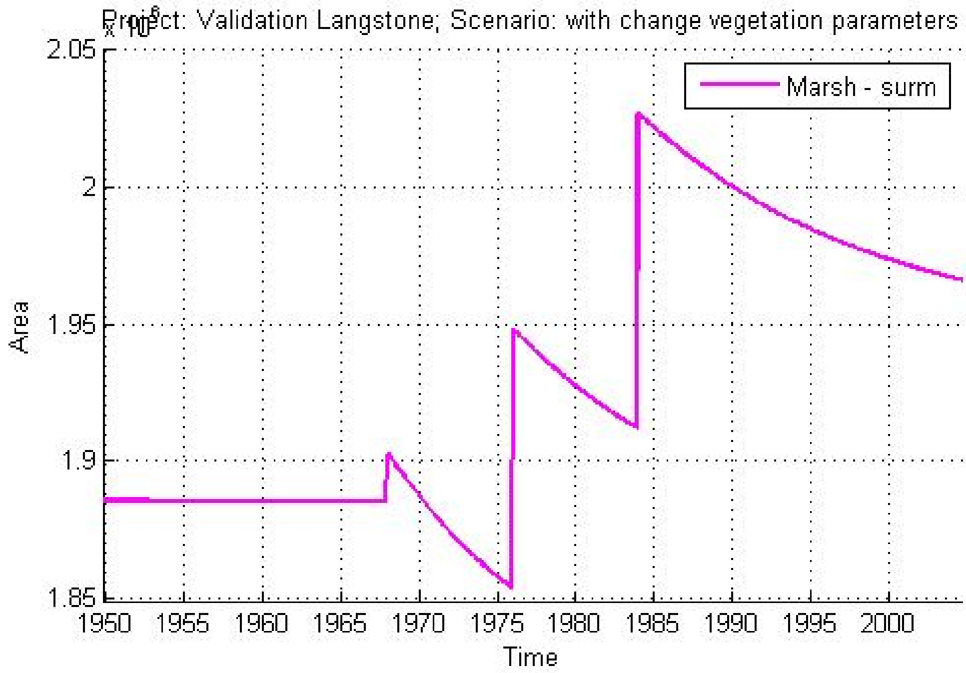

Figure 39: Moving surface marsh with vegetation change

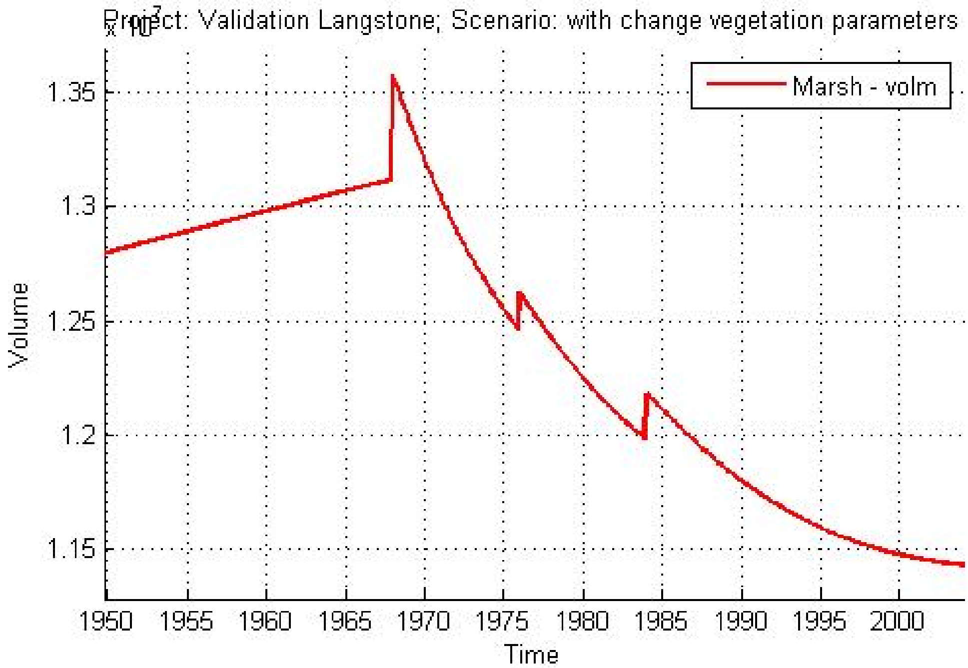

Figure 40: Moving volume marsh with vegetation change