Long-term Morphological Evolution of the Norderneyer Seegat

M.Sc. Thesis (final version)

Jan-Moritz Müller

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Niedersächsisches Landsamt
für Ökologie
-Forschungsstelle Norderney -

TU Delft

Preface

This report forms my Master of Science thesis and is the completion of my study Civil Engineering at the faculty of Civil Engineering and Geosciences at the Delft University of Technology.

This MSc thesis has been carried out in cooperation with the Coastal Research Station on the East Frisian island of Norderney and focuses on the consequences of sea level rise on the tidal inlet of Norderneyer Seegat.

First of all, I would like to thank my supervisors prof. dr. ir. M.J.F. Stive (Delft University of Technology), dr. ir. Z.B. Wang (Delft University of Technology and WL | Delft Hydraulics), dr. J. Cleveringa (RWS-RIKZ), dr. A.P. Oost (RWS-RIKZ) and ir. J.P. Noppen (Delft University of Technology) for sharing their knowledge. I gratefully thank ir. T.J. Zitman (Delft University of Technology) for his patience and the excellent support during the last year. I would extend a very special thank to Dipl.-Ing. H.-D. Niemeyer and his team at the Coastal Research Station on the island of Norderney, who offered me the opportunity to carry out a part of my work at their institute and who supported me generously with any kind of data I needed. Finally, I would like to thank my parents showing their interest and supporting me during my study.

Delft, October 2004

Jan-Moritz Müller

Summary

This study focuses on the consequences of sea level rise on the tidal inlet of Norderneyer Seegat, which is located in the East Frisan Wadden Sea. The Norderneyer Seegat is located between the islands of Juist and Norderney in the North and the East Frisian mainland coast in the South. The Wadden Sea landscape is mainly shaped by the tides. The tides constantly transport huge amounts of water and within sediments, which are gradually deposited, forming both sublitoral and intertidal shoals. The shoals performing intertidal flats are only visible during low tide. At low tide, the water recedes in narrow channels. These tidal channels work as a distribution system for water and sediment. The volumes of channels (water) and flats (sediment) are assumed to tend to a dynamically equilibrium state.

A rising sea level disturbs this equilibrium. Due to the sediment import into the basin, the flats are continuously growing following the sea level rise. For most of the tidal basins of the Wadden Sea, the net amount of sediment transport into the basin is adequate to compensate the effects of the present rate of sea level rise (1,5 mm/year). If this would not be the case, the whole landscape of the Wadden Sea would change. This would have serious consequences for the safety of the coastline against the sea, because the intertidal flats effects a significant attenuation on incoming waves.

To investigate if the system is capable to adapt to the changes with a sea level rise being significant accelerated compared to present conditions, the numerical model ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast, Stive and Wang, 1996) is applied. The ASMITA modeling concept is based on empirical equilibrium relations between intertidal flats, tidal channels and the ebb-tidal delta performing the morphodynamic elements of the Wadden Sea area. The empirical equations implemented in ASMITA contain of empirical parameters. These parameters depend on regional properties. A part of the study is spent to the determination of these empirical parameters for the Norderneyer Seegat. To determine these parameters, topographic and hydrodynamic datasets are used provided by the Coastal Research Station on the East Frisian Island of Norderney (Germany).

After calibrating the ASMITA model it is possible to calculate the development of the intertidal flats and the channels of the Norderneyer Seegat, due to an observed averaged sea level rise of about 1,5 mm/year. The calculations are limited to the volumes of the elements of intertidal flats and tidal channels. Using reconstructions of historical morphological states of this area for the years 1650, 1750 and 1860, which have been developed at the Coastal Research Station, the results of the ASMITA model, are validated. Therefore, it is necessary to take into account the simplifications made in large-scale and long-term modeling. After reproducing the trends of the evolution in this area over the past 350 years, predictions can be made about the consequences of scenarios with an accelerated sea level rise. This aims to contribute to an estimate of the consequences of global climate change or land subsidence.

At the end of the study, conclusions are drawn, about the consequences of a increase in sea level rise for the tidal inlet of Norderneyer Seegat. Therefore, different scenarios of sea level rise are simulated. Besides this, data analysis and modeling long-term developments of large-scale morphologies is discussed. The report is finalized with some recommendations and aspects to be studied in future.

Zusammenfassung (German)

Ziel der vorliegenden Arbeit ist es, die Folgen von Meeresspiegelanstieg auf die Morphologie des Wattenmeeres abschätzen zu können. Dazu wird ein Modell angewendet, das basiert ist auf empirischen Gleichgewichtsbeziehungen zwischen den morphologischen Einheiten: Platen, Priele und Riffbogen. Diese Gleichgewichtsbeziehungen beinhalten unterschiedlich viele empirische Parameter, die regional abhängig sind. Deshalb wird ein Teil der Arbeit darin bestehen, diese empirischen Parameter fuer das Norderneyer Seegat zu bestimmen. Zur Bestimmung der Parameter werden Datensaetze zur Topografie und zur Hydrodynamik verwendet, die durch die Forschungsstelle Küste auf Norderney zur Verfügung gestellt werden.

Nach Kalibrierung des morphodynamischen Modells ASMITA ist es möglich, die morphologischen Entwicklungen des Norderneyer Seegats als Folge eines beobachteten, gemittelten Meeresspiegelanstieges von 1,5 mm/a zu berechnen. Die Berechnungen beschränken sich auf die Volumina von Platen (Sediment) und Prielen (Wasser). Mit Hilfe von rekonstruierten morphologischen Zuständen für die Jahre 1650, 1750 und 1860, die durch die Forschungsstelle Kueste Norderney angefertigt wurden, wird die Aussagekraft des Modells unterstrichen. Dazu ist es nötig, alle Vernachlässigungen und Vereinfachungen zu berücksichtigen, die eine Langzeitsimulation mit sich bringt. Da es gelingt, die Entwicklung der letzten 350 Jahre tendenziell zu reproduzieren, können Aussagen ueber die Konsequenzen von beschleunigten Meeresspiegelanstiegsszenarien getroffen werden. Damit soll ein Beitrag geliefert werden zur Folgenabschätzung von des Meeresspiegelanstiegs als Folge globaler Klimaänderung.

Das morphodynamische Modell ASMITA, mit dem die Simulationen durchgeführt wurden, ist basiert auf empirischen Gleichgewichtsbeziehungen zwischen den morphologischen Einheiten, die sind Teilgebiete des Wattenmeeres sind. Die Entwicklung der einzelnen Teilgebiete ist abhängig von dem Zustand der jeweils anderen Teilgebiete. Die morphologischen Einheiten sind stets bestrebt, einen Gleichgewichtszustand zu erreichen, der vor allem abhängig ist vom Wasservolumen, das während einer Tide in das Seegat ein- und wieder ausströmt, dem sog. Tideprisma. Da sich das System Wattenmeer in ständiger Veränderung befindet, ist davon auszugehen, dass nie ein absoluter Gleichgewichtszustand eintritt, man spricht deshalb auch vom "dynamischen Gleichgewicht". Eine Ursache für diese ständige Veränderung ist der steigende Meeresspiegel. Als Folge des Anstieges nimmt die Wassertiefe im Watt zu, wodurch sich das System von seinem Gleichgewicht entfernt. Als Reaktion findet eine Anpassung an den neuen Zustand statt. Diese Anpassung geschieht u.a. durch ein Anwachsen des Meeresbodens. Der Meeresboden versucht also dem Meeresspiegel zu folgen um so wieder zu einem Gleichgewichtszustand zu kommen. Das dafür benötigte Sediment wird durch den Flutstrom vom Riffbogen, der sich vor der Öffnung zwischen zwei Inseln befindet, ins Seegat transportiert. Da der Anstieg des Meeresspiegels ein mehr oder weniger kontinuierlicher Vorgang ist, muss das Sedimentvolumen staendig angepasst werden. In der Vergangenheit scheinen die Transportmechanismen leistungsfähig genug und der Sedimentvorrat ausreichend gross gewesen zu sein, um das System Wattenmeer in einem mehr oder weniger unverändertem Gesamtzustand zu halten. Die Frage ist allerdings, ob dies auch bei einem beschleunigten Anstieg des Meeresspiegels bzw. einem zusätzlichen Absacken

des Meeresbodens (der durch die Förderung von Erdgas im Wattenmeer eintreten kann) der Fall ist. Auf diese Frage soll durch die Anwendung des morphodynamischen Modells ASMITA eine Antwort gefunden werden. Die Anpassungsfähigkeit ist bis zu einer bestimmen Anstiegsrate gegeben. Ein Anstieg über dieser kritischen Rate, hat dramatische Veränderungen, wie z.B. ein Verschwinden der Platen, zur Folge. Da die Platen im Wattenmeer die Funktion eines natürlichen Wellenbrechers vor der Festlandküste haben, ist es für die Planung von Küstenschutzbauwerken von Interesse ihre Entwicklung abschätzen zu können.

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1 Introduction

1.1 Objective of the study

This study focuses on the consequences of a rising sea level on the tidal inlet of Norderneyer Seegat, which is located in the East Frisian Wadden Sea. As a consequence of a rising sea level, the morphology of the Wadden Sea adapts. Understanding and modeling the morphological response of the coastal zone to a rising sea level is essential for policy decision making with respect to preservation of the coast line and the socio-economic and nature values of this region.

To make an estimation about the morphological changes that will take place due to sea level rise, the numerical model ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast, Stive and Wang, 1996) is applied. The ASMITA modeling concept is based on empirical equilibrium relations between intertidal flats, tidal channels and the ebb-tidal delta that are the morphodynamic elements of the Wadden Sea area. The model describes the development of volumes of intertidal flats, tidal channels and the ebb-tidal delta over time-scales of decades and centuries. The simulation results have to be seen as a ‘semi-empirical’ extrapolation of the observed evolution. The empirical equations implemented in ASMITA consist of some empirical parameters. These parameters are depending on regional properties. A part of the study is spent to the determination of these empirical parameters for the tidal inlet Norderneyer Seegat and its catchment area. For determining these parameters, topographic and hydrodynamic data-sets will be used that are provided by the Coastal Research Station on the East Frisian island of Norderney (Germany).

In the end of the study, more insight should be available about the capability of the tidal inlet of the Norderneyer Seegat, to adapt to changing morphological boundary conditions, caused by an increase in rise in sea level. The intertidal flats effects a significant wave demping in front of the coastline of the mainland. If the water depth increases in the Wadden Sea, the waves that reach the coastline will be higher and create higher wave run up at. Therefore, a prediction of the development of tidal channels and intertidal flats is of high importance for long-term planning in coastal engineering. The objective of this study is, to allow an estimation of a maximum rate of sea level rise that can be compensated by the net amount of sediment transport into the basin. Furthermore, with the ASMITA model it should be possible to explain developments of the volumes of intertidal flats, tidal channels and ebb-tidal delta that have taken place in the past.

1.2 Study area

Introduction

The tidal inlet of the Norderneyer Seegat is part of the large-scale natural system of the European Wadden Area. In the following, some general type properties and the development of the landscape of the Wadden Area will be described.

The European Wadden Sea

The European Wadden Area (fig. 1-1) covers the western Danish, German and northern Dutch North Sea coast. It has a total length of about 500 km and a maximum width of 35 km. The Wadden Area is bordered towards the North Sea by 20 back barrier islands. Between these islands and the mainland the typical Wadden Sea landscape is situated with its tidal channels and the intertidal flats that are dry during low water and flooded during high water.

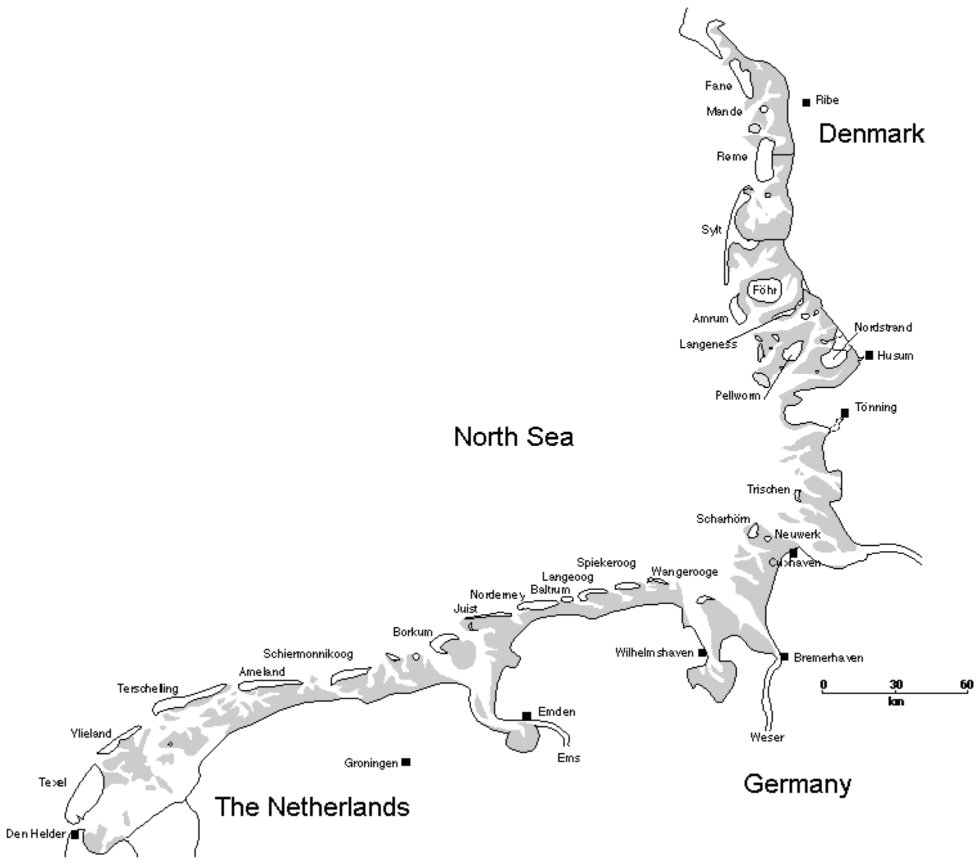

Figure 1-1 European Wadden Sea (after WWF)

The German Wadden Sea

The German North Sea coast has the shape of a bight; it is therefore also called the German Bight. The coastline west of the estuaries of the rivers Elbe, Weser and Jade is called the East Frisian coast. In Northern direction of the estuaries, it is called the North Frisian coast. Although all coastlines in the German Bight are Wadden Sea areas, they differ significantly (fig. 1-1).

Comparing the two island sheltered coastlines, highlights that the East Frisian Islands are differently shaped in than the North Frisian Islands. The North Frisian Wadden Sea are remnants of former mainland due to the destruction of vast marshland by storm surges. The East Frisian Islands are the result of sediment transport processes along the coastline. They change their shape during long time-periods, but they are not disappearing. We can see this by looking to the statistic of the size of the island of Norderney for the last 350 years. The shape is changing dramatically but the size of the surface is staying the nearly the same.

The Lower Saxony Wadden Sea

The East Frisian Islands (German: *Ostfriesische Inseln*) are a chain of islands in front of the coastline of the German federal state of Lower Saxony. It extends from the river Ems in the West to the river Jade in the East (see fig. 1-2).

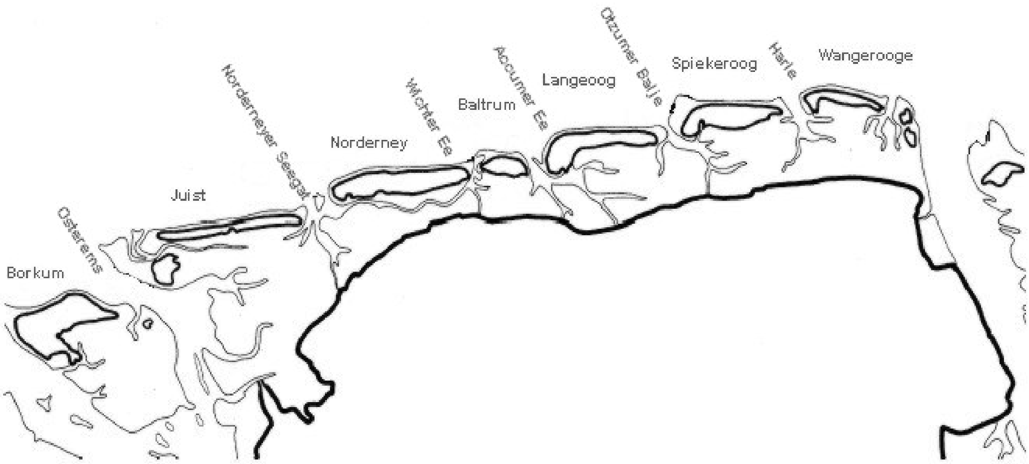

Figure 1-2 Wadden Sea area of Lower Saxony

Most of the islands don't allow cars. The exceptions are Borkum and Norderney, which are also the most crowded islands. The islands are connected to the mainland by ferries. The islands of Langeoog, Norderney and Borkum can be reached by ferry tide independent. The frequented connections to the infrastructure of the mainland are an indicator for the importance of the economic value of the islands to the region. This economic value is more or less completely based on tourism. To guarantee the continuity of the tourism, coastal protection is one of the main tasks that must be fulfilled. One of the most important reasons for the guests to come to the island is the nature.

The historical evolution of this area was influenced by interventions in favour of coastal protection on the barrier islands. Since the last 200 years, tourism has played an increasingly important role on the islands. Therefore, buildings and infrastructure were created. To avoid changes of the morphology of these islands one tried to fix the tidal inlets between two islands. In that way, the nature in this region was forced into a permanent state of a temporary situation. Many of the investigations that have been carried out on subjects of morphological changes, of the physical properties and the physical process that take place in this region are economical founded.

The disappearance of the islands Buise, which was located between Juist and Norderney, is one example that indicates that we are dealing with a large, coherent morphological system. For coastal zone management in this area, it is crucial to appreciate the entire system. This will be subject of the present study. Because of the cyclical character of these developments, it seems that morphological patterns of the East Frisian Islands migrate from the West to the East. This process is steered by the behaviour of the tidal inlets due to the sediment transport driven by waves and tidal currents.

Considering long-term changes of the morphology, one has to take into account sea level rise. The consequences of sea level rise are arising during long time-periods of hundreds years.

In the history, the Wadden Sea coast was not always located on the place where it is today. During the last 500 years, significant changes have been taking place. Most of the islands altered due to the drift from the West to the East and from the North to the South. The movement to the South is an adaptation to sea level rise causing erosion of the dunes on the North side of the islands and silting up at the Wadden coast in the South. Due to the winds that are blowing predominantly from westerly directions and the residual tidal currents being directed eastward, the sediment, transport heads also from the West to the East along the North Sea coast. The islands are also migrating in this direction. This takes place by eroding the West point of the islands- and on the Eastern part the sediment is settling down.

The tidal inlet "Norderneyer Seegat"

The Norderneyer Seegat is located between the two islands Norderney in the East and Juist in the West. The tidal inlet between these two islands has a width of 3500 m and a maximum depth of 25 m (fig. 1-3). In the year 1975 the total surface area of the tidal basin was 102,7 10^6 m^2, consisting of 82,9 10^6 m^2 eulitoral area and 19,8 10^6 m^2 sublitoral area. The mean tidal range of 2,37 m results in a tidal prism of 155,6 10^6 m^3 (NIEMEYER, 1994). During the last 100 years, a rise in mean high water level of 0,25 m and a rise in mean low water level of 0,103 m was observed (Coastal Research Station). The distance in the area of the eastern watershed between the island Norderney and the mainland is 3 km and in the area of the western watershed between Juist and the mainland about 10 km (fig. 1-3).

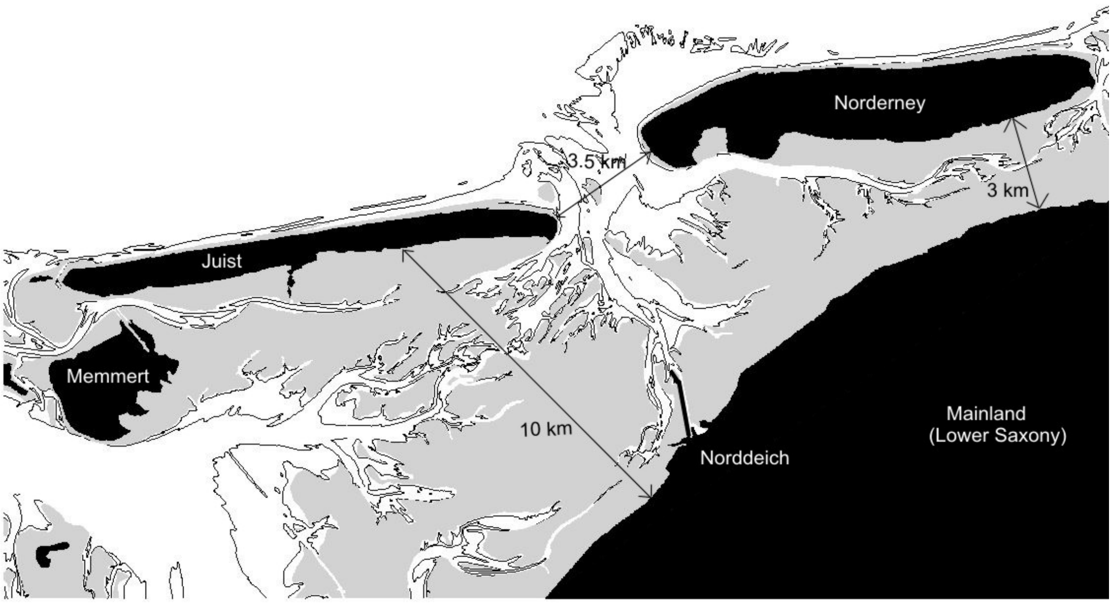

Figure 1-3 Tidal inlet of Norderneyer Seegat

Norderney

The island of Norderney has a dune core in the west and a sand flat in the east (see fig. 1-4). The settlement of Norderney is located in at the western part of the island. Because the island is moving to the East, the Western beaches have been protected against erosion by groynes and seawalls, their construction started in 1858. Eastwardly the size of the beaches increases, particularly downdrift of the area where the shoal of the Norderneyer Seegat ebb-tidal delta welds at the shore. At the South side of the island, there are no sandy beaches, but intertidal flats. In 1840, a dyke was constructed to create a small polder to protect the town. In 1880, the harbour was build behind the flood spit. In the middle of the island another polder was created 1922 the Grohde Polder (see fig. 1-4) where currently the airport is located. In the Second World War, the Suedstrandpolder (see fig. 1-4) was constructed in order to reclaim land for an airfield. This plan was abandoned and the area became a nature reserve. The Eastern part of Norderney has, as most of the other Wadden Sea islands a positive sand balance. The Ostplate is covered with dunes and sand flats. No artificial dykes or dune ridges have been constructed there. During extremely high tides, large parts of this area are inundated. There are no houses and no infrastructures. This natural area takes one third of the whole island. During strong storm surges, the dunes can be heavily eroded in the eastern part of this area. The island has experienced eastward displacement, while its western end remained stable since the implementation of underwater groynes at the beginning of the 20th century.

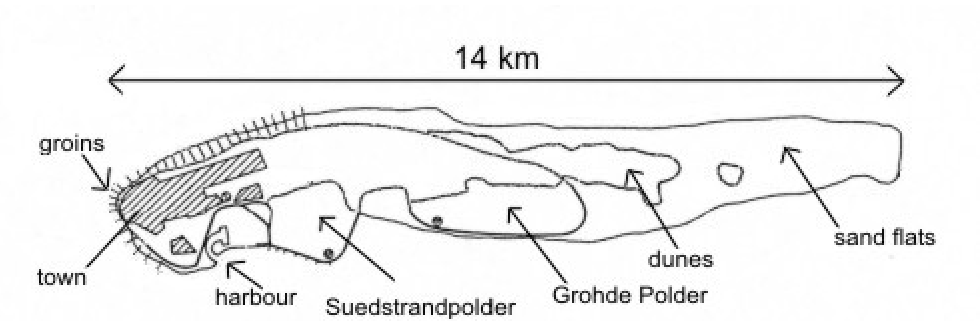

Figure 1-4 Island of Norderney

Juist

The island of Juist is with its length of 17 km the longest of the 7 East Frisian Islands. Massive coastal protection structures are not necessary because this island is relatively stable since the last 100 years. In the western part of the island, there is a big fresh water lake with a length of 1800 m and a width of 600 m. After a severe storm surge in 1651 the island was broken in two parts. More than two centuries later the island was reconnected to the lost part. Now the Hammer Lake is separated from the beach by dunes. The island of Juist has a harbour on its south site. Due to the small water depths in the Wadden area where the port of Juist is located, the island can only be reached by ships at high water.

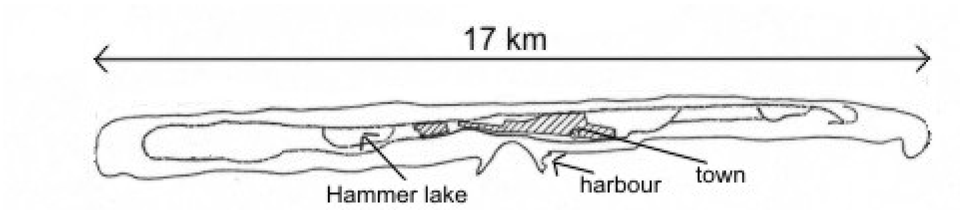

Figure 1-5 Island of Juist

1.3 Morphological evolution in history

To understand more about the long-term morphological processes that take place in the Wadden Sea, it is important to know the morphological developments that formed it to its present shape. According to ZAGWIJN (1986) and VAN DER SPEK (1994), part of the Wadden Sea islands has the tendency to shift eastward and landward under the influence of the preceding rise of the sea level. Historical geological findings also show that in the course of time the system has become considerably smaller. In the following four figures one can see how the tidal inlet of the Norderneyer Seegat developed in the last 350 years. The charts that are shown in figure 1-6, 1-7, 1-8 and 1-9 are reconstructions made by HOMEIER (1962).

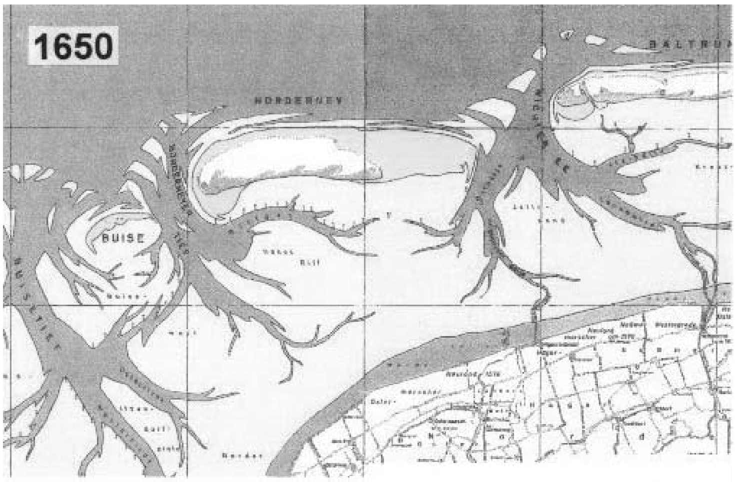

Figure 1-6 State of Norderneyer Seegat in 1650 (HOMEIER, 1962)

There are significant differences between the topography of the Norderneyer Seegat in the year 1650 and that in 1960. The most important difference is that there were two tidal inlets between the islands of Juist and Norderney (fig. 1-6). The rests of the disappearing island Buise performed shelter against waves from the North for the mainland coast. Caused by currents a lot of sand was transported from Buise to Norderney. Therefore, Buise provides also a sand supply for Norderney.

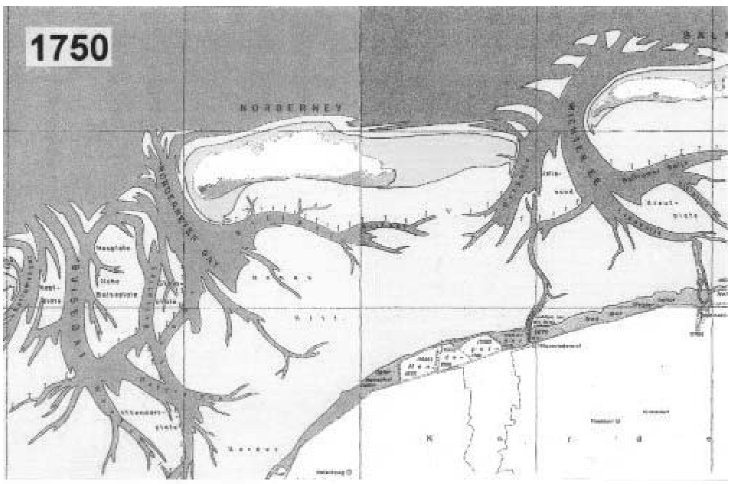

Figure 1-7 State of Norderneyer Seegat in 1750 (HOMEIER, 1962)

In the year 1750 the island of Buise has already disappeared (see fig. 1-7). The old tidal inlet of Buise is now disappearing as well. In 1750, the bigger amount of water follows the channel close to Norderney. Buise is still protecting the main land coast against incoming waves.

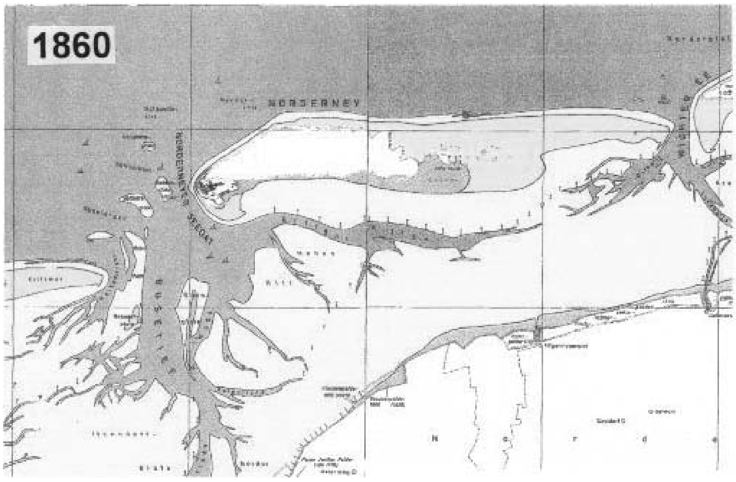

Figure 1-8 State of Norderneyer Seegat in 1860 (HOMEIER, 1962)

In 1860, the island of Buise has turned into an intertidal flat or shoal (see fig. 1-8). The tidal inlet of Buise is silted up totally. The Busetief is now the main channel between Juist and Norderney, a tributary to the tidal inlet Norderneyer Seegat. At Norderney the first coast protection interventions have been taken place. Especially in the South of the settlement of Norderney, a dyke was build. Also a little polder was created. In 1858, one started to fix the state and the form of the islands by protecting the beaches.

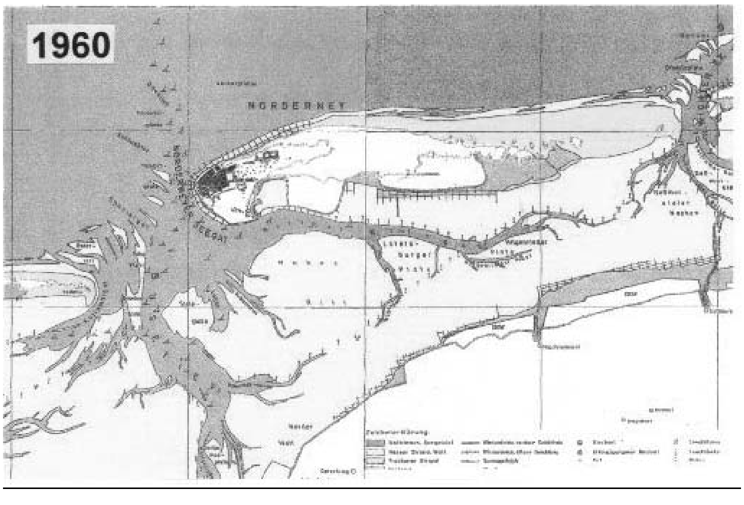

Figure 1-9 State of Norderneyer Seegat in 1960 (HOMEIER, 1962)

In figure 1-9 it can be seen, that in 1960 the gap between the islands Juist and Norderney has almost turned to one tidal inlet. Nevertheless, two tidal channels of the Buisetief and the Norderneyer Seegat are still present. The natural changes of the morphology from the beginning of the 20th century on are very small because human activities were intensified. Coastal engineers are trying to avoid unfavourable developments and to force the favourable ones. Changes in the morphology were unwelcome. The coast protection was strengthened. Especially the west point of Norderney where the town is located, has been protected against currents and waves by 32 groins and a strand wall over a length of 6 km. In front of the port of Norddeich at the mainland a long breakwater was build to fix the approach channel to the port.

1.4 Research methodology

Introduction

In order to organize the work from the problem definition to the results and the conclusions through the entire project, it is useful to make a schematization of the most important steps that have to be done during the study. In this section, these steps will be explained. In figure 1-10, a schematization of the research process is given. In the following, the methodology will be described in general. The steps will be elaborated in detail, in the specific chapters.

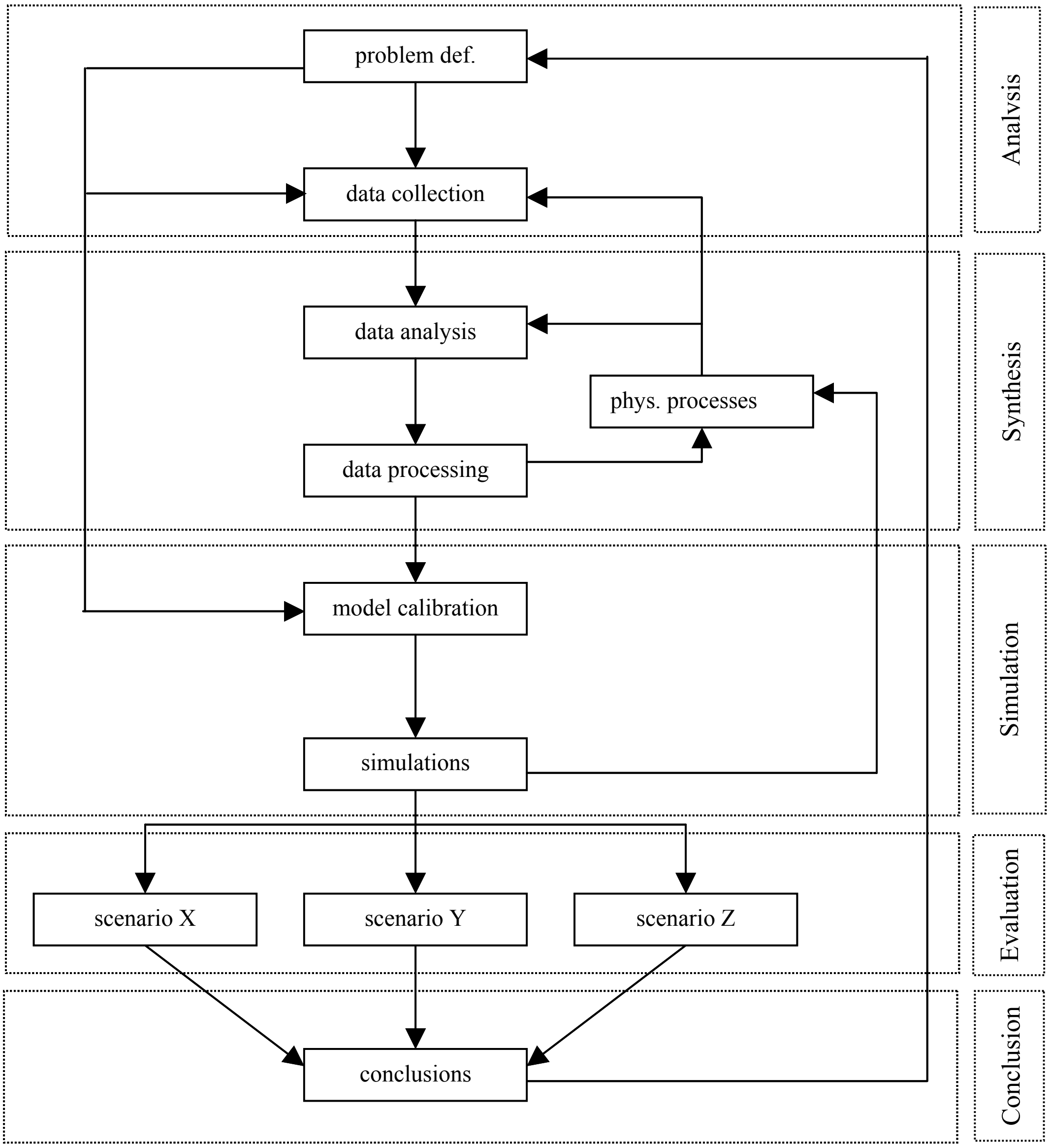

Figure 1-10 Schematization of the research process

Problem definition

At the beginning of the research, it is necessary to make a detailed definition of the problem. In the case of the present project, the problem definition was carried out by writing a workplan. The workplan already consists of a first overview of studies adressing the same purpose that have been done before. These studies are a useful base for starting further investigations. Another part of the workplan is a rough time planning.

The problem definition comprises the specification of the questions that are to be discussed. This specification also includes the question, which kind of results can be expected and how to get them. This question mainly influences the data collection and the calibration of the model. The definition of the problem is carried out in chapter 1 and chapter 2.

Together with the data collection, the problem definition represents the analysis phase of the research project.

Data collection

The process of collecting data takes two forms: gathering data that already had been collected by someone else, for other purposes, and creating new data. In this study, the first form of collecting data will be dominating. Data sets will be used that exist already. For creating new data, it would be necessary to make new measurements, what is not a subject of this study. The question, what kind of data is needed, mainly depends on the targets that are formulated in the problem definition and on the model that will be used. In case of the present study, it was necessary to get any kind of information about the volumes of the Wadden Sea elements as intertidal flats or tidal channels. To determine the volumes, information as surface areas and water depths were needed. These data sets were provided by the Coastal Research Station on the island Norderney. The volumes were needed to make predictions of the development of the tidal inlet by applying the ASMITA numerical model.

Data analysis

Considerable analysis of historical data and secondary information has to be done to help define in clear and precise terms what is the problem or opportunity. An important part of the data analysis is to check how the data sets are determined and how reliable they are. Different reference levels of the water depths can significantly influence the determination of volumes in the Wadden Sea basin.

Another aspect of the data analysis is to inventory which kind of data one can get and how to combine it. It is useful to take one kind of data e.g. measurements of water levels from one source. If one combines one kind of data from different sources, it is possible that they are determined in different ways. Data sets of the same kind of information can be determined in different ways and can vary. Therefore, it is important to handle them separately from each other and not mixing them. The data analysis will be part of chapter 3.

Data analysis and data processing form together the synthesis phase of the research project, in which the knowledge of the analysis phase will be translated into possible applications.

Data processing

Some data sets are not in the form needed. Therefore, the specific information that is needed for applying the methods or computer programs must be derived from the data sets. It is possible to extend the information by combining different data sets with each other. So, the tidal prism of a tidal inlet can be calculated using the tidal range and the surface areas of a tidal basin. In this study, it is necessary to have information about different volumes of the tidal basin. The data processing will be done in chapter 3.

Study of physical processes

After completing the information that is needed for the investigations, a first analyses of the physical processes is made that play an important role in the study area. In case of the present study, there will be a consideration of the morphodynamical processes and of the morphological properties of the tidal inlet of Norderneyer Seegat. It is of interest if the tidal inlet is importing or exporting sediment or if it is more flood- or more ebb-dominated according to some indicators, as the diagram of DRONKERS or averaged flood and ebb duration. The study of the physical processes also gives information about the quality of the data that has been collected and if additional data will be needed. The study of the physical processes is documented in chapter 4.

Model calibration

Before making simulations with a numerical model, it is necessary to calibrate it. During the calibration procedure, some variables and parameters have to be chosen in a way, that the model is able to reproduce the specific physical processes of the natural system in the investigation area. In the present study, some empirical parameters used in the numerical model ASMITA are determined. To control, if the model is working in the right way, 'independent' measurements have to be compared with the results of the calculations. The model calibration depends on the targets that are formulated in the problem definition. In the present case, the model is used to make predictions of changes in volume of the different elements of the Wadden Sea due to a rising sea level. To interpret the results of the simulations, it can be useful to compare these with the insights from the study of the physical processes. The model calibration is part of chapter 5.

Simulations

When the model is calibrated and capable to simulate the processes in the study area with sufficient accuracy, one can start making the calculations that are needed for the investigation. In this case simulation are carried out in order to make predictions of the behavior of the tidal inlet of the Norderneyer Seegat due to different rates of sea level rise. It is useful to keep some (measurement-) data that are not used for the calibration, to compare the results of the simulation. The simulations are done in chapter 5.

Scenarios

In the present study, the simulations that are carried out with numerical models are divided in different scenarios. The simulations are estimations of the consequences of rates of sea level rise of 1.5 mm/year, 5 mm/year and 10 mm/year. The scenarios in chapter 5 are useful to be able to draw conclusions from the simulations. By investigating different scenarios, the results of the entire research work will be evaluated.

Conclusions

At the end of the investigations, the conclusions are summarized to give an answer to the problem that was formulated in the problem definition of the project. Together with the conclusions, recommendations are given in order to give an impulse for further research. The conclusions are documented in chapter 6.

2 Theoretical background information

Introduction

The topography of the Wadden Sea is complex. To understand the development of this topography it is useful to divide it into morphological elements that influence each other. Commonly one distinguishes the following elements (fig. 2-1):

- Barrier island
- Tidal channel
- Flat
- Ebb-tidal delta

In this chapter, the properties of these morphological elements will be described. Besides these descriptions, a collection of morphological equilibrium equations belonging to the certain elements will be made.

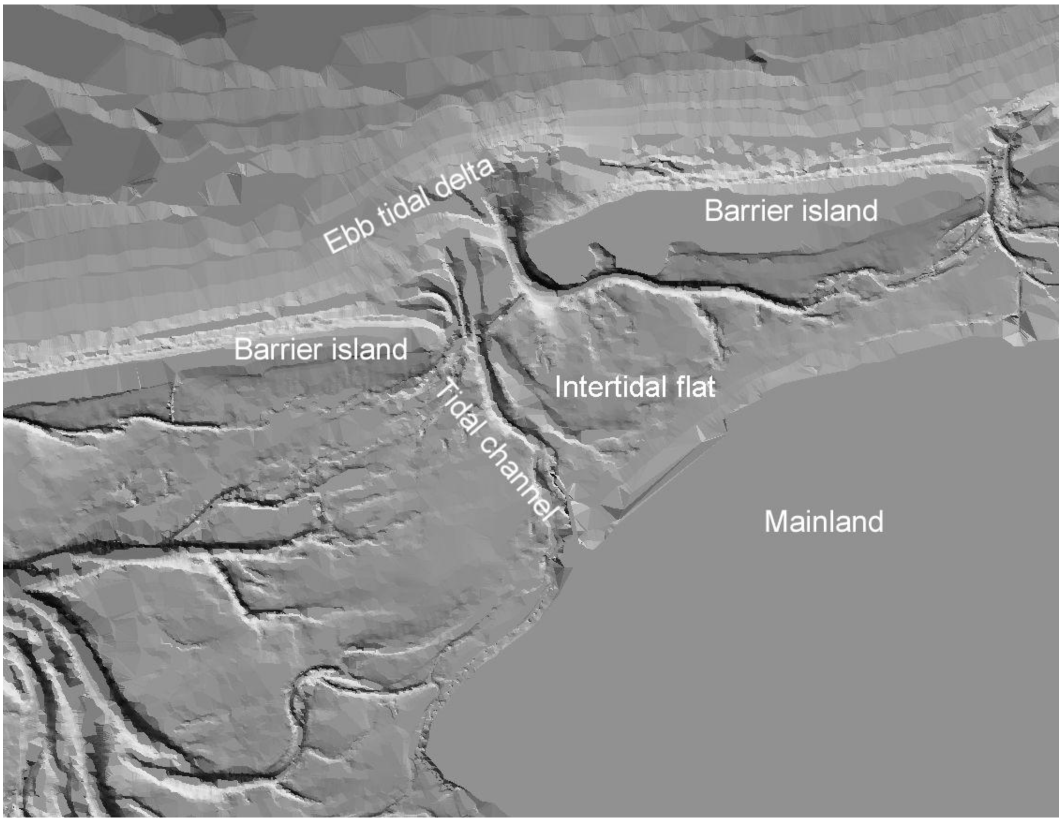

Figure 2-1 Morphological units of the Wadden Sea

The area between the barrier islands and the mainland is the tidal basin. The tidal basin is connected with the open sea by tidal inlets, which are the gaps between the islands. The landscape of the Wadden Sea is characterized by meandering and branched channels. In some areas of the Wadden Sea, rivers are discharging into the North Sea, like in Elbe estuary. In river estuaries, the salt water of the open sea and fresh water coming from the rivers are mixing. This is not the case in the tidal linlet of the Norderneyer Seegat. The morphology of the Wadden Sea is not fixed but dynamic. The reasons for these changes are different. Important influencing factors are:

- Bathymetry of the basin
- Winds and waves
- Tidal range and tidal currents
- Sediment transport capacity
- Erosion and sedimentation
- Inlet discharge and related salinity and density variation
- Relative sea level rise
- Change of tidal amplitude
- Closure works
- Dumping and dredging
- Extraction of gas and oil in the Wadden Sea

The tidal volume is the amount of water that is entering the tidal basin during flood and leaving it during ebb period.

The tidal prism is the volume of water between Mean Low Water (MLW) and Mean High Water (MHW) in the tidal basin. It is based on the bathymetry of the tidal basin. In short basins, relative to the length of the tidal wave, the tidal motion has the character of a standing wave which results in a tidal volume of about twice the tidal prism. This also means, that there is nearly no slope in the water surface. Although the tidal wave is moving from the West to the East in front of the Barrier Islands of Lower Saxony, the water level inside the tidal basin is more or less going up and down without horizontal propagation.

2.1 Empirical relationships

The physical processes that influence the shape of the morphodynamic elements of the Wadden Sea are complex. Thus, to understand them it is necessary to know some geometric properties of the topography. These geometric properties of the Wadden Sea are influenced by the environment, especially by the hydraulic boundary conditions. By developing to a certain state, the morphology is going to change to an equilibrium situation, fitting to the boundary conditions. When the environmental factors do not change, the tidal inlet tends to a morphological equilibrium. If the environmental factors change, it will develop to a new equilibrium state. In this state of balance, relationships exist between the equilibrium state and the hydrodynamic parameters. When changes occur in the boundary conditions, with these relationships it should be able to predict the new equilibrium state. Therefore, research has been carried out to find a relation between the morphological balance and the tidal prism. The basics for these relations were found in the United States (O’BRIEN, 1969; JARRET, 1976; and WALTON and ADAMS, 1976) and more recently in other parts of the world (EYSINK and BIEGEL, 1990-1995). In the description of the morphodynamic elements of the

Wadden Sea, a selection of the empirical relationships will be shown. The difference between the values of the empirical relations and the values, measured in nature could be an indicator of the stability of a tidal inlet.

For the morphological units of the Wadden Sea, an empirical relation holds between the volume of the element and the tidal prism. The tidal prism is dependent on the tidal range (H) and the surface area at low water level (A_b):

$$V_e = f(P) \tag{2-1}$$

or

$$V_e = f(H, A_b) \tag{2-2}$$

The equations contains coefficients and exponents. The values of these coefficients and exponents are determined empirically. This means, that they are derived from measurements in the nature and therefore they are region-dependent. In chapter 5 the empirical coefficients in the equilibrium equations will be adapted to the regional attributes of the Norderneyer Seegat.

2.2 The dynamic equilibrium

As mentioned in section (1.1), the Wadden Sea morphology always tends to come to a dynamic equilibrium state. Dynamic equilibrium means in this context, that the condition of the system is characterized by an overall balance in the processes of change, made possible by the systems flexibility and resulting in relative stability of the morphological state despite constant change and small disturbances. If changes take place in the system, it will adapt to a new equilibrium state.

This dynamic equilibrium of the system would be reached if short-term morphological changes do not affect the morphology over a long period. The rise of the sea level is not a short-term change but a long-term change. It will cause a rise in the water depth of the Wadden Sea. By this increasing water depth, the dynamic equilibrium of the Wadden Sea will be disturbed. Because of the increased water depths in the tidal channels and on the intertidal flats, the averaged current speeds will decrease. Therefore, there will be a disproportionate reduction in the capacity of the sediment transport, because the sediment transport capacity is a power function of the current speed. The flood stream will carry on the sediment from the open sea into the tidal basin and there, the sediment will deposit. In a system that is in equilibrium, the ebb current will transport nearly the same amount of sediment from the basin, back to the open sea. In a disturbed system with an increased water depth, the ebb currents will be slower than the flood currents resulting in a longer ebb period. Because of their smaller current velocities, the ebb currents will not have enough force to transport the sediment back to open sea. Therefore, a certain amount of sediment will stay in the tidal basin. This additional sediment will cause a decreasing water depth resulting in a state of the tidal basin that is closer to its equilibrium situation. The net sediment transport from the open sea into the tidal basin will enable the sea bottom to follow the rising sea level. If a tidal inlet is importing sediment for reaching a new equilibrium state can be seen on some hydrodynamic parameters as shown in chapter 4.

2.3 Morphological elements of the Wadden Area

2.3.1 Tidal Basin

The tidal basin consists of the tidal channels and the intertidal flats, which will be described later. Through the gap between the islands, the tidal wave enters into the basin. On its sides, the basin is limited by the so-called watersheds. The watershed is the area between one island and the mainland, with the highest topography and therefore the lowest water depths. If one can pass a tidal basin from the mainland to the island by foot, this will be on the watershed. In an ideal situation, there are no tidal current on the watershed, because the tidal wave that is coming from the one tidal inlet meets the tidal wave from the other tidal inlet in this area. However, because the tidal wave passes the inlets from west to east, small currents develop over the watershed. In some tidal basins, one has to distinguish between the topographic watershed and the hydraulic watershed. This comes, because for example in the case of the watershed between Norderneyer Seegat and the Osterems, parts of the tidal wave from the Osterems are entering the tidal basin of the Norderneyer Seegat via the watershed.

According to EYSINK (1991) the basin is characterized by:

- Size
- Relative area of the channels and tidal flats
- Shape of storage curve (hypsometric curve, see figure 4-4)
- Natural accretion rate.

2.3.2 Barrier islands

The barrier islands are situated on the seaward side of the Wadden Sea. They are shaped and sustained by wind, waves and tides. Barrier islands consist of a shoreface, beach, dunes and overwash areas.

There are two sorts of islands along the German Wadden Sea coast, barrier islands and marsh islands. The islands of Pellworm, Nordstrand and the Halligen in the northern part of the German North Sea coast remnants of old marsh areas. These islands were flooded frequently and covered by marine sediment.

In contrast to the marsh islands, the barrier islands, that we can find along the southern North Sea coast in The Netherlands and in Germany, owe their existence to landward directed sand transport and the accumulation of shoals. Dunes stabilize these islands.

2.3.3 Ebb-tidal delta

The ebb-tidal delta is located on the seaward side of the tidal inlet and is mainly influenced by the tidal current and the waves. It consists of various shoals. The velocity of the ebb-tidal flow decreases when it leaves the channel between the islands, resulting in settlement of the sediment in the ebb-tidal delta area. On the other hand, high waves bring the sediment of the ebb-tidal delta in suspension. Therefore, HAYES (1979) divided the ebb-deltas into 3 forms and made a classification:

- tide-dominated,
- mixed-energy and
- wave-dominated.

The tide-dominated delta tends to protrude into the sea and has well-developed shoals. In a mixed-energy climate the delta has a smooth and curved outer shoal, and the wave-dominated delta has very little accumulated sediment in the ebb-tidal delta. The properties of the ebb-tidal delta can be determined by the difference between the delta bathymetry and a virtual bathymetry that would be there if there was no inlet. The determination of the ebb-tidal delta volume according to this definition will be shown in chapter 3.

EYSINK (1991) characterized the ebb-tidal delta by:

- sand volume (determined in chapter 3)
- overall size
- characteristic dimensions of channels on the outer delta

The volume of the ebb-tidal delta is related to the tidal prism and wave climate (WALTON and ADAMS, 1976). Deltas in a high wave-energy climate are relatively smaller then deltas in a low wave-energy climate.

LUCK (1975) described the development of the ebb-tidal delta of tidal inlet of Norderneyer Seegat. This tidal inlet actually consists of two gaps that are divided by a shoal. Northward of the tidal inlet, longshore sediment transport creates a series of sand reefs, which are shifted around the inlet in a curved path. The sand is transported from the east end of the updrift island Juist via the sand reefs of the ebb-tidal delta to the middle sand reef and from the middle sand reef further via another ebb-tidal delta sand reef series to the west end of the downdrift island Norderney. This processes are still observable in the Norderneyer Seegat, however the middle sand reef between the two islands is disappearing.

EYSINK approximated the volume of the ebb-tidal delta by the relation:

$$V_{delta} = \alpha_{WA} \cdot P^{1.23} \qquad (2\text{-}3)$$

with:

V_{delta} Sand volume of the ebb-tidal delta [m^3]

α_{WA} Empirical coefficient the importance of wave conditions [m$^{-0.23}$]

P Tidal prism [m^3]

The empirical coefficient α_{WA} depends on the wave climate:

low wave energy coast: $\alpha_{WA} = 8.64*10^{-3}$

moderate wave energy coast: $\alpha_{WA} = 6.44*10^{-3}$

high wave energy coast: $\alpha_{WA} = 5.33*10^{-3}$

For the Wadden Sea EYSINK (1990) found the following relation, which is consistent with a moderate wave energy coast:

$$V_{delta} = 6.57 \cdot 10^{-3} \cdot P^{1.23} \qquad (2\text{-}4)$$

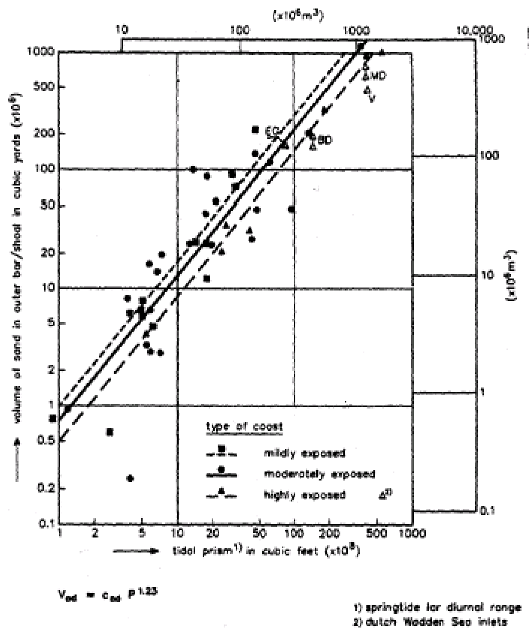

Figure 2-2 Equilibrium relation ebb-tidal delta (EYSINK, 1990)

2.3.4 Channel

The tidal channels (sublitoral zone) can be seen as the distribution-system of the inlet. It transports the water and sediment into and out of the tidal basin. ESCOFFIER (1940) found a relation between the maximum flow velocity through a channel and a parameter X, related to the area of the wet cross-section of the channel (such that a larger area gives a larger value of X).

ESCOFFIER defined a velocity (V_{cr}) such that below this velocity no erosion will take place. The horizontal line in figure 2-3, assuming it is independent of the channel geometry, represents this critical velocity.

Figure 2-3 can be divided in 3 parts, the first part (A-B) is characterized by a low velocity and a small area, the low velocity will give sedimentation resulting in a decrease of flow-area and eventually the cross-section will be silted up. In the second part (B-D) the velocity is higher than the critical value and erosion will take place, this means that the value of X will increase and the inlet will 'move' along the curve to point D. The last part (E-D) has a large cross-sectional area and a low velocity, the low velocity results in a decrease in area, but a decrease in area causes a increase in velocity and sedimentation will take place until point D is reached.

Both point B and D represent an equilibrium situation only point D is a stable point as a deviation of point D will result in erosion or sedimentation such that the inlet will return to point D, and point B is an unstable situation as a small deviation will result in a bigger deviation and the inlet will tend to move to point A (in case of a decrease of area) or to point D (see arrows in Figure 2-3). When the system is in a situation of (dynamic) morphological equilibrium (point D in Figure 2-3) a well-established relation between the cross-sectional area of the tidal channels and the tidal prism exists (EYSINK and BIEGEL, 1992).

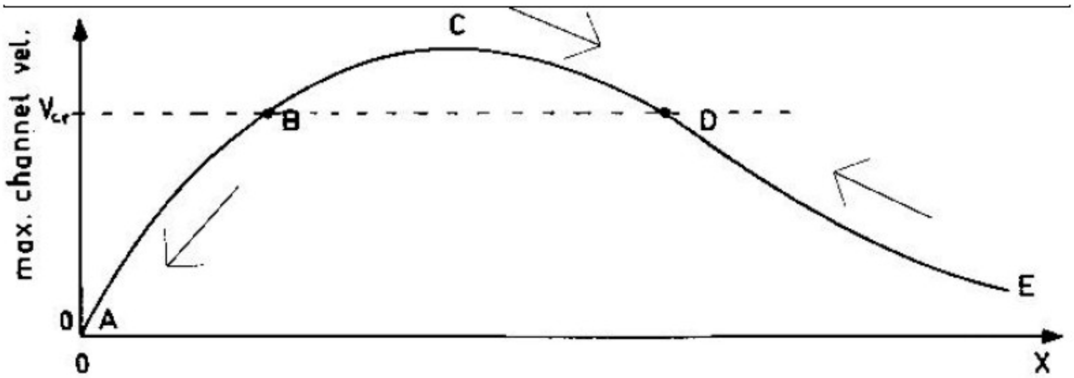

Figure 2-3 Velocities in tidal channel according to ESCOFFIER (1940)

EYSINK (1991) characterized the channel dimensions by:

- flow area
- width (at MSL and MLW)
- mean and maximum depth
- channel volume (below MSL and MLW)

Many empirical studies were carried out, to find an relationship between the cross-sectional area of the tidal inlet and the tidal prism entering the basin. They show that there exists an almost linear relation. EYSINK (1990) stated that for ‘ throat area - tidal prism ‘ relationship a good description is presented by:

$$A_{MSL} = \alpha_A \cdot P \qquad (2\text{-}5)$$

with:

A_{MSL} Flow area below MSL (Mean Sea Level) [m^2]

α_A Empirical coefficient for the equilibrium flow area [m^{-1}]

P Mean tidal prism [m^3]

The parameter α_A gets a value of 70 10^{-6} [m^{-1}] for the Wadden Sea.

EYSINK and BIEGEL (1992) found for the relation between the tidal prism and the channel volume below MSL the equilibrium condition:

$$V_{channel} = \alpha_c \cdot P^{1.55} \qquad (2\text{-}6)$$

with:

$V_{channel}$ Channel volume below MSL [m^3]

P Mean tidal prism [m^3]

α_c equilibrium coefficient (for the Wadden Sea: 1.6 10^{-6} [(m^3)$^{-0.55}$])

2.3.5 Intertidal Flats

The intertidal flats are the areas in the intertidal (eulitoral) zone; this means that they are flooded during high tide and falling dry during low tide. During the dry periods, the flats are a good spot for birds (feeding ground) and seals (resting-place). The presence and shape of the intertidal flats depend on the tidal range, basin area, shape and orientation of the basin relative to the dominating wind-direction (EYSINK, 1993). Large basins allow significant wave action due to larger fetch lengths, especially with long and deep basins orientated in the wind direction. This wind-induced wave action is likely to prevent the extensive growth of the intertidal flat areas. Besides that, the average height of the intertidal flats is determined by the tidal range. As the tidal range increases, the average intertidal flat height increases as well.

As mentioned before, the intertidal flats are defined as the area of the Wadden Sea between MHW level and MLW level. This could lead to the assumption, that the crest of the intertidal flats always reaches the MHW level. Of course, this is not the case. In the shore zone, there is almost everywhere land above the MHW line, so the schematized profile shown in the left part figure 2-4 can be found. On the other hand, the crest of most of the sandbanks and shoals doesn't reach the MHW line. Thus, to make an approximation of the intertidal volume by multiplying the intertidal area with the mean tidal range doesn't lead to useful results (right part of figure 2-9).

EYSINK (1991) stated that individual intertidal flats can be characterized by:

- relative size
- shape
- mean and maximum levels (relative to MSL and MHW).

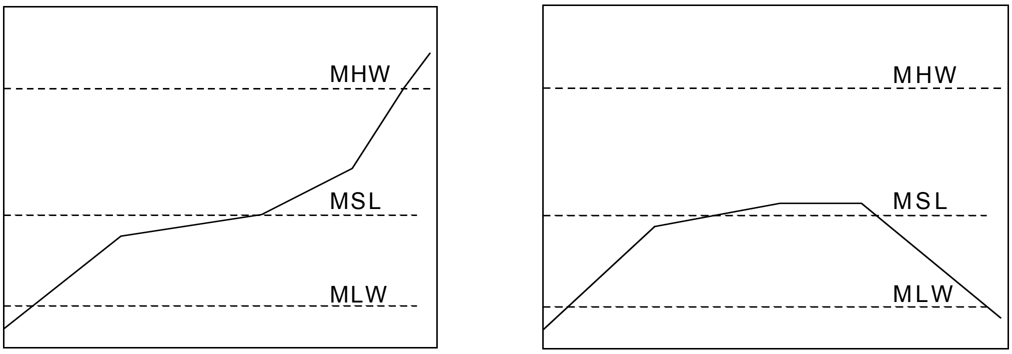

Figure 2-4 Schematization of intertidal flat profile

To get more information about the surface area that is covered by water at various sea levels, one has to look at the hypsometric curve (figure 4-4). The hypsometric curve shows the distribution of the surface areas over the different water depths (see section 4.1.1). To calculate the volume of the intertidal flats, EYSINK (1991) showed the distribution of the water depths of the profile in the shore zone and the shapes belonging to the profiles. In chapter 3 a simplified method will be presented, how the total intertidal flat volume including sandbanks and shore zones, can be estimated.

The relative flat area (A_{flat} / A_{basin}) depends on the size of the basin and - less importantly - on the tidal range H. According to EYSINK (1991), the relative flat area for the Wadden Sea appears to be distinctly dependent on the size of the basin. EYSINK (1991) stated that the relative intertidal flat area affects the tidal prism:

$$P = A_{\text{basin}} \cdot H - V_f \qquad (2\text{-}7)$$

with:

P Tidal prism [m^2]

H Tidal range [m]

V_f intertidal flat volume [m^3]

A_{basin} Surface area total basin [m^2]

The area of the intertidal flats is largely dependent on the area of the tidal basin and the tidal range, EYSINK (1991) found for the Wadden Sea a relationship between relative flat area (A_{flat} / A_{basin}) and the size of the basin.

The relation between flat area (above Mean Low Water) and basin area found for German Bight is (RENGER and PARTENSKY, 1974):

$$\frac{A_{flat}}{A_{\text{basin}}} = 1 - 2.5 \cdot 10^{-5} \sqrt{A_{\text{basin}}} \qquad (2\text{-}8)$$

with:

A_{flat} intertidal flat area [m^2]

A_{basin} total basin area [m^2]

This means that a larger basin has a relatively smaller tidal flat area. This is due to wind, which has more effect on a long basin than on a smaller one (longer fetch-length), and thus causes more wave-action along the edges of the basin.

$$V_{fe} = \alpha_{fe} \left(\frac{A_{flat}}{A_{\text{basin}}} \right) \cdot A_{\text{basin}} \cdot H \qquad (2\text{-}9)$$

In ASMITA the time-averaged surface area of channel and flats are used. This means that equation (2-8) has not to be taken into account. In this case, a time-invariant flat area is used in the equilibrium relations, thus the relations reduces to:

$$V_{fe} = \alpha_{fe} \cdot A_f \cdot H$$

with:

V_f	volume of intertidal flats above MLW (m^3)
α_{fe}	empirical coefficient for the average tidal flat level (-)
A_f	area of intertidal flats measured at MLW (m^2)
H	mean tidal range (m)

The empirical coefficient α_{fe} is depending on regional properties of the tidal inlet. EYSINK (1991) assumed α_{fe} to be 0,5 for the Dutch Wadden Sea. It can vary from the one area to another. In chapter 5 the value of this parameter is determined for the tidal inlet of the Norderneyer Seegat.

2.3.6 Relationship between cross-section and tidal prism

Another equilibrium relation that is important for the adaptation process of the tidal inlet is the relation between the channel profile at the narrowest cross-section between the barrier islands and the tidal prism that has to get through it. Empirical studies have shown that the cross-section of a tidal inlet is almost linearly related to the tidal prism.

GERRITSEN and DE JONG (1985) have found the following relation for the Western part of the European Wadden Sea:

$$TV_{throat} = 3.3 \cdot 10^4 \cdot A_{channel,throat} - 79.2 \cdot 10^6 \qquad (2\text{-}10)$$

with:

$A_{channel,throat}$ Cross-section area at the throat of the tidal inlet [m^2]

$TV_{channel,throat}$ Tidal volume at the throat [m^3]

EYSINK (1990) found that for the throat area – tidal prism the following relationship can be presented:

$$A_{MSL} = \alpha_A \cdot V_{ctv} \qquad (2\text{-}11)$$

with:

A_{MSL} Flow area below Mean Sea Level (MSL) [m^2]

α_A Empirical coefficient for the equilibrium flow area [m^{-1}]

V_{ctv} Characteristic tidal volume (mean tidal prism) [m^3]

- For the Wadden Sea area α_A is equal to 70 10^{-6} [m^{-1}] relative to MLW,
- for the Western Scheldt α_A is equal to 80 10^{-6} [m^3] relative to MSL and
- for the tidal inlets on the East Coast of the United States α_A is equal to 85 10^{-6} [m^{-1}] relative to MSL.

2.4 Hydraulic impact factors

2.4.1 Tide

The tidal movement of the sea is caused by the gravitational attraction of the sun and the moon on the oceans, and the rotation of the Earth (see fig. 2-5). The precise pattern at any location along the coast depends on the shape of the coastline and on the profile of the seafloor.

If there is just one high and one low water a day, and fluctuations in the tide are primarily due to changes in the declination of the moon, with the smallest tides when the moon's declination is least, the tide is called diurnal. Only a small proportion of tidal stations have truly diurnal tides.

If the tide is semi-diurnal, there are two sets of high and low water a day. Fluctuations in the tide are primarily caused by the relative positions of the sun and moon, with spring and neap tides. Tides in Europe are primarily semi-diurnal.

When the two tides combine to form a higher tidal range than average, it is called spring tide. This occurs when the earth, sun and moon are in line, which may occur in two ways. If the moon is between the earth and the sun there is a new moon. Alternatively, when the moon is on the far side of the earth from the sun there is a full moon. When the sun and moon are at right angles to each other, the moon is in its first or last quarter, and the solar and lunar tides are out of phase. Thus, the tidal range is lower than normal, and the tides are called neaps.

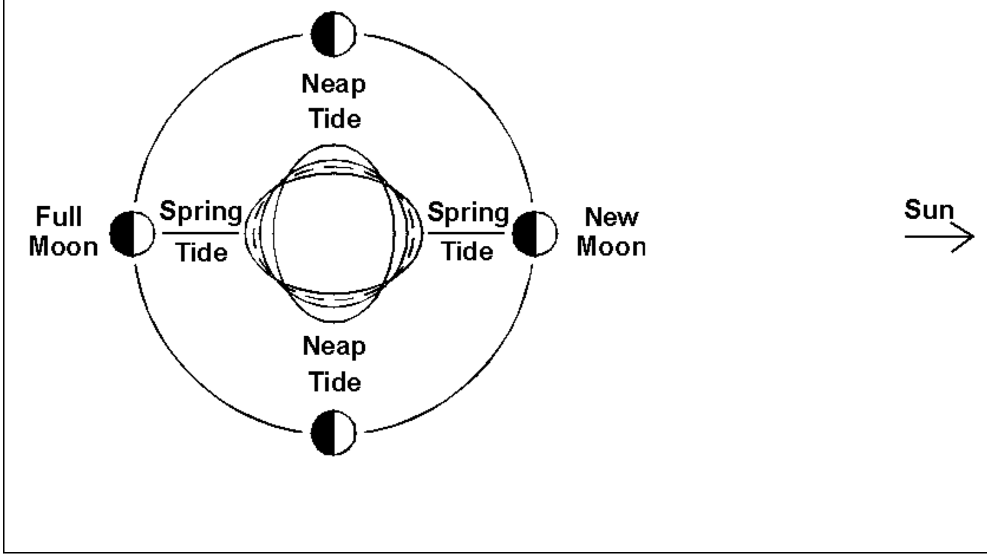

Figure 2-5 Schematisation of the tides

2.4.2 Tidal range (vertical tide)

Most of the large-scale morphological developments in the Wadden Sea are influenced by the difference in water level between mean high water and mean low water, the tidal range. To identify the effect of the tidal range on the morphology of a tidal inlet system, HAYES (1979) made a classification.

Micro tidal	tidal range < 1.0 m
low meso tidal	tidal range 1.0 - 2.0 m
high meso tidal	tidal range 2.0 - 3.5 m
low macro tidal	tidal range 3.5 - 5.5 m
high macro tidal	tidal range > 5.5 m

Table 2-1 Classification of tidal ranges

A microtidal range is commonly found in combination with relatively small tidal inlets in between barrier islands. The ebb tidal deltas in offshore direction of these inlets do not become very large. Mesotidal ranges are favorable for maintenance of smaller barrier islands, large inlets and large ebb tidal deltas. A mesotidal range seems to encourage the formation of tidal flats and salt marshes to a larger extent. A macrotidal range induces a coastline of tidal flats, in which barrier islands and ebb tidal deltas are absent, for example in the Weser estuary or Elbe estuary.

The tidal range in Norderney has a value of 2.4 m and would be characterized as high meso tidal due to this classification.

Along the Southern North Sea Wadden coast the tidal wave is propagating from the Southwest to the Northeast. The tidal range has its minimum near Den Helder in the Netherlands and reaches its maximum at the mouth of the river Elbe. From this point the wave height is decreasing towards the Danish coast. Due to the limited depth in the tidal basins the energy and celerity decreases. The tidal basins in the Wadden Sea are relatively short compared to the wave length of the tidal wave. Thus, the tidal wave has more a standing character there.

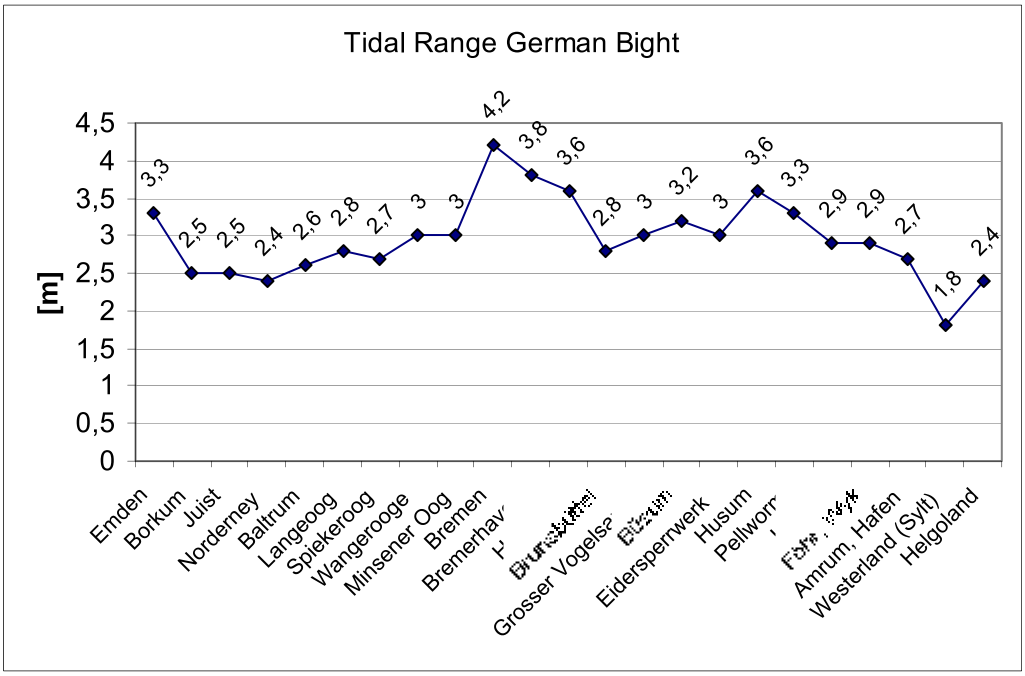

Figure 2-6 Tidal ranges along the German North Sea coast

Figure 2-6 shows the variation of the tidal range along the German North Sea coast. The difference in high water level and low water level in the western part of the German Wadden Sea is 2 - 3,5 m (meso tidal) increasing to 3,5 - 5 m (macro tidal) at the mouth of the river Elbe and Weser and then decreasing to 1 - 2 m in Sylt. Further in the North at the Danish North Sea coast the tidal range is decreasing to 0 - 1 m (micro tidal).

The tidal wave propagates along the British coast towards the south and then turns again along the Belgian, Dutch and German coast in a northerly direction towards Denmark and Norway. Another part of the Atlantic tidal wave approaches the Channel from the south (Figure 2-7). The crest of the tidal wave circulates round this point once during this tidal period, and the tide has increasing magnitude as one moves away from the centre. In general, the tide rotates anti-clockwise in the Northern hemisphere, and clockwise in the Southern. The amphidromic point of the northern tidal wave is further away from the coast than the one from the southern tide. There is a third amphidromic point in the North Sea closed to the coastline of Norway. However, this amphidromic point has less influence to the tidal range in the Southern North Sea.

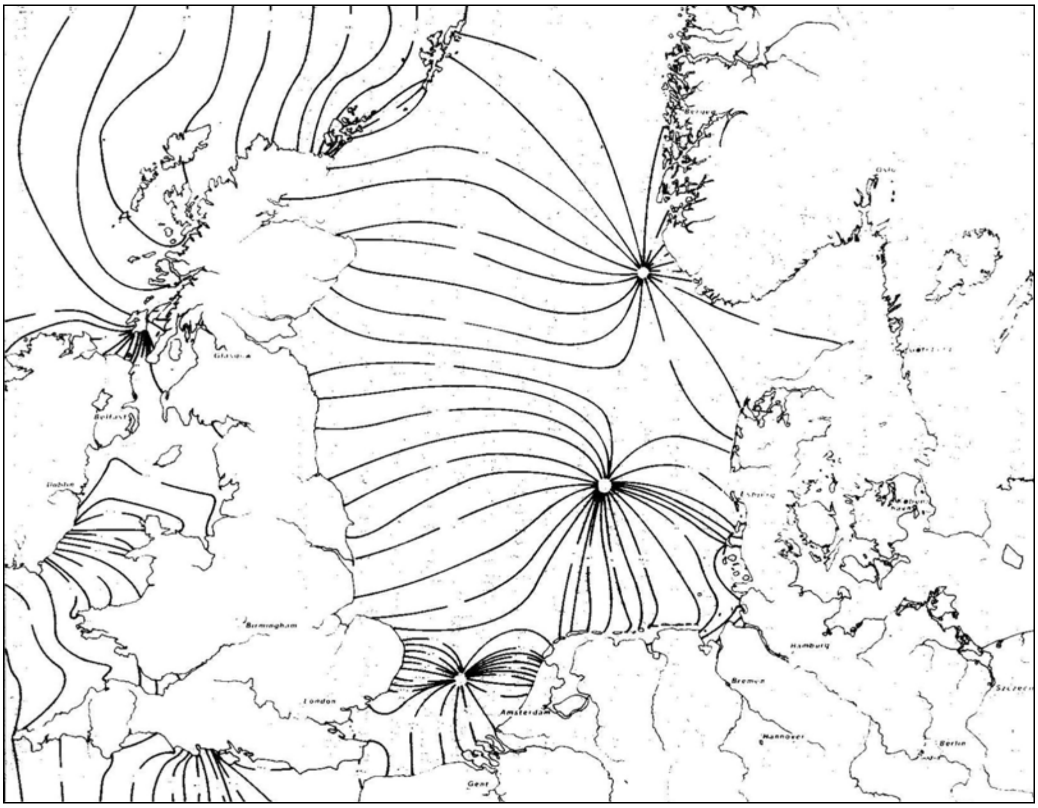

Figure 2-7 Amphidromic system (DHI; 1966)

Between the estuaries of Jade and Eider the largest tidal ranges occur in the German Bight where also the estuaries of the rivers Elbe and Weser are located. Because of the river discharges and the high tidal elevations, tidal channels separate the islands and sandbanks. Flood or ebb tidal delta cannot be found here. Further in the North, the islands are looking like the islands in the southern part of the German bight. Here the impact of the tidal range on the shape of the coastal morphology can be seen.

Beside the regular tidal elevation with its currents the storm surges have an important impact on changes of the Wadden Sea. Storm surges are tidal waves that are more than 1,5 m higher than normal. The reason for this increase is atmospheric influences like wind force, wind direction and atmospheric pressure. Heavy storm surges in the German Bight may occur when winds from northwesterly directions reach 8 Bft or more. Water levels under such conditions rise more than 2.5 m above mean high water.

In figure 2-8, the development of the tidal range in the Norderneyer Seegat during the last 350 years is shown (GOLDENBOGEN, KUNZ, NIEMEYER, SCHROEDER, 1998).

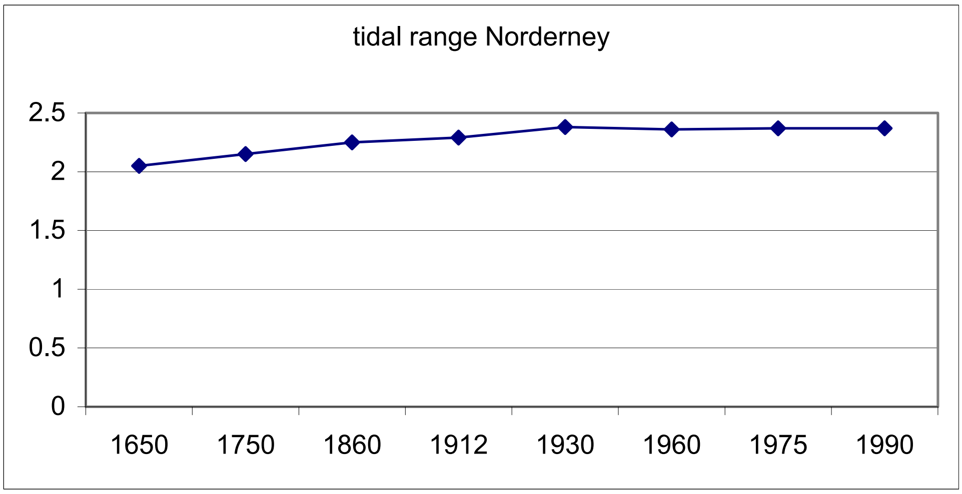

Figure 2-8 Development of the tidal range in Norderney

The tidal range in Norderney has increased in the past 350 years with 30 cm.

2.4.3 Tidal currents (horizontal tide)

Ebb and flood currents in the open North Sea are mostly in opposite directions. The flood current is directed from the West and the Northwest into the German Bight and so into the tidal inlets of the East Frisian Islands. The tidal current velocities are quite small at the open sea, but they increase towards the narrow tidal inlets, where the tidal currents that fill or empty the basins are concentrated. In tidal creeks at the narrowest place between two islands the flood current velocity can reach values up to 150 cm/s as in the small inlet Wichter Ee between Norderney and Baltrum (KOCH, NIEMEYER, 1980).

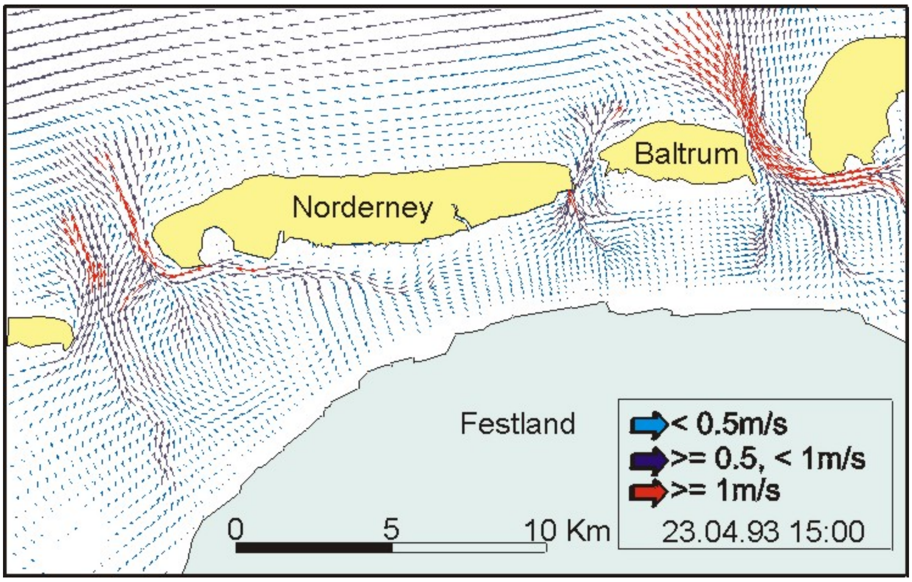

Figure 2-9 Tidal current pattern (KAISER, NIEMEYER; 1996)

The main reasons for sediment transport and hence for morphological changes of the Wadden Sea are tidal currents. If the tidal current are fast, a bigger amount of sediment can be transported, than by slower current velocities. If one proceeds from the assumption that the tidal wave has the shape of a regular sinus, this slack water periods and the duration of falling and rising sea level have to be equally long. In this case there would be no residual sediment import or export to a tidal basin. Only the horizontal tide behaves like a sinus, not the vertical tide. However, the shape of the tidal wave is slightly irregular. This irregularity is influenced by the topography of the Wadden Sea and is called tidal asymmetry.

Figure 2-9 shows the current pattern in the 3 tidal inlets between Juist and Langeoog (Norderneyer Seegat, Wichter Ee, Accumer Ee).

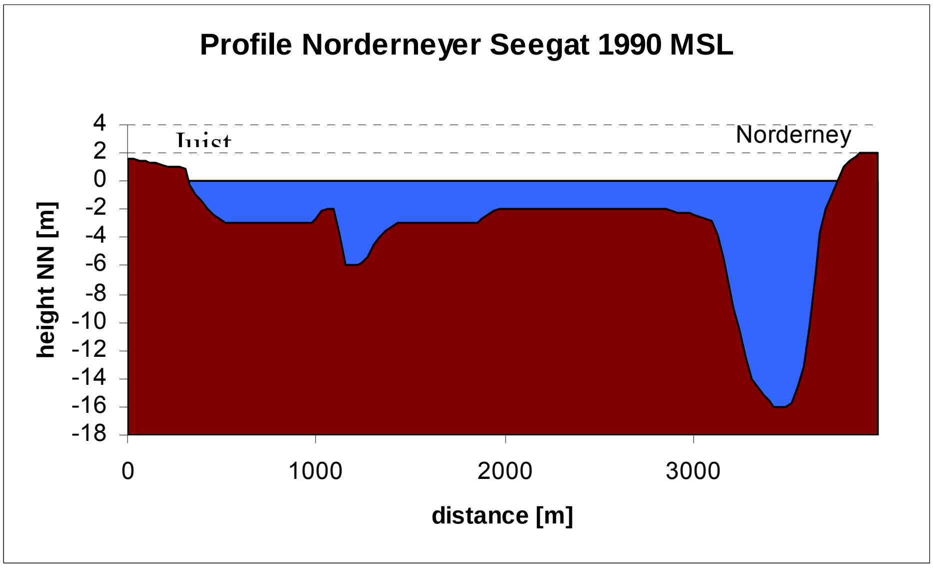

Figure 2-10 Cross-section tidal inlet Norderneyer Seegat

In the Norderneyer Seegat between Juist and Norderney are two channels with high current velocities. The western channel is the disappearing old tidal inlet and the eastern channel the new tidal inlet (see cross section figure 2-10).

The maximum tidal current velocities in the Norderneyer Seegat reach values up to 1,5 m/s.

2.4.4 Sea level rise

According to many recent studies, mean sea level has risen about 15 cm over the past 100 years. It is customary to express sea level rise relative to the surface level of landmasses close to the sea. This relative rise is a combination of the absolute change in the ocean's surface level and subsidence of the land.

Changes in the level of the ocean's surface is usually a global scale change, such as melting of glaciers and polar ice caps that adds to the actual volume of water in the ocean. Vertical movement of the land surface can occur due to tectonic effects, sedimentation, extraction of ground water and oil. For example, due to the retreat of the last ice age, melting glaciers relieved large amounts of pressure on the continents and caused various regions around the world to rise. This effect, which is called glacial rebound, cause the sea level in a particular region to lower. Because regional and global processes can either amplify or counteract one another, we refer to sea level rise at any given location as Relative Sea Level (RSL).

About 18 000 years ago, during the maximum of the last glacial period, global sea level was 120 m to 175 m lower than in the present (JELGERSMA; TOOLEY 1993). In this time, the land was covered by ice masses. When these ice masses were melting due to increasing temperature the water was flowing to the oceans. Consequently, the level of the North Sea was rising by 21 mm/yr over a time period of 8900 to 7100 BP (STREIFF, 1989 (see figure 2-11).

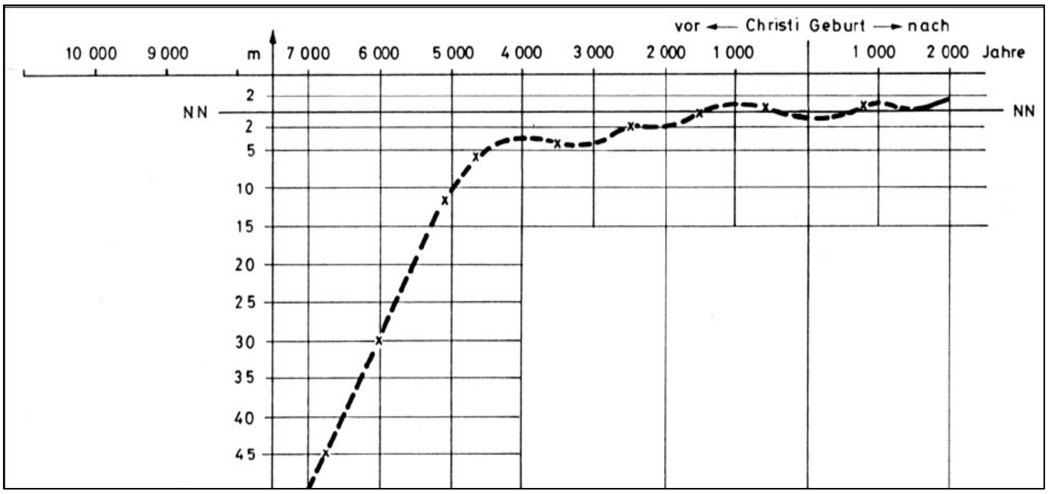

Figure 2-11 Sea level rise during the past 9000 years

The registration of the rate of sea level rise was improved in the last 100 years by installing gauges along the coast. The change in water level registered by the gauges shows a lot of fluctuation. By averaging the measurements, an increase in sea level of 0.2 to 0.25 mm/yr over the past 100 years is obvious (JENSEN et al., 1990, 1993; TROEPPE, 1993). In the 20 years from 1970 to 1990, an increase in mean high water level to 6.7 mm/yr can be recognized. This acceleration could be a result of long-term cyclic fluctuations and human activities, rather than a consequence of a climate change (TROEPPE, 1993). From 1990 to 1997 the MHW level did not change significantly at the German gauges.

One reason for sea level change is simply the amount of water available to the global ocean. Glaciers hold large amounts of fresh water that can be released when global temperatures rise and melt some of the ice. Although the added heat increases sea level because there is a greater volume of water in the oceans, it also has the effect of thermally expanding ocean water. In fact, sea level rise due to thermal expansion contributes more to sea level rise than does simply adding more water to the system.

An important factor to consider is that coastlines are not regular and they do not have the same slope. A rise of a few cm does not sound like a great concern, but those areas with very mild slopes will have a large change in regional sea level with only a small global rise. An accelerated rise in sea level would inundate coastal cities, wetlands, and lowlands. In some parts of the world entire nations are at risk of going under water with rising seas. For example, the European Wadden Sea coast would be threatened by a rising sea level. Therefore investigation on the behaviour of the morphology of the Wadden Sea due to Sea level rise is necessary.

How is it possible to reconstruct the sea level that was present in the history? One method applied by ROHDE is to look for old storm surge levels documented on houses and other buildings. With this method, it is possible to make a reconstruction of the level of the storm surges over the last 300 years. In addition, he investigated the change of the mean high water level 150 years ago. From both analysis it follows that the averaged rate of sea level rise in the last 100 years seems to be in the order of magnitude of 25 cm. Extrapolating this rate of sea level rise back to history, the mean sea level had to be about 75 cm lower than in the year 2000. In this approach, an acceleration of the changes is neglected. LASSEN et al. (1984) found out that the storm surge gauge in Cuxhaven settled in the ground during 100 years from 1855 to 1955 by 26 cm. If those uncertainties are taken into account, an averaged sea level rise of about 14 cm in the last 100 can be assumed.

A result of the rising sea level is, that storm surges occur more often and that the storm surge levels of the sea are much higher than before. A task of the inhabitants of the coastal regions was to protect themselves against the sea.

Coastal areas would become more vulnerable to flooding for four reasons:

- A higher sea level provides a higher base for storm surges to build upon; a one-meter rise in sea level would thus enable a 15-year storm to flood many areas that today are only flooded by a 100-year storm (KANA et al., 1984).
- Beach erosion would leave particular properties more vulnerable to storm waves.
- Higher water levels would increase flooding due to rainstorms by reducing coastal drainage (TITUS et al., 1987).
- Finally, a rise in sea level would raise ground water tables in coastal areas.

Possible responses can be divided in three categories: erecting walls to hold back the sea; allowing the sea to advance and adapting to it; and raising the land.

2.4.5 Waves

The forcing caused by waves plays also an important role in coastal changes. The impact to the changes inside the tidal basin is relatively small, because waves generally break at a water depth of about twice their height, so they break before entering the tidal basin (EYSINK and BIEGEL, 1992). The predominantly western and northwestern directions of wind, sea and swell create a system of longshore currents with northeastern direction on the northwestern beach and southeastward near the main channel of the tidal inlet [NIEMEYER 1986]. The wave-generated longshore currents transport the sediment of the seaward extending ebb-tidal delta onshore and limit the area over which the ebb-tidal delta can spread. Because waves break at the water depth of about twice their height, only a limited amount of wave energy can pass the shoal of the ebb-tidal delta and enter the basin (EYSINK and BIEGEL, 1992). Once the waves have entered the basin, they extend due to the diffraction patterns, so the wave energy is spreading over a big area.

As for the tidal range, a general classification for the effect of waves on the tidal inlet morphology has been made.

Classification	Wave Height H_s (m)
Low wave energy	< 0.6
Medium wave energy	0.6 – 1.5
High wave energy	> 1.5

Table 2-2 Wave classification (HAYES; 1979)

For the Wadden Sea basins, the impact of waves is only important during severe storm surges. In this case, they reach the first tidal flats of the basin. However, for the development of the ebb tidal delta waves play an important role.

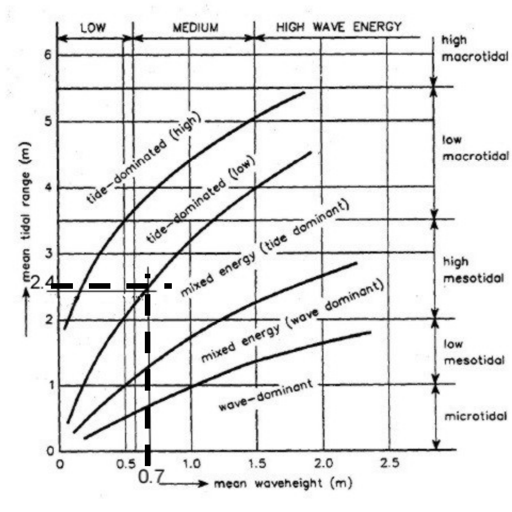

Figure 2-12 Wave- / tide- dominace (HAYES; 1979)

According to the diagram of HAYES (1979) (see fig, 2-12), the Norderneyer Seegat is tide dominated. The impact of the waves is of less importance.

3 Data analysis

Introduction

One of the most important steps in numerical modeling is analyzing the available data. This step has to be carried out very carefully because the validity and accuracy of the subsequent work is dependent on a carefully done data analysis.

The objective of the data analysis is to investigate:

- What sort of data is available (inventory)?
- Interpreting and processing (make it fit for use).
- Is it usable (quantity, reliability)?

In this chapter, these methods will be presented. All the data used are coming from Coastal Research Station of the Lower Saxonian Central State Board for Ecology (Forschungsstelle Kueste Norderney) in Germany, where a remarkable data-base for the hydrographical and morphological data was created.

3.1 Which data are available?

For short-term developments of the Wadden Sea morphology, much information is available. Short-term in morphodynamic time-scales means decades to years. Older data sets contain of uncertainties. With statistical methods and by comparing these data, it should be possible to reduce these uncertainties. The oldest sources of information, that are available for the study area, are registers of dykes from the 16th century. These documents contain information about the length of dykes and about the size of areas belonging to one dyke section. From the 18th century on the first documents of the authorities are preserved from which can be seen when and where polders were created or areas were flooded.

3.1.1 Geographic Information Systems (GIS) in coastal research

A geographic information system, or GIS, is a data management system used to store, manage, analyse or display spatial information. The data-sets in a GIS are usually referred as themes or data layers. All the themes in a GIS are based on geographically referenced data. The graphical representations that are known as features, can take the form of points, lines or polygons. From these features, it is possible to get information about surface areas and volumes. Therefore, a triangulated irregular network (TIN) data model has to be created. In the present case, the digital elevation information is represented by contour lines. All the vertices of the contour lines are used as points for triangulation.

3.1.2 Resources

At the Coastal Research Station of the Lower Saxonian Central State Board for Ecology (Forschungsstelle Kueste Norderney), an extensive database was created, which contains many data on the development of the East Frisian Wadden Sea. It is important to distinguish between data that are taken by measurements from nature and information that has been reconstructed. Therefore, the dates of the reconstructed sets are printed italic.

Which data are available?

- table of the total basin areas of the years *1650, 1750, 1860*, 1912, 1930, 1960, 1975 and 1990 in m^2
- table of the intertidal basin areas of the years *1650, 1750, 1860*, 1912, 1930, 1960, 1975 and 1990 in m^2
- table of the sublitoral basin areas of the years *1650, 1750, 1860*, 1912, 1930, 1960, 1975 and 1990 in m^2
- table of the salt marsh areas of the years *1650, 1750, 1860*, 1912, 1930, 1960, 1975 and 1990 in m^2
- table of the tidal volumes of the East Frisian Wadden Sea tidal basins of the years *1650, 1750, 1860*, 1912, 1930, 1960, 1975 and 1990 in m^2
- figure of the correlation of total basin areas and tidal volumes of the years *1650, 1750, 1860,*1930, 1960, 1975 and 1990
- figure of the correlation of basin areas and tidal volumes for the tidal basins and subsystems in the East Frisian Wadden Sea of the years 1960, 1975 and 1990

data	1650	1750	1860	1912	1930	1960	1975	1990
hw and lw line (GIS)	r	r	r					
topography				m	m	m	m	m
tidal range	r	r	r	m	m	m	m	m
mhw				m	m	m	m	m
mlw				m	m	m	m	m
tidal prism	r	r	r	m	m	m	m	m

Table 3-1 Available Data measured (m) and reconstructed (r)

In Germany, the reference surface for leveling is the mean sea level of the North Sea. Altitudes are given in “Meter über Normalnull” (m ü. NN), which means meter above mean sea level, based on the mean sea level of Amsterdam (NAP). In order to get comparable surface area and volume values for different states of the Wadden Sea morphology it is useful to define NN as a general reference level. The mean high water level is defined in cm above NN and the mean low water level in cm below NN.

The data-sets used in this study are all referenced to the NN level. For administrating and analysing them, the geographical information system (GIS) was applied. The GIS program ARCVIEW was used to create a 3 dimensional (x-, y- and z- coordinates) morphological model of the Wadden Sea morphology. With the GIS program, it is possible to make various kinds of analysis such as to calculate volumes and surface areas of the area of interest.

The most important information from the database are volumes and areas of the Wadden Sea region and their changes in the time. To get information about the volumes, the water depths of the tidal basins have to be known. Because the reconstructed charts consist only of surface areas, mean low water line and mean high water line, this kind of information is only available for the measured data sets from 1930 to 1990. The data-sets of the years 1650, 1750 and 1860 only give information about the surface area. For making long-term calculations with the semi empirical numerical model ASMITA, it is necessary to have the volumes of the sublitoral and eulitoral parts of the Wadden Sea. In addition, it is necessary to get information about the tidal prism belonging to a tidal basin. Because of the need in information, it was decided to make estimations of the volumes belonging to the areas. This has been done by a simple approach. For the topographies of the tidal inlets Osterems, Norderneyer Seegat and Accumer Ee for the years 1930, 1960, 1975 and 1990, the volumes were calculated with the ArcView program. The tidal inlets were divided into one intertidal, one sublitoral and one supralitoral part. For each of these parts of the three the tidal inlet topography a correlation with the surface area belonging to the volume was made. For all the cases the same tendency was found. The bigger the tidal inlet surface area is the bigger are the volumes. Fore the dependency between the surface area and the volume, simple formulas were derived. The idea is to make an approximation for the volumes belonging by the surface area of the years 1650, 1750 and 1860 using these simple formulas. To check the plausibility of theses estimations of the volumes, empirical relationships from the literature were applied. With the completed datasets, it becomes possible to make long-term calculations of the morphological development of the tidal inlet.

One could think that these estimations are improper because the past was estimated, using data from the present, and then one uses these data to estimate the present with the ASMITA program. The uncertainties in this procedure are limited, by using the historical data from the nautical charts. There are some parameters used in this process that can be seen as reliable. In addition, the values of 1750, 1860, 1930, 1960, 1975 and 1990 are only for supporting and checking the results of ASMITA. The only input data are volume and area of 1650.

Year	MHW [m]	MLW [m]	MTR [m]
1650			2,05
1750			2,15
1860			2,25
1912	+ 0,99	- 1,30	2,29
1930	+ 1,06	- 1,32	2,38
1960	+ 1,10	- 1,26	2,36
1975	+ 1,11	- 1,26	2,37
1990	+ 1,17	- 1,20	2,37

Table 3-2 Development of tidal range and water levels (CRS Norderney)

3.1.3 Tidal basin topography

The topography of the tidal basin consists of two elements, the intertidal flats and the tidal channels (see chapter 2). The surface area and the volume of these elements can be determined using the ARCVIEW computer program. Therefore, the basin area has to be split up. Figure 3-1 until figure 3-4 show the way from the measured topography to the volume and surface area of each element.

Figure 3-1 Contour lines of the Norderneyer Seegat topography (1975)

Figure 3-1 shows the contour lines of the topography of the area of interest in the East Frisian Wadden Sea.

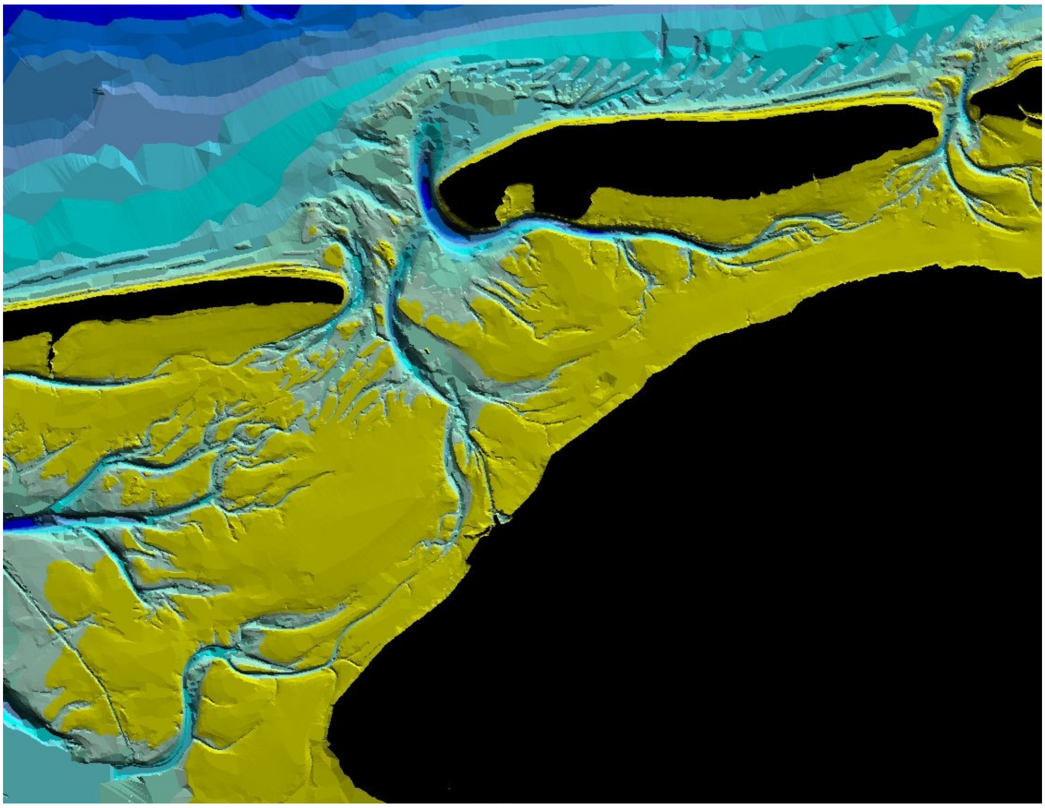

Figure 3-2 Image of the 3-D volume-model of Norderneyer Seegat (1975)

In figure 3-2 the three dimensional model is shown. By using the ARCVIEW extension "3-D Analyst" a triangulated irregular network (TIN) was created, to get a 3-D surface model. From this model values for volumes and areas can be calculated.

The 3-D volume models for the years 1960, 1975 and 1990 are visualized in appendix A.

Figure 3-3 Eulitoral part of the Norderneyer Seegat (1960)

eulitoral (60)	between 1.1 m NN and –1.26 m NN	Area: 7,38E+07 m^2	Volume: 8,63E+07 m^3

Figure 3-3 shows the eulitoral part of the Tidal basin, which is defined as the sediment volume between MLW-level and MHW-level.

From figure 3-3 it can be seen, that in the region of the western and eastern border of the study area (watersheds) the intertidal flats are dominant. The tidal channels are underrepresented in this area. Therefore, a changing position of the watersheds mainly influences the volume of the intertidal flats.

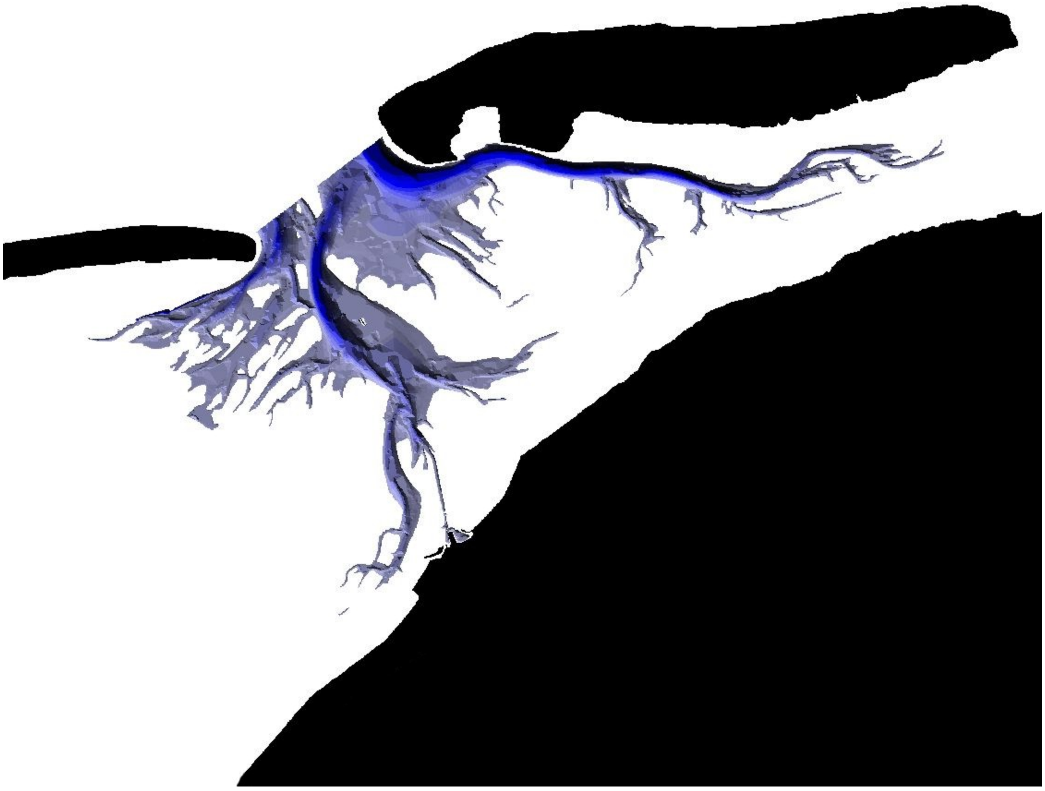

Figure 3-4 Sublitoral part of the Norderneyer Seegat (1960)

sublitoral (60)	below –1.26 m NN	Area: 2,68E+07 m^2	Volume: 6,42E+07 m^3

Figure 3-4 shows the sublitoral part (tidal channels) of the tidal basin, which is represented by the water volume between below the MLW-level (NN - 1.2m).

So far the properties of the 2 parts of the tidal basin are determined that are important for modeling the Wadden Sea with the numerical model ASMITA. To determine the third element of ASMITA, the ebb-tidal delta, is much more difficult and will be shown in the following section.

3.2 Determining the ebb-tidal delta volume

One of the information that is needed to be known, is the volume and the surface area of the ebb-tidal delta. The ebb-tidal delta is located on the seaward side of the tidal inlet and usually consists of several shoals. In the model of EYSINK and STIVE (1989), the ebb-tidal delta was supposed to be the main source for the demand of sediment inside the tidal basin. Therefore, information about the amount of material available from the ebb-tidal delta is very important. It is difficult to calculate the volume of the ebb-tidal delta, because it is shaped irregularly. WALTON and ADAMS (1976) defined the ebb-tidal delta as the accumulation of sediment above the topography that would have been there if there was no tidal inlet. To approximate this "no-inlet" topography in this area, they connected the submarine contours of the barrier island on one side of the inlet to the contours of the island on the other side (fig. 3-5).

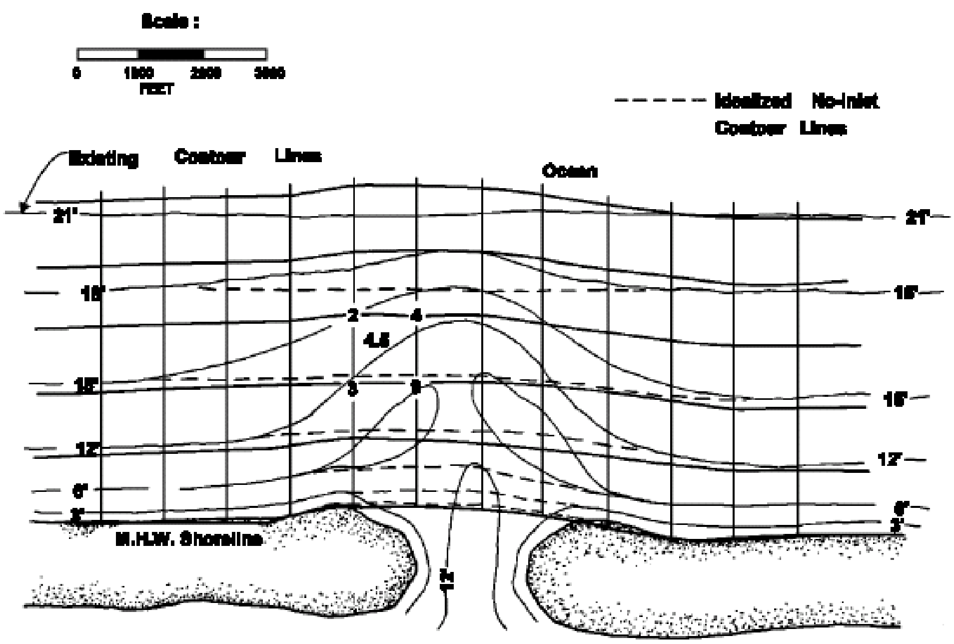

Figure 3-5 Ebb-tidal delta (WALTON and ADAMS, 1979)

This approach is used in the present study to determine the volume of the ebb-tidal delta of the Norderneyer Seegat. In this way, a regularly shaped "no-inlet" sea bottom profile between the islands Juist and Norderney was created. To get a the fictive sea bottom that fits as proper as possible to the real profile of the up- and down-drift island beaches, “no-inlet” topography was created for each data set individually. Therefore, the “no-inlet” topography is not the same for 1960, 1975 and 1990.

By comparing the "no-inlet" topography from the real topography the volume of the ebb-tidal delta topography according to the definition of WALTON and ADAMS was found. In figure 3-6, the real topography and the virtual topography of the year 1975 are shown (see also appendix B).

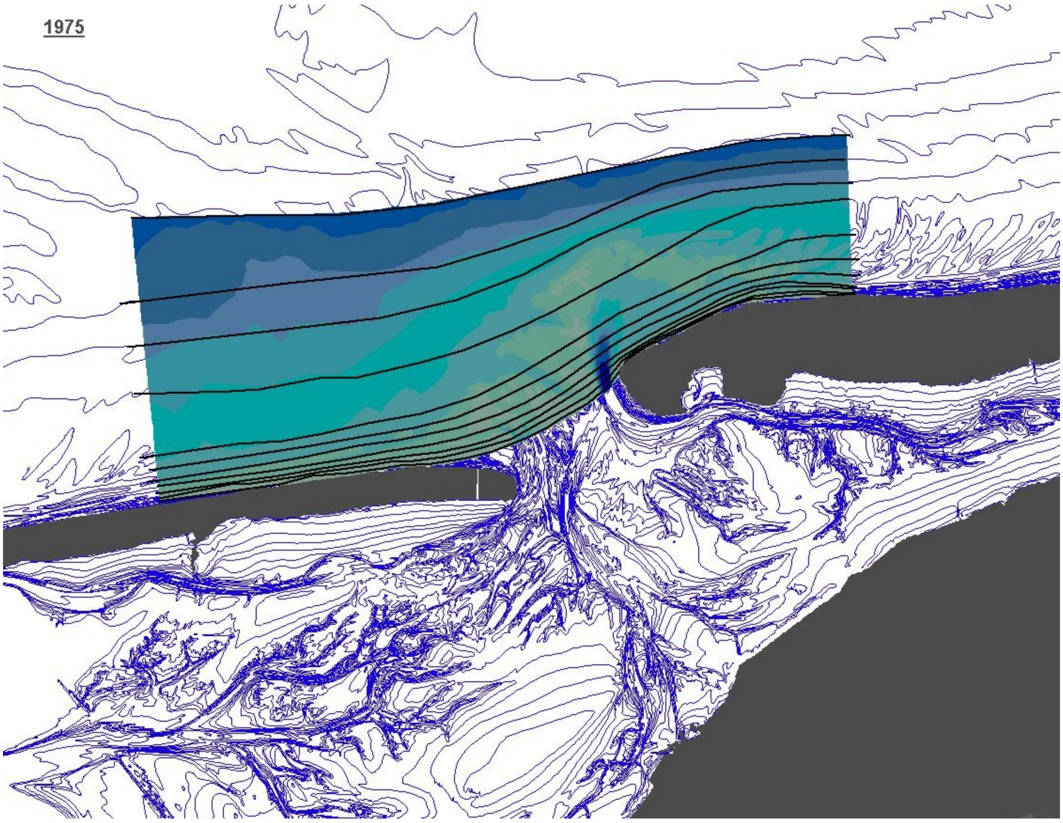

Figure 3-6 Ebb-tidal delta with "no-inlet" topography

When determining the volume of the ebb tidal delta according to the method of WALTON and ADAMS (1976), first one has to define the area of the ebb tidal delta. There are four limitations to this area. One on the beach side, one on the offshore side and one on the up and down drift boundaries respectively. To determine the extension of this area it is useful to define criteria for the position of the boundaries:

- Beach side: usually the depth contours are very close to one another on the beach side, because the slope of the beach is steep compared to other parts of the Wadden Sea topography. For the beach side boundary the 0 m depth was taken.
- Offshore side: the offshore boundary of the ebb tidal delta area depends on the influence of the ebb tidal delta on the morphology. If the longitudinal axes of the two islands covering the tidal inlet are more or less in one line, the influence is expected to be relatively small. If one of the axes is shifted more in offshore or beach direction, than the other one, the influence of the outer delta on the morphology will be stronger. In this case, one has to take a deeper depth line as offshore boundary.
- Up and down drift boundary: in general one could say that the bigger the ebb-tidal delta area in up and down drift direction is, the better the results of the delta volume are. This is valid up to the point where the next ebb-tidal delta is influencing the topography. In the area where the depth contours are parallel to each other, the up and down drift boundary has to be located. In this region,

it is not necessary to define a precise place of the boundary, because the "no-inlet" topography and the real topography are nearly the same, so the difference will be negligible.

In the case of the Norderneyer Seegat, the beach side boundary was defined on the 0m depth contour along the beach, the offshore boundary was defined on the -14m depth contour and the up and down drift boundaries were set ca. 8km in up drift direction and ca. 5 km in down drift direction. For this ebb tidal delta area a "difference-topography" was calculated and plotted (see fig. 3-7). In the areas with white color inside the frame of the ebb-tidal delta area, the difference between the "no-inlet" topography and the real topography is less than 1m in depth. One can see that the area chosen by the criteria described above represents the ebb-tidal delta topography well. In the boundary zones of this area, the influence of the ebb tidal delta decreases.

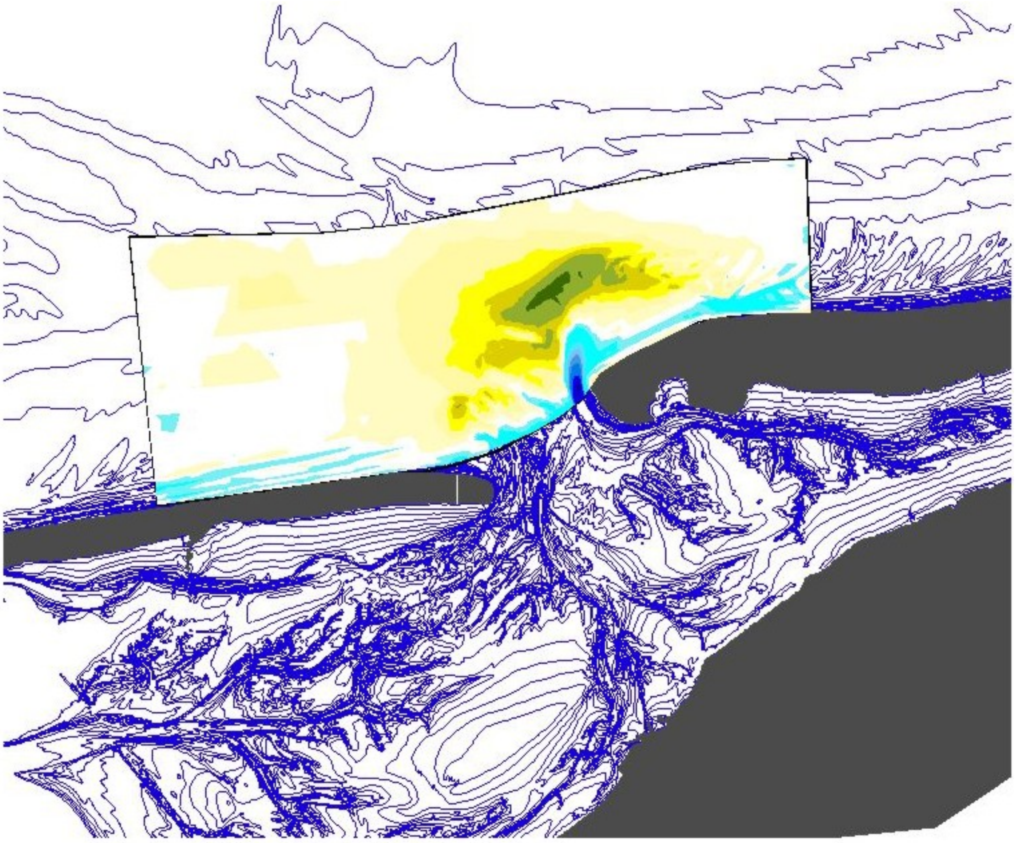

Figure 3-7 Difference between real topography and "no-inlet" topography

A disturbing element in determining the ebb-tidal delta volume is the tidal channel that is connecting the tidal basin with the open sea. In the volume balance, this tidal channel always counts negative because it is much deeper that the “no-inlet” topography. This disturbance makes the determination method uncertain. In the following, the influence of the channel will be studied more in detail.

The result of the dominance of the channels is a negative ebb-tidal delta volume near the inlet. This dominance becomes less important by expanding the whole area of the ebb-tidal delta.

As mentioned above, the volume of the ebb-tidal delta is sensitive to the definition of the "no-inlet" topography. To make an estimation of the error that can occur by taking different "no-inlet" topographies, five versions of a fictive topography with different sizes were checked (see fig. 3-8).

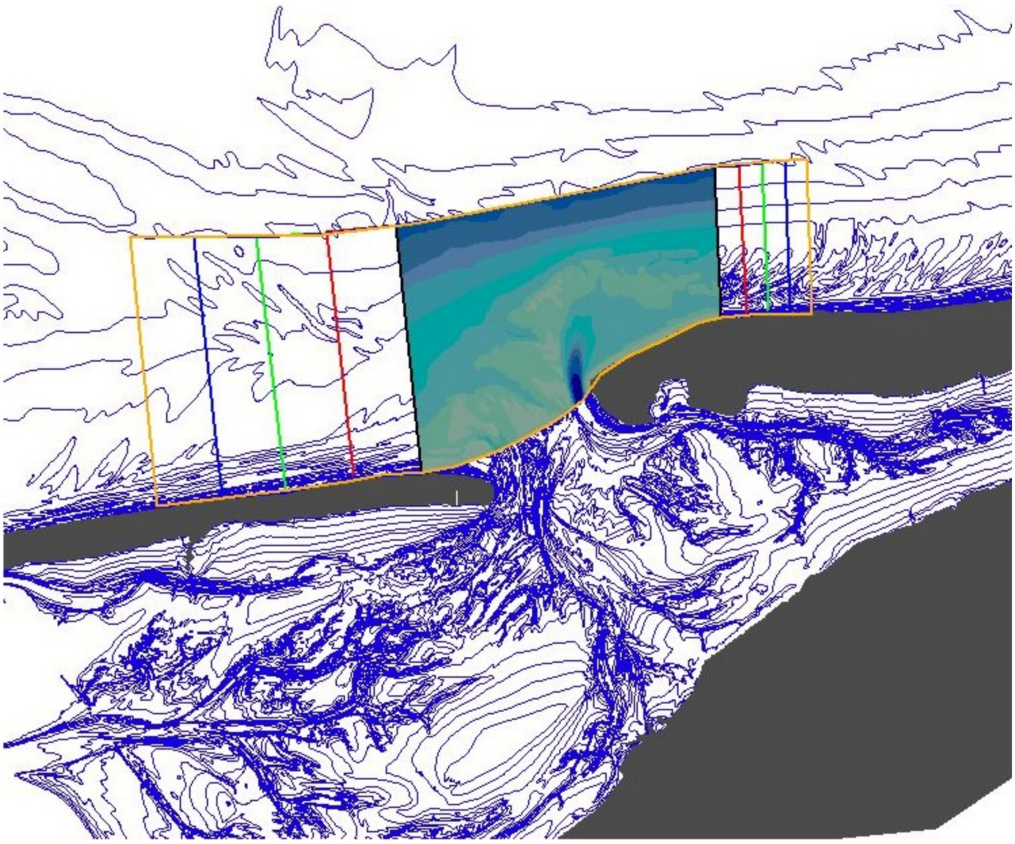

Figure 3-8 Five different sizes of the ebb-tidal delta

For each of the five areas, the volume of the resulting "difference-topography" was calculated. For the smallest version the volume of the ebb-tidal delta topography becomes negative. This happens, because the channels of the real topography become dominant in the volume balance. In the following steps, the area of the ebb-tidal delta was extended in up and down drift direction. An extension in offshore direction was not carried out, because the –14 m-depth contour was assumed to be the basis for all of the five versions. In figure 3-9, the results of the calculation of the ebb-tidal delta volume are shown with increasing surface areas. It can be noticed, that from the third version on, the determination of the ebb-tidal delta volume becomes reliable and certain, because the volume does not change with increasing surface area. That means that the difference between the "no-inlet" topography and the real topography becomes negligible in the adjacent regions.

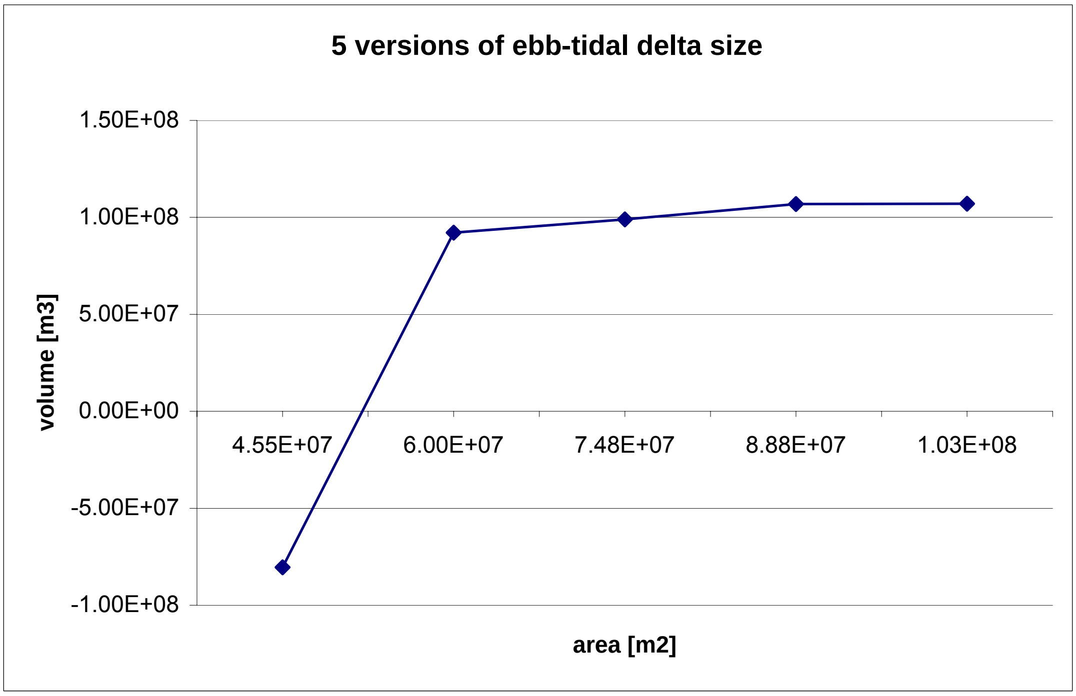

Figure 3-9 Relation between ebb-tidal delta volume and area (1975)

In table 3-3 the ebb-tidal delta volumes for the years 1960, 1975 and 1990 are shown. The value for 1960 doesn't fit to the other ones because there is an interpolation uncertainty in the morphological model. This error results from a lack in depth information in offshore direction.

In chapter 5, for the computations the ebb-tidal delta volume for 1960 was assumed to be of the same order of magnitude as in 1975 or even bigger. Therefore, in the computations a value of 1.2 E+7 was applied. This assumption is based on the 3-D models shown in Appendix A.

Year		Inlet	No inlet	Difference
1990	Area [m^2] Volume [m^3]	8.80E+07 5.73E+08	8.89E+07 4.86E+08	**8.73E+07**
1975	Area [m^2] Volume [m^3]	1.03E+08 6.72E+08	1.03E+08 5.65E+08	**1.07E+08**
1960	Area [m^2] Volume [m^3]	9.83E+07 6.15E+08	1.04E+08 5.69E+08	***4.57E+07***

Table 3-3 Volume and area of Norderneyer Seegat ebb-tidal delta

The values for the years 1960, 1975 and 1990 were added to the diagram of WALTON and ADAMS (1976). They showed, that the values of the outer bar sand volume correlates with the tidal prism of the inlet. In figure 3-10 the graph of WALTON and ADAMS is shown extended by the values of the Norderneyer Seegat for the years 1960, 1975 and 1990. It can be seen that they fit perfectly to this correlation.

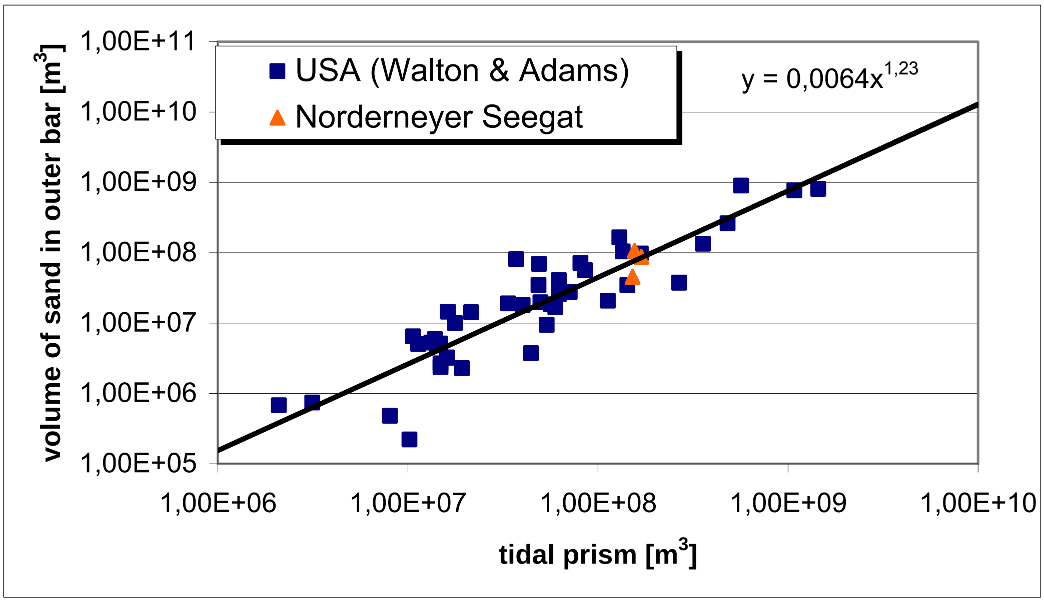

Figure 3-10 Outer bar sand volume / tidal prism relationship

Conclusions

The precision of the method developed by WALTON and ADAMS depends on the size of the ebb-tidal delta area. With an increasing area, the method becomes more reliable.

The tidal inlet Norderneyer Seegat in Germany fits perfectly to the outer bar sand volume / tidal prism correlation of WALTON and ADAMS (1976)

The GIS computer program ARCVIEW is a useful tool for determining volume and surface area of irregular shaped topographies of the ebb-tidal deltas according to the definition of WALTON and ADAMS.

For the year 1960 a sediment volume of the ebb-tidal delta was estimated of 1.2E+8. This estimation is based on the 3-D models shown in Appendix A.

3.3 Reconstructing historical volumes

3.3.1 Idea and method

The reconstructed data of the East Frisian Wadden Sea are a remarkable source of information about the topography of the German North Sea and its development over the last 350 years. For calculating the development of the volumes of intertidal flats or tidal channels, information about the water depth is needed. To reconstruct the water depths from older sea charts is difficult because the methods in measuring water depths changed in the history.

It was decided to make a rough estimation of the water depths. For this estimation, the surface area was correlated to the volume of the Wadden Sea. To improve this correlation, the Wadden Sea was divided into the three parts, which are sublitoral, eulitoral and supralitoral area and volume. For the sublitoral case, a more or less linear correlation was found. Besides the tidal inlet of Norderneyer Seegat the tidal inlets Osterems and Accumer Ee were investigated in the same way. The tidal inlet of Osterms is located in westerly direction of Norderney between the islands Borkum and Juist. The Accumer Ee is the tidal inlet between Baltrum and Langeoog in the East of Norderney. The linear correlation was found here too.

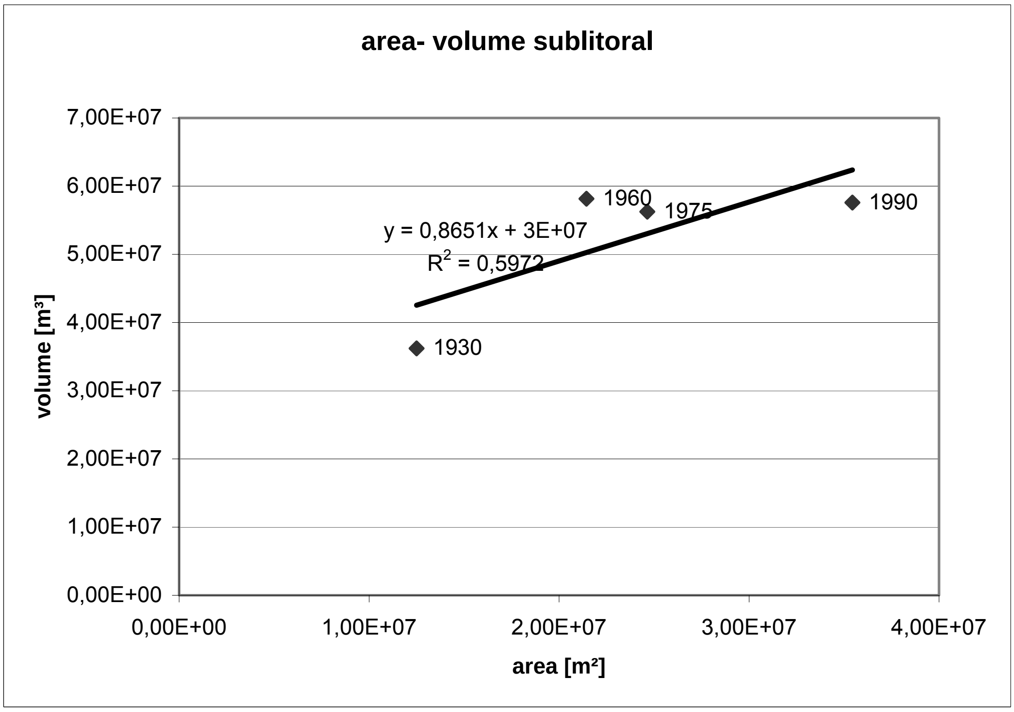

Figure 3-11 Correlation between area and volume of tidal channels

For the eulitoral area it seems to be a little bit more complex. All investigations were carried out on the measurements of the years 1930, 1960, 1975 and 1990. The data for 1930 has to be handled carefully, because the density of the points that are measured is less. The denser the measurements the better the calculation of the volumes.

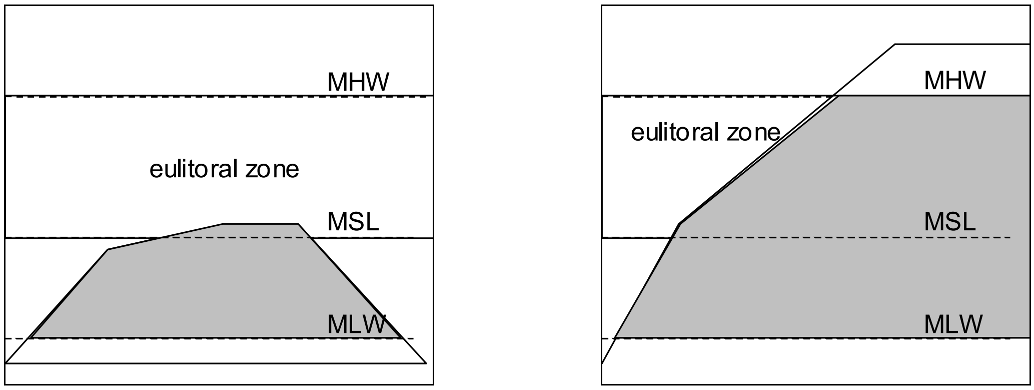

Figure 3-12 Eulitoral volumes at the shoals and on the beach

The eulitoral volume is defined by the sediment volume between mean high water and mean low water. If one looks to the right part of figure 3-12, one can see that there is just a small intertidal sediment volume. In the left part of figure 3-12 the intertidal volume is much bigger. The problem in the eulitoral zone is, that most of the flats don’t reach the high water line. A linear correlation between surface area and sediment volume cannot be expected.

The idea is, to find the volumes belonging to a certain surface area for the reconstructed data series 1650, 1750 and 1860 by looking to the correlation diagram of the specific tidal inlet. It is clear, that this way of determining the volumes can only be a rough approximation. It could be possible, that the correlation was completely different in the earlier years. This is not very probable, because from the reconstructions it can be seen, that the total surface area of the investigated tidal inlets didn't change so much in the last 350 years. Therefore, it could be stated that the tidal inlets are more or less stable during this time.

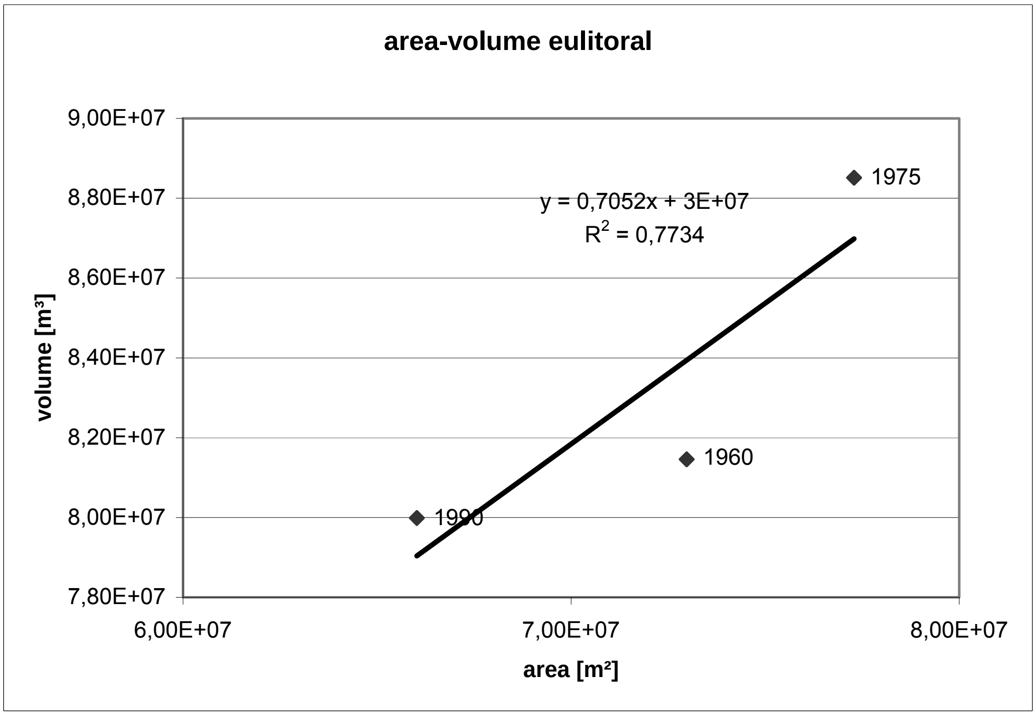

Figure 3-13 Correlation between area and volume of intertidal flats

By comparing the surface area of the different tidal inlets along the East Frisian coast, NIEMEYER (1995) showed that there occurred only small changes in size. He found out, that the maximum decrease of the surface area of the Norderneyer Seegat was about 10% in 1860 compared with its state of 1650. Therefore, it can be assumed, that no big changes disturbed the system. For the tidal inlet Osterems a maximum decrease can be found in 1975 compared with the data from 1650. The decrease of 23% in surface area originates from the partial draining of the Lay Bay. The tidal inlet Accumer Ee decreased in 1860 with 23% compared with 1650, when the adjacent inlet in easterly direction (Otzumer Balje) increased. During this time the watershed of the Accumer seems to have moved in easterly direction. The changes in size of the channels and tidal flats are in the same order of magnitude. It has to be mentioned that due to the land reclamation in the Lay Bay which belongs to the area of the Osterems the supralitoral area decreased with more than 40% from 1650 to 1975. This was the biggest change in this area. A comparable change has been taken place at the Harle Bay, which is located close to the Weser estuary.

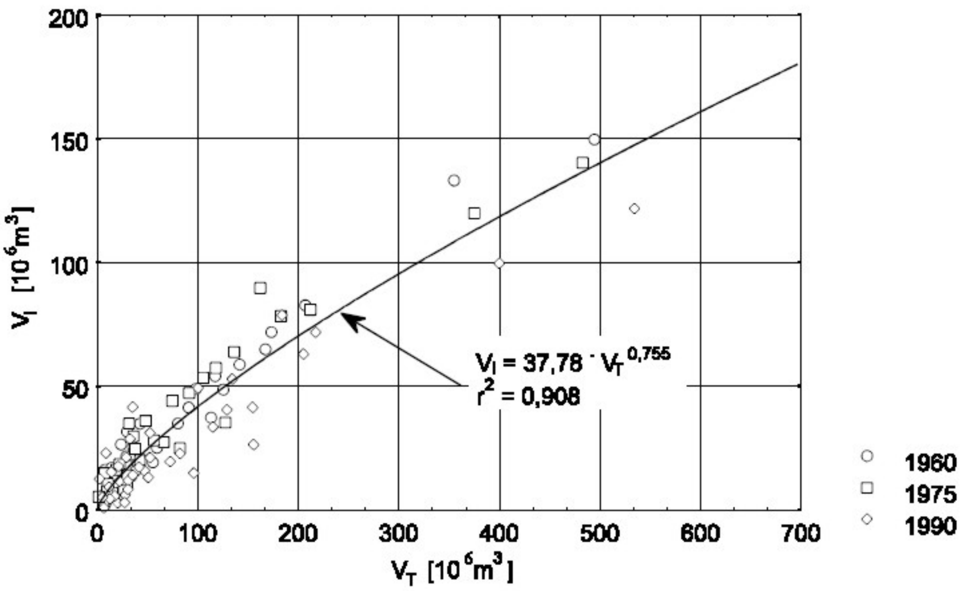

Figure 3-14 eulitoral sediment volume (V_I) as a function of the tidal volume (V_T) (GOLDENBOGEN, KUNZ, NIEMEYER, SCHROEDER, 1998)

In figure 3-14, the correlation between the tidal volume and the eulitoral sediment volume for the entire East Frisian Wadden area is shown. It can be seen, that there is a relation between the two quantities, which is characterized by a strong spreading. This correlation will not be used for the reconstruction of the eulitoral volumes of the Norderneyer Seegat, because it concerns the whole area of the East Frisian Waddden Sea.

3.3.2 Applying the volume-area correlations

A first application of the simple correlations derived above is shown in figure 3-15. The surface areas of the years 1650, 1750, 1860, 1912 and 1930 published by NIEMEYER (1995) were used to determine the sediment and water volumes of the elements by applying the correlations. For the years 1960, 1975 and 1990 volumes determined from real measurements were used. For the years 1650, 1750, 1860 a slight decrease of the intertidal flat volume can be seen. The water volume of the channel seems to be stable. This corresponds to the expected reaction of the tidal basin to sea level rise. From beginning of the 20th century on the volumes start changing a lot in different directions. In 1960 an increase in volume of the tidal channel and of the flats occurred. 15 years later in 1975 the channel volume decreased while the intertidal flats increased. From 1975 to 1990 both elements moved in the opposite direction.

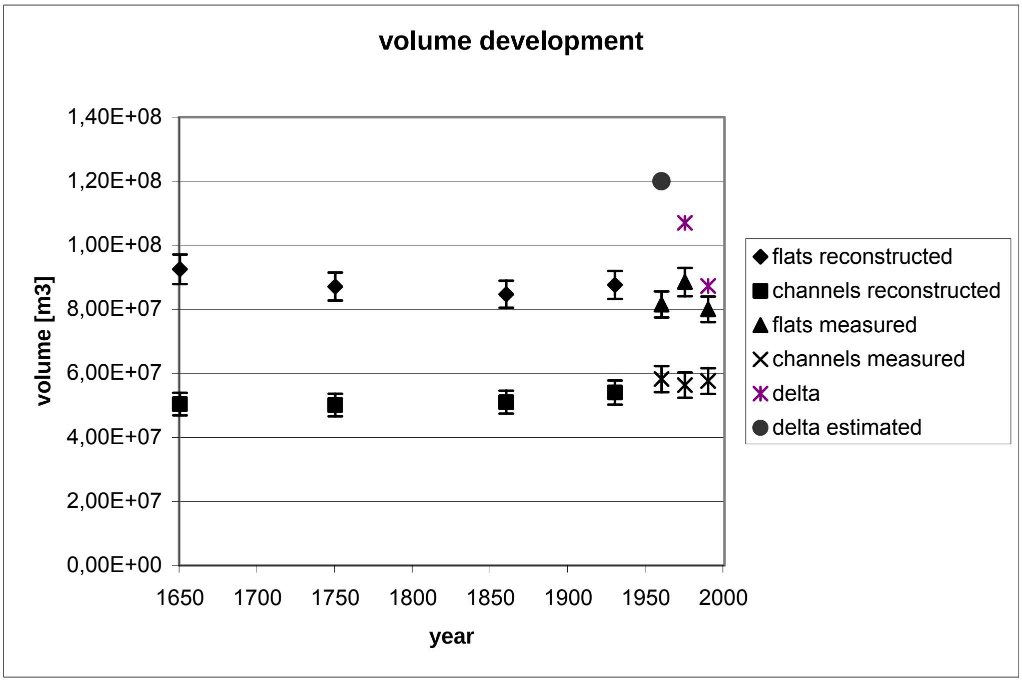

Figure 3-15 Development of the volumes reconstructed and measured

In table 3-4, the values of the volumes of the Norderneyer Seegat are shown. The estimated volumes are printed italic. These values are also used in chapter 5 for calibrating the ASMITA model and for comparing the results of the model runs with the situation in nature.

year	flat volume	channel volume	delta volume
1650	*9,25E+07*	*5,04E+07*	
1750	*8,71E+07*	*5,01E+07*	
1860	*8,47E+07*	*5,10E+07*	
1930	*8,76E+07*	*5,40E+07*	
1960	8,15E+07	5,82E+07	*1,20E+08*
1975	8,85E+07	5,63E+07	1,07E+08
1990	8,00E+07	5,76E+07	8,73E+07

Table 3-4 Reconstructed (italic) and measured volumes of the Norderneyer Seegat

The accuracy of the volumes of intertidal flats and tidal channels is strongly dependent on the position of the watersheds. In case of the Norderneyer Seegat the position of the eastern watershed is not very certain. Therefore, a change of the position of the watershed of about 100 m in easterly or westerly direction causes an uncertainty of 5 % of the volumes. In figure 3-15, this uncertainty is shown by the “5 %”- error bars.

3.3.3 Possible reasons for volume fluctuations

By analysing the available data sets, it is also important to interpret them. It cannot be expected to reproduce the fluctuations in volume between 1930 and 1990 with a long-term simulation program like ASMITA accurately. Therefore it must be investigated what the reasons are for these changes. As described above, there could be several reasons for severe changes of the morphology:

1. the fixation of the four migrating tidal inlets (Norderneyer Seegat, Wichter Ee, Otzumer Balje and Harle) since the middle of the 18th century in order to protect there developing holiday and health resorts (NIEMEYER, 1995),
2. artificial acceleration of resedimentation of the storm surge bays at the mainland coast by land reclamation and partial enclosure of these areas by dyking,
3. moving watersheds.

The interventions described in the first item, were intensified from the middle of the 20th century. From this time on, beach nourishment had been carried out at the island of Norderney. In table 3-5 the most important nourishment activities at the island of Norderney are summarized.

Year	Length (m)	Volume ($10^3 m^3$)	Fill type	Purpose	Borrow site
1951-52	6.000	1250	Raising beach	Filling groyne fields	Wadden area
1967	2.000	240	Raising beach	Filling groyne fields	Foreshore
1976	1.000	400	Raising beach	Filling groyne fields	Ebb delta shoal
1982	1.500	470	Raising beach	Filling groyne fields	Ebb delta shoal
1984	1.700	410	Raising beach	Filling groyne fields	Ebb delta shoal
1989	1.80	450	Raising beach	Filling groyne fields	Ebb delta shoal
1992	2.100	500	Raising beach	Filling groyne fields	Ebb delta shoal
1994	1.300	320	Raising beach / shoreface	Groyne fields /shoreface	Ebb delta shoal

Table 3-5 Most important beach nourishment activities in Norderney

The amounts of sediment that are transported from the tidal flats to the groyne fields are not big enough to influence the large-scale development of the morphology. Furthermore, according to the definition of the tidal flats and the tidal channels the material was transported within the intertidal flat element. For modelling the long-term behaviour of the tidal inlet, these impacts are not important, because they were carried out only from 1951 to 1994.

The volumes that were moved in the tidal basin to stabilize the islands on their places by filling up the beaches don't correspond to the fluctuations in volume shown in figure 3-15.

To investigate the reason for these fluctuations in volumes described in point 2, the morphologies of the tidal inlet were compared with each other. For changes between the years 1960 – 1975 and 1975 – 1990, difference topographies were determined by using the ARCVIEW computer program.

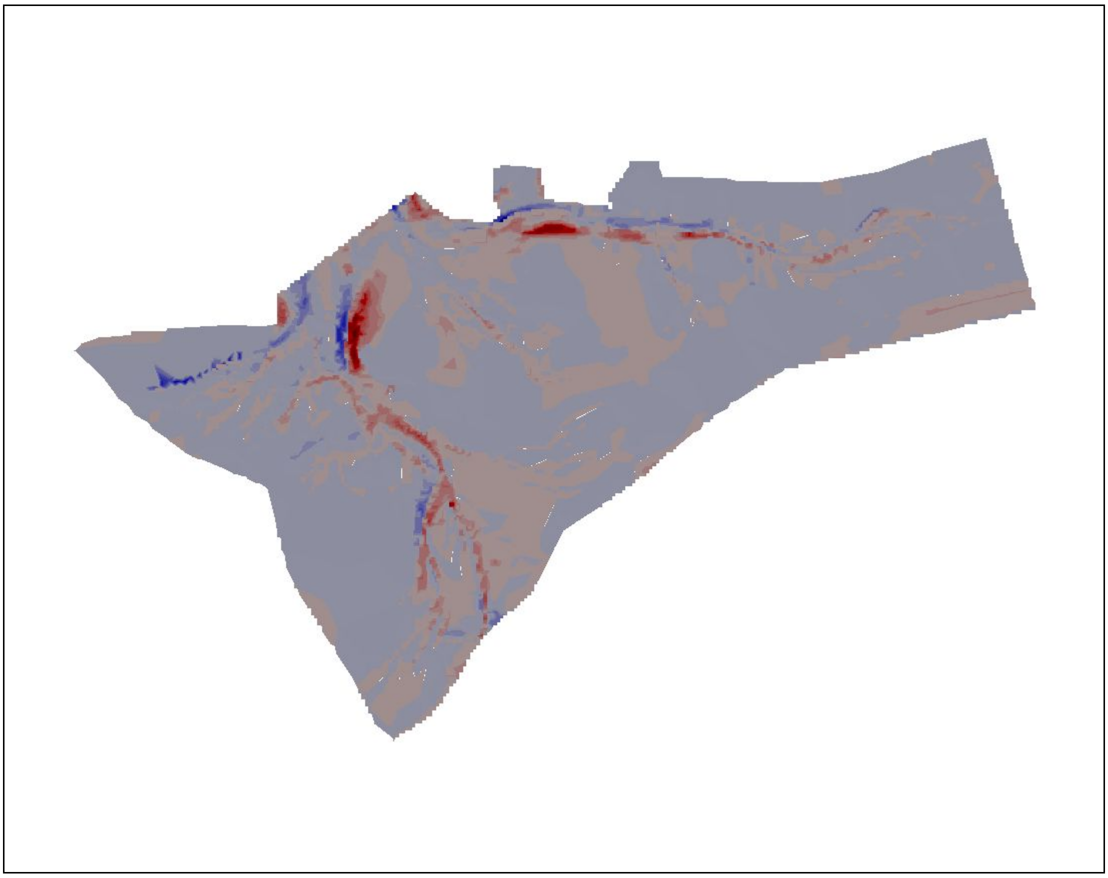

Figure 3-16 Morphological changes between 1960 and 1975

In figure 3-16 the difference morphology for 1960 – 1975 is shown. In red colored areas, sedimentation has taken place and in blue colored areas sediment was eroded. The similar definition is valid for the changes between 1975 and 1990 in figure 3-17. It can be seen, that there is no remarkable increase or decrease inside the tidal inlet. According to figure 3-15, the intertidal flat volume has to increase in the order of magnitude of 8 E+6 m^3. Such changes cannot be found in the difference-topographies. A conclusion from this investigation is, that there must be another reason for the fluctuations.

Another observation that can be made in figure 3-16 and 3-17 is, that some channels are moving inside the tidal basin. In areas where dark red areas and dark blue areas are located beside each other, a tidal channel is moving in the direction from red to blue. This movement of the tidal channels does not have any consequence for the total amount of sediment, because the sediment volume that eroded is almost the same that was settled down in the sedimentation zone.

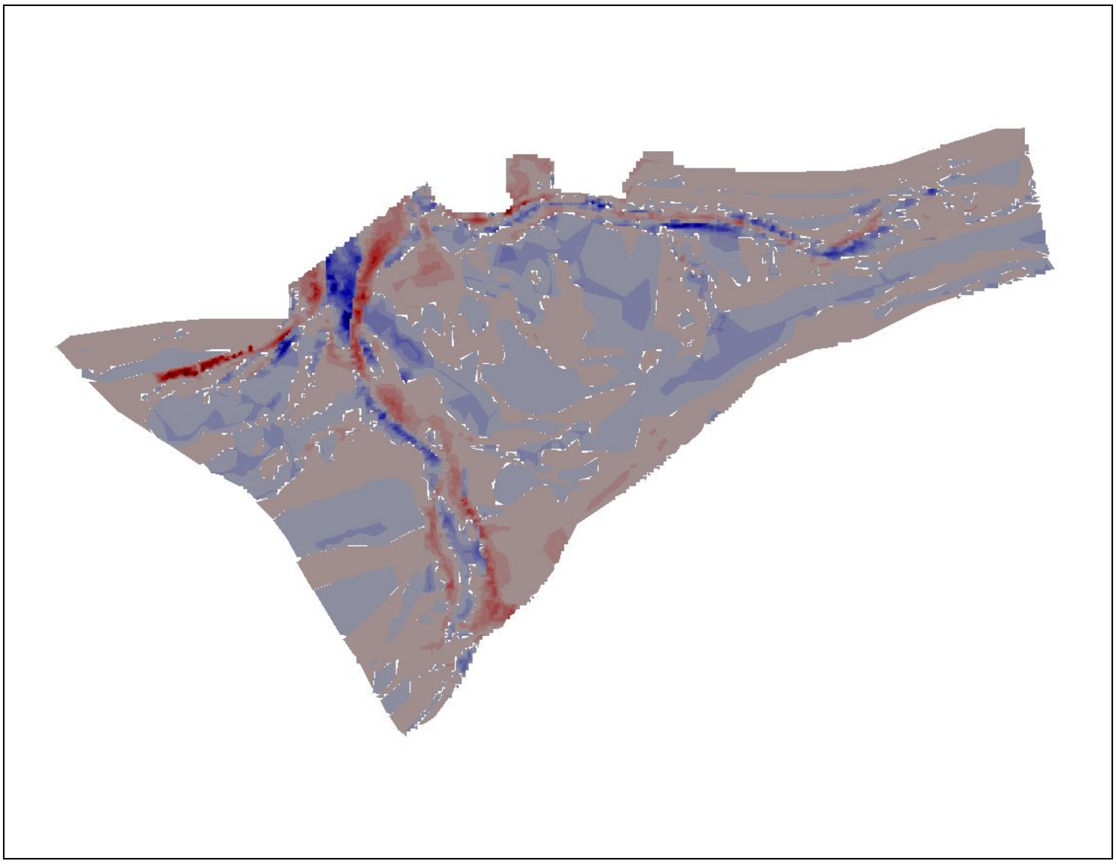

Figure 3-17 Morphological changes between 1975 and 1990

Besides the fixation of the islands, another remarkable interventions have been carried out in the region of the East Frisian Islands. In easterly direction from the Norderneyer Seegat in the Lay Bay land was reclaimed. The time of intensive land reclamation activities agrees with the time of the fluctuations in figure 3-15. These activities don't have direct consequences to the Norderneyer Seegat because the Lay Bay is located in the tidal inlet of the Osterems. By carrying out land reclamation the total basin surface area becomes smaller. Due to this reduction, the whole morphodynamical system of a tidal basin changes. These changes lead us to the possible reasons for fluctuating volumes described in point 3. The changes influence the position of the watersheds between the tidal basins. The distance between the island Juist and the mainland is about 8 km in the area of the watershed. When the watershed between the Osterems and the Norderneyer Seegat moves to the East or to the West, the total surface area and the volumes of the Norderneyer Seegat change a lot. Such changes of the position of the watersheds can declare the remarkable increase and decrease of the intertidal flat volume. Tidal channels are underrepresented in this region.

Fore the use of ASMITA the volumes and the surface areas have to be determined in such a way, that the total surface area of the basin stays always the same. This means that it is assumed that the watersheds do not move. Thus, the values used in the computations differ from these published by NIEMEYER (1995).

3.4 Usability of the data

Looking to the correlations in figure 3-11 and figure 3-13 one can see that the value for the year 1930 is always separated from the other values. This means that this value has to be handled carefully. The different density in measured points causes this derivation. For the year 1930 there are significantly less water-depth information available than in 1960, 1975 and 1990. The different densities in poly-lines are shown in figure 3-17.

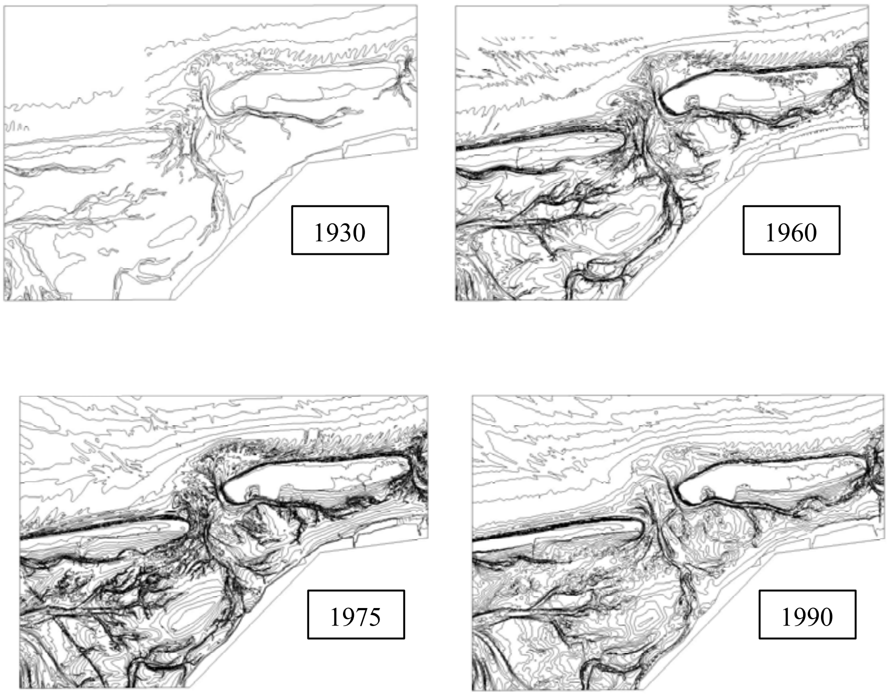

Figure 3-18 Different densities in contours

Because the volumes and surface areas are calculated by dividing the whole area in irregular triangles, the accuracy is strongly related to the density of poly-lines. In table 3-6, the different numbers of triangles that are created by the 3-D Analyst for the same area of interest are shown. It becomes clear, that for the year 1930, a result for the volumes and the surface areas with the same exactness as for the other years cannot be expected.

Year	Number of triangles
1930	23260
1960	138360
1975	297386
1990	206301

Table 3-6 Different number of triangles of the volume model

One reason for the strongly fluctuating volumes in the years 1960 to 1990 could be found in the method of determining the volumes of channels, intertidal flats and ebb-tidal delta. As already mentioned before, the computer program ARCVIEW calculates the negative or positive volume of a topography by interpolating triangles between the available data points or poly-lines. This interpolation causes a error. The grade of this error is dependent on the density of available information.

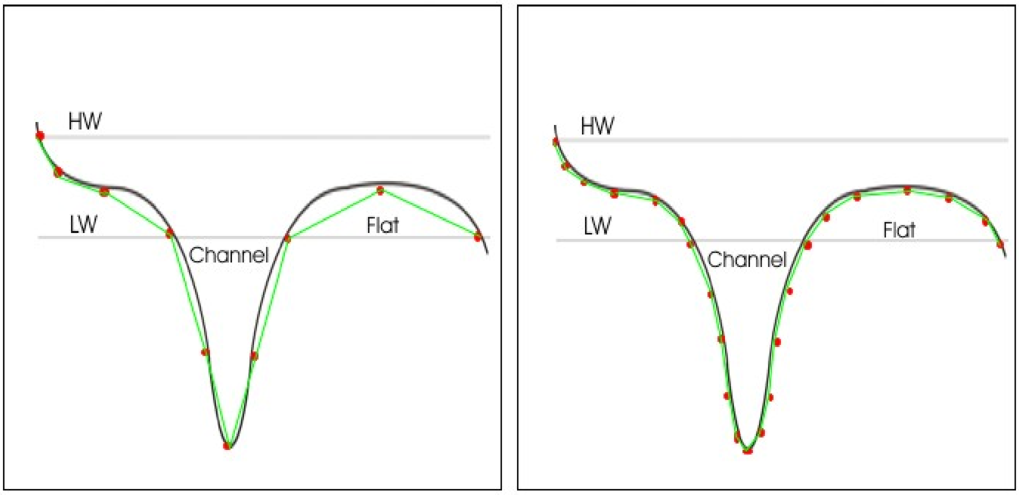

Figure 3-19 Schematisation of channel and flat cross-section

In figure 3-18, the problem of the interpolation error of the volume model is illustrated. In the left part of the figure, the natural profile (black line) is represented only by a few measured depth points (red points). To determine the volume of the topography the computer program used interpolates between the available information (green line). In the right part of the figure, the same profile is represented by many depth points. Here, the interpolated volume model fits much better to the real topography. It can be seen, that the interpolation error results in a bigger water volume of the tidal channel and a smaller sediment volume of the intertidal flats. Looking to the available data sets of the tidal inlet of the Norderneyer Seegat, one can see that the density in information for the years 1960, 1975 and 1990 is very different. The highest density of depth information is available for the year 1975 followed by the data of the year 1990. This results in a different number of triangles representing the topography. In figure 3-19 it can be seen, that for the data with the highest depth information density, the biggest volume for intertidal flats (sediment) and the smallest volume of the tidal channels (water) was calculated.

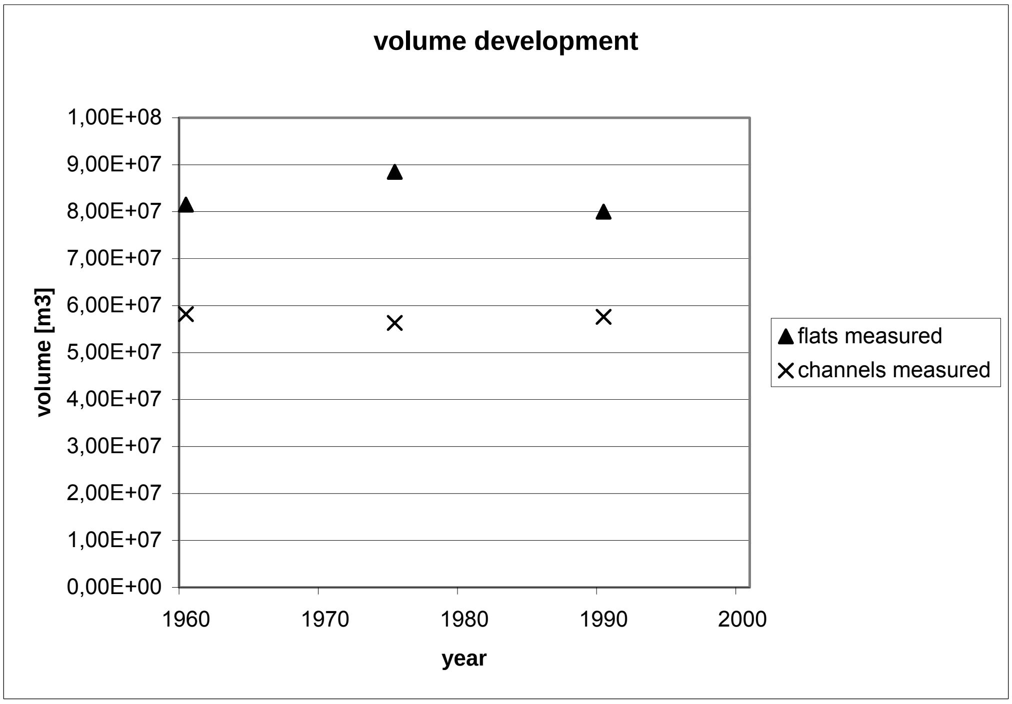

Figure 3-20 Development of volumes

It seems reasonable to assume, that the fluctuations in volumes from 1960 to 1975 and to 1990 partly origins from the different information densities. However, this should not mean, that the reasons for the development shown in chapter 5 are not valid anymore. With the insights from above, the magnitude of changes shown in figure 3-20 that cannot be reproduced with ASMITA, can be explained.

Another source of uncertainty that has to be taken into account is the inaccuracy of the water depths measured in the Wadden Sea. According to ROMMEL (2004), the averaged error that origins form the measurements of the water depth in the Wadden Sea area can be up 7,5 cm. That means, that in case of the Norderneyer Seegat with a total surface area of about 106 km^2 the error of the volumes is in the order of magnitude of 8 10^6 m^3. From the error, that possibly origins just from the measurements, neglecting the error caused by the interpolated triangles, it can be seen, that it is not very useful to look on the quantities of sediment changes to detailed. By modeling large-scale developments that take place in long-term time scales, it is interesting to concentrate on tendencies and qualitative developments.

4 Hydrodynamic & Morphodynamic processes

Introduction

In chapter 4, the main reasons will be discussed, that are responsible for the large-scale development of the morphology of a tidal inlet. In a way, all the processes that are described separately are connected to each other.

One of the most important forces that forms the morphology of the Wadden Sea, when considering long term evolutions, are the currents. Such currents are mostly caused by the tides. The periodic rising and falling water level is caused by the gravitation forces of the moon and the sun to the rotating earth. When the sea level rises (flood period), the water masses are moving through gaps between the islands and fill up the tidal basin. When the maximum sea level is reached (high water), the direction of the current turns and the tidal wave leaves the Wadden Sea (ebb period). The difference in water level between high water and low water is called tidal range. The water volume belonging to this tidal range that is entering and leaving the tidal basin is called the tidal prism. This amount of water and the current patterns depend on the morphology of the tidal basin. This interaction is shown in figure 4-1.

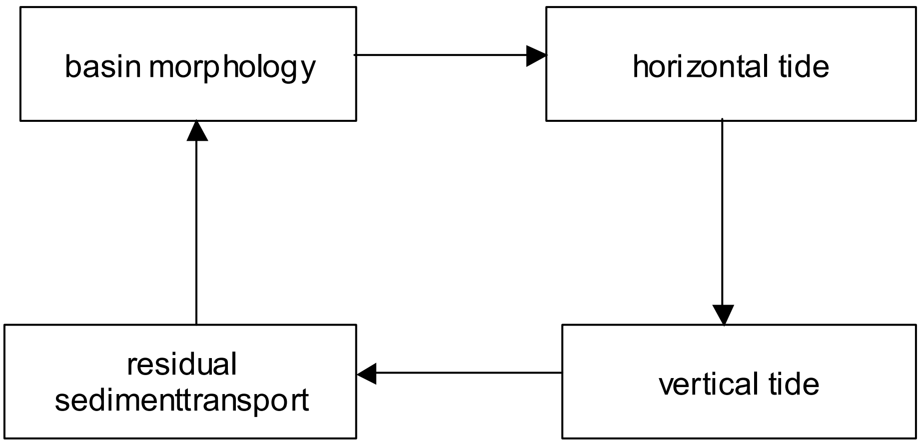

Figure 4-1 Interaction scheme of the mophodynamic system

4.1 Tidal asymmetry

The tide shows a periodic behaviour with respect to water levels (vertical tide), flow velocities (horizontal tide) and discharges as well as associated sediment transport. Several factors influence the tidal motion; so one half of a period is not necessarily a mirror image of the other half. This is called tidal asymmetry. Besides the astronomically dominated main constituents in shallow marginal or coastal seas additional frequencies do occur. The shallow water constituents of the tide are also called compound tides and overtides. They are mainly caused by nonlinear nature of the physics governing the motion of water. Such influences can be dependence of the velocity of a tidal wave on the actual water depth, nonlinear bottom friction or advection of momentum.

To characterize asymmetry we distinguish between ebb - and flood dominance. For instance, if the duration of water level rise is shorter than that of water level fall, the asymmetry of the vertical tide is called flood-dominant. If the duration of rising water level is longer than that of falling water level, the asymmetry is called ebb-dominant.

- Flood period < ebb period → flood dominance
- Flood period > ebb period → ebb dominance

The horizontal tide will be called asymmetric if it generates a residual sediment transport. The asymmetry may be associated with a difference in the magnitude between maximum ebb - and flood velocities. This type of asymmetry tends to induce a residual bed load and suspended load transport of sediment. For instance, if the maximum flood velocity exceeds the maximum ebb velocity, a residual sediment transport in flood direction occurs.

Another type of asymmetry that affects the residual transport of sediment is associated with a difference in the durations of slack water. Between the flood and ebb periods when the current direction of the current is turning, there are moments where the water masses are not moving, the so-called slack water. A situation in which the duration of slack water before ebb exceeds the duration of slack water before flood drives a residual sediment transport in flood direction. Because the water is not moving at this moment, the sediment particles suspended in the water can settle down to the sea floor. Therefore, the duration of the slack water period at high water and at low water and their difference is very important for investigating sediment transport and morphological changes. If the residual sediment transport is in the flood direction, it will be called flood-dominant and vice versa. This settled sediment partly gets in suspension, when the current velocities of the following flood- or ebb-period exceed a critical value. This critical current velocity mainly depends on the grain size of the sediment.

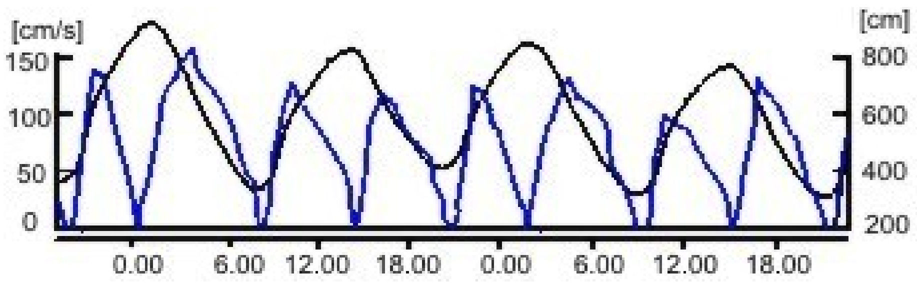

Figure 4-2 Vertical (black) and horizontal (blue) tide in the Norderneyer Seegat

Figure 4-2 shows the tidal velocities (blue) and the tidal elevation (black). From this picture it can be seen, that in the Norderneyer Seegat, the slack water time during low water is longer than that during high water.

According to the theory from above, this gives the tidal inlet an ebb dominant character.

The interaction between tidal motion and morphology determines the degree and nature of tidal asymmetry and thus determines the large-scale morphological behaviour of tidal basins.

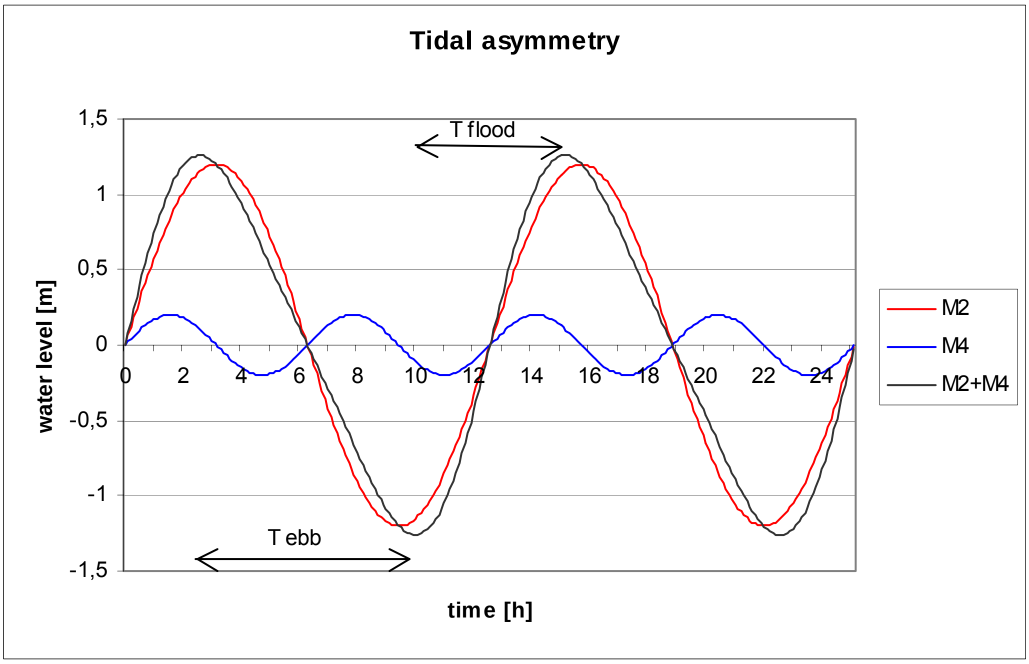

Figure 4-3 Schematisation of tidal asymmetry

It has been mentioned that the origin of the tidal asymmetry is the non-linear interactions with itself and with the tidal components. This distortion of the M2 tide in shallow estuaries plays an important role in sediment transport. Factors such as friction and channel morphology generate shallow water overtides such as M4 and M6. When these are added to the M2 tidal current, maximum ebb and flood are shifted closer to high or low water resulting in a tidal current that is distorted from the M2 component. Whether the shift goes towards low or high water depends on the hyposometric curve (fig. 4-4) of the area. The hypsometric curve will be explained in the next section.

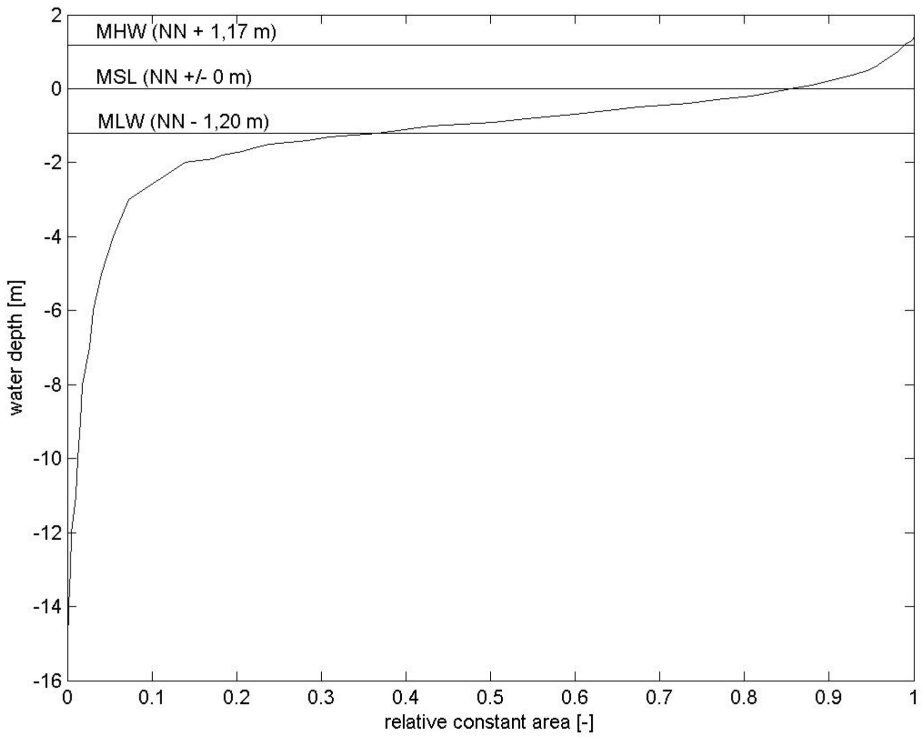

Figure 4-4 Hypsometric curve Norderneyer Seegat

4.1.1 Tidal asymmetry by basin hypsometry

The tidal curve of the Norderneyer Seegat in fig. 4-5 has a slight asymmetric shape. Because the averaged steepness of the ebb branch is gentler than that of the flood branch, the flood duration is shorter than the ebb duration. The averaged flood duration is 6:04 and the ebb duration 6:21 (WSA Emden).

It is difficult to find an explanation for the shorter flood duration in the hypsometric curve of figure 4-4. The basin hypsometry is defined as the vertical distribution of the basin surface area with height (BOON and BYRNE, 1981; DRONKERS, 1989; VAN DE KREEKE, 1988). When the tidal wave is entering the tidal inlet, the sea level is starting to rise at MLW. The hypsometric curve is relative gentle between MLW and MSL, so the water masses can expand over a big area. This should result in a gentle tidal curve because the water level is expected to rise slowly. Above MSL the slope of the hypsometric curve becomes steeper, so the water masses can not spread over the area but have to fill up the inundated basin. Therefore, the tidal curve has to rise faster than before. The measured tidal curve becomes now gentler.

An explanation for the asymmetry of the tide in the Norderneyer Seegat can be found by looking to the cross section of the tidal inlet. During flood, when the water level rises, the water masses must pass the narrow inlet between the islands of Juist and Norderney. This results in a delay in water level rise inside the basin compared with the rising water level at the open sea. When the tidal wave has reached its maximum height at the sea, the water level is still rising inside the basin. Than the level is falling outside and the water masses cannot flow into the tidal basin anymore. The consequence is that ebb currents begin to flow back from the basin to the open sea. The delay of the tidal curve inside the basin compared with the tidal wave at the open sea is, that the tidal amplitude is a little bit smaller inside the basin than outside. The water masses can leave the basin faster then entering it. This leads to the tidal asymmetry, which can be characterized as flood-dominated.

NUMMEDAL, HUMPHRIES (1978), FITZGERALD and NUMMEDAL (1983) have suggested that duration and asymmetry in tidal flow is controlled by the variation in basin surface area relative to the inlet cross-section area.

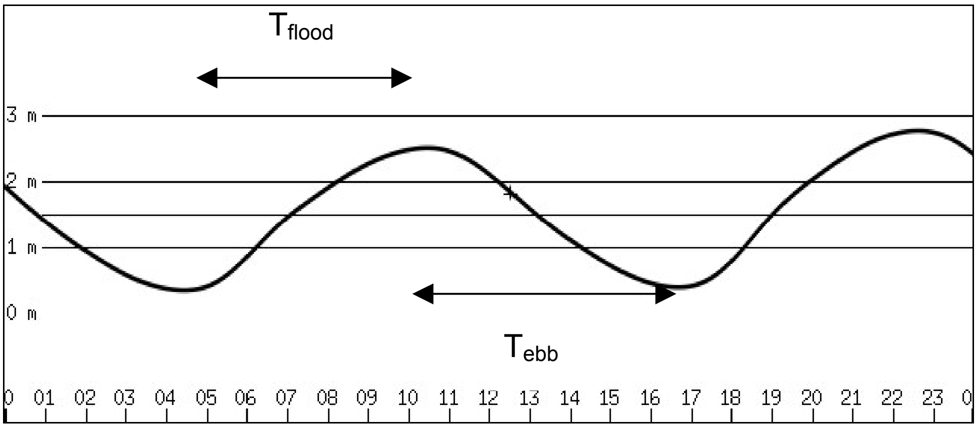

Figure 4-5 Tidal curve Norderneyer Seegat

The tidal curve measured in the tidal inlet of the Norderneyer Seegat can be characterized as flood dominated. The duration of rising water level (T_{flood} = 6:04) is shorter that the duration of falling water level (T_{ebb} = 6:21).

4.1.2 Tidal asymmetry by channel geometry

The asymmetric shape of the curve describing water level over an M2 tidal cycle (see figure 4-5) is the result of overtide generation such as M4. Overtide generation is caused by non-linearities due to bottom friction and continuity constraints. Overtides become important when a/h becomes large, where a is tidal amplitude and h is bottom depth.

Determining whether there is a flood-dominance or an ebb-dominance in the tidal inlet Speer and Aubrey (1985) and FRIEDRICHS and AUBRAY (1988) studied the influence of geometry and bathymetry of short, friction-dominated and well-mixed estuaries using 1D numerical models. Well-mixed means in this respect that density-driven currents are not significant. They concluded that the parameters determining the tidal asymmetry in such an estuary are:

- the ratio of the tidal amplitude and the mean water depth, a/h, and
- the ratio of the volume of water stored between low and high water in tidal flats and marshes and the volume of water contained in the channels below mean sea level Vs/Vc.

Relatively shallow estuaries tend to be flood-dominant and estuaries with relatively much intertidal flats tend to be ebb-dominant. Based on the results of FRIEDRICHS and AUBRAY (1988), SPEER et al. (1991) constructed the graph in Figure 4-6, which shows the influence of the two parameters on the asymmetry of the vertical tide. SPEER and AUBRAY (1985) found in general that stronger friction produced larger M4/M2 ratios.

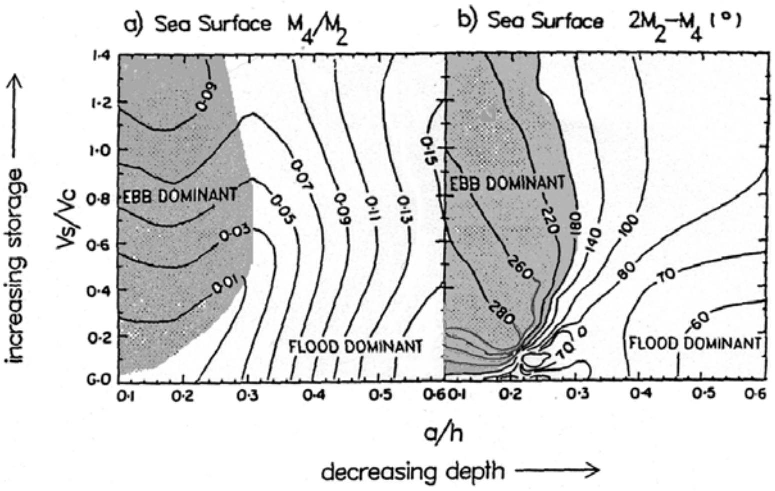

Figure 4-6 Flood- / ebb- dominance (FRIEDRICHS, AUBREY; 1988)

Figure 4-6 shows the contour plots of the parameters that determine non-linear distortion as a function of a a/h and Vs/Vc, resulting from 84 model systems. The 180 ° contour separates the plots into flood and ebb-dominant regions (FRIEDRICHS and AUBREY, 1988). It show that below the contour of Vs/Vc = 0.3 the ebb- or flood dominance depends almost on a/h. That means that an increase of the water depth h leads to ebb-dominance. When the ebb-dominance is associated with an export of sediment, a positive feedback occurs that may lead to a drowning of the system. Stability of a tidal basin requires that such a positive feedback stays away, otherwise the morphological equilibrium can not be reached anymore.

Applying the diagram of FRIEDRICHS and AUBREY (1988) to the tidal inlet of the Norderneyer Seegat with the ratios a/h = 0.4 and Vs/Vc = 1.2 leads to the classification towards flood dominance.

DRONKERS (1998) defined the morphological equilibrium by the ratio of channel depth at HW and LW and the ratio of wet surface at HW and LW. The ratio H_{HW}/H_{LW} of high water and low water average channel depth is plotted against the ratio S_{HW}/S_{LW} of high water and low water wet surface. The curve $y = \sqrt{x}$ represents the condition for approximately equal flood and ebb duration (DRONKERS, 1998). Each tidal basin that is in equilibrium has to be located on the curve. Figure 4-7 shows, that most of the Dutch tidal inlets are slightly flood dominated.

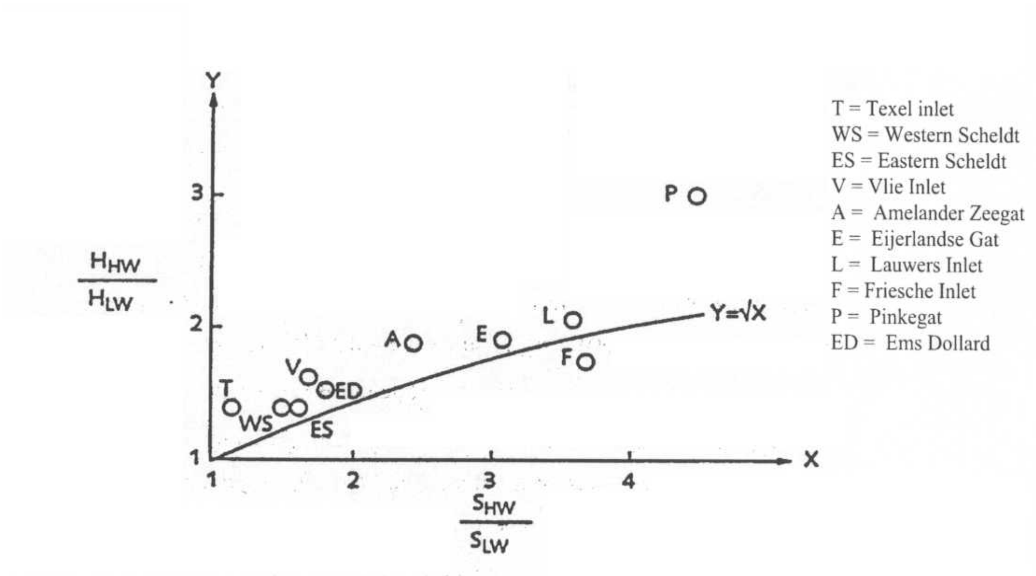

Figure 4-7 Flood- /ebb- dominance in the Dutch wadden sea (DRONKERS; 1998)

Supplementing the diagram of DRONKERS (1998) with some tidal inlets of the East Frisian Wadden Sea it can be seen, that the German and the Dutch tidal inlets behave in a similar way (figure 4-8). From figure 4-8, the tidal inlet of Norderneyer Seegat can be classified as slightly flood-dominant.

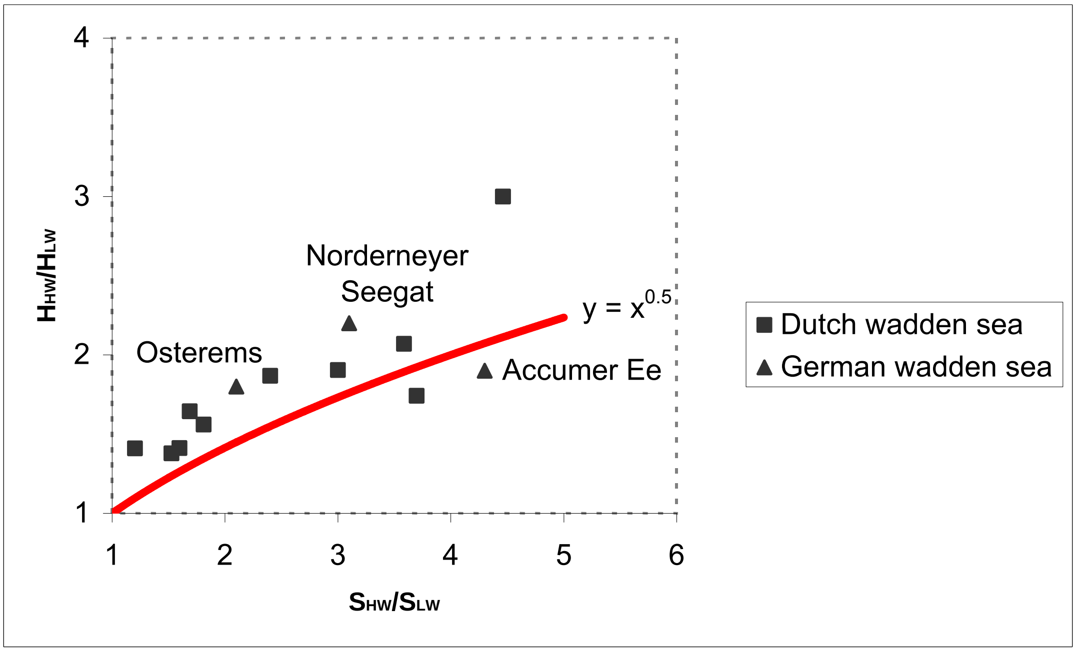

Figure 4-8 Diagram Dronkers supplemented with 3 German tidal inlets

According to the Diagram of DRONKERS the tidal inlets Osterems and Norderneyer Seegat are flood-dominated, but the tidal inlet Accumer Ee ebb-dominant.

5 Simulations

Introduction

In chapter 5 the ASMITA numerical model will described in general. A semi-empirical model, like ASMITA, is based on the physics of sediment-exchange between elements and empirical knowledge of the equilibrium state. It has proved to be valuable for hindcast of long-term effects. Subsequently, the empirical equilibrium parameters in ASMITA will be determined for the tidal inlet of the Norderneyer Seegat. Finally, the calibrated model will be applied to simulate the evolution of the Norderneyer Seegat for different scenarios of future sea level rise.

The computer program that will be used is called ASMITA (Aggregated Scale Morphological Interaction between Tidal inlet and the Adjacent coast, Stive and Wang 1996). ASMITA is based on a so-called ‘behaviour-oriented’ approach. This approach includes the assumption that the morphological developments tend to an (dynamic) equilibrium state.

The model contains empirical parameters reflecting characteristics of large-scale morphological evolutions of tidal inlet systems. ASMITA concerns long-term average sediment import or export as well as sediment redistribution within the inlet system. To estimate the parameters, the model is fitted to field data on the historical morphological evolution of the Norderneyer Seegat. Subsequently, these parameter estimates are used to predict the morphological behaviour of the Norderneyer Seegat in response to expected future sea level rise. The reconstructed historical data sets of the Coastal Research Station in Norderney is used to improve the reliability of the validity of the behaviour-oriented approach by extending the time span with supporting data.

5.1 ASMITA

In the ASMITA model a tidal inlet is schematised into three morphological elements. The inlet evolution is described in terms of changes in the integral state of these elements. These elements contains are:

- the intertidal flats (dry sediment volume between MHW and MLW)
- the tidal channels (wet water volume below MLW)
- the ebb-tidal delta (dry sediment volume)

It can be extended by two additional sediment sources, the adjacent coastline on the seaward side of the downdrift and updrift barrier islands. As shown in chapter 2, these elements have an important impact on the development of the ebb-tidal delta. All the ASMITA elements are interacting with each other (see figure 5-1). Model parameters reflect the sediment exchange between the elements and the element integrated erosion or sedimentation characteristics. It is also possible to reduce the number of elements. The selection of elements used for a calculation depends on the available data. If there is no reliable information available about the ebb-tidal delta volume, one can reduce the model to only flat and channel volumes. This will be the case for the long-term simulations of the Norderneyer Seegat.

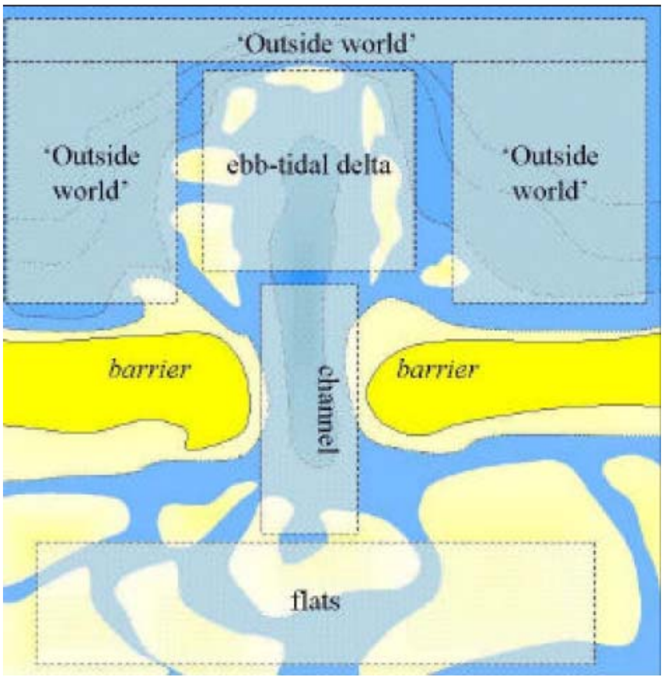

Figure 5-1 Schematisation of ASMITA elements (VAN GOOR, 2001)

Besides the volumes and the surface areas of the different elements, there are also parameters in ASMITA that describe the state and the properties of each element. One of the most important parameters is the local equilibrium sediment-concentration of the elements (c_e) relative to the overall equilibrium concentration (c_E). When an element is in a morphological equilibrium ($V=V_e$) the local equilibrium concentration is equal to the overall equilibrium concentration. If c_e is smaller then c_E there is a tendency to sedimentation and when c_e is larger then c_E the system tends to erode ($V<V_e$). This behaviour can be modelled with an power relation:

$$c_e = c_E \left(\frac{V}{V_e} \right)^n \qquad 5.1$$

with:

c_e	Local equilibrium sediment concentration in element [-]
c_E	Overall equilibrium concentration [-]
V	Actual volume of element [m^3]
V_e	Equilibrium volume of element [m^3]
n	2, negative for wet volumes (channel), positive for dry volumes [-]

The exponent n is determined by the power in the relationship between sediment transport and flow velocity. Whether n is positive or negative depends on the definition of the volume of the element. In case of 'wet' volumes accretion ($c_e>c_E$) means a decrease of volume and erosion ($c_e<c_E$) means sedimentation. In this case the n is negative. A reversed situation applies for the 'dry' volumes (n positive).

An important concentration parameter in ASMITA, that influences the capability of the system to adapt to a new equilibrium state, is the sediment concentration in the outside world (c_E), in the model concept this is the overall sediment supply for the system. A higher concentration in the outside world gives a higher concentration in the elements, resulting in higher potential of the transport rates. The adaptation rate of the tidal inlet is thus also determined by the 'outside world'-concentration.

5.2 Coefficients

5.2.1 Overall equilibrium concentration (c_E [-])

The overall equilibrium concentration determines the availability of sediment in the outside world. The concentration is defined as cubic meters bottom per cubic meters water instead of kilograms sediment per cubic meters water. The magnitude of this parameter can be derived by estimating the sediment transport caused by waves. This is about 1 to 2 million m^3 along the Dutch coast annually. According to Van Goor (2001) this leads to a range of the concentration from 1.2e-4 to 2.4e-4, where as Buijsman (1997) used 2e-4.

For the Norderneyer Seegat an overall equilibrium concentration c_E of 1.0e-4 turned out to be valid. This parameter was estimated by trying.

5.2.2 Horizontal diffusion (δ [m³/s])

As mentioned before, tidal asymmetry can lead to a net sediment transport during a tidal period. In the ASMITA concept, this net transport is described by a diffusion phenomenon. The diffusion coefficient (δ) represents the tide residual exchange capacity between two elements. It originates from the mass balance equation and is used in ESTMORPH (WANG and KARSSEN, 1992).

The coefficient depends on the cross section the sediment-transport is passing when entering the tidal basin and the average distance between the centers of two elements, so it is estimated based on length-scales. The diffusion coefficient represents the tide residual sediment transport capacity, which is dependent on the sediment type, the corresponding settling velocity and the tide-averaged velocity. In case of no sediment variation and the tide averaged velocity is constant when the system is in a morphological equilibrium (ESCOFFIER, 1940), the assumption can be made that the dispersion is value. BUISMAN (1997) used values ranging from 500 m^3/s up to 1500 m^3/s for the Zoutkamperlaag in the Dutch Wadden Sea.

Because the rate between the different characteristic lengths can be used as a scale factor for diffusion coefficients, according to KRAGTWIJK (2001) the diffusion coefficient can be determined by equation (5.2).

$$\delta_{Ney} = \sqrt{\frac{A_{Ney}}{A_{zoutk}}}\delta_{zoutk} \qquad 5.2$$

with:

δ_{zoutk}	diffusion coefficient Zoutkamperlaag (m^3/s)
δ_{Ney}	diffusion coefficient Norderneyer Seegat (m^3/s)
A	area (m^2)

By knowing the diffusion coefficient for the tidal inlet of Zoutkamperlaag, it is possible to estimate the specific value for the Norderneyer Seegat.

For the Norderneyer Seegat a diffusion-coefficient δ_{oc} of 900 m^3/s and δ_{fc} of 700 m^3/s was found.

5.2.3 Vertical exchange (w_s [m/s])

The rates of erosion or sedimentation are expressed as an average vertical exchange per element. The vertical exchange is not the same as the settling velocity although they have the same dimension. According to BUISMAN (1997) the values for the vertical exchange coefficient range from 1e-5 to 1e-4 m/s. The vertical exchange is influenced by the waves, which stir up sediment from the sea bottom. This means, that the vertical exchange of the delta is higher than on the flats, where the wave climate is much calmer.

For the flats and channels of the Norderneyer Seegat w_s is assumed to be 1.0 e-4 m/s. This parameter was estimated by trial and error.

5.2.4 n-parameter [-]

This parameter is used in the relation between volume variation of the equilibrium volume and the local equilibrium concentration. This parameter is related to the non-linear relation between sediment transport and mean velocity.

The value of 2 is in compliance with the third power most commonly used in sediment transport formula (BUISMAN (1997), VAN GOOR (2001) and KRAGTWIJK 2001).

5.2.5 Tidal range (H [m])

With the tidal range and the surface areas the tidal prism is calculated. The tidal prism is used to determine the equilibrium volumes for the elements.

5.3 Morphodynamic simulations

5.3.1 1-element model

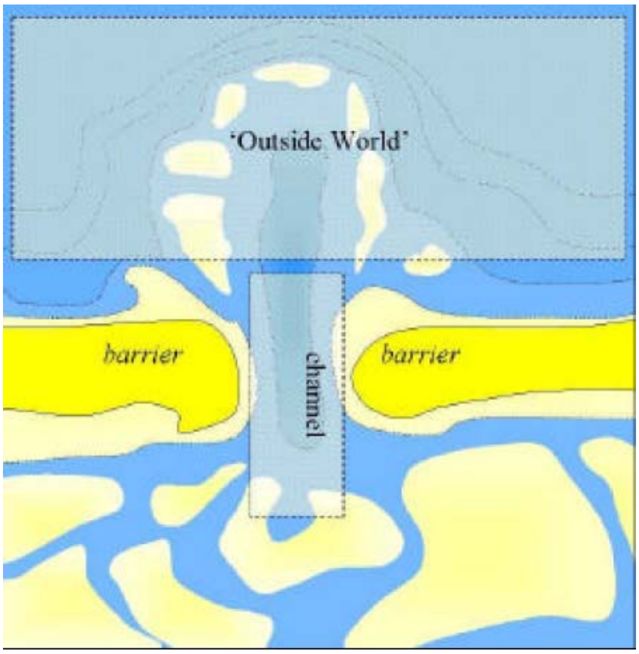

Figure 5-2 Schematized 1-element model (VAN GOOR, 2001)

The morphological changes are determined by the deviation of the actual sediment concentration in the element from the local equilibrium concentration. It is assumed that there is only diffusion/dispersion transport between the channel and the outside world. The outside world is always in dynamic equilibrium, in contradiction to the elements, which can deviate from their dynamic equilibrium. Erosion occurs when the actual concentration (c) is smaller than the equilibrium concentration (c_e) and with a larger concentration, accretion occurs.

$$\pm \frac{dV}{dt} = w_s \cdot A \cdot (c - c_e) \qquad 5.3$$

with:

±	=	Positive for dry volumes, negative for wet volumes [-]
dV/dt	=	Rate of volume change due to erosion or accretion [m^3/s]
w_s	=	Vertical exchange coefficient [m/s]
A	=	Area of element [m^2]
c	=	Actual sediment concentration [-]

c_e = Local equilibrium concentration [-]

The sediment can be distributed between the elements and between the elements and the outside world.

The diffusive transport:

$$T_{1\to 2} = \delta_{1,2} \cdot (c_1 - c_2) \qquad 5.4$$

with:

$T_{1\to 2}$ Sediment transport between two elements [m^3/s]

$\delta_{1,2}$ Horizontal exchange rate between two elements [m^3/s]

According to the sediment mass balance the accumulation of transport to an element must equal the rate of volume change of the element:

$$\sum \delta_{1,2} \cdot (c_2 - c_1) = w_s \cdot A_1 \cdot (c_1 - c_e) \qquad 5.5$$

In ASMITA the rise of the sea level is an external forcing. It causes an increase of the wet volume and a decrease of the dry volume.

The rising sea level is expressed by equation:

$$\pm \frac{dV}{dt} = -A \cdot \frac{d\zeta}{dt} \qquad 5.6$$

with:

$\pm$ Positive for dry volumes, negative for wet volumes [-]

$d\zeta/dt$ Relative sea-level rise [m/s]

Combining equation (5.3) and (5.6) gives:

$$\pm \frac{dV}{dt} = w_s \cdot A \cdot (c - c_e) - A \cdot \frac{d\zeta}{dt} \qquad 5.7$$

With 3 base-equations ((5.1), (5.5) and (5.7)) and three unknown variables (c, ce and V, the rest of the variables should be known or estimated), this problem can be written as a partial differential equation of volume versus time (dV/dt = f(V)). In the next subsections, this formulation will be used for the 1, 2 and 3 element models.

The critical rate of sea level rise for an one-element version of ASMITA can be described by:

$$\left(\frac{d\zeta}{dt}\right)_{critical,c} = \frac{w_{sf} \cdot \delta_{co} \cdot c_E}{\delta_{co} + w_{sf} \cdot A_c} \qquad 5.8$$

5.3.2 2 – element model

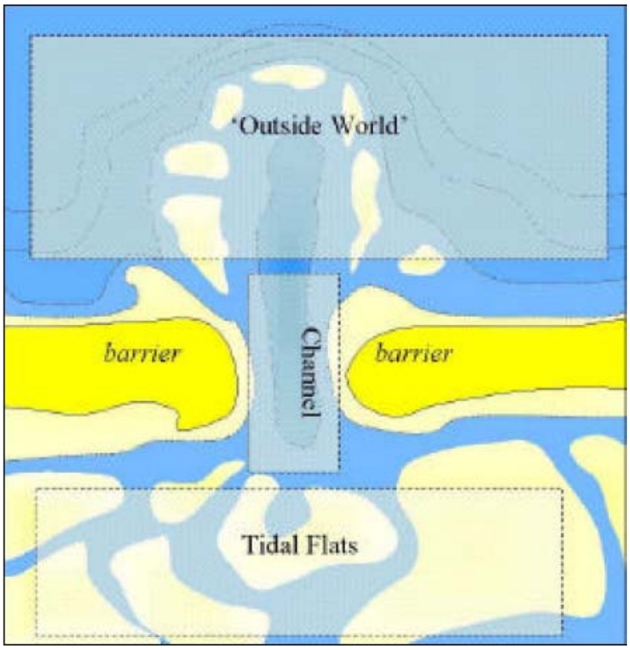

Figure 5-3 Schematization of 2-elements model (VAN GOOR, 2001)

In a 2-element version, the tidal flats are assumed to be separated from the outside world by the channels. As in a 1-element version, it is assumed that there is only diffuse transport between the tidal flats and the channel and between the channel and the outside world.

Equilibrium volumes:

$$V_{fe} = f\left(A_b, H\right) \qquad 5.9$$

$$V_{ce} = f(V_{ctv}) \qquad 5.10$$

For the relation between the local and the global equilibrium concentration applies:

$$c_{fe} = c_E \left(\frac{V_f}{V_{fe}} \right)^n \qquad 5.11$$

$$c_{ce} = c_E \left(\frac{V_c}{V_{ce}} \right)^{-n} \qquad 5.12$$

As V_f is defined as a dry volume, n is positive in contrast with negative value for the channel relation, the absolute value is for both formulations the same and is determined by the sediment transport formula.

The rate of volume change is given by:

$$\frac{dV_f}{dt} = -A_c \cdot \frac{d\zeta}{dt} + w_{sf} \cdot A_f \cdot (c_f - c_{fe}) \qquad 5.13$$

$$\frac{dV_c}{dt} = A_c \cdot \frac{d\zeta}{dt} - w_{sc} \cdot A_c \cdot (c_c - c_{ce}) \qquad 5.14$$

These volume changes due erosion and accretion balance the diffusive transport in order to fulfill the mass balance:

$$\delta_{cf} \cdot (c_c - c_f) = w_{sf} \cdot A_f \cdot (c_f - c_{fe}) \qquad 5.15$$

$$\delta_{co} \cdot (c_E - c_c) - \delta_{cf} \cdot (c_c - c_f) = w_{sc} \cdot A_c \cdot (c_c - c_{ce}) \qquad 5.16$$

In the 2-element version the development of one element depends strong on the state and the development of the other element. The same will be the case for the 3-element version. For the dynamic equilibrium situation the volume changes of the tidal flats and channels have to be zero. With a constant relative sea-level rise the system will evolve to a volume which differs from the equilibrium volume but is constant in time, the so-called dynamic equilibrium volume (V^*).

The solution for V^*_{fe} and V^*_{ce} becomes then:

$$V^*_{fe} = \left[1 - \frac{d\zeta}{dt} \cdot \frac{1}{c_E} \cdot \left(\frac{A_f}{\delta_{cf}} + \frac{A_f + A_c}{\delta_{co}} + \frac{1}{w_{sf}} \right) \right]^{\frac{1}{n}} \cdot V_{fe} \qquad 5.17$$

$$V_{ce}^* = \left[1 - \frac{d\zeta}{dt} \cdot \frac{1}{c_E} \cdot \left(\frac{A_f + A_c}{\delta_{co}} + \frac{1}{w_{sc}}\right)\right]^{-\frac{1}{n}} \cdot V_{ce} \qquad 5.18$$

V^*_{fe} can also be related to a critical relative sea-level rise as well, but as n is positive for dry volumes V^*_{fe} decreases instead of increases with increasing relative sea-level rise. The solutions for the critical relative sea-level rise regarding the tidal flats and the channels are:

$$\left(\frac{d\zeta}{dt}\right)_{critical,f} = \frac{c_E}{\frac{1}{w_{sf}} + \frac{A_c + A_f}{\delta_{co}} + \frac{A_f}{\delta_{cf}}} \qquad 5.19$$

$$\left(\frac{d\zeta}{dt}\right)_{critical,c} = \frac{w_{sf} \cdot \delta_{co} \cdot c_E}{\delta_{co} + w_{sf} \cdot (A_c + A_f)} \qquad 5.20$$

5.3.3 3-element version

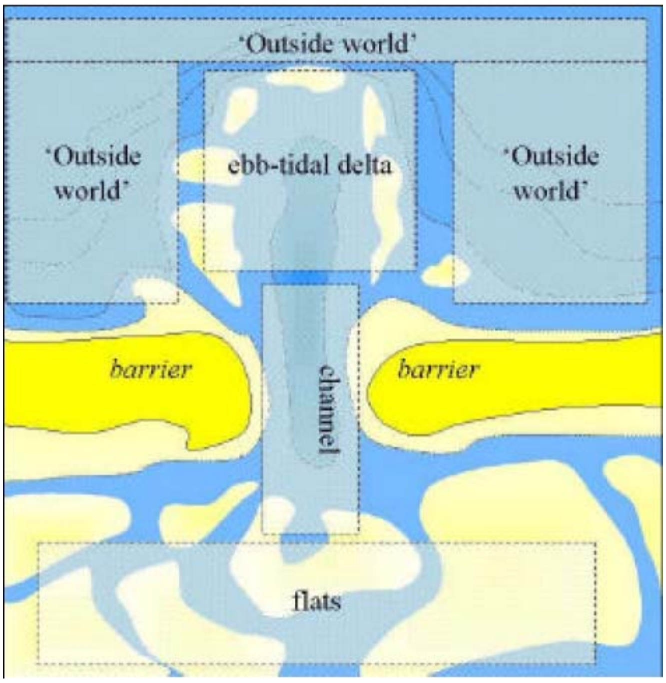

Figure 5-4 Schematization of 3-element model (VAN GOOR, 2001)

For a better understanding of the behaviour of the tidal inlet of Norderneyer Seegat, a more detailed version of the ASMITA numerical model will be applied. In this 3-element version besides the tidal channel and the intertidal flats, also the volume of the ebb-tidal delta will be included. This expanded version can only be applied to the development of the 60 years from 1960 to 1990, because detailed information is needed about the volume of the ebb-tidal delta. This detailed information can be get from accurate measurements. To make the model better fit to the developments that took place in history in the Norderneyer Seegat, the equilibrium relations will be adapted by using the empirical parameters derived in 5.4.4.

The ebb-tidal delta lies at the seaside of the channel, the channel loses his connection with the outside world and the ebb-tidal delta takes over the function. Transports are possible between tidal flats and channel, between channel and ebb-tidal delta and between ebb-tidal delta and the outside world.

Analogously to the 1- and 2-element versions, for the three elements the same model set-up will be done, starting with the equilibrium relations for element-volumes:

$$V_{fe} = f\left(A_b, H\right) \qquad 5.21$$

$$V_{ce} = f\left(V_{ctv}\right) \qquad 5.22$$

$$V_{de} = f\left(V_{ctv}\right) \qquad 5.23$$

The local equilibrium concentration is determined by:

$$c_{fe} = c_E \left(\frac{V_f}{V_{fe}} \right)^n \qquad 5.24$$

$$c_{ce} = c_E \left(\frac{V_c}{V_{ce}} \right)^{-n} \qquad 5.25$$

$$c_{de} = c_E \left(\frac{V_d}{V_{de}} \right)^n \qquad 5.26$$

V_f and V_d are defined as ‘dry’-volume and thus n is positive in contrast with the negative value for the channel relation.

The rate of volume changes are given by:

$$\frac{dV_f}{dt} = -A_c \cdot \frac{d\zeta}{dt} + w_{sf} \cdot A_f \cdot \left(c_f - c_{fe}\right) \qquad 5.27$$

$$\frac{dV_c}{dt} = A_c \cdot \frac{d\zeta}{dt} - w_{sc} \cdot A_d \cdot \left(c_c - c_{fe}\right) \qquad 5.28$$

$$\frac{dV_d}{dt} = -A_d \cdot \frac{d\zeta}{dt} + w_{sd} \cdot A_d \cdot (c_d - c_{de}) \qquad 5.29$$

In order to fulfill the mass-balances for all elements:

$$\delta_{cf} \cdot (c_c - c_f) = w_{sf} \cdot A_f \cdot (c_f - c_{fe}) \qquad 5.30$$

$$\delta_{cd} \cdot (c_E - c_c) - \delta_{cf} \cdot (c_c - c_f) = w_{sc} \cdot A_c \cdot (c_c - c_{ce}) \qquad 5.31$$

$$\delta_{do} \cdot (c_E - c_d) - \delta_{cd} \cdot (c_c - c_d) = w_{sd} \cdot A_d \cdot (c_d - c_{de}) \qquad 5.32$$

This solution is analogous to the solution of the 2-element model, only the dynamic interaction between the elements has increased by adding an element to the model. For the dynamic equilibrium situation the volume-changes have to be zero. Based on equation (5.30), (5.31) and (5.32) the solution for V^*_{fe} , V^*_{ce} and V^*_{de} becomes then:

$$V^*_{fe} = \left[1 - \frac{d\zeta}{dt} \cdot \frac{1}{c_E} \cdot \left(\frac{A_f}{\delta_{cf}} + \frac{A_f + A_c}{\delta_{co}} + \frac{A_f + A_c + A_d}{\delta_{do}} + \frac{1}{w_{sf}} \right)\right]^{\frac{1}{n}} \cdot V_{fe} \qquad 5.33$$

$$V^*_{ce} = \left[1 - \frac{d\zeta}{dt} \cdot \frac{1}{c_E} \cdot \left(\frac{A_f + A_c}{\delta_{co}} + \frac{A_f + A_c + A_d}{\delta_{do}} + \frac{1}{w_{sc}} \right)\right]^{-\frac{1}{n}} \cdot V_{ce} \qquad 5.34$$

$$V^*_{de} = \left[1 - \frac{d\zeta}{dt} \cdot \frac{1}{c_E} \cdot \left(\frac{A_f + A_c + A_d}{\delta_{do}} + \frac{1}{w_{sd}} \right)\right]^{\frac{1}{n}} \cdot V_{de} \qquad 5.35$$

The solution is analogous to the solution of the 2-element model. The volumes defined as dry volumes (V^*fe and V^*de) are expected to decrease with increasing sea-level rise and the wet channel volume increases.

By adding an extra element in the model, the interaction between the element increases which is also reflected in the critical sea-level rise:

$$\left(\frac{d\zeta}{dt}\right)_{critical,f} = \frac{c_E}{\frac{1}{w_{sf}} + \frac{A_c + A_f + A_d}{\delta_{co}} + \frac{A_f + A_c}{\delta_{cd}} + \frac{A_f}{\delta_{cf}}} \qquad 5.36$$

$$\left(\frac{d\zeta}{dt}\right)_{critical,c} = \frac{c_E}{\frac{1}{w_{sf}} + \frac{A_c + A_f + A_d}{\delta_{do}} + \frac{A_f + A_c}{\delta_{cd}}} \qquad 5.37$$

$$\left(\frac{d\zeta}{dt}\right)_{critical,d} = \frac{w_{sd} \cdot \delta_{co} \cdot c_E}{\delta_{do} + w_{sd} \cdot (A_c + A_f + A_d)} \qquad 5.38$$

5.4 Linearised 2-element model

In order to come to a proper calibration of the ASMITA model and to get more insight to the morphological processes that play an important role in the system, it is possible to simplify the model in a linearised version. A disadvantage could be that the predictive capability is influenced negative by this simplification.

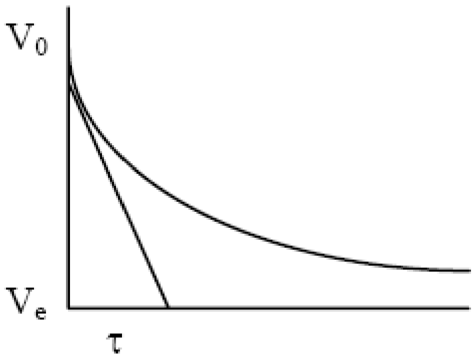

Figure 5-5 Morphological time scale

In ASMITA, the basic assumption is that the elements attempt to from a disturbed initial state to an equilibrium situation by an asymptotic evolution (fig. 5-5). The morphological time scale τ indicates the characteristic adaptation time. By linearising the ASMITA model equations; the model is simplified to the morphological time-scale being the only important parameter. Therefore, with the linearised version of the model it is easier to calibrate the system than by using the non-linearised version. In the present study, the linearised version is applied to determine the empirical equilibrium parameters for the tidal inlet of the Norderneyer Seegat.

In the linearised ASMITA approach, one basic assumption is, that the total basin surface area does not change significantly in time. This assumption can also be made in case of the Norderneyer Seegat if one accepts the fact that the accuracy of the simulation decreases. The same assumption is valid for the tidal range. In table 5-1 the development of the total surface area and for the tidal range in time is shown, with its averaged value and the standard deviation is shown. We can see that the standard deviation is quite small. Nevertheless, it is interesting to investigate, what a changing total surface area will cause in an ASMITA calculation.

year	1650	1750	1860	1930	1960	1975	1990	averaged	standard deviation
A [km^2]	110	102	99	107	103	103	106	104	4
TR [m]	2,05	2,15	2,25	2,38	2,36	2,37	2,37	2,28	0,1

Table 5-1 Development of basin area (A) and tidal range (TR)

A linearised version of ASMITA was extended in that way, that it is able to justify its calculation to the changing basin area. Of course, this model is not able to run autonomously. It always needs as an input value the development of the basin area. But with this approach it is possible to adapt the empirical parameters in such a way, that they are valid for a tidal inlet, that behaves in this specific way.

5.5 Adaptation of empirical parameters

In the ASMITA model the equilibrium situation of the elements is calculated by empirical relations (see chapter 2). The parameters occurring in these relations depend on regional properties of the Wadden Sea area. If morphological changes occur in a tidal basis, the new equilibrium situation can be calculated with the empirical relations. If it can be assumed that a tidal inlet is in a dynamical equilibrium state, the volumes of the elements tidal channel, intertidal flat and ebb-tidal basin have to be more or less equal to the volumes that are calculated with the empirical relations.

Intertidal flats

The equilibrium relation for the intertidal flats used in ASMITA is:

$$V_{fe} = \alpha_{fe} A_b H \qquad 5.37$$

with:

V_{fe} equilibrium volume of intertidal flats above MLW (m^3)

α_{fe} empirical coefficient for the average tidal flat level (-)

A_b area of intertidal flats measured at MLW (m^2)

H mean tidal range (m)

Tidal channel

The equilibrium relation for the tidal channel that is used in ASMITA was derived by EYSINK and BIEGEL (1992). This relation has two variables, the factor α_c and the exponent.

$$V_{fe} = \alpha_c P^{1.55} \qquad 5.38$$

with:

V_{fe} Channel volume below MSL [m^3]

P Mean tidal prism [m^3]

α_{ce} equilibrium coefficient (for the Wadden Sea: 1.6 10^{-6} [(m^3)$^{-0.55}$])

With the best fitting function, it should be possible, to determine the empirical parameters of equation 5.37 and 5.38. These specific parameters for the tidal inlet of the Norderneyer Seegat can influence the calculations of ASMITA in such a way, that the reaction to a disturbance of the dynamic equilibrium occurs in way that is typical for this region.

parameter af	parameter ac	parameter bc
0,375	2,8e-4	1,37

Table 5-2 Optimised initial volumes and empirical parameters

In table 5-2 the initial volumes and the empirical coefficients are shown that belong to the best fitting ASMITA calculations. The parameter af belongs to the empirical relation of the intertidal flat (eq. 5.37). The parameter ac is the factor and bc the exponent of the empirical equilibrium relation of the intertidal channels. Comparing the values of the parameters that are specific for the tidal inlet of the Norderneyer Seegat with the standard values that are given in equation 5.37 and 5.38, it can be seen, that the degree of deviation varies. The parameter of the intertidal flats differs only little from the standard value (af = 0,25). In contradiction the parameters of the tidal channel equilibrium relation are in another order of magnitude compared to them, derived by EYSINK and BIEGEL (1992).

The equilibrium equations for the Norderneyer Seegat are:

$$V_{fe} = 0{,}349 \cdot A_b \cdot H$$

$$V_{ce} = 2{,}8 \cdot 10^{-4} \cdot P^{1{,}37}$$

5.6 Computations

5.6.1 2-element version

The development of the two elements with increasing relative sea-level rise has been investigated in a test run with three different rates of sea level rise (0 mm/y, 1,5 mm/y, 5 mm/y and 10 mm/y). In this kind of simulation with two elements and over a long time-period of 350 years, it cannot be expected, to achieve high accurate results. It is possible to get the development of an averaged volume.

In a 2-elements model, the intertidal flats are always connected to the outside world by the tidal channel. The sediment transport is simulated by the diffusion coefficient in all elements. In contradiction to the intertidal flat and the channel elements, the outside world is always in equilibrium.

The import values that are used for this first 2-element version are shown in table 5-3, 5-4 and 5-5 the input parameters for the different simulations are shown.

Element	Area	Volume	W_s	$\delta_{\rightarrow c}$	$\delta_{\rightarrow ow}$	c_E	Tidal Prism	SLR
Tidal Flat	8,87E+7	9,25E+7	1,0E-4	700		1,0E-4	1,4E+8	1,5 mm/y
Channel	2,11E+7	5,04E+7	1,0E-4		900	1,0E-4	1,4E+8	1,5 mm/y

Table 5-3 Input values

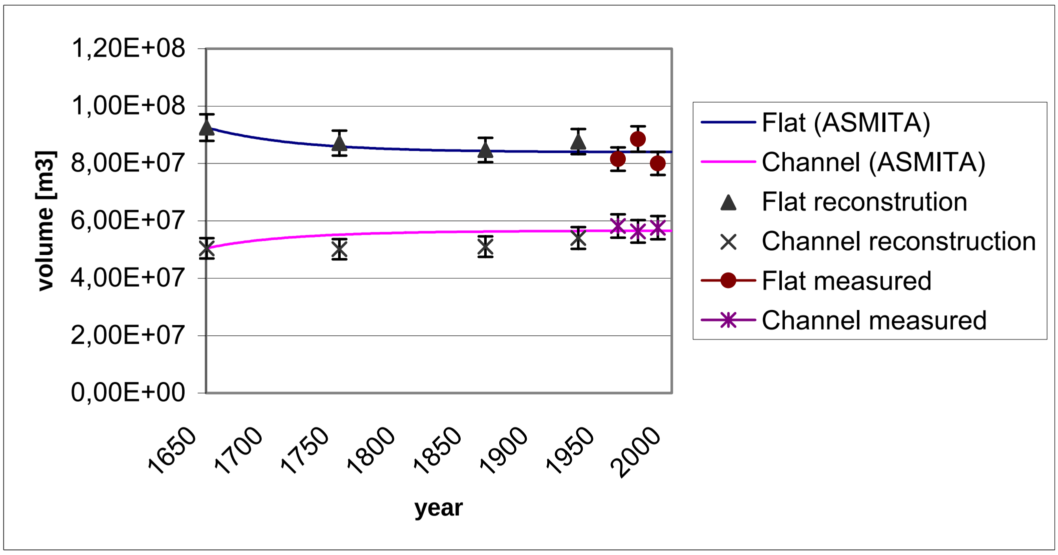

Figure 5-6 Results of 2-element version with a sea level rise of 1,5 mm/year

In figure 5-6, the simulation results are shown for the scenario with a sea level rise of 1,5 mm/year (present situation). Here, it can be seen, that the exponential curve of the development calculated by ASMITA, fits well with the averaged volume that where estimated from the reconstructions and determined from measurements. A rise in sea level of about 1,5 mm/year has been recognized in the past.

From figure 5-6, it can be seen, that slight decrease in volume of the intertidal flats will take place and the volume of the tidal channel will increase. This is the reaction of the system that can be expected because of a rising sea level. The rate of changes that is calculated, seems to correspond with the averaged changes observed during the past 350 years. At the end of the observation period to which the results of the calculations are compared, there are some fluctuations in volume. For the time period from 1960 to 1990, very detailed information with a high degree of exactness is available so these are no averaged values. To understand the developments during this time a 3-elements version of ASMITA including the ebb-tidal delta will be applied later.

Element	Area	Volume	W_s	$\delta_{\rightarrow c}$	$\delta_{\rightarrow ow}$	c_E	Tidal Prism
Tidal flat	8,87E+7	9,25E+7	1,0E-5	700		1,0E-4	1,4E+8
Channel	2,11E+7	5,04E+7	1,0E-5		900	1,0E-4	1,4E+8

Table 5-4 Input values

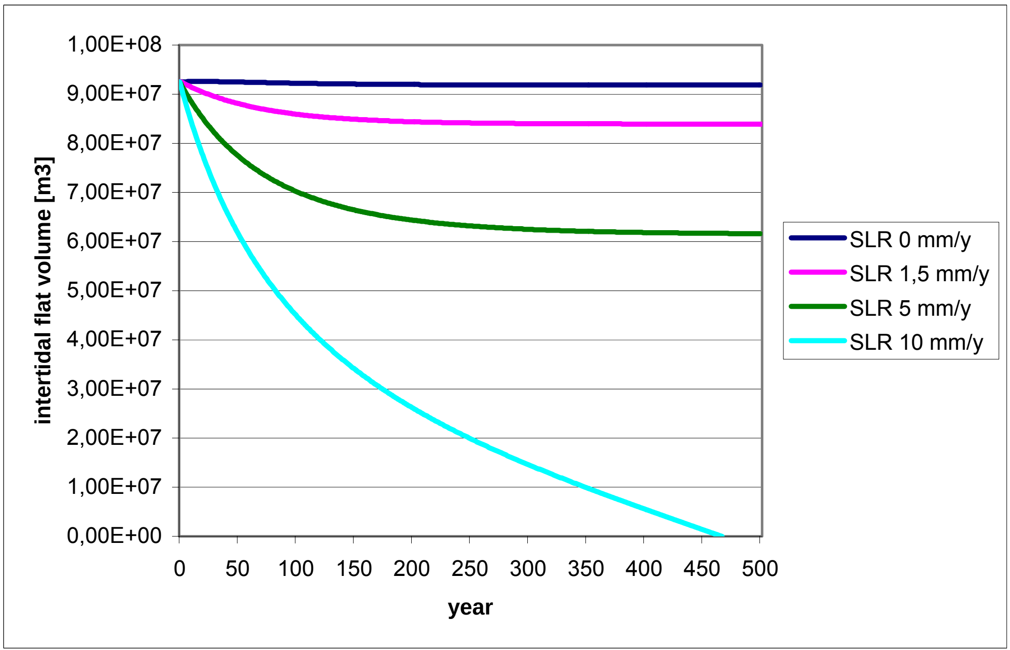

Figure 5-7 Results for the intertidal flats with 4 scenarios of SLR

In figure 5-7, the simulation results for the intertidal flats due to 4 scenarios of sea level rise (0 mm/year, 1,5 mm/year, 5 mm/year and 10 mm/year) are shown.

As expected, in the scenarios shown in figure 5-7 without any sea level rise, almost no changes in volume of the intertidal flats and of the tidal channels will take place. With an increasing rate of sea level rise, the system loses its capability in adapting to the new situation. With an increasing rate of sea level rise, the complete tidal system of the Wadden Sea changes. In the most extreme case (10 mm/year) the intertidal flats would disappear completely within 500 years.

In figure 5-8 it can be seen, that in contradiction to the intertidal flats, the volume of the tidal channel increase with higher rates of sea level rise. It can be recognized, that the capability to adapt to a new situation, is less compared with the intertidal flats.

From figure 5-7 it can be seen, that for a rate of sea level rise of 5 mm/y the intertidal flat volume decreases with 25% within 100 years. For 10 mm/y the decrease would be 50 % in 100 years.

Element	Area	Volume	W_s	$\delta_{\rightarrow c}$	$\delta_{\rightarrow ow}$	c_E	Tidal Prism
Tidal Flat	8,87E+7	9,25E+7	1,0E-4	700		1,0E-4	1,4E+8
Channel	2,11E+7	5,04E+7	1,0E-4		900	1,0E-4	1,4E+8

Table 5-5 Input values

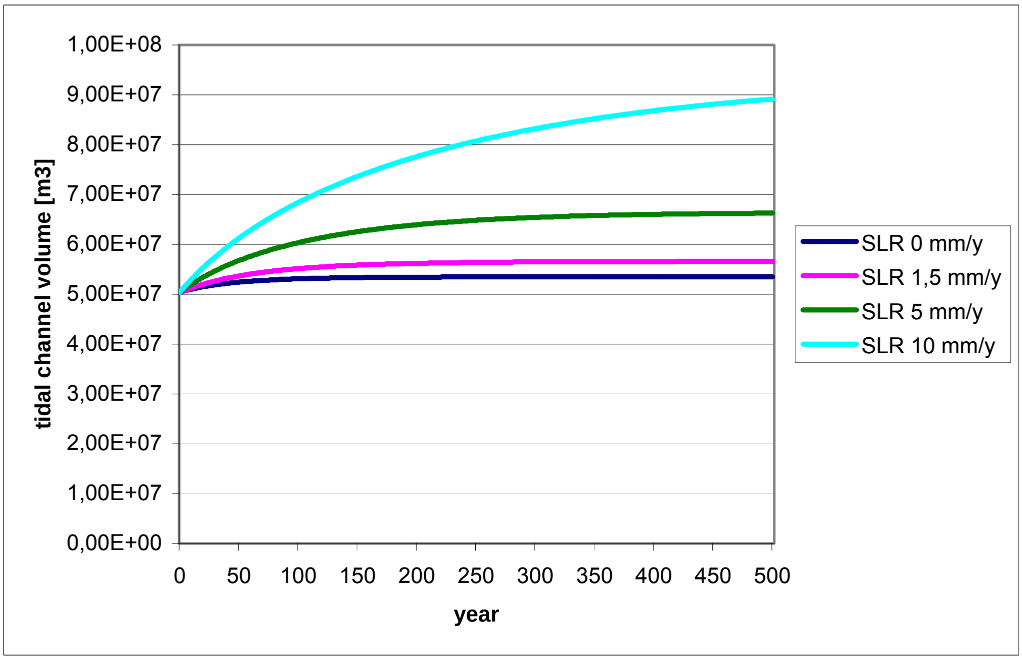

Figure 5-8 Results for the tidal channels with 4 scenarios of SLR

From the relatively slow reaction of the tidal channels to a rising sea level, it can be concluded, that the intertidal flats determine the critical rate of sea level rise for a certain tidal inlet system. The critical rate would be reached, if the volume of the intertidal flats is going to disappear completely. This would be the case, if the asymptotic evolution approaches the value zero. By applying equation 5.19, the critical rate of sea level rise for the intertidal flats can be approximated with 9 mm/year. This critical rate of sea level rise would cause a state of the Wadden Sea morphology, where the intertidal flats does not appear during low water.

Applying the 2-element version of the ASMITA model leads to a critical rate of sea level rise for the tidal inlet of the Norderneyer Seegat of 9 mm/year.

5.6.2 3-element version

Figure 5-9, 5-10 and 5-11 the calculations of the 3-element ASMITA model are shown, compared with the measured values from nature for the elements. It can be seen, that it is difficult to make an exact reproduction of the changes that occurred in the nature.

By applying the 3-element version, it will be tried, to give an answer to the question, how the tidal inlet can behave in the way, that the volume of the intertidal flats increases between 1960 and 1975 and decreases between 1975 and 1990, while the volume of the tidal channel just develops opposite. Therefore, the assumption was made, that the volume of the ebb-tidal delta was in 1960 of the same order of magnitude or even bigger that 1975. This seems to be obvious, because from the 3-D TIN model (see appendix A) it can be seen that the total volume of the ebb-tidal delta for 1960 is comparable to them from 1975 and 1990. The small volume that was calculated in chapter 3, is assumed to be the result of the low density in depth points that is available for 1960.

Element	Area	Volume	W_s	$\delta_{\rightarrow c}$	$\delta_{\rightarrow d}$	$\delta_{\rightarrow ow}$	c_E	Tidal Prism
Flat	7,76E+7	8,15E+7	1,0E-4	800			2,0	1,5E+8
Channel	2,56E+7	5,82E+7	1,0E-4		1000		2,0	1,5E+8
Delta	9,83E+7	1,20E+8	1,0E-4			1200	2,0	1,5E+8

Table 5-6 input values 3-element version

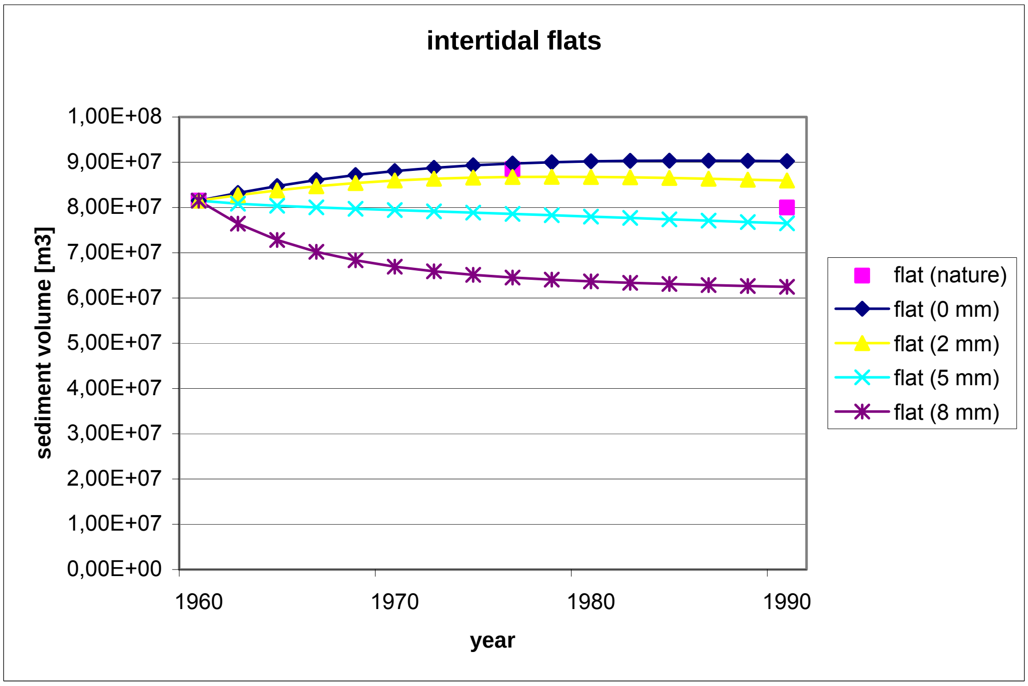

Figure 5-9 Calculation results and observations of intertidal flat for 3-element version

Considering only the measurements, it can be seen, that the volume of the intertidal flats increases during the 15 years from 1960 to 1975 and decreases from 1975 to 1990 (see fig. 5-10). This development can have different reasons. Besides the transport of sediment from the ebb-tidal delta into the tidal basin, also the consequence of moving watersheds has to be considered. Just small changes in the position of the watersheds, can cause big changes in the volume of the intertidal flats.

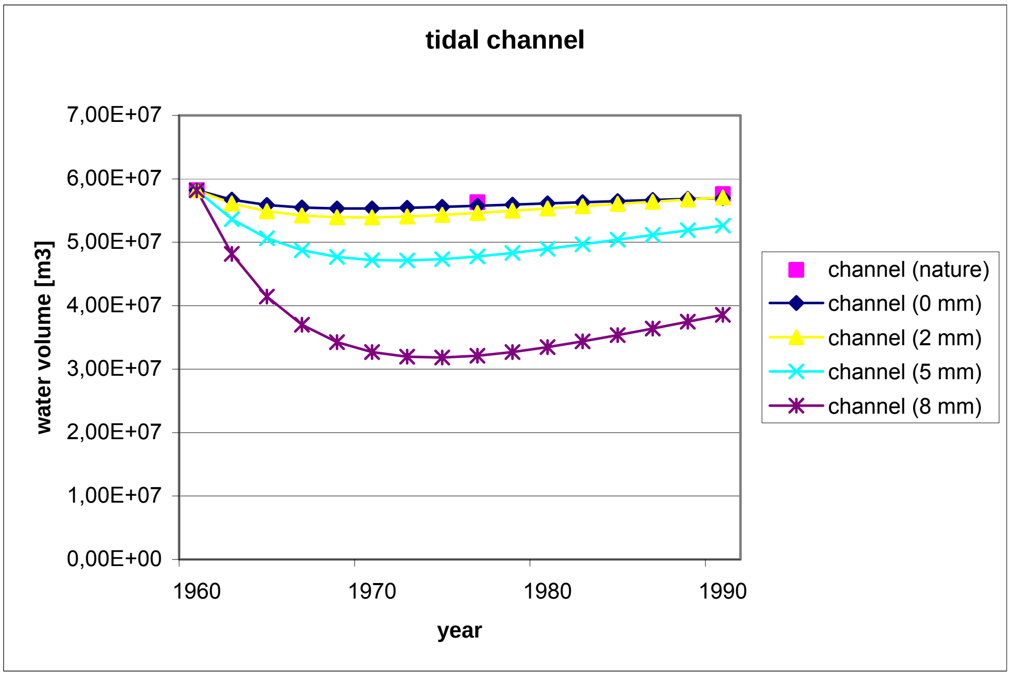

Figure 5-10 Calculation results and observations of tidal channel for 3-element version

The opposite development compared with the tidal channels can be seen in the volume of the tidal channel (see fig. 5-10). Here the water volume in the channels decreases before recovering and tending to a new steady state situation. This development could be the result of a sediment import from the ebb-tidal delta into the tidal basin.

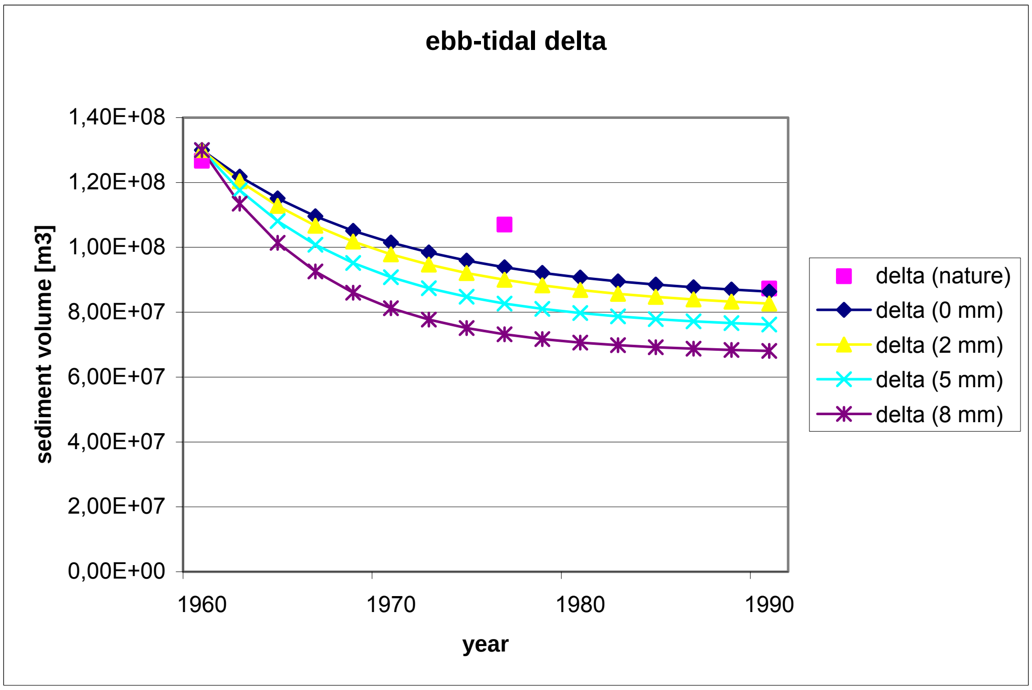

Figure 5-11 Calculation results and observations of ebb-tidal delta for 3-element version

The volume of the ebb-tidal delta is decreasing from a high value in 1960 to a much lower value in 1990 (see fig. 5-11). The exact development of the volume cannot be simulated. More information has to be get about the ebb-tidal delta volume of 1960. The value for the volume in 1960 is estimated based on the observation from satellite photos and sea charts that the amount of sediment stored in the delta was in 1960 much bigger than in 1990.

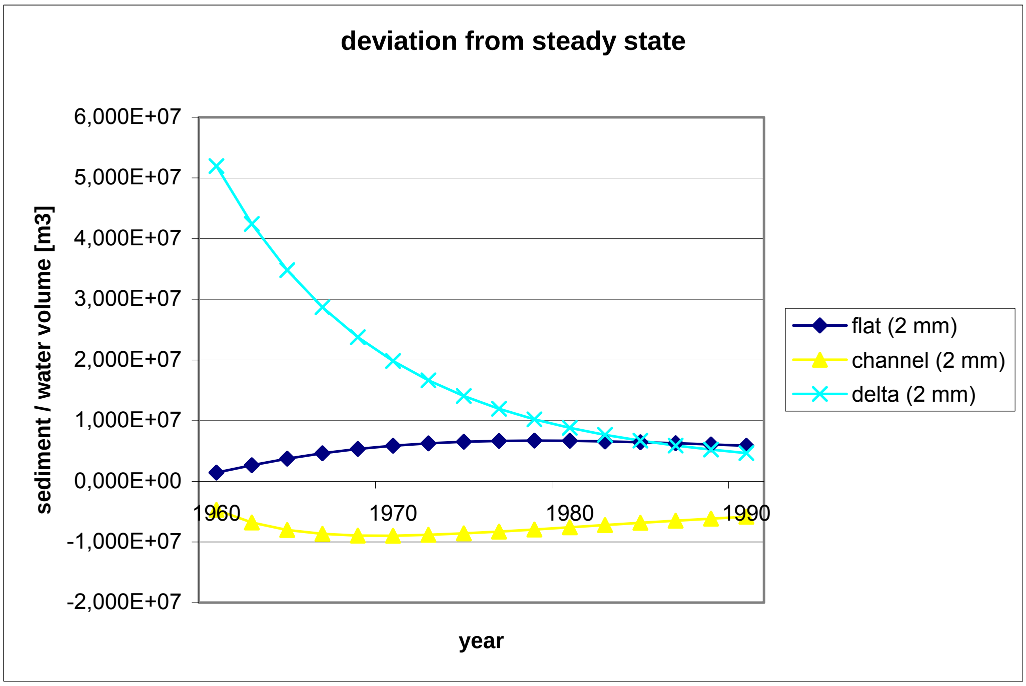

Figure 5-12 Deviation from steady state for all units of 3-element version

In figure 5-12 it can be seen, that the intertidal flats and the tidal channel were very close to their steady state conditions in the beginning of the simulation period. The ebb-tidal delta was far away from a steady state situation, a big amount of sediment was in the delta area, which disturbed the system from its equilibrium. During the following years, the system tried to reach a new equilibrium state by distributing the sediment surplus over the tidal basin area. Consequently, the water volume in the tidal channels was decreasing due to sedimentation, and the intertidal flat volume was increasing. With decreasing volume in the ebb-tidal delta, the system changed back towards the steady state situation, which has not been reached in 1990.

This analysis of the changes that occurred in the tidal inlet of the Norderneyer Seegat give an insight in the processes that caused the deviation from the averaged volumes that was observed before with the 2-element model. The changes can only be simulated qualitatively. For a better simulation of the amounts of sediment that are transported between the elements, more investigation of the transport processes and the diffusion coefficients has to be carried out.

As mentioned before, the development of the ebb-tidal delta volume depends on various factors. It could be that in relatively short time periods huge amounts of sediment were transported by wave induced currents from the eastern beach of the updrift island Juist into the delta area. If this happened before 1960, the system was disturbed and tried to come to a new equilibrium state. The sediment of the 'too big' ebb-tidal delta was distributed over the tidal basin, which results in a decreasing channel volume and an increasing flat volume.

6 Discussion, Conclusions and Recommendations

In the past five chapters, many investigation and studies about the development of tidal inlets in general and about the Norderneyer Seegat in particular have been carried out. In chapter 6 the results will be interpreted and discussed and some final conclusions will be drawn. At the end, some recommendations will be given on aspects to be studied.

6.1 Discussion

The target of the study was to focuses on the consequences of a rising sea level on the tidal inlet of Norderneyer Seegat. To make simulations of the present and future developments of the volumes of intertidal flats and tidal channels in Norderneyer Seegat, the ASMITA numerical model was applied.

The determination of the volumes of the different parts in the tidal inlet turned out to be unexpected sensitive to the position of the watersheds. Moving watersheds mainly cause a change of the intertidal flat volume, because tidal channels are underrepresented in the region of the watershed. For simulating the volume changes due to natural processes based on the assumption that the changes occur by sediment transport mechanisms, the problem raises, that the volume of the intertidal flats can change dramatically, without the need of any sediment transport.

Another factor that influences the accuracy of the determination of the volumes is the density of depth information. A lower density causes an underestimation of the water volume of the channel and of the sediment volume of the intertidal flats. Therefore, the values of the volumes are strongly dependent on the exactness of the determination method.

Part of the present study was, to investigated, if the tidal inlet of Norderneyer Seegat has the tendency towards ebb- or flood-dominance. This has been done with some test criteria such as the averaged duration of the flood- and ebb-period (fig. 4-5), the graph of FRIEDRICHS and AUBREY (fig. 4-6) or the graph of DRONKERS (fig. 4-7). It came out, that there is a slight tendency towards flood-dominance, what means, that sediment import takes place from the open sea (ebb-tidal delta) into the tidal basin. This is also the result of the simulations carried out with the ASMITA model. From the simulation results it can be seen, that for the present rate of sea level rise, a slight decrease of the intertidal flat volume and a slight increase of the tidal channel volume takes place. The tendency of need in sediment becomes more dramatic with an increasing rate of sea level rise. With increasing sea level, the system loses its capability to adapt to a new equilibrium situation.

Many factors that influence the behavior of the tidal basin were discussed in this study. One of them is the grain size of the sediment. In the approach of the ASMITA model, the influence of the averaged grain size is represented by the vertical exchange coefficient. Inside the basin, the sediment is distributed in such a way, that the fine sediment is located in the muddy areas closed to the shoreline, where the tidal currents are slow. The rougher sediment settles down in the deeper areas of the shoals and in the tidal channels. That results from the fact that fine sediment cannot be stored in deeper channels and on shoals, where high current velocities occur. Due to the low current velocities in the areas of the watersheds, fine sediment can be find there as well. By protecting the coastline against erosion, several kinds of breakwaters, strand walls and polders were created during the last 100 years. Often, these interventions reach the tidal channel and deeper areas of the Wadden Sea area. The result could be that the fine sediments cannot settle down anymore in the shallow areas of the tidal basin. This would mean, that the total amount of fine sediment stored inside the tidal basin decreased during the last 100 years. A decreasing quantity of fine sediment would influence the morphological time scale of the adaptation processes of the tidal inlet system. For further investigations, it would be interesting, to look more in detail on this problem.

6.2 Conclusions

Here the main conclusions are shown that can be drawn from the study. Conclusions to specific problems can be found in the specific chapters.

- According to the Diagram of DRONKERS, the tidal inlets Osterems and Norderneyer Seegat are flood-dominated, but the tidal inlet Accumer Ee ebb-dominant. Therefore it can be concluded, that the Norderneyer Seegat and the Osterems are importing sediment into the tidal basin and, due to the diagram of DRONKERS, the Accumer Ee exports, sediment out of the basin.

- For a rate of sea level rise of 5 mm/year, a dramatical loss in volume of the intertidal flats (~25% in 100 years) can be expected. The decreasing intertidal flat volume would cause an increase in wave height for the mainland coast.

- A rate of sea level rise of 9 mm/year turned out to be the critical value for the tidal inlet of the Norderneyer Seegat. Consequently, the intertidal flats would disappear completely. This would cause a change of the whole landscape of the Wadden Area.

- During the study it became clear, that semi-empirical models as ASMITA are not suitable to make exact calculations of the size of the volumes of morphological elements. Furthermore, these models can be used to estimate trends over long time periods. Therefore, the percentages I develop before have to be seen as trends of sediment loss.

6.3 Recommendations

To give recommendations what can be done, to improve the insight to the topics that are discussed in the present study, some ideas and questions remaining will be presented in this last part of the report.

- More investigation has to be done about the accuracy of the methods for determining the volumes of the different parts in the Wadden Sea. The sensitivity of the volumes to small errors in the measurements or to uncertainties caused by the interpolations between the measured water depths has to be investigated. This has to be done to make the values of the volumes comparable to each other.

- It has to be studied, what the consequences are of coast protection interventions to distribution of different sediment grain sizes of the Wadden Sea area. Could a change in an averaged grain size or the distribution of it, influence the capability of the tidal system to adapt to new morphological boundary conditions? A change in averaged grain size will have consequences on the time scales of the adaptation capability of the tidal basin.

- It would be advisable, to connect topographic data-sets of the West- and the East Frisian Wadden Sea and to determine the volumes of the tidal inlets from Marsdiep to Harle by using one method, so that all the values are really comparable to each other. If such a data base of Wadden Sea volumes would be created, for the measurements of different years, it should be possible to get a better insight to the morphological interactions of basins and deltas between Den Helder to the river mouth of the river Jade. This could give more insight, how the interventions like creating polders influence the supply with sediment in down- and updrift direction.

- In the present study the development of the increasing sea level was investigated by using static values of rates of sea level rise. So it was assumed, that the rate of sea level rise is stable over the whole simulation period. This is a simplification of the development that takes place in nature. Therefore it has to be investigated, how these developments change with a dynamic rate of sea level rise.

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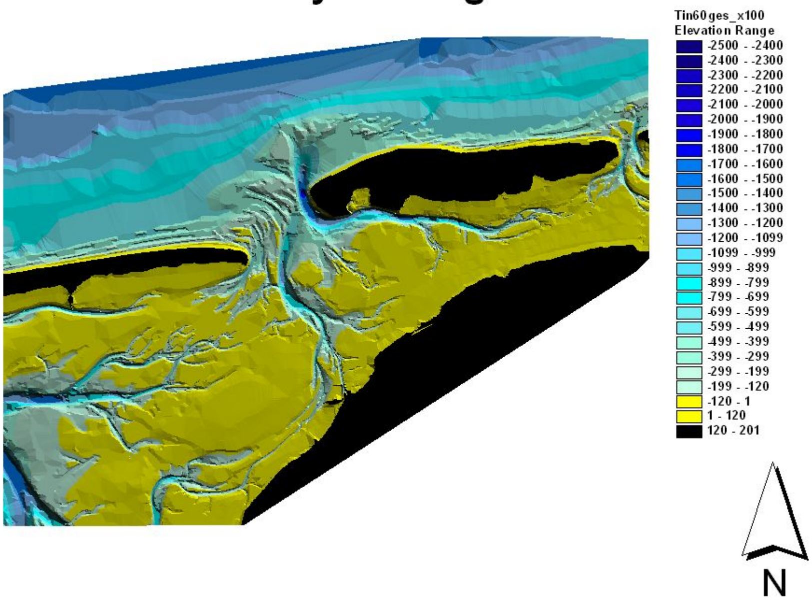
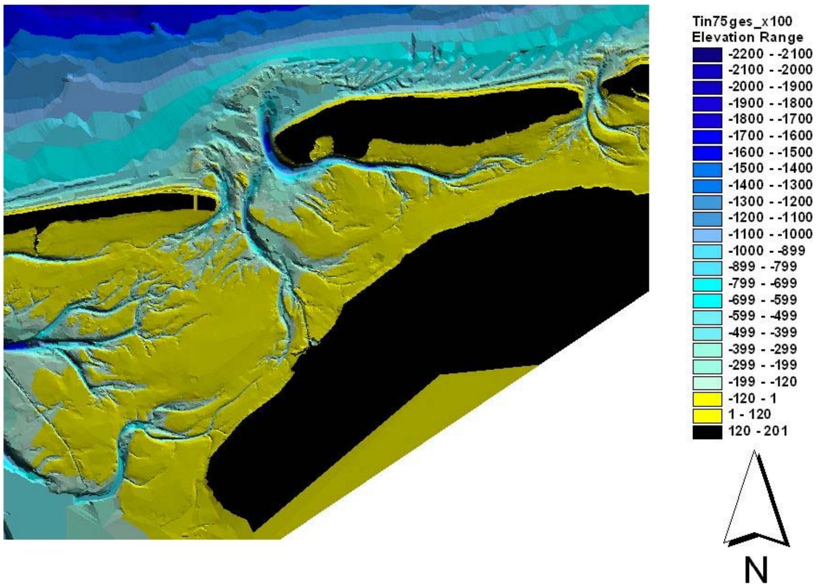
Appendix A 3-D TIN model of the tidal inlet

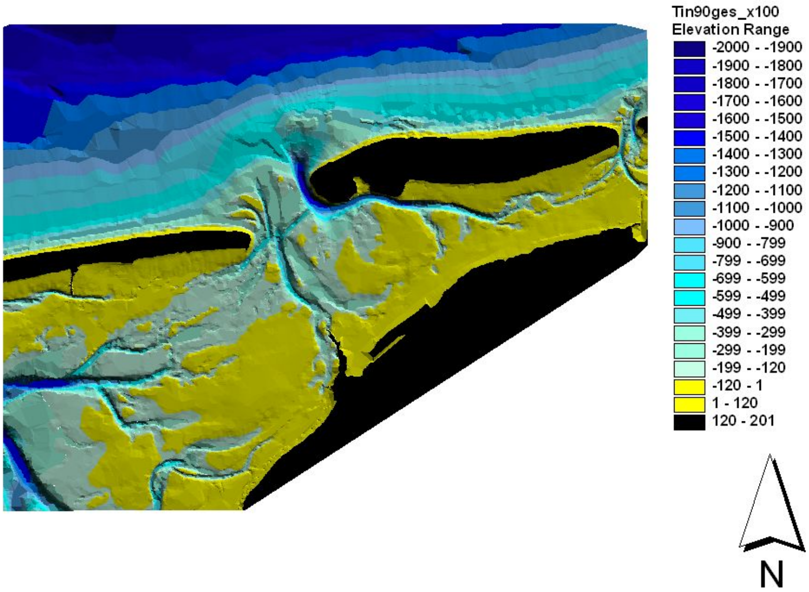
Norderneyer Seegat 1960



Norderneyer Seegat 1975

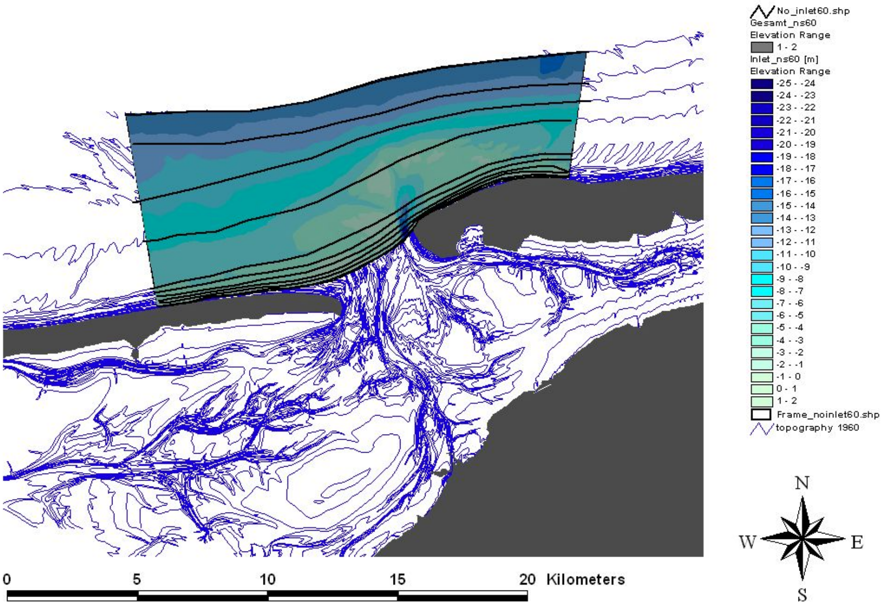


Norderneyer Seegat 1990

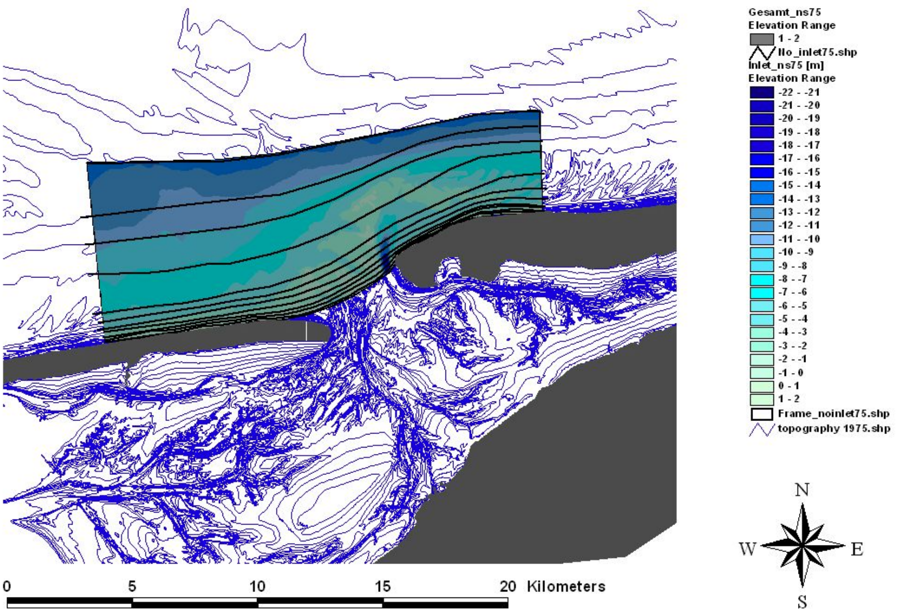


Appendix B Ebb-tidal delta and ‘no-inlet’ topography

ebb-tidal delta Norderneyer Seegat 1960



ebb-tidal delta Norderneyer Seegat 1975



ebb-tidal delta Norderneyer Seegat 1990