Master of Science graduation thesis

Effect of changes in outer-delta bottom topographies on salt water intrusion

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Effect of changes in outer-delta bottom topographies on salt water intrusion

by

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Preface

With this thesis the final stage for the fulfilment of my Master of Science programme in Civil Engineering is completed. In this graduation thesis the effect of changes in the bottom topography of the outer delta of an estuary on the amount of salt water intrusion is analysed. I have studied these effects with a computational model which I have developed for the research in this study.

The research objective is developed based on input of the engineering and consultancy firm Grontmij. The determination of the scope of the research took some time and was a tough period. Large knowledge gaps are present about the effects of bottom topography adaptations in the outer delta. As a result it was difficult to define research questions which were possible to answer within the available time of a Master of Science graduation project and with the information and tools that were available. An effective period started after the research questions were defined to the end of the research period.

I would like to thank all the members of my graduation committee for their commitment and feedback during my thesis work. A special thanks to Sander van Rooij for his contribution in defining the scope of this thesis, the feedback on draft versions of this report and the help with analysing the simulation results. Additionally I would like to thank Erik Mosselman for his detailed comments on draft versions of this thesis report which were very useful.

Last, but not least, I would like to thank my family for providing me the possibility to study and for their support, and the colleagues of Grontmij for their interest in my research and for the pleasant time I had in the office.

Rick van Aarle
De Bilt, November 2015

Summary

Estuaries are characterised as a transitional zone between fresh river water and saline ocean water and therefore a brackish water environment is present. The location of this brackish water zone depends mainly on the river discharge and the tidal forcing. River discharges and water level patterns are changing in some estuaries, because of climate change and human interventions, which result in a changed salt water intrusion distance. In most deltas the salt water intrusion distance will increase because of climate change and human interventions. This could result in problems for agriculture and for drinking water production.

A few preventive measures are known to reduce salt water intrusion. These measures reduce salt water intrusion but have also other (negative) side effects or are difficult to implement in an estuary. Therefore other measures are developed. This study addresses the effect of adaptations in the bottom topography of an outer delta on the salt water intrusion distance. The idea of adaptations to reduce the intrusion of salt water into estuaries has been developed from the Balance Island concept which is a solution that could possibly decrease the salt water intrusion into estuaries. It was originally developed for application in the Haringvliet estuary in the Netherlands.

The possibilities and effectiveness of reducing salt water intrusion by changes in the bottom topography of an outer delta are largely unknown. A computational model of a bifurcated estuary is developed to study the possibilities and effectiveness of a changed outer-delta bottom topography for reducing salt water intrusion. The simulation model is based on the Hau estuary which is located in the Mekong delta in Vietnam and this estuary is used as a case study. Three kinds of outer-delta bottom topography adaptations are considered:

- The Seaward Extension variant. In this variant the coastline of the estuary is adapted and extended in offshore direction. The aim of this variant is to shift the estuarine character and the horizontal salinity profile in offshore direction.
- The Island variant. An arch shaped island is created in the outer delta of the estuary. The effect aimed at is a reduction of the tidal water level range and tidal prism in the estuary and the creation of a brackish water basin between the island and the coast to reduce the salt water intrusion distance.
- The Enlarged Estuary variant. Land area is removed in this variant to create a larger wet estuary area. The purpose of removing land area is to decrease the outflow of brackish water out of the estuary.

The Seaward Extension variant increased the salt water intrusion in the first four months of low discharge (dry season conditions). This increase occurred because of a decreased shallow water area at the outflow area of the estuary. As a result the estuary has less shallow area where brackish water could be retained during outflow. The brackish water leaves the estuary faster and this water is not able to flow back into the estuary during flood.
After four months a lower salt water intrusion is seen because of a more even (improved) discharge distribution between the two branches in the considered bifurcated estuary. As a result less water is circulated between the estuary branches which results in a reduced salt water intrusion after 4 months. The effect of less water circulation on the salt water intrusion distance gains relative importance when time continues. After 4 months this effect overrides the salinity increasing effect of the decreased retaining area for brackish water.

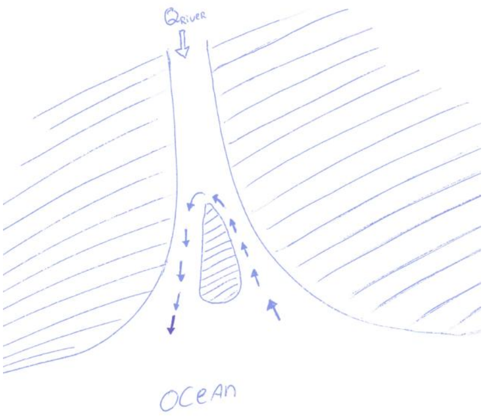

Figure 0.1: Water circulation in bifurcated estuaries

The Island variant increased the salt water intrusion in the first two months of the simulation with a low discharge (dry season conditions). This increase occurred because of increased salinity levels at the Southern side of the outer delta area between the island and the estuary's outflow. This increase in salinity in the outer delta area results in a larger salt water intrusion distance. A decrease in salinity occurred at the Northern side of the outer delta area between the island and the estuary's outflow. The increase and decrease in salinity occurred because of the cross-sectional flow area versus the brackish water outflow area ratio difference between the two sides. At the Northern side this ratio is

smaller than at the Southern side. The effect of increased salinity levels at the Southern side of the area has a larger influence on the salt water intrusion distance than the effect of decreased salinity levels at the Northern side of the area.
After two months a lower salt water intrusion distance occurs because of a more even (improved) discharge distribution between the two estuary branches and a reduction of the tidal range and the tidal prism in the estuary. Less water circulation and a smaller tidal prism result in a reduced salt water intrusion after 2 months and these effects gain relative importance when time continues. After 2 months the effect of less water circulation and a reduced tidal prism overrides the salinity increasing effect of the increased salinity in the area between the island and the estuary's outflow.

A decreased salt water intrusion occurred in the Enlarged Estuary variant. Because of the increase in wet estuary area in this variant more brackish water is held in the estuary system. As a result a larger brackish water zone develops which functions as a larger obstacle for salt water intrusion. The location of this brackish water zone is shifted in landward direction because of the increased wet estuary area. Because of the larger size of the brackish water zone the effectiveness of the brackish water zone as an obstacle for salt water intrusion is increased and as a result a smaller salt water intrusion distance occurs.

The most important aspects that influence the amount of salt water intrusion into estuaries because of a changed estuary bottom topography are:

- the effectiveness of the brackish water zone as an obstacle for salt water intrusion.
- the discharge distribution between the estuary branches in a bifurcated estuary.
- the magnitude of the tidal range and prism in the estuary.

The changed effectiveness of the brackish water zone as an obstacle for salt water intrusion has the largest influence when time periods of approximately up to 2 months with a low discharge (dry season) are considered. The effectiveness of the brackish water zone is increased when more brackish water is present in the estuary system and when the brackish water zone area is larger. A changed effectiveness of the brackish water zone is directly noticeable in the salt water intrusion distance and can be significant. The effect of a changed effectiveness of the brackish water zone as an obstacle for salt water intrusion can be seen as a short-term effect.
When longer time periods are considered the effect of a changed discharge distribution and a change in magnitude of the tidal range and prism becomes noticeable in the amount of salt water intrusion. An improved discharge distribution between estuary branches results in less water circulation in the estuary system and therefore in less salt water intrusion. A smaller tidal range and prism results in a smaller inflowing water volume during the rising period of the tide and results in less salt water intrusion. The effect of less water circulation and a smaller tidal range and prism on the salt water intrusion gains relative importance when the conditions of low discharge continues and can be seen as a long-term effect.

The Enlarged Estuary variant is the most effective variant considered in this study in reducing the salt water intrusion distance, which is quite remarkable. Adaptations based on enlarging the wet estuary area were not the most self-evident type of adaptations based on literature research. This variant showed salt water intrusion reductions of 5.6 (5 ppt salinity limit), 11.2 (2 ppt salinity limit) and 9.3 (0.5 ppt salinity limit) kilometre after 2 months and 17 (5 ppt salinity limit), 15.7 (2 ppt salinity limit) and 20 (0.5 ppt salinity limit) kilometre after 8 months with a constant low discharge (dry season conditions) in the studied Hau estuary.

The research gives insight into the importance of mechanisms that are influenced by a changed outer-delta bottom topography for the amount of salt water intrusion. The results of this research provide a better understanding of the effect of certain adaptations in the outer-delta bottom topography on the salt water intrusion distance. The consequences of bottom topography adaptations for the salt water intrusion distance are better predictable for other estuaries with this research. Furthermore information about bottom topography adaptations and their possible effectiveness for reducing salt water intrusion has been gained.

Content

List of figures

List of tables

1 Introduction

Delta regions are among the most densely populated areas in the world and are often dealing with climate change and land subsidence. A combination of these three aspects may result in possible delta problems like a decrease in habitable area, floods, retreat of the coastline, poor water quality and increases of salt water intrusion. It may result in problems for agriculture, nature and ecology in the delta region. The problems in deltas are often very complex because of the various causes of the problems, different (conflicting) problems in the delta and because of many involved stakeholders.

One of these problems is salt water intrusion which occurs in the estuary area of a delta. Estuaries are located in deltas and are semi-enclosed coastal water bodies where the influence of both the tide and the river are present. In estuaries a transition zone is present between the saline ocean water and the fresh river water. The location of this transition zone changes during the year depending mainly on the river discharge and the tidal forcing. Salt water intrusion during low discharge conditions can be a problem because it has negative effects on agricultural land use and on the possibilities for drinking water production. Because of various reasons the intrusion of salt water has increased in many estuaries in the last decades and this is expected to continue in the future.

A few preventive measures to reduce salt water intrusion are known. The most commonly discussed measures to reduce salt water intrusion are:

- increasing the upland discharge
- decreasing the depth of the estuary
- construction of a low submerged sill
- damming off the estuary

Other possible measures include a bubble screen which is developed in the 1960s (Uittenbogaard et al, 2015) to separate salt and fresh water and creating an island in the outer delta of an estuary to partly block the intrusion of saline seawater and to increase the travelling distance of this saline seawater into the estuary. This last mentioned possible measure, the so-called Balance Island, was originally developed as a solution for the salt water intrusion problems in the Haringvliet estuary in the Netherlands (van Rooij et al., 2012). This measure has not been implemented in the Netherlands because not enough technical information about the functioning of the concept was known, the effectiveness of the measure was uncertain and time was needed for the development of the concept. Furthermore another solution (moving water inlets for agriculture and drinking water upstream) was already decided on before the effectiveness of the Balance Island could be demonstrated. More information about the Balance Island concept is given in Appendix A.

One of the ideas of the Balance Island concept is the possibility of influencing the estuarine character of an estuary by the creation of islands in the outer delta. When the estuarine character can be influenced by creating an island it is expected that the salt water intrusion is also influenced (van Rooij et al., 2012). In this study not only the effect of creating an island is considered, but other adaptations of the bottom topography of the outer delta as well.

Three kinds of effects because of adaptations in the outer-delta bottom topography are analysed in this study. These effects are:

- Reducing the tidal water level range and tidal prism in the estuary and to create a brackish water basin.
- Shifting the estuarine character of the estuary in offshore direction.
- Decreasing the outflow of brackish water out of the estuary.

These effects are expected to influence the estuarine character of the estuary and to reduce the salt water intrusion distance.

1.1 Problem description

The possibilities and effectiveness of reducing salt water intrusion by changes in the bottom topography of the outer delta are largely unknown. This bottom topography could be changed: to reduce the tidal water level range and tidal prism and to create a brackish water basin, to shift the estuarine character of the estuary in offshore direction or to decrease the outflow of brackish water out of the estuary. However it is unknown what the effect of a changed outer-delta bottom topography and changed hydrodynamic conditions in the estuary is on salt water intrusion.

1.2 Objective and research questions

<u>Objective</u>
To study the possibilities and effectiveness of three kinds of adaptations of the outer-delta bottom topography for reducing salt water intrusion.

<u>Research questions</u>

- Which aspects are influencing the salt water intrusion because of adaptations of the bottom topography? And which aspect has the largest influence?
- Which kind of outer-delta bottom topography adaptation is most effective?
- To what extent can salt water intrusion be influenced by adaptations of the bottom topography of the outer delta?
- To what extent can the results of this study be used in other tide dominated estuaries?

1.3 Research approach

Adaptations of the bottom topography of the outer delta are developed based on influencing the estuarine character of an estuary. The considered adaptations of the outer delta are:

- The creation of an island to develop a brackish water zone and to reduce the tidal water level range and tidal prism.
- The extension of the coastline in offshore direction to shift the estuarine character of the estuary in offshore direction as well.
- The enlarging of the estuary by removing land area to decrease the outflow of brackish water out of the estuary.

These bottom topography adaptations of the outer delta and their effect on the salt water intrusion distance are simulated in a model.

For the model simulations the Hau estuary in Vietnam is used (see Figure 3.1). This estuary is used because a feasibility study of the Balance Island concept is ongoing in this area, an increased salt water intrusion can be seen in the last years and because large tidal elevations are present. The present situation of the estuary is simulated and used as a reference situation. The results of the reference simulation are compared with the three variant simulations which give insight into the effect of outer-delta bottom topography adaptations on the intrusion of salt water.

Simulations are carried out with the Delft3D program to study the effect of outer delta adaptations on salt water intrusion. The program has the possibility to simulate salt water intrusion in a complex hydrodynamic environment.

The Delft3D model is developed from depth measurement data and is calibrated and validated with water level and salinity measurements (see Appendix C). Three outer delta variants are simulated and compared with the reference situation. All model simulations have the same boundary and initial conditions.

The simulated period resembles the beginning of the dry season. The results of the simulations are analysed and described in Chapter 4. Based on these results the research questions of Section 1.2 are answered and recommendations are given.

1.4 Outline of this report

This thesis report is organised as follows. Chapter 2 concentrates on background information about estuaries and salt water intrusion into estuaries. The characteristics of estuaries are described as well as the relevant processes for the hydrodynamics in estuaries and the important processes and mechanism which influence the salt water intrusion distance. In Chapter 3 a description of the modelled estuary is given and the developed Delft3D model is described. The development process of the Delft3D model is described as well as the boundary and initial conditions of the model and the characteristics of the modelled Hau estuary. The developed outer-delta bottom topography variants are described in Chapter 4. After this description the simulation results of the variants are described, analysed and compared with the reference situation. The effects of the three variants are discussed in Chapter 5. In Chapter 6 the conclusions are given and the research questions are answered. Recommendations are given in Chapter 7.

2 Background

In this chapter general information about estuaries is given and the processes and mechanisms which are important for salt water intrusion into estuaries.

2.1 Estuaries in general

An estuary is a semi-enclosed coastal water body in open connection with the sea and with a measurable dilution of salinity due to freshwater inflows. It functions as a transition zone between a river and a sea and is as a consequence also a transition zone between salt water and fresh water environments. In an estuary both the influence of the tide and the influence of a river are present. Furthermore wave influences in an estuary are present as well. Depending on the relative effect of wave heights and the tidal range an estuary can be classified as a tide or wave dominated estuary. Estuaries are characterised by density differences between the saline sea water and the fresh river water.

Bifurcated systems in estuaries can be present which results in bifurcations and mergers of branches within the estuary. Tidal junctions in estuaries control the division of the discharge and sediment amounts over a tidal network

Importance of estuaries
A part of the estuary has a brackish water environment because of the transition between the fresh river water and the saline sea water. This environment is crucial as feeding and breeding ground for many life forms and as a result this estuarine environment is important for many species.
Estuaries are not only important for nature but also for humans. Estuaries are important as a source of food because of the fertile ground and as a transport route between the river and the sea. Because of these and other positive aspects of estuaries, estuaries are one of the most densely populated areas in the world. However estuaries are also fragile and often too densely populated. Climate change influences are present in estuaries which will result in a new equilibrium situation forced by nature. Humans can and will, to a certain extent, influence this equilibrium situation.

Important physical processes and aspects in estuaries
Hydrodynamic and morphodynamic processes, and the amount of salt water intrusion into estuaries depends on a combination of various processes and aspects. The most important processes and aspects are described in this section. These processes influence each other and most of them are depending for a part on the bottom topography of the estuary. In fluvial estuaries this topography changes over time which makes the description and modelling of the various processes in an estuary very complex.
Important processes and aspects in estuaries are:

- Intrusion of the tide
  Tidal waves intrude into estuaries. Tidal waves are considered as shallow water waves in estuaries because of their large wave length and as a consequence their wave speed is $c = \sqrt{gh}$. During the intrusion of the wave into the estuary, shoaling, amplification and dampening could occur. Because of the dependence of the wave speed on the water depth the tidal wave can become asymmetric when travelling upstream. Tidal asymmetry is one of the mechanisms which generates tidal residual sediment transport. The intrusion of the tide results in higher salinity levels in the estuary because of the intrusion of saline seawater. The intrusion of the tide also affects the shape of the estuary. Large tidal elevations in the estuary mouth results in a funnel shape of the delta.
- River discharge
  The river discharge has a large influence on the processes in the estuary especially in the upstream part of the estuary. It does not only influences the shape and the size of the

estuary but counteracts also the intrusion of the tide and of salt water. The combination of the river discharge and the tidal elevation mainly determines the shape and dimension of the estuary as well as the salt water and the tidal intrusion distance.

- Mixing
  The mixing of water in the estuary is an important factor for the salt water intrusion distance. The mixing of water in estuaries can be classified as well-mixed, partially-mixed or stratified. In Section 2.2.1 more information is given about the factors which influences the mixing in estuaries.
- Waves
  Waves generated by wind in open seas influence the hydrodynamics in the estuary mouth and in the outer delta. These kind of waves do not travel over large distances into estuaries.
- Longshore currents and longshore sediment transport
  Longshore currents and sediment transport along the coast can influence processes in the outer delta and in the mouth of estuaries. Depending on the situation the flow velocity pattern is influenced and spits, shoals or barriers could develop around estuary mouths.
- High water slack (HWS) and low water slack (LWS)
  During HWS and LWS fine sediments have the opportunity to settle because of small flow velocities. The occurrence and duration of this process is important for the morphodynamic development of the estuary. The maximum salt water intrusion occurs around HWS.
  When the flow velocity direction is changing from ebb to flood currents we speak of LWS and from flood to ebb of HWS.
- Flood and ebb dominant estuaries
  The occurrence of flood or ebb dominance in estuaries tells something about the duration and magnitude of flow velocities in ebb direction compared with the flood flow velocity magnitude and duration. Flood or ebb dominance of the estuary system has also influence on morphologic and hydrologic processes and on the intrusion of salt water.
  Estuaries which have a larger flood velocity magnitude (and a shorter duration) than the ebb velocity magnitude (and duration) during a tidal cycle are flood dominant. When the ebb velocity magnitude is larger than the flood magnitude velocity (and the duration shorter) during a tidal cycle the estuary is ebb dominant.
- Tidal prism
  The tidal prism is the total volume of water entering the estuary during the rising tide. As a result the tidal prism gives information about hydrodynamic processes in the estuary. A large tidal prism means a large inflow volume of water during the rising tide and will result in a larger salt water intrusion compared with a situation where a smaller tidal prism is present.
- Discharge distribution in bifurcated systems
  The geometry of the area around a bifurcation point has a large influence on the discharge distribution between side channels. Other aspects which influences the discharge distribution between the side channels are the depths and the roughness of the side channels. When only tidal discharges are considered the following two effects can be seen between branches in an estuary. First of all a net discharge transport from shallow channels into deeper channels will occur. Secondly a net discharge transport from channels with a lower bed roughness into channels with a larger bed roughness will occur. These effects are described in the PhD dissertation of Buschman (Buschman, 2011).

Classification of estuaries

Estuaries can be classified on a range of different aspects. The most general classification is the division between tide and wave dominated estuaries. Other classifications of estuaries are based on: the geometry, the type of mixing, the geology and the tidal range. The tidal range is often used because of the relative importance of the tidal range on processes in the estuary. Three classes can be classified based on the tidal range, which are: macro-tidal estuaries (tidal range larger than 4 metre), meso-tidal estuaries (tidal range between 2 and 4 metre) and micro-tidal estuaries (tidal range lower than 2 metre).

2.2 Salt water intrusion in estuaries

Estuaries are characterised as a transition zone between fresh river water and saline ocean water. This transition from fresh water to saline water can be very gradual or more abrupt. The transition zone or brackish water zone changes location during the season. The transition zone and their location depends on various processes which are described in this section. The amount of salt water intrusion into estuaries is difficult to predict because of the various involved processes and because of their complex 3 dimensional interaction.

2.2.1 Important processes

Important processes which influences the amount of salt water intrusion are: the tidal range and prism, the river discharge, the mixing in the estuary, the wind and the shape of the estuary.

The tidal range and prism
The tidal range influences how much volume of saline water enters the estuary during a tidal cycle. When large tidal ranges occur a large volume of water will enter the estuary (a large tidal prism) and salt water can intrude into the estuary over a certain distance.

The river discharge
The river discharge can be seen as a resistance mechanism against the intrusion of the tide and of salt water. The salinity level in an estuary is the result of the balance between two opposing fluxes, a tide driven saltwater flux that penetrates into the estuary and a freshwater river flux that pushes the salt water back. The river discharge has also a strong influence on the type of mixing that occurs in an estuary.

The mixing in the estuary
Important factors for the mixing process in estuaries are the density differences between fresh and salt water, the tidal range, the river discharge, the shape of the estuary and the water depth. If there are no tides and the estuary cross sections are regular the intrusion takes the shape of a wedge with stagnant seawater. The penetration of seawater into rivers with a fresh water flow is due to the 2.8% difference in density. Saline wedges are however very uncommon in estuaries during low discharge conditions (Savenije, 2012). They only occur in narrow estuaries, often man made or non alluvial estuaries, with a large river discharge and a small tidal range.

In estuaries where the mixing of salt and fresh water is minimal, the water column becomes stratified with a fresh water top layer and a salt water bottom layer. In stratified estuaries a salt wedge will develop.
Partially mixed estuaries are more influenced by tides than stratified estuaries and are typical of meso-tidal to macro-tidal environments. Tidal turbulences caused by the ebb and flood flows entering and exiting the estuary destroys the interface between the salt wedge and the overlying fresh water and will produce a more gradual vertical salinity gradient through the water column.
Well mixed estuaries are dominated by tidal activity. In well mixed estuaries there is hardly a vertical salinity gradient and as a result the salinity is uniform from surface to bottom. Most of the alluvial estuaries are of the well mixed or partially mixed type, especially in the dry season when low river discharges occur. (Savenije, 2012)

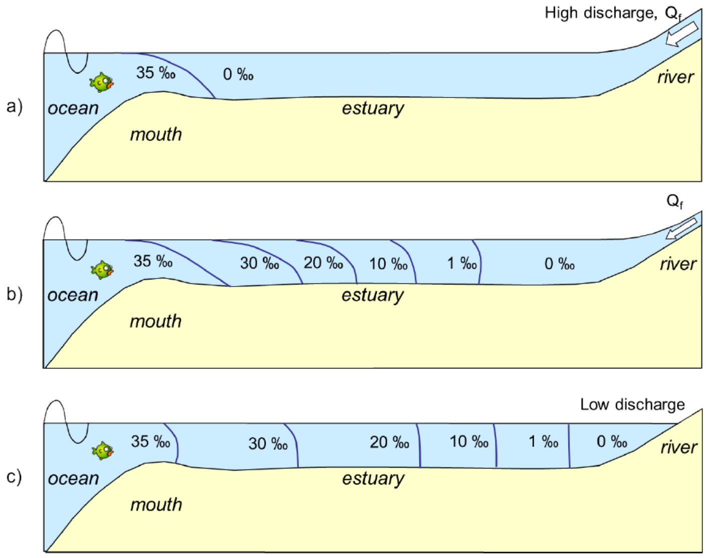

Figure 2.1: Vertical distribution of the salinity in stratified (a), partially mixed (b) and well mixed (c) estuaries (Savenije, 2012)

In a well mixed estuary the variation of the salinity along the longitudinal axis of the estuary is gradual. The shape of the curve along the longitudinal axis can differ depending on the situation at hand. The differences are in the salinity gradient decline in longitudinal direction and are very much linked to the geometry of the estuary.

The mixing process in an estuary is complex and depends largely on the characteristics of the estuary. Main driving forces for mixing are density differences, tide driven mixing, fresh water mixing and mixing because of wind forces.

An indication of the type of mixing that occurs can be given by the Estuarine Richardson number. This parameters considers the tidal energy per tidal period needed for mixing against buoyancy and on the other hand the kinetic energy per tidal period supplied by the tidal current for realizing mixing. If the Estuarine Richardson number is very large, we expect the estuary to be strongly stratified and the flow to be dominated by density currents. If the Estuarine Richardson number is very small, we expect the estuary to be well mixed, and we might be able to neglect density effects. An Estuarine Richardson number smaller than 0.08 indicates a well mixed situation, a number larger than 0.8 indicates a strongly stratified estuary and a number between 0.08 and 0.8 indicates an transition from a well mixed to a strongly stratified estuary. The Estuarine Richardson number can be calculated with equation 2.1.

$$Estuarine\ Richardson\ number = N_r = \frac{\Delta\rho}{\rho} * \frac{g*h*T*Q_f}{P_t*v_0^2} \qquad (2.1)$$

With:
Q_f = The fresh water discharge which enter the estuary [m^3/s]
T = The tidal period [s]
P_t = The volume of water entering the estuary between LWS and HWS [m^3]
ρ = The density [kg/m^3]
h = The water depth [m]
v_0 = The amplitude of the tidal flow velocity at the estuary mouth [m/s]

The wind
When wind blows for a longer period in a certain direction it could result in a water flow of the top water layer into that same direction. In order to balance that water flow an opposite flow occurs at the bottom of the estuary which results in a mixing mechanism. However for long time scales, which we are interested in for the salt water intrusion distance, wind effects play a minor role.

The shape of the estuary
The shape of the estuary influences the occurrence of turbulence. A large depth of the estuary is in favor of an increased salt water intrusion distance.

2.2.2 Important mechanisms in this study

Three important mechanisms in this study are explained in this section. These mechanisms come back in the following chapters of this report.

Brackish water zone
All estuaries have a transitional zone from saline to fresh water. This zone is a brackish water zone and can also be named a brackish water basin depending on the situation. This brackish water environment has influence on the intrusion of salt water. The importance of this mechanism is not yet known.

Water circulation in bifurcated estuaries
Water flows in and out the branches of a bifurcated estuary because of occurring tidal motions. A larger inflowing volume of water compared to the outflowing volume of water (or vice versa) could occur when a single branch is considered. The difference between these volumes is compensated by other branches and result in a larger outflowing volume compared to the inflowing volume in another branch (or vice versa). Because the difference in inflow and outflow volume of a single branch a certain volume of water is circulated in the estuary system. A certain volume of water flows into the estuary by one of the branches and leaves the estuary through another branch. The amount of circulation depends on the geometry around the bifurcation point and on the differences between the branches in for example the depth, roughness, length and width. Besides the influence on the water circulation volume the geometry also influences the fresh river discharge distribution between estuary branches. These distribution is important because the large importance of fresh river discharge on the salt water intrusion distance.

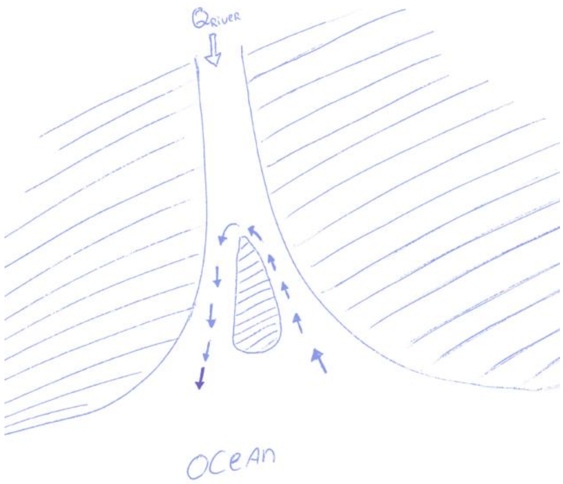

Figure 2.2: Water circulation in bifurcated estuaries

Tidal prism
The tidal prism is the total volume of water entering the estuary during the rising tide. When the tidal prism volume is influenced larger or smaller volumes of water will enter the estuary. When the tidal prism is larger more water will enter and leave the estuary during a tidal cycle. This affects the amount of salt water intrusion.

3 Model set-up

Information about the modelled estuary in this study is given in Section 3.1. In the rest of this chapter information is given about the developed computational model and about the implemented boundary and initial conditions in the model simulations for this estuary.

3.1 The Hau estuary

The Hau estuary in Vietnam is a bifurcated estuary and is modelled in this study. The Hau estuary has two branches in the most downstream part (the last 35 km) which are the Tran De branch and the Dinh An branch. The Hau estuary is located in the Mekong delta and is an alluvial tide dominated estuary. The Hau estuary has some characteristics of a funnel shaped estuary however the curvature of the funnel shape is not very large.
The Hau river is a branch of the Mekong river. Just before the Mekong river enters Vietnam it splits up into two branches, the Hau river (also known as the Bassac river) and the Tien river (also known as the Mekong river). Fifty kilometre downstream of the border between Cambodia and Vietnam there is a connecting river between the Hau and Tien river. This connecting river is the Vam Nao river and has a strong influence on the discharge distribution between the Hau and Tien river. In downstream direction after the Vam Nao connecting river there are no connections between the Hau and Tien river anymore.

Figure 3.1: Situation overview with the Hau estuary marked in gray

The width of the Tran De branch is in the order of 1.5 kilometre and the depth in the order of 8 metre. The Dinh An branch has a width in the order of 2.0 kilometre and a depth of 10 metre.

The river discharge of the Hau river flows into the South China Sea and from this sea the tide intrudes into the estuary. The tide in the South China Sea is semidiurnal and can have amplitudes of up to 3 to 3.5 metre (Bucx and Minh, 2010; Nguyen, Savenije, Pham and Tang, 2008). The tide intrudes into the Hau estuary and in some periods there will also be salt water intrusion into the estuary up to Can Tho (80 kilometre from the estuary mouth). The coastal zone of the Vietnam coast has a depth of 8 metre in the first 10 kilometres from the coastline to the South China Sea. In offshore direction, after this 10 kilometre, a steep slope to depths of 20 metres and more is present.
The tidal movements in the South China Sea are very complex. The main reason for this is the complex geographical configuration of the area. The South China Sea can be seen as a large basin with small and large connections to the Pacific Ocean, Indian Ocean and other basins and seas. Besides the influence of two different oceans and their tidal signal the complexity of the signal is enlarged because of the bottom topography of the South China Sea. Deep sea regions and shallow parts can be found in the area. As a result amphidromic systems are present in this area which increases the complexity of the tidal signal of the South China Sea even more (Akdag, 1996).

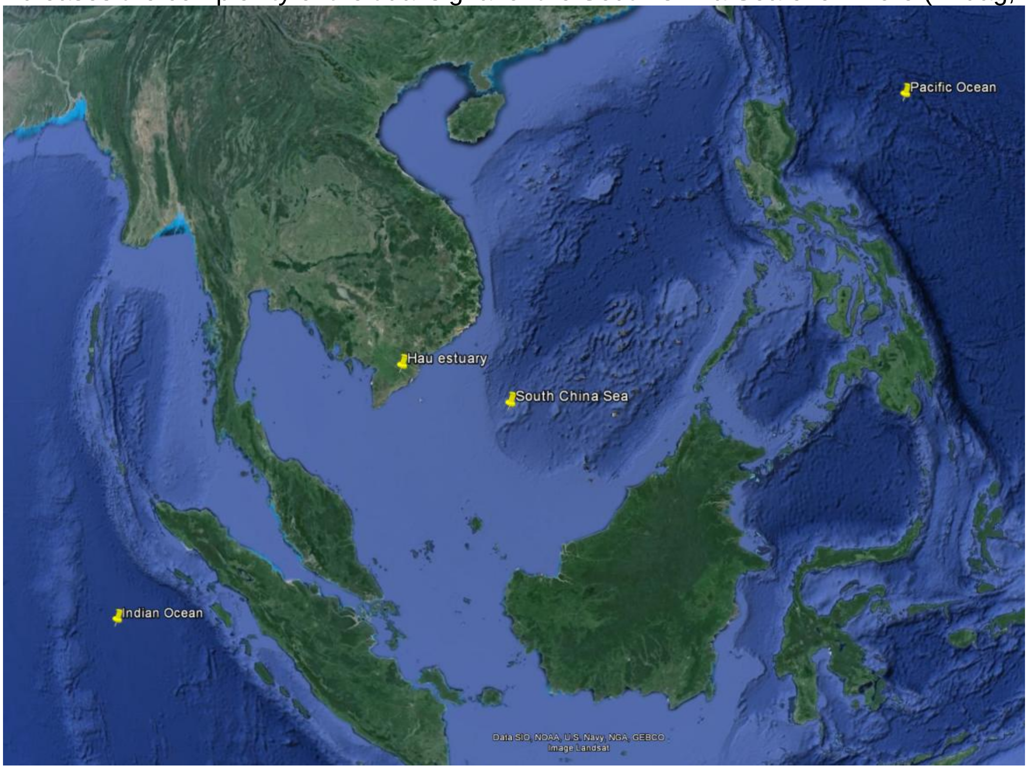

Figure 3.2: Geographical situation South China Sea

3.2 The Delft3D model

Information about the developed Delft3D model and the used input and boundary conditions are given in this section.

3.2.1 Model set-up

The Delft3D model is developed during this MSc study and is established from depth measurements of governmental projects in Vietnam between 2009 and 2011. These measurement data are obtained with the help of a PhD student of Delft University of Technology.

The model has a rectangular grid with a fine resolution in the river area and around the river mouth and a coarser resolution in the area of the South China Sea. The fine grid cells have an area of 500 m^2 and the coarser cells have grid areas of 1,000 m^2 to 1,500 m^2. The model has 16,000 grid cells in total. The Hau river in the model has a length of 160 kilometre from the river mouth to the model boundary in upstream direction. The outer delta in the coastal zone has a rectangular shape with a length of 55 km in offshore direction and a width of 90 km in the direction parallel to the coastline as can be seen in Figure 3.3 and Figure 3.4.

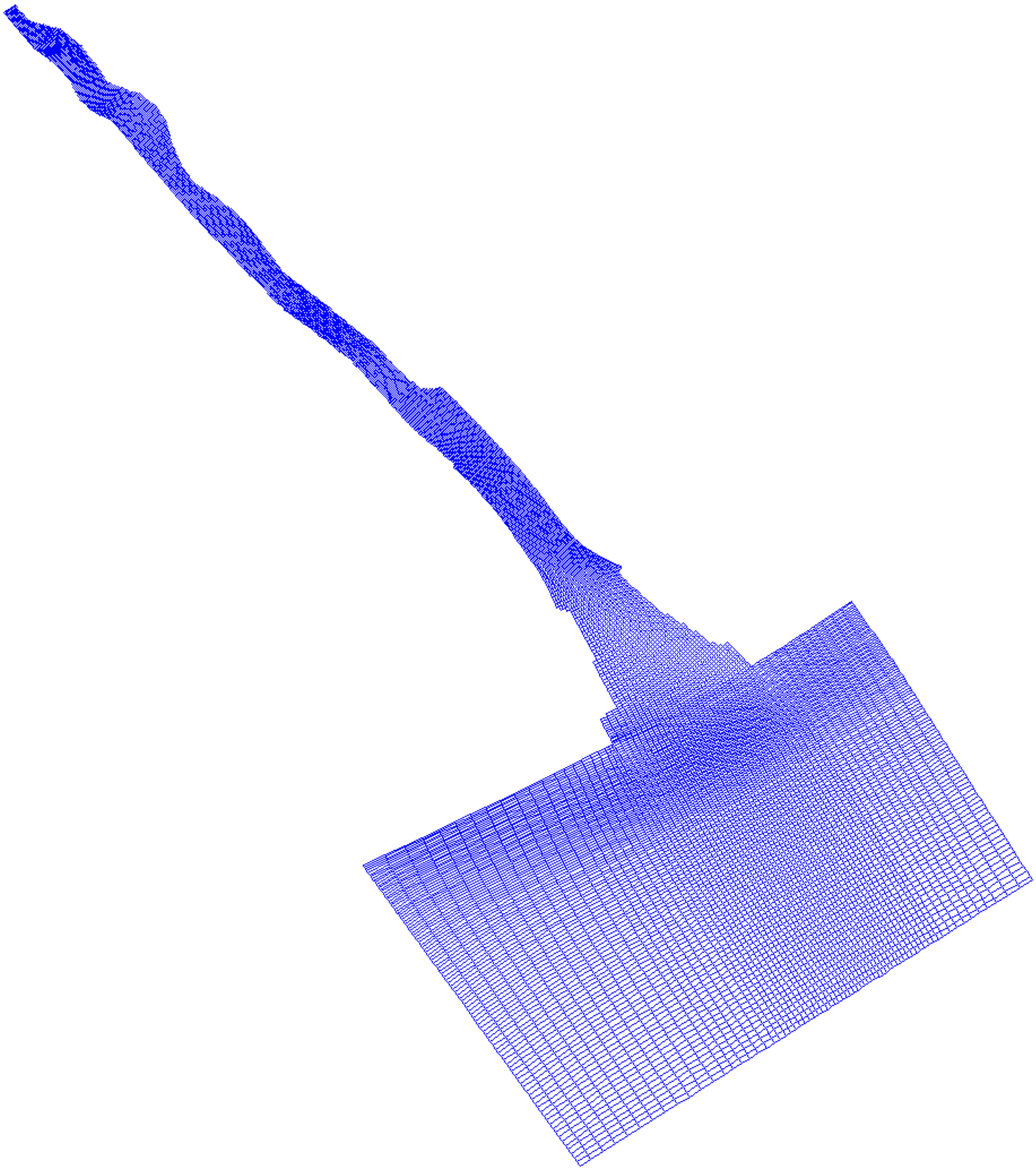

Figure 3.3: Delft3D grid of the model simulations

The bottom topography of the model is based on the received depth measurements of governmental projects. Grid cells have depth values based on depth measurements in the surroundings of the grid cell. Grid cells located outside the river area have depth values of -5 metre in the model. As a consequence these grid cells present an area above the water level during model simulations and are in fact dry cells. There is no intention to create a perfect match between the real situation of the estuary and the model. The aim is to develop a model with features of a real estuary and which could be used in this model study. As a result small river tributaries in the model are neglected for sake of simplicity. Other simplifications and the relation of the developed model to the real situation are described in Appendix E.

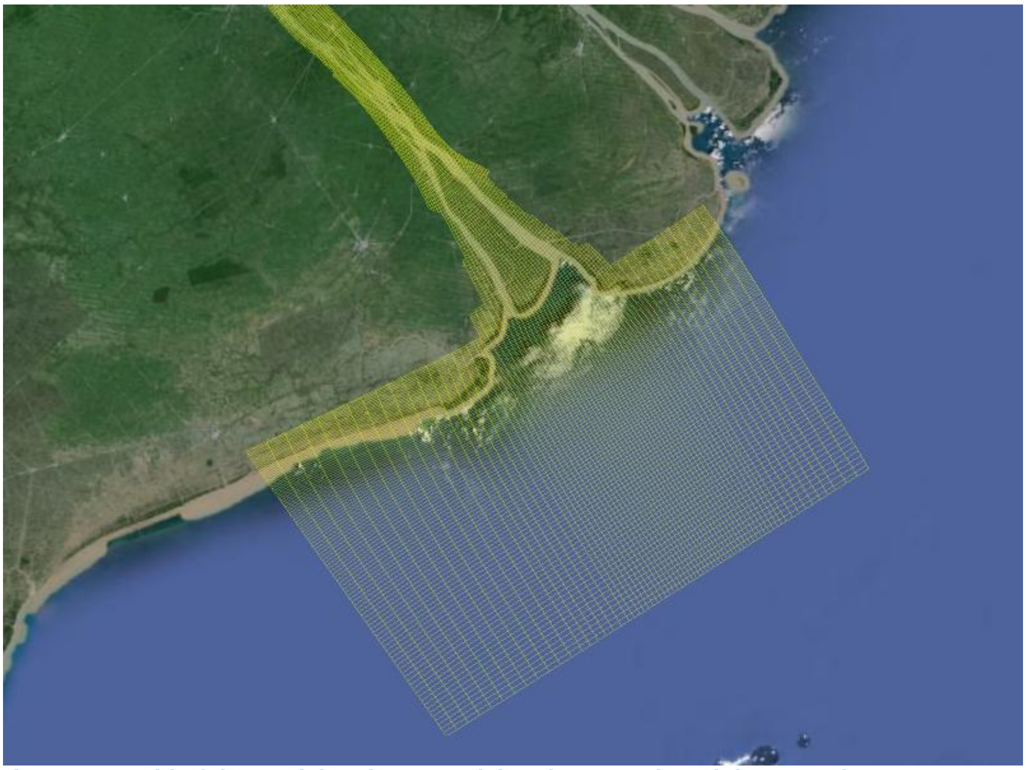

Figure 3.4: Grid of the model at the outer delta, river mouth and the most downstream part of the Hau river

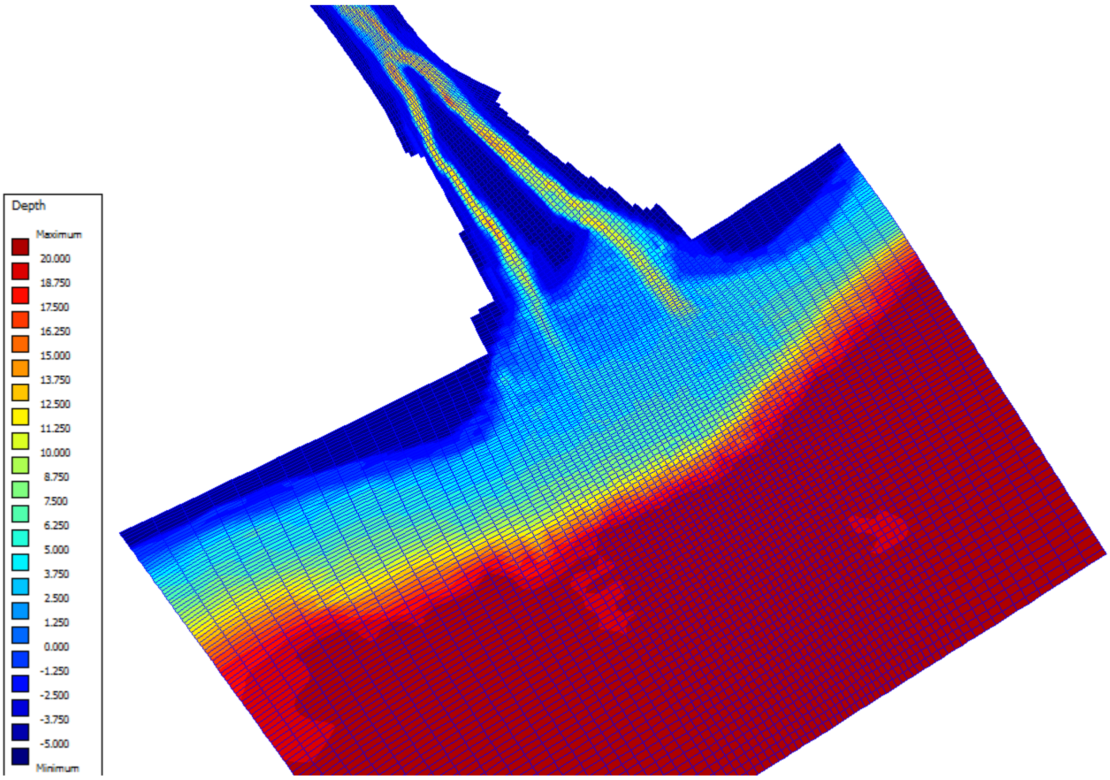

Figure 3.5: Delft3D bottom topography of the reference situation

A layered model is used to include the salt water intrusion accurately. A model with one layer gives different model results than a layered model. A model with 10 layers is used. In the situation without any islands in the outer delta the estuary is expected to be well mixed because of a Estuarine Richardson number of 0.07 (see calculation Appendix F). An Estuarine Richardson number lower than 0.08 indicates a well mixed estuary. More information about the Estuarine Richardson number is given in Section 3.2.1. A layered model is used because the salt water intrusion is more accurate and because the distribution of the horizontal flow velocity over depth and the influence of the bottom roughness is included better compared with a single layered model. Furthermore situations could possibly occur in model variants with a changed outer delta bottom topography which are not of a well mixed situation.

The distribution of the layer thickness for each grid cell is established from a percentage of the total water depth. Each grid cell has the same amount of layers. The percentage of the water depth for each layer in the σ-layering is given in table 3.1.

Table 3.1: σ-layering used in the model (layer 10 is the layer closest to the bottom)

σ-layer	percentage
1	15
2	15
3	15
4	10
5	10
6	10
7	10
8	5
9	5
10	5

A Chezy coefficient of 55 $m^{0.5}/s$ is used in the model which is more or less equal to a roughness of Nikuradse of 0.1 metre.

In Figure 3.6 the Delft3D grid is given and the orientation of the axis in the model. The orientation of the axis is important in order to understand the Delft3D results. Negative flow velocities for example are flood velocities. These velocities are negative because they flow in opposite direction as the positive axis of the model.

The used parameters in the Delft3D simulations are given in Appendix B. The sensitivity of the model results for the most import parameters is researched and described in Appendix D.

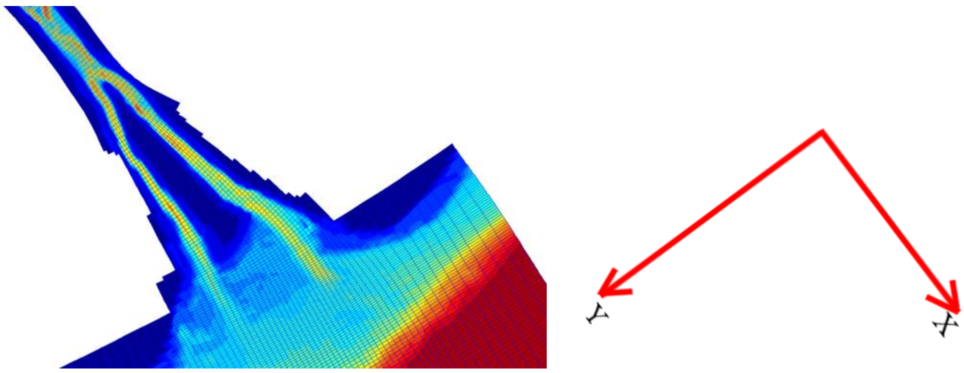

Figure 3.6: Orientation axis of the Delft3D model (left), orientation axis of the Delft3D model (right)

3.2.2 Boundary conditions

A discharge boundary is present at the upstream end of the model. The other boundary is located at the South China Sea side of the model and is a water level boundary. The used boundary conditions are described in this section. These boundary conditions are developed based on calibrations and measurement data of the estuary. This calibration process is described in Appendix C.

Upstream boundary (discharge)
At the upstream side of the model a discharge boundary is applied. Discharges in the estuary are measured at Chau Doc, Tan Chau and Can Tho (see Figure 3.1 for an overview of the locations). The first two stations mentioned are upstream of the Vam Nao connecting river. At the Can Tho station a large tidal influence is present so the river discharge is difficult to determine from the discharge measurements. The discharge measurements of the Chau Doc and Tan Chau station of the years 2010 and 2011 are available and are used in this study to determine the effective river discharge into the Hau estuary. The measurement data are gained from the data portal of the Mekong River commission (www.mrcmekong.org). The stations Chau doc and Tan Chau are located 180 kilometre upstream from the river mouth.
A discharge ratio between the Hau and Tien river after the Vam Nao connecting river is used to compute the discharge boundary for the model. Discharge ratios are published in the past, see Table 3.2. A more recent discharge ratio is found in a study of Nguyen and Savenije (Nguyen et al., 2008) which is a ratio of 42/58 during the dry season and 53/47 during the wet season between the Tien river and Hau river after the Vam Nao connecting river. In this study a discharge distribution of 50/50 is used between the two rivers.

Table 3.2: Overview discharge rations Tien and Hau river (Nguyen and savenije, 2008)

Model name	Discharge Computed (m^3/s)[a]	Tien river below Vam Nao (%)	Hau river below Vam Nao (%)	Co Chien (%)	Cung Hau (%)	Dinh An (%)	Tran De (%)	Ba Lai (%)	Ham Luong (%)	Tieu (%)	Dai (%)	Others (%)[b]
NEDECO 1974	2385	51.0	49.0	13.0	15.0	28.0	21.0	0.0	15.0	2.0	6.0	0.0
VNHS 1984	1926	55.0	45.0	13.0	18.0	27.0	18.0	0.0	17.0	1.0	6.0	0.0
SALO89 1991	2274	43.6	54.4	11.8	7.8	25.6	24.3	1.6	13.6	5.2	2.0	8.1
Nguyen Van So 1992	–	–	–	11.0	12.0	19.0	16.0	1.0	14.0	1.5	6.0	19.5
VRSAP 1993	2280	49.7	44.3	10.9	4.5	18.2	18.0	0.1	8.7	2.3	8.4	28.9

[a] Total discharge of both the Tien and the Hau rivers, upstream of the Vam Nao connection.
[b] Internal (inland) canal system.

An overview of the daily averaged discharge into the Hau estuary based on the discharge measurements at Tan Chau and Chau Doc from the Mekong River Commission data of 2010 and 2011 with the 50/50 ratio is given in Figure 3.7. The measurements at these two stations are on an hourly interval which results in negative discharges during the dry season on some moments in time because of tidal influences. The averaging of the measured discharge over a day results in positive discharges only. The use of a constant positive daily discharge instead of a positive and negative hourly discharge does not affect the results in the area of interest because the discharge boundary is located at a large upstream distance.

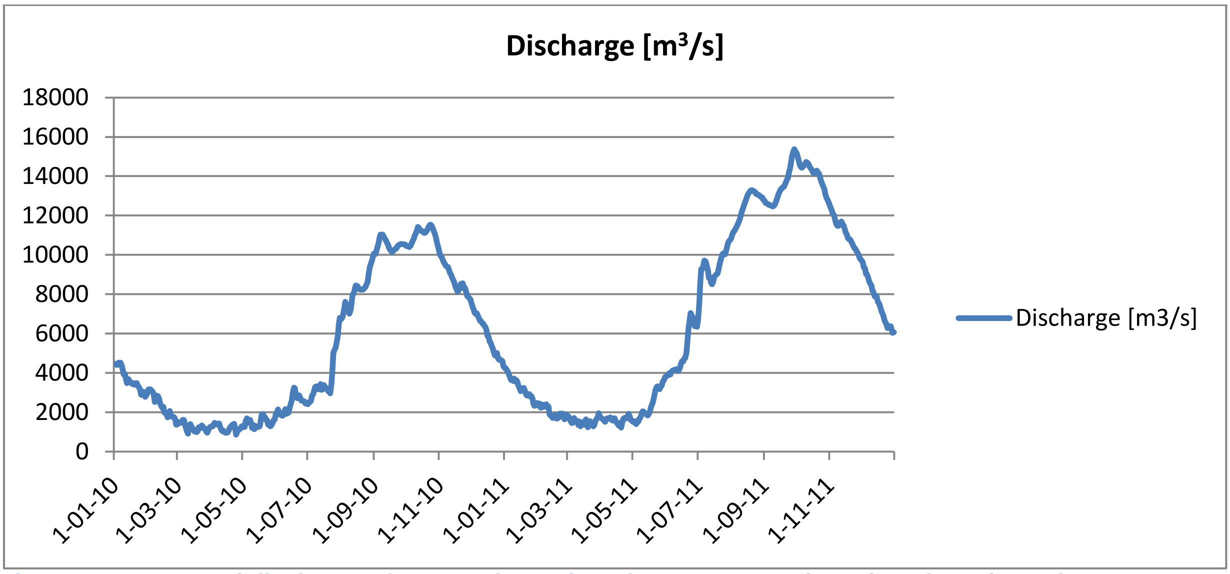

Figure 3.7: computed discharge of 2010 and 2011 into the Hau estuary based on the 50/50 ratio

Based on the data in Figure 3.7 a discharge of 1,000 m^3/s can be found during the dry season. This value is based on the measurement stations 180 kilometre upstream of the river mouths. In this 180 kilometre the discharge will be influenced by outflow through side channels for irrigation, evaporation, outflow by groundwater flow and by water extraction from the river. In the dry season the outflow will be larger than the inflow because of hardly any precipitation. The water outflow in the area between the measurement stations and the river mouth is unknown but is expected to be significant as can be seen in a rough estimation based on water use for irrigation only in Appendix C. As a result the effective fresh water inflow into the estuary which is needed for the boundary conditions is difficult to determine. Based on salinity measurements the discharge boundary is calibrated. Based on this calibration an average effective discharge value of 200 m^3/s is expected to occur during the dry season in the Hau estuary. The calibration process of the discharge boundary is described in Appendix C.

In the model simulations a constant discharge of 200 m^3/s is used which is not a very realistic situation. However it is justified in this case because the boundary is located far upstream of the area of interest (approximately 100 kilometre) and because of the large tidal discharge (13,000 m^3/s at the area of interest) influence compared with the river discharge. As a result positive and negative discharges are present in the model in the area of interest which does present the reality.

At the boundary a fresh river discharge is applied with a salinity of 0 parts per thousand.

Boundary at the South China Sea side (water level)
At the South China Sea side of the model a water level boundary is applied. Because of the complexity of the tidal signal in the South China Sea a Delft3D model of the entire South China Sea (SCSM) of Gerritsen (Gerritsen et al., 2003) is used to generate the water level boundary for the Hau Estuary Model (HEM). The signal of the SCSM is shifted in vertical direction to convert the water level signal to the same reference system as in the HEM. The vertical shift of the signal and the comparison of the signal with measured water levels is described in Appendix C.
The water level signal near the boundary is given in Figure 3.8. The range of the signal is 3.9 metre which is also described in literature (Nguyen et al., 2008)
Currents and the influence of (wind)waves are not included in the SCSM. The SCSM is based on only tidal conditions on various boundaries at the edge of the South China Sea. There are no boundary conditions specified in the HEM for (longshore) currents and (wind)waves. The tidal boundary signal of the HEM is compared with measurement data which includes the effect of wind on the water levels. Based on these results the water level boundary is adapted so it fits reality better and because of this some wind effect is included in the model eventually.
Longshore currents in the area are present. They are relative weak (0.2-0.3 m/s), change direction during the year because of the monsoon and does not have a direct large influence on salt water intrusion. On average over the year the longshore currents are in South-West direction.

At the water level boundary a salinity condition of 35 parts per thousand is applied.

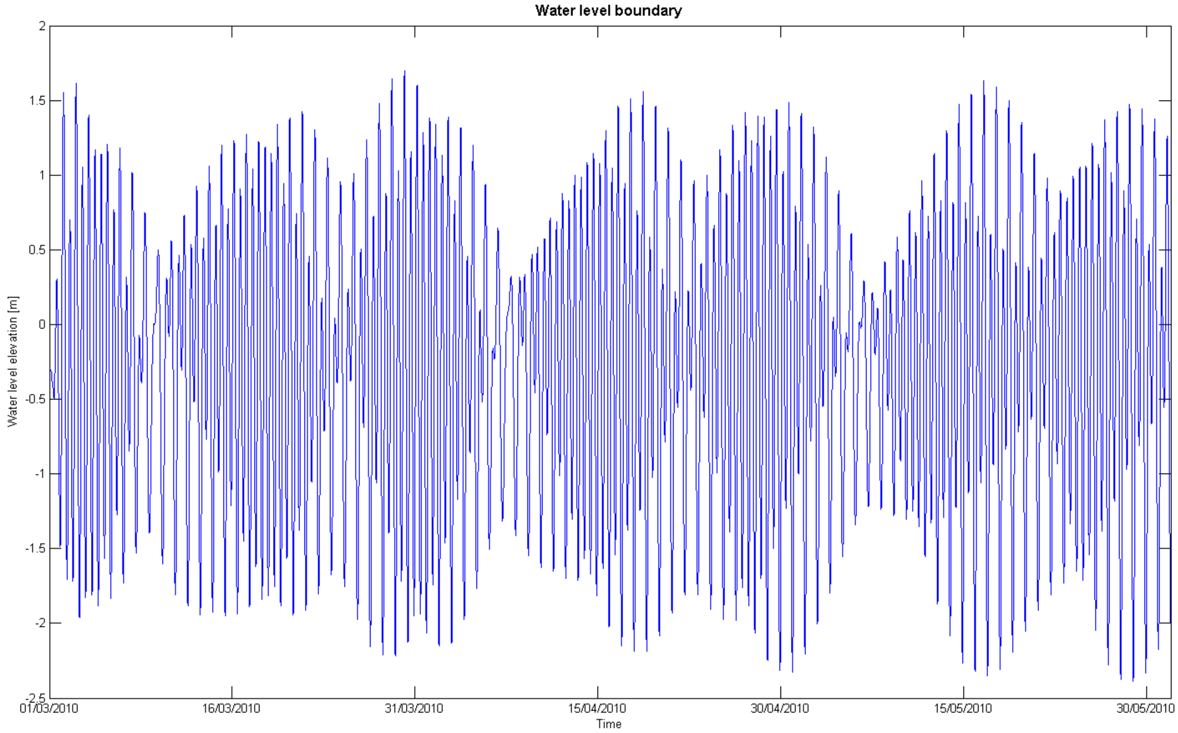

Figure 3.8: Water level boundary in the Delft3D model computations

3.2.3 Initial conditions

In the model simulations initial conditions for the water levels and the salinity levels need to be given. The applied initial conditions are described in this section.

The initial condition for the water level is a value of -0.3 metre in the entire model. The tidal signal applied at the boundary needs approximately 10 hours to reach the upstream boundary of the model. After these 10 hours the initial conditions for the water level in the model are disappeared and the water levels are totally based on the discharge and water level boundary.

The initial condition for salinity in all the model simulations is 0 parts per thousand in the entire model. Salt water will flow into the model by the water level boundaries at the South China Sea side of the model. The model simulations intend to model the dry season period with a small river discharge starting from the conditions for salinity as in the rain season (large discharge). In the rain season the outer delta of the estuary (in fact the South China Sea) is filled with salt water and the estuary itself by fresh water.

Model simulations show that the outer delta of the Delft3D grid of the HEM is completely saline after a few tidal cycles. Model comparison of a model with a salinity of 0 ppt as initial conditions in the entire model and a model with a salinity like at the end of the rain season in the model (high salinity in the outer delta of the Delft3D model) as initial conditions show small differences in model results when a dry period of 3 months is simulated (3 months with a small discharge). The same trend developments in salinity are seen, however the simulation with a cold start (no salt water in the entire model) showed a phase lag of only 2 days behind the simulation with starting conditions for salinity as in the rain season. As a consequence initial conditions of 0 ppt are used in the model simulations in this model study.

In this study all simulations are executed with a salinity of 0 parts per thousand as initial condition for the entire model. Because of this all the simulations could start with the same initial conditions and the comparison of variants could be done independently of certain initial conditions for salinity based on one of the variants.

3.3 Model simulations

The model simulations of all the variants are executed for a period of 9 months. This large period is used in order to study short term and long term effects. All simulations use the same boundary and initial conditions. The only difference between the model simulations are adaptations in the bottom topography to model adaptations of the outer delta.

4 Analysis of variants

In this chapter the four different model simulations and their results are described. In Section 4.1 the results of the reference situation are given. In the following three sections the three considered variants are described. In the first part of each section a description of the variant is given, the aspects on which the variant is developed and which adaptations are made with respect to the reference situation. In the second part of each section the results of the variant are given and causes and explanations for these results. These simulation results are all compared with the reference situation. At the end of this chapter tables are given with the salt water intrusion and salinity results of all the variants.

4.1 Reference situation

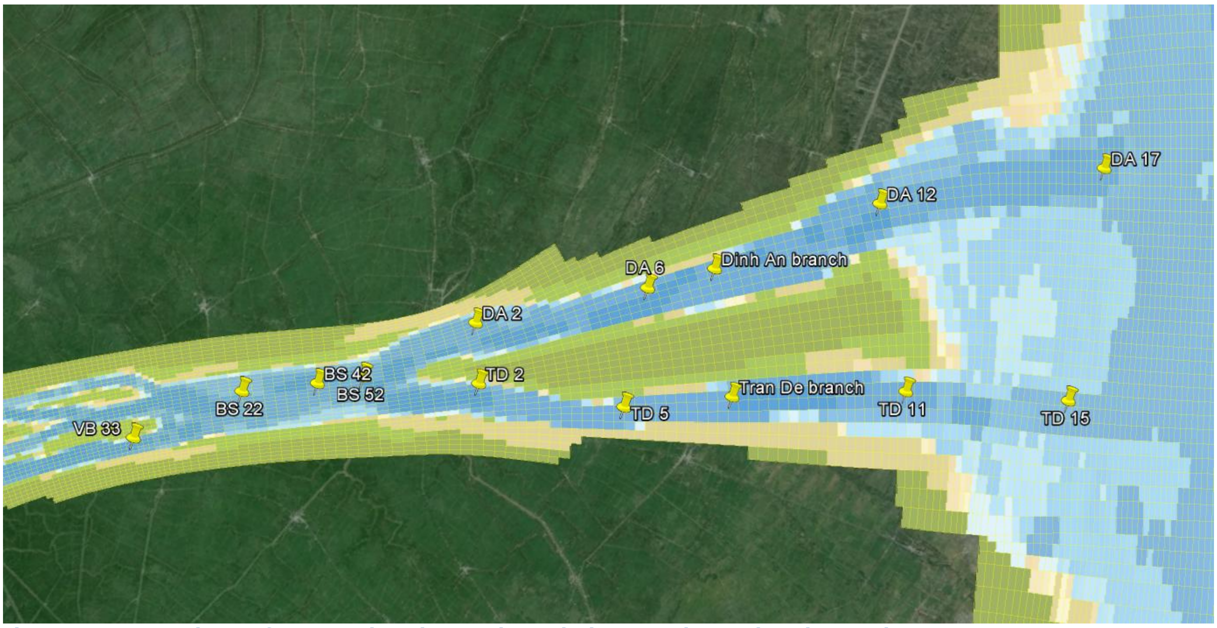

Figure 4.1: Overview reference situation and used observartion points in Section 4.1

The developed topography of the reference situation is described in Section 3.2.1. The model simulation results show the following hydrodynamic aspects and results:

- The occurring tidal ranges. At the model boundary at the South China Sea a tidal range of 3.75 metre occurs (see Appendix C) and upstream of the bifurcation point a tidal range of 2.5 metre (location BS 42).
- The estuary is flood dominant. The water level rising period is shorter than the falling period. Higher flood velocities occur than ebb velocities.
- Discharge distribution and water circulation. An uneven discharge distribution and water circulation between the two estuary branches is recorded. An import of water occurs through the Tran De branch and an export of water occurs through the Dinh An branch. Water is circulated in the system (see Figure 4.2) and the Dinh An branch receives more fresh river water discharge than the Tran De branch. See Figure 4.4 for the cumulative discharges through the branches after a period of 3 months.
- Well mixed vertical salinity profile. The estuary is expected to be well mixed because of an Estuarine Richardson number of 0.07 as described in Appendix F. Simulation results show also a well mixed estuary. An almost uniform vertical salinity profile is recorded on all locations during almost the entire simulation period. However small differences in salinity

over the vertical are present on some moments in time. These moments do not occur often and are present during the beginning of salt water intrusion. When salinity level differences are present they are mixed and show an uniform distribution over the vertical within a period of 6 hours. The vertical salinity profiles show the same results in all the model simulations and are not further considered in this report.

- The instantaneous discharge upstream of the bifurcation point. Instantaneous ebb discharge peaks of 13,000 m^3/s and instantaneous flood discharge peaks of 23,000 m^3/s occur upstream of the bifurcation point. This discharge is large compared with the river water discharge boundary of 200 m^3/s.

In Table 4.1 and Table 4.2 salt water intrusion distances and salinity levels are given at different moments in time. In Figure 4.3 the salinity development of a location (BS 42) upstream of the bifurcation can be seen. Measured salinity levels of the Hau estuary are given in Appendix C.

Table 4.1: Salt water intrusion distance

	Intrusion after 2 months [km]	Intrusion after 5 months [km]	Intrusion after 8 months [km]
5 ppt limit	38	48	49
2 ppt limit	51.5	57	59
0.5 ppt limit	57	67.5	71

Table 4.2: Salinity levels at some locations

location	Salinity after 2 months [ppt]	Salinity after 5 months [ppt]	Salinity after 9 months [ppt]
DA 17	33.0	33.4	33.4
DA 12	21.5	22.1	22.1
DA 6	9.0	12.5	13.8
DA 2	6.4	10.0	11.1
BS 52	4.8	8.5	9.4
BS 22	2.9	6.0	7.3
VB 33	0.6	2.4	3.3
TD 15	25.3	26.5	27.6
TD 11	21.4	24.3	25.2
TD 5	11.8	16.3	17.5
TD 2	8.6	12.9	14.1

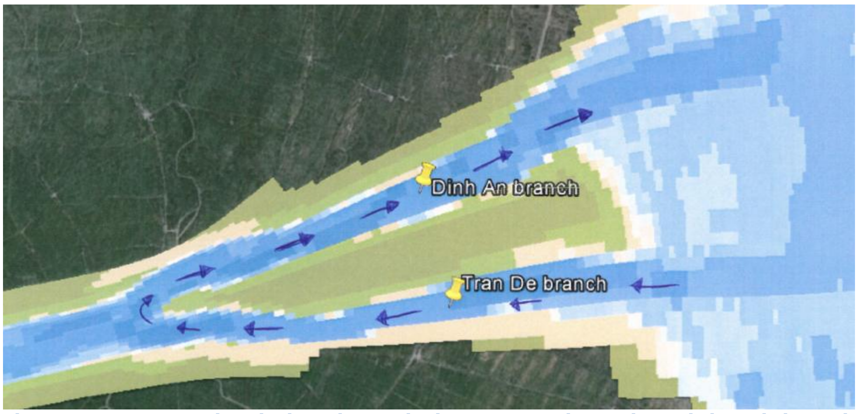

Figure 4.2: Water circulation through the Tran De branch and the Dinh An branch

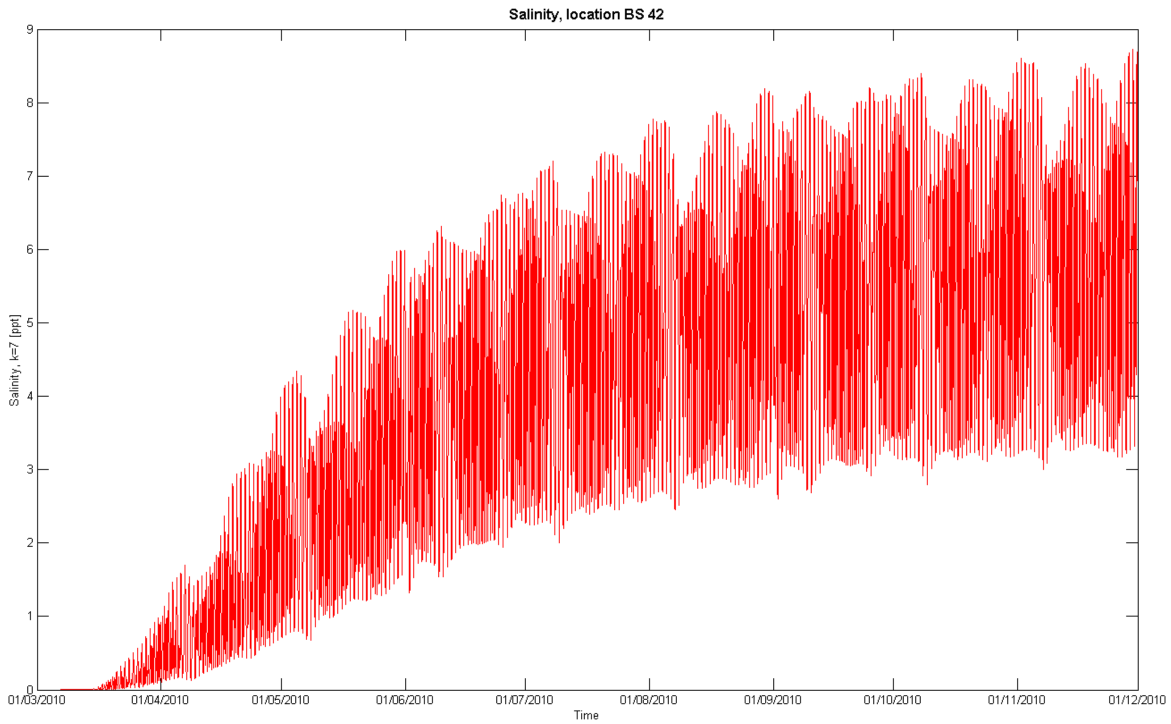

Figure 4.3: Salinity development location BS 42

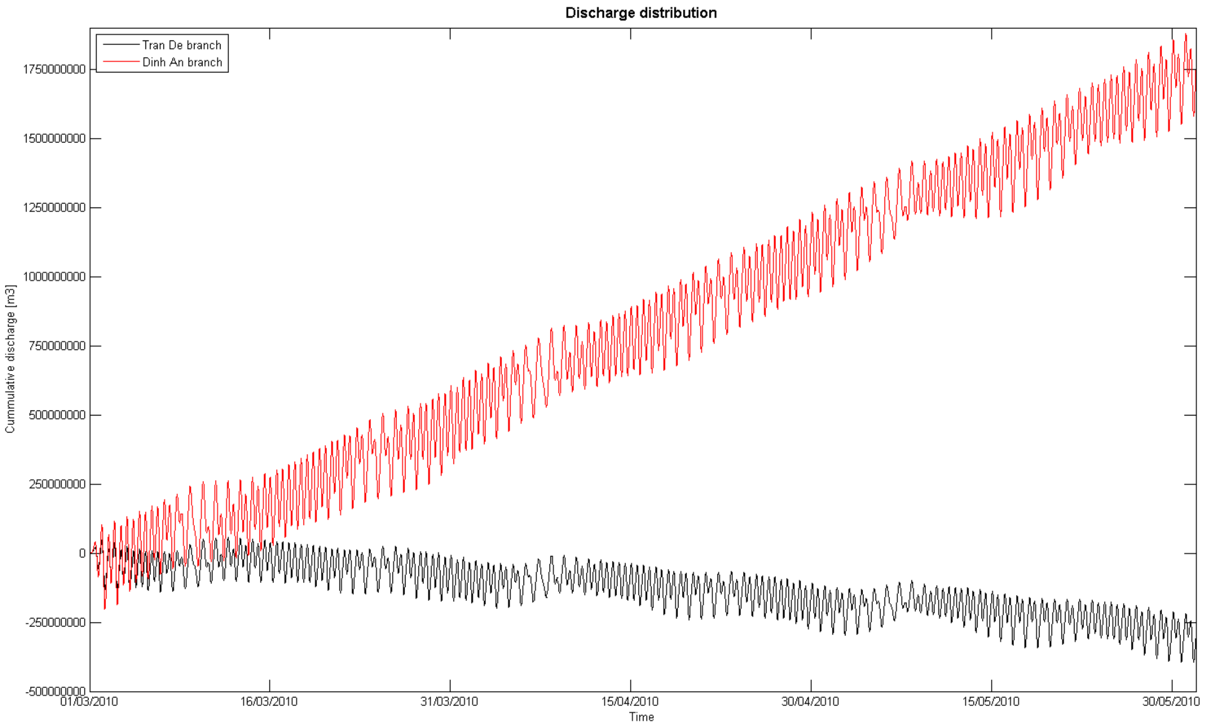

Figure 4.4: Water circulation because of an uneven discharge distribution

4.2 Seaward Extension variant

The Seaward Extension variant is based on the concept of expanding the estuary in offshore direction to reduce salt water intrusion. Because the expanding of the estuary in offshore direction the estuary entrance is shifted in offshore direction as well. The expectation is that because of this shift the horizontal salinity gradient shifts in offshore direction as well.

The bottom topography of the Seaward Extention variant is developed from the topography of the reference situation. The adaptations made are the extension of the Northern coastline, Southern coastline and of the natural island between the two estuary branches in offshore direction. As a consequence the shallow outflow area of the Tran De and Dinh An branches which was present in the reference situation disappeared.
The depths of the 'extended' Tran De and Dinh An branches are enlarged in this variant to have more or less the same cross sectional area in the extended branches as in the most downstream part of the branches in the reference situation. In Figure 4.5 the cross-sections of the extended branch in the Seaward Extention variant and of the most downstream part of the reference situation for both branches can be seen. An overview of the bottom topography of the Seaward Extention variant and of the reference situation can be seen in Figure 4.6.

The expected effects of the outer delta adaptations on the salt water intrusion are:

- A horizontal shift of the horizontal salinity gradient in offshore direction over a distance comparable with the length of the extension.
- Lower salinity levels in the estuary.

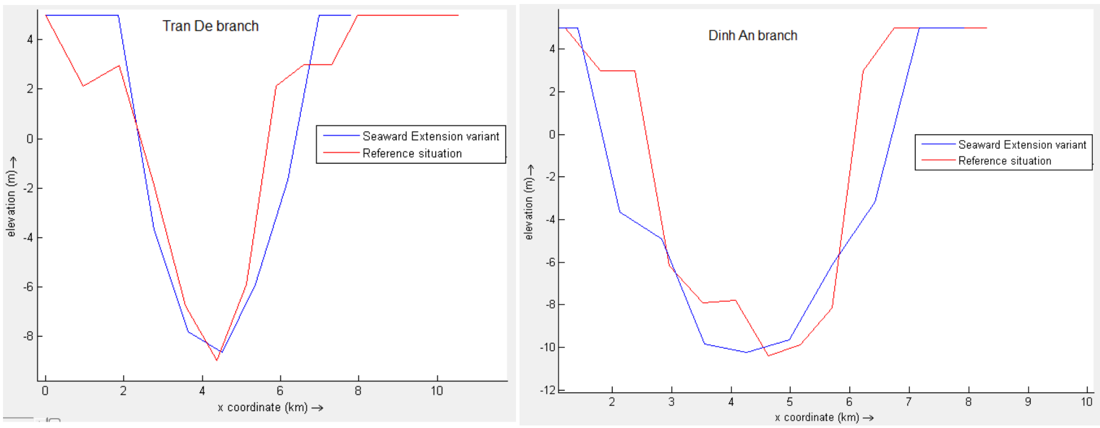

Figure 4.5: Cross sections Tran De and Dinh An branches at the most downstream part of the reference situation and at the most downstream part of the Seaward Extension variant

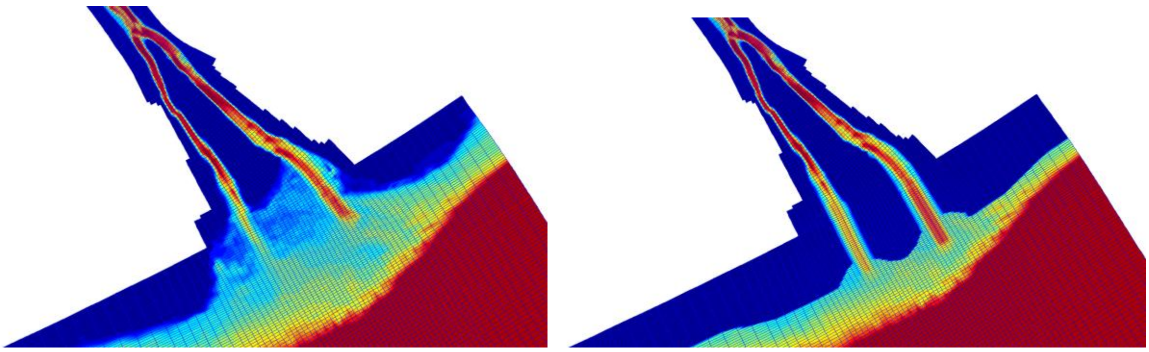

Figure 4.6: Bottom topography reference situation (left) bottom topography Seaward Extension variant (right)

4.2.1 Results

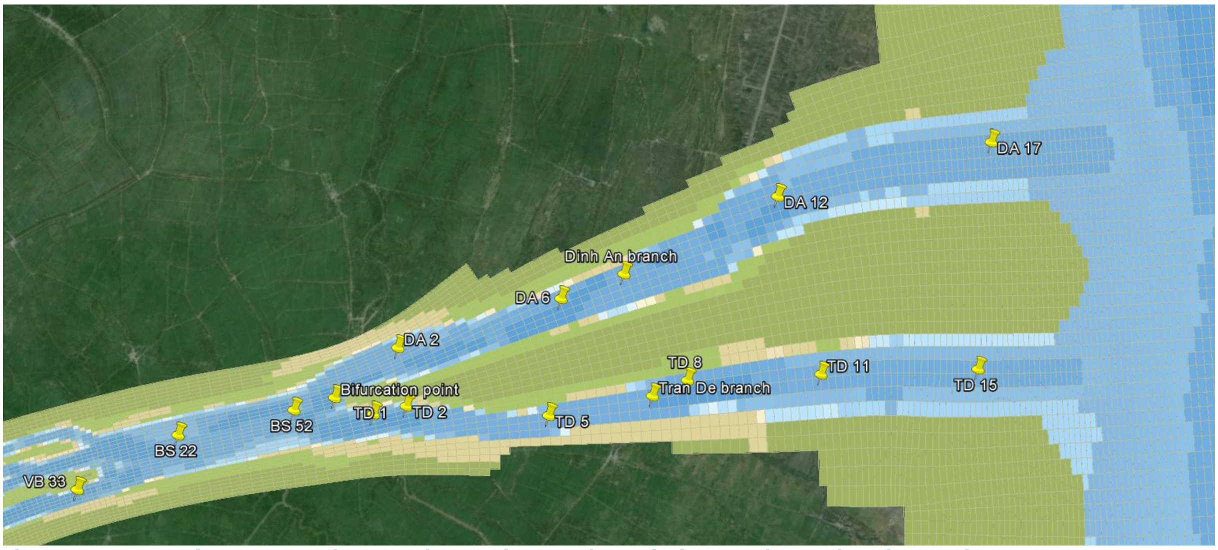

Figure 4.7: Overview Seaward Extension variant and used observation points in Section 4.2

Observed results

Higher salinity results are recorded in the entire estuary in the first 3 months. After 3 months an area of lower salinity levels forms just downstream of the bifurcation point in the Tran De branch. This area increases in time and after 9 months the area of lower salinity levels is from location TD 1 until location TD 8. After 4 months a transition can be seen in the area upstream of the bifurcation point. After 4 months lower salinity levels are recorded in this area while in the first 4 months higher salinity levels are present. After approximately 5 months lower salinity levels are present in the entire area upstream of the bifurcation point. In the Dinh An branch and downstream of location TD 8 in the Tran De branch higher salinity levels occur during the entire simulation period. Salinity level results can be seen in Table 4.4 and in Figure 4.10 to Figure 4.13.

The salt water intrusion distance shows an increase after 2 months and a decrease after 8 months. After 5 months only a small difference is recorded as can be seen in Table 4.3 and Figure 4.10 to Figure 4.12

The discharge distribution between the Tran De and Dinh An branch is changed in this variant simulation (see Figure 4.8). In the Seaward Extention variant a more even discharge distribution occurs which results in less fresh river water flow through the Dinh An branch, more fresh river water through the Tran De branch and less water circulation between the branches compared with the reference situation.

Causes for the change in salinity levels and salt water intrusion distance

The cause for the increased salinity levels is a decreased brackish water zone area in the variant situation. Because of the geometry of the Seaward Extension variant the shallow zone after the outflow of the two branches is disappeared. In the reference situation the discharge quantity and flow velocities shows a decrease in magnitude in this shallow area. Because the decrease in discharge more brackish water stays in the system and will be able to return into the estuary at the moment the tide rises. As a result the water entering the estuary during the rising tide has got a lower salinity in the reference situation than in the situation of the Seaward Extension variant. In the variant situation large discharge quantities are present until the end of the estuary's outflow. On that location it flows into an area where a longshore current is present. As a result a lot of the brackish water disappears out of the estuary system and cannot come back into the system during the rising tide. This principle can be seen in Figure 4.9 and results in a decrease in area and volume of the brackish water zone.

The cause of the lower salinity levels recorded after 3 and 4 months is the improved discharge distribution between the estuary branches. Because more fresh river water flow through the Tran De branch this branch shows lower salinity levels after 3 months. Because the more even discharge distribution less water is circulated in the estuary between the two branches and this results in lower salinity levels upstream of the bifurcation point after 4 months.

The effect of a decreased brackish water zone has a larger impact on the salinity levels in the first 3 months than the more even discharge distribution. The decrease of the brackish water zone is directly noticeable and can be seen as the most important short term effect in this system.
The effect of a more even discharge distribution and as a result less water circulation becomes visible in the salinity results after a longer period and can be seen as a long term effect. When during a period of months less water is circulated between the branches the effect will become more and more visible. In this system in overrides the effect of the disappeared brackish water basin after 4 months.

Review expectations
The horizontal salinity gradient did not shift in the expected direction. Because of the removed shallow water area at the estuary's outflow less brackish water is held in the system. As a result the inflowing water is more saline and the horizontal salinity gradient shifts in landward direction instead of in offshore direction and higher salinity levels occur.

Usefulness Seaward Extension concept
For the considered estuary this variant is not useful for reducing the salt water intrusion. The variant shows positive results after a period of 4 to 5 months of low discharge conditions but negative results in the period before. Low discharge conditions for such a long time are not likely to happen. Furthermore the positive results after 4 months are small.

Table 4.3: Differences in salt water intrusion (compared with Table 4.1)*

	difference after 2 months [km]	difference after 5 months [km]	difference after 8 months [km]
5 ppt limit	5.3 & 1.2**	0.1	-0.4
2 ppt limit	1	-0.1	-3.5
0.5 ppt limit	1.6	-0.1	-1.4

** 5.3 km in the Dinh An branch and 1.2 km in the Tran De branch

Table 4.4: Salinity level differences at some locations (compared with Table 4.2)*

location	Salinity after 2 months [ppt]	Salinity after 5 months [ppt]	Salinity after 9 months [ppt]
DA 17	1.1	1.0	1.0
DA 12	4.0	3.5	3.5
DA 6	3.3	2.8	2.3
DA 2	2.3	1.7	1.2
BS 52	1.0	0.0	-0.3
BS 22	0.6	-0.1	-0.5
VB 33	0.2	-0.1	-0.4
TD 15	5.0	4.1	3.8
TD 11	5.0	3.0	2.5
TD 5	1.5	-0.1	-0.8
TD 2	1.0	-0.3	-0.8

* The reference situation is used as reference, negative values indicate a reduction of salt water intrusion or salinity levels in the Seaward Extension variant.

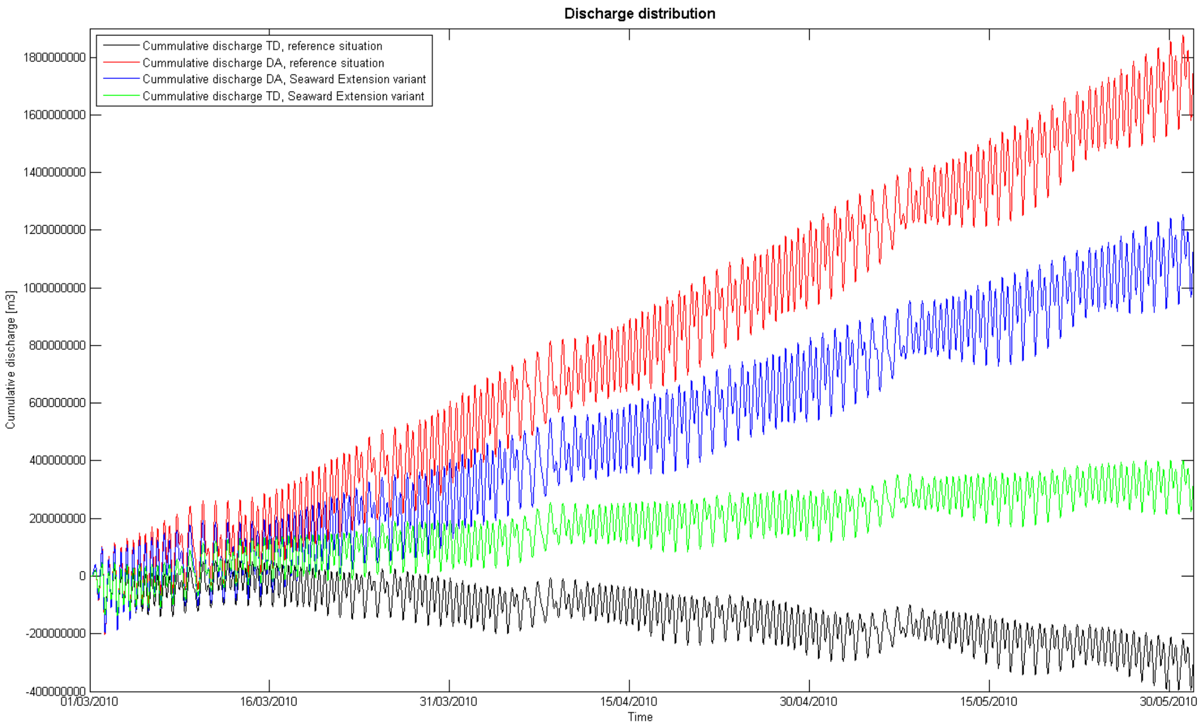

Figure 4.8: Discharge distribution over the branches in the reference situation and in the Seaward Extension variant

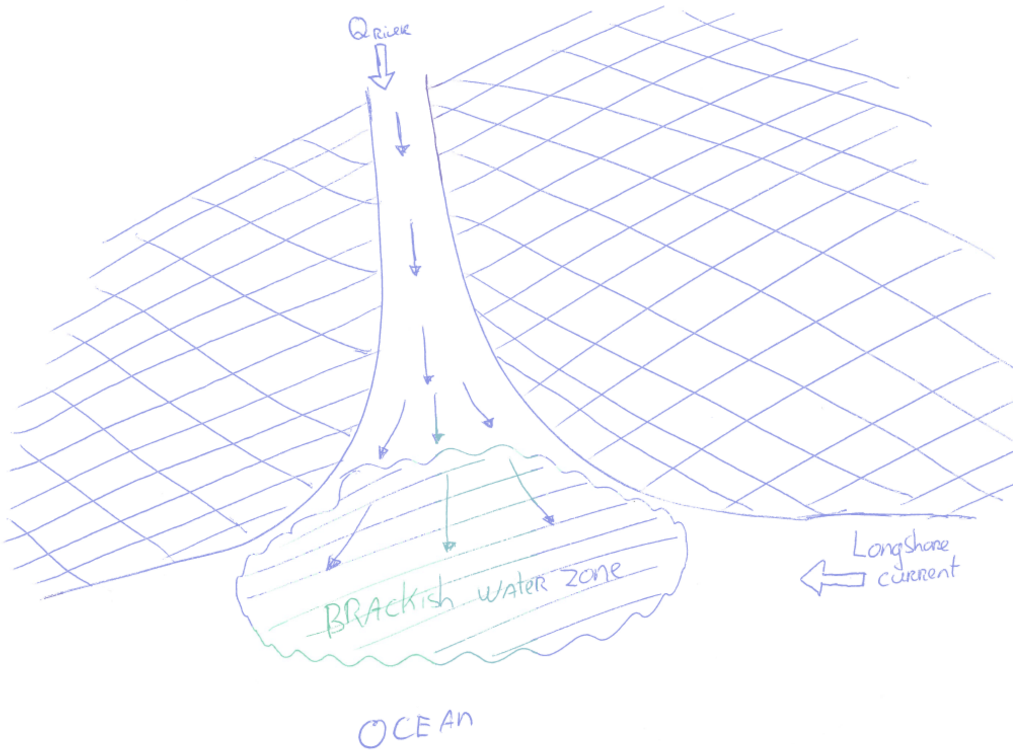

Figure 4.9: Brackish water zone which is exposed to a longshore current

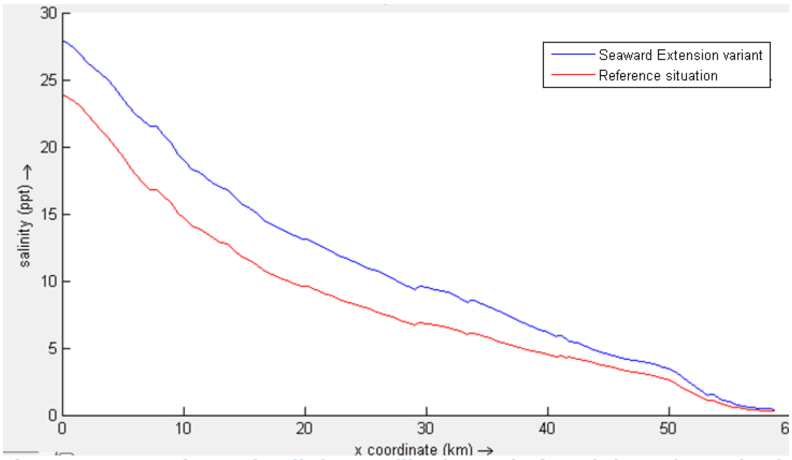

Figure 4.10: Horizontal salinity profile through the Dinh An branch after 2 months of simulation

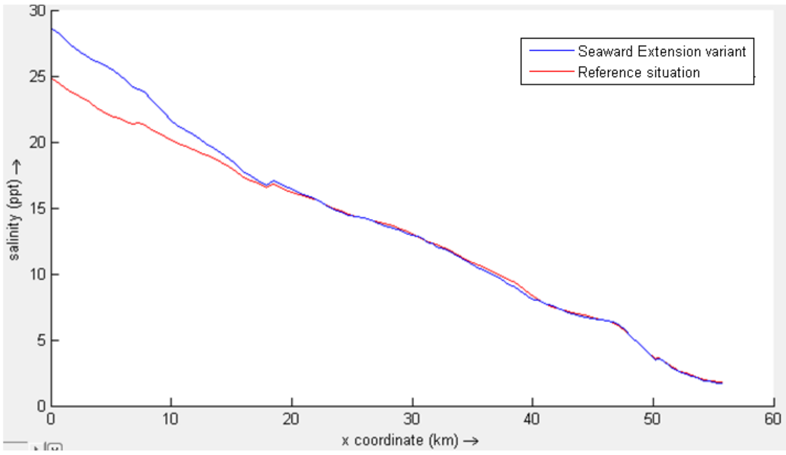

Figure 4.11: Horizontal salinity profile through the Tran De branch after 5 months of simulation

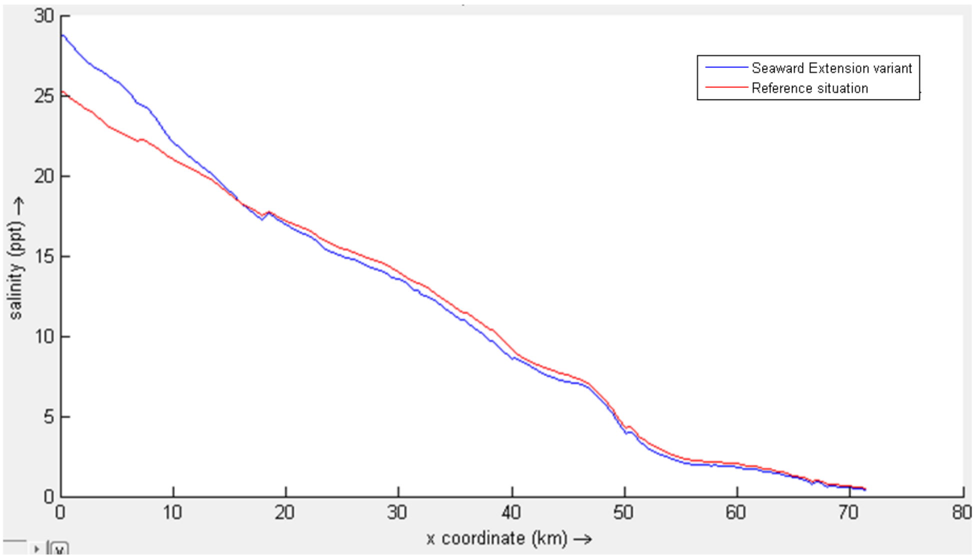

Figure 4.12: Horizontal salinity profile through the Tran De branch after 8 months of simulation

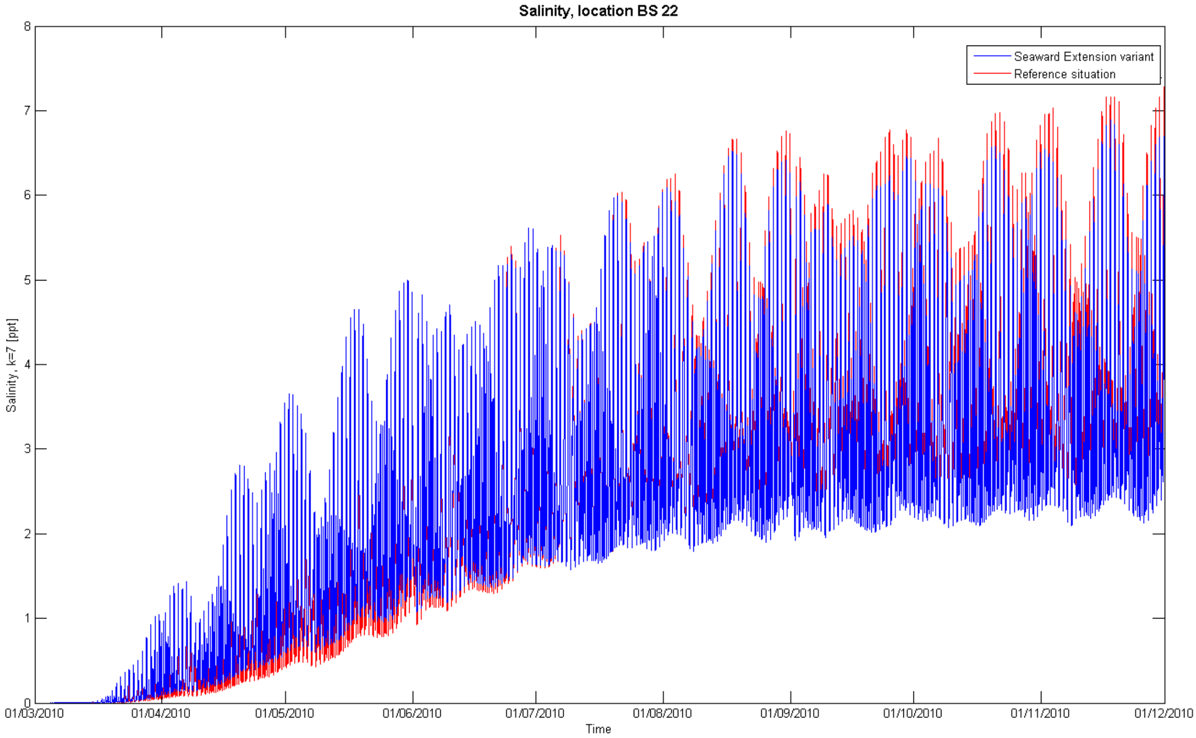

Figure 4.13: Salinity development location BS 22 (located 20 km upstream of the bifurcation point)

4.3 Island variant

An arch shaped island of 20 kilometre in length is created in the outer delta of this variant. The idea of this variant is to reduce the tidal range and prism in the estuary and to create a brackish water basin between the island and the estuary. This is expected to result in less salt water intrusion and lower salinity levels in the estuary.

The bottom topography of the Island variant is created by changing the depth values of the reference situation to create an arc shaped island. As a consequence of the created island smaller water flow openings between the estuary and the South China Sea are created. These openings are expected to be morphological out of equilibrium during the conditions of the rain season when large river discharges occur. Because of this it is expected that the channels to these openings and the openings between the island and the coast will deepen itself. That is why the depth values in the area of the island openings and at the channel location in the shallow outer delta are adapted. The depth in the area of the openings is increased on average by two metres. The developed bottom topography of the Island variant can be seen in Figure 4.14.

The expected effects of the outer delta adaptations on the salt water intrusion are:

- Less salt water intrusion and lower salinity levels in the estuary because of a smaller tidal range and a smaller tidal prism.
- Less salt water intrusion and lower salinity levels in the estuary because of a brackish water basin in the area between the estuary's outflow and the island.

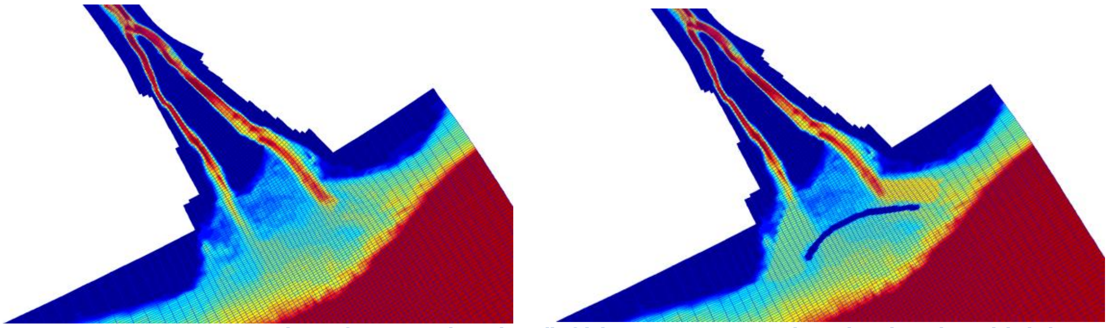

Figure 4.14: Bottom topography reference situation (left) bottom topography Island variant (right)

4.3.1 Results

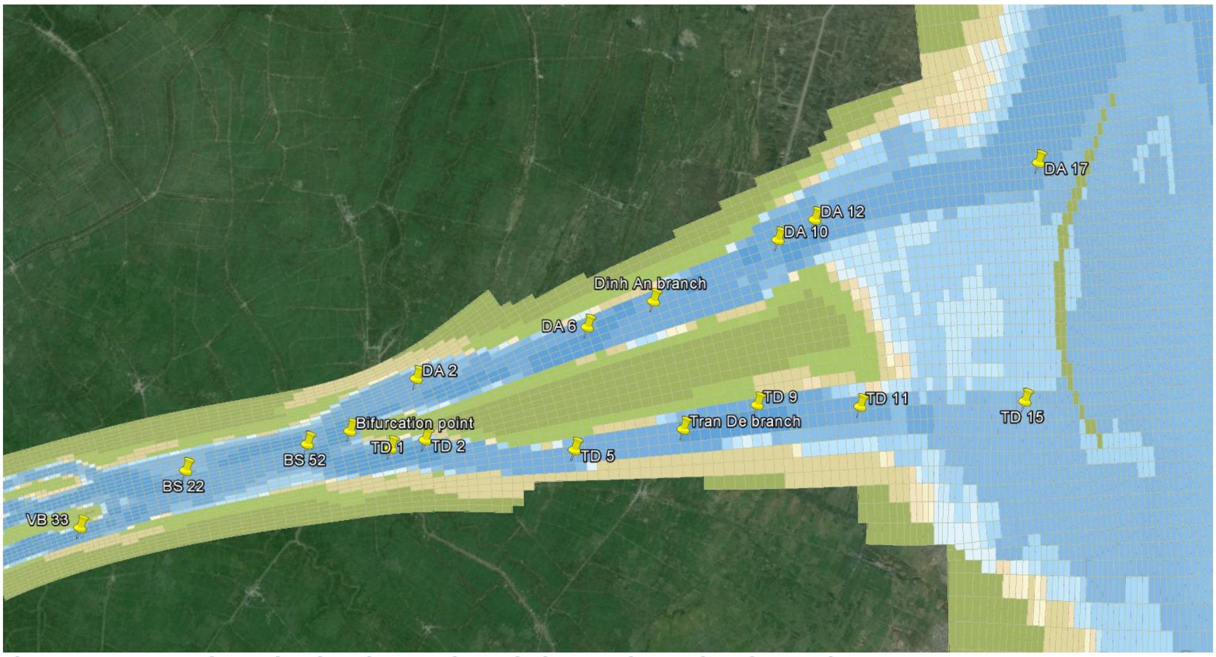

Figure 4.15: Overview Island variant and used observation points in Section 4.3

Observed results
In the Dinh An branch lower salinity levels can be seen in the first month. After this month higher salinity levels occur in the upstream part of the branch (from the bifurcation point to location DA 10). In the most downstream part of the branch lower salinity levels occur during the entire simulation period.

In the entire Tran De branch higher salinity levels occur in the first three months. After this period the most upstream part of the Tran De branch becomes less saline. This area increases over time in downstream direction until location TD 9 after a simulation period of 9 months with a constant discharge.

In the area upstream of the bifurcation point slight larger salinity levels are recorded in the first 2 months. After these 2 months lower salinity levels are recorded in the area upstream of the bifurcation point (see Table 4.6 and Figure 4.20).

In the area between the island and the outflow of the Tran De and Dinh An branches a change in salinity levels is recorded. In the outflow area of the Tran De branch higher salinity levels are present and in the area of the Dinh An branch lower salinity levels as can be seen in Figure 4.21.

An increase in salt water intrusion is recorded in the first 2 months. After this period a reduced salt water intrusion is recorded as can be seen in Table 4.5.

A salt transport between the openings North and South of the island is present. Salt is imported through the Southern opening and exported through the Northern opening. See Figure 4.22 to Figure 4.24 for an overview of the transport pattern.

The tidal range and the tidal prism are decreased in the Island variant. The tidal range is decreased by 0.1 metre just upstream of the bifurcation point (the high water level is decreased with 0.05 metre and the low water level is increased with 0.05 metre). The tidal prism just upstream of the bifurcation point is decreased by 1.15E+07 cubic metre. Which is an average decrease in instantaneous discharge of 530 cubic metre per second when a rising period of 6 hours is considered. This is a relative small amount when instantaneous flood discharge peaks of 23,000 cubic metre per second occur. The tidal prism in the reference situation is in the order of 2.3E+08 cubic metre and a decrease of 1.15E+07 cubic metre is a tidal prism decrease of 5 percent.

The discharge distribution between the Tran De and Dinh An branch is changed in the variant simulation. In the Island variant a more even discharge distribution is present which results in less fresh river water flow through the Dinh An branch, more fresh river water through the Tran De branch and less water circulation between the branches compared with the reference situation (see Figure 4.16).

Causes for the change in salinity levels and salt water intrusion distance
The cause of the increased salinity levels is the occurrence of significant higher salinity levels in the Southern part of the shallow area between the estuary's outflow and the island. Because of this salinity increase water with a higher salinity enters the Tran De branch. As a result the Tran De branch and the area upstream of the bifurcation point are more saline in the first months.

There are three causes for the occurrence of lower salinity levels.

Because of the lower salinity in the outflow area of the Dinh An branch lower salinity levels occur in the entire Dinh An branch in the first month and in the entire simulation period at the most downstream part of the Dinh An branch.

Because of the more even discharge distribution between the Tran De and Dinh An branch less water is circulated in the estuary which results in lower salinity levels upstream of the bifurcation point and in the upstream part of the Tran De branch.

The occurrence of a smaller tidal range and of a smaller tidal prism contributes also to lower salinity levels.

A result of the salt transport through the Northern and Southern openings of the island is higher salinity levels in the outflow area of the Tran De branch (and lower salinity levels in the outflow area of the Dinh An branch) as can be seen in Figure 4.21 to Figure 4.23. This effect is directly noticeable and is the most important short-term effect is this system on salt water intrusion. The increase in salinity in the Tran De area has more impact than the decrease in salinity in the Dinh An area because increased salinity levels are recorded upstream of the bifurcation point in the first 2 months.
The Southern and Northern opening are almost equal in size. However more brackish river water flows out the estuary through the Northern opening as through the Southern opening. As a result the brackish water outflow pushes the salt water over larger distances back in the Northern opening compared with the Southern opening. As a consequence salt import through the Southern opening occurs and salt export through the Northern opening.

The effect of less water circulation and of a smaller tidal range and prism becomes visible in the salinity results after a longer time period. These mechanisms need time to gain relative importance and can be seen as long-term effects.

Review expectations
A smaller tidal range and prism occurred in the simulation of the variant. Although the decrease was small it resulted in lower salinity levels and less salt water intrusion. The relative importance is not known because the more even discharge distribution also contributed to a decrease in salinity levels and salt water intrusion.

A less effective brackish water basin as an obstacle for salt water intrusion was created in this variant instead of the expected increase in effectiveness. As a result higher salinity levels occurred and the intrusion of salt water was larger in the first months. This result also shows that the brackish water basin is pretty effective as an obstacle for salt water intrusion in the reference situation and it is difficult to improve this effectiveness by adaptations in the outer delta.

Usefulness Island concept
The island variant is an useful solution when longer periods of low discharge occurs (which could be possible for the considered estuary and in other estuaries as well). The variant simulation shows lower salinity levels after 2 months. When reducing salt water intrusion is considered the Island variant could be further optimised to improve the effectiveness in reducing salt water intrusion. However other considered island variants in this research process (not included in this thesis report) showed that optimising variants is very time consuming and will often introduce other negative effects when salt water intrusion is considered or will result in unrealistic variants.

Table 4.5: Differences in salt water intrusion (compared with Table 4.1)*

	difference after 2 months [km]	difference after 5 months [km]	difference after 8 months [km]
5 ppt limit	1.6 & 0.4**	-1.2	-1.6
2 ppt limit	-0.1	-1.8	-5.5
0.5 ppt limit	0	-1.3	-3.1

** 1.6 km in the Dinh An branch and 0.4 km in the Tran De branch

Table 4.6: Salinity level differences at some locations (compared with Table 4.2)*

location	Salinity after 2 months [ppt]	Salinity after 5 months [ppt]	Salinity after 9 months [ppt]
DA 17	-1.5	-1.2	-1.2
DA 12	-0.5	-0.4	-0.5
DA 6	0.7	1.0	0.8
DA 2	0.7	0.6	0.2
BS 52	0.2	-0.8	-1.2
BS 22	-0.1	-1.0	-1.5
VB 33	-0.1	-0.5	-0.7
TD 15	6.5	5.5	4.5
TD 11	6.7	4.8	4.3
TD 5	1.3	-0.8	-1.5
TD 2	0.4	-1.5	-1.8

* The reference situation is used as reference, negative values indicate a reduction of salt water intrusion or salinity levels in the Island variant.

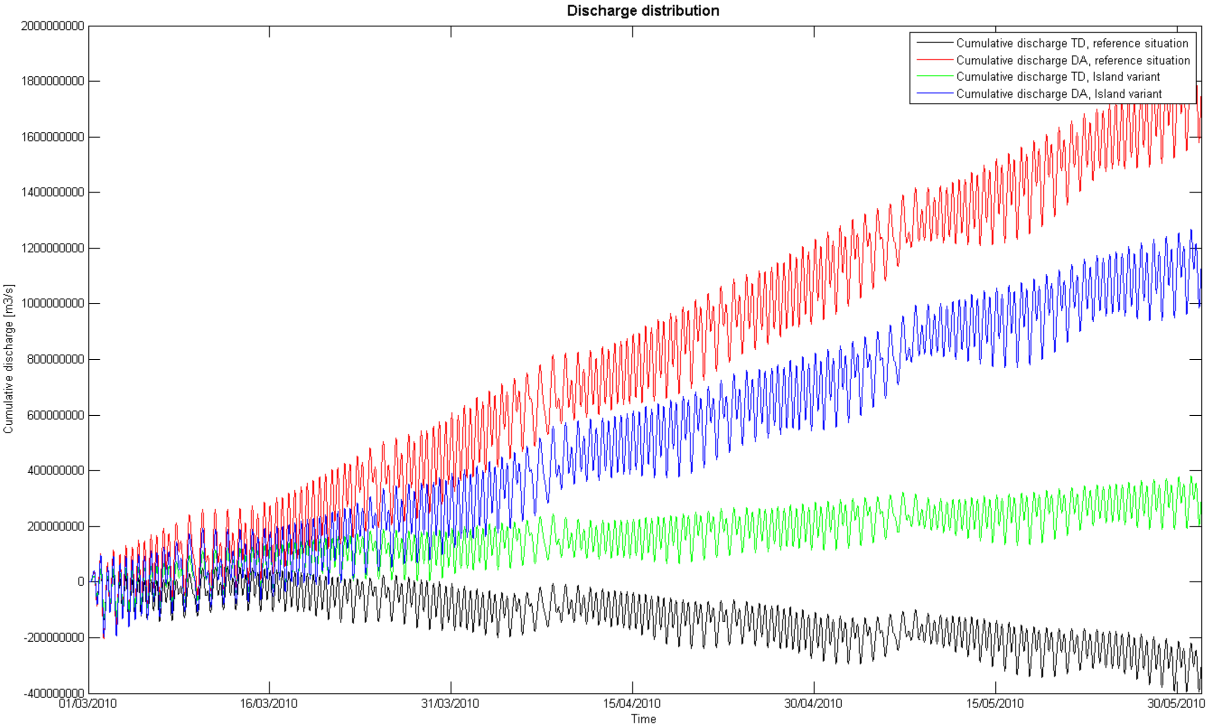

Figure 4.16: Discharge distribution over the branches in the reference situation and in the Island variant

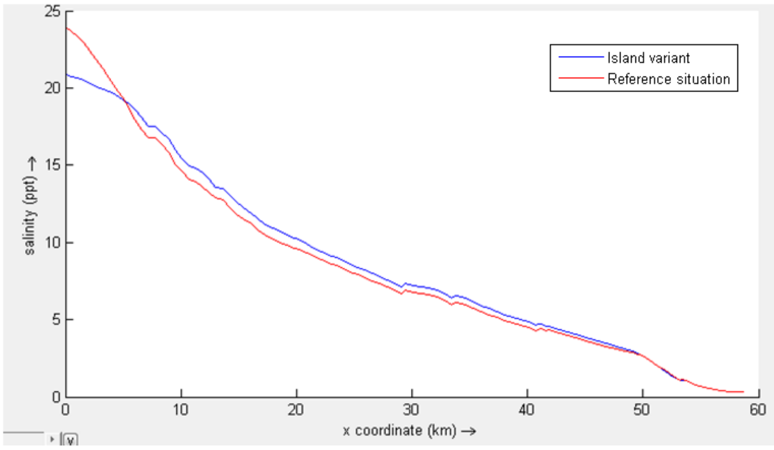

Figure 4.17: Horizontal salinity profile though the Dinh An branch after 2 months of simulation

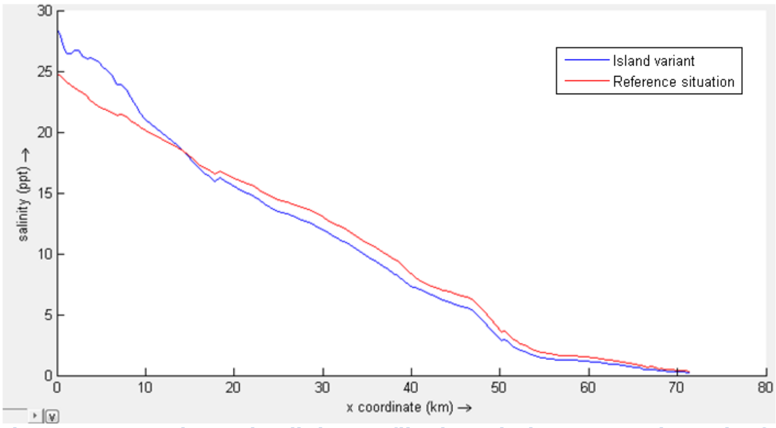

Figure 4.18: Horizontal salinity profile though the Tran De branch after 5 months of simulation

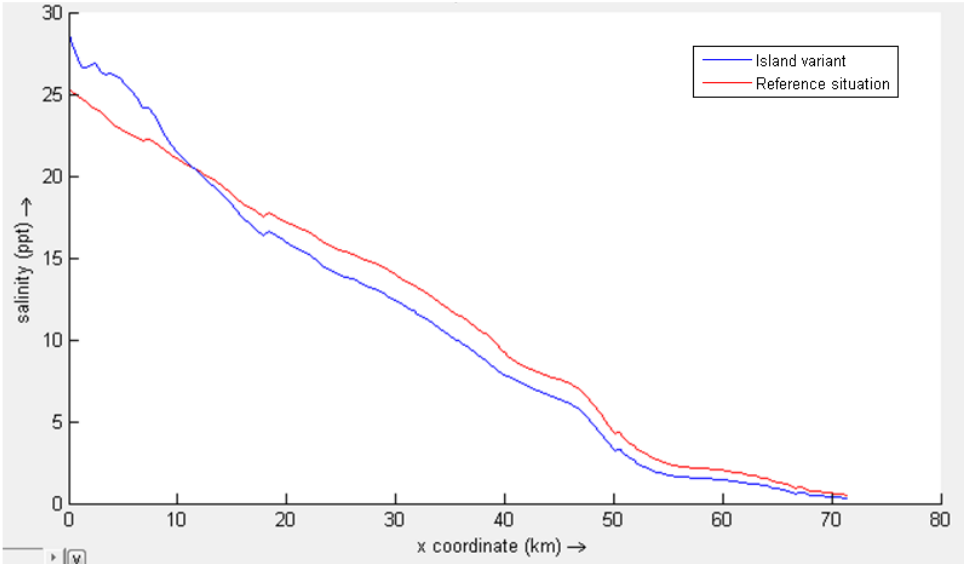

Figure 4.19: Horizontal salinity profile though the Tran De branch after 8 months of simulation

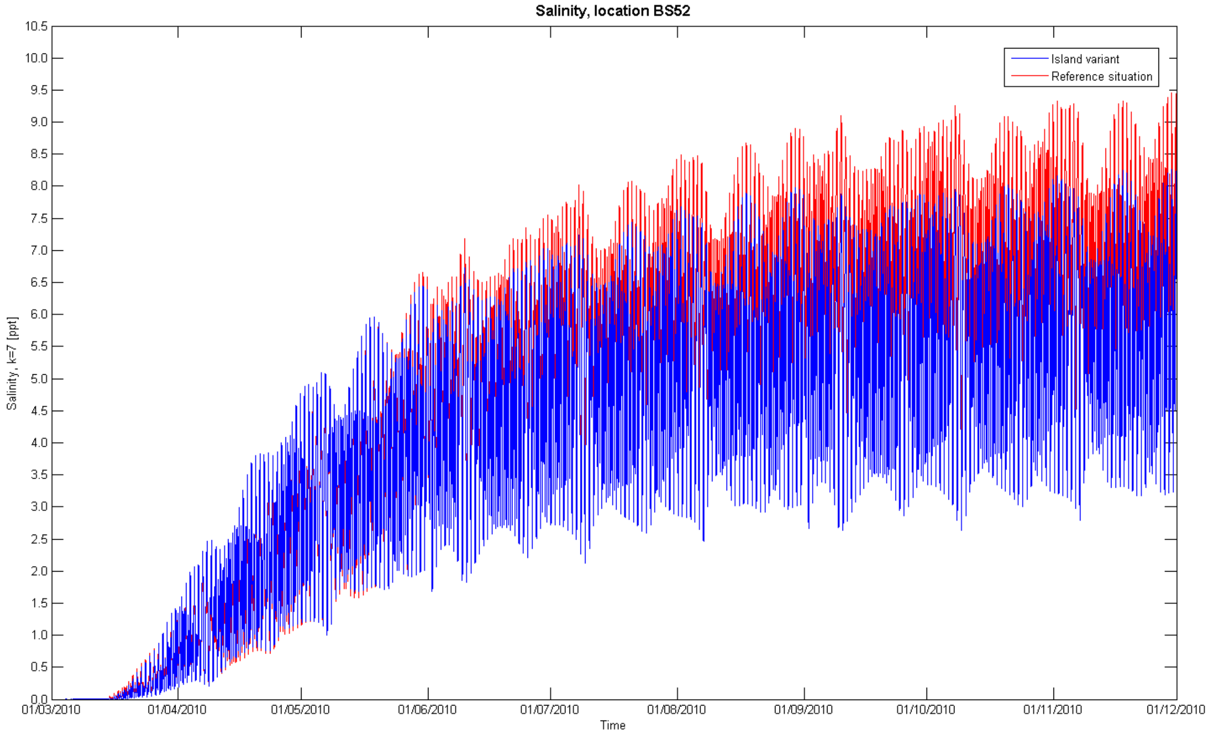

Figure 4.20: Salinity level development location BS 52 (upstream of the bifurcation point)

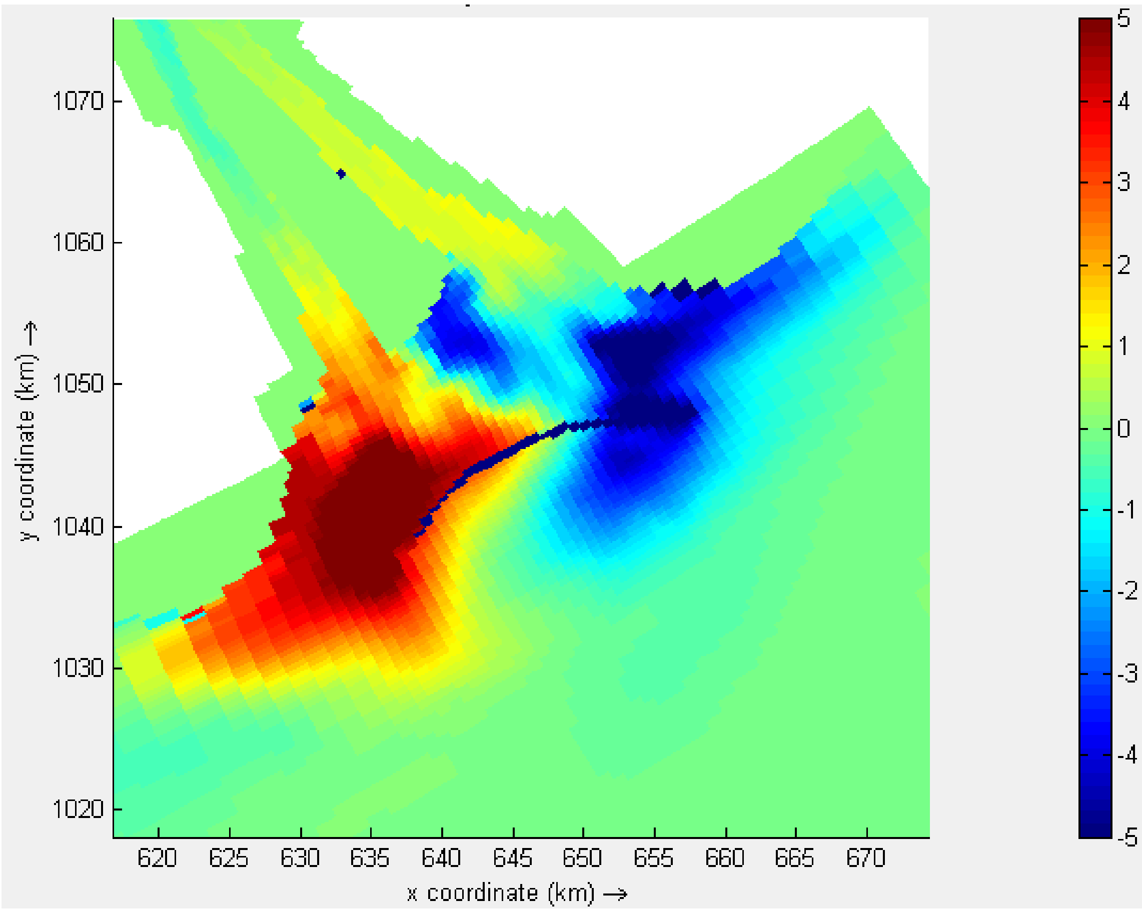

Figure 4.21: Salinity differences [in ppt] outer delta*

* The reference situation is used as reference, negative values indicate a reduction of salinity levels in the Island variant.

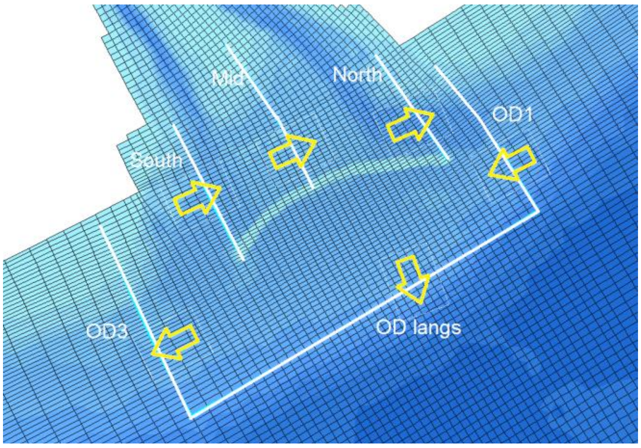

Figure 4.22: Location cross-section observations in the model simulation and the cumulative direction of salt transport into the outer delta

Figure 4.23: Coordination axis of the Delft3D model

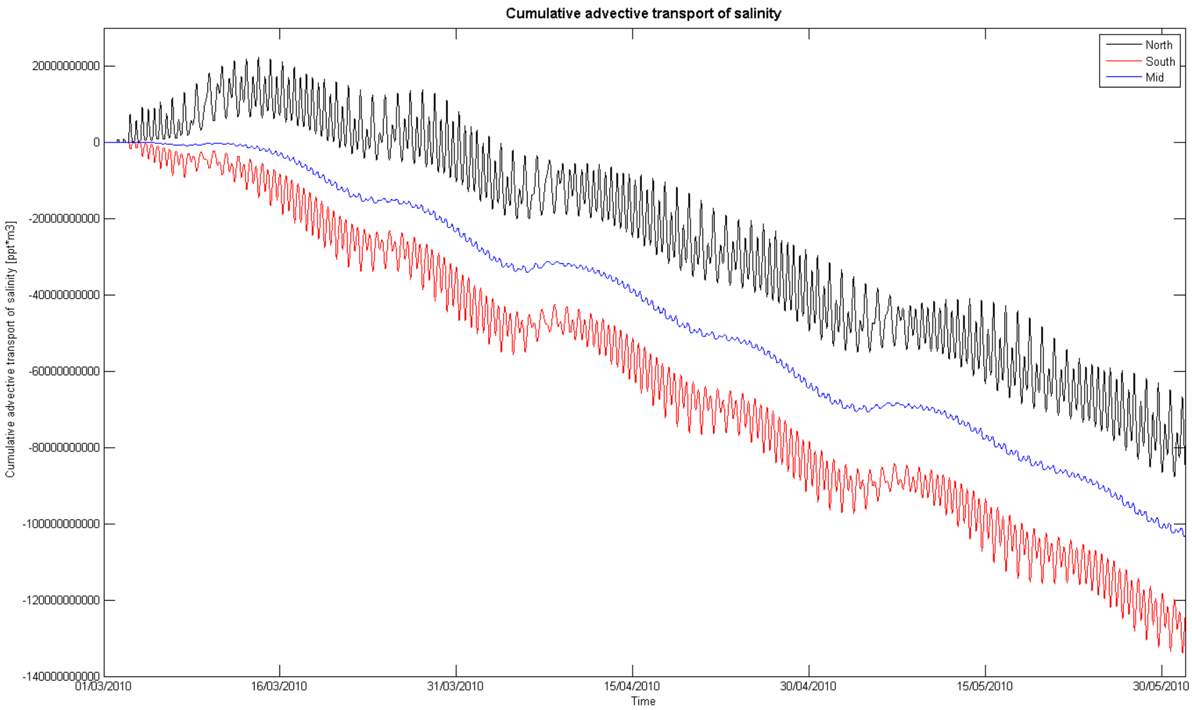

Figure 4.24: Cumulative salt transport in the outer delta

4.4 Enlarged Estuary variant

The natural island between the Dinh An branch and the Tran De branch is removed and replaced by a shallow area in the Enlarged Estuary variant. This idea is developed as a result of various studied variants at the beginning of this study (not described in this report) where islands and extensions of the coast were considered. Most of these variants showed a negative influence on reducing salt water intrusion because more brackish water flowed out of the system. As a result of these variants the idea arose of a variant based on holding more brackish water into the estuary system and the Enlarged Estuary variant is developed.

The bottom topography of the variant is developed by giving the area of the former island between the Tran De and Dinh An branches depth values of 4 metre. The depth of the Tran De and Dinh An branches of the reference situation are decreased in the variant situation because this is also expect to happen in a natural situation when the former island would be removed. Cross-sections of the bottom profile of the reference situation and of the Enlarged Estuary variant can be seen in Figure 4.25.

The expected effects of the estuary adaptations on saline water are:

- An increase of salt water intrusion and in salinity levels into the estuary because of an increased cross-sectional flow area which makes it easier for saline water to flow into the estuary.
- Less outflow of brackish water.

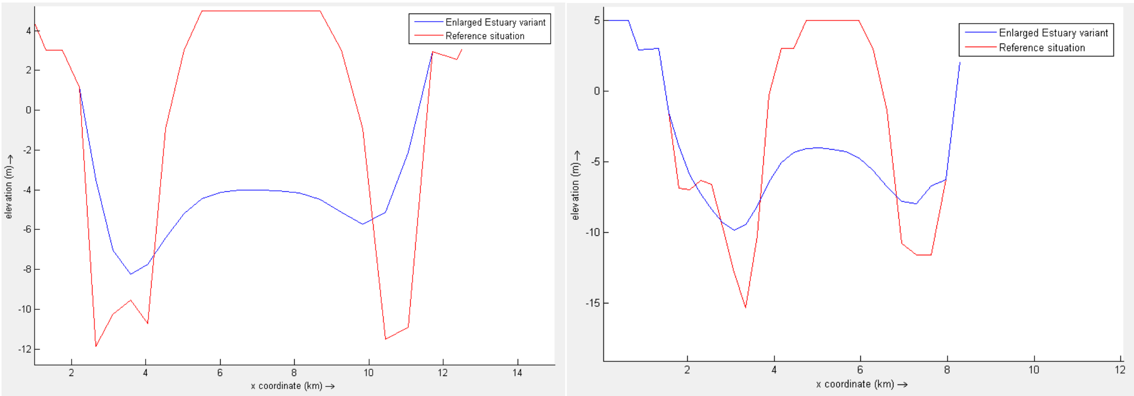

Figure 4.25: Cross sections on 1/2 (left figure) and 4/5 (right figure) of the entire estuary width seen from the estuary mouth (around location TD 7 and TD 3)

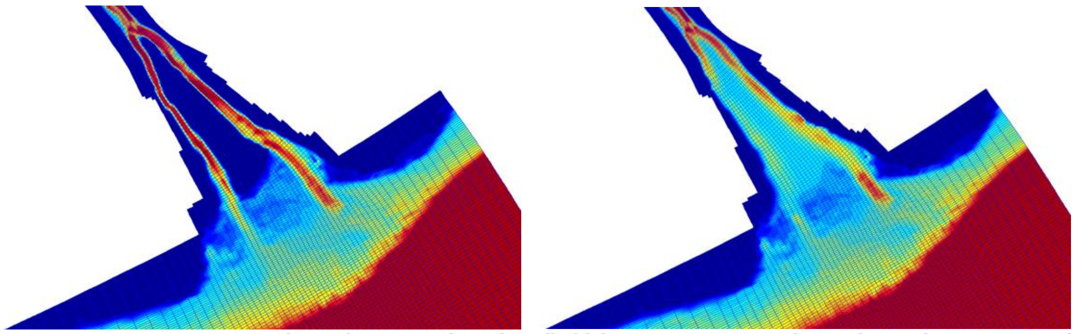

Figure 4.26: Bottom topography reference situation (left) bottom topography Enlarged Estuary variant (right)

4.4.1 Results

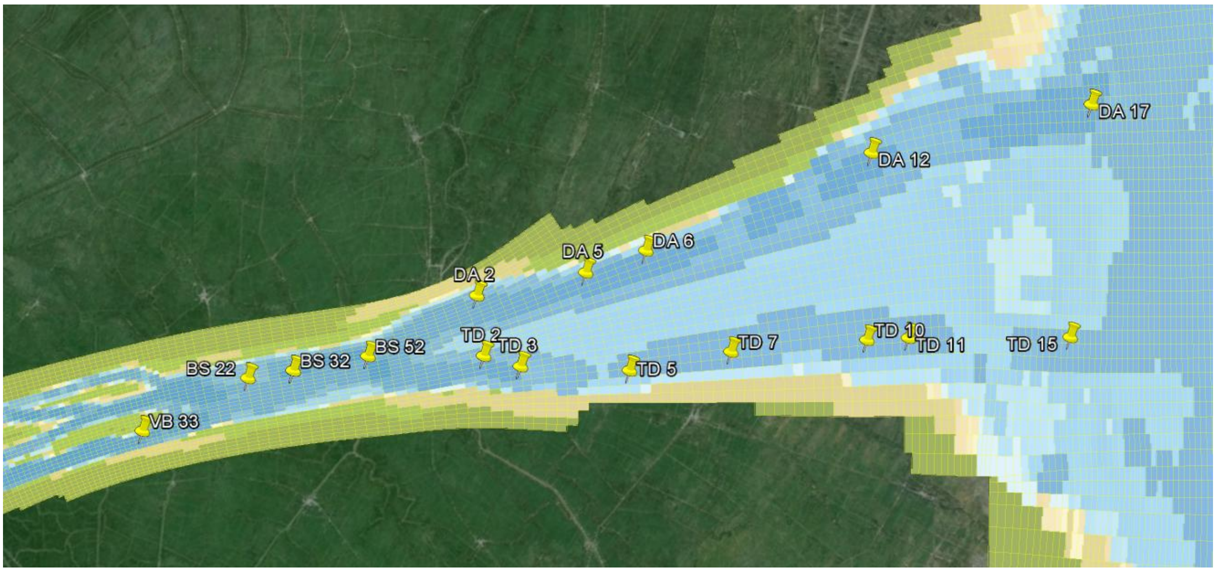

Figure 4.27: Overview Enlarged Estuary variant and used observation points in Section 4.4

Observed results

The most downstream part of the estuary (more or less downstream of location TD 10 and DA 5) has higher salinity levels in the variant situation in the entire simulation period. The entire area upstream of location TD 7 and DA 5 has lower salinity levels in the entire simulation period (see Figure 4.31).

A decrease in salt water intrusion is recorded in the entire simulation period. Large reductions are recorded when the 0.5, 2.0 and 5.0 parts per thousand limits for salinity are considered as can be seen in Table 4.7 and in Figure 4.28 to Figure 4.30.

Causes for the change in salinity levels and salt water intrusion distance

The increased salinity levels in the most downstream part of the estuary occurs because of the enlarged cross-sectional inflow and outflow area of the estuary. As a result the saline water can enter the estuary easier which results in a higher salinity in this area.

The decrease in salinity level in the upstream part of the estuary and the decrease in salt water intrusion occurs because of the (improved) functioning of the brackish water zone in the Enlarged Estuary variant as an obstacle for salt water intrusion. The location of the brackish water zone is shifted in upstream direction because of the geometry of the variant and moves over smaller horizontal distances during a tidal cycle as can be seen in Figure 4.32 to Figure 4.34. The movement over smaller distances occurs because of smaller flow velocities in the area of the brackish water zone (the area of the island in the reference situation). Because of the shift in upstream direction and because of smaller flow velocities less brackish water flows out of the system. As a result the brackish water zone in the Enlarged Estuary variant increases in volume and area and is a very effective obstacle for salt water intrusion. This results in lower salinity levels upstream of this brackish water zone.

Review expectations

An increase in salinity levels is recorded but only for the most downstream part of the estuary. The recorded lower salinity levels in the upstream part of the estuary were not expected but makes this variant very interesting for reducing salt water intrusion.
Less brackish water outflow is seen in the simulation results and this was also expected.

Usefulness Enlarged Estuary concept

The Enlarged Estuary concept is useful to reduce salt water intrusion in estuaries comparable with the modelled estuary. The concept is very effective in reducing salt water intrusion and the positive effect of the variant is directly noticeable in the salt water intrusion results of this estuary.
The Enlarged Estuary variant is maybe more difficult to implement in a real situation than the other considered variants. This is because land area is removed instead of created which could be a problem for densely populated estuary areas.

Table 4.7: Differences in salt water intrusion (compared with Table 4.1)*

	difference after 2 months [km]	difference after 5 months [km]	difference after 8 months [km]
5 ppt limit	-5.6	-13.5	-17.0
2 ppt limit	-11.2	-11.5	-15.7
0.5 ppt limit	-9.3	-16.0	-20.0

Table 4.8: Salinity level differences at some locations (compared with Table 4.2)*

location	Salinity after 2 months [ppt]	Salinity after 5 months [ppt]	Salinity after 9 months [ppt]
DA 17	1.3	1.3	1.3
DA 12	5.0	5.2	5.0
DA 6	2.5	2.6	2.2
DA 2	-1.8	-2.5	-2.7
BS 52	-3.5	-5.3	-6.0
BS 22	-2.7	-5.0	-5.7
VB 33	-0.5	-2.1	-2.7
TD 15	2.0	2.1	1.9
TD 11	0.3	0.2	-0.2
TD 5	-7.2	-9.0	-9.0
TD 2	-5.8	-7.5	-8.0

* the reference situation is used as reference, negative values indicate a reduction of salt water intrusion or salinity levels in the Enlarged Estuary variant.

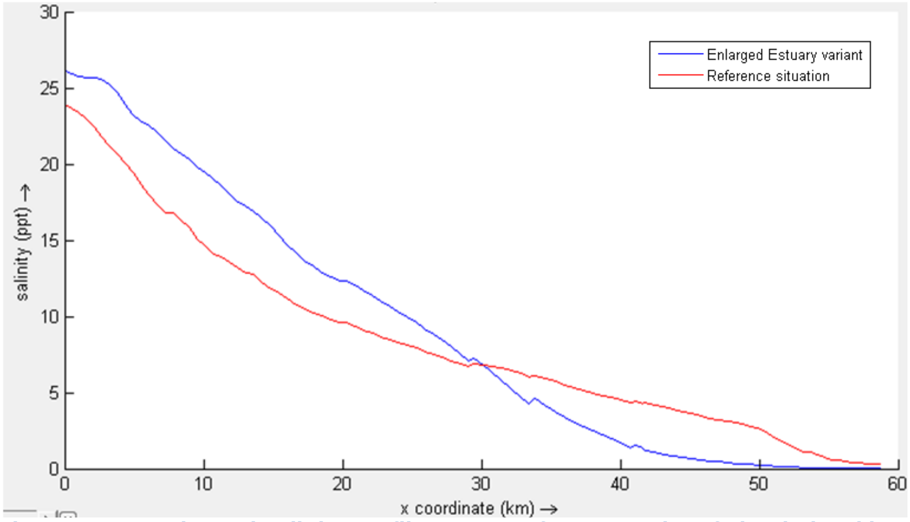

Figure 4.28: Horizontal salinity profile estuary after 2 months of simulation (through the former Dinh An branch)

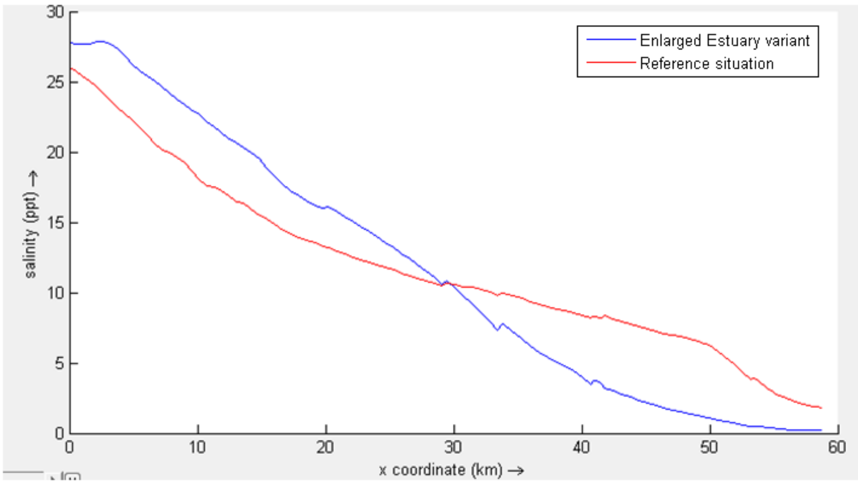

Figure 4.29: Horizontal salinity profile estuary after 5 months of simulation (through the former Dinh An branch)

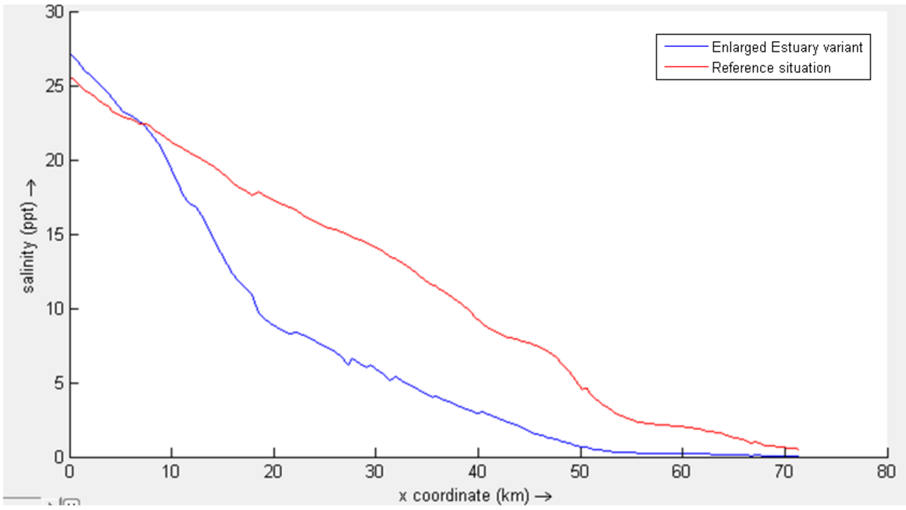

Figure 4.30: Horizontal salinity profile estuary after 8 months of simulation (through the former Tran De branch)

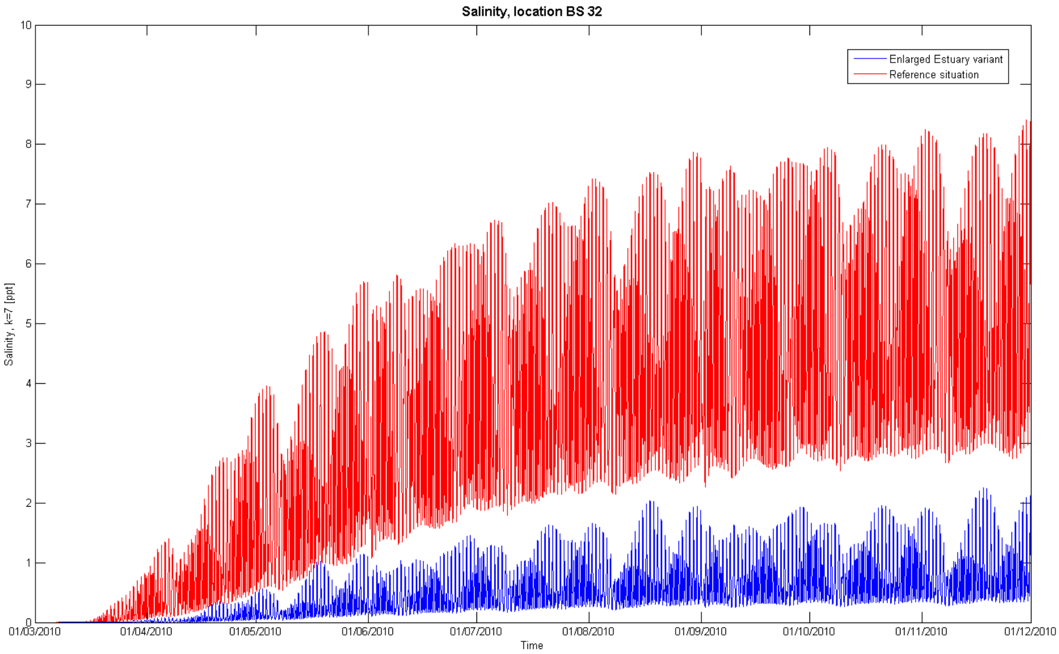

Figure 4.31: Salinity development location BS 32

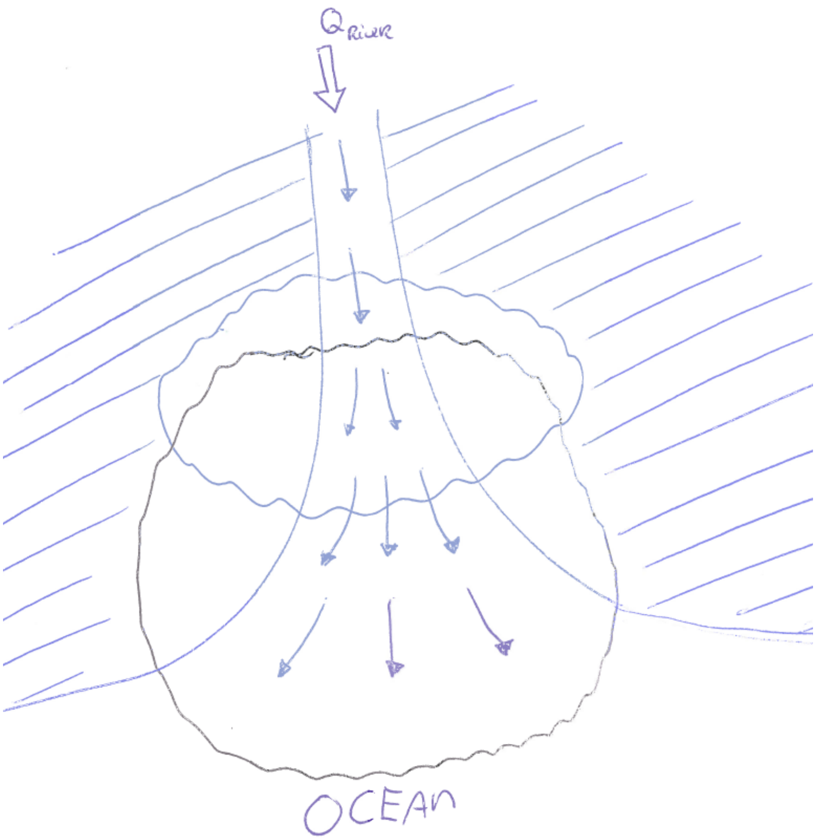

Figure 4.32: Principle of shifting the brackish water zone in landwards direction and the movement over smaller horizontal distances during a tidal cycle. Location of the brackish water zone in a reference situation in black and in an estuary with increased wet estuary area in blue during a tidal cycle.

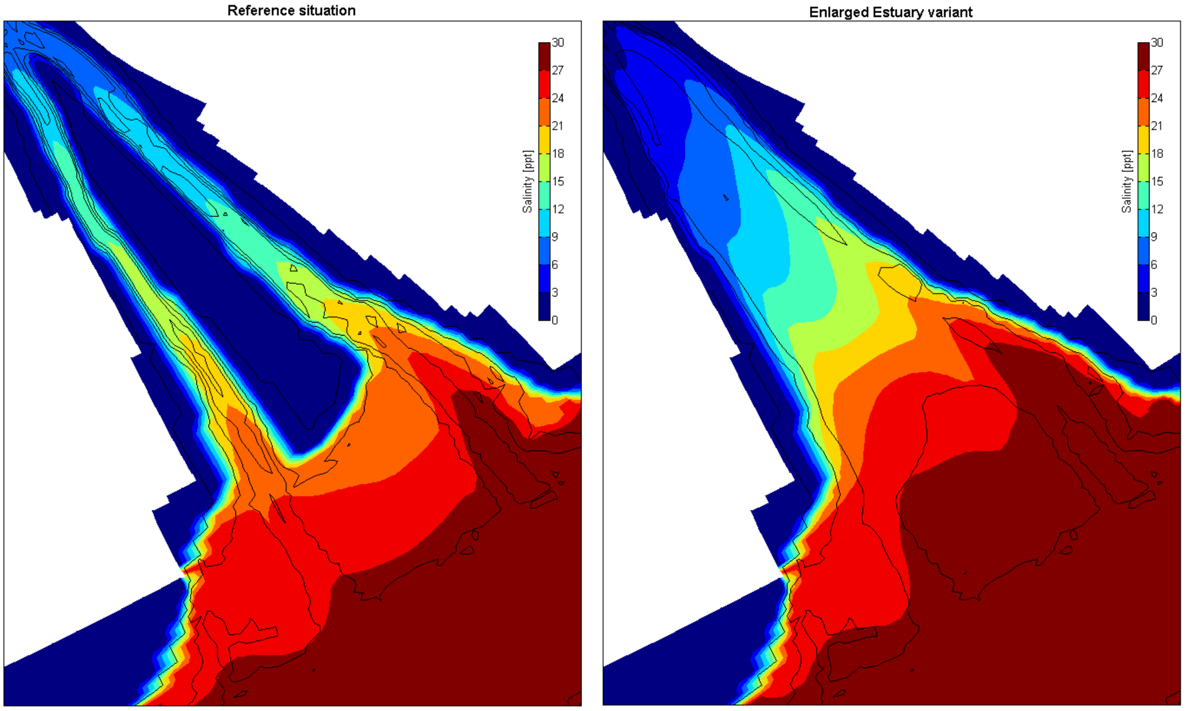

Figure 4.33: Difference in location of the brackish water zone at HWS after 4 months in the reference situation compared with the Enlarged Estuary variant

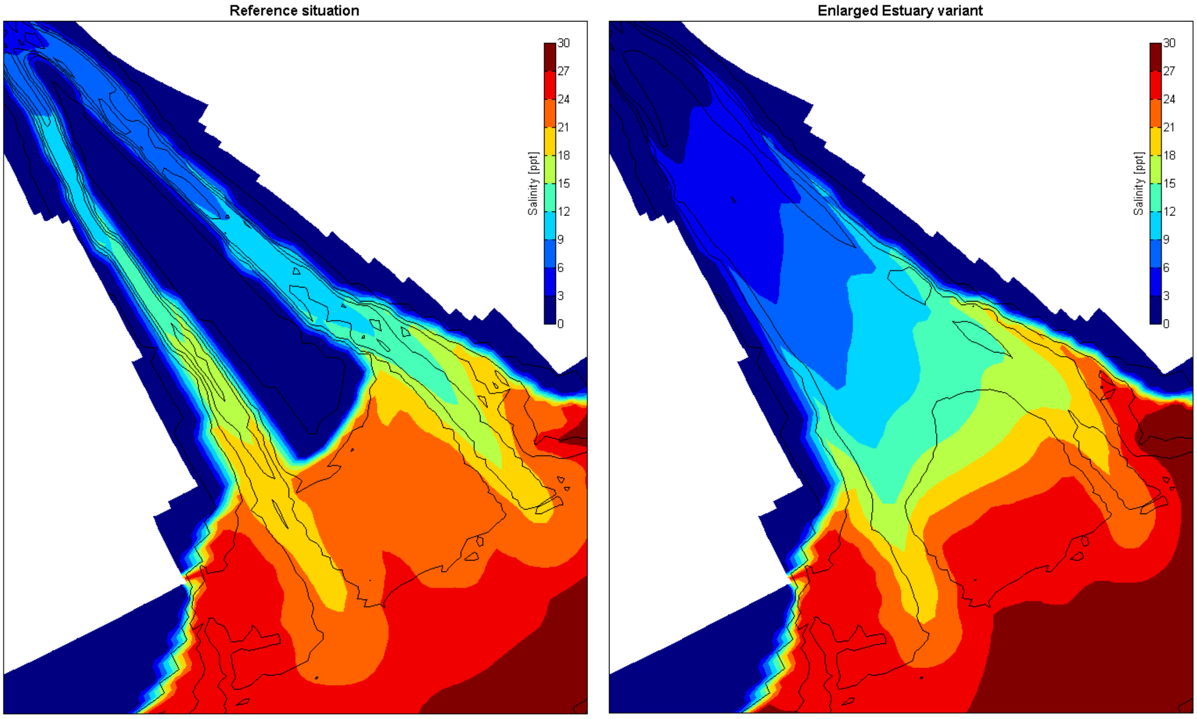

Figure 4.34: Difference in location of the brackish water zone at LWS after 4 months in the reference situation compared with the Enlarged Estuary variant

4.5 Overview results

The three different variants are qualitatively compared in this section. The variants are compared with the available knowledge and with the expected effects on a few aspects. In Table 4.9 a score is given for these aspects for the three variants. For each variant an explanation is given to argue the score. At the end of this section overview tables are given of the salinity levels on locations in the studied estuary and of the salt water intrusion distances of the three variants. These tables are a repetition of the results from Table 4.1 to Table 4.8.

Table 4.9: Comparison of the three kinds of bottom topography adaptations on various aspects

	Seaward Extension variant	Island variant	Enlarged Estuary variant
expected results in other estuaries are the same	-	±	+
morphologic stability	++	-	+
influence on water safety during high discharges	±	-	+
effectiveness on reducing salt intrusion for the studied estuary	-	+	++
effectiveness on reducing salt intrusion in general	±	+	++
usefulness variant for the studied estuary	--	+	++
usefulness variant for etuaries in general	-	+	++
cost-benefit variant	±	-	±

Seaward Extension variant

In this variant a reduction of the brackish water zone and more outflow of brackish water volume resulted in an increased salt water intrusion in the first 4 months.

The salt water intrusion results of this type of adaptation does not have to be the same in other estuaries. It all depends on the effect of the adaptation on the brackish water zone and on the outflow volume of brackish water. This kind of adaptation in other estuaries could result in an equal brackish water zone area and outflow volume as in the present situation but shifted in offshore direction just like the extension. If this happens the horizontal salinity profile into the estuary is shifted in offshore direction as well. An extension of the coastline in offshore direction does not have to result in a more even discharge distribution between branches in a bifurcated estuary. However when the discharge distribution is more even in other estuaries it results in less salt water intrusion because of less water circulation in the estuary system.

The extension in seaward direction does not have a large influence on the morphological process compared with the reference situation. The extended area needs some protection against erosion because of increased exposure to waves and because of a steeper gradient of the banks compared with the reference situation. It is expected that the estuary after this adaptation decreases in depth at the outflow area because of the input of river sediment. When time continues and the sediment input is the same as in the past an equal bottom topography in the outflow area could develop as is now present in the reference situation.

No influence on the water levels during high discharge events is expected because of the bottom topography adaptation. The extended channel area has a larger depth but a smaller cross-sectional flow area compared with the reference situation. As a result the flow resistance is not considerable changed and no increase or decrease in water levels is expected during high discharge events.

In the studied estuary the variant is not effective in reducing salt water intrusion. Only after 4 months of low discharge conditions a reduction could be seen and this reduction is rather small. In general this kind of variant could be effective when the brackish water zone is shifted equally in offshore direction and no increase in brackish water outflow is gained.

Because of the fact that the variant is not effective in reducing salt water intrusion it is not an useful variant for the studied estuary. In general this type of variant could be effective in reducing salt water intrusion when the brackish water zone is shifted equally in offshore direction and no increase in brackish water outflow is developed. However this means the development of a specific shallow outflow area where the brackish water could be retained during outflow. The development of this area increases the costs, is difficult to construct, depends totally on the brackish water zone and the bottom topography will change over time because of the dynamic environment with an unknown effect on the salt water intrusion distance. As a result it is difficult to implement this variant with an equally shifted brackish water zone in offshore direction and without an increase in brackish water outflow.

The costs for this kind of variant are large and the effect on reducing salt water intrusion small. However new land area is created in this type of variant which could be used in densely populated areas for urbanisation or industries and could result in large financial benefits.

Island variant

The island in this variant influences the brackish water zone which results in an increased salt water intrusion in the first 2 months. After 2 months a decrease in salt water intrusion is recorded because of a decrease in tidal range and prism and because of a more even discharge distribution between the two estuary branches.

The effect of an island on the salt water intrusion does not have to be the same in other estuaries and depends on the location of the island and of the brackish water zone. The salt water intrusion increased because of a higher salinity concentration at the South side of the area between the island and the coast. This increase in salinity occurs because of the developed island. Situations in this or in other estuaries could occur where the location of the island enlarges the brackish water area and decreases the outflow of brackish water. As a result a more effective obstacle for salt water intrusion could be present and a reduction of salt water intrusion into the estuary could occur. An island does not have to result in an improved discharge distribution between branches in a bifurcated estuary. However when the discharge distribution is improved in others estuaries it will also result in less salt water intrusion.

The developed island in this variant needs heavy protection against erosion. It is constructed in an area where large forces are present because of flow currents and waves. Without this protection the island is not expected to be stable and it will erode or be reshaped.

During high discharge events the island functions as an obstacle for outflowing river water. The variant has a decreased cross-sectional outflow area because of the island. As a result increased water levels are expected to occur in the estuary during these high discharge events.

The Island variant is effective in reducing salt water intrusion for the studied estuary. The location of the island could maybe be optimised so the variant could even be more effective. In general this type of adaptation of the bottom topography will be effective in reducing salt water intrusion. The effect of islands is a decrease in tidal range and prism in general for most estuaries and could influence the brackish water zone and outflow volume. In the development process of an island the location and the shape of the island is important for the influence on the brackish water area.

The variant is effective in reducing salt water intrusion for the studied estuary. After 2 months a smaller salt water intrusion is recorded. This effectiveness could maybe be increased if the location and shape of the island is optimised. However the developed island is very large and needs protection to be stable which decreases the usefulness of the variant. In general this kind of bottom topography adaptation can be useful to decrease the salt water intrusion. However the usefulness depends very much on the circumstances in the estuary. The stability of an island, the water depth on the location of the island and the influence on the brackish water zone are important aspects which determines of this kind of variant is useful on a specific location.

The construction of an island results in high costs because a large obstacle needs to be created on a location with a certain water depth. This obstacle needs also protection against erosion. The benefits are a reduction of salt water intrusion and new created land area. The land area is expected to be less valuable than in the Seaward Extension variant because no direct connection with the mainland is available which make the area less suitable for industry and urban development. However this depends very much on the location and environment of the island.

Enlarged Estuary variant

The removed island between the two estuary branches resulted in less brackish water outflow and a shift of the brackish water zone in landwards direction. The brackish water zone increases in area and volume and is a more effective obstacle for salt water intrusion. As a result a decreased salt water intrusion is recorded.

When an increase in wet estuary area results in a decreased outflow of brackish water in other estuaries it will also results in less salt water intrusion. A larger brackish water zone in area and volume results in a more effective obstacle for salt water intrusion.

The Enlarged Estuary variant is a large morphologic adaptation. The expected response of the estuary system is that it will decrease the cross-sectional flow area in the area of the removed island because of sedimentation. The amount of sedimentation over a year depends very much on the discharge during the rain season. With some maintenance dredging in the estuary the cross-sectional flow area could be maintained in this area. The sediment input of the river is expected to be decreased in the last decades which could result in a new equilibrium situation with a larger cross-sectional area compared with the reference (present) situation.

The increase in wet estuary area results in an increased discharge capacity and less flow resistance during high discharge events. The variant is expected to have lower water levels during high discharge events compared with the reference situation.

The Enlarged Estuary variant is very effective in reducing salt water intrusion in the studied Hau estuary. In general this type of variant is expected to be effective when the brackish water zone is increased in area and volume as an obstacle for salt water intrusion.

This type of variant is useful in the studied estuary because of the large salt water reductions. This variant is expected to have large reductions in estuaries in general and is as a result also useful for other estuaries. A negative side effect of this kind of adaptation is the loss of land area which decreases the usefulness of this kind of adaptation in densely populated estuaries.

Removing land area is in general cheaper as the creation of new land area. However in the developed variant a large area need to be removed which result in large construction costs and costs because of the disappearance of valuable land area. The benefits are the large salt water intrusion reductions.

Reference situation

The effectiveness of the brackish water zone as an obstacle for salt water intrusion of the reference situation is difficult to increase as can be seen in the results of the variant simulations. In the reference situation an effective brackish water zone as obstacle for salt water intrusion is present. Adaptations of the outer delta which add new land area have a negative effect on this brackish water zone because more brackish water flows out of the estuary. As a consequence the brackish water zone is less effective in this variants as an obstacle for salt intrusion and an increased salt water intrusion occurred.

Tables 4.10 and 4.11 gives an overview of the salinity levels on locations in the studied estuary and of the salt water intrusion distances of the three variants. These tables are a repetition of the results from Table 4.1 to Table 4.8.

Table 4.10: Overview salt water intrusion reference situation and model variants

Salt water intrusion limit	Salt water intrusion reference situation [km]			Salt water intrusion differences Seaward Extension variant [km]*			Salt water intrusion differences Island variant [km]*			Salt water intrusion differences Enlarged Estuary variant [km]*		
	2 months	5 months	8 months	2 months	5 months	8 months	2 months	5 months	8 months	2 months	5 months	8 months
5 ppt limit	38	48	49	5.3 & 1.2	0.1	-0.4	1.6 & 0.4	-1.2	-1.6	-5.6	-13.5	-17.0
2 ppt limit	51.5	57	59	1	-0.1	-3.5	-0.1	-1.8	-5.5	-11.2	-11.5	-15.7
0.5 ppt limit	57	67.5	71	1.6	-0.1	-1.4	0	-1.3	-3.1	-9.3	-16.0	-20.0

Table 4.11: Overview salinity levels reference situation and model variants

location	Salinity reference situation [ppt]			Salinity differences Seaward Extension variant [ppt]*			Salinity differences Island variant [ppt]*			Salinity differences Enlarged Estuary variant [ppt]*		
	2 months	5 months	9 months	2 months	5 months	9 months	2 months	5 months	9 months	2 months	5 months	9 months
DA 17	33.0	33.4	33.4	1.1	1.0	1.0	-1.5	-1.2	-1.2	1.3	1.3	1.3
DA 12	21.5	22.1	22.1	4.0	3.5	3.5	-0.5	-0.4	-0.5	5.0	5.2	5.0
DA 6	9.0	12.5	13.8	3.3	2.8	2.3	0.7	1.0	0.8	2.5	2.6	2.2
DA 2	6.4	10.0	11.1	2.3	1.7	1.2	0.7	0.6	0.2	-1.8	-2.5	-2.7
BS 52	4.8	8.5	9.4	1.0	0.0	-0.3	0.2	-0.8	-1.2	-3.5	-5.3	-6.0
BS 22	2.9	6.0	7.3	0.6	-0.1	-0.5	-0.1	-1.0	-1.5	-2.7	-5.0	-5.7
VB 33	0.6	2.4	3.3	0.2	-0.1	-0.4	-0.1	-0.5	-0.7	-0.5	-2.1	-2.7
TD 15	25.3	26.5	27.6	5.0	4.1	3.8	6.5	5.5	4.5	2.0	2.1	1.9
TD 11	21.4	24.3	25.2	5.0	3.0	2.5	6.7	4.8	4.3	0.3	0.2	-0.2
TD 5	11.8	16.3	17.5	1.5	-0.1	-0.8	1.3	-0.8	-1.5	-7.2	-9.0	-9.0
TD 2	8.6	12.9	14.1	1.0	-0.3	-0.8	0.4	-1.5	-1.8	-5.8	-7.5	-8.0

*the reference situation is used as reference, negative values indicate a reduction of salt water intrusion or salinity levels in the variant simulation.

5 Discussion

In this study the effects of adaptations in the outer delta have been studied with computational models. The results of these models are given in Chapter 4. In this chapter the results of the simulations, the effect of bottom topography adaptations in other estuaries and the reliability of the results are discussed.

What are the influencing aspects that increase or decrease the salt water intrusion in the outer delta variants?

The influencing aspects are:

- the effectiveness of the brackish water zone as an obstacle for salt water intrusion.
- the discharge distribution between the estuary branches.
- the magnitude of the tidal prism and range.

The brackish water zone in an estuary functions as an obstacle for the intrusion of salt water. The effectiveness as an obstacle is determined by the area and volume of the brackish water zone. When more brackish water is held in the estuary system the brackish water zone increases in area and volume. As a result the brackish water zone is more effective as an obstacle and smaller salt water intrusion distances occur. The location of the brackish water zone influences its effectiveness as an obstacle for salt water intrusion as well. In the studied estuary a shift of the brackish water area in offshore direction increases the outflow of brackish water out of the studied estuary because of the presence of a longshore current in this area (see Figure 5.1). As a result the brackish water zone decreases in area and volume and higher salinity levels occur in the estuary. When the brackish water zone is shifted in landward direction it becomes larger in area and lower salinity levels occur (see Figure 5.1). In this situation the system captures more brackish water into the estuary and this enlarged and shifted brackish water zone functions more effectively as an obstacle for the intrusion of salt water. The effect of a shift in location of the brackish water zone on salt water intrusion depends on the local circumstances in an estuary.

A more even discharge distribution results in less circulation of brackish water and therefore in a decrease of the salt water intrusion distance. Adaptations of the outer-delta bottom topography could influence the discharge distribution between estuary branches in a bifurcated system.

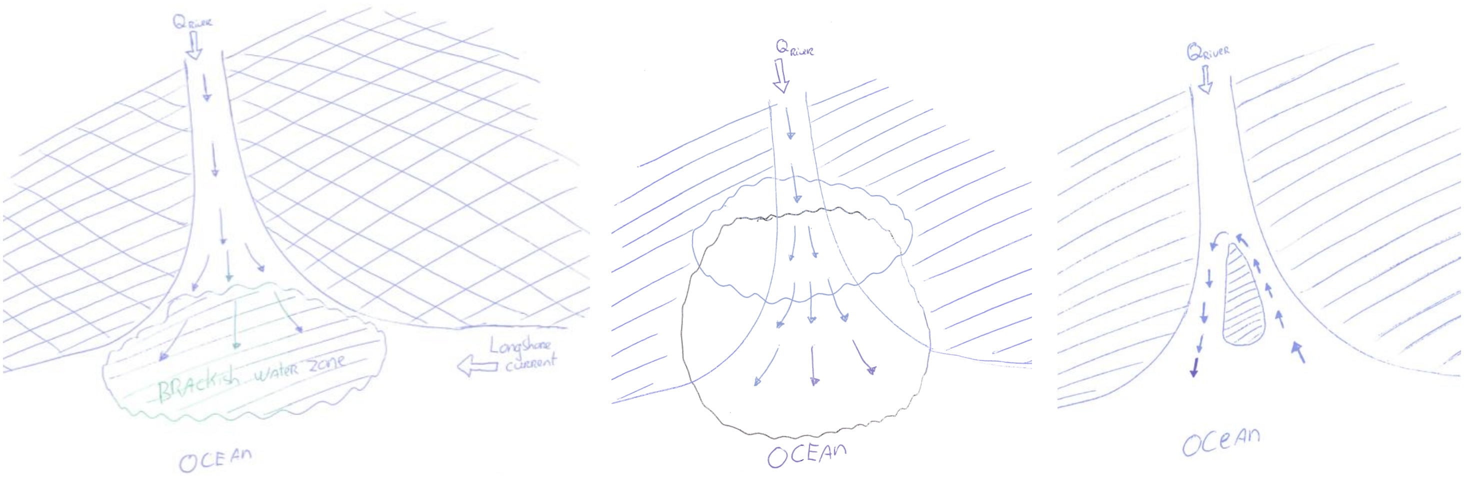

Figure 5.1: Outflow of brackish water out of the estuary because of a longshore current in the left figure, shift of the brackish water zone in landwards direction (in black is the reference situation, in blue the shifted situation) in the central figure, water circulation in a bifurcated estuary in the figure at the right

A reduction of the tidal range and the tidal prism reduces the salt water intrusion distance. However the quantitative influence on salt water intrusion is difficult to determine based on the simulation results of the Island variant. The Island variant is developed with the intention to reduce the tidal prism and range in the estuary system. When results were analysed a reduction of the tidal range was recorded but only a small difference in tidal prism. Besides a smaller tidal range and prism a more even discharge distribution occurred which also contributes to a reduced salt water intrusion after 2 months compared with the reference situation.

In table 5.1 the influencing aspects and their effect on reducing salt water intrusion for the Hau estuary are given for each simulated variant. A positive sign indicates a positive influence of the considered aspect on reducing salt water intrusion, a negative sign a negative influence on reducing salt water intrusion and a plus-minus sign indicates no influence of this aspect on the amount of salt water intrusion.

Table 5.1: Influence of the aspects on reducing salt water intrusion for the Hau estuary

	Seaward Extension variant	Island variant	Enlarged Estuary variant
Effectiveness of the brackish water zone as an obstacle	-	-	+
the discharge distribution between estuary branches	+	+	*
magnitude of the tidal prism and range	±	+	±

* Only one estuary branch present in this variant

Effect of outer delta adaptations on salt water intrusion in other estuaries.

Three kinds of variants and their effects have been studied which are:

- the extension of the coastline in offshore direction to shift the estuarine character of the estuary in offshore direction as well (Seaward Extension variant).
- the creation of an island to develop a brackish water zone and to reduce the tidal water level range and tidal prism (Island variant).
- the enlarging of the estuary by removing land area to decrease the outflow of brackish water out of the estuary (Enlarged Estuary variant).

These variants could influence three aspects that influence the salt water intrusion, which are: the effectiveness of the brackish water zone as an obstacle for salt water intrusion, the discharge distribution between the estuary branches and the magnitude of the tidal range and prism.

Two of the variants add new land area in the outer delta and influence the brackish water zone negatively compared with the reference situation. As a result a larger salt water intrusion occurred. The effect on the brackish water zone does not have to be the same in other estuaries because this depends on the local circumstances of the specific estuary and on the design of the adaptation.

Enlarging the estuary by removing land area resulted in a larger brackish water zone in area and volume. As a result this zone is more effective as an obstacle for salt water intrusion and the intrusion of salt water is less. When more brackish water is held in the system of other estuaries the brackish water zone will also become a more effective obstacle and the intrusion of salt water will be less. The removing of land area in other estuaries will result in a larger or equal brackish water zone in area and volume.

A more even discharge distribution in the studied estuary is seen in the results of the Island variant and the Seaward Extension variant and this effect is noticeable in the salt water intrusion on time scales of months. These kinds of adaptations do not necessarily result in a more even discharge distribution in other bifurcated estuaries. The effect of a more even discharge distribution is a decrease in salt water intrusion and this will be the same for other bifurcated estuaries.

A reduction of the tidal range and prism like in the Island variant results in a reduced salt water intrusion. A reduction in other estuaries in tidal range and prism will also result in a reduction of the salt water intrusion distance.

How useful and reliable are the model results?

The computational model is based on the Hau estuary in order to achieve a model with features of a real estuary. These features are the tidal elevations, discharges, velocities and salt water intrusion into the estuary. The results of the developed model give an indication of the effects of bottom topography adaptations in the outer delta on salt water intrusion. This indication results in more insight into the functioning of the variants and the aspects which increase or decrease the salt water intrusion distance.

An important result of the study is insight into the important influencing aspects for the intrusion of salt water, such as the influence the brackish water zone and the discharge distribution. These aspects need to be taken into account when changing the outer-delta bottom topography is considered to reduce salt water intrusion in other estuaries. The large influence of the river discharge on the salt water intrusion distance is another aspect which became clear. These results can be used in other estuaries where salt water intrusion is a problem. As a result of this study insight into the importance of these aspects is obtained. When salt water intrusion in other estuaries is considered these aspects are important and need to be studied in detail to gain insight whether the influence of bottom topography adaptations will be positive.

Results of this study do not give information about the quantitative effectiveness of adaptations in other estuaries. As has been seen in this study the effect of certain adaptations are complex and difficult to predict and this effectiveness study is only based on one estuary. With this study, predictions of the effect of outer-delta bottom topography adaptations can be made better and more accurate for other estuaries. The quantitative effectiveness in other estuaries of certain outer delta adaptations is unknown. As a consequence the effectiveness results of this study cannot be used to predict the quantitative effectiveness of adaptations for other estuaries with different geometry, tidal forcing and river discharge.

The reliability of the quantitative results for the Hau estuary are difficult to determine. The results gives a good indication of the effectiveness of adaptations for the Hau estuary, but a more elaborated calibration and validation of the model is needed to judge the reliability of these quantitative effects.

The influence of fresh river discharge on the salt water intrusion distance.

The amount of river discharge has a significant influence on the salt water intrusion distance as described in Appendix D. During the development of the Delft3D model the influence of the river discharge became visible. Appendix D shows results of the sensitivity of the model to the amount of river discharge. A discharge of 200 m^3/s results in a salt water intrusion of 55 km after 3 months and a discharge of 1,000 m^3/s results in a salt water intrusion of 15 km in the reference situation. The discharge parameter has a significant influence on the salt water intrusion distance. The importance of the river discharge is larger than expected based on literature research.

The influence of water level increase/decrease on the salt water intrusion distance.

A water level increase or decrease has only a small influence on the salt water intrusion distance for the area of a salinity of 5 parts per thousand or less. In appendix D the sensitivity of the model results to the applied water level boundary is given. Water level boundaries have been applied with a vertical shift of the entire water level signal of +0.3 and of -0.3 metre in the reference situation. An increase in water level boundary signal showed increased salinity levels until the 5 parts per thousand limit. And a decrease of the water level resulted in a decrease of the salinity levels until the 5 parts per thousand limit. In the area of salinity levels of 5 parts per thousand or less (which is an interesting area for salt water intrusion problems) no significant differences are seen in the salt water intrusion distance.

It is difficult to influence the tidal prism by the creation of islands in the outer delta.

The intention of the Island variant was to reduce the tidal range and the tidal prism. Although a very large island is implemented in this variant the reduction of the tidal prism remained small. In order to reduce the tidal prism considerably a large part of the estuary opening need to be closed off (an even larger closure than implemented in the Island variant).

Salt water intrusion into the Hau estuary.
The variant simulations show that it is difficult to improve the effectiveness of the brackish water basin of the reference situation with adaptations which add land area to the estuary (like the Seaward Extension variant and the Island variant). Adaptation variants which add land area are resulting in a less effective brackish water basin as an obstacle for salt water intrusion compared with the reference situation.

An additional effect of these two variants is a more even discharge distribution between the two branches in the estuary which results in a positive effect on reducing salt water intrusion. However a more even discharge distribution can also be obtained with other smaller and more effective implementations in the estuary.

Removing the natural island between the two branches in the Enlarged Estuary variant showed positive results in reducing salt water intrusion for the modelled Hau estuary. The brackish water basin area is enlarged, shifted in upstream direction and moves over smaller horizontal distances during a tidal cycle. Less brackish water flows out of the system and the brackish water zone functions more effectively as an obstacle for salt water intrusion compared with the reference situation. The removal of the natural island is a large morphologic adaptation. The expected response of the system is that it will decrease the cross-sectional flow area in the area of the removed island by sedimentation. With some maintenance dredging and because of decreased sediment input over the last decades a larger cross-sectional flow opening area could develop compared with the present (reference) situation.

The developed model in this study is based on the Hau estuary. The model is calibrated and validated. The exact relation between the model and reality is however not known because too little recent information and measurement data were available and the model could not be calibrated and validated in detail. However a detailed validation and calibration was also not necessary for this study in order to gain study results for the general effect of adaptations in estuaries. For the Hau estuary a reliable indication of the effectiveness and of the salt water intrusion problems is given with the model. However how accurate these results exactly are is unknown. The salinity levels in the estuary during the dry season are a very important aspect to know in more detail to calibrate and validate the model. Furthermore the river discharge is an important parameter but the data of this parameter have a large uncertainty during the dry season in the studied estuary.

6 Conclusions

In this chapter the research questions of Section 1.2 are answered.

1. *Which aspects are influencing the salt water intrusion because of adaptations of the bottom topography? And which aspect has the largest influence?*

The aspects influencing the salt water intrusion because of outer-delta bottom topography adaptations are:

- the effectiveness of the brackish water zone as an obstacle for salt water intrusion.
- the discharge distribution between the estuary branches.
- the magnitude of the tidal prism and the tidal range.

The effectiveness of the brackish water zone as an obstacle for salt water intrusion has the largest influence when time periods of up to approximately 2 months are considered. The effect of an influenced brackish water zone is directly noticeable (short-time effect) and has large influences as can be seen in the Enlarged Estuary variant, the Seaward Extension variant and in the Island variant.

When longer time periods are considered the influence of a changed discharge distribution between estuary branches (reduced water circulation) and a change in magnitude of the tidal range and prism becomes visible. These effects gain relative importance when the period of low discharge conditions continues and can be seen as long-term effects. The study results do not provide information about the relative importance of a changed discharge distribution versus a changed tidal range and prism.

The influence of a changed discharge distribution and a change in magnitude of the tidal range and prism theoretically overrides the influence of a changed brackish water zone effectiveness after a certain period when the applied boundary conditions are everlasting. However when a longer period than 7 months is needed this situation is not realistic anymore.

The importance of the long-term effects in estuaries depends also on the occurring river discharges during the year. When long periods of low discharges occurs these long-term effects have a relative larger importance compared with situations which only have low discharges during a short period.

2. *Which kind of outer-delta bottom topography adaptation is most effective?*

Adaptations based on increasing the effectiveness of the brackish water zone as an obstacle for salt water intrusion are most effective when short time scales are considered. Increasing this effectiveness can be obtained by reducing the outflow of brackish water out of the estuary with for example outer-delta bottom topography adaptations. The effectiveness of the adaptations depends on the circumstances of the specific estuary and the adaptations made in the bottom topography. It is expected that for a lot of estuaries the focus on increasing the effectiveness of the brackish water zone for reducing salt water intrusion is most effective. This is certainly the case for the studied Hau estuary as can be seen in the salt water intrusion distance results of the different variants in Table 4.10 where the Enlarged Estuary variant showed a large salt water intrusion reduction compared with the two other variants.

3. *To what extent can salt water intrusion be influenced by adaptations of the bottom topography of the outer delta?*

This depends on the local circumstances of each estuary, and on the kind and magnitude of the adaptations in the bottom topography. In the Hau estuary increases and decreases in salinity are seen in the variant simulations.

The maximum increases in salt water intrusion distance in this study are 5.3 (5 ppt salinity limit), 1.0 (2 ppt salinity limit) and 1.6 (0.5 ppt salinity limit) kilometre after 2 months in the Seaward Extension variant. These increases are because of a decrease in area and volume of the brackish water zone. More extreme increases in salt water intrusion can be achieved with other outer delta adaptations of the bottom topography. However these other adaptations are not considered in this study because the objective of this study is focussed on reducing salt water intrusion instead of increasing them.

The maximum decreases in salt water intrusion distance in this study are 5.6 (5 ppt salinity limit), 11.2 (2 ppt salinity limit) and 9.3 (0.5 ppt salinity limit) kilometre after 2 months and 17 (5 ppt salinity limit), 15.7 (2 ppt salinity limit) and 20 (0.5 ppt salinity limit) kilometre after 8 months in the Enlarged Estuary variant. These decreases in salinity occur because of the increase in area and volume of the brackish water zone and because of a shift in upstream direction of this zone. The salt water intrusion distance differences of all three variant simulations can be seen in Table 4.10.

4. *To what extent can the results of this study be used in other tide dominated estuaries?*

The main result which can be used in other tide dominated estuaries is the importance of the influencing mechanisms. When changing the outer-delta bottom topography in other bifurcated estuaries is considered the influence on the brackish water zone, on the discharge distribution and on the tidal prism is important for the amount of salt water intrusion. A changed effectiveness of the brackish water zone as an obstacle for salt water intrusion is directly noticeable (short-term effect) and the effects of a changed discharge distribution and changed tidal prism and range are noticeable on longer time scales (long-term effect).

With the simulation results, predictions of the (possible) effects of certain outer-delta bottom topography adaptations in other estuaries can be made better.

Results of this study do not give information about the quantitative effectiveness of outer-delta bottom topography adaptations in other estuaries, although the results can be used to give an indication of the possible effectiveness.

7 Recommendations

General recommendations are given for changing the topography of the outer delta of an estuary to reduce salt water intrusion into estuaries as well as recommendations specific for the Hau estuary.

General recommendations: changing the outer delta to reduce salt water intrusion

- It is recommended to focus on decreasing the outflow of brackish water to reduce salt water intrusion when bottom topography adaptations are considered instead of decreasing the tidal range and prism. The volume and area of the brackish water zone have a large influence on the amount of salt water intrusion. Shallow areas near the estuary’s outflow could be useful to retain the brackish water and to decrease the outflow out of the estuary.
- Study the effectiveness and possibilities of reducing salt water intrusion by acting on river discharge. The river discharge is very effective in pushing back the intruded salt water. Acting on river discharge to reduce salt water intrusion by flushing events has potential in becoming a solution to reduce salt water intrusion. The possibilities of acting on river discharge depends on the environment of the estuary and the possibilities of influencing the river discharge (the possibilities of using water retention reservoirs for example). Besides the possibility to influence the river discharge, the effectiveness of reducing salt water intrusion by increasing the river discharge needs to be studied and the required volume for flushing events.
- Further research on the location of the brackish water zone and on the possibilities to influence this zone in estuaries. The effectiveness of the brackish water zone as an obstacle for salt water intrusion has a large influence on the salt water intrusion distance. When the effect of adaptations on this brackish water zone is better known, adaptations could be developed, which influence the brackish water zone positively and make it a more effective obstacle for salt water intrusion. To know the effect of adaptations, the location of the brackish water zone before any adaptations are made need to be known and need to be studied in detail. Further research on the functioning of the brackish water zone, on the location of this zone during the year and on the possibilities to influence the effectiveness of this brackish water zone is recommended.
- Gain more general insight into the effects of adaptations of the bottom topography of outer deltas with computational model studies in other estuaries. These computational model studies can give more insight into the possibilities of reducing salt water intrusion by changing the outer-delta bottom topography. Will the same qualitative and quantitative results be obtained? Will the same relative importance of mechanisms be found? Which differences can be seen between the modelled estuaries? With model studies in other estuaries a rule of thumb or an equation for the effectiveness of reducing salt water intrusion can maybe be developed.
- Besides the salt water intrusion distance, other effects because of changes in the bottom topography of the outer delta need to be studied. Adaptations of the outer delta do not only influence the salt water intrusion distance but other aspects as well. They may for example have an effect on water safety during high discharge events, on the morphology of the estuary and on nature. All these effects need to be taken into account when adaptations of the outer-delta bottom topography are considered.
- Gaining more measurement data of water depths and salinity levels when outer delta adaptations in reality are considered. When more measurement data (and more recent data) of the estuary are available a more detailed and better validated and calibrated model can be developed. As a result the effectiveness of adaptations in the outer-delta bottom topography can be predicted with a larger reliability.
- More measurements of the effective river discharge into estuaries to decrease the uncertainty of this parameter. The effective fresh river water discharge amount into estuaries has a large influence on the salt water intrusion distance but this parameter has

often a large uncertainty during the dry season. To predict and model salt water intrusion into estuaries accurately the effective fresh river water discharge quantity need to be known. When this parameter is more accurate, better salt water intrusion predictions can be made and the influence of discharge changes can be linked to the salt water intrusion problems. More measurements of this fresh river discharge parameter during the dry season could reduce the uncertainty of this parameter.

- More detailed studies on the causes of salt water intrusion and on the effect of all kinds of adaptations in the estuary need to be executed. When these processes are known in more detail new kinds of solutions which are attractive to implement into estuaries could maybe be developed to reduce salt water intrusion. This could result in solutions in natural estuaries without the need of building weirs and without the negative effects of these weirs.

Recommendations: reducing salt water intrusion into the Hau estuary

- Interesting solutions to reduce the salt water intrusion besides outer-delta bottom topography adaptations into the Hau estuary which could be considered are:
  - realise a more even discharge distribution between the Tran De and Dinh An branch. Adaptations in the branches or at the bifurcation point could be made to influence the discharge distribution. The discharge distribution in the present situation in the dry season needs to be studied further as well because no measurement information about this distribution is available at the moment.
  - increase the river discharge amount during the dry season. This results in less salt water intrusion. The possibilities of using water from retention reservoirs, influencing the discharge distribution at the Vam Nao connecting river or decreasing the water extraction amount should be investigated.
  - a close off of one of the branches in the dry season. A weir in one of the branches which is only closed during low discharge conditions could reduce salt water intrusion. When the weir is closed during low discharge conditions no salt water intrudes through the closed branch anymore. Because of the closing of one branch more fresh river water flows through the other branch and this increases the fresh river water discharge through the open branch.
- Adaptations in the Hau estuary to reduce salt water intrusion need to be well analysed before implementation. The Hau estuary is a complex environment with different (conflicting) problems and many stakeholders. When bottom topography adaptations are considered the negative influences of these adaptations need to be taken into account as well. The Enlarged Estuary variant for example is very effective in reducing the salt water intrusion distance. However the variant also influences the aquaculture (shrimp farming), the mangrove system and other nature aspects in the Hau estuary area.

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Appendices

A - BALANCE ISLAND CONCEPT

The Haringvliet case

The Balance Island concept has its origin as a solution for a problem in the Haringvliet delta in the Netherlands. The Haringvliet delta is located in the Southwest of The Netherlands. It was an open estuary until 1970. In that year the construction of sluices in the estuary were completed and the Haringvliet estuary became a closed estuary. The sluices are open during ebb conditions for discharging fresh water from the Rhine and Maas into the sea and closed during flood conditions. The sluices are constructed as a part of a delta plan to protect the hinterland against flooding.

As a result of the Haringvliet sluices a fresh water basin developed behind the sluices and a salt water environment before the sluices. The strong division of salt and fresh water around the sluices has got a negative influence on nature and ecology in that area. Animal and vegetation species which lived in brackish water conditions died for a large part. As a result the special and rare ecosystem changed considerably. Furthermore fish species could not swim from the sea water into the river system anymore.

Figure 0.1: The Haringvliet estuary and the Haringvliet sluices

At the beginning of the 21st century the hindered possibility of fish species to migrate from the sea into the river system became an issue in the politics of the European Union. Decisions and actions were made to restore the possibilities for fish migrating. An action which needed to be taken by the Netherlands was to create a possibility for fish to swim from the sea into the river system. In order to achieve this the Netherlands aimed to (partly) open the Haringvliet sluices.

A consequence of opening the Haringvliet sluices is (some) salt water intrusion into the Haringvliet estuary behind the sluice complex. This could have a positive effect in developing brackish water eco-systems but has also negative aspects. These negative aspects arise because of changed usage of the Haringvliet water area behind the sluices compared with the period before 1970. Behind the Haringvliet sluices agricultural areas and inlets for drinking water are present. Both aspects will negatively be affected by salt water intrusion. As a result the action of The Netherlands to open the sluices delayed some years. The Balance Island concept is developed as a possible solution to create a possibility for fish to migrate but with no or less negative influence on the hinterland.

General Balance Island concept

The Balance Island concept consists of a few ideas. These ideas are:

- The possibility of creating stable islands of sand without protection in the outer delta.
- The possibility of influencing the estuarine character of an estuary by creating islands. The intrusion of the tide and the intrusion of saltwater into the estuary can be influenced by islands in the outer delta.
- The possibility of influencing velocity patterns in the outer delta with created islands.

Balance Island concept in the Haringvliet case

The Balance Island concept for the Haringvliet consisted of the creation of an island in the shallow foreshore of the estuary in order to reduce the salt water intrusion distance. Because of the island a basin in the outer delta is created where salt and fresh water can mix. As a result the intruded water into the estuary will first go through the basin and will have a lower salinity level. The intrusion length of the salt water depends among other things on the salinity level. Because of a lower salinity level the water will intrude over a shorter distance. Moreover the average salinity of the intruded water will also be less. With a balance island the sluices could be opened for a longer period and/or will have less (negative) influence on the hinterland.

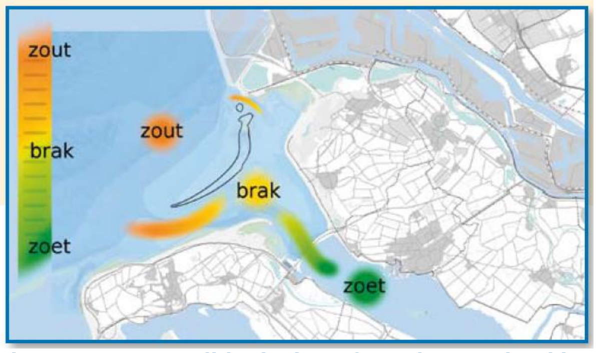

Figure 0.2: A possible design of a Balance Island in the Haringvliet estuary

At the moment the Haringvliet estuary is not in an equilibrium state because of human interference in the past. Research showed that four possible (natural) end situations are possible for this estuary. With the Balance Island concept the estuary is forced to develop one specific situation which is situation 3 in Figure 0.3. The Balance Island is not meant as a static island in this estuary. It should be made out of sand without manmade protection works on it, although vegetation could develop and this could function as protection. The island location in the estuary could be dynamic just like other processes in the estuary.

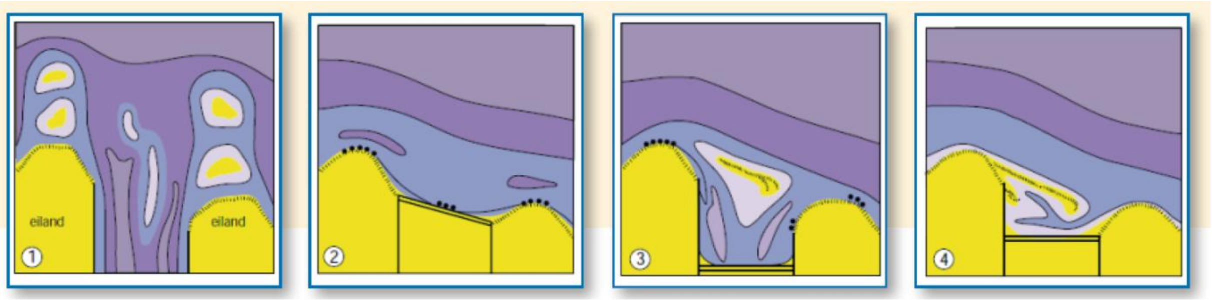

Figure 0.3: Overview: four possible dynamic situations for the Haringvliet estuary

A Balance Island in the outer delta of the Haringvliet estuary has great potential in becoming a high quality area for nature development for example for species which live in a brackish water habitat. Areas with a brackish environment have been becoming scarce in the last decades.

The concept of Balance Island fits in the new strategy principle of ‘building with nature’. This concept has got potential in being a sustainable, a low maintenance and a flexible solution for sea level rise and salinity problems. The Balance Island concept showed also to be an economically feasible solution for the Haringvliet case.

A combination of all these arguments showed that the Balance Island has got potential as a solution for the Haringvliet case. Because of this it is interesting to investigate if there are other deltas in de world where this concept could be a solution for certain problems in the delta. However there are some knowledge gaps about the applicability of the concept.

Research results Haringvliet case
For a first indication of the effectiveness in reducing the salinity concentration in the Haringvliet case usage is made of equations and work of Savenije. With the creation of a Balance Island the horizontal particle excursion in the Haringvliet could increase with 10 kilometre to a total of 20 kilometre. For the Haringvliet situation a decrease of 30 percent in salinity for every 10 kilometre of estuary length is expected. In a test where the Haringvliet sluices were opened the salt water intruded over a distance of 10 to 13 kilometre. With the reduction of 30 percent in salinity it is expected that the salt intrusion distance will also be reduced by 30 percent. Which results in a possible reduction of 3 to 4 kilometre in the Haringvliet case.

After the winning of the Delta Water Award and the Delta Alliance Young Professional award in 2012 and with the expected reduction effect of 30 percent in salinity a more detailed study is done to the Balance Island concept for the Haringvliet estuary. A simple Delft3D model was developed by de Kort (de Kort, 2013) where simplified estuary shapes and the Haringvliet estuary were modelled in. The study showed difficulties in creating the desired effect of reducing the salinity levels. Some model variants showed an increase in salinity because the fresh water left the estuary faster because of an island in the outer delta, other variants showed a reduction of salinity. The location of the island showed large importance on the effects. The model study for the Haringvliet case showed a reduction of 30 percent in salinity (from 3.6 to 2.5 ppt) on 10 kilometre distance from the estuary mouth and a reduction of salt water intrusion of 2 kilometre when the 0.5 ppt salinity level is used.

The effectiveness of the Balance Island concept for the Haringvliet is based on increasing the distance for particles to travel from the North Sea into the Haringvliet estuary and on creating a mixing basin between the estuary and the North Sea.

After these studies more information is gained about the effectiveness of a Balance Island to reduce salt water intrusion, however how effective the concept could be in other deltas in the world is still unknown. Three knowledge gaps regarding the technical possibility of the concept are:

- Is it possible to create stable islands in the outer delta of certain deltas?
- What is the effectiveness of created islands in the outer delta on reducing salt water intrusion? And what is the effect of created islands on other processes in the delta?
- Are there deltas present where a Balance Island could be a solution for the specific delta problems?

B - PARAMETERS USED IN THE DELFT3D SIMULATIONS

In this appendix an overview of the most important settings of the 3D Delft3D model are given.

Time frame

Simulation period:	1-3-2010 to 1-12-2010
Time step:	60 seconds

Vertical layering

Number of layers:	10
Layer thickness [%]:	15, 15, 15, 10, 10, 10, 10, 5, 5, 5 (from top to bottom)

Processes

Constituents:	Salinity

Initial conditions

Uniform value water level:	-0.3 metre
Uniform value salinity:	0 parts per thousand [ppt]

Boundaries

Upstream boundary:	Constant discharge boundary (200 m^3/s)
Salinity condition	0 parts per thousand [ppt]
Thatcher-Harleman time lag:	0 minutes
Downstream boundary:	Time series water level signal
Salinity condition:	35 parts per thousand [ppt]
Thatcher-Harleman time lag:	90 minutes

Physical parameters

Chezy roughness coefficient:	55 $m^{0.5}/s$
Horizontal eddy viscosity	1 m^2/s
Horizontal eddy diffusivity	10 m^2/s
Model for 3D turbulence	κ-epsilon model

Output

Store map results:	120 minutes (10 minutes for some parts of the simulation period)
Store history interval:	5 minutes

C - VERIFICATION AND CALIBRATION OF THE DELF3D MODEL

In this appendix simulation results of the reference situation of the Delft3D model are given. Some of the results are compared with real life measurements in order to investigate how realistic the model results are with respect to the actual situation in the Hau estuary. Furthermore is the discharge determined where the salt water intrusion in the model is similar with measured salt water intrusion. The topics that are described are:

- The water level boundary
- The discharge boundary
- The salt water intrusion
- The vertical salinity distribution
- The flow velocities

Water level boundary
Two water level measurement stations and one hydraulic model of the South China Sea are available for this study in the study area. A perfect match between modelled and measured water levels is not possible. The reasons for this are the complexity of the tidal signal in the study area, local influencing factors as the wind and the shape of the estuary, the few measurement stations and a time lag between bathymetry survey and water level measurements of 1 to 2 years.

The water level boundary in the model is generated from the South China Sea Model (SCSM) of Gerritsen (Gerritsen, 2003) for the period of 1-3-2010 to 1-6-2010. The SCSM does not use the same reference system for elevation as used in the created Hau Estuary Model (HEM) in this study. The developed HEM is based on the Hon Dau national elevation landmark of Vietnam. As a result the bathymetry of the model is in the Hon Dau reference system so all the other data in this study should be as well. The reference system of the SCSM is probably a reference system in Singapore because that is the study area where the SCSM is developed for. In order to convert the generated water level signal of the SCSM to a water level signal with Hon Dau as reference system, water level measurements of the Hau estuary are used.

Two water level measurement stations are present in the modelled Hau estuary where measurement data are available from and which can be used in this study. It is a station at Can Tho and a station downstream of the Dinh An branch. The measurement data of the Can Tho station are in the Hon Dau reference system. The measurement data of the Dinh An station are in ‘Charts datum’. The conversion factor from chart datum of Dinh An to Hon Dau reference system is not known. So this station is only used to check the tidal range and tidal signal of the Delft3D results.

Figure 0.4: Overview location measurement stations

The water level signal gained from the SCSM is shifted vertically with -0.3 metre based on the water level measurements and the Delft3D model simulations. This is resulting in the following Delft3D model results of the reference situation for the water level signal at the Can Tho and Dinh An measurement stations and at the boundary of the Delft3D model on the South China Sea side.

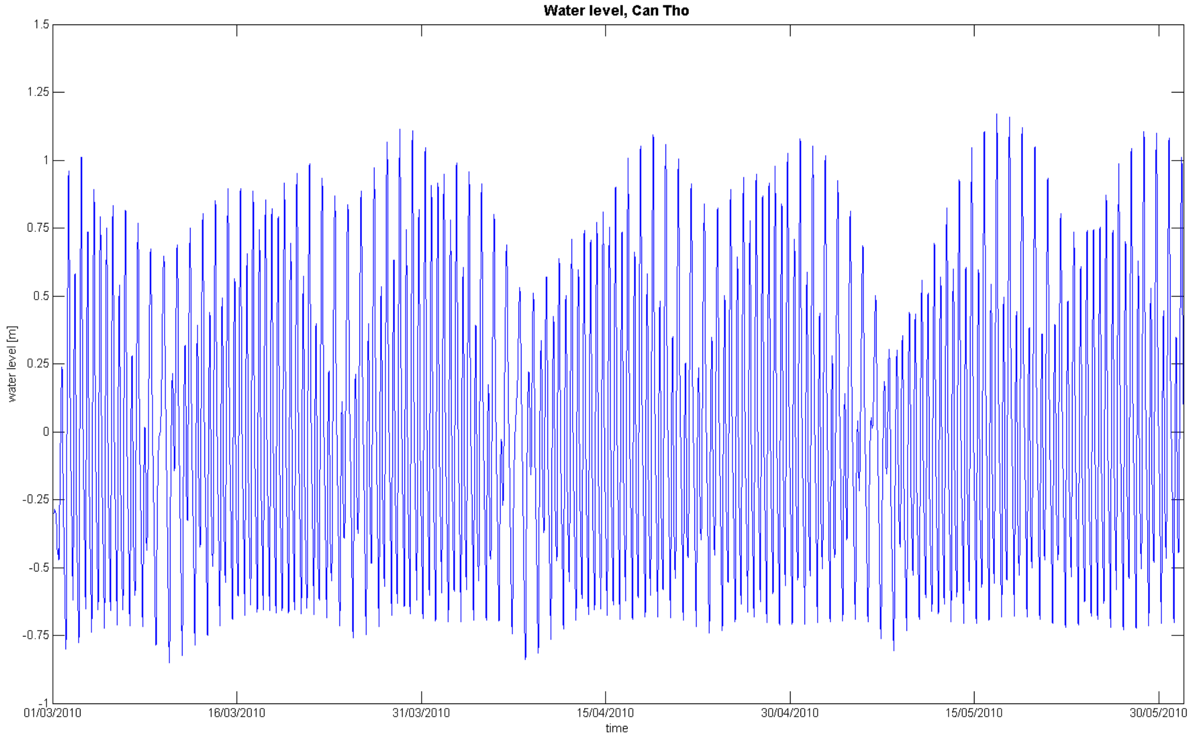

Figure 0.5: Water level signal Delft3D simulation at Can Tho

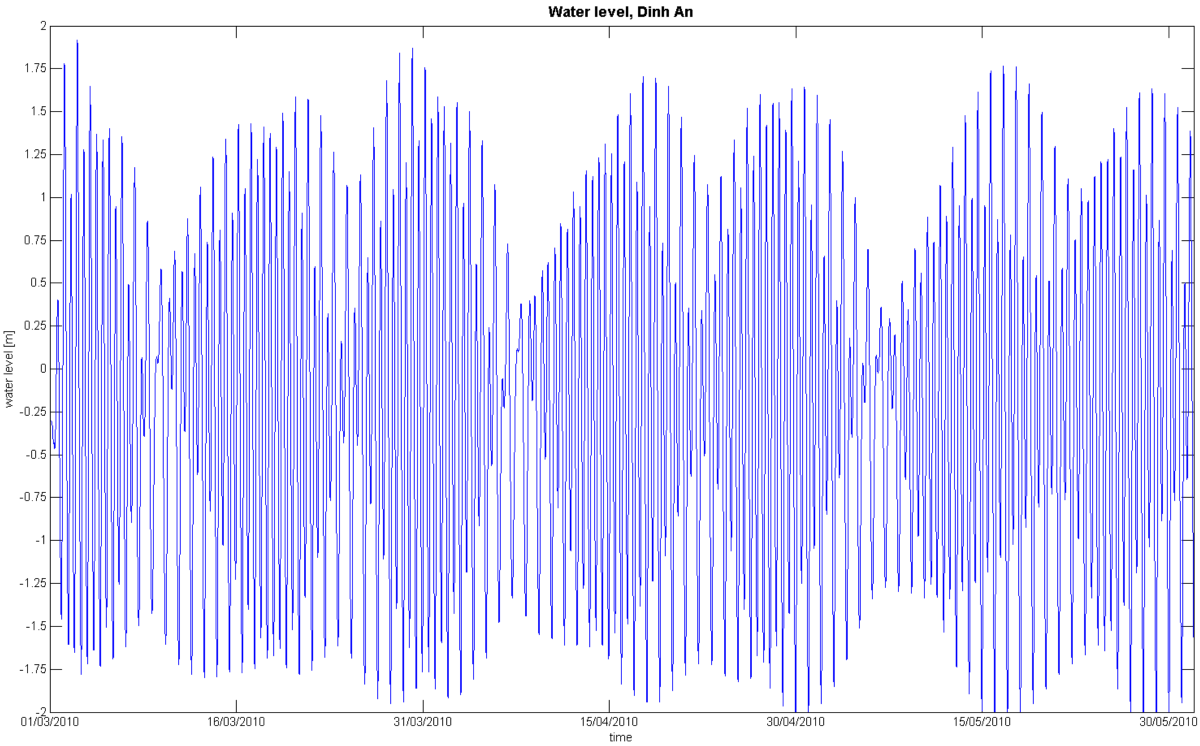

Figure 0.6: Water level signal Delft3D simulation at the Dinh An measurement location

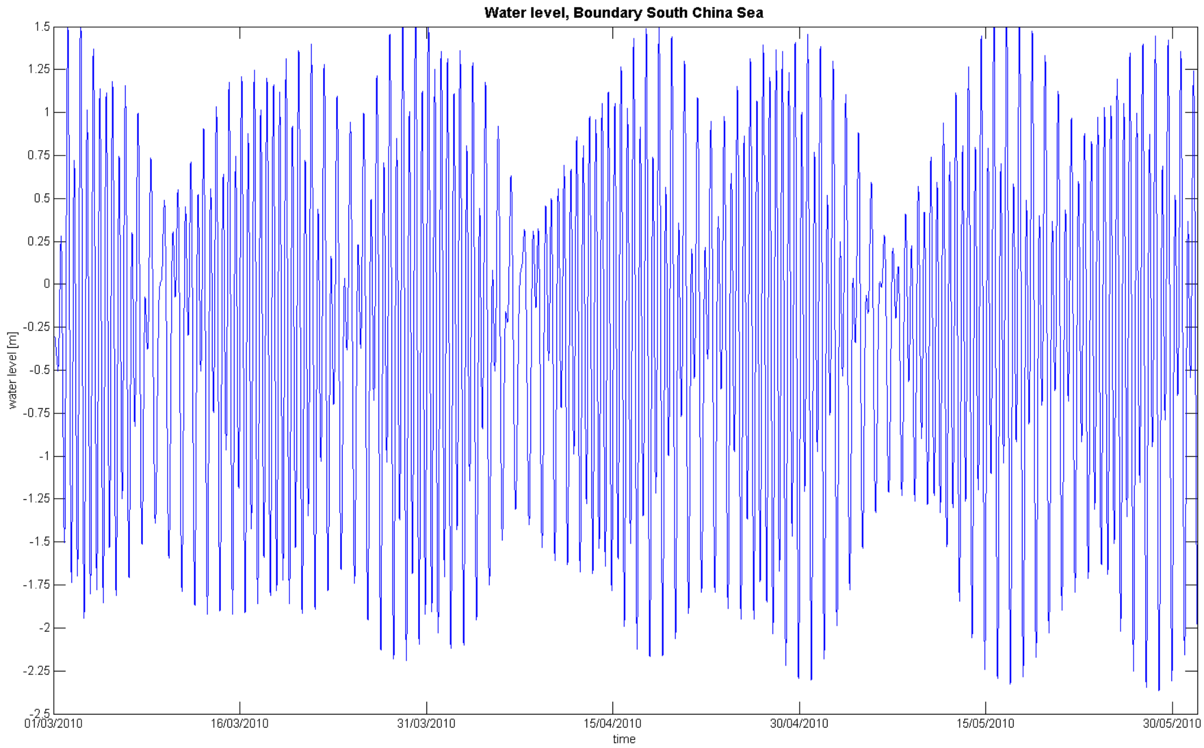

Figure 0.7: Water level signal Delft3D simulation at the South China Sea boundary

<u>Can Tho</u>
The Delft3D model results at Can Tho shows a tidal range of 2.0 metre with a maximum of 1.1 metre and a minimum of -0.9 metre in Hon Dau reference level (Figure 0.5). The lowest high water value in this period is 0.3 metre and the highest low water value is -0.7 metre. These data can be compared with the measurement data of the Can Tho station (also in Hon Dau reference level) which can be seen in Figure 0.8.
The measured data at Can Tho shows a tidal range of 2.4 metre with a maximum of 1.3 metre and a minimum of -1.1 metre. The lowest high water in this period is 0.8 metre and the highest low water is -0.5 metre. There is a small difference between the measured and modelled tidal range and maximum and minimum water level. There is also some difference between the shapes of the tidal signals of the modelled and measured data. The differences are because of the complexity of the tidal signal in the South China Sea, only a few qualitatively well measurement datasets to calibrate the boundary water level signal, local influencing factors as the wind and the shape of the estuary and because of a time lag between the bathymetry survey and water level measurements.
A perfect match between modelled and measured waterlevels is not possible. The modelled results are always an approximation of the reality and of the measurements.

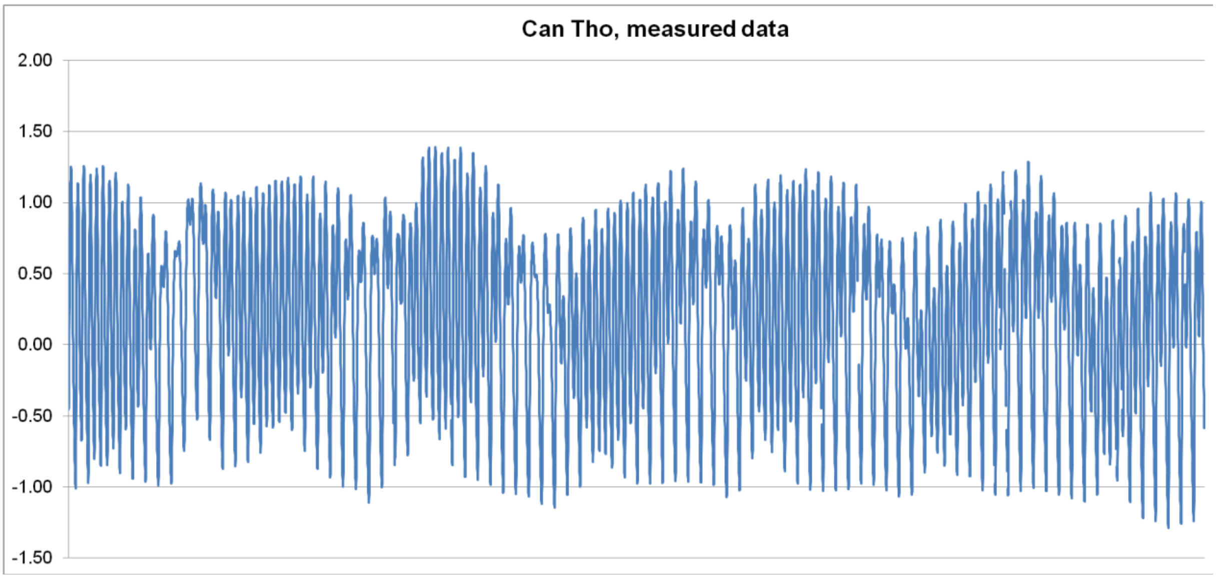

Figure 0.8: Measured water level signal at Can Tho in the period 1-3-10 to 1-6-10 (In the Hon Dau reference system)

<u>Dinh An</u>
The Delft3D results in Figure 0.6 show a tidal range of 3.8 metre with a maximum of 1.8 metre and a minimum of -2.0 metre. Measured data of this station are given in Figure 0.9. The reference system for elevation of these data are different from the reference system used in the Delft3D model.
The measured data shows a tidal range of 2.8 metre with a maximum of 4.7 metre and a minimum of 1.9 metre. In an article of Nguyen (Nguyen and Savenije, 2006) measurement information of a station near My Thanh in the Tran De branch is given which should be comparable with the Dinh An station. This information shows a tidal range of 3.3 metre during one month of observations.

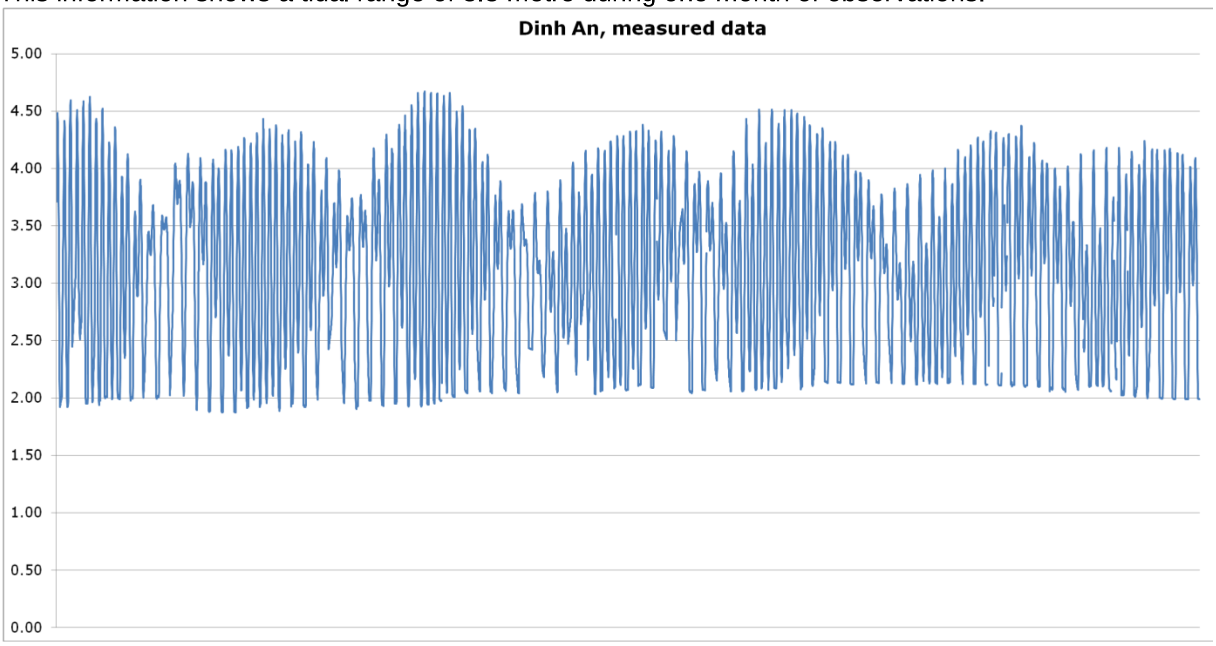

Figure 0.9: Measured water level signal in the Dinh An in the period 1-3-10 to 1-6-10

<u>Water level boundary South China Sea side</u>
The water level boundary at the South China Sea side in the Delft3D model shows a tidal range of 3.9 metre with a maximum of 1.6 metre and a minimum of -2.3 metre (see Figure 0.7). This tidal range is comparable with measurements at the Poulo Condore (Dao Con Son) island station 80 kilometre of the coast of the Mekong Delta (see measurement data of this station in Figure 0.35 in Appendix E).

Discharge boundary
The discharge boundary is based on measurements of the Chau Doc and Tan Chau measurement stations. These stations are located 180 kilometre upstream of the river mouths (see Figure 3.1 for an situation overview).The expected discharge which flows into the Hau river is 50 procent of the total measured discharges of the Chau Doc and Tan Chau stations. This is because there is a connecting river between the Hau and Tien river after the measurement stations which is called the Vam Nao river. In Figure 0.10 the computed discharge into the Hau river is given based on the 50/50 distribution between the Hau and Tien river.

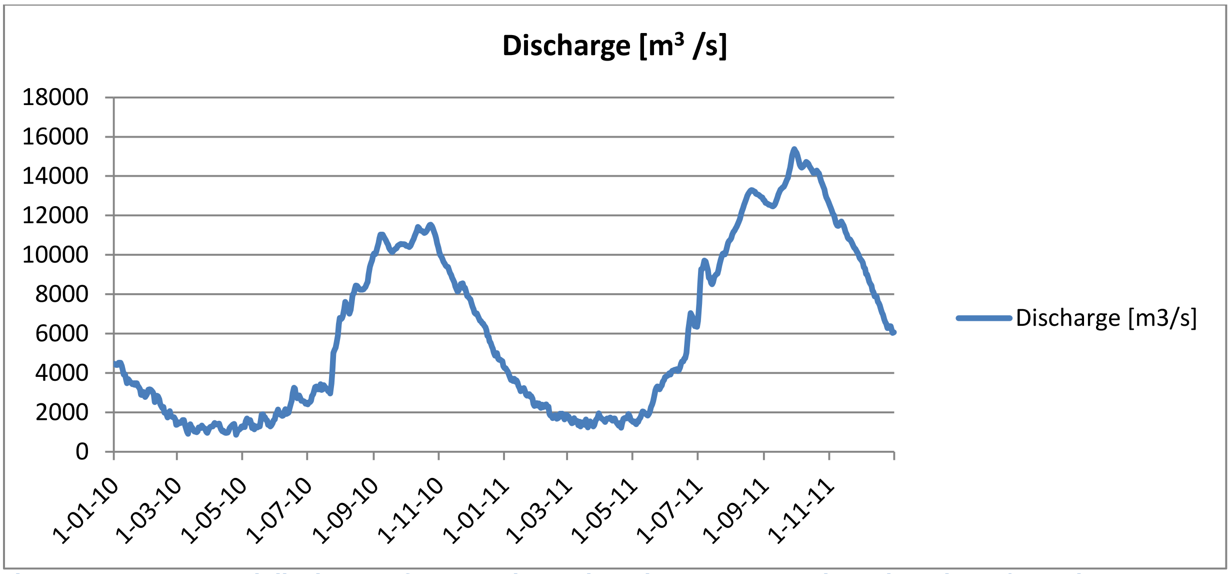

Figure 0.10: Computed discharge of 2010 and 2011 into the Hau estuary based on the 50/50 ratio

In the area between the measurement stations and the river mouths the discharge will be influenced. During the dry season it is expected that the discharge decreases because of water outflow by side channels for irrigation, evaporation, outflow by groundwater flow and by water extraction from the river. The decrease in discharge over this 180 kilometre is an unknown parameter but will be substantial. This can be seen from the following very rough estimation of the outflow by side channels.

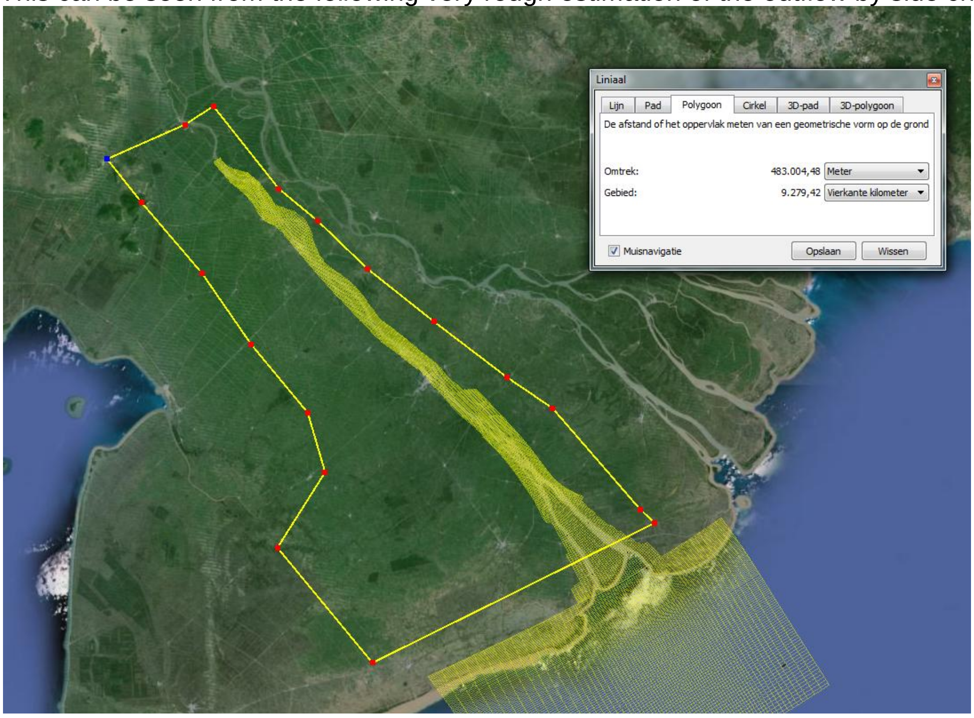

Figure 0.11: Area which may use water from the Hau river for irrigation

The area which may use the Hau river water for irrigation (irrigation by side channels for agricultural and natural areas) is 9,300 km^2. If we consider a water use of 10 millimetre a day for one square meter this will result in a required amount of water (outflow) of 1,100 m^3/s. This is a very rough calculation and maybe overestimates the water use per square meter and the drainage area. However the calculation shows that the outflow will be substantial. Values for extraction and evaporation are not considered.

Table 0.1: Rough estimation outflow side channels

Rough estimation outflow side channels		
Area	9.3E+09	m^2
water use per day per m^2	1.0E-02	m/day
total water use per day	9.3E+07	m^3/day
total water use per second	1.1E+03	m^3/s

The outflow of water from the Hau river system will be substantial but how large this value in reality in the dry season is, is unknown. The salt water intrusion length into the estuary is very sensitive for the discharge amount into the river system as can been seen in Appendix D. The next section about salt water intrusion shows that when a discharge of 200 m^3/s is applied the salt intrusion distance is comparable with the salt water intrusion measured during the measurement campaign of Nguyen and Savenije in 2005 (Nguyen and Savenije, 2006). These measured data are used in this study as the salt water intrusion into the estuary during the dry season in normal years. More extreme salt water intrusion is measured during some years of more extreme droughts. In the model study all situations are modelled with a discharge of 200 m^3/s.

Salt water intrusion

The discharge amount has a large influence on the salt water intrusion as can be seen in Appendix D. The netto discharge into the Hau river system is difficult to determine. Salinity measurements of Nguyen and Savenije (Nguyen and Savenije, 2006) are used to calibrate the discharge value in the Delft3D model. A discharge value is used which shows comparable salt water intrusion lengths as the measurements of Nguyen and Savenije.

Nguyen and Savenije have measured in the Dinh An and Tran De branch on April and May 2005 and on June 2006. The largest salt water intrusion is measured in the measurement campaign of April 2005. These results are given in Figure 0.12 and Figure 0.13 and are used to calibrate the discharge in the Delft3D model. These measurements show a salt water intrusion of 50 kilometre from the river mouth in upstream direction. This is measured during one day so does not have to be the most extreme value of that period.

A discharge in the model of 200 m^3/s shows a similar salt water intrusion distance as the measured salt water intrusion distance. The salt water intrusion length and shape from the river mouth in upstream direction of the Delft3D model with a discharge of 200 m^3/s and of the measurement campaign are given in Figure 0.12 and Figure 0.13. The results of the Delft3D model are after a period of 3 months with a constant discharge of 200 m^3/s.

There is a large similarity between measured and modelled results when a discharge value of 200 m^3/s is used. Therefore the value of 200 m^3/s is used in the model runs to study the effect of a changed bottom topography of the outer delta on salt water intrusion.

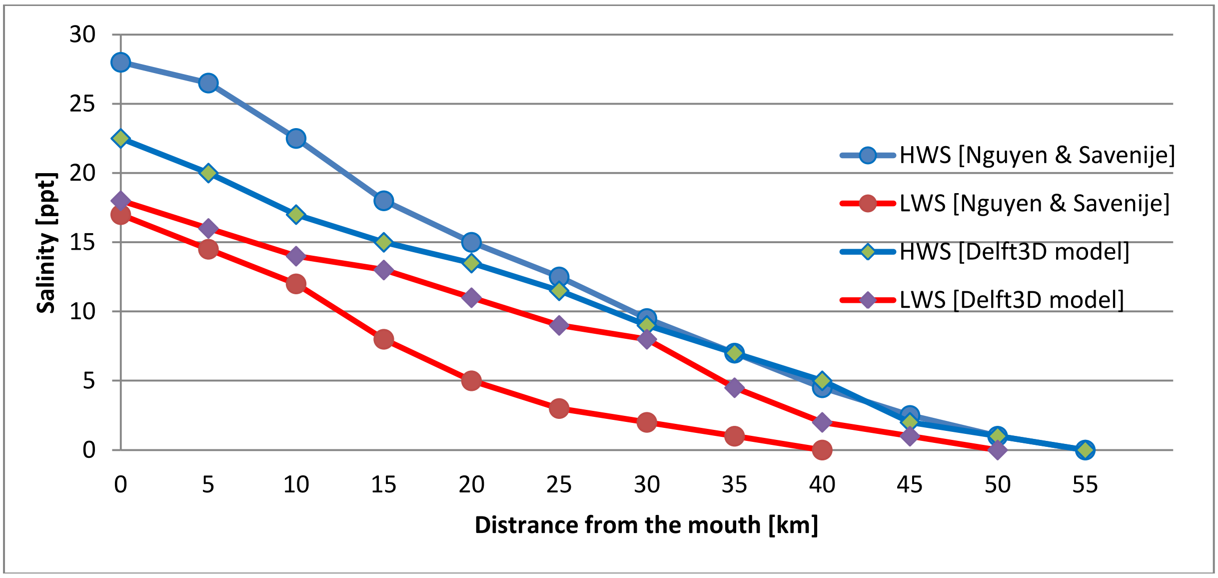

Figure 0.12: Salinity distribution measured in the Tran De branch on 8 April 2005 (rounds) and of the Delft3D model (diamonds), values of the salinity at HWS (blue), and LWS (red) are given

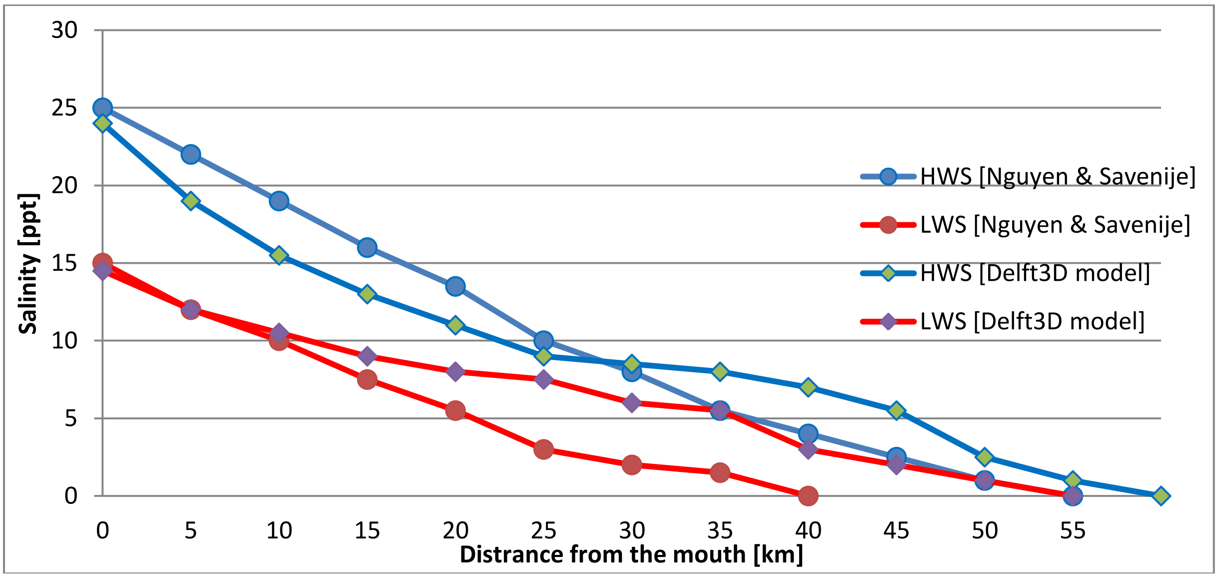

Figure 0.13: Salinity distribution measured in the Dinh An branch on 9 April 2005 (rounds) and of the Delft3D model (diamonds), values of the salinity at HWS (blue), and LWS (red) are given

Vertical salinity distribution

The model simulations with a discharge of 200 m^3/s show a very good mixing which results in no or a small gradient in salinity over depth. This is in accordance with a well mixed estuary which should be the case as described in Appendix F (a low Estuarine Richardson number) and is also described by Nguyen (Nguyen and Savenije, 2006). The following two figures show the vertical salinity profile in the Dinh An branch and at a location 40 km upstream of the river mouth (upstream of the bifurcation point) just after high water slack. In the figures a very small change in salinity over depth can be seen.

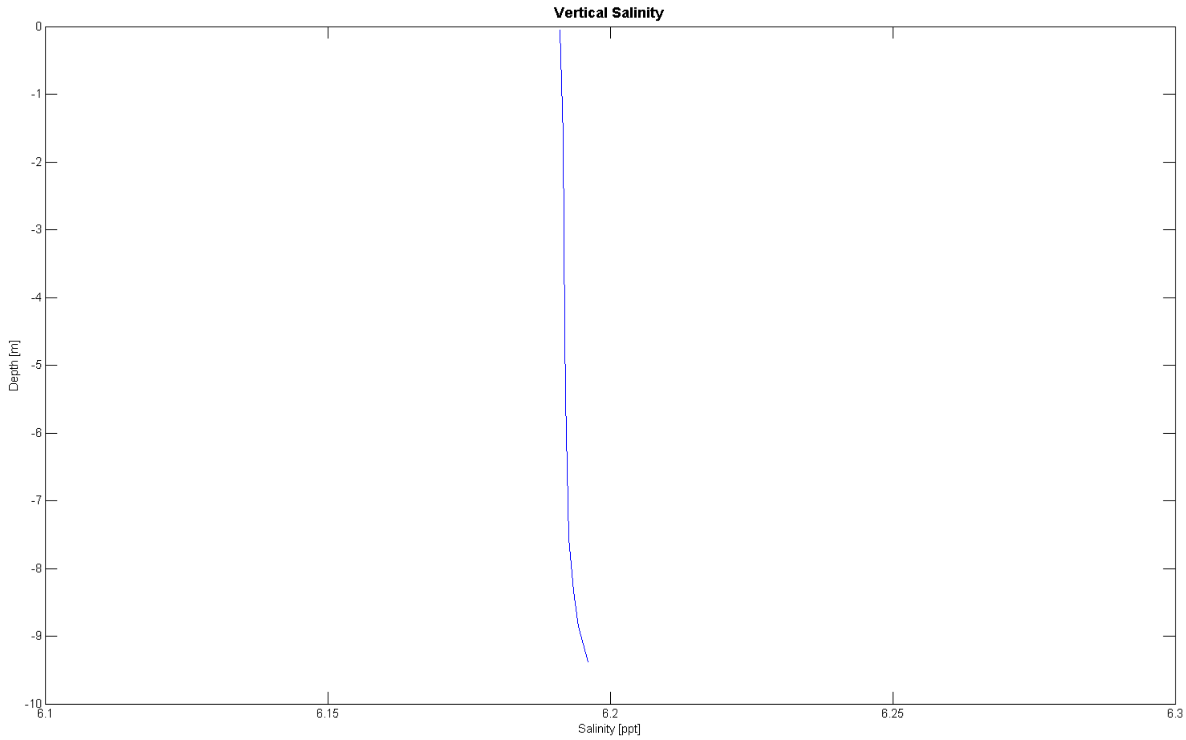

Figure 0.14: Vertical salinity 40 kilometre upstream of the river mouth

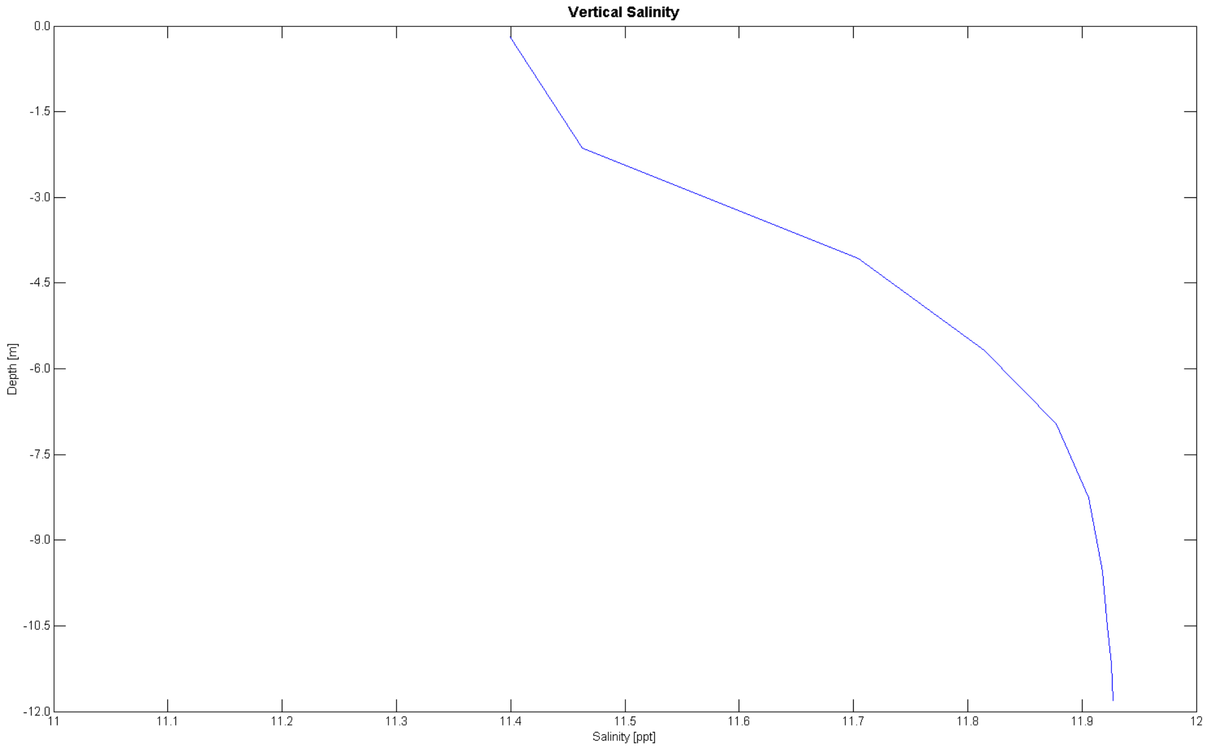

Figure 0.15: Vertical salinity Dinh An branch

Flow velocities
The horizontal flow velocities at the river mouth of the Dinh An branch and at Can Tho (80 kilometre upstream of the river mouth) in the reference simulation are given. At the river mouth the velocities are a bit larger than 1 m/s. The results give an indication of the occurring horizontal flow velocities.

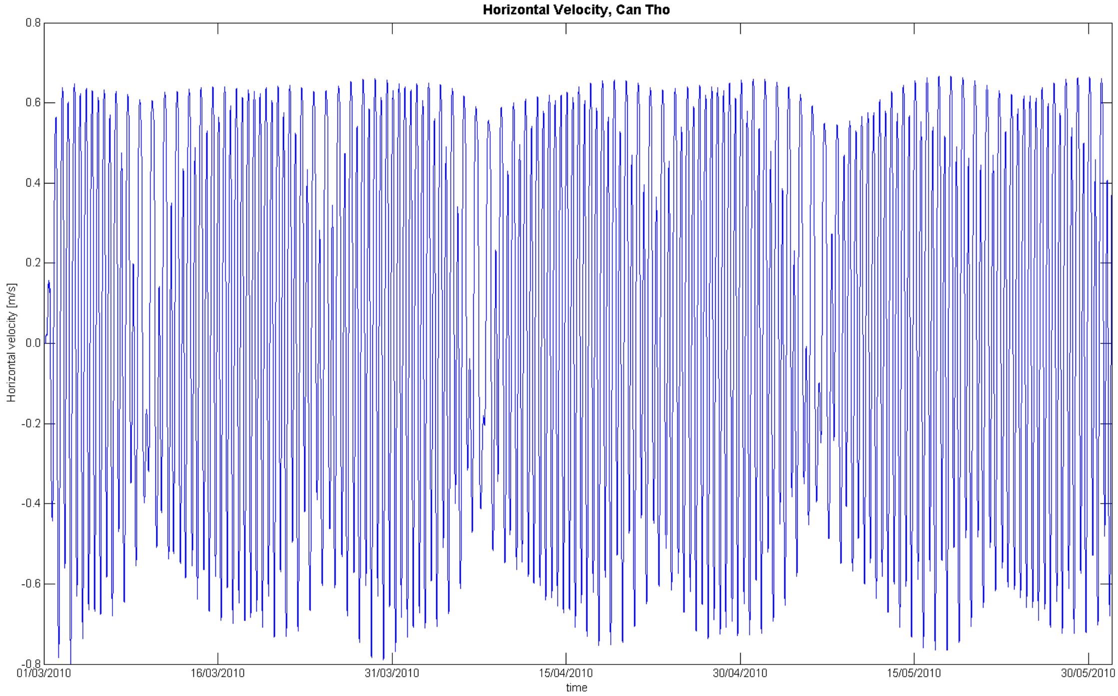

Figure 0.16: Horizontal velocity Can Tho at a 50% depth

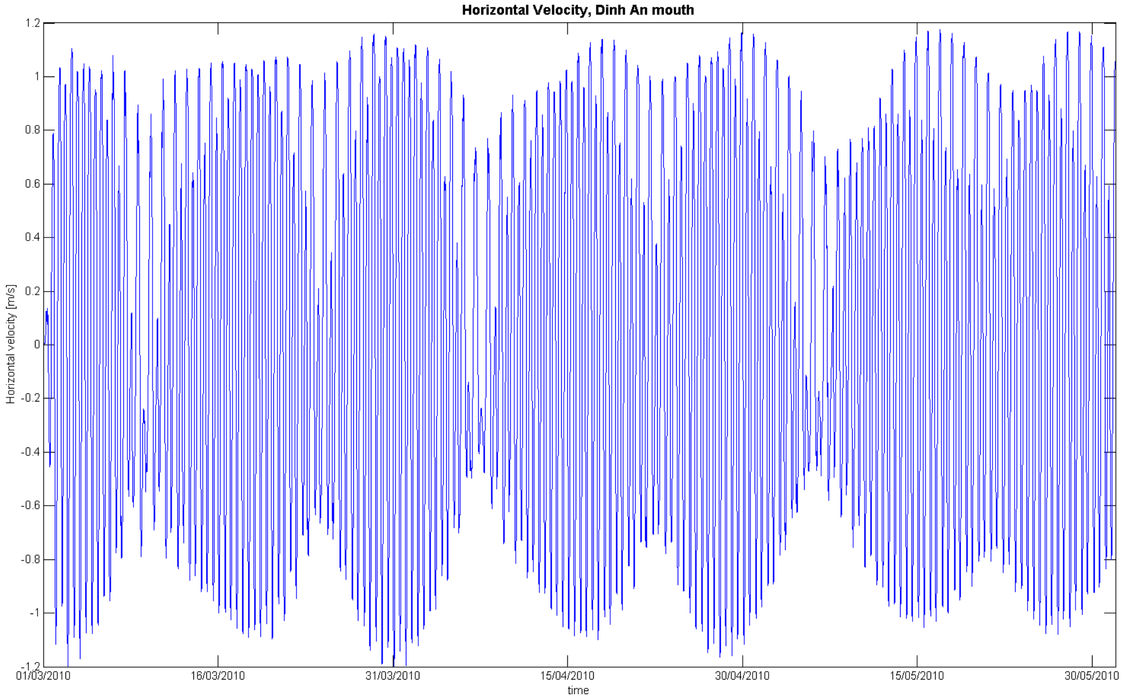

Figure 0.17: Horizontal velocity Dinh An mouth at a 50% depth

D - SENSITIVITY ANALYSIS

Delft3D model simulation results are analysed with different boundary conditions. What is the influence on the model results when a higher or lower water level boundary is applied? And when a larger or smaller discharge at the boundary is applied? In other words what is the sensitivity of the model to the applied boundary conditions.

The discharge boundary is studied for values of 150, 200, 250, 500, 750 and 1,000 m^3/s. The water level boundary is studied for the water level signal which is used in this study for the reference and variant simulations (see Section 3.2.2 and Appendix C), an increase of the signal with 0.3 metre, a decrease of the signal with 0.3 metre and a signal of the tidal prediction software database TPXO7.2.

For both boundaries the main observations of the sensitivity are given in the first lines of the specific section. These observations are described in more detail in the rest of the section with the help of text and figures.

Discharge boundary:
The discharge amount has a large influence on the salt water intrusion distance, some influence on the water levels and a small influence on the flow velocities and instantaneous discharge (river discharge and tidal discharge).

Discharge influence on salt water intrusion:
With a discharge of 150, 200 and 250 m^3/s the salt water intrudes over a distance of 55 kilometre after 3 months. When a discharge of 500 m^3/s is applied the salt water only intrudes over a distance of 40 kilometre and with a discharge of 750 m^3/s only over 20 kilometre after 3 months. An increase in discharge is very effective in pushing the intruded salt water back. Figure 0.21 to Figure 0.23 shows the salt water intrusion for the discharges of 200, 500 and 750 m^3/s after a simulation period of 3 months.

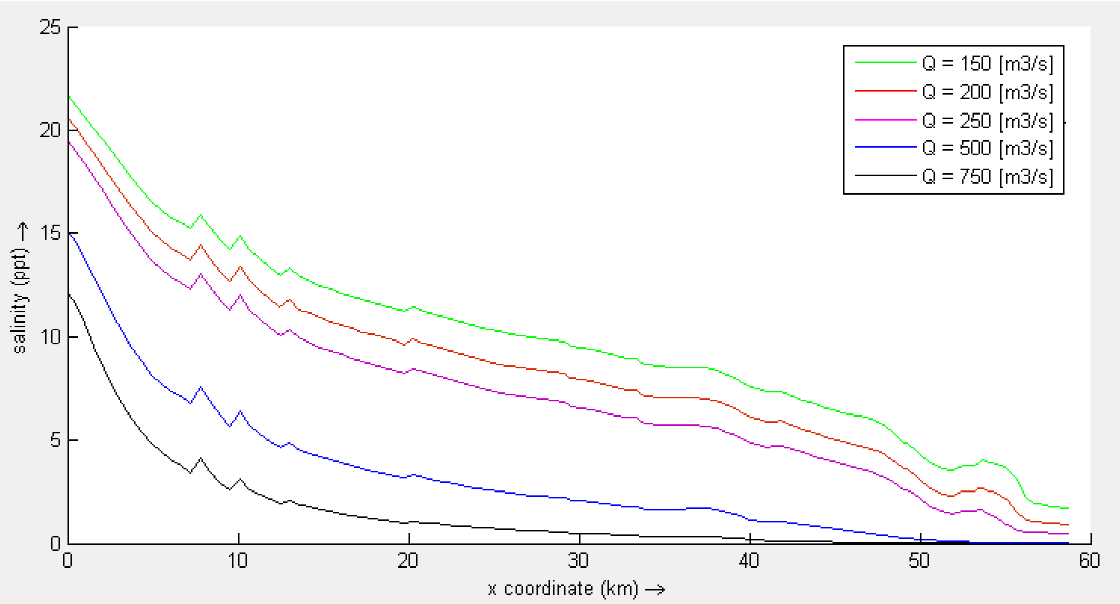

Figure 0.18: Horizontal salinity profile after a simulation period of 3 months with various discharge conditions (x=0 is located at the river mouth)

Discharge influence on water levels:
The amount of discharge has some influence on the water levels. When the discharge increases higher water levels occur. The effect of an increasing discharge is a vertical shift in upward direction of the water level signal on every location for the whole simulation period. When a discharge of 200 m^3/s is changed in a discharge of 1,000 m^3/s the water level signal at Can Tho increases with 10 centimetre (see Figure 0.19) and at the Dinh An branch an increase of less than 3 centimetres occurs. When the large discharges of the wet season are considered a considerable water level increase can be seen of 1.0 to 1.6 metres for a discharge change from 200 m^3/s to 14,000 m^3/s for example.

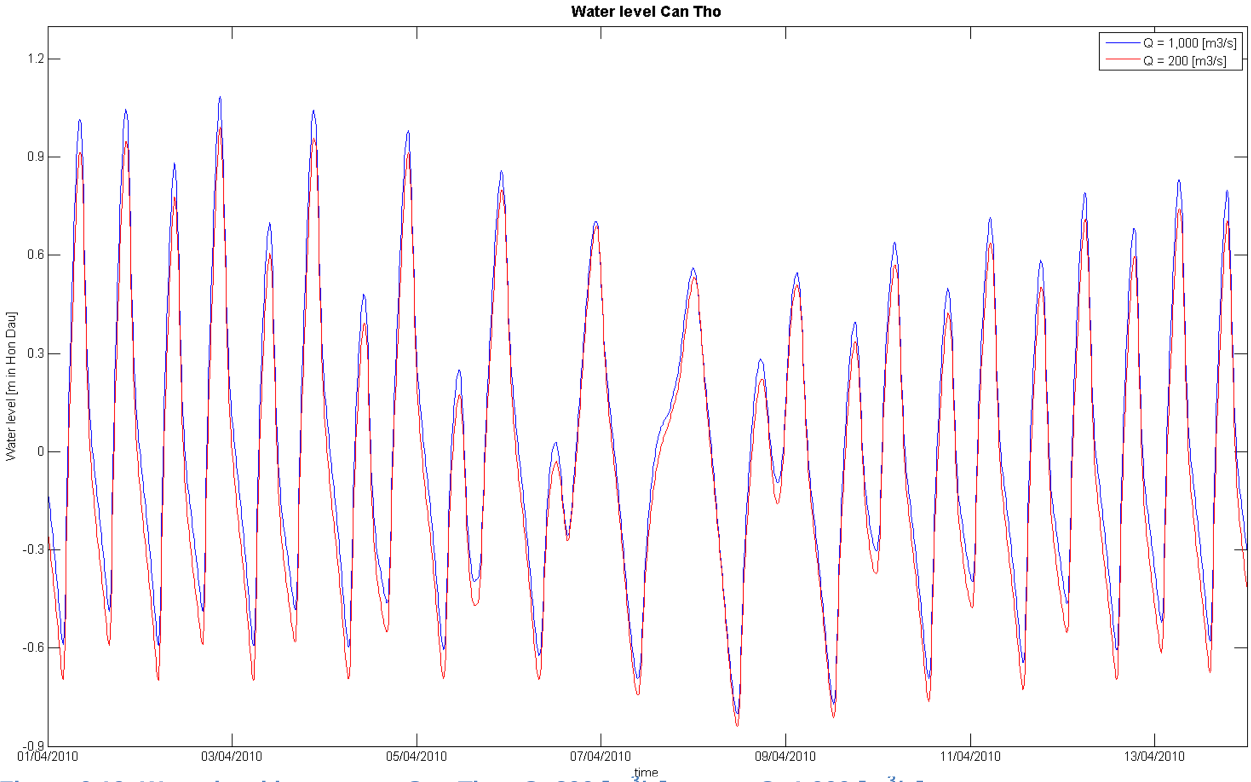

Figure 0.19: Water level increase at Can Tho Q=200 [m^3/s] versus Q=1,000 [m^3/s]

<u>Discharge influence on flow velocities and instantaneous discharges:</u>
The instantaneous discharge for the Dinh An branch with a discharge of 200 m^3/s is given in Figure 0.20. The discharge has maxima of up to 13,000 m^3/s (ebb direction) and minima up to -22,000 m^3/s (flood direction). An increase from 200 m^3/s to 1,000 m^3/s will not significantly increase the instantaneous discharge or the flow velocity.

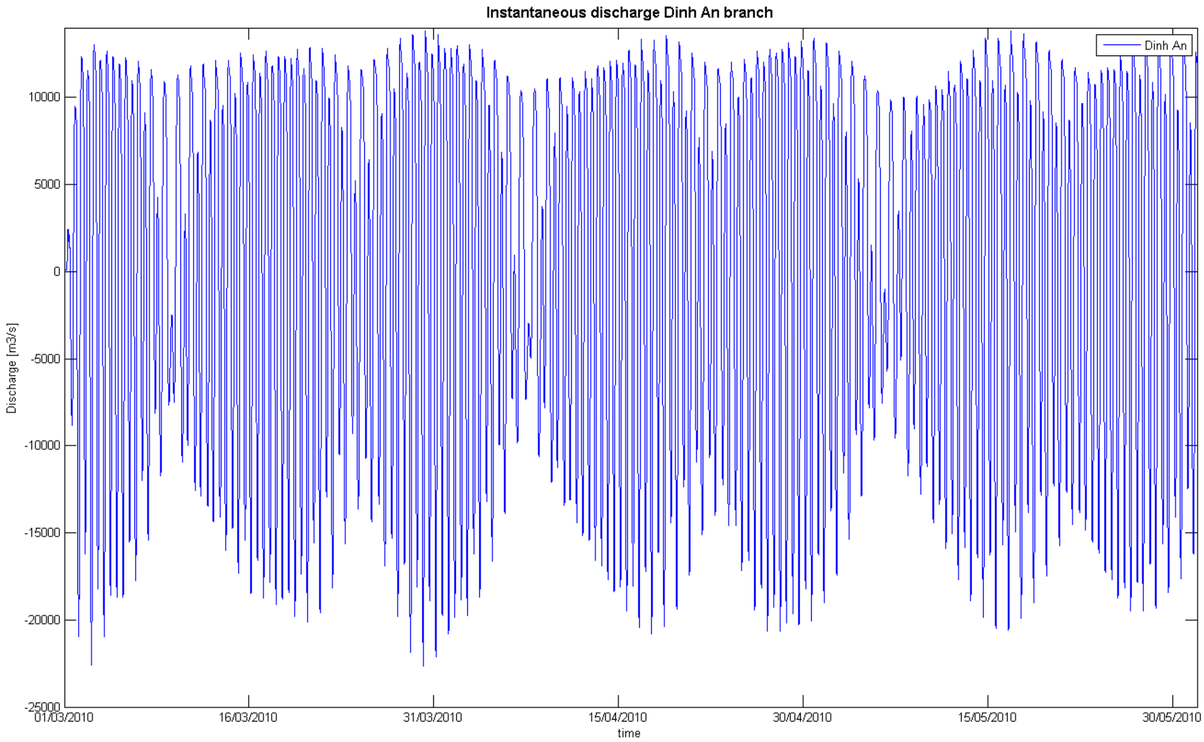

Figure 0.20: Instantaneous discharge Dinh An branch with a discharge of 200 m^3/s

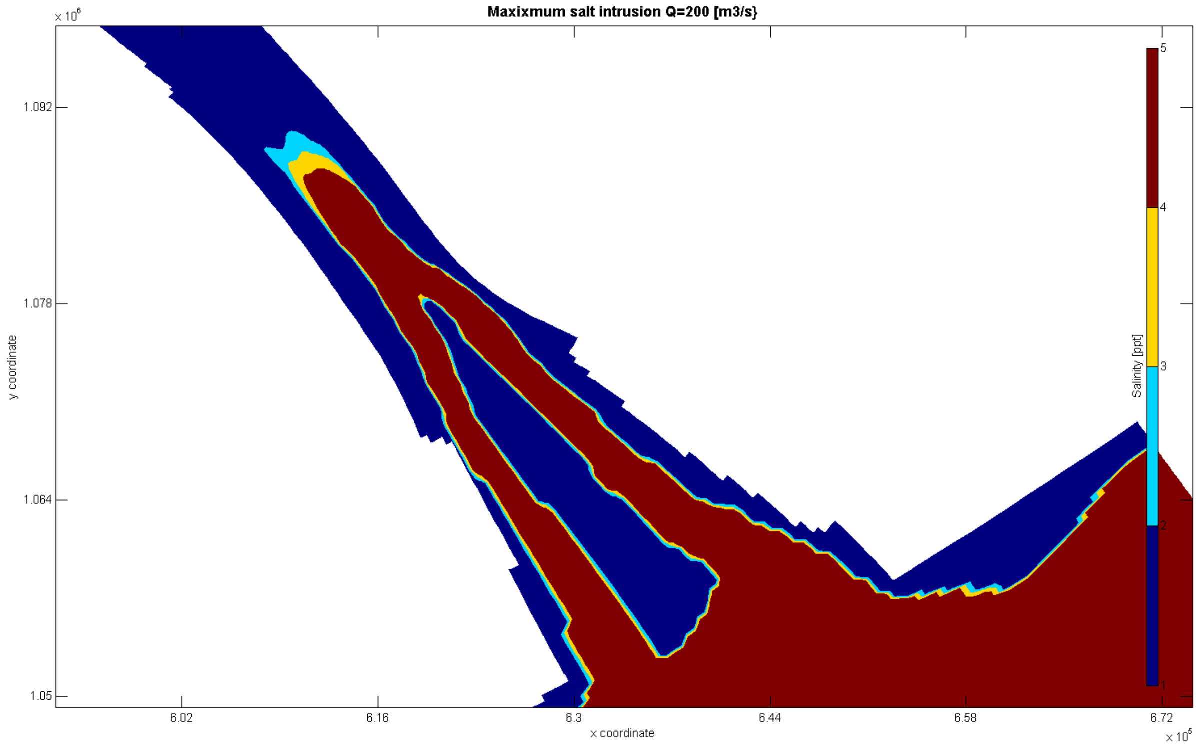

Figure 0.21: Maximum salt water intrusion after a simulation period of 3 months with a discharge of 200 m^3/s

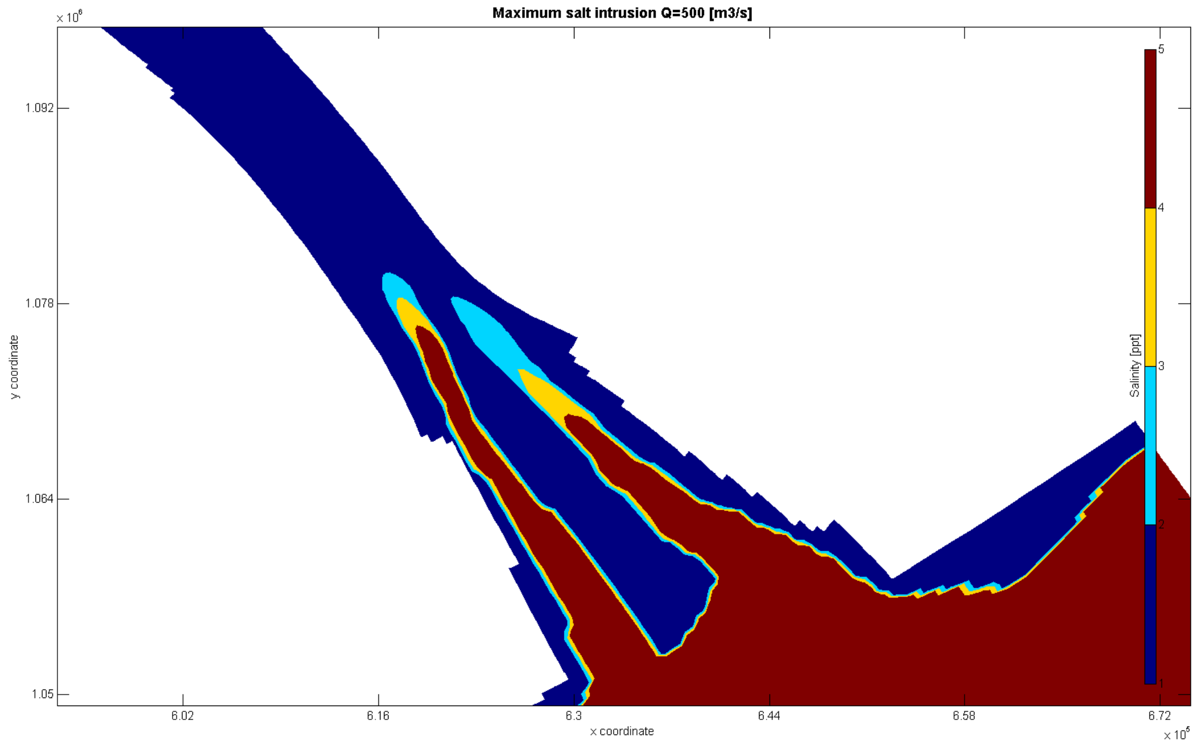

Figure 0.22: maximum salt water intrusion after a simulation period of 3 months with a discharge of 500 m^3/s

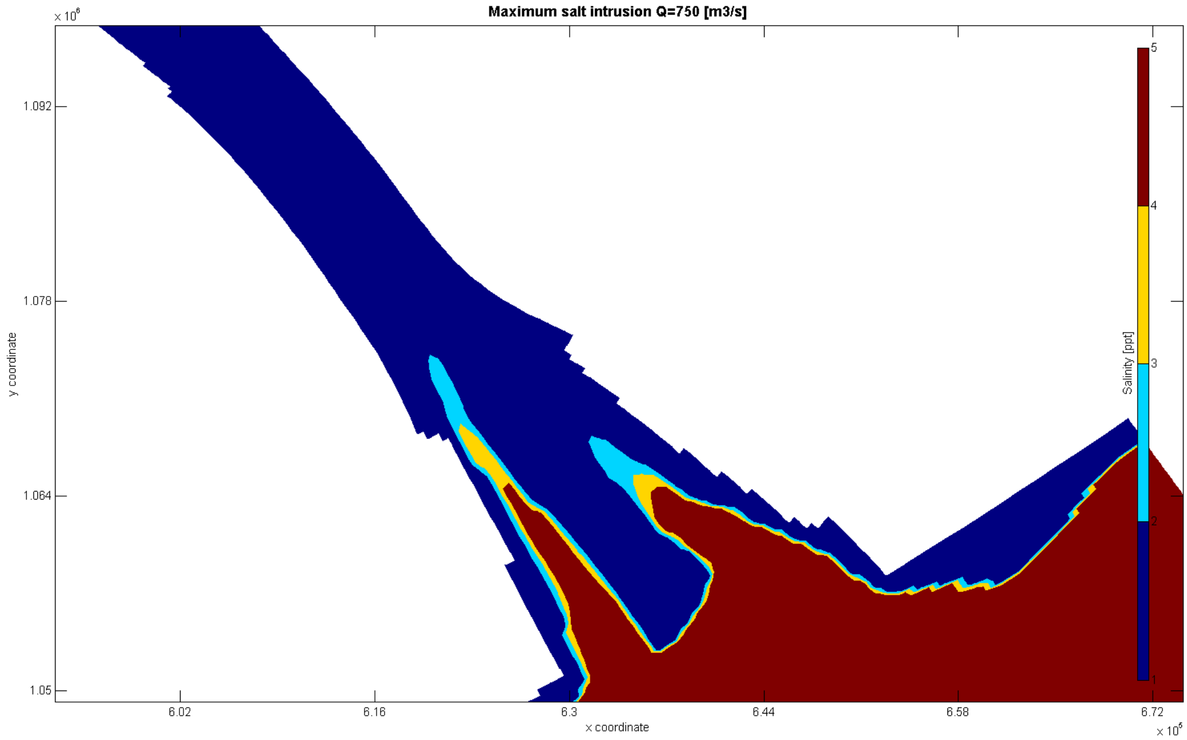

Figure 0.23: Maximum salt water intrusion after a simulation period of 3 months with a discharge of 750 m^3/s

Water level boundary:
The sensitivity of the results of the Delft3D simulations to the water level signal at the boundary is studied. Four different water level boundaries are considered. Three signals are from the South China Sea Model (SCSM) which are the water level boundary used in the simulations in this study (named 'signal standard' in this appendix), a signal with an increased elevation of 0.3 metre and a signal with a decreased elevation of 0.3 metre with reference to the signal used in the model simulations in this study. The fourth signal is from the tidal prediction database TPXO7.2 which consist of tidal constituents with an amplitude and a phase.

The four different signals show a water level increase/decrease in the whole estuary which is almost equal as the increase/decrease of the boundary signal. The change in water level signal has only a small influences on the instantaneous discharges and on the salt water intrusion distance. It has some influences on the salinity levels in the estuary especially at the first 40 kilometre into the estuary (seen from the river mouth).

<u>Water level boundary influence on water levels in the estuary:</u>
When a water level change of +0.3 metre is applied at the boundary of the Hau Estuary Model all the water levels in the model will increase by 0.3 metre. The same happens when a water level change of -0.3 metre is applied at the boundary and a decrease of 0.3 metre occurs.

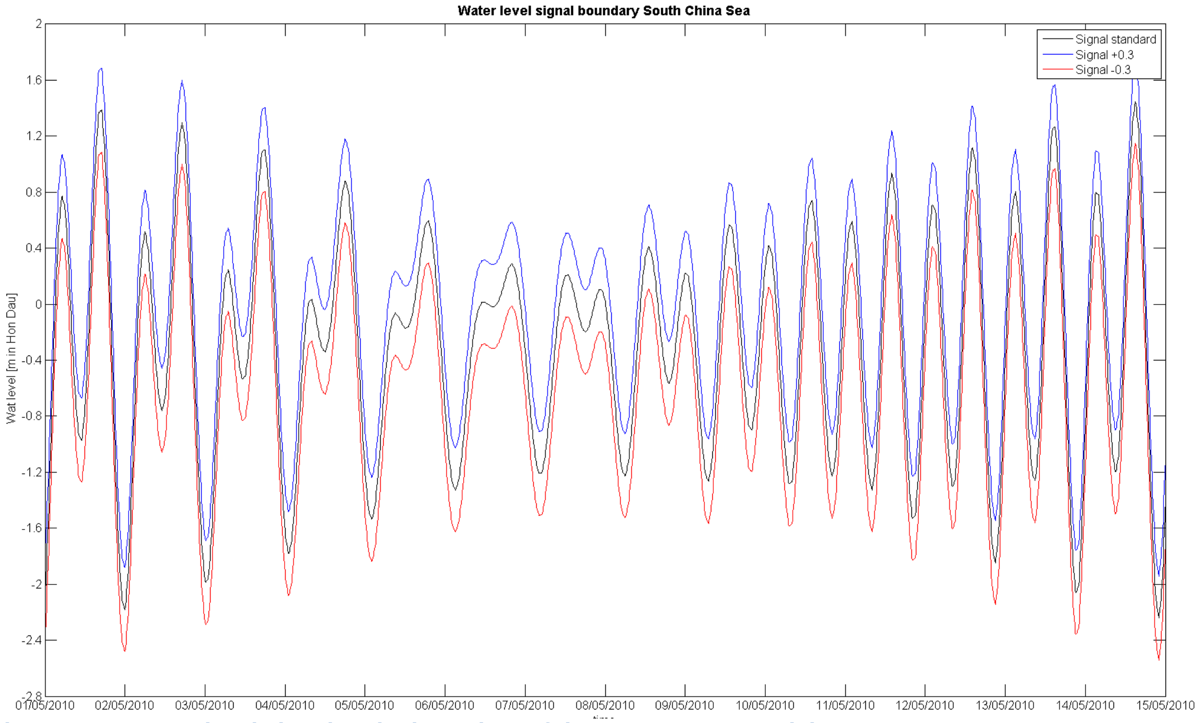

Figure 0.24: Water level signal at the boundary of the Hau Estuary Model

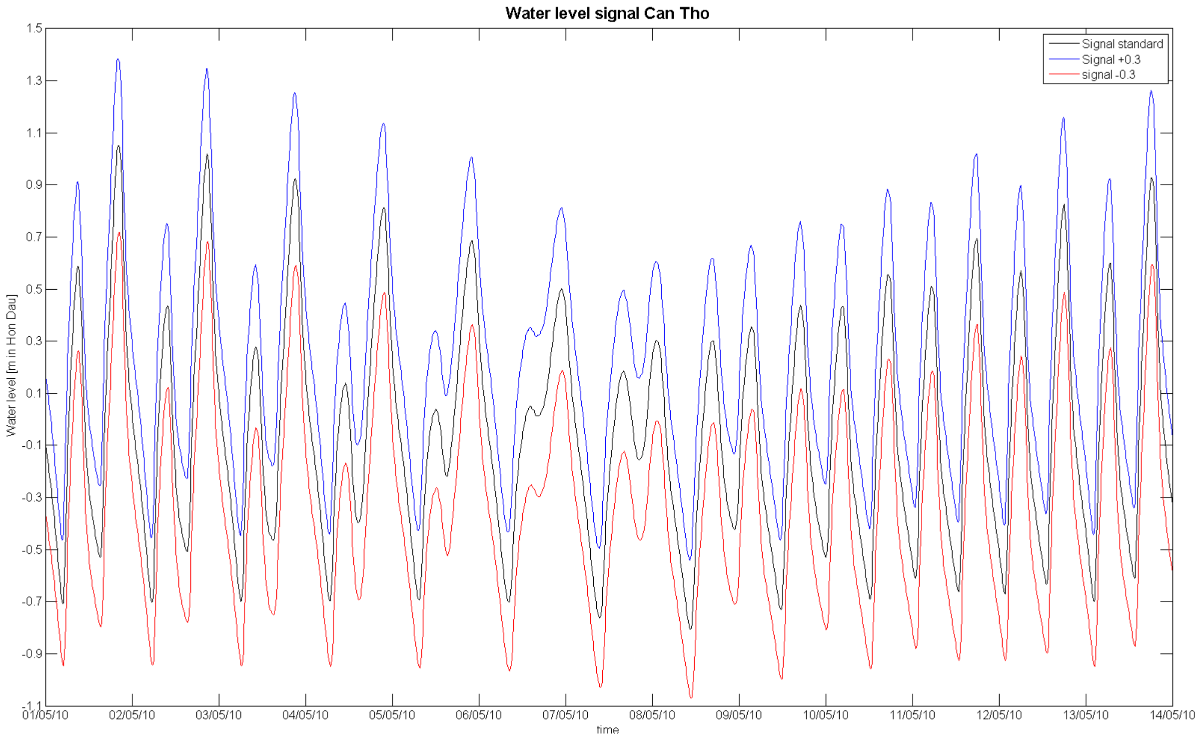

Figure 0.25: Water level at Can Tho (80 km upstream of the river mouth)

Water level boundary influence on salt water intrusion:
When the water level is increased the salinity levels will change in the first 30 to 40 kilometre, seen from the river mouth in upstream direction, (an increase in the Dinh An branch and a decrease in the Tran De branch). However after this first 30 to 40 kilometre the salinity levels for the different water level boundaries are almost equal. The final salt water intrusion distance is almost the same for the three applied boundary conditions as can be seen in the horizontal salinity profiles of the Dinh An (Figure 0.26) and Tran De (Figure 0.27) branches when you consider a salinity of 5 parts per thousand or less.

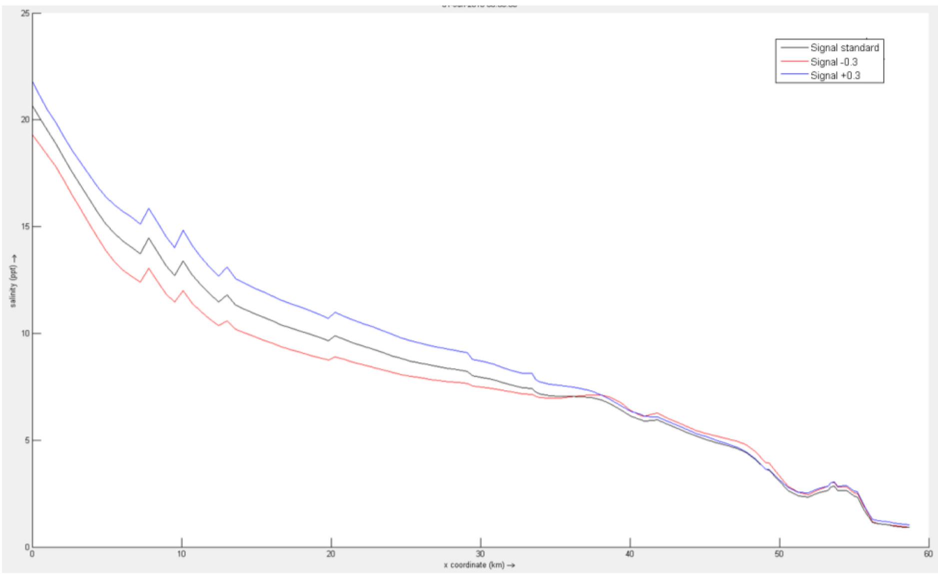

Figure 0.26: Horizontal salinity profile through the Dinh An branch at 92.5% of the depth

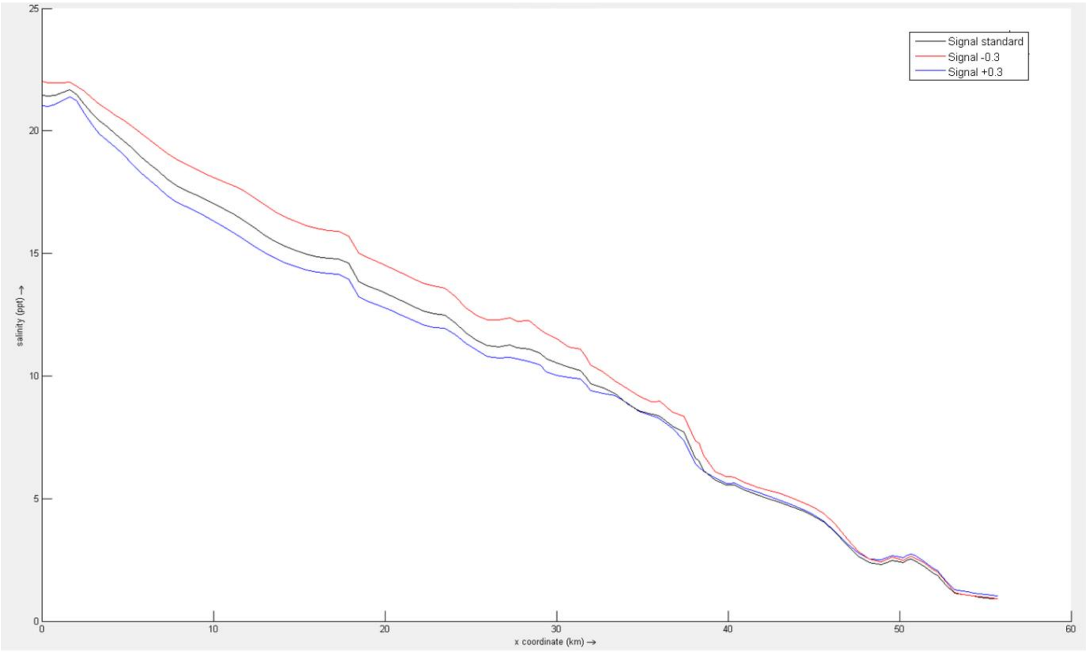

Figure 0.27: Horizontal salinity profile through the Tran De branch at 92.5% of the depth

Water level boundary influence on the instantaneous discharge:
The change in water level has only a small influence on the discharges in the system as can be seen in Figure 0.28 where the instantaneous discharge of the Dinh An branch is given for different water level boundary conditions.

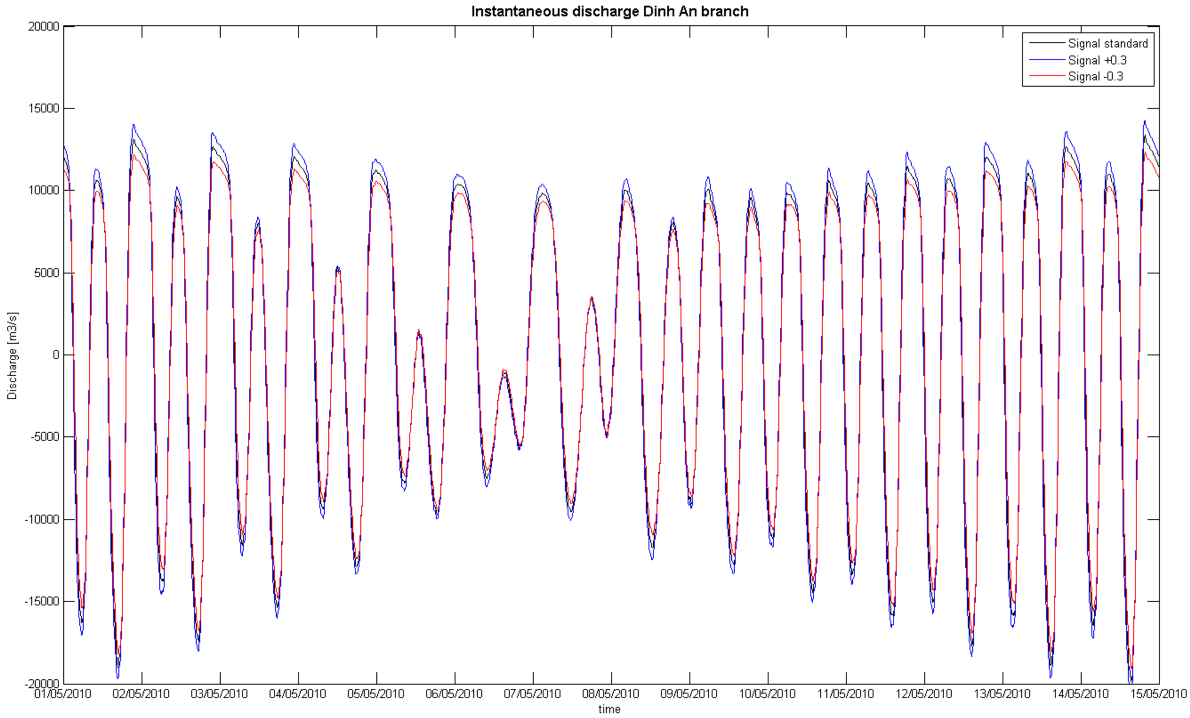

Figure 0.28: Instantaneous discharge in the Dinh An branch

South China Sea Model (SCSM) versus TPXO7.2 boundary signal

In the model of this study the signal ‘standard’ as described in previous pages is used, which is the signal of the SCSM with a vertical shift of -0.3 metre (see Appendix C). This signal is compared with the generated signal of the TPXO7.2 database which is a tidal prediction software database. In the study the signal of the South China Sea Model is used because this signal could be vertically shifted and was expected to be more realistic as the TPXO7.2 database because of the complexity of the tidal signal in the South China Sea.

When the two signals are compared they show a good agreement in shape and range, and the signals have a large similarity. The results of the model simulations when salt water intrusion, salinity levels and water levels in the estuary are considered are also similar for the two different water level boundary signals. In Figure 0.29 to Figure 0.32 the water levels signals on two locations in the model are given for both water level boundary conditions.

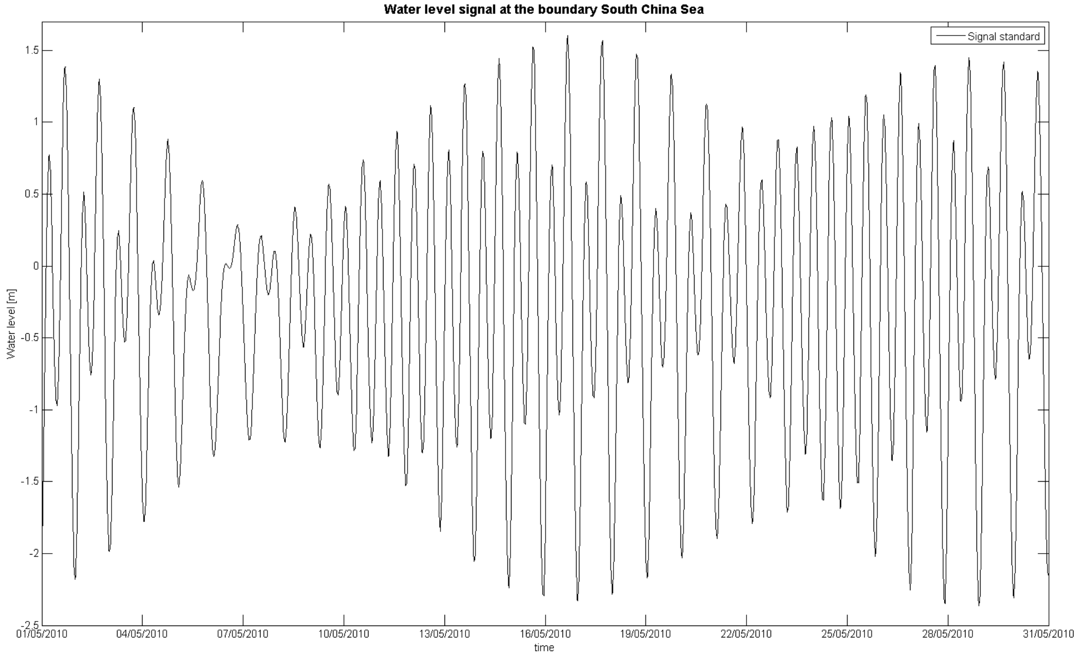

Figure 0.29: Water level signal ‘standard’ at the boundary of the South China Sea

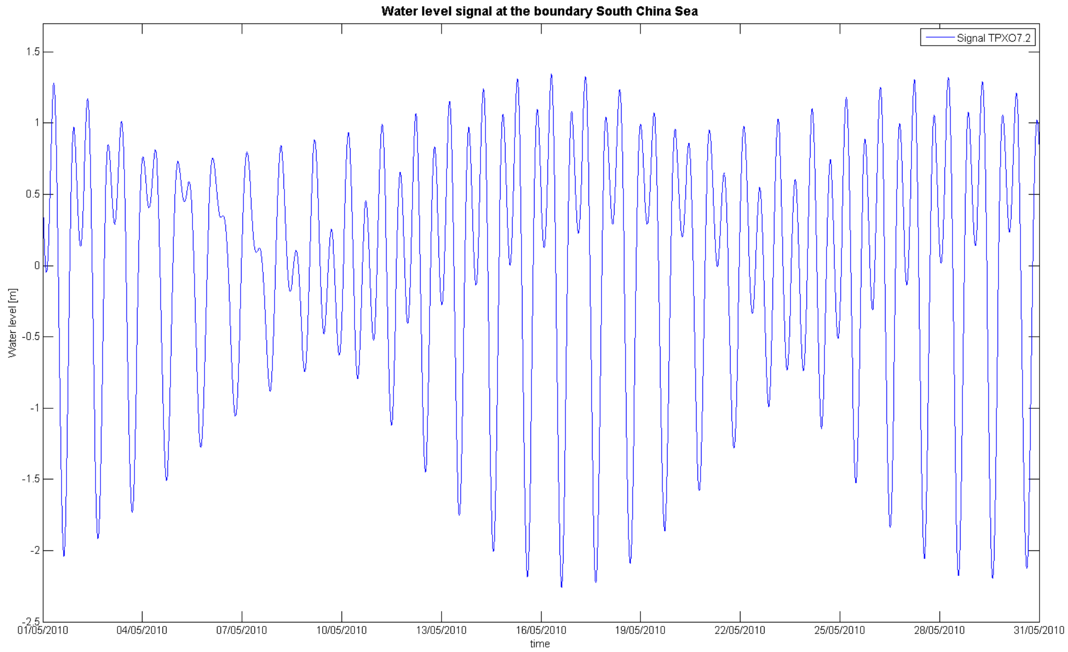

Figure 0.30: Water level signal TPXO7.2 database at the boundary of the South China Sea

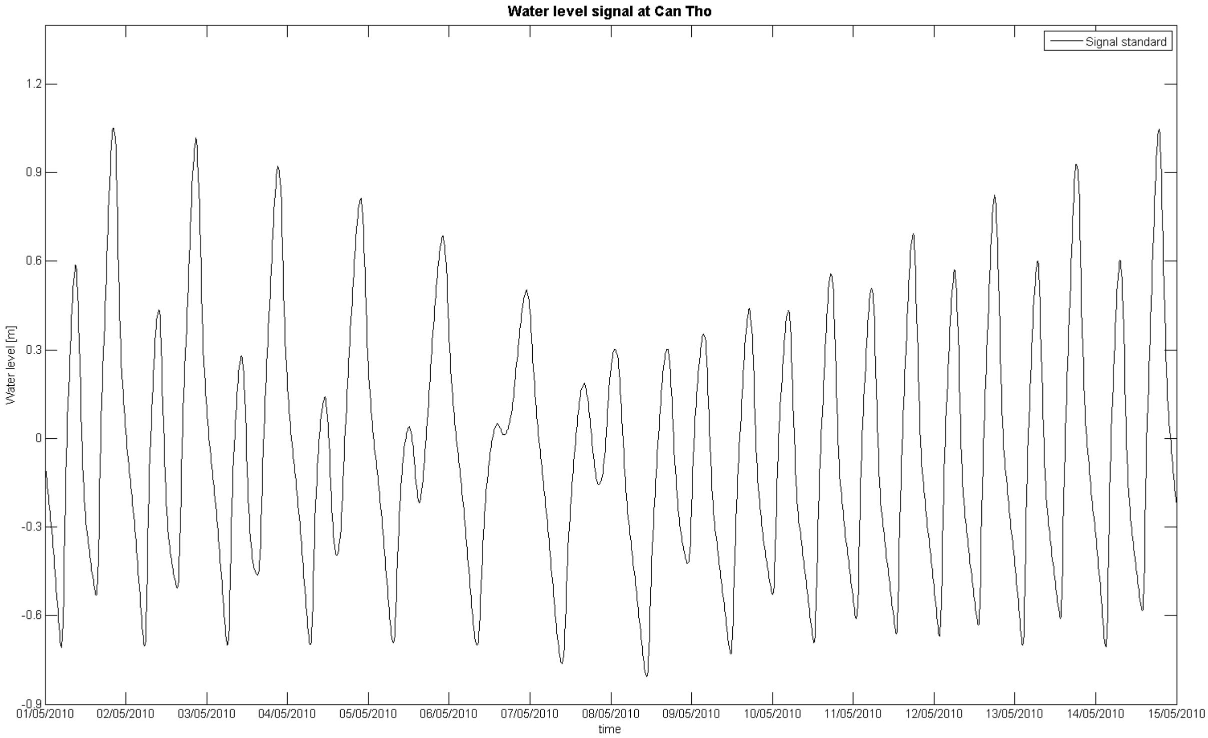

Figure 0.31: Water level at Can Tho (80 km upstream of the river mouth) with the 'standard' water level boundary

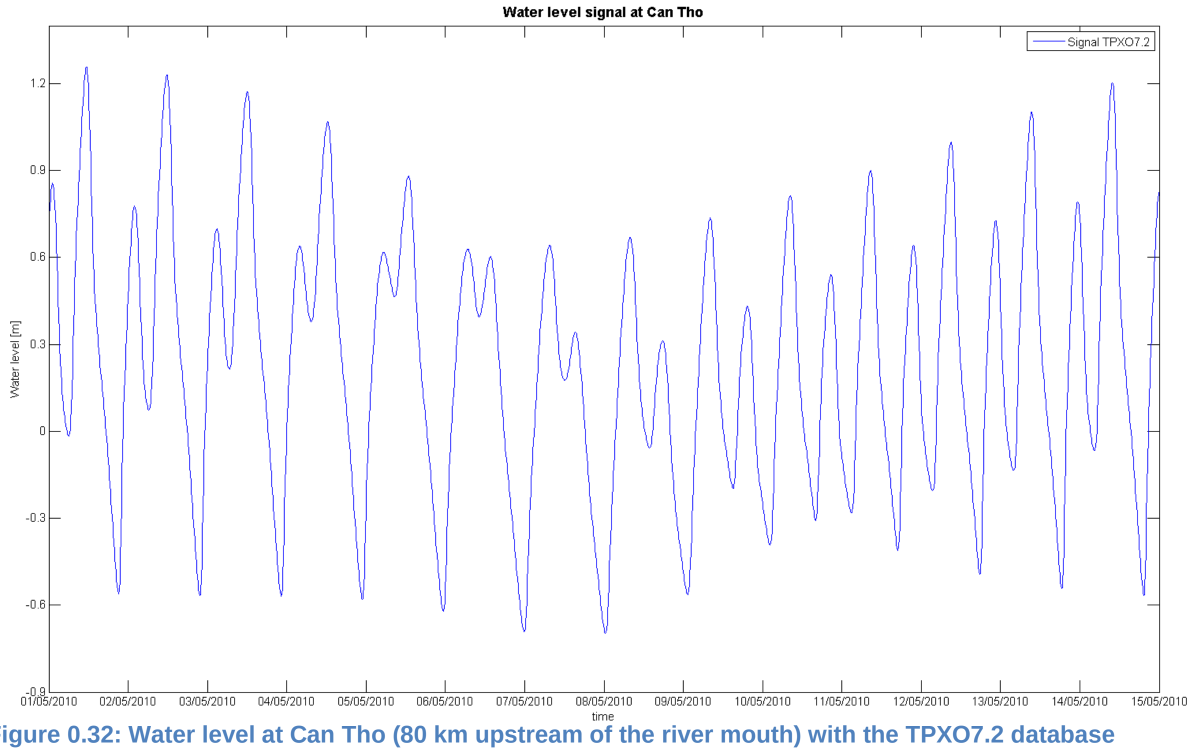

Figure 0.32: Water level at Can Tho (80 km upstream of the river mouth) with the TPXO7.2 database boundary signal

E - DELFT3D MODEL VERSUS REAL SITUATION

The developed Delft3D model in this study is based on the Hau estuary which is located in the Mekong delta in Vietnam. The model includes the Tran De and Dinh An branches which are in the most downstream part of the bifurcated Hau estuary. A perfect match between the model and the real situation is not possible because the model depends on various measurement data of the estuary which are measured on different moments in time. There are some measurement data available however when a perfect model needs to be created in relation to reality more measurement data and data on different moments in time are required. The Hau estuary in this study is used as a study object. Of this estuary a Delft3D model is made with the measurement data which were available. Some simplifications are made in the Delft3D model but a realistic model for the intrusion of salt water into the Hau estuary is developed. In the text below the used measurement data, the simplifications and the used boundary conditions are described for the people who read this MSc report with special interest for the Hau estuary in Vietnam.

The bathymetry of the model is based on measurement campaigns in and around the Hau estuary. Detailed measurement data of governmental projects in Vietnam of the period 2009-2011 are used for the river mouth area in the coastal zone. These data are available for the area 15 kilometre in offshore direction to 5 kilometre into the Tran De and Dinh An branches. For the coastal area in more offshore direction usage is made of the General Bathymetric Chart of the Oceans (GEBCO). Measurement data of cross shore profiles are available for the Hau river on every 500 metre from the mouth of the river to the upstream end of the model. These cross-sections contains depth samples on every 80 metre on average in cross shore direction. Grid cells outside the area of depth measurements have depths of neighbour cells for the outer delta or negative depths (so land above water) for the river area. The slope of the banks of the river is approached by this process but will not be completely similar with the real situation because the large measurement distance in cross shore direction and therefore the difficulty to create a gentle slope for the banks in the model.

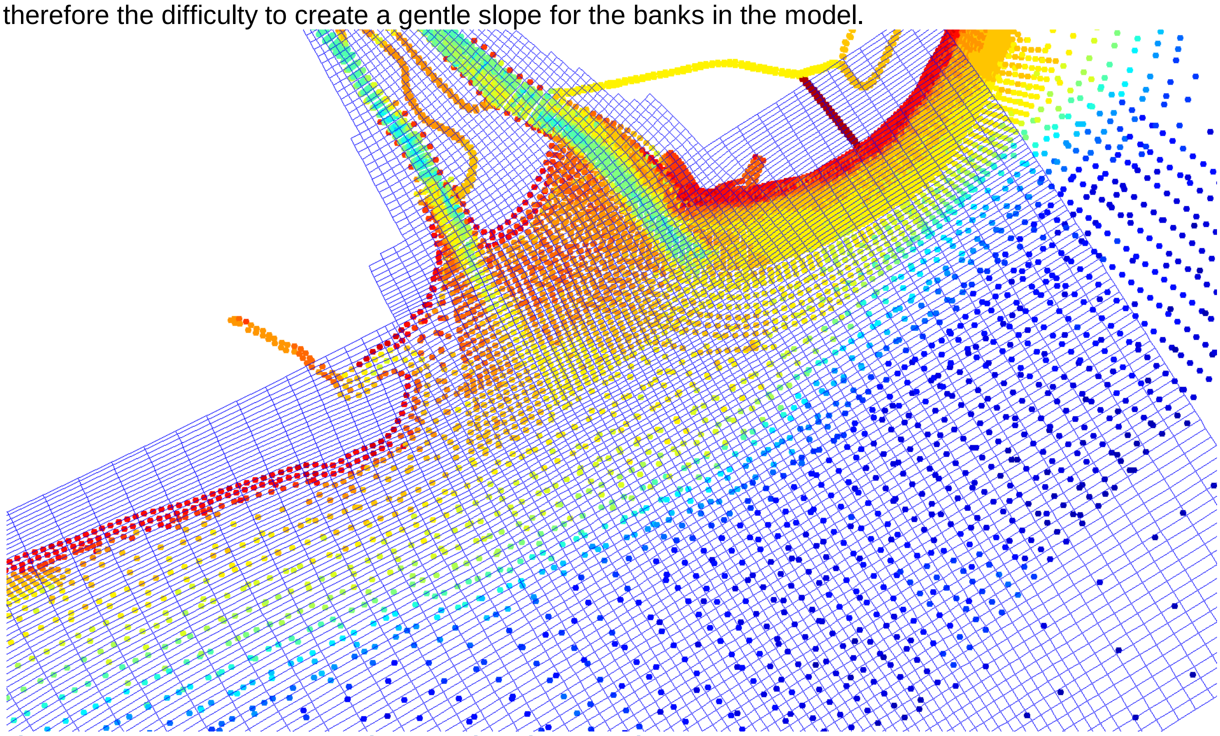

Figure 0.33: Measurement samples overview river mouth

Small side channels and tributaries through islands in the estuary system are neglected (for example the river tributary through the island between the Tran De and Dinh An branches as can be seen in Figure 0.33 and Figure 0.34). This is done because these small tributaries and side channels have only a small influence on the hydrodynamics and on the salt water intrusion during the dry season and to make the Delft3D model not to complex. The neglecting of tributaries and side channels does have some influence on the hydrodynamics and on the salt water intrusion into the estuary, however the expected influence is small.

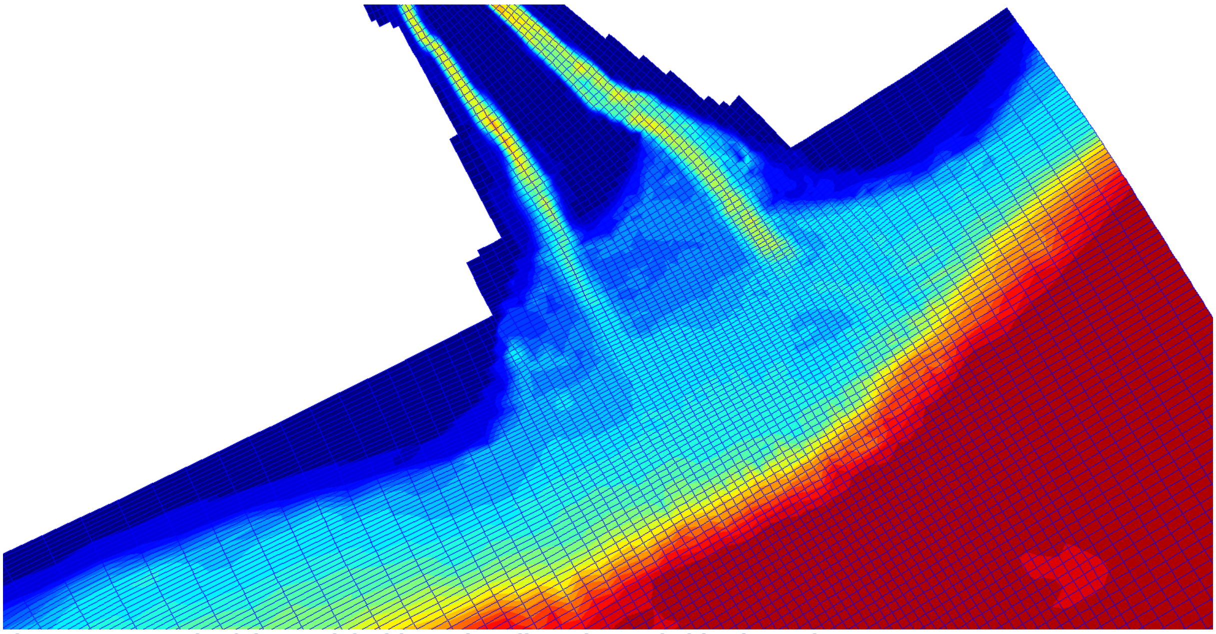
Figure 0.34: Depth of the model without the tributaries and side channels

The boundary conditions have a large influence on the hydrodynamics and on the amount of salt water intrusion. Measurements of the discharge and water levels are not very accurate for this estuary. The discharge used in the model is 200 m^3/s which is determined from river discharge measurements 180 kilometre upstream from the river mouth, an unknown outflow of discharge from the system and salt water intrusion measurements. Water levels in the model are compared with water level measurements around the Hau estuary as much as possible. However there are not much measurement stations available and the measurements depends on the time depending forcing which makes it difficult to compare model results with bathymetry information and measured water levels of different moments in time. The generated boundary water level signal is the best available signal that was possible to generate for this study. More information about the discharge and the water level boundary is described in Appendix C and D. In Figure 0.36 the water level boundary of the model is given and in Figure 0.35 the measured water level at the measurement station at the island of Dao Con Son (Poulo Condore) located on a distance of 40 kilometre from the water level boundary of the model. These signals show a well agreement especially concerning the tidal range.

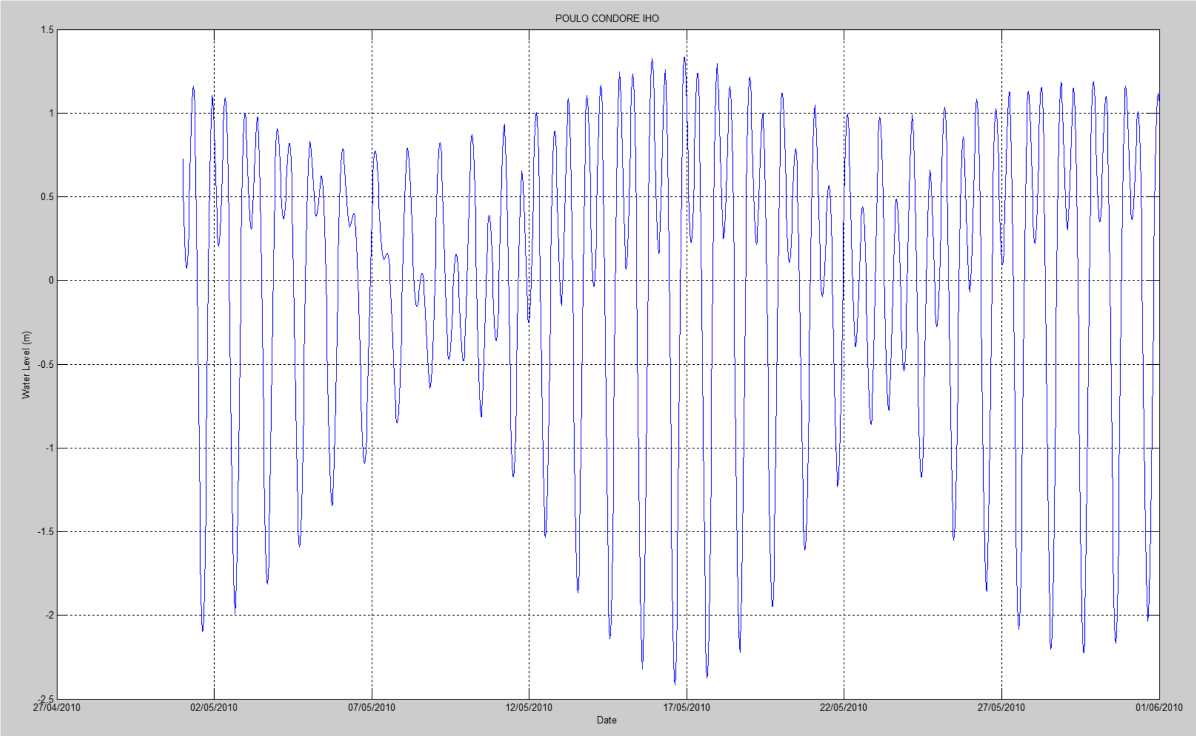

Figure 0.35: Water level signal tidal measurement station Poulo Condore

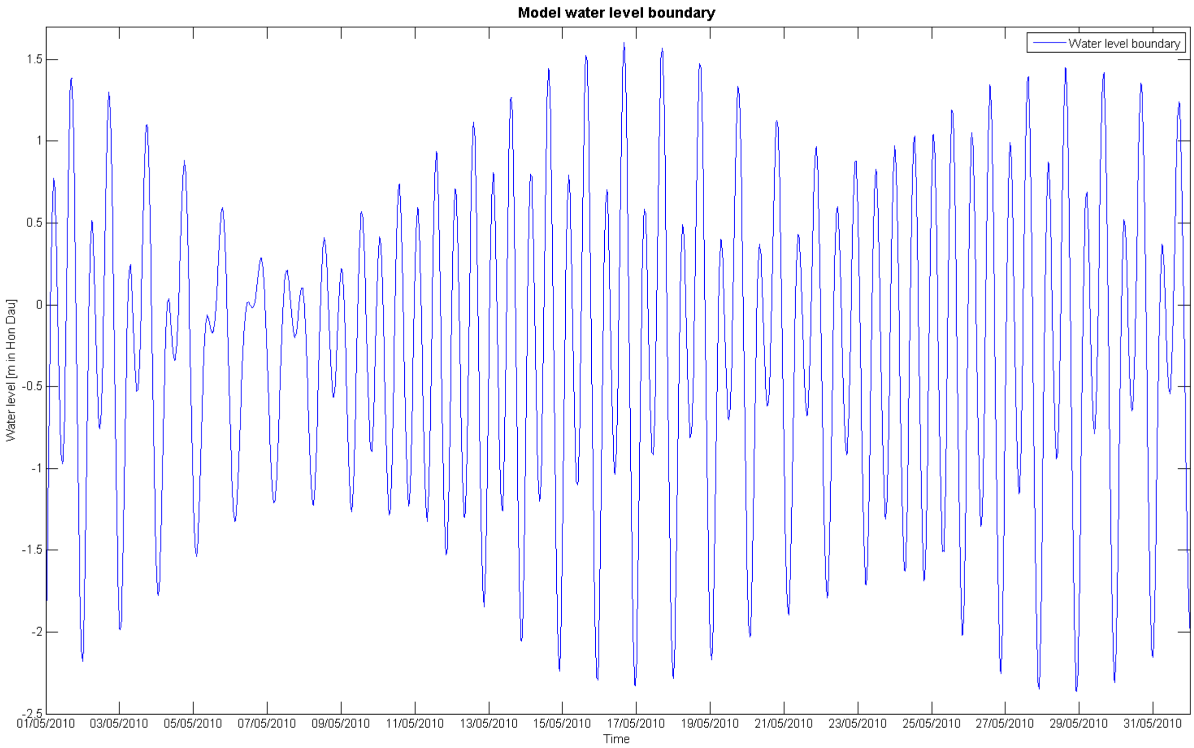

Figure 0.36: Water level signal at the boundary of the Delft3D model

F - RICHARDSON NUMBER MODEL ESTUARY

The Estuarine Richardson number (N_r) can be calculated with equation 0.1. The Estuarine Richardson number is calculated for the Tran De and Dinh An branch for total discharges of 250 (100/150), 500 (200/300), 1,000 (400/600) and 14,000 (4200/9800) m^3/s and these results are given in Table 0.2. This Estuarine Richardson number gives an indication about the mixing of salt and fresh water in the estuary. A value smaller than 0.08 suggest a well mixed estuary, a value between 0.08 and 0.8 suggest the transition zone from well mixed to strongly stratified and a value larger than 0.8 suggest a strongly stratified estuary.

$$N_r = \frac{\Delta\rho * g * h * T * Q_f}{\rho * v_0^2 * P_t} \qquad (0.1)$$

With:
Q_f = The fresh water discharge which enter the estuary [m^3/s]
T = The tidal period [s]
P_t = The volume of water entering the estuary between LWS and HWS [m^3]
ρ = The density [kg/m^3]
h = The water depth [m]
v_0 = The amplitude of the tidal flow velocity at the estuary mouth [m/s]

The total discharge is distributed between the Tran De and Dinh An branch. The Dinh An branch will have an expected discharge share of up to 70 percent of the total discharge in the wet season. The other 30 percent of discharge will flow through the Tran De branch (Nguyen et al., 2008)
A tidal period of 44,700 seconds is used because the tidal signal is semidiurnal.
The volume of water entering the estuary is determined from the MSc report of Linh (Linh, 2012) and from simulation results of the Hau Estuary Model in the reference situation with no bottom topography adaptations in the outer delta. The volumes found are in the same order. For the Tran De a value of 2.67E8 m^3 is found in the report of Linh and a value of 2.00E8 m^3 is found in the Delft3D model. For the Dinh An branch a volume of 3.35E8 m^3 is found in the report of Linh and a volume of 3.00E8 m^3 in the Hau Estuary Model.
The used densities are 1,000 kg/m^3 for the river discharge and 1,035 kg/m^3 for the saline sea water.
The water depth for the branches are based on the same measurements as used to generate the bathymetry of the model.
The amplitude of the flow velocity at the estuary mouth is determined from Delft3D model runs and is based on the top layers.

In Table 0.2 the Estuarine Richardson number for both branches for various discharges are given. As can been seen it is expected that the estuary is well mixed during low discharge. This is similar as the vertical salinity profiles in the model runs show during low discharge conditions as can be seen in Appendix C.

Table 0.2: Estuarine Richardson number for various discharge conditions

	Tran De branch				Dinh An branch			
Q_f [m^3/s]	100	200	400	4200	150	300	600	9800
h [m]	11	11	11	11	12	12	12	12
T [s]	44700	44700	44700	44700	44700	44700	44700	44700
P_t [m^3]	2.00E+08	2.00E+08	2.00E+08	2.00E+08	3.00E+08	3.00E+08	3.00E+08	3.00E+08
V_0 [m/s]	1.0	1.0	1.0	1.0	1.2	1.2	1.2	1.2
N_r [-]	**0.08**	**0.17**	**0.34**	**3.54**	**0.06**	**0.13**	**0.26**	**4.18**

A fresh river discharge of 250 m^3/s results in an averaged Estuarine Richardson number of 0.07 for the Hau estuary. This Estuarine Richardson number indicates a well mixed estuary. In the model simulations in this study a river discharge of 200 m^3/s is used and this also results in a well mixed estuary based on the Estuarine Richardson number.