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WL | Delft Hydraulics

Morphodynamics of the Lister Tief tidal basin

Research Report

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Robbert-Jan Nortier

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CLIENT:

TITLE: Morphodynamics of the Lister Tief tidal basin

ABSTRACT:

The Wadden Sea is characterized by barrier islands separated by tidal inlets consisting of a system of inter-tidal flats and channels. It is an ecologically valuable area. Accelerated sea-level rise due to climate change combined with human interference which may cause land subsidence can have significant impact on the Wadden Sea system. A major question of concern is how vulnerable the Wadden Sea system is to the relative sea-level rise.

The present study focuses at the apparent deviant behaviour of the Lister Tief tidal basin compared to Dutch tidal basins in the Wadden Sea. All the tidal basins in the Dutch Wadden Sea appear to import sediment such that the deposition in the basins tend to cope with the low sea-level rise rate of about 20 cm/century at present. The Lister Tief, a tidal basin located between Germany and Denmark, appears to be eroding sediment despite the sea-level rise. Long-term modelling, needed for large scale systems like the Wadden Sea, can be done by the model ASMITA. It is a semi-empirical model which appears to be a powerful tool for simulating the long-term morphological development under influence of sea-level rise.

In this study the Lister Tief basin is compared with the tidal basins in the Dutch Wadden Sea concerning aspects including the hypsometry and tidal asymmetry. Moreover, results of application of the ASMITA model are compared with the development of parameters representing hypsometry and tidal asymmetry under relative sea-level rise. The hypothesis was that the hypsometry of the Lister Tief could be the reason for the deviant behaviour of the Lister Tief tidal basin.

From the analysis carried out in this study it appears that the Lister Tief tidal basin is not behaving differently than Dutch tidal basins under relative sea-level rise. The basin hypsometry does have a significant influence on the tidal asymmetry, but results from the analysis do not explain the loss of sediment in the Lister Tief tidal basin. From an analysis and the application of the ASMITA model it becomes clear that the model agrees with the development of parameters representing the basin hypsometry.

REFERENCES:

VER.	ORIGINATOR		DATE	REMARKS	REVIEW		APPROVED BY	
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Preface

The present Master of Science thesis forms the completion of my study at Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Civil Engineering, Division of Hydraulic and Offshore Engineering. The work has been carried out at WL | Delft Hydraulics in cooperation with the National Institute for Coastal and Marine Management (RIKZ), part of the Directorate-General of Public Works and Water Management (Rijkswaterstaat).

This thesis concerns the influence of relative sea-level rise on the morphodynamic behaviour of the Lister Tief tidal basin in particular and coastal inlets and tidal basins more in general. A comparison of field observations of the Lister Tief tidal basin with existing theories on tidal asymmetry and the modelling concept of ASMITA is part of the study.

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. A.P. Oost (RWS-RIKZ), ir. J.P. Noppen (Delft University of Technology) and last but certainly not least ir. T.J. Zitman (Delft University of Technology) for sharing their knowledge and showing their support during this thesis. Also Thorsten Piontkowitz of the Danish Coastal Authority and Jacobus Hofstede of the Innenministerium des Landes Schleswig-Holstein are gratefully acknowledged for sharing their information. Furthermore, I am grateful that WL | Delft Hydraulics offered me the opportunity to carry out my work at their institute and I would like to thank my temporary colleagues and fellow graduate students at WL | Delft Hydraulics for the pleasant time. Finally, I would like to thank my family, friends and especially my girlfriend for showing their interest and support during the years I spent in Delft.

Delft, January 2004

Robbert-Jan Nortier

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Summary

The Wadden Sea is characterized by barrier islands separated by tidal inlets consisting of a system of inter-tidal flats and channels. Sea-level rise (SLR) combined with land subsidence influence this Wadden Sea system. In a survey (Wang & vd Weck 2002) assigned by RIKZ to WL | Delft Hydraulics, the significance of field observations of the Lister Tief tidal basin was discussed. The Lister Tief tidal inlet is located between the northernmost German Wadden Isle Sylt and the first Danish Wadden Isle Rømø. Field observations seem to suggest an exception to the generally accepted idea that tidal basins of the Wadden Sea area are silting up at lower rates of sea-level rise (up to 20 centimetre per century). This tidal basin might be exporting sediment under influence of relative sea-level rise.

Tidal flow is the major driving force for the morphological development of the Wadden Sea. The morphology of the system has an important influence on the water movement. A basin with relatively deep tidal channels and a relatively large area of intertidal flats will induce more ebb-dominant tides, while more flood-dominant tides will be induced by small areas of intertidal flats and relatively shallow tidal channels. Sea-level rise will increase the channel depth and reduce the inter-tidal area of the basin. Increase in channel depth will cause more ebb-dominance whereas reduction of intertidal flats will cause more flood-dominance. Which of these effects wins depends on the morphology of the basin under consideration. It is believed that herein a possible explanation for the behaviour of the Lister Tief can be found.

Long-term modelling, needed for large-scale systems like the Wadden Sea, can be done by the model ASMITA. It is a so-called behaviour orientated model in which a mathematical system of empirical equations is used to describe the observed development. This model has never been applied to a tidal inlet which exhibits the behaviour as the Lister Tief tidal basin does.

Primary objective of this study is to investigate whether the observed behaviour of the Lister Tief can be attributed to the relative increase in channel depth or decrease in tidal flat area. Moreover the concept of the ASMITA model is studied and compared with existing theory about morphological development due to tidal asymmetry, as it is believed that the local back-barrier geometry has great influence on the strength of the asymmetry. Also, ASMITA is applied to the specific case to assess if it will predict the apparent sediment export of the tidal basin under sea-level rise.

In order to accomplish the objectives, a comparison between theory of morphology and tidal asymmetry on the one hand and the modelling concept of the ASMITA model on the other hand has been performed. Tidal asymmetry causes residual sediment transport. Tidal asymmetry is caused by the deformation of the tidal wave as it propagates in shallow waters and is therefore strongly related to the basins geometry. The average depth of the basin and the area of inter-tidal flats in the basin are of importance. These characteristics are determined by the hypsometry. In this study three digitized datasets were available for the Lister Tief tidal basin, roughly from the years 1967, 1987 and 1994. From these datasets the hypsometry was derived.

Theoretical considerations by Friedrichs & Aubrey (1988) and Dronkers (1998) describe tidal asymmetry by the use of indicating “hypsometric” parameters for the morphology of a basin, leading to a graph dividing a plane into a flood dominant and an ebb dominant area. The development of the basin according to this approach is compared with the determinant parameter using a single element approach in ASMITA. This determinant parameter is the ratio between equilibrium volume and actual volume of the considered element. All hypsometries of the Lister Tief lead to an increase in flood dominance with increasing relative sea level heights. For the Lister Tief the determinant parameter in ASMITA predicts ebb dominance in principle. Under an instantaneous sea-level rise the ratio decreases corresponding with a situation of more flood-dominance.

These operations were also done for the “Marsdiep” basin and the “Borndiep”. For these two Dutch tidal basins two digitized datasets provided by the RIKZ were used. When performing these operations for the Dutch tidal basins, the same trend is observed as the Lister Tief tidal basin. Also these tidal basins show a development towards flood dominance under rise of relative sea-level height. For these two tidal basins, the same coefficient in the empirical relation for equilibrium channel volume in the ASMITA approach is chosen as for the Lister Tief for reasons of comparability. This has lead to a prediction of ebb dominance for the Borndiep. However a calibrated coefficient, as follows from the study of van Goor (2001) predicts a situation of near equilibrium. In this study, the above mentioned approach should be considered only in the light of the direction in which the basin is developing.

A simulation with the actual ASMITA model in a two element approach is performed. Calibration of the tidal basin upon the last hundred years shows ultimately the observed trend that inter-tidal flats are decreasing and the volume of channels is increasing. Apparently the tidal basin is out of equilibrium, according to this two element approach. For present time, the tidal basin is slightly out of equilibrium indicating ebb-dominance. Forecasts, based upon the calibration, show a further decrease of intertidal flats and increase of channel volume under different scenarios of sea-level rise. Depending on the latter, it can be expected that the tidal basin will develop towards its dynamic equilibrium where the basin keeps pace with the sea-level rise. From the simulation it appears that the ASMITA model, with in this case a two element approach, can reasonably describe the development of the Lister Tief tidal basin.

From the application of the model and comparing the model concept with theoretical considerations concerning tidal asymmetry, it is concluded that the model formulation is sufficient to predict the observed behaviour under relative sea-level rise. When a basin is out of equilibrium in one way or another, it will try to reach a state of equilibrium. In the case under consideration, sea-level rise accelerates this development towards equilibrium as it reduces the tidal flat volume and increases the channel volume. Overall, it appears that the local back barrier configuration can be responsible for the observed export of sediment in the Lister Tief tidal basin. According to dimensionless parameters which can predict ebb- or flood dominance, the tidal basin develops at present time towards a situation of flood dominance, coming from a situation of near equilibrium. It is recommended to do more research on the historical development of the basin. More reliable data can provide a better understanding of the cause for the apparent out of equilibrium state of the basin.

1 Introduction

1.1 General

The National Institute for Marine and Coastal Management (Rijksinstituut voor Kust en Zee, RIKZ), part of the Netherlands Ministry of Transport, Public Works and Water Management is responsible for advising the Ministry for an optimal management of the Wadden Sea area. RIKZ assigned WL | Delft Hydraulics to provide a literature survey concerning sea-level rise and morphological development in the Wadden Sea (Wang & v.d. Weck 2002). This survey gave an overview of the current knowledge with respect to the Wadden Sea, in particular the response of the Dutch Wadden Sea to climate development. Besides, the significance of field observations of the Lister Tief tidal basin, which is located in the German-Danish Wadden Sea, was discussed. These observations seem to show an exception to the generally accepted idea that tidal basins of the Wadden Sea area are silting up at comparatively low rates of relative sea-level rise (up to 20 centimetre per century). Recommendations were made for further investigation to gain better understanding in the observed behaviour.

From their analysis, Wang & v.d. Weck (2002) concluded that the probably erosive behaviour of the Lister Tief tidal basin is most likely related to the propagation and deformation of the tidal wave as a consequence of the tidal basins characteristics. Due to its propagation in shallow waters such as the Wadden Sea, the tidal wave is deformed. This deformation causes asymmetry in the tidal wave and is strongly related to the morphology. If for instance the flood period is shorter than the ebb-period then the maximum flood-velocity will be higher than the maximum ebb-velocity because the same volume of water has to be transported during flood and ebb. Due to this asymmetry, residual sediment transport takes place. This implies that a shallow back barrier area influences tidal asymmetry which in turn causes changes in the overall morphology of the tidal basin. It is presumed that this is an important cause for the observed behaviour of the Lister Tief tidal basin.

Tidal inlets are complex coastal systems which can be studied and simulated with (semi-) empirical models. An example of a semi-empirical model is ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast, Stive and Wang 1996). This model has been developed by WL | Delft Hydraulics. The model is a so-called behaviour-orientated model. This means that the model is in fact a mathematical system of equations that displays the same behaviour as the natural phenomenon at hand. In the case of ASMITA the mathematical system is based on empirical relations. Up till now, ASMITA has never been applied to tidal basins with a sediment exporting character like the Lister Tief tidal basin. Moreover, ASMITA is not integrated with a tidal flow model. One of the aims was to see whether the model formulation is sufficient to exhibit the behaviour as observed in the Lister Tief tidal basin, and perhaps provide a possible reason for this behaviour.

1.2 Problem analysis

In the above mentioned study (Wang & v.d. Weck 2002) there are still some unanswered questions. The data available for this study were insufficient for an in-depth assessment of the interaction between tidal motion and morphology in the Lister Tief basin. To this end data is gathered, which may explain the deviant behaviour of this tidal basin.

Empirical models are not able to predict changes in sediment transports as a consequence of changes in the distortion of the tidal wave due to the fact that there is no integration with a tidal flow model, like there is in for instance a process-based model. However, the morphodynamic behaviour of tidal basins and thus also the Lister Tief can be predicted using parameters reflecting aspects of the morphological, hydrodynamic or geometrical state of the basin like storage volume, tidal amplitude and average depth of the tidal basin. From this perspective, two aspects appear to be important: the average depth of the tidal channels in the basin, and the extent of intertidal flats in the basin. Ebb-dominant tides are brought about by basins with relatively deep tidal channels and a relatively large area of intertidal flats, whereas more flood-dominant tides are induced by small areas of intertidal flats and relatively shallow tidal channels. Relative sea-level rise, relative with respect to the bottom, yields an increase of the channel depth in the basin and a reduction of its inter-tidal area. The increase of the channel depth will cause more ebb-dominance whereas reduction of intertidal flat area will cause more flood-dominance. Which of these effects will prevail, depends on the configuration of the basin at hand.

1.3 Objectives

The present study is meant to clarify the above mentioned phenomena with respect to the Lister Tief tidal basin. Especially, the morphodynamic development of the tidal basin under relative sea-level rise is of interest. A comparison of field observations of the Lister Tief tidal basin with existing theories on tidal asymmetry and the modelling concept of ASMITA is part of the study. In short, the following objectives function as a guideline for the study:

- To clarify the probably deviant morphological behaviour of the Lister Tief tidal basin under relative sea-level rise.

- To find out if the ASMITA model formulation is sufficient to explain the described behaviour in general and in this specific case.

1.4 Methodology

First, a literature survey is carried out in which tidal inlets and relevant processes among barrier coasts are studied. As shown by Wang & v.d. Weck (2002), the hypsometry is of importance. The basin hypsometry, or hypsography, is defined as the distribution of basin surface area with height. Its role in the morphological evolution of a tidal basin is assessed on the basis of readily available literature (chapter 2).

To check the hypothesis that the presumably deviant hypsometry is the cause of the anomalous behaviour, relevant data concerning the basin hypsometry were gathered in cooperation with RIKZ. These field data are the basis for calculating parameters reflecting aspects of the morphological, hydrodynamic or geometrical state of the basin. Under the assumption that the basin configuration remains the same, the development of the basin under relative sea-level rise is analyzed. To compare these results with the development of the basin according to the ASMITA formulation, a schematised and simplified version of the model is deployed in which a single element approach is considered. This is the subject of chapter 3. The actual application of the full model is dealt with in chapter 4.

2 Literature Survey

2.1 Introduction

In this chapter the literature survey is presented. Section 2.2 handles tidal basins in general and the morphological processes that take place within these tidal basins. Also an overview is given of important empirical relationships regarding tidal basin characteristics such as channel volume or the volume of the ebb-tidal delta. ASMITA is partly based on these relations. Since tidal asymmetry plays an important role in shallow waters such as the Wadden Sea, the development of the tide and its asymmetry is explained in section 2.3. Especially on intertidal flats, complicated morphological processes take place. These are considered in section 2.4. To get a notion of location and orientation of the case study section 2.5 describes the Lister Tief tidal basin.

2.2 Tidal basins

2.2.1 Physics of tidal inlets

Many tide-dominated coasts are characterised by a large number of inlets: this is also true for the Wadden Sea area.

A tidal inlet consists generally of a basin, a gorge, an outer delta and two adjacent coasts. The outer delta is formed by a by-passing shoal system with an ebb-dominated main channel and a number of flood marginal channels. The adjacent coasts are in the Wadden Sea predominantly barrier island coasts. The gorge of the inlet is usually dominated by the main channels. The tidal basin consists of a meandering branched channel system with intertidal sand- and mud flats and marshes.

As the name in indicates, the natural evolution of a tidal basin is governed primarily by the tide. In addition, wind-generated surface waves may play a significant role as well. They are especially influential on intertidal and subtidal shoals. Wind waves, however, are not the subject of this study.

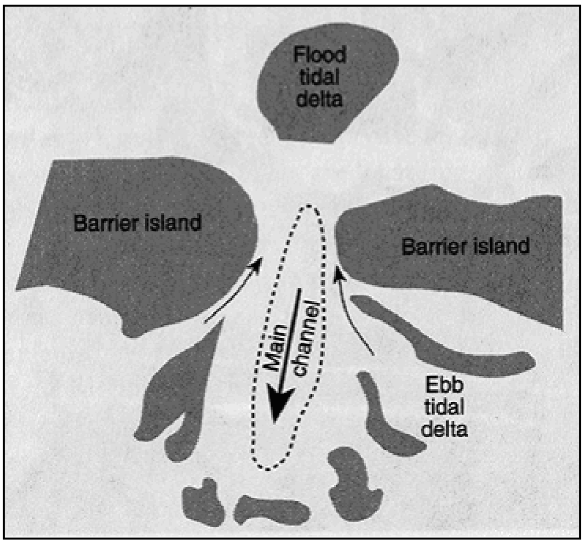


Figure 2-1 Tidal Inlet

Tidal waves occur due to gravitational attraction between the earth and the sun and the moon. Due to the large tidal discharges in the inlet gorge there is a strong sediment exchange between the basin and the adjacent coast. During the ebb phase, the flow velocities decrease and sediment is deposited, thus creating the outer delta. Reversely, the divergent flood flow forms a flood-tidal delta within the tidal basin.

At the macro-scale level, we can distinguish the basin consisting of a system of channels, shoals and marshes as has been discussed before. The gorge is usually dominated by the main channel. The outer delta involves a bypassing shoal system, an ebb-dominated main channel and a number of flood channels. Together they form a sediment circulation system, as is schematised in Figure 2-2. The (external) forcing like wave- and tide induced transport can also be seen this figure.

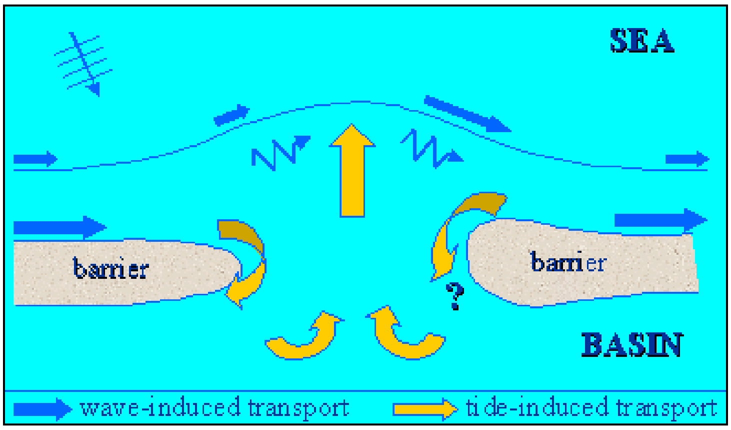


Figure 2-2 Schematic diagram of (residual) sediment transport

2.2.2 Classification of tidal inlets

The objective of classification of tidal inlets is to be able to compare different situations within the same class of tidal inlets. Tidal inlets can be classified according to (Steijn, 1991):
- Geometric parameters, which focuses primarily on the appearance or morphotype of an inlet.
- Hydraulic parameters, which focuses primarily on the shaping parameters, i.e. the underlying physical parameters.

The second approach, the hydrodynamic classification, is addressed hereafter. Two acting forces are generally used to classify tidal inlets: tides and waves on the seaward side of the inlet. The tidal range primarily depends on the ocean tides and their interactions with the continental shelf. The wave conditions are generated seaward of the inlet. An inverse relation between tidal range and the length of a barrier island seems present around tidal basins: large tidal ranges apparently result in shorter barrier islands. Hayes (1979) used the following classification with respect to the tide:
- microtidal: tidal range $\leq$ 1.0 m.
- low mesotidal tidal range 1.0-2.0 m.
- high mesotidal tidal range 2.0-3.5 m.
- low macrotidal tidal range 3.5-5.5 m.
- high macrotidal tidal range $\geq$5.5 m.

Wave action also influences the inlet morphology. It moves sediment onshore and limits the area over which the ebb tidal delta can spread out. The wave climate is generally characterised by the annual mean significant wave height H_s at deep water:

- low wave energy H_s <0.6 m.
- medium wave energy 0.6 m.≤ H_s ≤1.5 m.
- high wave energy H_s >1.5 m.

The actual classification of tidal inlets is based on a combination of the tidal range and wave energy classifications as described above. The relative effect of waves and tides seems to be of great importance. Hayes (1979) used the following five classes of tidal inlets with respect to tide wave dominance: (Figure 2-3)

1. wave dominated inlets;
2 .mixed energy-wave dominant;
3. mixed energy-tide dominant;
4. tide-dominated-low;
5. tide-dominated high.

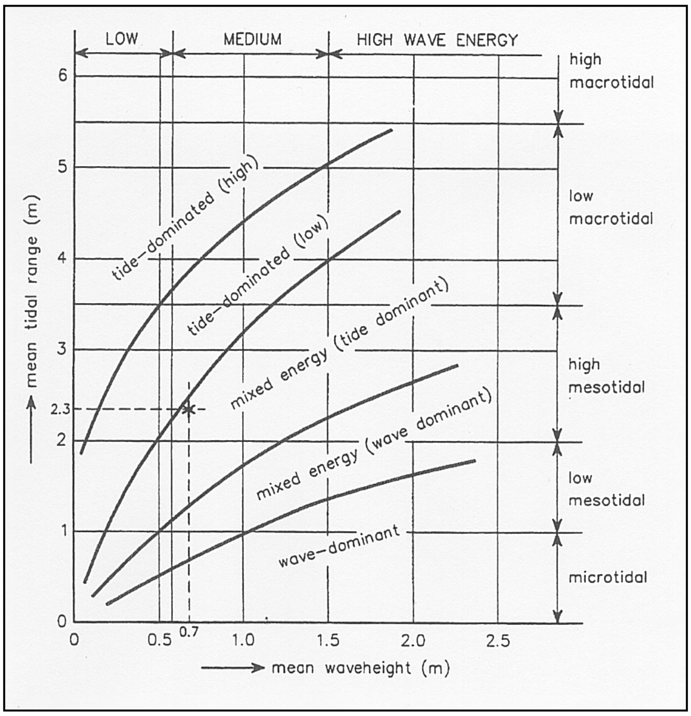


Figure 2-3 Hydrodynamic classification of tidal inlets

In section 2.6, the Lister Tief tidal basin will be classified and compared with a number of Dutch tidal basins in the Wadden Sea. A comparison with respect to hydrodynamic features, but also with regard to the main characteristics such as basin area is presented.

2.2.3 Equilibrium relations

Process-based models consist of a number of modules which describe waves, current and sediment transport respectively. Depending on whether the dynamic interaction of these processes with the bed topography is taken into account, these modules are used in series or in a time-loop. These kinds of models essentially work at the hydrodynamic time scale (typically one tidal period).

The physical processes governing the morphological evolution of a tidal inlet system are very complex. This complexity is mainly induced by a great variety of space- and time scales that act in the vicinity of tidal inlets. Tidal inlets tend to evolve during time spans in the order of decades to centuries. Process based models are thus not par excellence suited to model large systems like tidal inlets.

As an alternative, however, semi-empirical models like ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet system and the Adjacent coast) are available. As stated before, ASMITA is a behaviour-orientated model. This means that the model is in fact a mathematical system of equations that displays the same behaviour as observed. The concept in these kinds of models is to schematise the inlet system into various entities which dynamically interact with each other. Each of these elements is influenced primarily by the basin-related tidal prism and secondarily by wave-related hydrodynamics. Each of these elements is described by one morphological variable representing its morphological state (Stive & Wang, 2000). The hypothesis is that an equilibrium state can be defined for each element. An empirical relation is required for each element to define the morphological equilibrium state. The model principles of the ASMITA model will be handled later. First, the focus will be on the empirical relations for tidal inlets.

A tidal inlet can be schematised into a number of morphological elements which are described by one morphological variable representing its bathymetry:

- for the ebb-tidal delta this is: total volume of the delta V_d above a fictive sea bottom, which would be there if there was no inlet (sand volume);
- for the tidal flat: total volume of the flat V_f between MLW and MHW (sand volume);
- for the channel: the total channel volume under MSL V_c (water volume);
- for the two coast elements: the volume below MSL and above a certain depth line V_{c1} and V_{c2} (water volume).

Various empirical relationships exist between the above mentioned morphological variables and the governing hydrodynamic conditions (Eysink, 1991). An important parameter is the tidal prism. The mean tidal prism is here defined as the volume of water present in a tidal basin between the MLW and the MHW level, excluding any freshwater flow, and is usually based on systematic bathymetric surveys of the tidal basin. Eysink (1991) used the term *characteristic tidal volume* which is equal to the tidal prism.
Eysink (1991) found a relation between the flow area below MSL in the gorge and the tidal prism. This yield:

$$A_{msl} = c_A \cdot P \qquad (2.1)$$

In which:

A_{msl}	Flow area below MSL [m^2]
c_A	Empirical coefficient [m^{-1}]
P	Tidal Prism [m^3]

For the (Dutch) Wadden Sea the coefficient c_A is on average equal to $70 \cdot 10^{-6}$ m^{-1}.
A relationship for channel volume of a tidal basin or estuary and tidal prism is presented by:

$$V_c = c_c \cdot P^{1.5} \tag{2.2}$$

In which:

V_c	Channel volume below MSL [m^3]
c_c	empirical coefficient [m$^{-1.5}$]
P	Tidal Prism [m^3]

The empirical coefficient c_c is on average $65 \cdot 10^{-6}$ m$^{-1.5}$ for the (Dutch) Wadden Sea.

The outer delta may function to a limited extent as a "buffer" for sediment. When changes in the inlet system occur, the outer delta will be affected pretty rapidly. On a much larger time scale, the outer delta has to return to its equilibrium value. This will be repaid by adjacent coastlines in the longer term. Walton and Adams (1976) derived relations for inlets on sandy coasts in the United States. An important one is the relationship for the sand volume stored in the outer deltas and the tidal prism:

$$V_o = c_o \cdot P^{1.23} \tag{2.3}$$

In which:

V_o	Sand volume stored in the outer delta [m^3]
c_o	empirical coefficient [m$^{-1.23}$]
P	Tidal Prism [m^3]

Finally, an important empirical relationship between the relative tidal flat area and the total basin was derived. Renger and Partenscky (2000, from lecture notes CT5303) found for the German Bight (from Norderney to the Hever tidal basin):

$$\frac{A_f}{A_b} = 1 - 2.5e^{-5} \cdot A_b^{0.5} \tag{2.4}$$

In which:

A_f	flats' area, i.e. area above MSL [m^2]
A_b	basin area (flats and channels) [m^2]

It must be noted that the above mentioned relation between flats' area and basin area does not depend on the tidal prism. However, the tidal prism in turn does depend on the development of the flats. When considering the following relation between flats and tidal prism:

$$P = H \cdot A_b - V_f \tag{2.5}$$

In which:

P	Tidal Prism [m^3]
V_f	Volume of flats between MHW and MLW [m^3]
H	Tidal Range [m]
A_b	Basin Area at MHW [m^2]

It becomes clear that a decrease in tidal flats will initiate an increase in tidal prism and vice versa. The tidal prism in turn influences the other equilibrium relations. Obviously, the tidal flat volume is a steering parameter in the process.

The morphological relations described above make a practical approach regarding the morphodynamic development of tidal inlets possible. The empirical relations are suitable to make an initial judgement on how a tidal inlet or basin will respond to hydraulic or morphological changes. Furthermore, these relationships are the basis of ASMITA.

2.3 Tidal asymmetry

As outlined in the previous section, the tide plays an important role as driving force for sediment transport. In the survey prepared for RIKZ (Wang & vd Weck, 2002) it was already concluded that the distortion of the tidal wave, leading to increasing ebb-dominance at sea, could be a main reason for the behaviour of the Lister Tief tidal basin. But what is the nature and origin of tidal asymmetry? Here, a summary is given of the propagation and distortion of the tidal wave in general, but in particular in the Northern Wadden Sea.

The tide is caused by the gravitational attraction of the Sun and the Moon on the oceans, and the rotation of the Earth. It has its origin in the southern hemisphere because there is more water than in the northern hemisphere. The tidal wave propagates via the Atlantic Ocean and reaches the North Sea after 2 or 3 days. When the tidal wave is near the British Isles, it enters the North Sea from two different directions. First of all, the wave propagates along the Irish coast and the British coast in a northerly direction and then around Scotland into the North Sea. The Coriolis effect compels the current to make an anticlockwise circular motion through the North Sea. The tidal wave then propagates along the British coast towards the south and then turns again

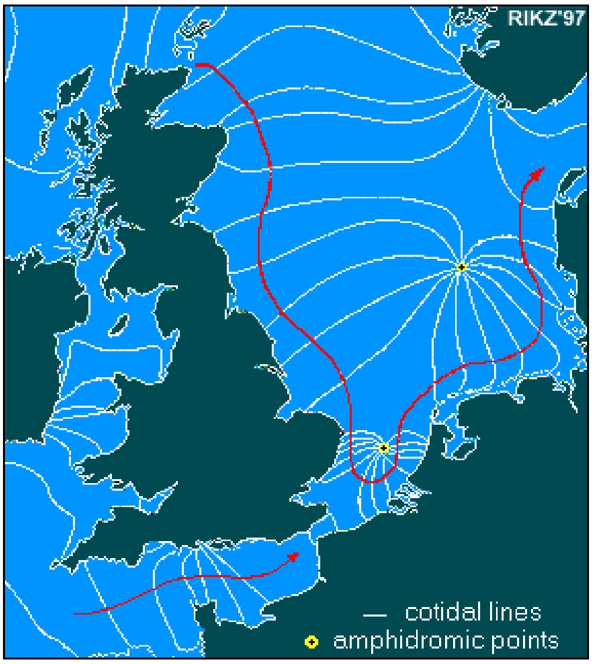


Figure 2-4 Propagation of the tide in the North Sea

along the Belgian and Dutch coast in a northerly direction towards Denmark and Norway. Another part of the Atlantic tidal wave approaches the Channel from the south at an average speed of 200 metres per second and is then, to a large extent, blocked.

The lines of simultaneous high- and low water (cotidal lines) in Figure 2-4 show that there are two points in the North Sea where the lines intersect and around which the tide rotates. At these nodes there is almost no tidal motion at all. They are called amphidromic points.

The tidal movement is periodic but practically never a pure sine. Deviations in the periodic movement are called tidal asymmetry. Two forms of tidal asymmetry are distinguished. The first one refers to the flood-period not being equal to the ebb period. If for instance the flood period is shorter than the ebb-period then the flood velocity will be higher than the ebb-velocity. After all, the same amount of water has to be transported during flood and ebb. The tide is then called flood-dominant. Another form of tidal asymmetry is that the duration of high water slack and low water slack is different. If the high water slack is longer than the low water slack, sediment has more time to settle during high water than low water and thus the tide is called flood dominant.

So far, the tide is discussed in a qualitative way in terms of duration and propagation. However, we are able to predict the tide quite accurately. The astronomical tide is usually described with harmonic components. The frequency of these components is determined astronomically. As stated before: the tide is caused by the attraction of the sun and the moon on the oceans. The moon provides relatively the largest tide-generating force on earth. This tidal component is usually referred to as M_2, the semi-diurnal lunar tide. The solar tide component (also semi-diurnal) is referred to as S_2. Most of these astronomical frequencies are grouped around integer numbers per lunar or solar day.

The linear combination of two tidal components with frequencies of e.g. ω_1 respectively ω_2 ($\omega_2 > \omega_1$) lead to an amplitude modulation of frequency $\omega_2 - \omega_1$. This leads, in terms of harmonic components, to sub-harmonic tides (spring - neap tide cycle etc.). Besides the astronomically dominated main constituents, in shallow marginal or coastal seas additional frequencies occur. The shallow water constituents are also called overtides. They are mainly a result of the non-linear dynamic processes which are present in the physics governing the motion of water. These overtides occur due to interaction of M_2 with itself, but they can also occur due to interactions of different components. These non-linear interactions between tidal components are very important because they can induce asymmetries in tidal velocity, which in turn can influence sediment transport.

Speer et al. (1991) stated that the sense of asymmetry of the tide can be largely defined with the relative phase difference between the quarter-diurnal constituent M_4 and the semi-diurnal constituent, M_2. The relative phase difference of the sea-surface level is defined as twice the phase of M_2 minus the phase of M_4: $2\varphi_{M2} - \varphi_{M4}$ (appendix E). Relative phases between 0° and 180° indicate that falling takes longer than rising tide and thus a tendency towards flood dominance. A direct measure of this distortion is the sea-surface amplitude ratio M_4/M_2 that can be defined as: $M_4/M_2 = a_4/a_2$.

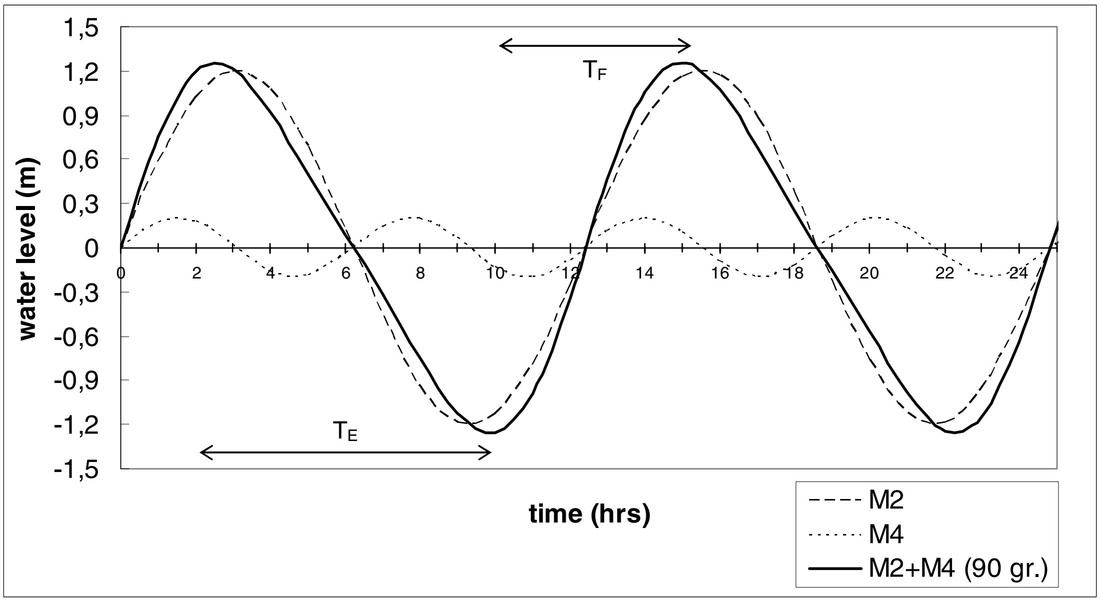


Figure 2-5 A relative phase difference of 90 degrees takes falling longer than rising tide and thus a tendency towards flood dominance.

This amplitude ratio gives an indication of the intensity of the asymmetry. The amplitude ratio in the basin is not always the same as the ratio outside the basin. The reason is the interaction between components when the tidal wave propagates in the basin. Basins geometry plays a significant role in this process. Research (Friedrichs & Aubrey 1988, Speer et al. 1991) points out that parameters based on storage volume, tidal amplitude and average depth of the tidal basin can create a rather good idea of the type of asymmetry in the basin.

Two non-dimensional parameters can be used to characterise the tidal basin or estuary. These parameters are responsible for different types of asymmetry. The first parameter is a/h and represents the ratio of the offshore M_2 tidal amplitude to the mean (estuarine) channel depth. It measures the relative shallowness of the estuary. The second parameter is V_s/V_c and this represents the ratio of the volume of water stored between mean high and low water above tidal flats and marshes, and the volume of water contained in channels at mean sea level (Friedrichs and Aubrey, 1988). The amount of tidal flats in a tidal basin is of great importance because the volume of water that channels must carry to flood areas of tidal flats has a significant effect on the sense of asymmetry that occurs. Figure 2-6 gives an illustration of the mentioned parameters.

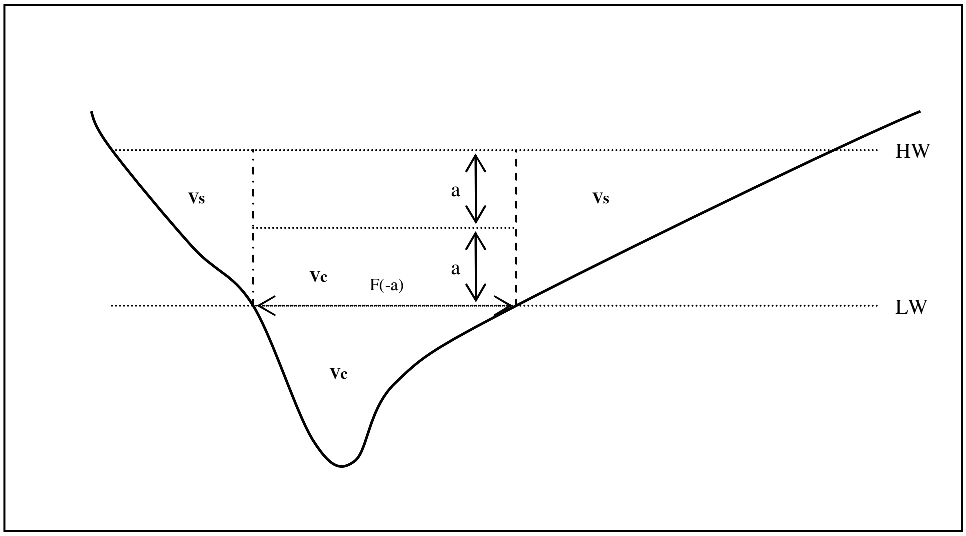


Figure 2-6 Definition sketch morphological parameters

Speer and Aubrey (1985, 1&2) and Friedrichs and Aubrey (1988) used a 1-D numerical model to study the influence of geometry and bathymetry of short, friction dominated and well-mixed estuaries. Based on these results, Speer et al. (1991) constructed the graph in Figure 2-7.

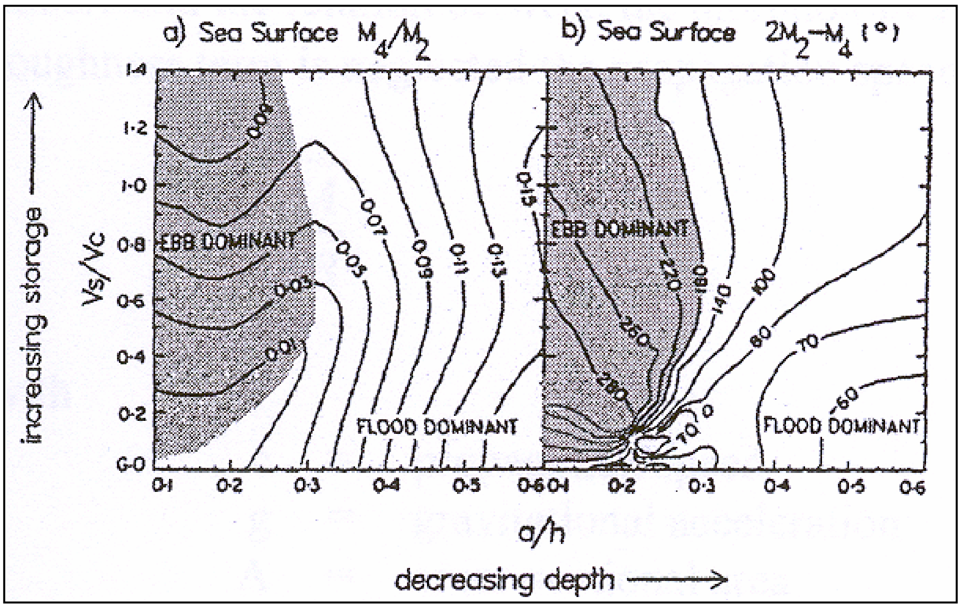


Figure 2-7 Contour plots of the parameters that determine non-linear distortion as a function of a/h and V_s/V_c , resulting from 84 model systems. The 180° contour separates the plots into flood and ebb-dominant regions. (after Friedrichs and Aubrey, 1988)

Figure 2-7 is of particular use to indicate the state of a tidal basin. It can be seen as an indicating graph to distinguish ebb- or flood dominated tidal basins. In Wang et al. (1999, 2002), it was concluded that the theory of Dronkers (2001) and that of Friedrichs and Aubrey (1988) qualitatively agree with each other, despite the use of different indicating parameters for tidal asymmetry and different parameters to describe the morphology of the tidal basin. Friedrichs and Aubrey (1988) used a rectangular cross-section for their models. It is possible to write theory of Dronkers (1986) in terms of the parameters used by

Friedrichs and Aubrey (1988). This will be explained to some more depth in the next paragraph, after Wang et al. (1999, 2002).

If we consider a long-stretched channel and schematise the tidal motion to 1-dimensional flow, the celerity of the tidal wave can be approximated as:

$$c = \sqrt{g \frac{A}{B}} \qquad (2.6)$$

With
c = celerity (m/s)
g = gravitational acceleration (m^2/s)
A = cross-sectional area of cross-section in a basin (m^2)
B = storage width, i.e. width of the cross-section at the water surface (m).

From the above equation one can see that the celerity of the high water will be equal to that of the low water if

$$\frac{A_H}{A_L} = \frac{B_H}{B_L} \qquad (2.7)$$

With
A_H = cross-sectional area at high water (m^2)
A_L = cross-sectional area at low water (m^2)
B_H = storage width at high water (m)
B_L = storage width at low water (m)

When applying this to the cross-section schematisation used by Friedrichs and Aubrey (1988, Figure 2-8)

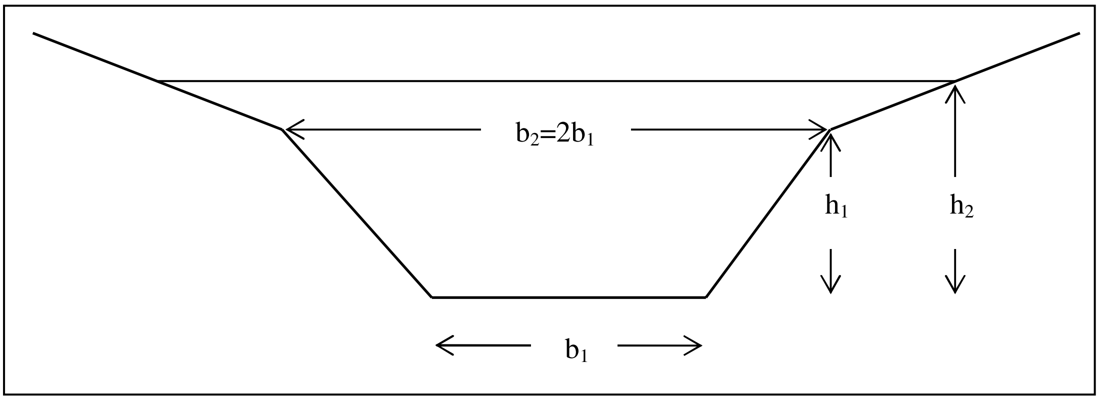


Figure 2-8 Geometry used by Friedrichs & Aubrey (1988); Trapezial model channel geometry (after Speer & Aubrey). All momentum is transported in the trapezoidal channel and sloping flats act in a storage capacity only.

this yields after some operations:

$$\frac{V_s}{V_c} = \frac{\frac{8}{3}\left(\frac{a}{H}\right)^2}{\left(\frac{3}{4}+\frac{1}{4}\frac{a}{H}\right)\left(1-\frac{a}{H}\right)} \tag{2.8}$$

With

V_s = storage volume (wet volume between HW and LW) above tidal flat (m^3)

V_c = wet volume of the channel (m^3)

a = amplitude of tide (m)

H = average water depth in the channel (m)

This relation of Friedrichs and Aubrey (1988) is now written in the two dimensionless parameters and is illustrated in Figure 2-8 as the solid line. It divides the plane into an ebb-dominant area (left of the line) and a flood-dominant area, similar to the contour plot in Figure 2-7.

Dronkers (1986, 1998) has put forward the inter-tidal area as a very important parameter as well. Based on an analytical solution of the tidal propagation in semi-enclosed basins, Dronkers comes to the conclusion that:

$$\Delta t_{flood} - \Delta t_{ebb} \infty H^- H_k^- - H^+ H_k^+ \tag{2.9}$$

With

Δt_{flood} = flood period at the mouth (h)

Δt_{ebb} = ebb period at the mouth (h)

H_k = A/b, cross-sectional area divided by the storage width (m)

H = Water depth (m)

and the superscripts + and - representing high water and low water, respectively.

The right hand side equals zero for the situations considered by Friedrichs and Aubrey in the cases that the flood period and ebb period are equal. In the case considered by Speer (1991) this leads to:

$$\frac{V_s}{V_c} = \frac{\frac{8}{3}\left(\frac{a}{H}\right)^2\left(1+\frac{a}{H}\right)}{\frac{3}{4}+\frac{1}{4}\frac{a}{H}} \tag{2.10}$$

Now, Dronkers (1998) is written in terms of the two dimensionless parameters as well. When plotting this in the same graph as equation 2.8, the agreement is evident. (Figure 2-9)

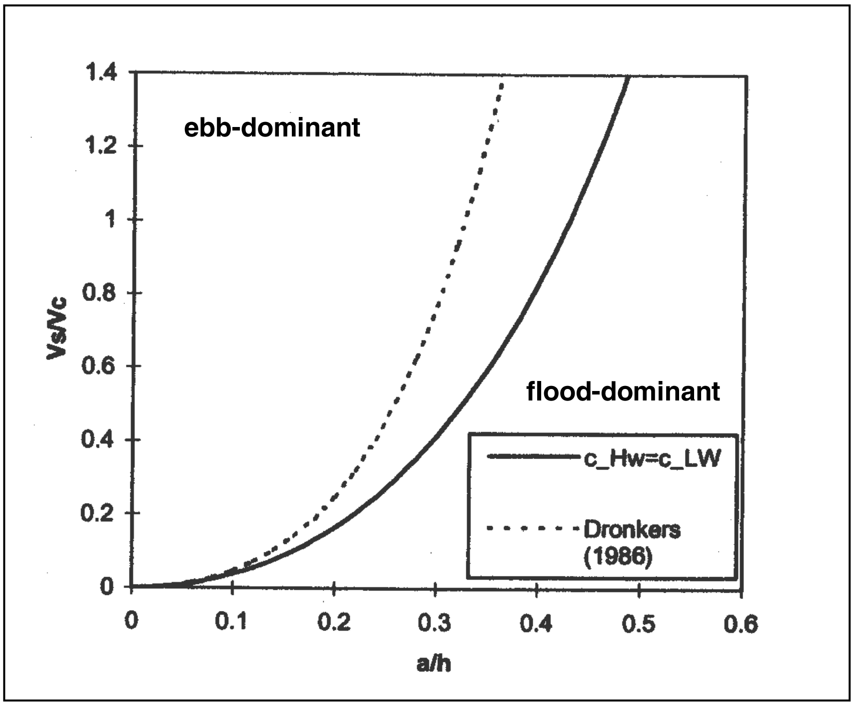


Figure 2-9 Tidal amplitude (a) to mean water depth of the channel ratio versus storage volume to wet volume of the tidal channels according to Friedrichs and Aubrey (1988) and Dronkers (1998). In the derivation the schematisation of Speer and Aubrey (1985) was applied.

The solid line divides the diagram into two areas. The upper left part is the part where the propagation of the low water is faster than high water making the tide ebb-dominant. The lower right part of the figure is the area where the tide is flood-dominant. Dronkers (dotted-line) made the distinction based on the duration of ebb- and flood period. From Figure 2-8 it follows that the two theories are qualitatively equal, revealing the same mechanism of the development of tidal asymmetry namely different propagation velocities of the tidal wave at different water levels. The state of a certain basin can be indicated by a point in this diagram. Sea-level rise will move the position of this point, either to the ebb-dominant direction or to the flood-dominant direction, depending on the hypsometry of the basin.

The basin hypsometry, or hypsography, is defined as the vertical distribution of basin surface area to height. There are for instance tidal basins with large intertidal areas and shallow channels, but also tidal basins with small intertidal areas and deep channels. In nature, all kinds of geometries can occur between these two examples. In Figure 2-10 an illustration of two tidal basin geometries is shown and represents the hypsometry.

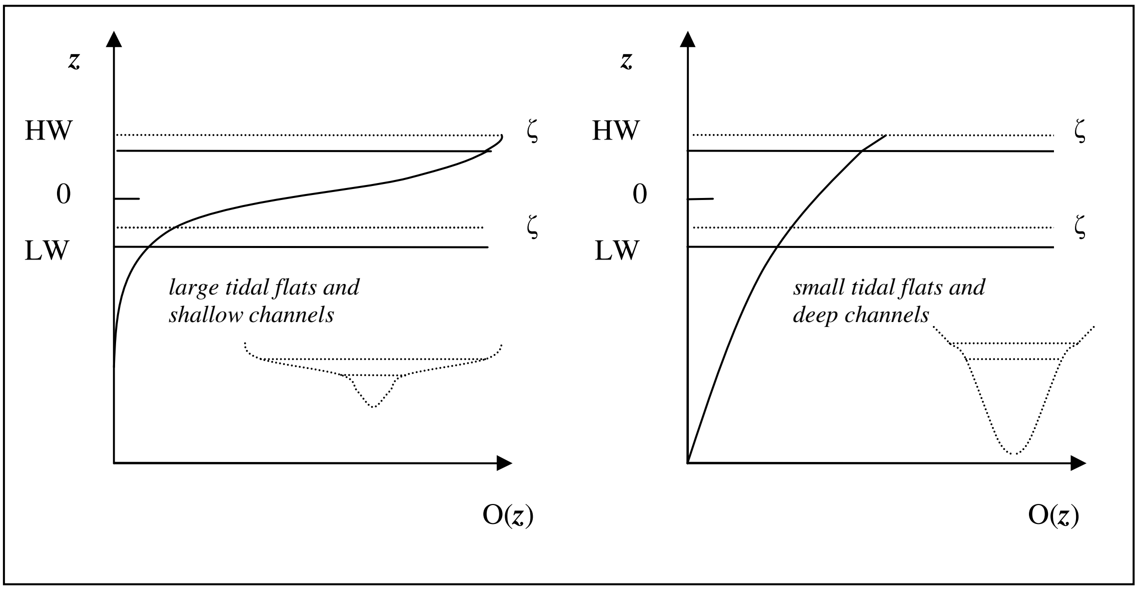


Figure 2-10 Different types of tidal basin geometry. O(z) is the basin surface area as a function of the distance z from a reference surface level.

The volume in the tidal basin is dependent on the distribution of the basin surface area over the height.

2.4 Physical processes

There are many processes that initiate or influence the sedimentology in tidal basins. Tidal asymmetry, elaborately discussed in the previous section, is merely one of them. A lot of processes play a part on a relative small scale but they can have large effects on the morphology of the back barrier basin. In this section some important physical processes are dealt with. An overview of processes is made from the perspective of the Dutch Wadden Sea. This part of the Wadden Sea has been subject of study for many years and the tidal basins tend to behave quite similar.

The concentration of suspended matter varies widely and changes with the stage of the tidal cycle and the strength of the tides. In general, the grain size of the sediment decreases from the inlet at sea towards the mainland. An increase in concentration of suspended material from the inlets to the shallow parts of the basin can be observed in tidal inlets (Oost, 1995). There are some mechanisms which can be the basis for a net sediment influx into a basin or estuary in spite of the absence of flood dominance or even in the case of weak ebb dominance (Eysink, 1993). These mechanisms are:

- Density currents due to salinity gradients
- Distortion of the tidal wave
- “Settling lag” effects
- “Scour lag” effects

The first one obviously relates in general more to an estuary with a significant amount of fresh water inflow, than to tidal basins such as the inlets in the Wadden Sea. Therefore, the latter three mechanisms are considered in more detail.

The distortion of the tidal wave has come forward in the previous section to a large extent. Groen (1967) showed in a theoretical way that a distorted tidal wave in a prismatic channel will result in a net inward sediment flux. According to Groen (1967) the period with low flow velocities around high water slack (HW-slack) is longer than around low water slack (LW-slack). Also, water depths relative to the bottom are on average lower during HW than during LW. This results in a higher siltation of suspended sediment at HW than at LW and hence a residual influx. The hypsometry can influence the distortion of the tidal wave such that the unbalance in flood and ebb dominance reduces and even becomes negative. The tidal wave in the Dutch Wadden Sea becomes asymmetrical in such a way that there is a tendency towards flood dominance.

Other mechanisms that play a role are “settling lag” and “scour lag” effects. These effects are not related to tidal distortion, but to changes in hydraulic conditions along a tidal channel. Higher current velocities are needed to erode particles from the bottom once they have settled, than the velocity at which these particles settle from suspension (after Oost 1995). This causes differences in locations within a certain body of water where particular sediment grains are eroded and settled (scour lag effect, Van Straaten en Kuenen 1957). Besides, sediments need a certain time to reach the bed after the flow velocity has dropped below the critical flow velocity for sedimentation (settling lag). In a prismatic channel with a symmetrical (with respect to velocity) tide no residual sediment transport will occur. Of course, this situation yields for zero sea-level rise. However, we have seen that in the Wadden Sea there is a considerable decrease in average depth from the tidal inlets in landward direction. The water body moves with the tides between the inlets and the shores and is spread out over the shallow inner parts at high tide and piled up in narrow prisms at low tide. After van Straaten en Kuenen (1957), Figure 2-11 shows that a particle will be transported by the flood current from its original starting point (1) in landward direction. The particle will start to settle from the point that the current velocity becomes too low for transport (3). As a consequence, the particle will settle somewhat further (5). However, the particle can only be eroded by during the subsequent ebb by water mass (B) which was landward from the original water mass (A).

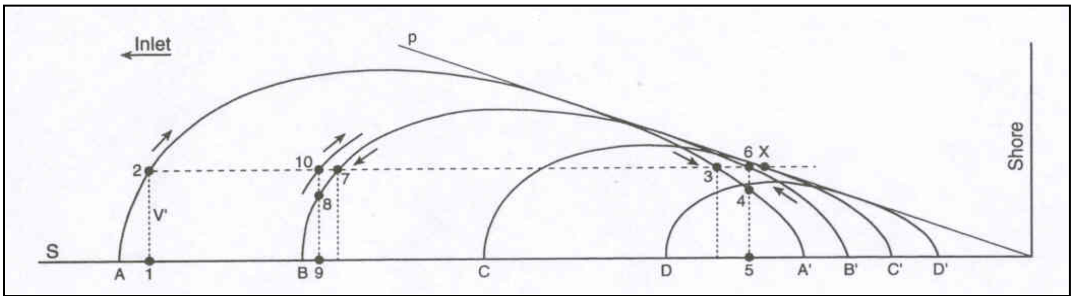


Figure 2-11 Settling lag effect. Numbers showing pathways of suspended particles during a number of successive tidal cycles (Van Straaten en Kuenen, 1957)

Hence, a particle will settle landward (9) from its original starting point (1) during the second slack water after ebb. Thus sediment is moved forth and back with a residual movement towards the coast until the movement stops or the sediment settles in an area where the ebb flow is too low to transport it again.

Scour lag refers to the phenomenon that a larger velocity is needed to get a particle (back) in suspension than the velocity at which the particle settled. In analogy with the example of settling lag, the velocity from which the particle can be eroded can only be caused by the water mass which comes from further inwards than the returning water mass in which it was originally suspended.

The scour lag and settling lag itself can not cause a residual movement of material in to a tidal basin. The effect of these processes is based on three circumstances (Van Straaten en Kuenen, 1957): the coagulated state of the suspended material, the inward decrease of the average tidal current velocities and the inward decrease of average depths. Obviously, the latter two circumstances are directly related to the hypsometry of a tidal basin. The processes described are mostly responsible for the sorting of sediments in the tidal basin. Coarse sediments can settle in areas with higher energy whereas fine sediments (low fall velocity) settle in areas with low flow velocity and low wave action. These fine sediments are thus located along the landward boundaries of the basin.

2.5 Lister Tief

In the previous sections, tidal basins and the distortion of the tidal wave in this specific kind of coast have been described. In the Dutch part of the Wadden Sea offshore tides are flood dominant. This means that the period of water-level rise is shorter than the period of water level fall. As a consequence, sand is imported in the basin. Due to this behaviour the basin compensates for sea-level rise. Once the sediment surface becomes too high erosion by wave action increases thus resulting in an equilibrium height with reference to sea-level.

As mentioned in the introduction, the Lister Tief tidal basin seems not to be importing sand into the system, although it is under influence of sea-level rise. This section focuses somewhat more on this specific tidal basin. First, the location and characteristics are discussed. Then, a short section is dedicated to the development of this part of the Wadden Sea.

2.5.1 Introduction

The Lister Tief inlet is located between the northernmost German Wadden Isle Sylt and the first Danish Wadden Isle Rømø. The back barrier lagoon exchanges water with the North Sea exclusively through one narrow tidal gully, named Lister Tief. The tidal basin is enclosed by the above mentioned islands, the mainland and two dams connecting the islands to the mainland. The Hindenburg dam is the dam connecting the Isle of Sylt with the German mainland and is built in 1927. The Rømø-dam was built in 1949 and connects Rømø with the Danish mainland. As a consequence of the construction of the dams, all tidal channels running over the highest parts of the intertidal area behind the islands were blocked. Fresh water is coming into the tidal basin via the rivers Vidå and Brede Å. This local river discharge is only 0,1% of the

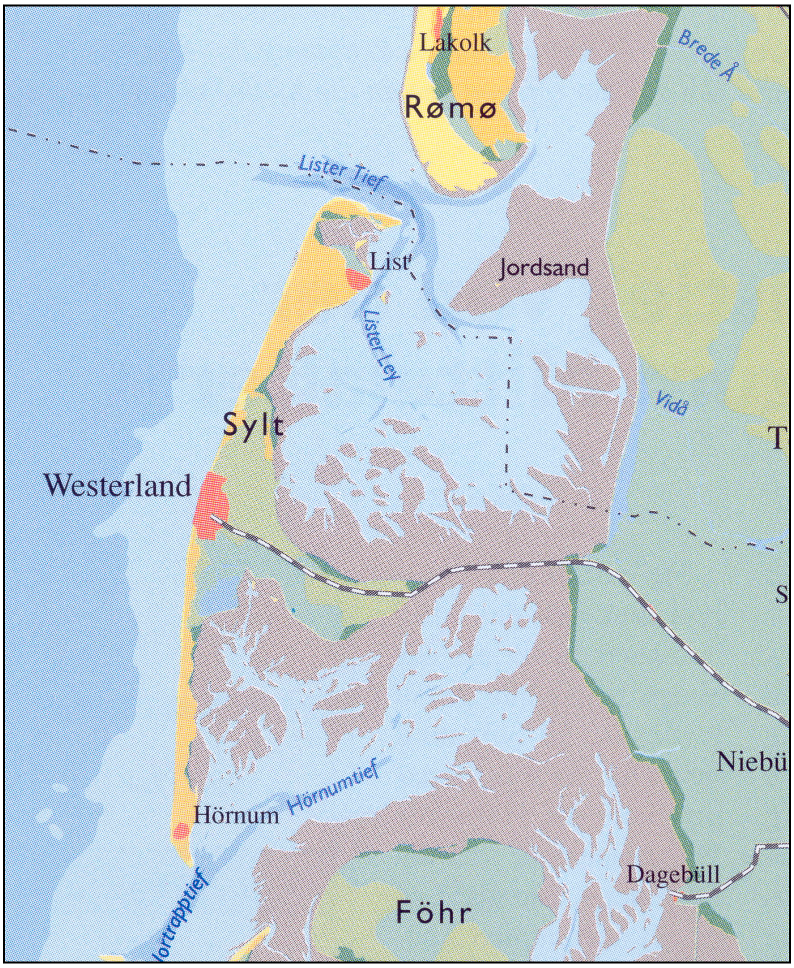


Figure 2-12 Lister Tief

tidal water exchange. The entire area of the Sylt-Rømø Bay is 411 km² large including 190 km² of tidal flats. The maximum depth at the inlet is 40.5 m. The tidal basin is drained through three main backbarrier tidal channels: the Rømø Dyb running in the North along the coast of Rømø, starting at the mouth of the Brede Å, the Hoyer Dyb in the middle, starting at the mouth of the Vidå, and the Lister Ley, running from South to North along the coast of Sylt.

2.5.2 Development "Nordsylter" Waddensea

From historical maps, Higelke (1998) reconstructed the (morphological) development of the Lister Tief tidal basin and found strong indications that a considerable amount of intertidal area eroded during the last centuries. However, his studies were based on sea maps instead of original soundings. This and observed irregularities in the various data cast some doubt on the accuracy of the results. Nevertheless, the available maps of the area do strongly suggest a decrease of intertidal area and hence a loss of sand. The reduction of supra- and intertidal area accelerated in the 20^{th} century. The island Jordsand in the centre of the basin disappeared rapidly. Intertidal area disappeared also due to land reclamation. As a consequence of this alteration, the total surface area of the Lister Tief was reduced from 445 kilometres squared in 1800 to 430 kilometres squared in 1900. As mentioned above, dams were built during the last century between Sylt and the German mainland and between Rømø and the Danish mainland. As a consequence, the total basin area was reduced from 430 in 1900 kilometres squared to 417 kilometres squared in 1991. Depth soundings and calculations showed that the total sediment loss of the Lister Tief back barrier basin amounts up to 13 million cubic metres over 25 years. (Kystinspektoratet, 1999). However, the overall standard deviation of the erosion calculation had been much larger than the actual erosion volume due to insufficient data quality. The standard deviation for the erosion volume of the area around is calculated to 86 million cubic metres (standard deviation being 21 cm. over the whole area). Therefore the Danish Coastal Authority concluded that it is not possible to state in which direction the basin is developing due to this large standard deviation. (Thorsten Piontkowitz, Kystdirektoratet). Based on the available data and observations, the working premise will be that the Lister Tief is most likely exporting sediment.

The island of Sylt is one of the most famous sites in Western Europe affected by coastal retreat. It is directly influenced by wave attack. Little change in the configuration of the coastline of Sylt is expected over the next 50 years if the present strategy of western shore protection, i.e. beach nourishment is maintained. However, this coastal retreat will probably be an important source of sediment. In the following table some characteristics of the Lister Tief are summarised. Different sources are available, German as well as Danish. In accordance with Wang & v.d. Weck (2002) the data of Kystinspektoratet (1999) is used.

Parameter	Quantity	Unit
Area	411	km^2
Intertidal area	190	km^2
Sub tidal area	221	km^2
Volume at mean water	$875 * 10^6$	m^3
Tidal Prism	$627 * 10^6$	m^3

Table 2-1 Characteristics of the Lister Tief tidal basin (Kystinspektoratet 1999, year of recording 1994)

2.5.3 Tidal asymmetry in the North Frisian Wadden Sea

As has been mentioned before, offshore tides are flood dominant in the Dutch Wadden Sea. Tidal asymmetry can be partly be generated at open sea. It is interesting to know the relative importance of this phenomenon with respect to the part of the Wadden Sea in which the Lister Tief tidal basin is located.

Therefore in Table 2-2 several harmonic constants are presented from which the measure of non-linear tidal distortion is derived. Similar to the explanation of tidal asymmetry, the relative phase difference between the M_2 harmonic and the quarter diurnal constituent M_4 is determined. An overview of topography of the North Frisisan Wadden Sea is given in appendix F.

Station	**Harmonic constants** (amplitude in mm., phase in degrees)		**Tidal asymmetry**	
	M_2	M_4	$2\varphi_{M2} - \varphi_{M4}$	$M_4/M_2 = a_4/a_2$
Cuxhafen	1344 013	114 271	115 *flood dominant*	0.085
Büsum	1562 006	88 197	175 *flood dominant*	0.056
Helgoland	1086 341	70 206	116 *flood dominant*	0.064
List West	845 354	114 175	173 *flood dominant*	0.135
List Hafen (back barrier)	809 23	66 215	191 *ebb dominant*	0.082
Esbjerg	656 065	61 285	205 *ebb dominant*	0.093
Borkum	1048 299	54 61	157 *flood dominant*	0.204

Table 2-2 Harmonic constants of a number of tidal stations along the German and Danish coastlines (source: Table des Marées des Grands Ports du Monde, Service Hydrographique et Océanographique de la Marine)

From Table 2-2, it becomes clear that the tide is becoming ebb-dominant when entering the tidal basin. Furthermore, the distortion of the tidal wave is partly generated outside the Lister Tief tidal basin as can be observed from the characteristics of the tidal wave from

Cuxhafen to Esbjerg. The cause for this development is likely to be found in the characteristics of the North Sea tidal system

2.6 Comparison Inlets

In section 2.2 several ways to classify tidal inlets were presented. Generally, tidal inlets are classified on a combination of tidal range and wave energy. Hayes (1979) used five classes of tidal inlets with respect to tide and wave dominance. Some information on the Lister Tief was presented in the previous paragraph. It is interesting to see how this tidal basin relates to Dutch tidal basins.

According to the wave information presented in Appendix A (Westerly wind between 247.5° and 315° are dominant) and the mean tidal range, the Lister Tief tidal basin is a mixed energy (tide-dominated) area. In Figure 2-13 the Lister Tief tidal basin is depicted. The classification of the Lister Tief is obvious mixed-energy. In this respect the Lister Tief does not differ from the Dutch tidal basins. However, the absolute value of tidal range and mean wave height should not be the only parameters to classify tidal inlets. The relative dominance of waves or tides is important as well as the surface area of the inlet basin.

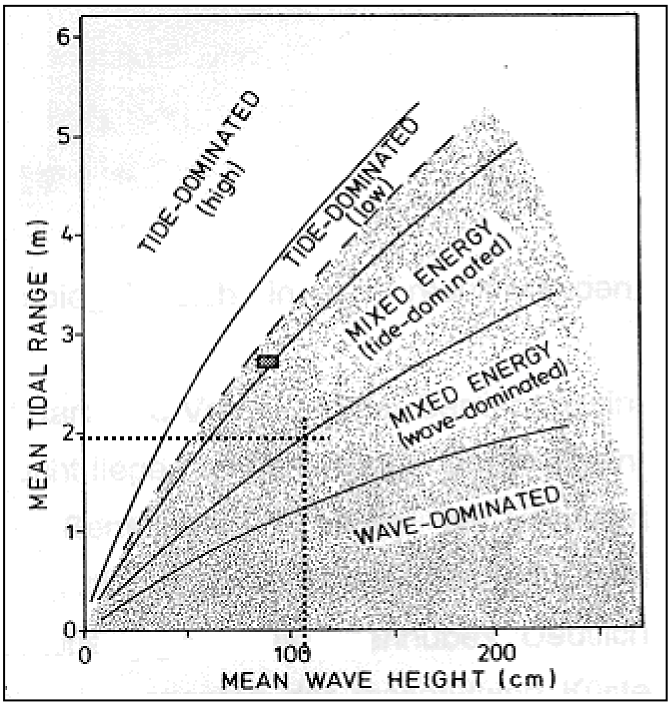


Figure 2-13 location Lister Tief tidal basin

To put the Lister Tief tidal basin somewhat more in the perspective of the Dutch tidal basins, Table 2-3 gives a summary of the tidal inlets of the Dutch Wadden Sea and their main characteristics. The Lister Tief basin is also considered in the table. It can be seen that the Lister Tief is not deviant in the main characteristics. There are tidal inlets in the Dutch Wadden Sea of comparable size and comparable tidal prism. The Amelander Zeegat is of the same order of magnitude considering all the main characteristics. From this comparison, it follows that the Lister Tief is comparable to the Dutch tidal basins.

Tidal Inlet / Basin	Basin area [km^2]	Tidal Range [m]	Tidal Prism [$*10^6$ m^3]
Marsdiep	656	1.65	1015
Eierlandse Gat	161	1.65	205
Vlie	719	1.90	1190
Amelander Zeegat	269	2.15	475
Pinkegat	52	2.15	80
Zoutkamperlaag	123	2.25	195
Eijerlanderbalg	35	2.40	48
Lauwers	128	2.45	210
Schild	31	2.45	42
Eems-Dollard	467	2.70	1095
Lister Tief	411	1.80	627

Table 2-3 Tidal inlets of the Dutch Wadden Sea and the Lister Tief tidal basin with their main characteristics. The relation between characteristics is given by equation 2.5.

2.7 The ASMITA concept

A possibility to model long-term development of tidal inlets is the aggregated scale model ASMITA. In this section the concept of the model is dealt with. The basic ASMITA concept consists of the approach that a tidal inlet can be schematised into a number of morphological elements. These elements are the ebb-tidal delta, the inter-tidal flat area, the total channel volume and two coast elements. For each element, one variable can be defined as integral state variable, representing the morphological state. Thus, the tidal inlet can be schematised into: (Figure 2-14)

- for the ebb-tidal delta this is: total volume of the delta V_d above a fictive sea bottom, which would be there if there was no inlet (sand volume);
- for the tidal flat: total volume of the flat V_f between MLW and MHW (sand volume);
- for the channel: the total channel volume under MSL V_c (water volume);
- for the two coast elements: the volume below MSL and above a certain depth line V_{c1} and V_{c2} (water volume).

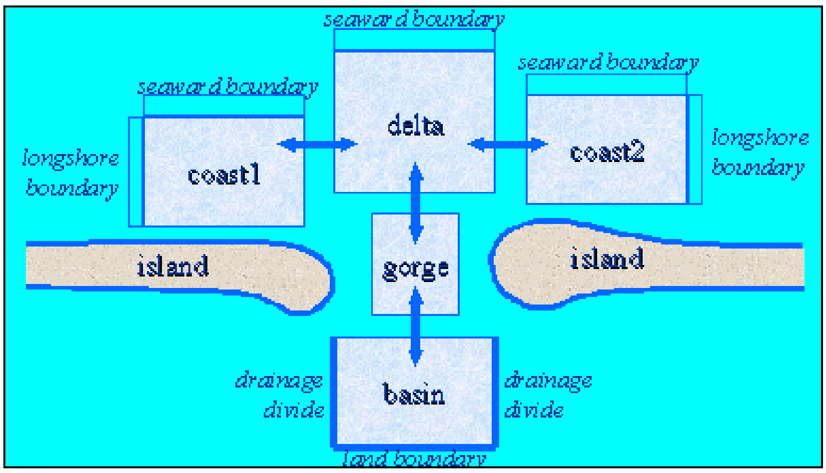


Figure 2-14 Schematisation of the ASMITA model.

The most important hypothesis used in the modelling concept is that a morphological equilibrium can be defined for each element depending on the hydrodynamic conditions (e.g. tidal prism) and morphometric conditions (e.g. basin area). An empirical relationship is needed for each element to define the morphological equilibrium state. No morphological changes take place when all elements in the system are in equilibrium. These relations (Eysink & Biegel 1992, ISOS) are derived for situations where tide-induced sediment transport is more significant than wave-induced sediment transport. However, the assumption is that these relations are generally valid.

Sediment exchange between the elements takes place depending on the difference in sediment concentration, where sediment always tends to move from a place with a high concentration towards a place with a low concentration. Significant is the concept of the equilibrium concentration. When all the elements in the system are in equilibrium, a constant sediment concentration is present for the whole system. The latter concentration is called the overall equilibrium concentration c_E. For each element there exists a local equilibrium sediment concentration c_e. This is defined such that it is equal to c_E if the element is in morphological equilibrium. For example, if c_e is larger than c_E, a tendency of erosion exists and vice versa. The local equilibrium concentration depends on the actual volume V and the equilibrium volume V_e. To represent this behaviour a power relation is used for the equilibrium concentrations. For the channel element, this means:

$$c_{ce} = c_E \cdot \left(\frac{V_{ce}}{V_c} \right)^n \tag{2.11}$$

According to the modelling concept morphological changes occur when the local sediment concentration deviates from the local equilibrium sediment concentration. For the tidal flat and the ebb-tidal delta this relation is inverted. For the flat this means:

$$c_{fe} = c_E \cdot \left(\frac{V_f}{V_{fe}} \right)^n \tag{2.12}$$

and for the ebb-tidal delta:

$$c_{de} = c_E \cdot \left(\frac{V_d}{V_{de}} \right)^n \tag{2.13}$$

Where:
V_e = equilibrium volume considered element (m^3)
V = actual volume considered element (m^3)
c_E = overall equilibrium concentration (-)
c_{ce} = equilibrium concentration channel (-)
c_{fe} = equilibrium concentration flat (-)
c_{de} = equilibrium concentration ebb-tidal delta (-)
n = commonly taken as 2 (in compliance with a third power for the sediment transport as a non-linear function of the mean flow velocity).

Morphological change

Changes occur when the local sediment concentration deviates from the local equilibrium sediment concentration. For example, erosion occurs when the sediment concentration is smaller than its equilibrium value and sedimentation occurs if it is larger than its equilibrium value. For the channel element, this reads:

$$\frac{dV_c}{dt} = w_s \cdot A_c \cdot (c_{ce} - c_c) \tag{2.14}$$

Again, for the dry volumes the equation changes:

$$\frac{dV_f}{dt} = w_s \cdot A_f \cdot (c_f - c_{fe}) \tag{2.15}$$

$$\frac{dV_d}{dt} = w_s \cdot A_d \cdot (c_d - c_{de}) \tag{2.16}$$

w_s = vertical exchange coefficient (m/s)
A_c = horizontal area of the channel element (m^2)
A_f = horizontal area of the flats (m^2)
A_d = horizontal area of the ebb-tidal delta (m^2)
c_f = actual sediment concentration flat (-)
c_d = actual sediment concentration channel (-)
c_d = actual sediment concentration delta (-)

A mass balance can be formulated for each element. For the channel this reads:

$$w_s \cdot A_c \cdot (c_{ce} - c_c) = \delta_{fc} \cdot (c_c - c_f) + \delta_{dc} \cdot (c_c - c_d) \tag{2.17}$$

For the flat:

$$w_s \cdot A_f \cdot (c_f - c_{fe}) = \delta_{fc} \cdot (c_c - c_f) \tag{2.18}$$

And for the delta:

$$w_s \cdot A_d \cdot (c_d - c_{de}) = \delta_{do} \cdot (c_E - c_d) + \delta_{dc} \cdot (c_c - c_d) \tag{2.19}$$

where:
δ_{fc} = horizontal exchange coefficient between flat and channel (m^3/s)
δ_{dc} = horizontal exchange coefficient between delta and channel (m^3/s)
δ_{do} = horizontal exchange coefficient between delta and outside world (m^3/s)

In Figure 2-15 the sediment balance is illustrated. The channel represents wet volume while the flat and the delta represent dry volume. The schematisation corresponds with a situation where a positive transport takes place and an increase of elements occurs.

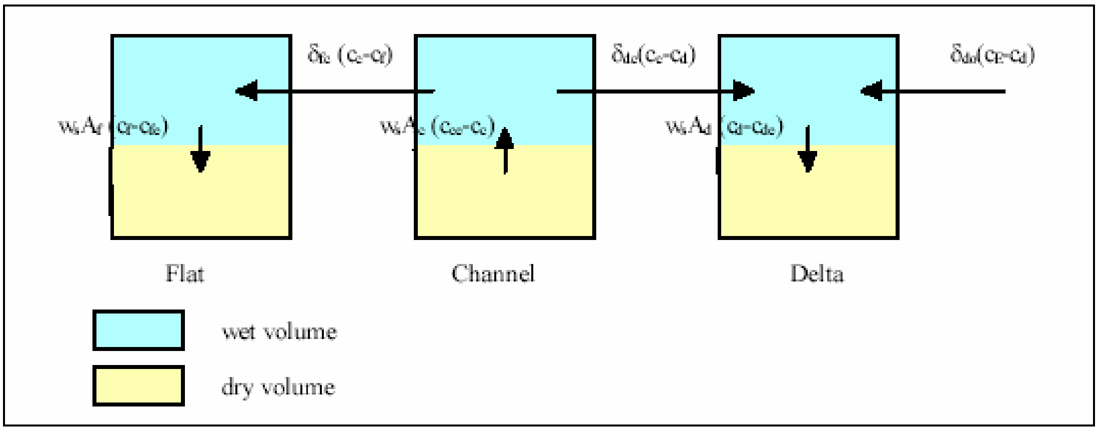


Figure 2-15 Sediment balance tidal inlet: transport between elements.

3 Response to sea-level rise

3.1 Introduction

In this chapter a comparison between, on the one hand, theory of morphology and tidal asymmetry and on the other hand the modelling concept of the ASMITA model is made. First, the general theories of Dronkers (2001) and Friedrichs and Aubrey (1988) are explained. It has been shown that these theories agree with each other in a qualitative sense (section 2.3). The question arises how these theories relate to ASMITA and if the model is capable of predicting sediment export in a tidal basin such as the Lister Tief. For this, the hypsometry of the basin should be known. With these data, it is possible to qualitatively assess the behaviour of the tidal basin based on hypsometric parameters. This assessment is carried out for the Lister Tief. The results are presented in section 3.4. Thereafter, the same operations are carried out for two Dutch tidal basins, namely the Marsdiep between the mainland and the Wadden Isle of Texel and the tidal basin Amelander Zeegat, between the Isles of Terschelling and Ameland. The purpose of this analysis is to place the results of the Lister Tief tidal basin in a broader perspective and to see whether it can provide us with an explanation for the loss of tidal flats.

3.2 Parameters indicating tidal asymmetry

According to Friedrichs and Aubrey (1988) two important parameters are responsible for different types of asymmetry (see chapter 2). The first parameter a/h represents the ratio of the offshore tidal amplitude to the mean (estuarine) channel depth. It measures the relative shallowness of the estuary. The second parameter is V_s/V_c and this represents the ratio of the volume of water stored between mean high and mean low water in tidal flats and marshes, and the volume of water contained in channels at mean sea level. Wang et al. (1999, 2002) concluded that the theory of Dronkers (2001) and that of Friedrichs and Aubrey (1988) qualitatively agree with each other, despite the use of different indicating parameters for tidal asymmetry and different parameters to describe the morphology of the tidal basin (Figure 2-9). The two theories basically reveal the same important mechanism of the development of tidal asymmetry: different propagation velocities of the tidal wave at different water levels. The state of a certain basin can be indicated by a point in the diagram as shown in Figure 2-9. Sea-level rise will move the position of this point, either to the ebb-dominant direction or to the flood-dominant direction depending on the hypsometry of the basin.

In the theory of Friedrichs and Aubrey (1988), the hypsometry manifests itself in the parameters V_s/V_c and a/h. It is possible to derive these morphological parameters if the distribution of surface area over the height of the basin is known. In this study, the hypsometry of the Lister Tief tidal basin is known for some periods of time. Digitized data sets from around 1967, 1987 and 1994 are available. These data sets can be used as input files in the Delft3D processor QUICKIN.

DELFT-QUICKIN is a program for the generation, interpolation or manipulation of space varying quantities such as bathymetries, initial conditions or parameter fields on rectangular or curvilinear grids. The main purpose of the QUICKIN program is to generate bathymetries for the Delft3D modules FLOW and WAVE. The pre-processor QUICKIN can determine the volumes and areas below a certain reference level. With these volumes and areas, the parameters V_s/V_c and a/h can be determined as can be seen in the following paragraph.

With the help of QUICKIN, the so-called hypsometric parameters can be determined. If these parameters are known, the point in the diagram (Figure 2-9) can be determined. Assuming that the bathymetry does not change, one can impose a certain instantaneous sea-level rise. The behaviour of the tidal basin under various sea-level rises is shown in the diagram of Figure 2-9 by various positions of the point. The derivation of the different morphological parameters is as follows: (see Figure 2-6)

For V_s, the volume of water stored on tidal flats between high and low water, we have

$$V_s = V(a) - V(-a) - 2F(-a)\cdot a \qquad (3.1)$$

For the channel volume under mean sea level, V_c,

$$V_c = V(-a) + a \cdot F(-a) \qquad (3.2)$$

The channel depth, at mean sea level, is

$$h = \frac{V_c}{F(-a)} = \frac{V(-a)}{F(-a)} + a \qquad (3.3)$$

in which:

V(a)= Volume at mean high water (m^3)
V(-a)= Volume at mean low water (m^3)
F(-a)= area at mean low water (m^2)
a= tidal amplitude (m)

The results of these calculations are discussed in section 3.4. In the following section, the modelling concept for a simplified single element approach in the ASMITA model is discussed. As will be shown the decisive parameters do also depend on the hypsometry of the basin.

3.3 Single element model

In this chapter, a single element model is considered under the assumption that channel evolution is dominated by diffusive transport between channel and the outside world and that this outside world is always in a state of equilibrium. The outside world represents elements such as ebb-tidal delta, adjacent coasts and tidal flats. The equilibrium state of the channel is derived from the empirical equilibrium relation for the channel volume which depends on the tidal prism.

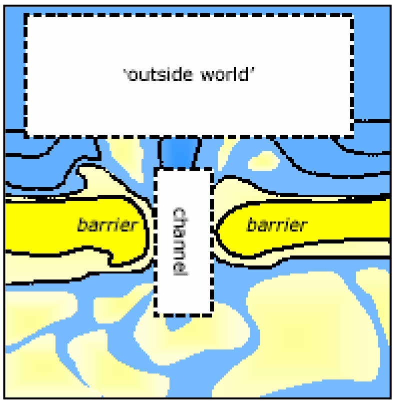


Figure 3-1 Single element model

The concept of the ASMITA model has been discussed in length in section 2.7. For comprehensibility reasons, here the main hypotheses and formulations are repeated and extended when sea-level rise occurs for the case of a single element approach.

In the model, the key-element is the equilibrium concentration. The local equilibrium concentration depends, in this case, on the actual volume V_c. To represent this behaviour, a simple power relation is used for the equilibrium concentrations.

$$c_e = c_E \cdot \left(\frac{V_e}{V}\right)^n \quad (3.4)$$

in which:

c_e = Local equilibrium concentration (-)
c_E = Global equilibrium concentration (-)
V_e = Equilibrium volume considered element (m^3)
V = Actual volume considered element (m^3)

Changes occur when the local sediment concentration, c_e, differs from the overall equilibrium sediment concentration, c_E. In general, this means:

$$\frac{dV}{dt} = w_s \cdot A \cdot (c_e - c) \quad (3.5)$$

in which:

w_s = vertical exchange coefficient (m/s)
A = Area considered element (m^2)

In this case, we are considering a single element namely the channel. Then, the sediment mass balance can be written as:

$$\delta_{co} \cdot (c_c - c_E) = w_s \cdot A \cdot (c_{ce} - c_c) \quad (3.6)$$

Where $\delta_{co} \cdot (c_c - c_E)$ represents the horizontal diffusive exchange between the channel and the outside world, with:
δ_{co} = diffusion coefficient between channel and outside world (m^3/s)

Combination of the above equations leads to:

$$\frac{dV}{dt} = \frac{w_s \cdot A \cdot \delta \cdot c_E}{\delta + w_s \cdot A}\left(\left(\frac{V_e}{V}\right)^n - 1\right) \tag{3.7}$$

The volume change as a consequence of sea-level rise can be written as: $A \cdot \frac{d\zeta}{dt}$

with:
A = Area element (m^2), in this case the channel element.
$d\zeta/dt$ = relative sea-level rise (m/s)

Now, combination with the foregoing will give:

$$\frac{dV}{dt} = \frac{w_s \cdot A \cdot \delta \cdot c_E}{\delta + w_s \cdot A}\left(\left(\frac{V_e}{V}\right)^n - 1\right) + A \cdot \frac{d\zeta}{dt} \tag{3.8}$$

When we assume in the first place equilibrium with zero sea-level rise:

$$\frac{dV}{dt} = \frac{w_s \cdot A \cdot \delta \cdot c_E}{\delta + w_s \cdot A}\left(\left(\frac{V_e}{V}\right)^n - 1\right) = 0 \tag{3.9}$$

The ratio between V_e and V determines the principal behaviour of the element. If $V_e/V>1$ erosion occurs in the channel element requiring export of sediment out of the basin, which is equivalent to ebb dominancy. In the opposite case flood dominancy occurs.

We have seen in the previous section that the different morphological parameters are dependent on the basin hypsometry. This applies as well for the relationships above. For the volume V of the basin, the relationship is clear. The volume V_e, which is the elements equilibrium relation, is dependent on the tidal prism (section 2.2.3). And the tidal prism in turn is related to the basin hypsometry. The tidal prism is defined as the volume at mean high water minus the volume at mean low water:

$$P = V(a) - V(-a) \tag{3.10}$$

3.4 Analysis hypsometry Lister Tief

From the previous sections, the relationship of the modelling concept of ASMITA and the basin hypsometry was shown. By means of DELFT-QUICKIN the various states of the tidal system are calculated and plotted (coordinates being hypsometric parameters V_s/V_c and a/h) in the diagram of Figure 2-9. Furthermore, the determinant parameters V and V_e can be calculated for the various sea levels. This parameter shows whether the system is ebb-dominant or flood-dominant according to the modelling concept of ASMITA. For reasons of simplicity, in the ASMITA analysis in this chapter only one element is considered namely the channel element. In this way, the development of the basin under sea-level rise according to this formulation can be determined easily.

The results of the calculation are summarised in Table 3-1. The calculation of the hypsometric parameters is given in Appendix B. Also, the hypsometry for the different datasets is depicted. The following remark concerning the 1987 dataset has to be made. With Danish and German authorities no existence of a 1987 dataset is known. German authorities suggested that the 1987 dataset is an assemblage of data from various sources. When comparing the hypsometry of the basin from the 1987 dataset with the other datasets, it seems to be slightly deviant in the upper part of the tidal basin. Because this dataset illustrates the hypsometry fairly well, this dataset is considered in this chapter as well.

Sea Level	1967			1987			1994		
	ASMITA	Friederichs & Aubrey		ASMITA	Friederichs & Aubrey		ASMITA	Friederichs & Aubrey	
	V_e/V	V_s/V_c	a/h	V_e/V	V_s/V_c	a/h	V_e/V	V_s/V_c	a/h
0.0 m.	**1.21**	**0.26**	**0.26**	**1.23**	**0.24**	**0.27**	**1.18**	**0.22**	**0.26**
0.2 m.	1.22	0.24	0.27	1.21	0.19	0.28	1.17	0.18	0.27
0.4 m.	1.20	0.18	0.28	1.20	0.17	0.28	1.13	0.14	0.27
0.6 m.	1.18	0.17	0.27	1.18	0.15	0.27	1.10	0.11	0.27
0.8 m.	1.15	0.14	0.27	1.15	0.12	0.27	1.06	0.09	0.27

Table 3-1 Analysis response hypsometric parameters and ASMITA to sea-level rise for the Lister Tief tidal basin.

From Table 3-1 we see for three available datasets of depths the Lister Tief tidal basin the change in parameters, according to the single element approach in ASMITA and the hypsometric parameters. When considering the determinant parameter in the single element approach for the ASMITA concept, it follows that for all datasets under zero sea-level rise $V_e/V>1$ (in the table given in bold). This implies that the equilibrium value for the channel is larger than the actual value leading to erosion of the channel, which is made possible by ebb-dominance. It can be concluded that the channel will develop through time towards its equilibrium. Imposing a theoretical sea-level rise leads in all cases towards a ratio of V_e/V larger than one. However, increasingly higher sea-levels lead to a decreasing ratio of these volumes, hence decreasing ebb dominance. Apparently the actual volume of the channel element increases more rapidly than the increase, as a consequence of the increase of the tidal prism, of the equilibrium volume. This shift to a situation with a certain ebb dominant behaviour to a situation with less ebb dominant behaviour can also be interpreted as a shift towards flood-dominance. In Figure 3-2 the development of the hypsometric parameters as they are observed in Table 3-1, is shown.

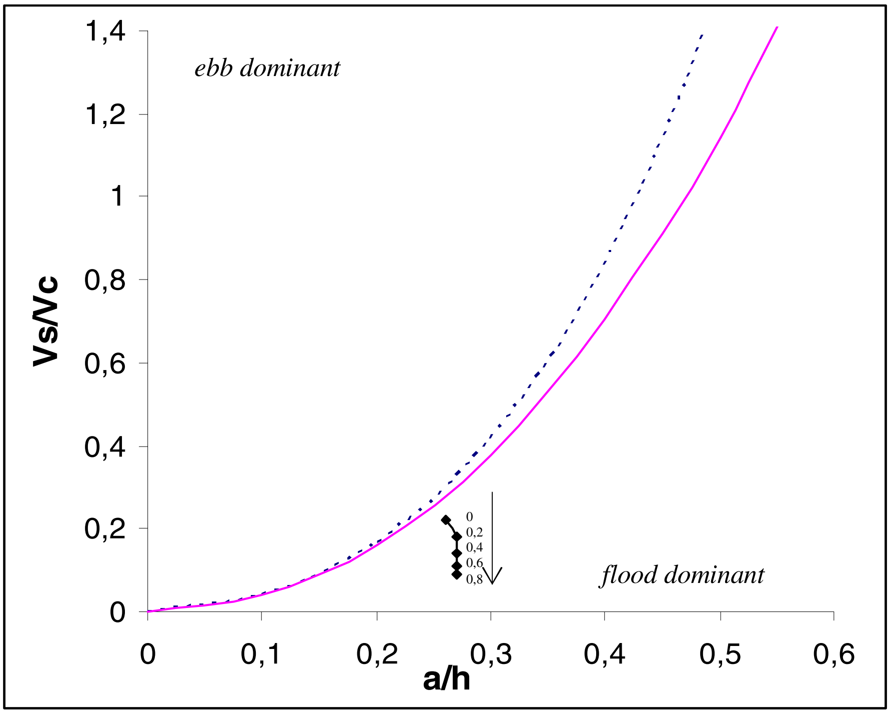


Figure 3-2 Development of Lister Tief tidal basin influenced by sea-level rise (used dataset 1994). The arrow represents the direction in which the basin is developing, corresponding to the parameters in Table 3-1.

Figure 3-2 is used because it is somewhat more straightforward than the exact diagram used by Friedrichs & Aubrey (Figure 2-7). As an illustration only the 1994 dataset was used because all datasets show the same trend. As can be seen in the figure, the hypsometric parameters position the state of the basin in the flood-dominant area, close to the "equilibrium" lines. Imposing a certain sea-level rise will move the position of the point away from the equilibrium line further into the flood dominant area. It should be stressed that an instantaneous sea-level rise was supposed to assess the behaviour. It is remarkable to see that when considering the first row of Table 3-1 with zero sea-level rise and for the three datasets, the described behaviour is confirmed through time. This situation with zero sea-level rise is an indication for what happened during time from 1967 until 1994. Here, also a shift towards more flood-dominance occurs.

When assessing the hypsometric curves in a qualitative sense, the above described development is a logical one. From history it is known that relative sea-level has increased. It has been observed that a considerable loss of intertidal flats has occurred during the last hundred years. Because of the increase of relative sea-level the volume in the channels increased rapidly at the expense of intertidal flats. At the moment, it can be derived from the hypsometry that the storage volume above intertidal flats will decrease as there is limited intertidal storage space left. In combination with the increase of channel volume this leads towards the observed situation of more flood-dominance.

To conclude: when comparing the parameters for the Lister Tief tidal basin, we see that the position of the tidal basin in the hypsometric graph is near the equilibrium line with a tendency towards slight flood-dominancy. Under sea-level rise the basin develops to a situation of more flood dominance.

According to the single element approach from ASMITA we see a similar shift towards a situation of more flood dominance when a certain sea-level rise is imposed. There is a discrepancy between the theoretical consideration and the single element approach of ASMITA. The hypsometry indicates a state of slight flood dominance while the determinant parameter in the model concept indicates ebb dominance. However, in the ASMITA approach only a single element is used and this approach was not extensively calibrated for this analysis. A comparison was made with a two element approach in chapter 4 after calibration; it appears that the chosen value for the coefficient in the empirical relation for the channel volume needs no adjustment. This does not explain the discrepancy yet. However, the equilibrium lines in Figure 3-2 do not exactly coincide, implying differences in approach. Apparently the lines distinguishing ebb- and flood dominance should not be taken strictly around this equilibrium. Therefore, it is important to establish that the development of the determinant parameter in the ASMITA approach as well as the hypsometric parameters is in the same direction, namely towards a situation of more flood dominance. In the next section, a comparison with two Dutch tidal basins will be done. Then also different empirical coefficients are considered to find the sensitivity of the approach for these coefficients.

3.5 Analysis hypsometry Marsdiep and Borndiep

To put the results of the previous section in perspective, the operations performed in section 3.4 were also done for the “Marsdiep” basin and the “Borndiep” or “Amelander Zeegat”. The Marsdiep basin is situated between the mainland of Noord-Holland and the Wadden Isle of Texel. The choice for this particular basin was made because of the orientation of the inlet. Like the Lister Tief tidal basin the Marsdiep inlet has its opening in a westerly direction. The inlet of the Amelander Zeegat is situated between the barrier islands of Terschelling and Ameland. The Amelander Zeegat was chosen because this inlet is of the same order of magnitude with respect to tidal range and tidal prism as the Lister Tief tidal basin. Several digitized bathymetric maps are available from RWS (2001). Here two maps for each inlet are considered, that cover roughly the same period of time in which the Lister Tief was analysed.

For these two Dutch tidal basins the same operations as for the Lister Tief tidal basin are carried out. That means that also a single element approach is considered as defined in the ASMITA model. And the hypsometric parameters are determined to position the state of the tidal basin in Figure 2-9. The behaviour under an instantaneous sea-level rise is investigated under the assumption that the tidal range remains the same. The results of these operations are summarized in Table 3-2 and Table 3-3. The calculation of the hypsometric parameters is given in Appendix C. In Appendix C the hypsometric curves are also depicted.

For the equilibrium relation of the single element in the ASMITA approach the same empirical relations (and coefficients) are used as for the Lister Tief case, for reasons of comparability. It should be noted that these are slightly different form the coefficients as they were found after extensive calibration by Kragtwijk (2001) and Van Goor (2001) for the Marsdiep and the Borndiep respectively. In this chapter the development of a tidal basin is the central issue and that justifies this approach. Although not shown in the Tables 3-2 and 3-3, a calculation with coefficients being calibrated based on the historical development in the basins show flood dominance for the Marsdiep and a situation around equilibrium for the Borndiep (Kragtwijk 2001 and van Goor 2001, respectively).

Sea Level	Marsdiep 1973			Marsdiep 1982		
	ASMITA	Friederichs & Aubrey		ASMITA	Friederichs & Aubrey	
	V_e/V	V_s/V_c	a/h	V_e/V	V_s/V_c	a/h
0.0 m.	**0.89**	**0.06**	**0.18**	**0.87**	**0.06**	**0.18**
0.2 m.	0.86	0.04	0.18	0.84	0.04	0.18
0.4 m.	0.82	0.03	0.18	0.81	0.03	0.18
0.6 m.	0.79	0.02	0.18	0.78	0.03	0.18

Table 3-2 Development parameters Marsdiep. Empirical coefficient in ASMITA approach the same as in Lister Tief case. Although not shown here, using calibrated values as determined in Kragtwijk 2001 show also obvious flood dominance.

Sea Level	Amelander 1973			Amelander 1982		
	ASMITA	Friederichs & Aubrey		ASMITA	Friederichs & Aubrey	
	V_e/V	V_s/V_c	a/h	V_e/V	V_s/V_c	a/h
0.0 m.	**1.59**	**0.53**	**0.29**	**1.65**	**0.51**	**0.32**
0.2 m.	1.55	0.43	0.31	1.57	0.39	0.34
0.4 m.	1.47	0.32	0.33	1.47	0.27	0.35
0.6 m.	1.37	0.21	0.35	1.36	0.17	0.36

Table 3-3 Development parameters Amelander Zeegat. Empirical coefficient in ASMITA approach the same as in Lister Tief case. Although not shown here, using calibrated values as determined in van Goor 2001 show a situation of equilibrium for zero sea-level rise.

Table 3-2 gives the results from the Marsdiep tidal basin. The ratio between equilibrium volume and actual volume as can be seen in the ASMITA columns is disturbed in such a way that it indicates flood dominance. When imposing sea-level rise this situation moves towards a situation indicating more flood-dominance. The hypsometric parameters confirm this behaviour. Actually, the strong position in the flood-dominant part of the plot of Friedrichs & Aubrey suggests that the Marsdiep develops towards a situation in flood-dominant direction. This situation is in line with reality where the Marsdiep tidal basin is suffering from an “out-of-equilibrium” state probably due to closure of the Zuiderzee in 1932 and perhaps even due to the overdepth as a result of the relatively recent formation of the basin around the second half of the 12th century. As a consequence the tidal basin has an importing character. This is confirmed from data analysis as well from simulations with ASMITA in Kragtwijk (2001).

Table 3-3 gives the results of the Amelander Zeegat. It should be noted that the Amelander Zeegat has, on a time scale of centuries, a relatively (morphological) stable history without much interference by man (Van Goor, 2001). This agrees with the hypsometric parameters in the sense that they indicate a certain state of morphological equilibrium. The behaviour of the tidal basin exposed to sea-level rise shows the same trend as we have seen in the other tidal basins: movement towards a situation with (more) flood dominance. This agrees as well for the single element approach in the ASMITA model.

3.6 Comparison development tidal basins

We have seen in the previous sections that the Lister Tief tidal basin is developing to a more flood dominant situation under sea-level rise when assessing the hypsometric parameters. It has been established that different approaches in determining hypsometric parameters has lead to slightly different equilibrium lines. Thus points in the diagram around these equilibrium lines should not be taken very strict. Moreover the single element approach of ASMITA, in case of the Lister Tief, shows that the channel element is out of equilibrium in such a way that ebb dominance occurs. However, sea-level rise will also move this parameter towards flood dominance as ebb dominance decreases while sea-level rise increases. For the Dutch tidal basins, the same coefficient in the empirical relation for equilibrium volume of the channel is chosen as for the Lister Tief for reasons of comparability. Although not shown here, the calibrated values for these coefficients as determined by Kragtwijk (2001) and Van Goor (2001) for the Marsdiep and the Borndiep show flood dominance and equilibrium for these basins respectively. Therefore, in this analysis it is very important to assess the analysis in the way that the basin is developing, so in a more qualitative sense, rather than establishing in a quantitative way that the basin is actually in a state of either flood- or ebb-dominance. However, according to the ASMITA concept all three tidal basins develop towards a situation of more flood dominance as the ratio between equilibrium volume and actual volume decreases in all cases.

As becomes clear from the development of the hypsometric parameters for all basins in Figure 3-3, the Lister Tief tidal basin is not behaving differently from the two Dutch tidal basins. The arrow in the figure points the direction in which the tidal basins develop under various levels of relative sea-level rise. All tidal basins tend to develop towards a situation of more flood-dominance under relative sea-level rise.

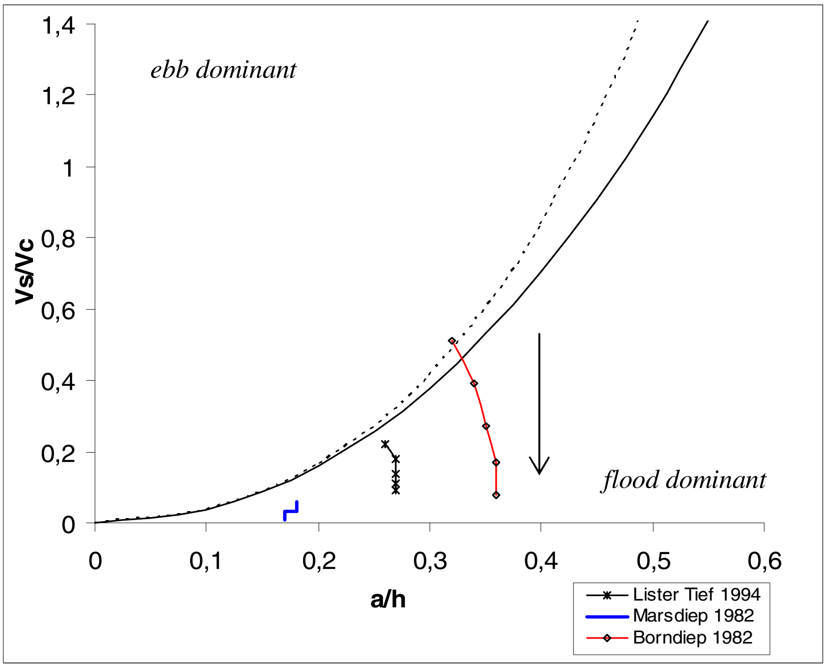


Figure 3-3 Development tidal basins under sea-level rise. The arrow represents the direction in which the basin is developing

4 The ASMITA Model

4.1 Introduction

As mentioned before, a possibility to model long-term morphological changes is the ASMITA model. However, ASMITA has never been applied to a basin with a possibly sediment exporting character like the Lister Tief tidal basin. Therefore, the Lister Tief case is simulated with this model and the results of this simulation are presented in this chapter.

The concept of this behaviour oriented model has been explained in section 2.7. Moreover, in section 3.3 the most important relations were repeated for a single element approach. In this chapter, the set-up for a 2 element ASMITA model with respect to the Lister Tief tidal basin is discussed. In the analysis in chapter 3 a single element approach was considered for ASMITA. To be able to compare the results of the actual ASMITA simulation and the hypsometric parameters, the model is based on the two elements channel and tidal flats. In section 4.2, input parameters are discussed. Section 4.3 shows the results of the actual ASMITA simulation applied to the Lister Tief tidal basin. The model is calibrated using data of the last hundred years.

4.2 Input parameters

To perform calculations with the ASMITA model, several parameters have to be defined. When these parameters are known and used as input, the model can predict the morphological behaviour over large periods of time. In this section these specific parameters are discussed and for the situation of the Lister Tief tidal basin the input value is given.

Diffusion coefficients (δ_{oc}, δ_{fc})

As came forward in the literature survey, asymmetry of the tide causes a non-zero residual sediment transport. At the aggregated scale in this model, the net effect is described as a diffusion type of sediment transport. The coefficient δ is the exchange coefficient between the various elements of the model. The larger δ, the larger the exchange of sediment between two related elements. Buijsman (1997) used values ranging from 500 m^3/s to 1500 m^3/s for the "Zoutkamperlaag".

Overall equilibrium concentration (c_E)

The outside world is represented by the coastal and offshore regions around the delta area. The concentration there is mainly determined by longshore transport. The model assumption is that this concentration is initially found in all elements. It is prescribed under the assumption that the outside world is in equilibrium, which physically means that there is no limitation for supply or accommodation of sediment adjacent to the system. 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. The average longshore transport west of Sylt amounts over 1 million m^3 per year, which thus will lead to comparable values.

Vertical exchange coefficient (w_{sc}, w_{sf})

This coefficient represents the vertical exchange rate in the elements, per unit area per second. It is not exactly the fall velocity, but more a sediment exchange coefficient between the bottom and the water volume. The larger $w_{s,}$ the larger the exchange of sediment between the bottom and the water volume. It is dependent on the long-tem residual effect of all kind of processes, which cause erosion or sedimentation. Buijsman (1997) used values ranging from 1e-5 to 1e-4 m/s.

Tidal range

It has become clear that the tide, represented by the tidal prism, has a significant influence on the system. All the more, because of its occurrence in the equilibrium relations as presented in section 2.2.3. With this value, the tidal prism and hence equilibrium volumes of the elements are calculated.

4.3 Application two element model

In the previous chapter the ASMITA model considered merely a single element approach of the Lister Tief namely the tidal channel. Here the application of the ASMITA model on the Lister Tief tidal basin will be done based on two elements: channel and tidal flats. These two elements are represented in the hypsometric parameters. After all, the parameter V_s (the volume of water stored on tidal flats between high and low water) gives information of the tidal flats and the parameter V_c represents the channel volume under mean sea level.

Including more elements in the application is currently not feasible since not enough information is present on for example the delta in front of the inlet. To get reliable results, the development of the Lister Tief is simulated during the last hundred years. Information regarding the state of the basin is known from around the year 1904 (Gätje, C., Reise K (Eds), 1998), although with uncertainties. The current state of the basin is also known (among others datasets 1967 to 1994). Purpose of this operation is to develop ideas on the evolution of the tidal basin and to calibrate the input parameters as described in section 4.2.

4.3.1 Calibration for the Lister Tief

First, an overview of the quantitative values of the input parameters described in the previous sections is given. The values given here are the calibrated values and are used in the actual simulation over the last hundred years for the two element model and for the forecast for the next 50 years.

Parameter	Value
δ_{fc}	800 m^3/s
δ_{oc}	800 m^3/s
w_{sc}	$1e^{-5}$ m/s
w_{sf}	$1e^{-5}$ m/s
c_E	0.00015 -
A_f	$2.40e^8$ m^2
A_c	$1.90e^8$ m^2
$V_{f,i}$ (initial flat volume)	$1.90e^8$ m^3
$V_{c,i}$ (initial channel volume)	$6.80e^8$ m^3
H	1.55 m
$d\zeta/dt$	18 cm/century

Table 4-1 Input parameters for the Lister Tief in 1904, after calibration.

The first 5 input parameters from Table 4-1 were initially chosen as the mean value as considered in Buisman, 1997. These mean values formed the starting point for the calibration. The other parameters in table 4-1 are specific for the tidal basin. The horizontal diffusion coefficient, the vertical exchange coefficient and the overall equilibrium concentration are influencing mainly the systems time scales. The actual initial disturbance, if there is any, depends on the ratio between element equilibrium volume and actual element volume. This disturbance determines the trend in which the basin is going to develop. Parameters that are given in the table are the values which were found after calibration.

In Table 4-2 the main characteristics for the Lister Tief that are used are given. It should be emphasized that the values presented in the table for the situation around 1900 suffer from particular uncertainty. Different methods and different levels were used in various studies. Furthermore, Higelke (1998) raised some doubt by presenting volumes under SKN (See Karten Null, MLWS) while probably NN (Normal Null, MSL) is meant resulting in inconsistent values. Especially the value given for the tidal prism by Gätje & Reise (1998, tidal prism of about $400e^6$ m^3 around 1900) is doubted. From analysis of these values it appears that the average height of tidal flats are rather large compared to the average tidal flat height derived from the present field data. It is believed that tidal flat levels are able to adapt rapidly to changes in water level (Eysink & Biegel, 1992). The most firm support is found in the rapid adaptation of the tidal flat levels in the Dollard after the increase of the MHW level due to deepening of the navigation channel to Emden (Eysink & Biegel, 1992). Moreover, from Wang & v.d. Weck (2002) it has appeared via an exploration on empirical relations with regard to the Lister Tief area that this situation is in line with the behaviour of the Dutch tidal basins of the Wadden Sea. Therefore, after performing a sensitivity analysis and a consistency check, the average flat height of the present state of the basin is used to adapt the initial volume of flats, also leading to a more reliable value of the tidal prism.

Parameter	**Lister Tief 1904**	**Lister Tief 1992**
Area of the basin: A_b	430 km^2	411 km^2
Area of tidal flats: A_f	240 km^2	180 km^2
Area of channels: A_c	190 km^2	231 km^2
Tidal Range: H	1.55 m.	1.80 m.
Tidal Prism: P	$487e^6$ m^3	$627e^6$ m^3

Table 4-2 Characteristics of the Lister Tief tidal basin used for calibration. Values derived from different sources (Gätje, Reise (1998), Kystinspektoratet (1999), Spiegel (1998))

The values presented in table 4-2 can be interpreted as a good indication of the actual values and thus the state of the basin at that certain point in time. From the table, it appears that tidal range increased significantly in this area. The question arises what is the cause for the increase in this area and whether this increase occurred gradually or rapidly as a consequence of an event.

From the characteristics, it becomes clear that the basin area has decreased and that the tidal range increased significantly. The result being that the driving force, in the model defined as the product of the basin area at mean high water and the tidal range, has increased. Therefore, this change is accounted for in the simulation. The graphs of the results are presented in the following figures. In the graphs the volumes derived from the three datasets used in chapter 3, are expressed by the points.

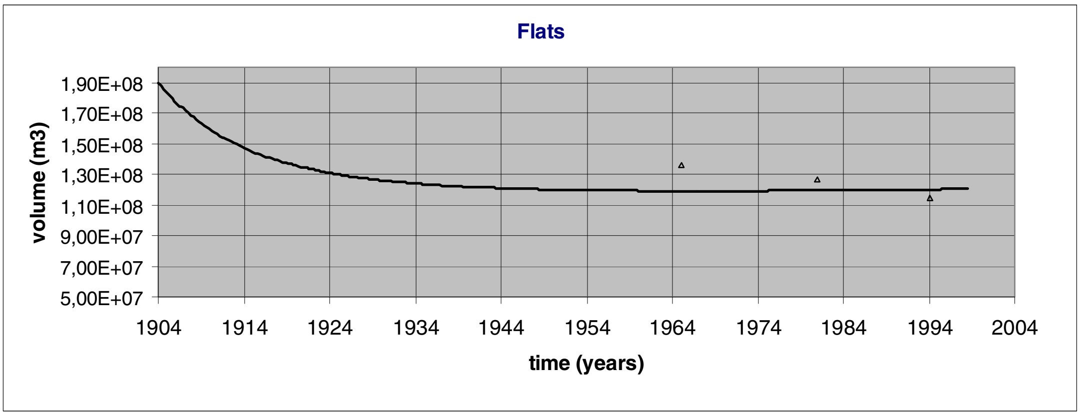


Figure 4-1 Development tidal flat volume over the last hundred years for the Lister Tief tidal basin.

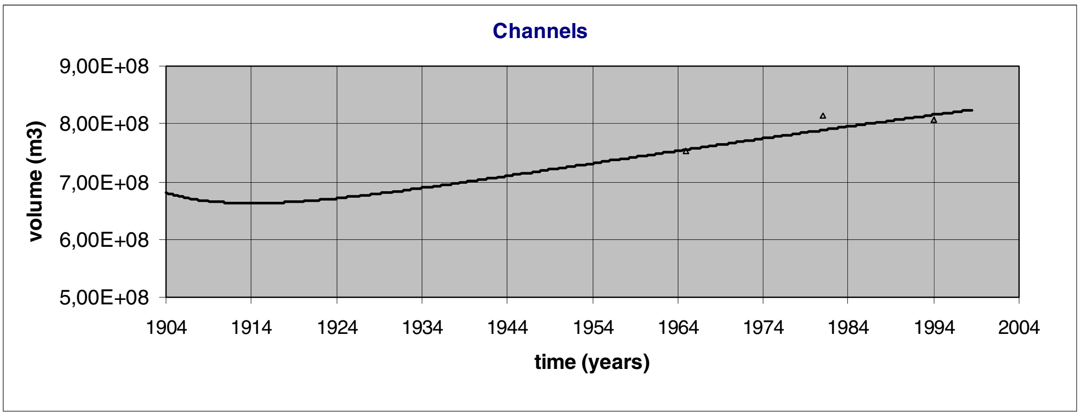


Figure 4-2 Development channel volume over the last hundred years for the Lister Tief tidal basin

These graphs are repeated in Appendix D, and the development of the tidal prism is depicted as well. Furthermore from the simulation results, transports can be calculated. These graphs are also depicted in Appendix D.

The decrease in flat area as well as the increase of channel area which has occurred during the last century is confirmed by the simulation of the two element approach of the back barrier area. Apparently, the tidal basin is out of equilibrium and the basin is developing towards its equilibrium value. Obviously, the development towards equilibrium has not finished yet. As far as the computed volumes are concerned, they should agree with the simulated volumes in a tolerable manner. By comparing volumes, it appears that the simulated volumes approach the "actual" volumes reasonably. It is noted that several different sources present slightly different characteristics of the actual present state of the basin. The simulated volumes are within these uncertainty ranges.

Furthermore, it appears that the development of the flat volume is faster than the development of the channel volume. The reason for the slower response of the channel volume is probably that the equilibrium channel volume is dependent on the tidal prism and the steering parameter for the tidal prism is the flat volume. Moreover the relative disturbance as a consequence of sea-level rise on the tidal flats is larger than the relative disturbance in the channels. Therefore it is believed that the flat area will adapt more rapidly to changes in water level than the channel volume (Eysink & Biegel, 1992).

4.3.2 Future Development Lister Tief

Now that the model has proven to simulate the tidal basin in a fairly good manner, a simulation for the next 50 years can be carried out for different rates of sea-level rise. As has been stated above, several different sources in literature present slightly different characteristics of the actual present state of the basin. Therefore, the simulation of the future will be done based on the results of the calibration by extrapolating these values with different rates of sea-level rise.

The simulations are performed until the year 2050 and with relative sea-level rise of 2 mm/year, 3.7 mm/year and 6 mm/ year corresponding with 20 cm/century, 37 cm/century and 60 cm/century. The Danish Coastal Authority based on models an expected sea-level rise of 37 cm during the coming hundred years. (T. Piontkowitz, Kystdirektoratet). The resulting graphs for the expected rate of sea-level rise of 3.7 mm/year are presented in the following figures. In appendix D these figures are repeated and graphs are added for the other scenarios of sea-level rise as well as graphs of the development of tidal prism and transports.

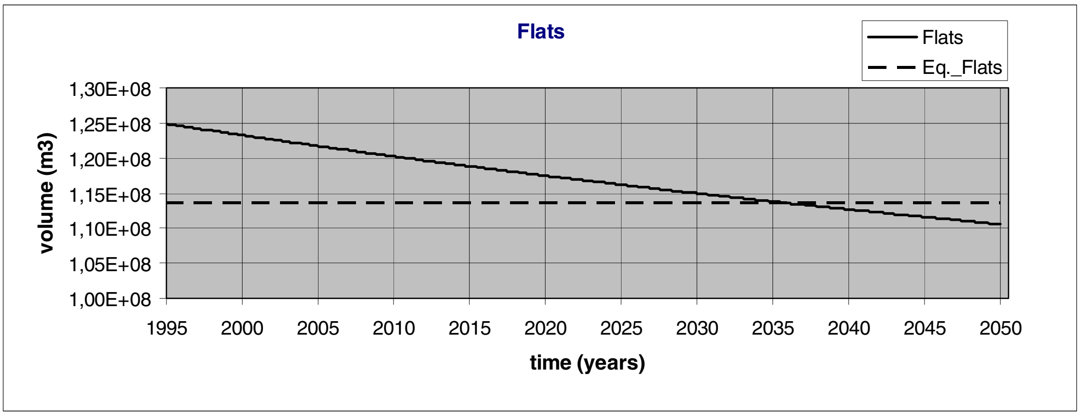


Figure 4-3 Development Flats of the Lister Tief under 3.7 mm/year Sea-Level Rise

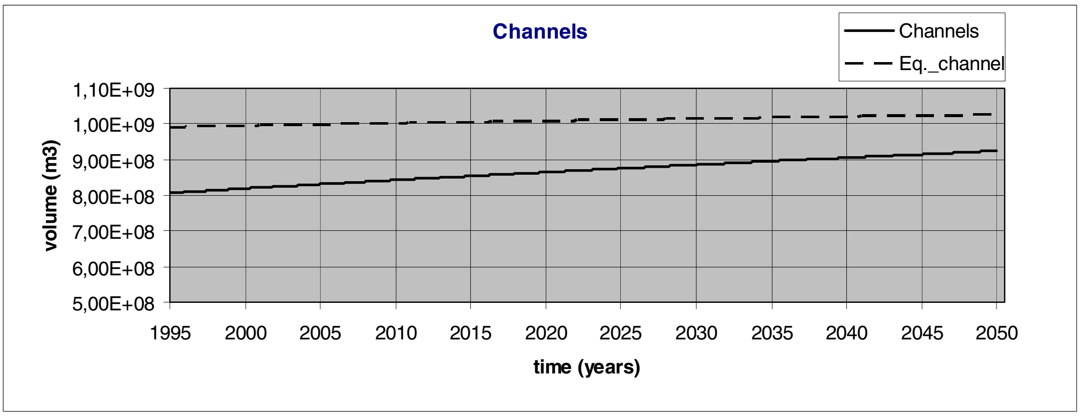


Figure 4-4 Development Channels of the Lister Tief under 3.7 mm/year Sea-Level Rise

From the graphs in Figure 4-3 and Figure 4-4 it becomes clear that the development towards equilibrium will continue. Higher rates of sea-level rise cause acceleration in this trend. (see appendix D). Depending on the rate of sea-level rise the volumes will cross their “static” equilibrium values at a certain moment. The equilibrium lines as plotted in the figures above namely concern the equilibrium value in case of zero relative sea-level rise. However, in case of a constant sea-level rise a “new” dynamic equilibrium volume originates. This new equilibrium volume is, for instance in case of the channel element, larger than the original equilibrium volume. A permanent difference between the equilibrium volume with sea-level rise and the equilibrium volume without sea-level rise is established. This difference is necessary to maintain the demand for sediment that drives sand into the system in such a rate that the basin does not drown.

4.4 Conclusion application ASMITA model

The ASMITA model, for this case with a two element approach, can reasonably describe the development of the Lister Tief tidal basin, despite its limitations. However, overall the model proves that the Lister Tief tidal basin is out of equilibrium. This comes to surface from simulations over the last century. Input parameters around 1900 indicate a significant surplus of tidal flats and a shortage of channel volume. The basin appears to be adapting and is around its equilibrium at present time for the tidal flats and still adapting for the channels. This is in line with the observed probably ebb dominant behaviour as observed. The reason for the rapid adaptation of tidal flats is believed to be correlated with the relatively large disturbance as a consequence of sea-level rise, compared to the channel volume. Moreover, the steering parameter for the equilibrium channel volume depends indirectly on the flat volume.

Forecasts based on ASMITA simulations with different rates of sea-level rise indicate a continuation of this trend. It is expected that the tidal basin will turn flood-dominant when its equilibrium values are reached after which the tidal basin keeps pace with sea-level rise. It is emphasized that this only counts for limited rates of sea-level rise and a situation in which the tidal basin does not suffer from human interference.

5 Representation relevant processes in the ASMITA model

5.1 Introduction

Up to here, the hypsometry of the Lister Tief tidal basin applied to theoretical parameters is studied as well as the modelling concept of ASMITA. The tidal basin also has been simulated in a two element approach with the mentioned model. It has become clear that the ASMITA model has a significant degree of schematisation. The question arises if the model covers the relevant processes sufficiently. Therefore, this chapter provides a discussion concerning which processes play an important role and whether or not it would be useful to give them more consideration in the actual model.

5.2 Representation of processes in ASMITA

We have seen in chapter 2 that there are several processes at different scales that can influence the morphology of a back barrier area. For a phenomenon like tidal asymmetry, it has been concluded that ASMITA is not capable of predicting changes in sediment transports as a consequence of changes in the propagation of the tidal wave. There is no integration with a tidal flow model. The question arises if the tidal range input is sufficient to model the development of the basin due to tidal distortion. The initial distribution of tidal flats and channels gives enough information to start the model. For lower rates of sea-level rise it has been established in similar situations that the shape of the tidal basin tends to follow the rise of the sea-level. This sea-level rise can be imposed in the model. In ASMITA after each time-step a change of volume of the amount of sea-level rise times the time step times the area is computed. The latter is taken as a constant. That means that no up-date of the area of the particular element takes place. In reality, a change of the area does occur. It is possible to overcome this to up-date the area of the element. Perhaps an update of the areas of the elements after each time step, derived from a representative hypsometry is a real possibility if this hypsometry is known.

Effects like scour lag and settling lag are obviously not integrated in the model explicitly. However, the underlying mechanisms like the inward decrease of the average tidal current velocities and the inward decrease of average depths are concealed in the hypsometry. In general a tidal basin tends to be divided in channels in the first part of the inlet and flats situated more land inward leading to the landward decrease of water depth. Settling lag effects are strongly dependent on the water depth. The long-term morphological model simulates the basins behaviour over several years up to hundred years. Furthermore these lag-effects seem to be covered in the model by the empirical relations. These relations have been elaborately studied over a lot of years. The existence of tidal basins in a (dynamic) equilibrium points out that these effects are (be it indirectly) accounted for.

5.3 Evaluation ASMITA model

From the previous sections it has become clear that there are several processes not being explicitly accounted for in the model. In the first place, there is no integration with a tidal flow model. However, it is very important to keep in mind that ASMITA is in principle an aggregated scale model. Elements in the model are primarily influenced by the basin related tidal prism and although the tidal flow is not actually simulated, this does not mean that the tidal driven processes are not simulated correctly. Herein, the robustness of the empirical relations is of eminent importance. These relations have proven their value in several studies now. Moreover when these relations are correctly calibrated they predict the behaviour as observed in the Dutch part of the Wadden Sea as well as the Lister Tief situation rather well.

Besides the fact that one can question the limited representation of several morphological processes, it should be emphasized that this model is one of the few models that are capable of predicting long term morphological behaviour. Furthermore, the strength of the model lies just in its simplicity. One can argue if the mentioned morphological processes are represented by the empirical relations that are the basis of this aggregated scale model. There are parameters which characterize some processes and these parameters can be adjusted for each case, for instance the equilibrium concentration. The equilibrium concentration represents the link between hydrodynamics, sediment transport and morphology of the basin. Besides the fact that it appears that most processes are accounted for, there are some critical remarks that can be made about (the use of) the model.

The empirical relations in which the geometric properties are related to hydraulic boundary conditions often are derived from a large number of tidal inlets along a certain coast in the world. The relationship for the amount of sand volume stored in the outer delta for example, was derived for outer deltas in the USA. It was found that this relation was valid for Dutch tidal basins as well. Eysink (1990) found a relation between the water volume in the channels and the characteristic tidal volume based on tidal inlets along the Dutch coast. Also this relation appears to be broader applicable. Mostly there are empirical coefficients in these relations and they have different values for different applications. The empirical coefficient in the relation for channel volume differs for the Wadden Sea and for the Eastern Scheldt. Therefore, these coefficients should be applied with great caution.

Another point of issue is the number of elements to be used. In the case under consideration, a two element approach was used. Thus, only interaction between the channel element and intertidal flats with the outside world was included. There is no general constraint to the number of elements that should be considered. The model appears to simulate the development of this tidal basin over the last hundred years rather well. It is unknown how sensitive the model will be when more elements are considered like for instance the ebb-delta and the barrier coasts. And perhaps there are elements that should be accounted for in any case to get reliable results. The intertidal flat element seems to be a main element because it functions as a steering parameter for the tidal prism. The tidal prism is the main variable in the empirical relations. The development of the sensitivity to the number of elements could be subject of further investigation. The ASMITA model should be applied to a well documented and extensive studied tidal basin.

When considering the above remarks in the scope of this thesis it is emphasized that although the model simulated the Lister Tief basin in a reasonable manner, caution is needed when interpreting the results or using input as general values. The sensitivity of variables has been subject of investigation, but no extensive analysis has been carried out in this study because this was no primary objective. If there is a desire to apply the model in a more elaborate way, it is recommended to use more elements. Moreover, extensive sensitivity analysis and data gathering can improve the model results. The results from this study can be used as a guideline for further model application. Although the empirical relations used in the model are to a large extent based on the Dutch situation, they appear to be applicable to the Lister Tief tidal basin.

6 Conclusions and Recommendations

6.1 Conclusions

The apparently anomalic behaviour of the Lister Tief tidal basin formed the starting point of this M.Sc. thesis in which the morphodynamics of tidal basins was studied. An analysis based on the modelling concept of ASMITA and hypsometric parameters, using the actual bathymetry, is carried out. Besides, the ASMITA model was set-up and implemented for the Lister Tief. To make a fair comparison possible, two tidal basins in the Dutch Wadden Sea were analysed as well.

6.1.1 Model concept and Theory

A comparison between theory on hypsometry of Dronkers (2001) and Friedrichs and Aubrey (1988) on the one hand and the concept of ASMITA on the other hand, has been made. The characteristics of the Lister Tief, Marsdiep and Borndiep basins under an enforced sea-level rise were analysed.

- For the Lister Tief the determinant parameter (the ratio between equilibrium volume and actual volume) following a single element approach from the modelling concept, predict ebb-dominant behaviour. An imposed sea-level rise results in a decrease of this ebb dominance. This can be interpreted as a shift towards flood dominance. The hypsometric parameters indicate behaviour near the equilibrium line between ebb- and flood dominance, with a slight tendency towards flood dominance. Enforcing sea-level rise moves this point away from this equilibrium line towards a situation with more flood dominance.

- When performing these operations for the Dutch tidal basins, the same trend is observed as the Lister Tief tidal basin. Also these tidal basins show a development towards flood dominance under relative sea-level rise. As the same coefficients were used in the empirical relations for all three tidal basins, the Ameland Inlet appears to be ebb dominant. However, after calibration (van Goor 2001) this changes in a situation of near equilibrium.

- It is established that it is important to asses these results in a qualitative sense. This means that the development of the tidal basins under consideration should be assessed rather than establishing that a tidal basin is either flood- or ebb dominant. Doing so, it is concluded that the Lister Tief is not behaving differently from the two Dutch tidal basins.

- From this analysis it is concluded that basin hypsometry has had a significant influence on the development of the asymmetry.

6.1.2 ASMITA model

The ASMITA model has been applied to the Lister Tief tidal basin in a two element approximation. First, the last century was simulated to see whether the model gave reliable results and for calibration purposes.

- The trend of the morphological development of the Lister Tief appears to be simulated in a proper manner. The volume of flats decreased and the channel volume increased in such a way that the tidal basin is developing to its equilibrium. This state of equilibrium is nearly the case for the tidal flats, but the channel volume has not reached its equilibrium value. The reason for the slower response of the channel volume is probably that the equilibrium channel volume is dependent on the tidal prism and the steering parameter for the tidal prism is the flat volume. Moreover the relative disturbance as a consequence of sea-level rise on the tidal flats is larger than the relative disturbance in the channels.

- Regarding the deviant behaviour of the Lister Tief it became clear from the simulation that the tidal basin was out of its equilibrium regarding tidal flat volume and channel volume. The adaptation from this disturbance develops in such a way that the tidal basin approaches its dynamic equilibrium. Sea-level rise accelerates this development as this will generally cause a reduction in intertidal flat area and an increase of channel depth. It appears that the tidal basin in present state has approached its (static) equilibrium value, which clarifies the slight ebb-dominant behaviour as observed.

- Forecasts for the next 50 years indicate a continuation of this trend. A further degradation of tidal flats and increase in channel volume will occur even under sea-level rise. However, after crossing its (static) equilibrium value the basin development can be expected to stabilize around its dynamic equilibrium. This new dynamic equilibrium causes permanent difference between the equilibrium volume with sea-level rise and the equilibrium volume without sea-level rise. This difference is necessary to maintain the demand for sediment that drives sand into the system in such a rate that the basin does not drown.

- The application of the aggregated scale model clarifies the question whether the model formulation is sufficient to exhibit the observed behaviour under relative sea-level rise, as the simulations with the model has showed that export of sediment occurs. When a basin is out of equilibrium in one way or another, it will try to reach a state of equilibrium. In the case under consideration, sea-level rise accelerates this development towards equilibrium as it reduces the tidal flat volume and increases the channel volume.

- The data used in this study for the historic situation suffered from particular uncertainty, regarding the amount of tidal flats, channels and tidal prism. Different methods and different levels were used in various studies. The cause is likely to be found in the use of nautical maps for the reconstruction of the historical development of the tidal basin and the use of different ordnance levels by the various authorities. In the two element study these uncertainties have been corrected for the best of our abilities.

6.1.3 General

- The deviant behaviour of the Lister Tief cannot be explained by hypsometric parameters indicating tidal asymmetry. Their present values as well as the development under influence of sea-level rise show similar behaviour as those of the Dutch Wadden Sea basins.

- ASMITA model concept agrees with theory of tidal asymmetry concerning the development under sea-level rise. However, whether a basin is importing or exporting depends on the initial state with respect to the equilibrium state of a basin. This cannot be simply related to the parameters indicating tidal asymmetry. ASMITA can only be applied if sufficient data concerning long-term morphological behaviour are available, because calibration is needed for the empirical relations.

- The reason of the deviant behaviour is still not exactly clear. There are indications that the tidal range increased significantly. It is unclear whether this increase occurred gradually or more rapid and how this relates to the Dutch situation.

6.2 Recommendations

From this study several conclusions were drawn. Some of them answer the research questions posed in the first chapter. The basin hypsometry does have a significant influence on the tidal asymmetry and analysis showed that for this tidal basin the state of the basin will become more flood dominant under influence of sea-level rise. This does not explain the exporting behaviour of the tidal basin.

However, to get more reliable results it is recommended to use more than two elements and investigate how this will improve the results. Therefore, more data are needed on other elements in the system such as the ebb tidal delta. Moreover, it is recommended to gather more reliable historical data on the development of geometric parameters of the tidal basin. These data can function as a tool to improve the model results, but it can also help to find an exact reason why the tidal basin is out of equilibrium.

Furthermore for future research the effects of human interventions, such as dam construction and sand mining in the ebb tidal delta should be analyzed.

Also the significant increase in tidal range draws the attention. It is unknown what caused the change in hydrodynamic situation and whether it changed gradually. Here, more data on the development of the tidal range over the last century can provide some answers to these questions.

References

Angremond, K., d', Velden, E.T.J.M., 2001. Introduction Coastal Engineering, college dictaat CT4300, Faculteit der Civiele Techniek en Geowetenschappen, Technische Universiteit Delft.

Battjes, J.A., 2000. Stroming in open waterlopen, College handleiding CT3310, Faculteit der Civiele Techniek en Geowetenschappen, Technische Universiteit Delft.

Battjes, J.A., 2000. Korte Golven, College handleiding CT4320, Faculteit der Civiele Techniek en Geowetenschappen, Technische Universiteit Delft.

Bartholdy, J., Folving, S., 1986. Sediment classification and surface type mapping in the Danish Wadden Sea by remote sensing, Netherlands Journal of Sea Research, Vol. 20 (No. 4), p. 337-345.

Biegel, E.J., 1992. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project, Annex data report, Part 1: Results, Calculations and methods Phase 2. WL | Delft Hydraulics, Report H1300.

Biegel, E.J., 1992. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project. Annex data report, Part 2: Selected data of the Dutch Wadden Sea. WL | Delft Hydraulics, Report H1300.

Boon, J.D., Byrne, R.J., 1981. On basin hypsometry and the morphodynamic response of coastal inlet systems, Marine Geology, Vol. 40, p. 27-48, Elsevier Scientific Publishing Company, Amsterdam.

Breuning-Madsen, H.,1995. Deposition of Fine-Grained Sediment in the Köningshafen Tidal Area, Sylter Wattenmeer Austausch Processe Teilprojekt B 4.2, Kopenhagen.

Buijsman, M.C., 1997. The impact of gas extraction and sea-level rise on the morphology of the Wadden Sea, WL | Delft Hydraulics, Report H3099.30.

Coastal Protection and Sea-level rise (CPSL), 2001. Final Report of the Trilateral Working Group on Coastal Protection and Sea-level rise. Wadden Sea Ecosystem No. 13 Common Wadden Sea Secretariat, Wilhelmshaven, Germany.

Dronkers, J. J., 1964. Tidal computations in rivers and coastal waters. North-Holland Publishing company, Amsterdam.

Dronkers, J., 1986. Tidal asymmetry and estuarine morphology, Netherlands Journal of Sea Research, Vol. 20 (No.2/3), p. 117-131.

Dronkers, J., 1998. Morphodynamics of the Dutch Delta, In: J. Dronkers and M. Scheffers (eds.), Physics of estuaries and coastal seas, Balkema, Rotterdam, p. 297-304.

Dronkers, J., 2001. Physics of Coastal Systems, Lecture Course Utrecht University, Institute for Marine and Atmospheric research, Utrecht.

Duijts, R.W., 2002. Tidal asymmetry in the Dutch Wadden Sea, M.Sc. thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences.

Ehlers, J., 1988. The Morphodynamics of the Wadden Sea, Balkema, Rotterdam.

Eysink, W.D., 1990. Morphological response of tidal basins to change, Proc. 22nd Int. Conference on Coastal Engineering, ASCE, Delft, July 2-6, Vol. 2, p. 1948-1962.

Eysink, W.D., 1991. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project, Phase 1, Inventory of available data and literature and recommendations on aspects to be studied. WL | Delft Hydraulics, Report H1300.

Eysink, W.D., Biegel, E.J. , 1992. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project, Phase 2, Investigations on empirical morphological relations. WL | Delft Hydraulics, Report, H1300.

Eysink, W.D., 1992. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project, Phase 3, Proposed set-up of a dynamic morphological model for Wadden Sea basins and estuaries based on empirical relations. WL | Delft Hydraulics, Report, H1300.

Eysink, W.D., 1993. Impact of sea-level rise on the morphology of the Wadden Sea in the scope of its ecological function, ISOS*2 Project, Phase 4, General considerations on hydraulic conditions, sediment transports, sand balance, bed composition and impact of sea-level rise on tidal flats. WL | Delft Hydraulics, Report, H1300.

Friedrichs, C.T., Aubrey, D.G., 1988. Non-linear tidal distortion in shallow well-mixed estuaries: a Synthesis, Estuarine Coastal and Shelf Science, Vol. 27, p. 521-545

Gätje, C., Reise K (Eds), 1998. Ökosystem Wattenmeer: Austauch-, Transport- und Stoffumsatzprozesse, Springe, Berlin.

Goor, M.A. van, 2001. Influence of Relative Sea-level rise on Coastal Inlets and Tidal Basins, WL | Delft Hydraulics/Delft Cluster, Report Z2822/DC03.01.03a.

Groen, P. 1967. On the residual transport of suspended matter by an alternating tidal current, Netherlands Journal of Sea Research 3, p. 564-574.

Hayes, M.O. 1979. Barrier Island morphology as a function of tidal and wave regime, in: Leatherman, S.P. (ed.), Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico, Academic Press, New york.

Kragtwijk, N.G., 2001. Aggregated scale modelling of tidal inlets of the Wadden Sea. WL | Delft Hydraulics/Delft Cluster, Report Z2822/DC03.01.03a.

Kreeke, J., van de, Robaczewska, K, 1993. Tide-induced residual transport of coarse sediment; application to the Ems estuary., Netherlands Journal of Sea Research, Vol. 31 (No. 3), p. 209-220.

Kruif, A.C. de, 2001. Bodemdieptegegevens van het Nederlandse kustsysteem. beschikbare digitale data en een overzicht van aanvullende analoge data. Rapport RIKZ/2001.041.

Kystinspektoratet, 1999. Morfologisk udvikling i Vadehavet, Lister Dybs Tidevandsomrade og Vadehavsfronten.

Oost, A.P., 1995. Dynamics and Sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian Inlet, a study of the barrier islands, ebb-tidal deltas, inlets and drainage basins, Thesis, University Utrecht.

Speer, P.E., Aubrey, D.G., 1985. A study of Non-linear tidal propagation in shallow Inlet/Estuarine Systems, Part 1: Observations, Estuarine Coastal and Shelf Science, Vol. 21 (No. 2), p. 185-205.

Speer, P.E., Aubrey, D.G., 1985. A study of Non-linear tidal propagation in shallow Inlet/Estuarine Systems, Part 2: Theory, Estuarine Coastal and Shelf Science, Vol. 21 (No. 2), p. 207-224.

Speer, P., Aubrey, D.C. , Friedrichs, C.T., 1991. Non-linear hydrodynamics of shallow tidal inlet/bay systems, in Parker B.B. (ed.) Tidal hydrodynamics, J. Wiley and Sons, New York.

Spiegel, F., 1998. Die Tidebecken des schleswig-holsteinischen Wattenmeeres: Morphlogischen strukturen und Anpassungsbedarf bei weiter steigendem Meeresspiegel, Christian-Albrechts-Universität zu Kiel.

Steijn, R.C., 1991. Some considerations on tidal inlets. A literature survey on hydrodynamic and morphodynamic characteristics of tidal inlets with special attention to "Het Friesche Zeegat", Report H840.45, WL | Delft Hydraulics.

Stive, M.J.F., Capobianco, M., Wang, Z.B., Ruol, P., Buijsman, M.C., 1998. Morphodynamics of a tidal lagoon and the adjacent coast. In: J. Dronkers and M. Scheffers (eds.), Physics of estuaries and coastal seas, Balkema, Rotterdam, p. 397-407.

Stive, M.J.F. , Wang, Z.B., Van Dongeren, A., De Vriend, H.J. , Dronkers, J., 2000. Coastal Inlets and Tidal Basins. College handleiding CT5303, Faculteit der Civiele Techniek en Geowetenschappen, Technische Universiteit Delft.

Straaten, L.M.J.U. van, and Kuenen, Ph. H., 1957. Accumulation of fine grained sediments in the Dutch Wadden Sea. Geologie and Mijnbouw, 19(1957)August, p. 329-354.

Umweltatlas Wattenmeer, 1998. Band 1 Nordfriesisches und Dithmarscher Wattenmeer, Eugen Ulmer GmbH & Co., Stuttgart.

Velden, E.T.J.M., van der, 2000. Coastal Engineering, vol. 2, college dictaat CT5309, Faculteit der Civiele Techniek en Geowetenschappen, Technische Universiteit Delft.

Walton, T.L., Adams, W.D., 1976. Capacity of Inlet outer bars to store sand, Proc. 15th Int. Conference on Coastal Engineering, ASCE, Hawaii, p. 1919-1937.

Walton, T.L. Jr., 2002. Tidal velocity asymmetry at inlets, ERDC/CHL CHETN IV-47, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Wang, Z.B., Jeuken, C., De Vriend, H.J., 1999. Tidal asymmetry and residual sediment transport in estuaries, a literature survey, Report Z2749, WL | Delft Hydraulics.

Wang, Z.B., van der Weck, A., 2002. Sea-level rise and Morphological development in the Wadden Sea, a desk study, Report Z3441, WL | Delft Hydraulics.

Morphodynamics of the Lister Tief Tidal Basin

Appendices

January, 2004

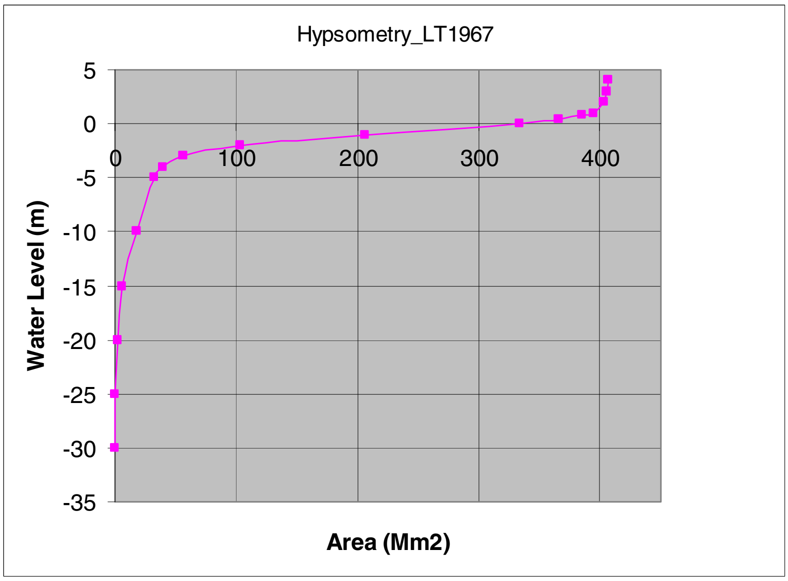
A Wave data

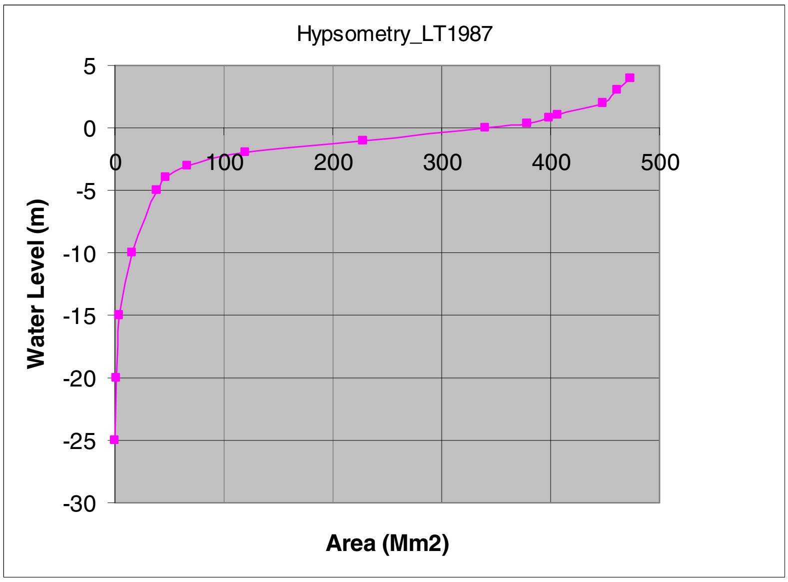
Wavestatistics, 4018 days, 01.10.86 - 30.09.97

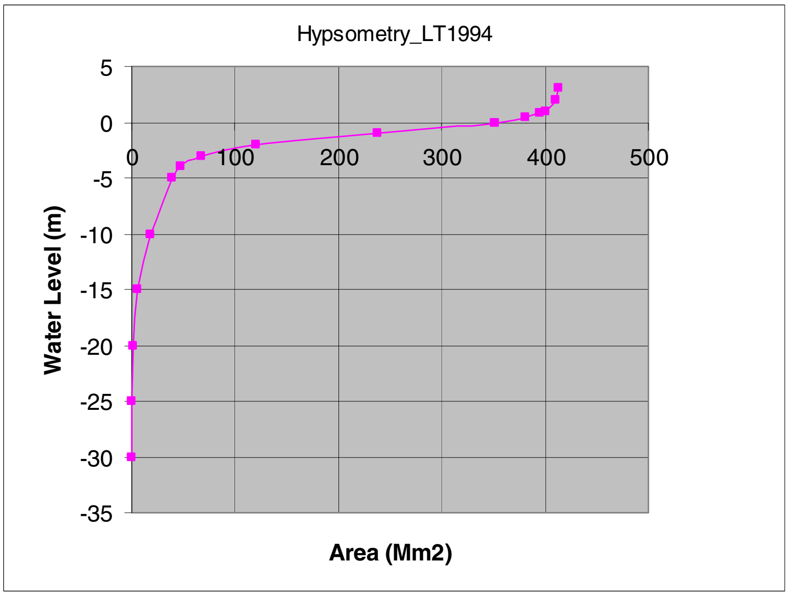
Hm0 [m]/Degree	0,0	22,5	45,0	67,5	90,0	112,5	135,0	157,5	180,0	202,5	225,0	247,5	270,0	292,5	315,0	337,5	
0,25																	
0,50	1,650	1,305	1,019	0,587	0,342	0,302	0,295	0,250	0,516	0,843	1,209	1,533	2,658	4,233	6,568	1,724	25,035
0,75	0,476	0,133	0,154	0,089	0,114	0,093	0,179	0,325	0,456	0,599	1,079	3,739	2,616	4,285	7,739	1,296	23,372
1,00	0,107	0,002	0,011		0,002	0,005	0,011	0,011	0,094	0,252	1,198	2,958	0,554	4,002	3,524	1,313	14,045
1,25	0,064	0,000			0,001		0,003	0,008	0,035	0,185	0,991	1,865	0,730	3,356	2,197	0,719	10,154
1,50	0,064	0,002							0,002	0,081	0,639	1,251	0,760	2,414	1,556	0,412	7,181
1,75	0,021								0,001	0,042	0,473	0,937	0,764	1,829	1,150	0,232	5,450
2,00	0,002								0,001	0,040	0,324	0,672	0,678	1,514	0,870	0,105	4,206
2,25									0,001	0,032	0,194	0,534	0,544	1,179	0,599	0,047	3,131
2,50										0,009	0,093	0,430	0,442	0,801	0,440	0,030	2,246
2,75											0,085	0,239	0,422	0,593	0,311	0,003	1,653
3,00											0,053	0,201	0,349	0,419	0,208	0,003	1,232
3,25											0,024	0,170	0,271	0,264	0,078	0,003	0,809
3,50											0,009	0,106	0,196	0,253	0,062		0,627
3,75											0,002	0,062	0,123	0,180	0,029		0,397
4,00											0,001	0,028	0,076	0,091	0,009		0,205
4,25												0,011	0,045	0,058	0,001		0,115
4,50												0,012	0,029	0,042			0,083
4,75												0,002	0,012	0,020			0,034
5,00												0,003	0,008	0,006			0,017
5,25												0,001	0,004				0,005
	2,385	1,443	1,183	0,676	0,459	0,400	0,488	0,594	1,108	2,082	6,374	14,754	11,283	25,540	25,34	5,888	100,0

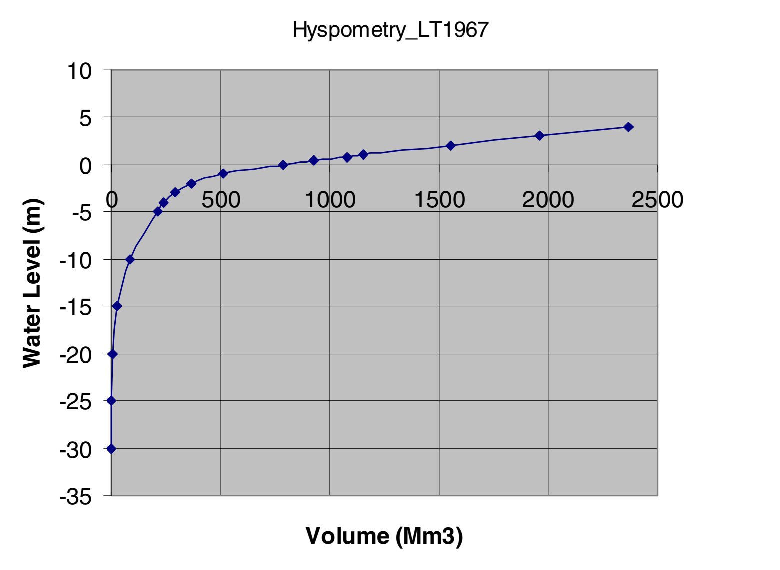
Source: http://www.iczm.de

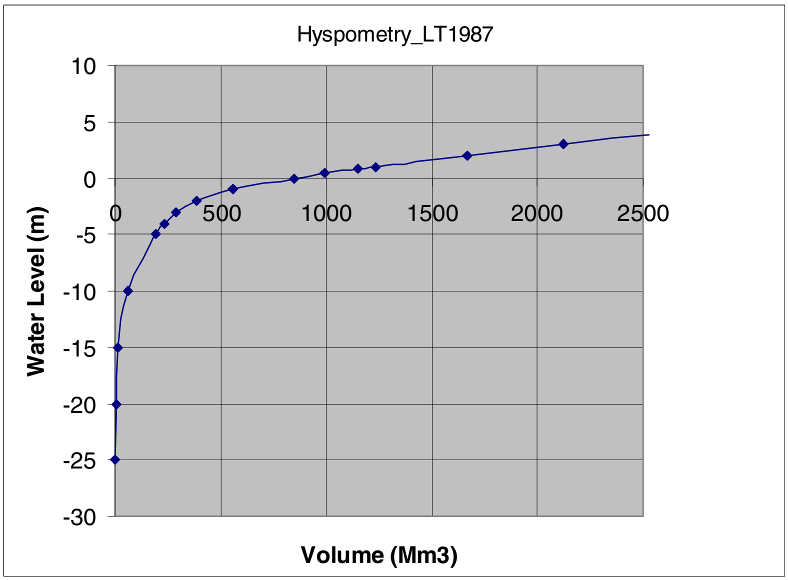
B Results calculations Lister Tief

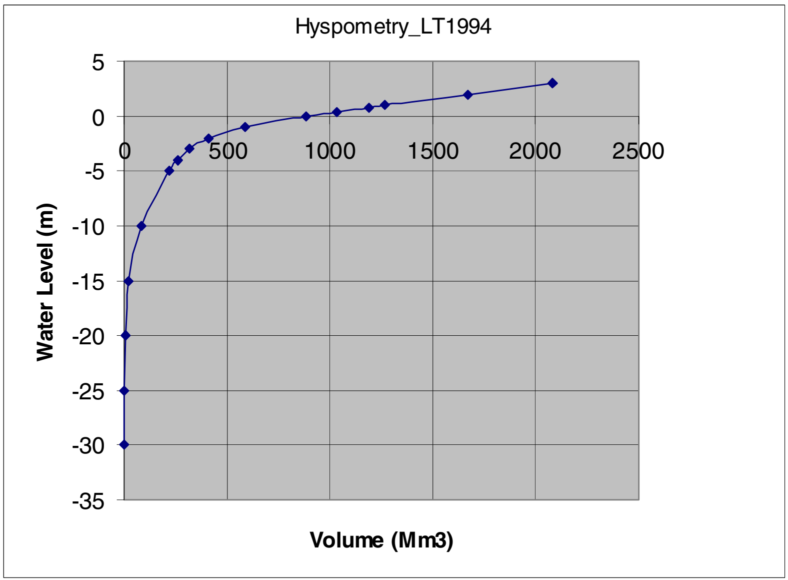

Hypsometry_LT1967
Water Level (m)
Area (Mm2)
5
0
-5
-10
-15
-20
-25
-30
-35
0
100
200
300
400


Hypsometry_LT1987
Water Level (m)
Area (Mm2)
5
0
-5
-10
-15
-20
-25
-30
0
100
200
300
400
500


Hypsometry_LT1994
Water Level (m)
Area (Mm2)
5
0
-5
-10
-15
-20
-25
-30
-35
0
100
200
300
400
500

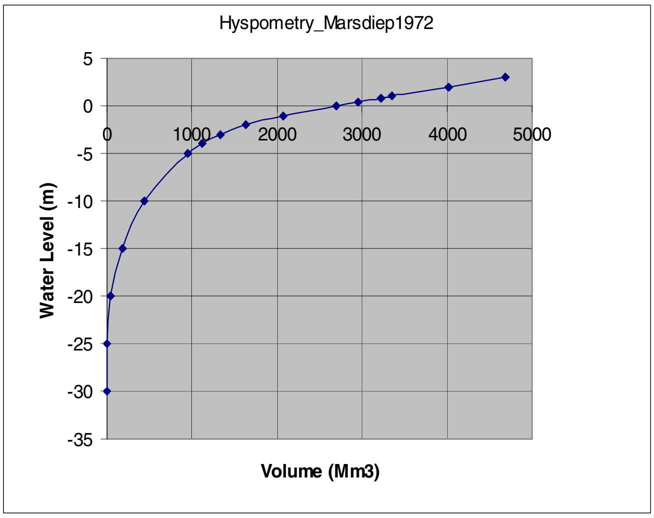

Hyspometry_LT1967
Water Level (m)
Volume (Mm3)
10
5
0
-5
-10
-15
-20
-25
-30
-35
0
500
1000
1500
2000
2500

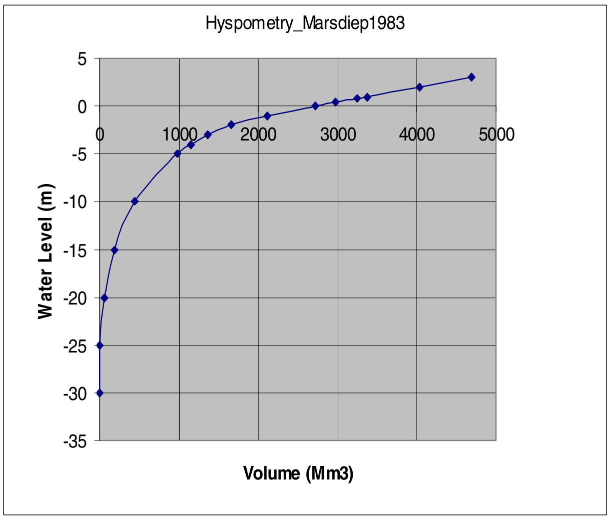

Hyspometry_LT1987
Water Level (m)
Volume (Mm3)
10
5
0
-5
-10
-15
-20
-25
-30
0
500
1000
1500
2000
2500

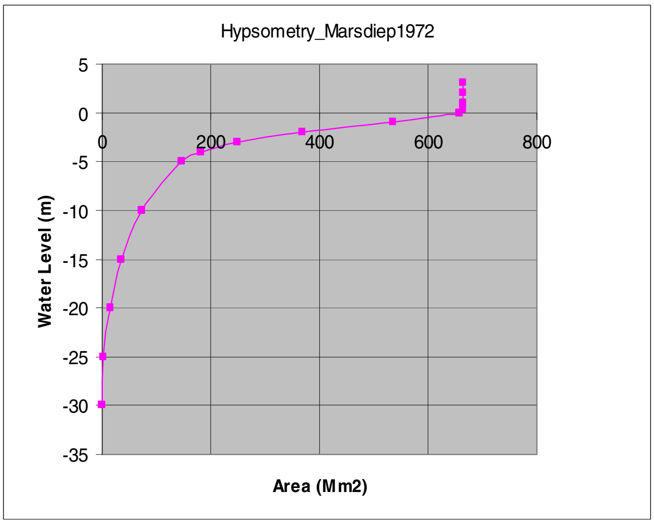

Hyspometry_LT1994
Water Level (m)
Volume (Mm3)
5
0
-5
-10
-15
-20
-25
-30
-35
0
500
1000
1500
2000
2500

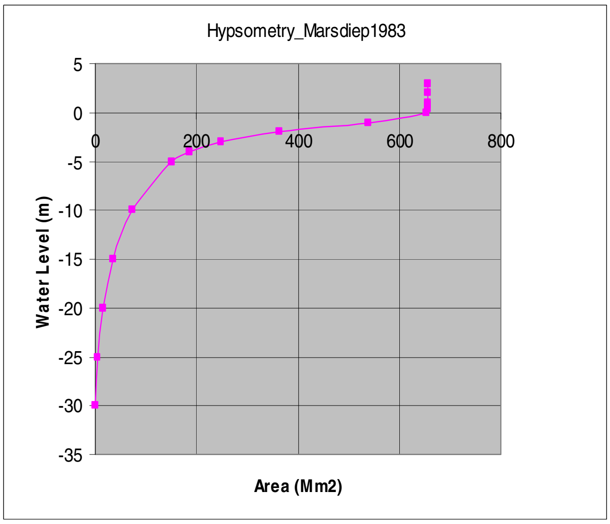
C Results Calculations Marsdiep and Borndiep

Hypsometry Marsdiep

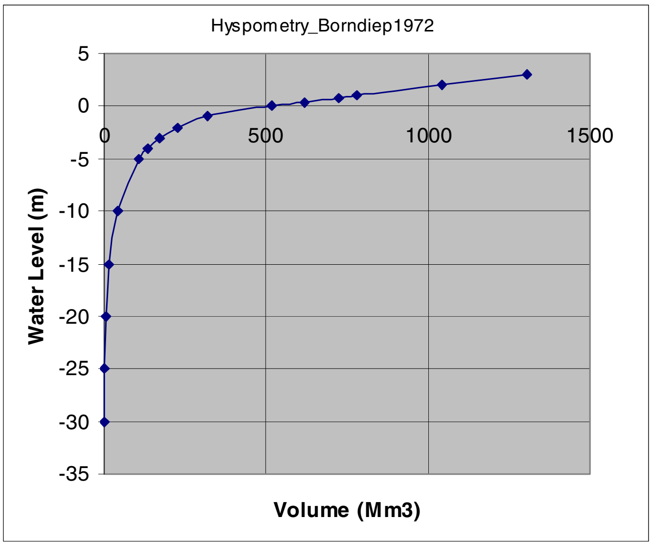


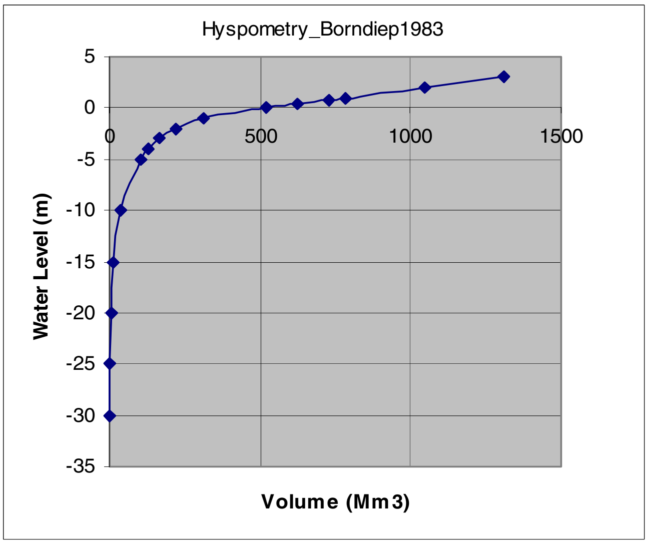


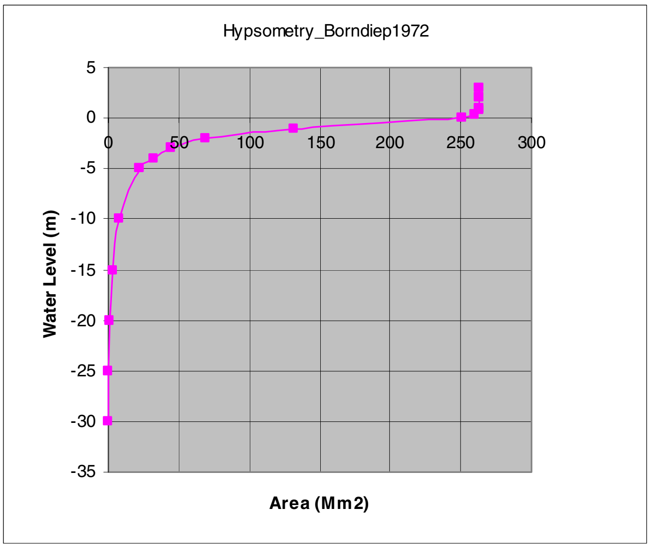


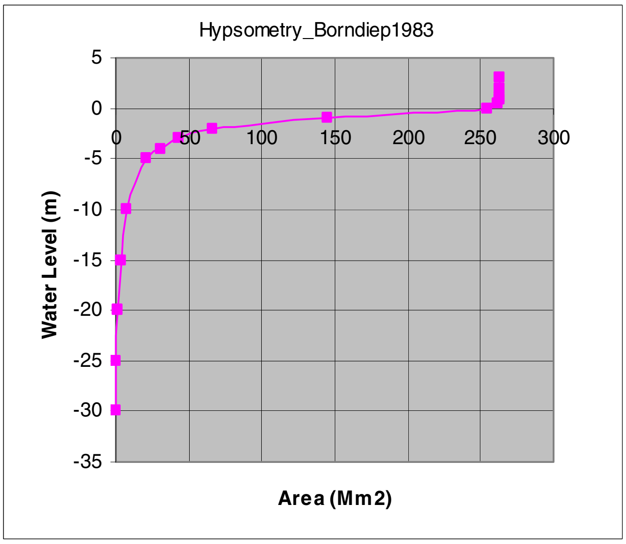


Hypsometry Amelander Zeegat





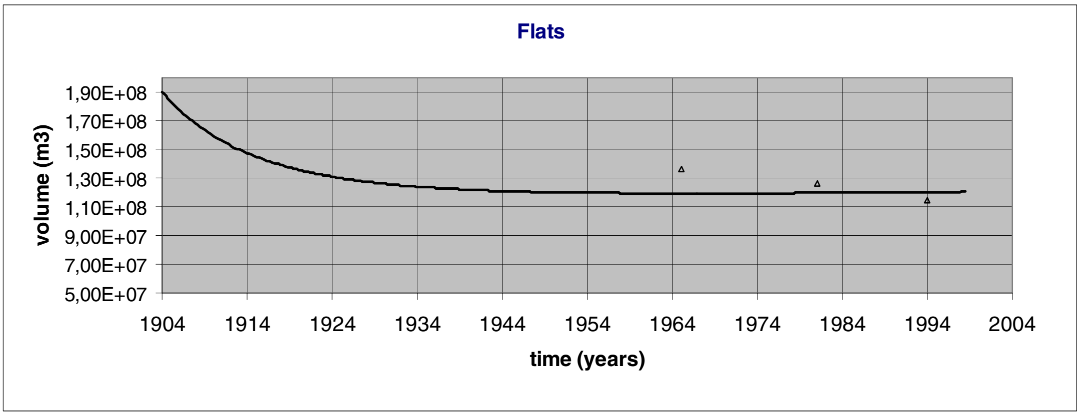


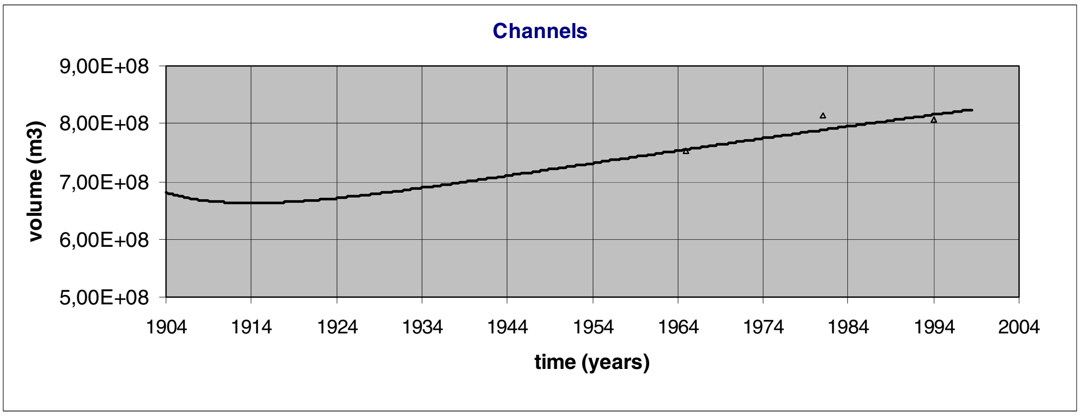


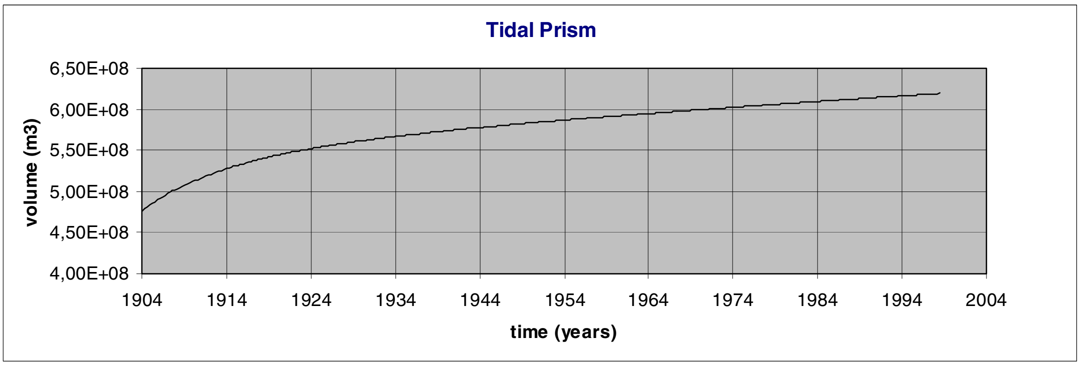
D Results ASMITA application

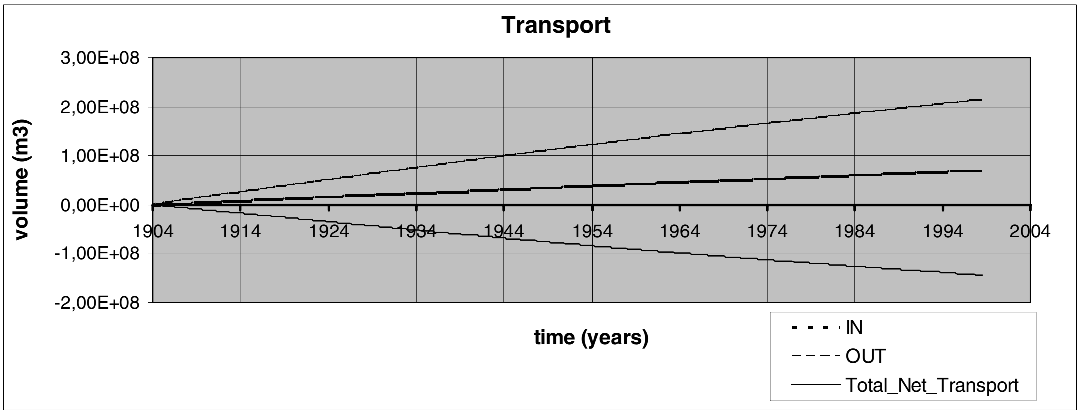
Simulation 1904-1994

sea-level rise: 1.8 mm/year



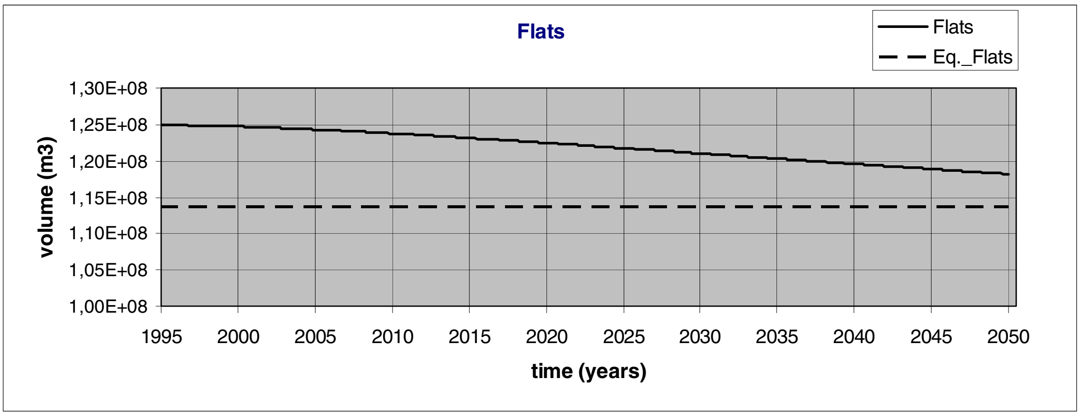


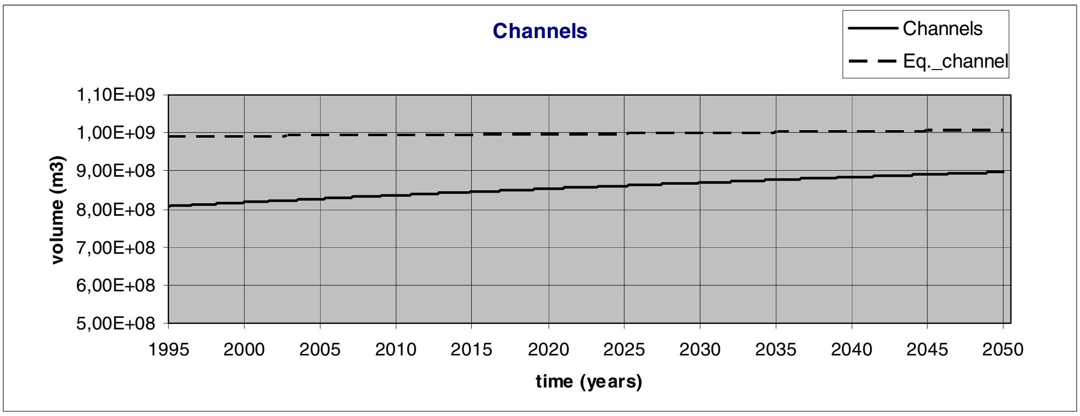


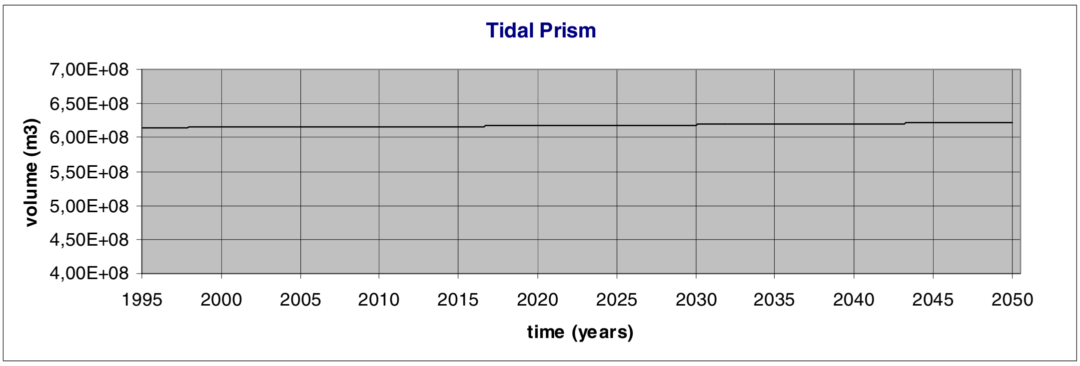


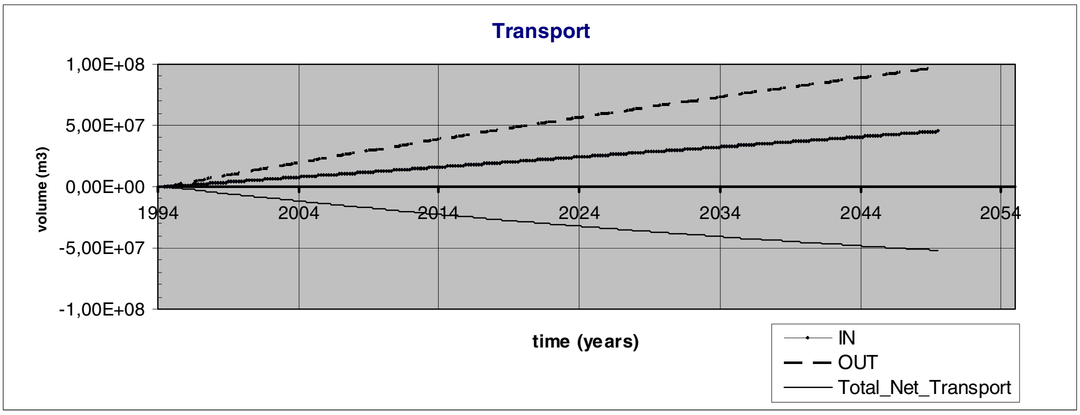
Simulation 1994-2050

In the graphs of the Flats and Channels also the development of the equilibrium value is depicted.
sea-level rise 2.0 mm/year



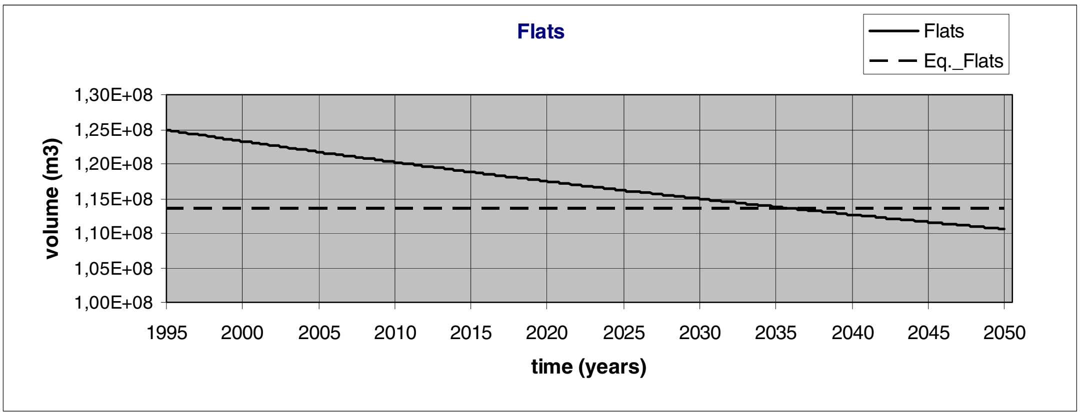


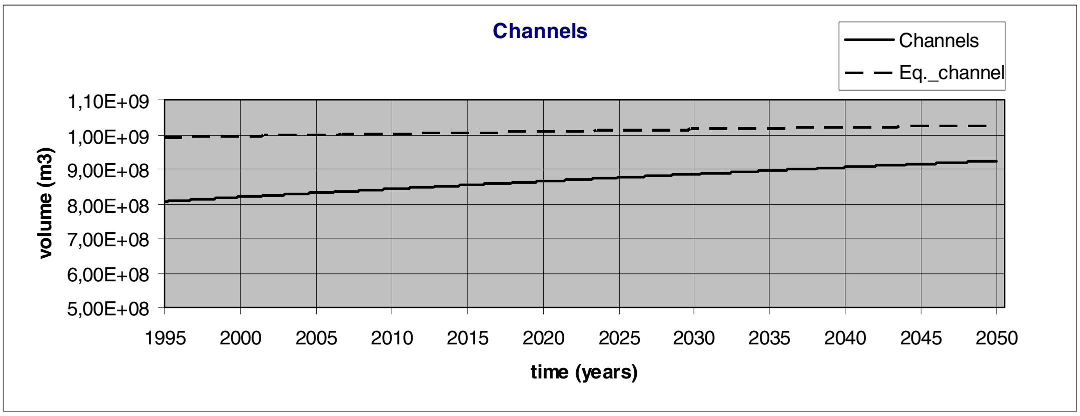


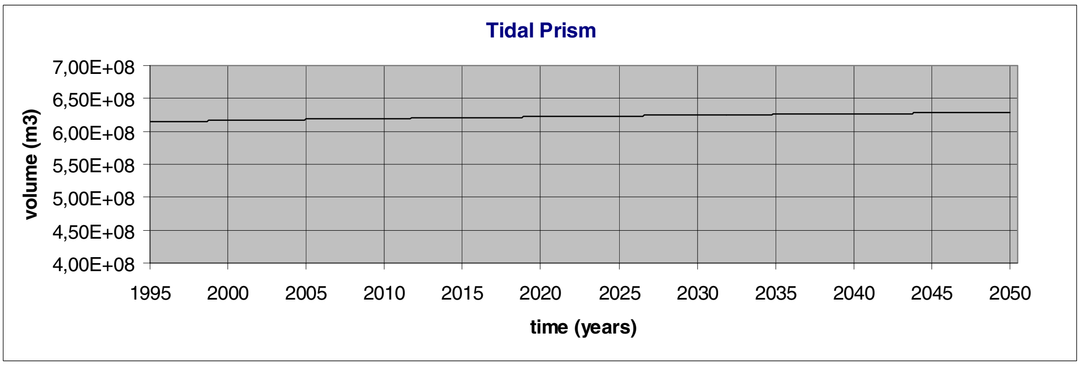


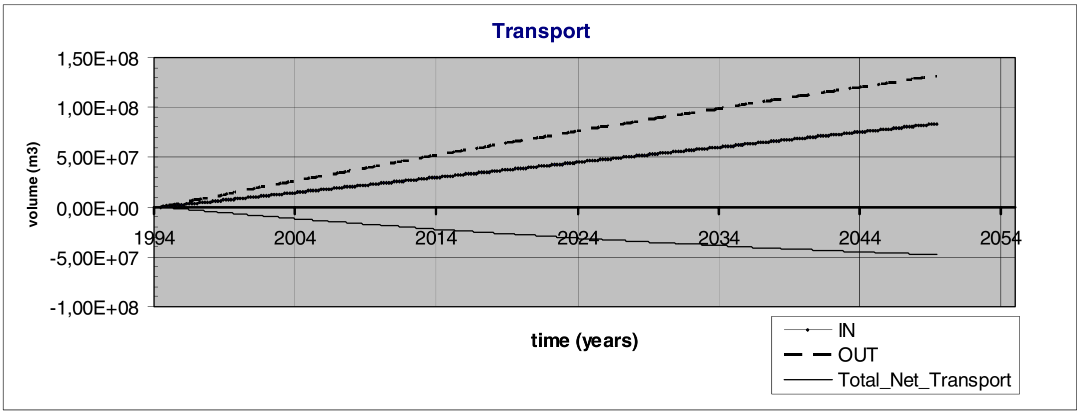
Simulation 1994-2050

In the graphs of the Flats and Channels also the development of the equilibrium value is depicted.
sea-level rise 3.7 mm/year



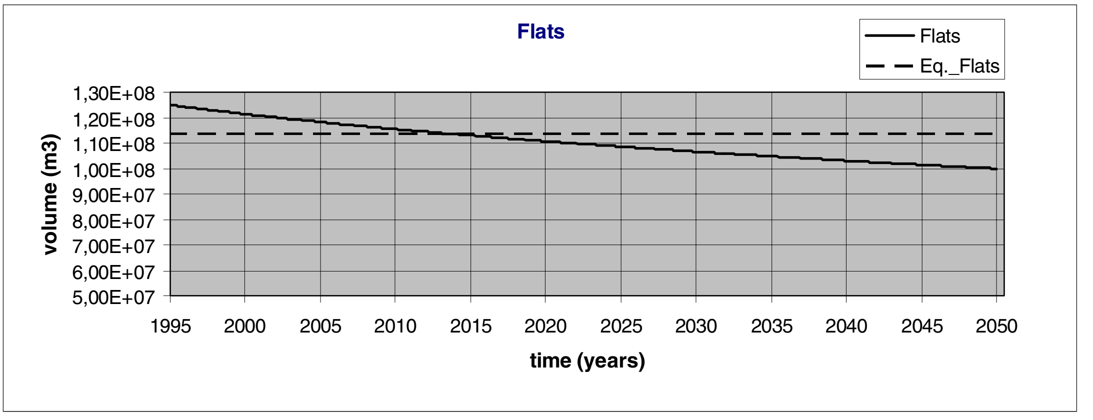


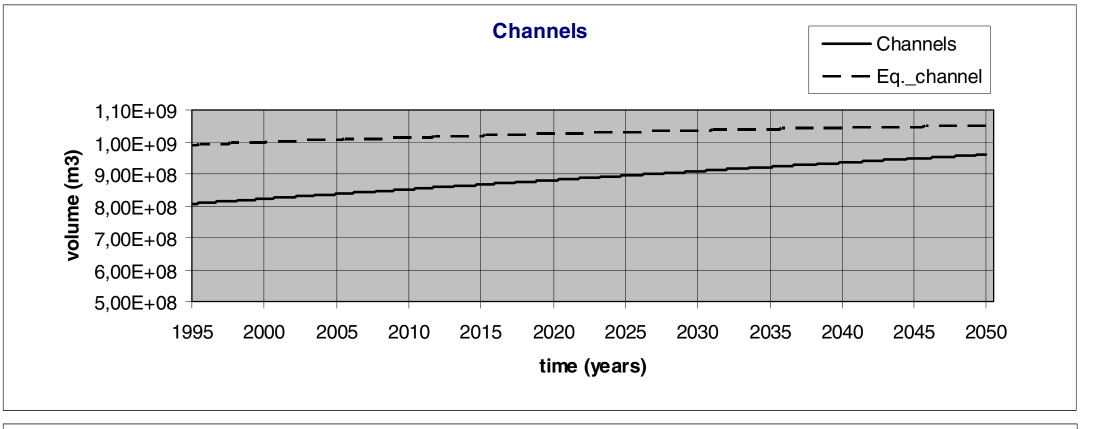


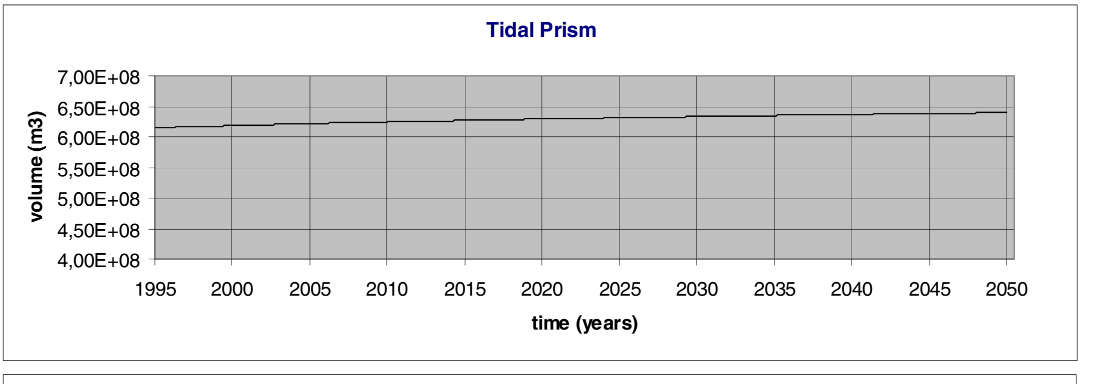


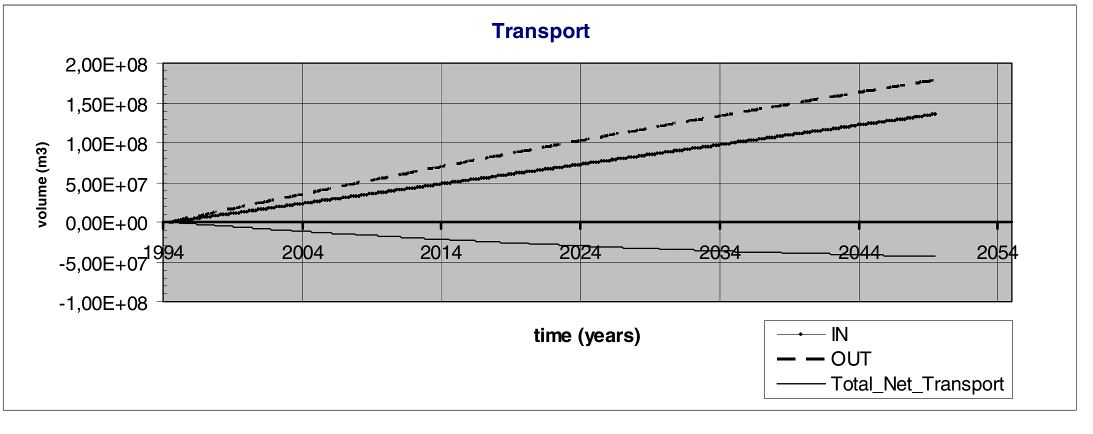
Simulation 1994-2050

sea-level rise 6.0 mm/year









E Relative Phases

An important overtide is the M_4 tide which is generated due to interaction of M_2 with itself as a result of the non-linear dynamic processes in shallow waters. The phase difference can be calculated from the harmonic analysis by writing the M_2-constituent as follows:

$$u_{M_2} = a_2 \cdot \cos(\omega_2 t - \varphi_2)$$

Herein, a_2 is the amplitude which is determined with the harmonic analysis; ω is the angle velocity and φ_2 is the phase of the M_2 constituent.

The angular velocity of the M_4 component equals twice the angular velocity of the M_2 constituent. This can be written in terms of the M_2 angular velocity, as follows:

$$u_{M_4} = a_4 \cdot \cos(\omega_4 t - \varphi_4)$$

$$= a_4 \cdot \cos(2\omega_2 t - \varphi_4)$$

a_4 is the amplitude of M_4; ω is again the angular velocity of the M_2 constituent. The phase difference between M_4 and M_2 is calculated relative to the time of maximum positive amplitude of the M_2 constituent; u_2 has its maximum at:

$$t = t_{\max,2} = \frac{\varphi_2}{\omega_2}$$

and u_4 has its maximum at:

$$t = t_{\max,4} = \frac{\varphi_4}{\omega_4} = \frac{\varphi_4}{2\omega_2}$$

The “distance” between the two maxima is then:

$$\mathrm{t}_{\max,2} - \mathrm{t}_{\max,4} = \frac{2\varphi_2 - \varphi_4}{2\omega_2}$$

and relative with respect to the period of M_2: $\omega_2 = \frac{2\pi}{\mathrm{T}_2}$

$$\frac{\mathrm{t}_{\max,2} - \mathrm{t}_{\max,4}}{\mathrm{T}_2} 2\pi = 2\varphi_2 - \varphi_4$$

F Overview North Frisian Wadden Sea

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