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RIKZ

Long - term morphological evolution of the Western Dutch Wadden Sea

Report

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P.F.C. van Geer

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Preface

The present report is the result of the research project undertaken in order to obtain the degree of Master of Science at Delft University of Technology. This research has been executed at WL | Delft Hydraulics.

The study concerns long-term morphologic development of the Western Wadden Sea.

First of all I would like to thank my supervisors Prof. dr. ir. M.J.F. Stive (Delft University of Technology), Dr. ir. Z.B. Wang (Delft University and WL | Delft Hydraulics), ir. J.G. de Ronde (Delft University and RIKZ), Dr. ir. ing. E.P.L. Elias (WL | Delft Hydraulics), ir. T.J. Zitman (Delft University) and Dr. J.E.A. Storms (Delft University) for sharing their knowledge and for their support during this study. I would also like to thank my temporary collegues and fellow graduates at WL | Delft Hydraulics for supporting me and making my stay at wl | Delft Hydraulics a pleasant one. Finally I would like to thank my family, my friends and girlfriend for their support during the years I spent in Delft.

Pieter van Geer
Delft, October 2007

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Summary

A large part of the Netherlands is located below mean sea level. This densely populated area is protected by dunes and dikes. Safety of people that live in this area is therefore dependant on the morphological development of those dunes. For a long time people have investigated the sediment budget and morphology of the Dutch Coast. To secure dry feet predictions are made of the evolution of this sediment balance in future.

One of the uncertainties in such predictions are estimations regarding future sediment demand of the inlets forming the Dutch Wadden Sea. This part of the Netherlands consists of several barrier lagoon systems. Due to the closure of the Zuider Sea in 1932 parts of the basins Marsdiep and Vlie are cut of. A morphologic reactions of all basins are observed in the following period.

Former studies tried to estimate the sediment demand of individual basins using a model on an aggregated scale. These ASMITA models schematize a basin into three elements representing flat, channel and delta areas. For each element an equilibrium is defined based on basin characteristics. The model describes the evolution of these individual elements towards this equilibrium after the system has been brought out of equilibrium. Recent analysis of field data lead to the conclusion that the basins forming the Western Dutch Wadden Sea can not be seen as isolated systems. Sediment exchange must have occurred over the boundaries of those basins. Furthermore also the surface areas of all elements is kept constant in time whereas measurements indicate that these basin characteristics change in time.

The objective of this study is to improve the prediction of long-term morphological development of the Western part of the Dutch Wadden Sea under influence of SLR and human intervention by eliminating the shortcomings of the existing models.

Watersheds are used to define boundaries between basins for schematization in ASMITA. Due to morphologic changes the placement of those boundaries does not have to be constant in time. In this study boundaries are determined for several bathymetries representing various years between the closure of the Zuider Sea and present. This is done by simulating water movement using the process based model Delft3D. Watersheds can be identified by connecting points with minimal standard deviation of the velocity to separate two inlets. The watershed between Marsdiep and Vlie concluded using this method shows a clear shift towards the East between 1932 and present. This indicates that not only sediment exchange over the boundaries has to be accounted for in ASMITA calculations, but also movement of the boundaries itself.

A comparison is made between basin characteristics analyzed with fixed basin boundaries and actual basin boundaries determined in this study. Furthermore also the influence of the reference level used to determine basin characteristics is assessed. This is done by comparing results of an analysis with fixed water levels in time to results obtained with actual water levels. Both aspects proved to have a significant effect on the trend of the concluded basin characteristics. This indicates the importance of including these aspects in ASMITA models used to predict future morphologic behavior of the Western Wadden Sea.

This study assesses the effect of three suggested adjustments to ASMITA. The adjustments concern exchange over the basin boundaries, inclusion of the movement of basin boundaries and recalculation of the element surface areas of individual elements inside a basin.

Exchange between two basins is achieved by allowing diffusion between the elements adjacent to the boundary that divides these two basins. The sediment exchange between basins is than modeled in the same way as sediment exchange between elements within one basin. Significant sediment transport from Marsdiep towards Vlie described in literature can not be reproduced using such relations. Possibly the driving forces for this sediment exchange are not modeled by a diffusive type phenomenon. Whereas such exchange of sediments is expected to influence the calculated sediment transport rates through individual inlets it is recommended to further investigate the cause of the exchange from Marsdiep towards Vlie concluded from measurements. Including a relation that describes this phenomenon more accurately will improve long-term predictions of the morphological development of the Western Dutch Wadden Sea.

Until now no relation has been found expressing the movement of the basin boundary as a consequence of changing basin characteristics. The effect of these changes however can be assessed by prescribing the changes of volumes and areas of individual elements due to this movement. Calculated development of basin characteristics show a direct and an indirect influence of these change. Obviously characteristics of elements adjacent to the boundaries that are moving are directly influenced by this movement. This direct change causes the tidal prism of both basins to be different. Equilibrium states of other elements inside those basins are influenced by the change of the tidal prism. This also alters sediment exchanges calculated between elements inside the basins. Results of computations including the movement of boundaries in this study indicate that both this indirect effect as well as the direct volume and area changes due to movement of the boundaries have a significant effect on predicted morphological development inside the Western Dutch Wadden Sea. Further investigations into the movement of boundaries between basins is recommended. Including a fair prediction of the changes due to this movement in future would lead to an improvement of the predictions made with ASMITA.

From data analysis it follows that mean flat heights tend to develop towards an equilibrium independent of the development of other basin characteristics. This development can be described with an exponential like relation. Such a relation can be included in ASMITA computations. With a calculated flat volume each time step also the flat surface area can be calculated. Together with the basin surface area this also provides the surface area of the channel element of that basin. In this way the development of the element surface areas in time can be approached and included in ASMITA calculations. Implementing this adjustment into ASMITA does not lead to a significant change of the simulated development of characteristic volumes. Element surface areas however are computed more accurately compared to surface areas that are kept constant in time. This adjustment leads to a better description of reality and is therefore considered to be an improvement of the ASMITA models used to predict morphologic development of the Western Dutch Wadden Sea.

1 Introduction

1.1 Background information

Along the Dutch coast beach nourishments are applied to maintain the present coastline. To be able to predict the volume of the sediment needed for these nourishments it is necessary to predict the future morphologic behavior of the coast under influence of sea-level rise and human interferences. Two important parameters in predicting this behavior are the amount of sediments that is exchanged with both the Westerschelde and the Wadden Sea. To determine the exchange of sediments between the tidal inlets of the Western part of the Dutch Wadden Sea and the adjacent coasts a long-term prediction of the morphologic behavior of the Wadden Sea is desirable. For predicting long-term morphologic behavior of a tidal inlet and its accompanying basin often semi-empirical models are used. This report describes a study in which adjustments to the semi-empirical model ASMITA are discussed to improve the prediction of the future morphologic behavior of the inlet systems Marsdiep Eierlandse gat and Vlie.

The Wadden Sea is one of the Dutch preserved nature parks and can be found in the north of the Netherlands. It lies behind a series of barrier islands and is connected to the North Sea by tidal inlets between those barrier islands. Together this forms a barrier lagoon system. The Western part of the Dutch Wadden Sea (Figure 1.1) consists of three islands and three inlets. Most south the Texel inlet is located with the channel Marsdiep. On the other side of Texel the Eierlandse gat is located and the most eastern inlet of the Western part is formed by the Vlie that runs through the Vlieland inlet. It is common accepted (Stive et. al., 1998) that a barrier lagoon system as described above adapts itself to a dynamic equilibrium in which the surface area of the flats and the area of channels have a fixed relationship. Although the IJsselmeer is now a lake containing fresh water it used to belong to the Western part of the Dutch Wadden Sea as well. Before the Zuider Sea was closed off in 1932 the Marsdiep and Vlie inlet reached into the Zuider Sea. After the closure the channels adapted themselves to the situation as it is today.

Figure 1.1: Overview of the Western part of the Dutch Wadden Sea

1.2 Former research

In order to understand and predict the developments of the barrier lagoon systems of the Western Dutch Wadden Sea many studies have been carried out in the past. Eysink and Biegel (1992) investigated the correlation between measured volumes and areas and equilibrium relations for of the individual basins. Stive et. al. (1998) introduced a semi-empirical model (ASMITA) for the computation of the development of the basin characteristics based on this equilibrium concept. Kragtwijk (2001) and van Goor (2001) investigated single inlets in the Dutch Wadden Sea. Boundaries between those systems are placed at the watershed assuming that at the long-term no sediment transport occurs at these boundaries. The study of Kragtwijk (2001) concerns the reactions of the Marsdiep and Vlie on the closure of the Zuider Sea. This is carried out with a fixed tidal range and excluding the effect of sea level rise (SLR). Van Goor (2001) investigated the response of several inlets including the Eierlandse gat to different scenarios of SLR. Also in this study a fixed tidal range was used. Elias (2006) amongst other things examines the sediment budget of the Western Dutch Wadden Sea.

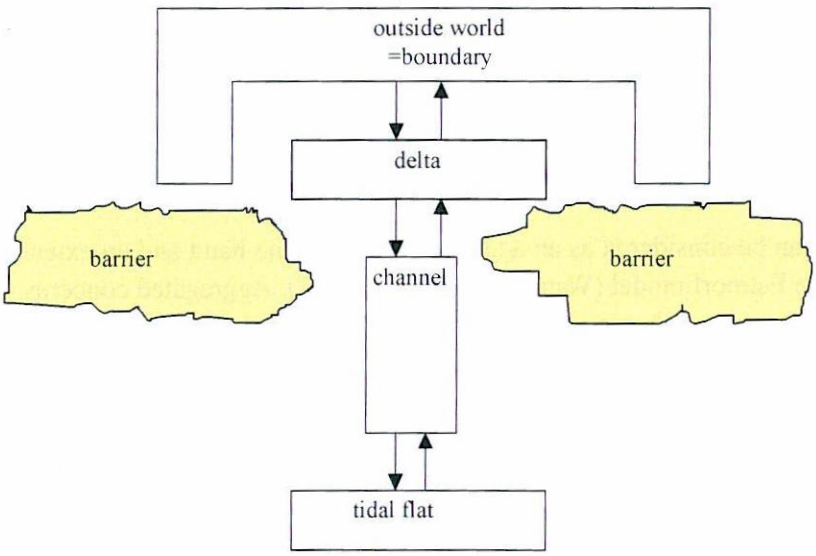


Figure 1.2: Schematization of a barrier lagoon system

1.3 Problem analysis

An important conclusion from the study of sand balances in the Dutch Wadden Sea is that we cannot describe the individual inlets separately as the major erosion occurs at the Marsdiep ebb-tidal delta and the main sedimentation in the Vlie basin. The complete sand-balance of the Western Wadden Sea must be considered as a whole. This indicates that sediment transport must have occurred from Marsdiep towards the Vlie basin. In ASMITA it is not possible to consider the Western Wadden Sea as a whole. The equilibrium relations are not valid for such a system. Although it is possible to define a hydro dynamical boundary, from morphological point of view this can not be considered as a borderline. To have large erosion of the ebb-tidal delta outside Marsdiep basin compensated with large accretion inside the Vlie basin, sediment transport must have occurred at the boundary between those basins.

Closing of large part of the basin area as is done in 1932 when the Zuider Sea was closed of will have a large effect on hydrodynamics. In first instance the tidal range in the back of the Marsdiep basin was significantly increased. The change of the hydrodynamics will also have an effect on the placement of the boundaries. Removing part of the basin influences the total basin surface area and possibly also the relative flat area. To reach a new equilibrium the basin will try to regain flat and/or channel surface area and volume. Until now the surface areas of the individual elements are kept constant in computations using ASMITA.

Shortcomings of the models used in previous studies can be summarized as follows.

- Instead of a fixed boundary at the watershed the systems should be described using a moving boundary because also the watershed between two basins could be moving.
- Sediment exchange between the flat areas of the different inlet systems creating a connection between the systems is not accounted for.
- Change of surface areas of individual elements has to be included in ASMITA.
- Because the coefficients in the equilibrium relations of the existing models appear to give wrong sediment exchange estimates these coefficients should be re-examined also taking the change of relative flat area into account.

1.4 Objective

The objective of this study is to improve the prediction of long-term morphological development of the Western part of the Dutch Wadden Sea under influence of SLR and human intervention. This will be done by eliminating the shortcomings of the existing models as mentioned above.

2 ASMITA

2.1 General approach

The ASMITA model (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast) was first introduced by Stive et. al. (1998). It is an aggregation on the one hand and an extension on the other hand of the ESTMORPH model. Aggregation concerns the fact that a tidal basin is schematized into only two morphological elements. The model is an extension because also the interaction between the tidal inlet and the adjacent coasts is taken into account.

In ASMITA three different morphological elements are defined, each represented by one state variable. These elements are:

- The ebb tidal delta, represented by the total volume of sediments (dry) above a fictitious sea bottom, which would be there if no inlet existed.
- The channels, of which the bathymetry is represented by the total water volume (wet) in the tidal basin below MLW.
- Total inter-tidal flats, represented by the total sediment volume (dry) in the basin between MLW and MHW.

This is illustrated in Figure 2.1.

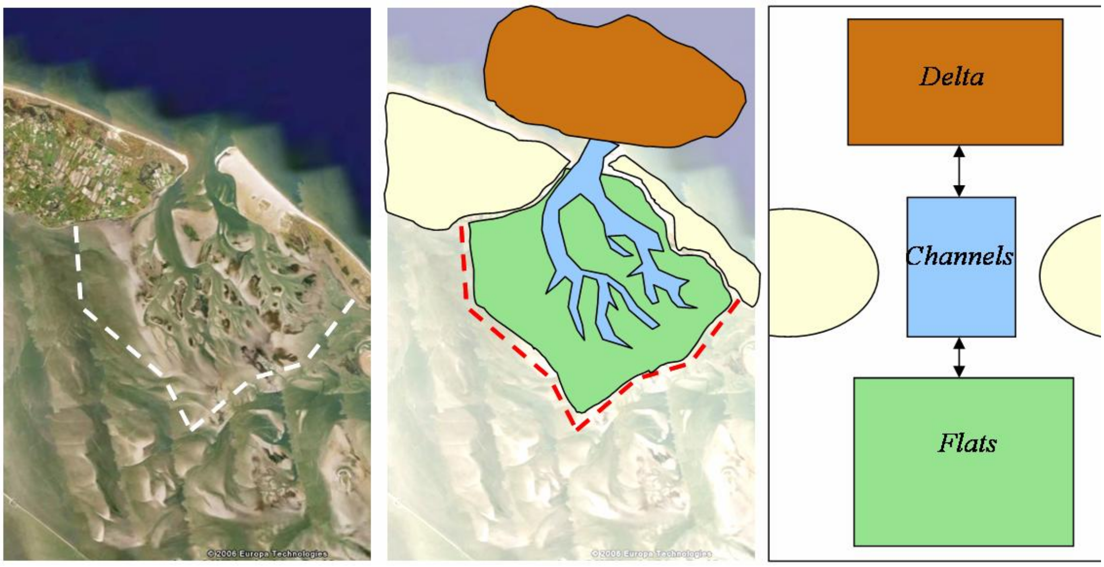


Figure 2.1: Morphological elements

The outside world boundary is schematized having an overall equilibrium concentration, which is not influenced by the developments of the different elements inside the model. Two ways of exchanging sediment between elements or between an element and the outside world are accounted for. In the first place this is the sediment exchange due to the in- and outgoing tidal prism. This is modeled using a diffusion term and therefore later on referred to as diffusive exchange. Secondly the sediment exchange as result of a net flow through an element. This is modeled using an advective term and therefore in this report referred to as advective exchange.

An important hypothesis in ASMITA is that each element tends to develop towards an equilibrium state. This can be defined for all elements using the long-term averaged hydrodynamic conditions like tidal range (*H*) and tidal prism (*P*):

$$V_e = f\left(P, H\right) \qquad (2.1)$$

When an element is out of equilibrium this induces a need or surplus of sediments. Whether the element develops towards its equilibrium depends on the availability of sediments, which is governed by the sediment need or surplus of the surrounding elements and the outside world.

Evolution towards equilibrium by sedimentation or erosion in an element is only possible if exchanges of sediment between the element with other elements and / or the outside world take place. Both the diffusive exchange and advective exchange can cause transport of sediments between an element and its environment. Diffusive exchange always leads to exchange of sediment from an element with a relative high concentration towards an element with a relative low concentration. Advective exchange leads to water with a different concentration entering the element balanced by an equal amount of water with the local sediment concentration leaving that element.

The internal sedimentation or erosion is governed by the difference between the actual sediment concentration and the equilibrium concentration, which is dependent on the deviation of the element from its equilibrium.

The movement of sediments causes a morphologic change of the elements resulting in different equilibrium concentrations. Using the schematization as explained above, the state of all elements in a tidal inlet system at a certain moment in time can be translated into a mathematical model which can be solved numerically according to the following scheme (Kragtwijk, 2001):

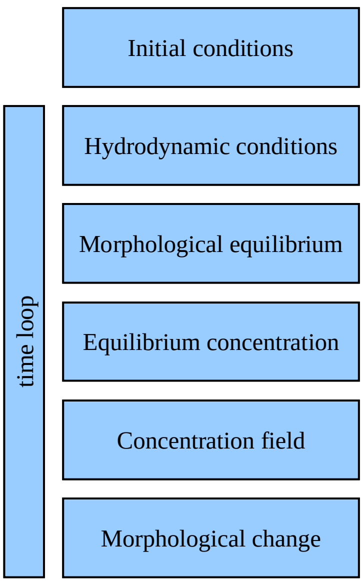


Figure 2.2: Calculation scheme ASMITA

In section 2.2 the variables describing the morphological elements as defined in ASMITA schematization will be clarified. The different calculation steps will be explained in section 2.3.

2.2 Definition of the element properties

In ASMITA volumes and areas inside a tidal basin are defined using the reference levels MLW and MHW (Figure 2.3):

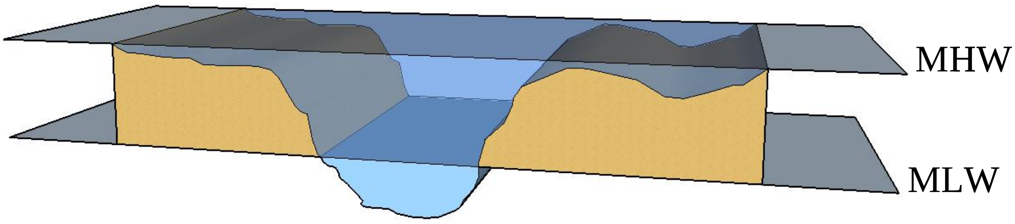


Figure 2.3: Definition of morphological elements

The *inter-tidal flat* volume is defined as the total sediment volume in the basin between MLW and MHW. The flat area is then defined as the dry area at MLW. Figure 2.4 illustrates the definitions for flat volume (V_f) and flat area (A_f).

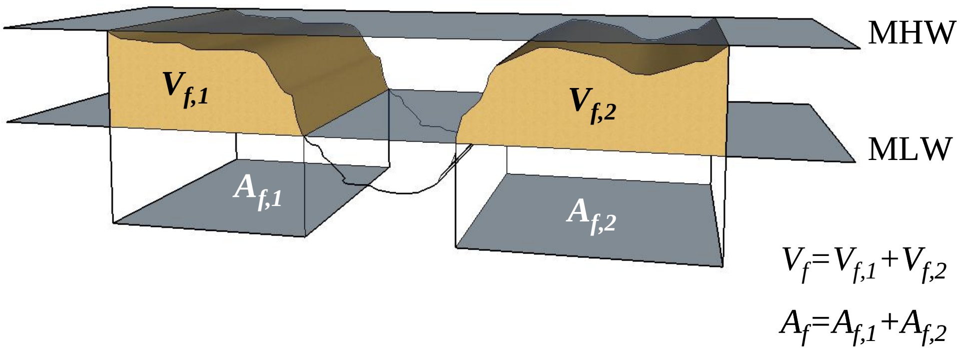


Figure 2.4: Definition of flat element

The *channel* element is defined as the total water volume (wet) below MLW. The channel area therefore equals the wet surface area at MLW. Channel area (A_c) and volume (V_c) are illustrated in Figure 2.5.

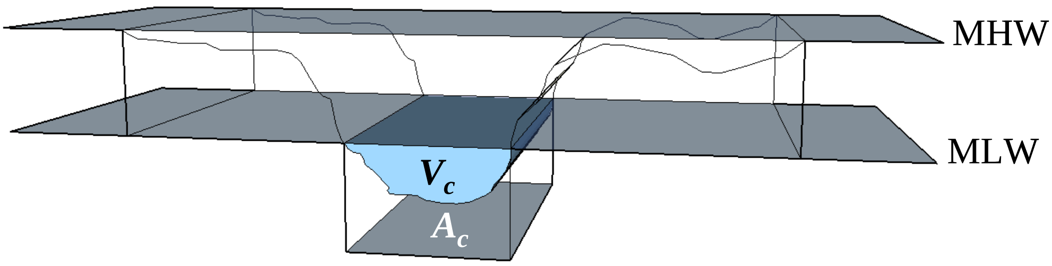


Figure 2.5: Definition of channel element

The basin area (A_b) equals the total wet area at MHW. the wet volume between MHW and MLW forms the tidal prism (P), as shown in Figure 2.6.

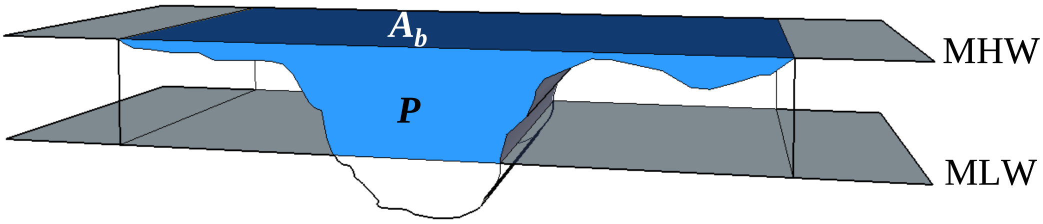


Figure 2.6: Definition of tidal prism and basin surface area

The *delta volume* (V_d) is defined as the total volume of sediments above a fictitious sea bottom, which would be there if no inlet existed. This is illustrated in Figure 2.7.

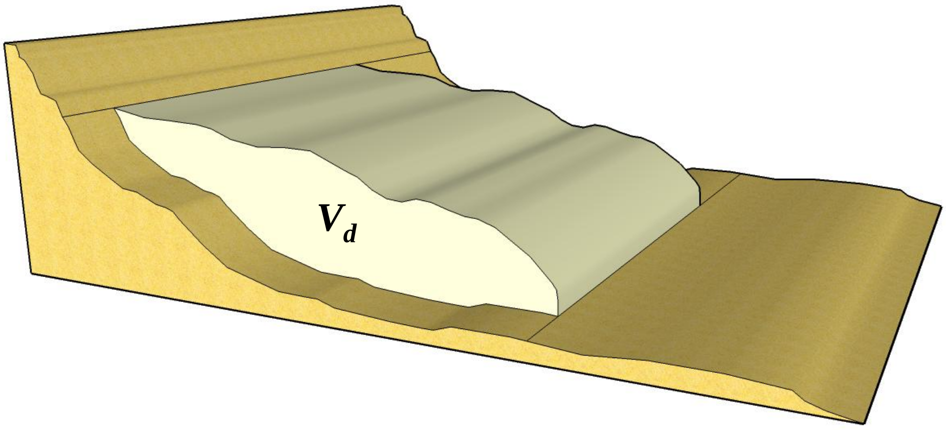


Figure 2.7: Illustration of the definition of the ebb-tidal delta volume (V_d)

2.3 Explanation of the calculation steps

2.3.1 Hydrodynamic conditions

As mentioned in section 2, equilibrium volumes can be calculated using the long-term averaged hydrodynamic parameters tidal range (H [m]) and tidal prism (P [m^3]). In ASMITA the tidal range is one of the input parameters. If the assumption is made that the length of the basin is small relative to the tidal wave length, the tidal prism can be calculated according to:

$$P = H \cdot A_b - V_f \qquad (2.2)$$

In this relation A_b [m^2] denotes the total basin area (wet area at MHW). V_f [m^3] represents the flat volume.

2.3.2 Morphological equilibrium

For each morphologic element Eysink (1991) amongst others developed equilibrium relations for the total volume. In case of a channel or delta element he related the equilibrium volume to the tidal prism. The relations used in the present ASMITA model will be discussed in this section

flats

If an inter-tidal flat reaches equilibrium mean flat height (h_{fe} [m]) and also an equilibrium surface area (A_{fe} [m^2]), the equilibrium flat volume (V_{fe} [m^3]) can be expressed by:

$$V_{fe} = h_{fe} \cdot A_{fe} \tag{2.3}$$

A general formulation for the relation between the total basin area and the equilibrium surface area of the inter-tidal flats is formulated by de Vriend (1996):

$$A_{fe} = A_b - \beta \frac{H}{h_c} A_b^{\frac{2}{3}} \tag{2.4}$$

in which h_c [m] represents the characteristic channel depth and β is a constant of proportionality. From the work of Renger and Partenscky (1974) it can be deduced that for the inlets in the German Bight this relation can be written as follows:

$$\frac{A_{fe}}{A_b} = 1 - 2.5 \cdot 10^{-5} \cdot A_b^{0.5} \tag{2.5}$$

in which:
A_{fe} [m^2] Equilibrium flat surface area
A_b [m^2] Basin surface area

According to Eysink and Biegel (1992) flats tend to develop towards an equilibrium flat height which is related to MHW. Consequently the equilibrium flat height can be related to the tidal range (2.6).

$$h_{fe} = \alpha_{fe} \cdot H \tag{2.6}$$

in which Eysink and Biegel (1992) also find:

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{2.7}$$

In this relation α_f is a coefficient which according to Eysink and Biegel (1992) should be 0.41 for all inlets of the Dutch Wadden Sea. Van Goor (2001) suggests values between 0.38 and 0.5 for systems in this area. Combining the relations for an equilibrium flat height and an equilibrium flat area gives an equilibrium flat volume:

$$V_{fe} = \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b} \right) \cdot A_b \cdot H \tag{2.8}$$

Channels

A well-known relationship from literature is the relationship between tidal prism and cross-sectional area at the narrowest point of a tidal inlet. Also cross-sectional area of the channels further inside the basin is related to the tidal volume that passes that channel section (Gerritsen and De Jong, 1984,1985). This suggests that integration along the channel would lead to a relation between the tidal prism and the channel volume (Eysink and Biegel, 1992):

$$V_c = \int_0^L A_{cr}(x) dx \tag{2.9}$$

in which:

V_c	[m^3]	Channel volume
A_{cr}	[m^2]	Cross-sectional flow area
L	[m]	Characteristic length of the channels inside a basin

In general relations for A_{cr} show proportionality with the tidal prism (P) defined as the total amount of water between MLW and MHW. Gerritsen (1990) found such a relation also fits data of several inlets of the Dutch Wadden Sea. In that analysis A_{cr} was defined as the cross-sectional channel area below mean sea level.

$$A_{cr} = c_A \cdot P \tag{2.10}$$

Substitution of (2.10) in (2.9) yields:

$$V_c = \int_0^L c_A \cdot P(x) dx \tag{2.11}$$

Integration of (2.11) typically leads to:

$$V_c = c_A \cdot c_s \cdot P \cdot L \tag{2.12}$$

In this relation, c_s is a constant depending on the shape of the basin. L can be expressed in the tidal prism, the length (L) –width (B) ratio of the basin and the tidal range (H). From this it follows that

$$L = \sqrt{\frac{\left(P + V_f\right) \cdot L}{H \cdot B}} \tag{2.13}$$

Substitution in equation (2.12) leads to (Eysink and Biegel, 1992):

$$V_c = c_A \cdot c_s^1 \sqrt{\frac{L}{H \cdot B}} \cdot P^{\frac{3}{2}} \tag{2.14}$$

in which c_s^1 is defined as a constant depending on the shape of the basin. Relation (2.14) expresses the channel volume below MSL. Eysink and Biegel (1992) also formulate empirical relations to convert channel volumes relative to MSL to channel volumes relative to MLW:

$$V_{c,MLW} = \frac{\beta_p}{\gamma_p} \cdot V_{c,MSL} \tag{2.15}$$

with:

$\beta_p = 0.16 \cdot P^{0.055}$ if $P < 160 \cdot 10^6$ [m^3]

$\beta_p = 0.44 + 7.74 \cdot 10^{-11} \cdot P$ if $P > 160 \cdot 10^6$ [m^3]

$\gamma_p = 1 - 1.0 \cdot 10^{-10} \cdot P$

The channel volume relative to MLW can thus be expressed by:

$$V_c = c_A \cdot c_s^1 \sqrt{\frac{L}{H \cdot B}} \cdot \frac{\beta_p}{\gamma_p} \cdot P^{\frac{3}{2}} \tag{2.16}$$

Based on this concept Eysink and Biegel (1992) obtained a best fit through data concerning the Dutch Wadden Sea (relation (2.17), see also Figure 2.8).

$$V_{ce} = 16 \cdot 10^{-6} \cdot P^{1.55} \tag{2.17}$$

The power 1.55 used in relation (2.17) does not follow from an analytical solution of relation (2.16). (2.17) can be presented as:

$$V_{ce} = \alpha_c \cdot P^{\beta_c} \tag{2.18}$$

With:

V_{ce}	[m^3]	Channel volume below MLW
P	[m^3]	Tidal prism
β	[-]	1,55
α_c	[-]	Coefficient

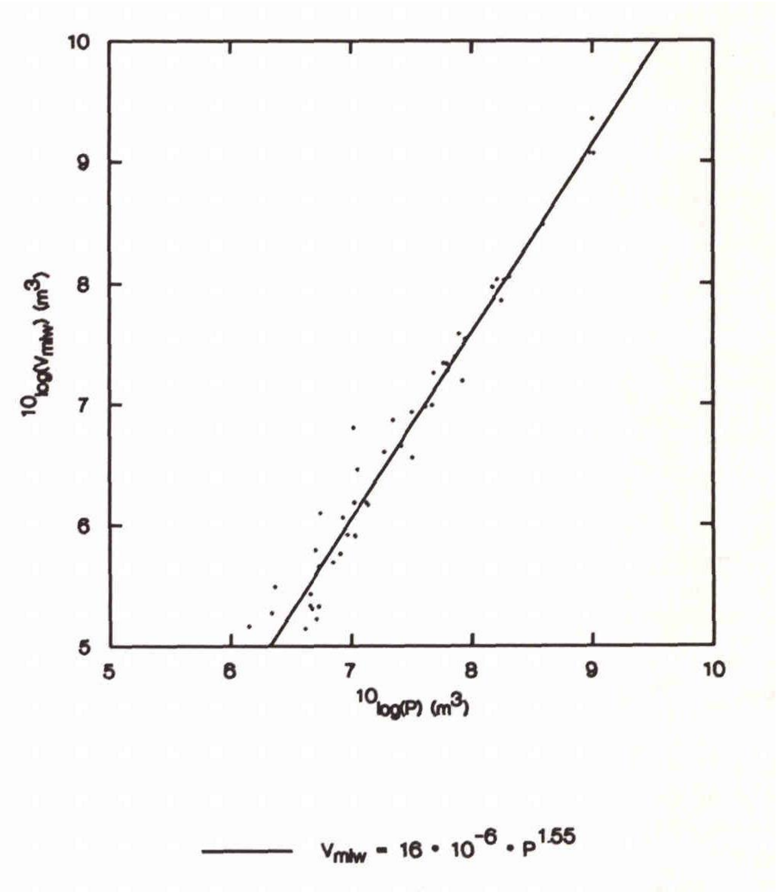


Figure 2.8: Relation for the equilibrium channel volume as presented by Eysink and Biegel (1992)

According to (2.16) α_c should be a function of the shape of the individual basins. The difference in the power of P between relation (2.16) and (2.18) makes calibration of α_c for a particular basin difficult. Relation (2.18) is adopted in ASMITA to calculate the equilibrium channel volumes. Methods for estimating α_c are explained in section 4.5.2.

If the flat area is calculated according to the formulation explained in the previous section and also the basin area (A_b) is know, the channel area (A_c) follows from:

$$A_c = A_b - A_f \tag{2.19}$$

Delta

For 44 inlet systems along the US coast, Walton and Adams (1976) defined a relation which describes the correlation between the tidal prism and the volume of the outer delta (See Figure 2.9). This relation reads:

$$V_{de} = \alpha_d \cdot P^{1.23} \tag{2.20}$$

In which the correlation coefficient α_d [$m^{-1.23}$] is dependant on the degree of wave exposure of the ebb tidal delta. Three different regimes are distinguished, namely high exposed, moderately exposed and mildly exposed.

Eysink (1990) found this relation also to be valid for inlets of the Dutch Wadden Sea and uses:

$$V_{de} = 65.7 \cdot 10^{-3} \cdot P^{1.23} \tag{2.21}$$

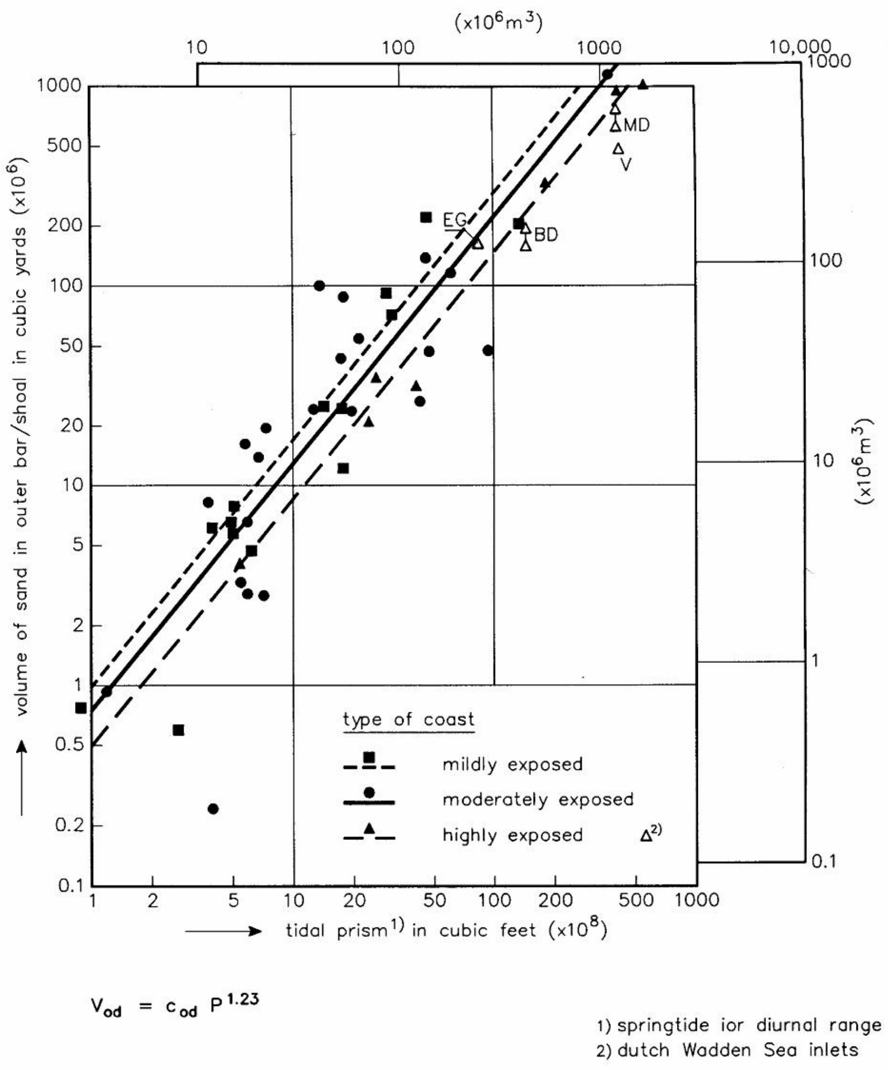


Figure 2.9: Sand volume of the outer deltas in USA and the Dutch Wadden Sea in relation to the mean tidal prism and wave climate of the inlet according to Walton and Adams.

2.3.3 Equilibrium concentration

A key element in the modeling concept is the equilibrium concentration (Stive et al., 1998). If all elements are in an equilibrium state constant sediment concentration is present in the whole system. This concentration is called the overall equilibrium concentration (c_E). For each element also a local equilibrium concentration is defined, which is equal to c_E when the element is in morphological equilibrium, larger than c_E if a tendency of erosion exist and smaller than c_E if a tendency of sedimentation exist. Therefore the local equilibrium concentration is dependant on the actual volume of an element (V_n), the equilibrium volume

($V_{n,e}$) and the overall equilibrium concentration (c_E). To represent this behavior a simple power relation is used for the local equilibrium concentrations:

$$c_{n,e} = c_E \cdot \left(\frac{V_{n,e}}{V_n} \right)^p \tag{2.22}$$

with:

n	[-]	Element number
$c_{n,e}$	[-]	Equilibrium sediment concentration of element n [-]
V_n	[m^3]	Volume of element n
V_{ne}	[m^3]	Equilibrium volume of element n (in case of constant tidal forcing only) [m^3]
p	[-]	Commonly taken as 2 if morphological state of element n is characterized by its wet volume or -2 in case of dry volume

2.3.4 Morphological change and concentration field

Last step in the ASMITA calculation scheme is the determination of the concentration field and morphological changes.

In general there are three factors contributing to the volume change of each element. At first a morphological change occurs when the local sediment concentration of an element differs from the equilibrium concentration. If the local sediment concentration is larger than the equilibrium concentration of that element ($c>c_e$) sedimentation occurs. When the local sediment concentration is smaller than the equilibrium concentration, erosion occurs. The contribution due to vertical exchange of sediment can be written as follows:

$$\frac{dV_{n,ex}}{dt} = \sigma_n w_{s,n} A_n (c_{n,e} - c_n) \tag{2.23}$$

in which:

σ_n	+1 if morphological state of element n is characterized by its wet volume, -1 in case of dry volume
$w_{s,n}$	Vertical exchange coefficient [m/s]
A_n	Horizontal area of element n [m^2]
c_n	Actual sediment concentration of element n [-]
t	Time

Besides the influence of vertical sediment exchange, also changes in MLW and MHW influence the volume of an element. An alteration of these mean water levels can be due to sea level rise or changes of the tidal range. Sea level rise causes elements expressed in dry volume to become smaller and elements expressed in wet volume to become larger. An increase of the tidal range results in a decrease of MLW and an increase of MHW. Assuming this to be equally distributed, MLW will than be decreased by half the increase of the tidal range. The effect of an increasing tidal range will therefore be opposite to the effect of SLR. Volume changes due to a change in MLW is illustrated in Figure 2.10. The delta element is not defined using reference levels MLW and MHW. Changes in these reference levels will therefore have no effect on the volume of this element.

$$\frac{dV_{n,slr}}{dt} = \eta_n \sigma_n A_n \left(\frac{d\zeta}{dt} - \frac{1}{2}\frac{dH}{dt} \right) \tag{2.24}$$

where:

$d\zeta/dt$	Sea level rise
η_n	0 in case of a delta element, 1 in case of a channel or flat element
dH/dt	Change of the tidal range in time

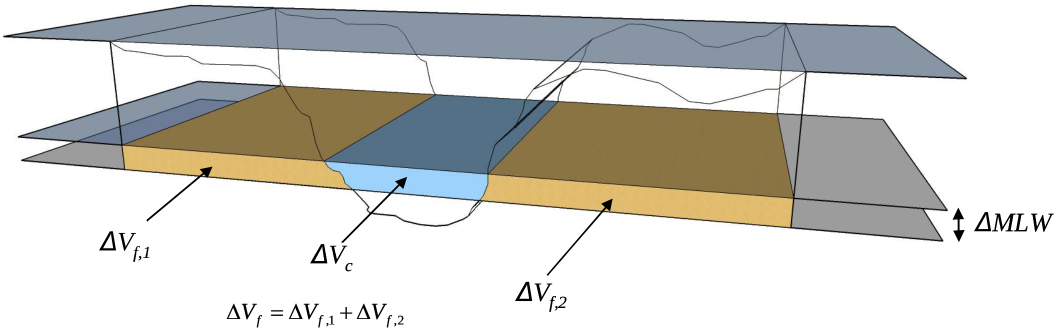


Figure 2.10: Illustration of volume changes due to a change of MLW

A third factor influencing de volume change of an element is the amount of dredging or dumping in that element:

$$\frac{dV_{n,b}}{dt} = -\sigma_n b_n \tag{2.25}$$

b_n Dredging or dumping [m^3/s], b_n is positive in case of dumping and negative in case of dredging

In total the volume change of an element is a summation of relations (2.23), (2.24) and (2.25):

$$\frac{dV_n}{dt} = c_E \sigma_n A_n \left(w_{s,n} \left(\gamma_n^* - c_n^* \right) + \frac{\eta_n}{c_E} \left(\frac{d\zeta}{dt} - \frac{1}{2}\frac{dH}{dt} \right) \right) - \sigma_n b_n \tag{2.26}$$

with:

c_E Outside world equilibrium concentration [-]

$$c_n^* = \frac{c_n}{c_E}$$

$$\gamma^* = \frac{c_{n,e}}{c_E} = \left(\frac{V_{n,e}}{V_n} \right)^p$$

The amount of vertical exchange depends on the availability of sediment. This availability is governed by the elements which are connected to element n. Also the sediment demand or supply of the outside world influences this availability.

As mentioned in section 2 sediment exchange between elements or between an element and the outside world is represented by a diffusion term and an advection term representing exchange due to the in- and outgoing tidal prism and exchange due to a net flow through the element. This can be written as:

$$w_{s,n}A_n\left(c_{n,e}-c_n\right)=\sum_m \delta_{n,m}\left(c_n-c_m\right)+\sum_m q_{n,m}\left(c_n-c_m\right)+\delta_{n,E}\left(c_n-c_{n,E}\right)+q_{n,e}\left(c_n-c_{n,E}\right) \quad (2.27)$$

in which:

$\delta_{n,m}$ Coefficient of horizontal exchange between elements n and m
$\delta_{n,E}$ Coefficient of horizontal exchange between element n and the outside world (not being another element)
$q_{n,m}$ Flow from element m into element n (advective transport)
$q_{n,E}$ Flow into element n from its environment (not being another element)
$c_{n,E}$ Concentration outside element n (not being other element)

Figure 2.11 illustrates these different contributions to the volume change of an element as mentioned above.

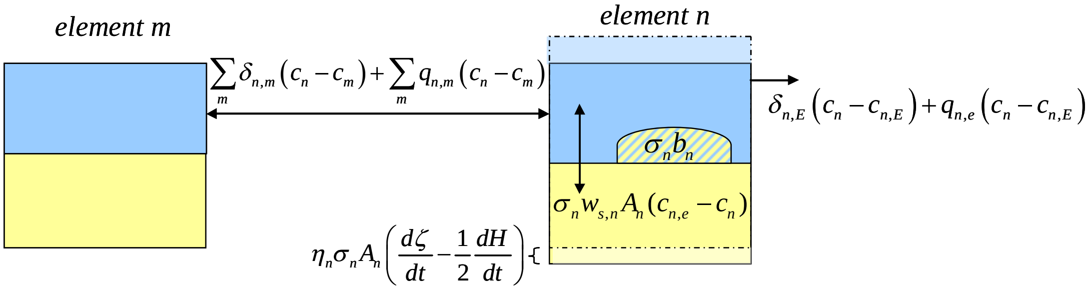


Figure 2.11: Schematization of the possible contributions to volume change of an element

2.4 Coefficients

2.4.1 Vertical exchange coefficients

This parameter represents the net vertical exchange between the water column and the bottom per unit area and per second. Although it has the same dimension as the fall velocity there is a difference. In ASMITA the vertical exchange coefficient describes the long-term residual erosion or sedimentation. This means that the vertical exchange is the long-term residual effect of all kind of processes, which cause erosion or sedimentation. Influences like wave action and sediment size determine vertical exchange coefficient. This creates different vertical exchange coefficients for each element. Buisman (1997) used values ranging from $1*10^{-5}$ to $1*10^{-4}$.

2.4.2 Diffusion coefficients

Generally asymmetry of tide leads to a non-zero tide-residual transport of sediments. At the scale of aggregation in ASMITA this net effect is described as a diffusion type phenomenon. The diffusion coefficients represent the tide-residual exchange capacity between two elements. Buisman (1997) used values between 500 m^3/s and 1500 m^3/s for the Zoutkamperlaag (which is part of the Friesche zeegat).

2.5 Possible adjustments of ASMITA

2.5.1 Equilibrium values and coefficients

A general equation for determining the equilibrium volume of the flat elements is:

$$V_{fe} = \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b} \right) \cdot A_b \cdot H \tag{2.8}$$

in which:
Vf = Sediment volume of element flat
H = Tidal range
and

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{2.7}$$

In ASMITA this formula is presented as

$$V_{fe} = \alpha_{specific} \cdot A_b \cdot H \tag{2.28}$$

comparing these equations gives

$$\alpha_{specific} = \alpha_{fe} \cdot \left(\frac{A_f}{A_b} \right) \tag{2.29}$$

If also the basin surface areas change in time relation (2.8) has to be used instead of relation (2.28).

Sediment exchanges between the Marsdiep delta and channel deduced from Kragtwijk (2001) do not match the sediment exchanges concluded from the sediment budget analysis of Elias et. al. (2006). It is suspected that this difference is caused by the chosen coefficients for the equilibrium relations and exchange coefficients. Kragtwijk (2001) did not include sea level rise (SLR) in the assessment of the behavior of the Marsdiep and Vlie after the closure of the Zuider sea. Including SLR in the simulations therefore requires different coefficients for the equilibrium volumes and exchange coefficients. Re-examining all equilibrium and exchange coefficients taking into account measured volumes, sediment exchanges (Elias et. al., 2006) and SLR could lead to a better description of the observed behavior of the Western Dutch Wadden Sea.

2.5.2 Flat area change

One of the equilibrium relations adopted in ASMITA is the relation between relative flat surface area and the total basin area (relation (2.5)). According to this relation a change in basin surface area leads to a different equilibrium flat surface area. A change in basin surface area can be caused for example by closing off part of that basin like for example the closure of the Zuider Sea. This forces the flat surface area to change towards a new equilibrium. Changes of the flat areas after the closure of the Zuider Sea can also be observed in the Dutch Wadden Sea (Chapter 3). A change in flat surface area directly affects the surface area of the channels in that basin. Relations (2.26) and (2.27) are used in ASMITA to calculate the volume change of an element. Both relations include terms containing the element surface areas. In the present formulation of ASMITA surface areas of each element are kept constant in time. This simplification is expected to have significant influence on a model predicting the reactions of the Marsdiep and Vlie on the closure of the Zuider Sea. The effect of the changing surface areas of flat and channel can be included by adding a relation that expresses the flat surface area of all elements each time step.

2.5.3 Sediment exchange between basins

The volume of sediments that has been eroded from the Texel ebb-tidal delta cannot entirely be found in the Texel basin. This is compensated by a surplus of sediments accreted in the Vlie basin that cannot be attributed to the erosion of the ebb-tidal delta of this basin (Elias, 2006). Consequently the sediment balance of the Western Wadden Sea has to be considered as a whole. As stated in section 1.3 it is not possible to simulate the Western Wadden Sea as one system. However a description of this area including boundaries between the basins does not necessarily mean that exchange of sediment between two basins cannot be accounted for. In this study the possibility of using the diffusion type transport already included in ASMITA to simulate the movement of sediment from one basin towards another is investigated.

2.5.4 Basin area change

A barrier lagoon system that is in near equilibrium can be assumed to have a fixed boundary at the watershed. This also holds for a combination of barrier lagoon systems. Closing of part of an individual basin will lead to a new equilibrium for the combined system. Elias (2006) suggests a conceptual model for the morphologic development of a Wadden Sea inlet that has to respond to large-scale human intervention in the basin. This includes different basin surface areas. The combined system tends to reach this new equilibrium forcing the watersheds to move. In such a system the assumption that fixed boundaries can be placed at the watersheds is not true. The closure of the Zuider Sea caused the combined systems of Marsdiep, Eierlandse gat and Vlie to develop towards a new equilibrium. This also causes A_b of the individual basins to change in time. Elias (2006) suggests a conceptual model for the morphologic development of a Wadden Sea inlet that has to respond to large-scale human intervention in the basin (Figure 2.12). The adaptation period takes place in a time period in the order of decades. The adjustment towards a new dynamic equilibrium will take centuries. According to this conceptual model the adaptation of the basins in the Western Dutch Wadden Sea in response to the closure of the Zuider Sea (1932) should have reached a near equilibrium state. Further adaptations are therefore still expected. Analysis of the field measurements presented in Chapter 3 leads to the same conclusion. To predict future behavior of the Western part of the Dutch Wadden Sea the adaptation of the different basin areas has to be taken into account.

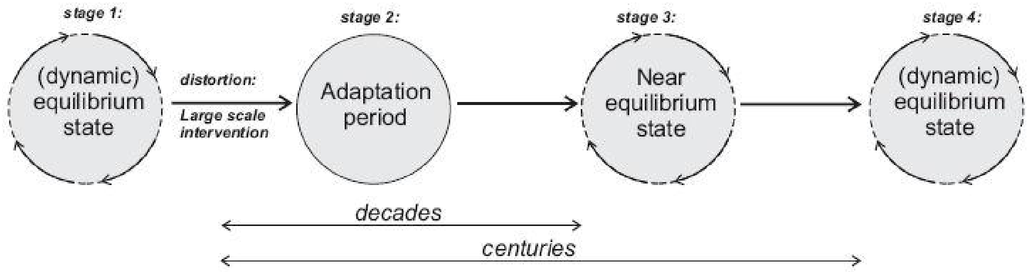


Figure 2.12: Conceptual model for Wadden Sea inlets impacted by large-scale intervention (Elias, 2006)

3 Data Analysis of the Dutch Wadden Sea

3.1 Available information

3.1.1 Bathymetric data

In the past many measurements of the bathymetry of the Dutch Wadden Sea have been carried out. Often these data are separated for the basins present in the Dutch Wadden Sea. Boundaries between those basins are defined according to Figure 3.1 and kept fixed in time. No justification for the exact placement has been found. The boundaries seem to represent the highest points in the bathymetry of 1998. RIKZ provided bathymetrical information for each basin indicated in Figure 3.1. Because of the fixed boundaries changes of the basin areas due to movement of these boundaries are not accounted for in this information. The data concern hypsometric curves of areas and volumes below a certain water level. Hypsometric information of these basins is given for various years different for each basin.

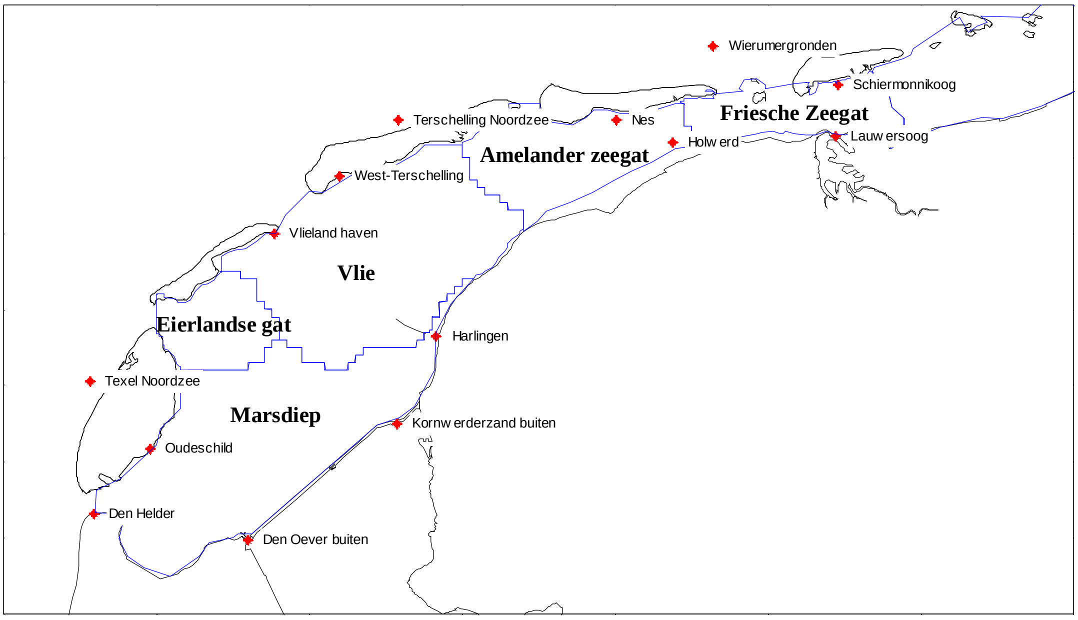


Figure 3.1: Measurement stations and basin boundaries RIKZ

The same depth measurements can also be subtracted from a database with UCIT (Universal Coastal Intelligence Toolkit, van Koningsveld et. al. (2004)). With this toolkit it is possible to extract bathymetries for a certain period inside a predefined polygon. The data available in this database (‘*vaklodingen data’*) cover the entire Dutch Wadden Sea for a period between 1926 and 2006. Measurements are carried out for a certain area in a certain period. As a consequence bathymetries of the entire Wadden Sea are always a combination of measurements carried out in different periods. Bathymetries retrieved from the database represent the bathymetries of 1926, 1948, 1975, 1981, 1991, 1998 and 2006. The segmentation of the measurement periods of the measurements used to form the bathymetry of 2006 is illustrated in Figure 3.2.

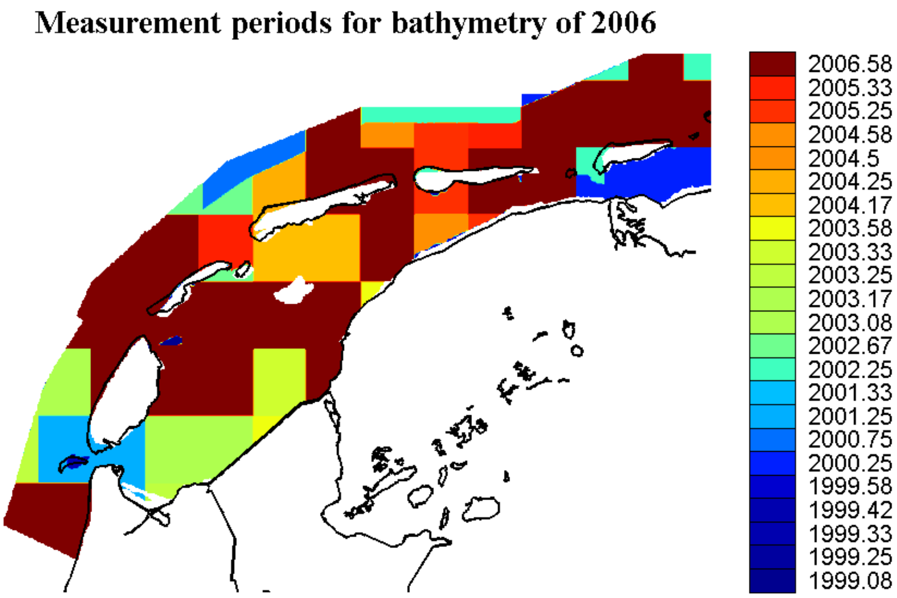


Figure 3.2: Measurement periods for the bathymetry of 2006

Similar figures for all subtracted bathymetries can be found in appendix D. This information does not include boundaries between the basins. Using the bathymetries it is possible to define basin boundaries. This enables the possibility to define different boundaries for different periods. In this way also changes of the basin surface areas can be accounted for. The procedure used in this study to locate boundaries between basins is described in section 3.2.

3.1.2 Tidal information

The volumes and areas in ASMITA are defined with reference levels MHW and MLW. For calculating the basin characteristics therefore also tidal information is required. Measured MHW, MSL and MLW at fourteen measurement stations are obtained from RIKZ (Dillingh 2006, personal communication). The location of these stations is indicated in Figure 3.1. Inside the Eierlandse gat there are no measurement stations. The stations were installed in various years. consequently the measurement periods differ. An overview of the periods for which measurements are available is given in Table 3.1.

Station name	first year of measurements	last year of measurements
Den Helder	1832	2005
Den Oever	1853	2005
Oude Schild	1878	2005
Texel Noordzee	1990	2005
Kornwerderzand buiten	1933	2005
Vlieland haven	1878	2005
Harlingen	1865	2005
West-Terschelling	1887	2005
Terschelling Noordzee	1990	2005
Nes	1964	2005
Holwerd	1969	1998
Wierumergronden	1981	2005
Lauwersoog	1970	2005
Schiermonnikoog	1966	2005

Table 3.1: Measurement periods

3.2 Approach

In former studies the characteristics of the basins in the Dutch Wadden Sea were determined using fixed boundaries as presented in Figure 3.1 as well as a fixed tidal frame. In reality both the tidal frame and the boundaries between basins have evolved in time. In this study the results using the conventional method are compared to results acquired when moving boundaries and evolving tidal frames are taken into account. Data are analyzed in three ways, using:

- fixed basin boundaries and fixed water levels
- fixed basin boundaries and actual water levels
- actual basin boundaries and actual water levels

For the analysis with fixed water levels MHW and MLW for the different basins are taken from Elias et. al. (2006). See also Table 3.2. The methods used for determination of the varying water levels and moving boundaries are explained below.

Basin	**HW (m NAP)**	**MW (m NAP)**	**LW (m NAP)**	**Tidal range (m)**
Marsdiep	0.825	0	-0.825	1.65
Eierlandse gat	0.825	0	-0.825	1.65
Vlie	0.95	0	-0.95	1.90
Amelander zeegat	1.075	0	-1.075	2.15
Friesche Zeegat	1.10	0	-1.10	2.20

Table 3.2: Water levels used for analysis as presented by Elias et. al. (2006)

Varying tidal frame

Basin characteristics are defined using MHW and MLW representative for the average water levels inside that basin. These water levels should be determined based on the measurements obtained from the fourteen measurement stations. Especially for the Eierlandse gat this is not straightforward. There are no measurement stations inside the basin and one of the nearest stations (Texel Noordzee) has only recently been installed (1990). One way to investigate water levels inside the basins is by simulating the water movement using a process based model. In this study a Delft3D model (v.d. Waal, 2007) is used. With this model the correlation between the measurement stations and average water levels inside the basin can be estimated. The model includes all measuring stations as observation points and is calibrated for the Western part of the Dutch Wadden Sea. Outcomes for the Amelander zeegat and Friesche zeegat are therefore ignored. Estimating a representative water level for each basin requires extra observation points placed inside the Eierlandse gat. Also extra observation points are included in the Marsdiep and Vlie basin. Figure 3.3 shows the observation points included in the model. MHW and MLW are water levels averaged over a long period including spring and neap tides. To avoid simulating for a long period the relation between the individual observation points representing the measurement stations and the average water level inside a basin is examined for three periods: One around spring tide; one around neap tide and a period in between.
From each run HW and LW are determined for the individual observation points. The average of the water levels at observation points Den Helder, Den Oever, DOOVBWT, Kornwerd and Harlingen is taken as a representative value for the water level inside the Marsdiep basin. The average water level inside the Eierlandse gat basin is approached by the average of the observation points eigat 1, eigat 2, and Zeegat Eierlandse gat and the average water level inside the Vlie basin is taken as the mean of the observation points West-Terschelling, VLIESMmat, BLAUWSOT and Harlingen.

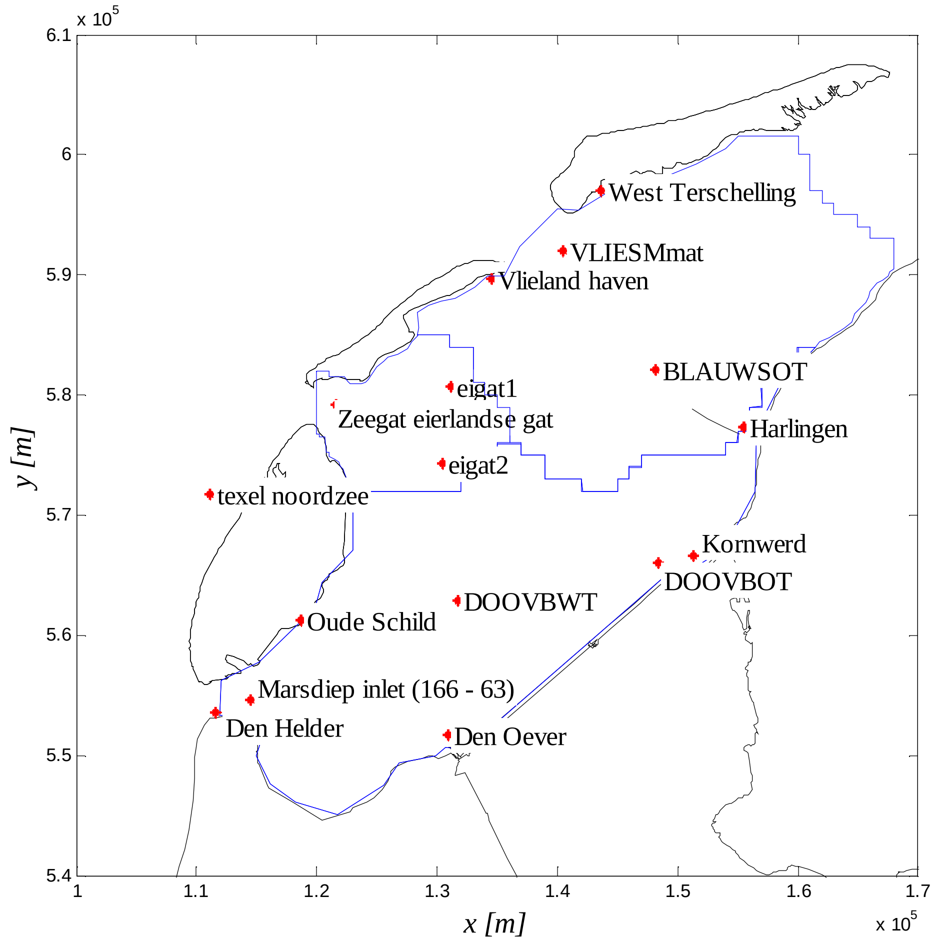


Figure 3.3: Observation points included in the Delf3D model

As an example Figure 3.4 compares HW and LW of the individual observation points in the Marsdiep basin with the estimated average water level of that basin during the three simulations. See appendix E for similar figures for Eierlandse gat and Vlie basin. Also the best estimation of the average water level based on values of the observation points which coincide with the measurement stations in reality is shown. In case of the Marsdiep the best estimate for the average water level inside the basin at HW is obtained by multiplying the HW value of observation point Den Oever by 1,1. LW in the Marsdiep basin is best approximated by the LW value of the same observation point. In Table 3.3 the best estimates are listed. In case of the Amelander Zeegat and Friesche Zeegat water levels predicted by the model are not reliable. The measurement stations inside the basin do not show large differences. It is assumed that the average water levels inside the basins can be represented by the measurements of only one station in that basin. From Table 3.2 it follows that none of the measurement stations in these two basins was installed before 1964. No tidal information before that year is available. Analysis with actual tidal information for the Friesche zeegat and Ameland basin are therefore only carried out for the period after 1964.

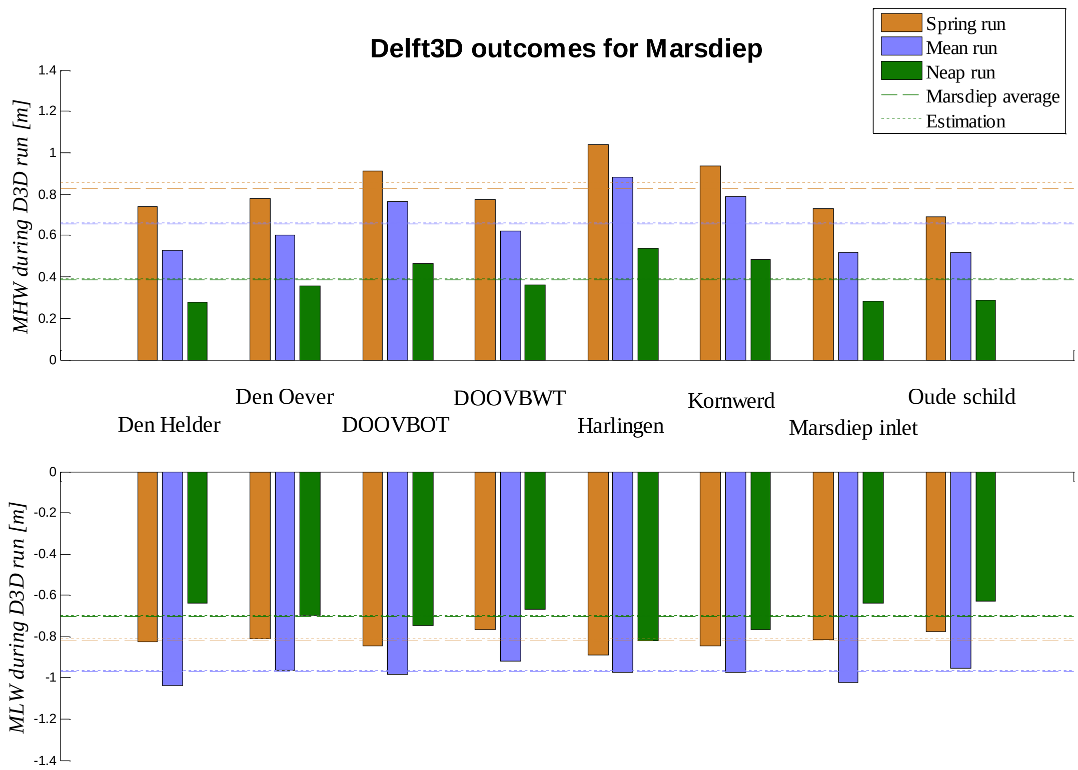


Figure 3.4: Comparison HW and LW of observation points with HW and LW of the Marsdiep basin

Basin	HW estimate	LW estimate
Marsdiep	$1.1 \cdot HW_{\text{Den Oever}}$	$LW_{\text{Den Oever}}$
Eierlandse gat	$\frac{(HW_{\text{Harlingen}} + HW_{\text{Oude Schild}} + HW_{\text{Vlieland haven}})}{3}$	$0.95 \cdot LW_{\text{Oude Schild}}$
Vlie	$\frac{(HW_{\text{Harlingen}} + HW_{\text{West-Terschelling}})}{2}$	$\frac{(LW_{\text{Harlingen}} + LW_{\text{West-Terschelling}})}{2}$
Amelander zeegat	HW_{Nes}	LW_{Nes}
Friesche zeegat	$HW_{\text{Lauwersoog}}$	$LW_{\text{Lauwersoog}}$

Table 3.3: Relation between measurement stations and water levels inside the basins of the Western part of the Dutch Wadden Sea

Based on the relations expressing the correlation between the average water level inside a basin and the water level at the measurement points (Table 3.3) the actual water level measurements can be translated into average water levels inside the basins. See appendix E for an overview of the calculated actual water levels. The water levels inside the Marsdiep show an increase in both MHW and MLW (Figure 3.5). The Vlie basin has a large increase in tidal range (Figure 3.6).

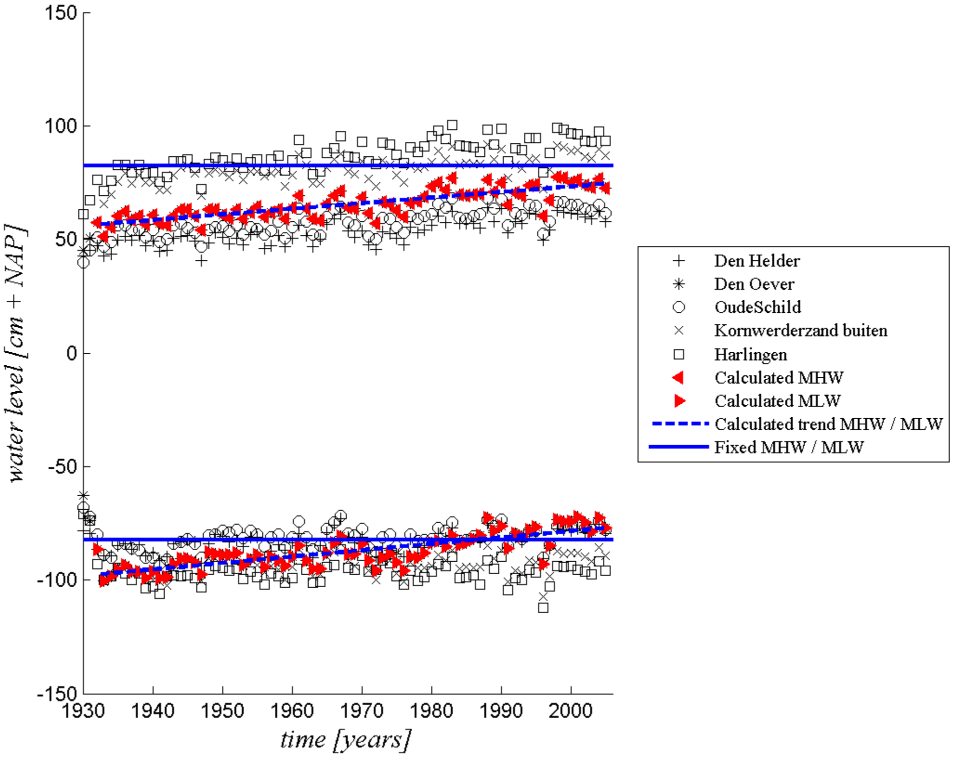


Figure 3.5: Water levels inside Marsdiep basin

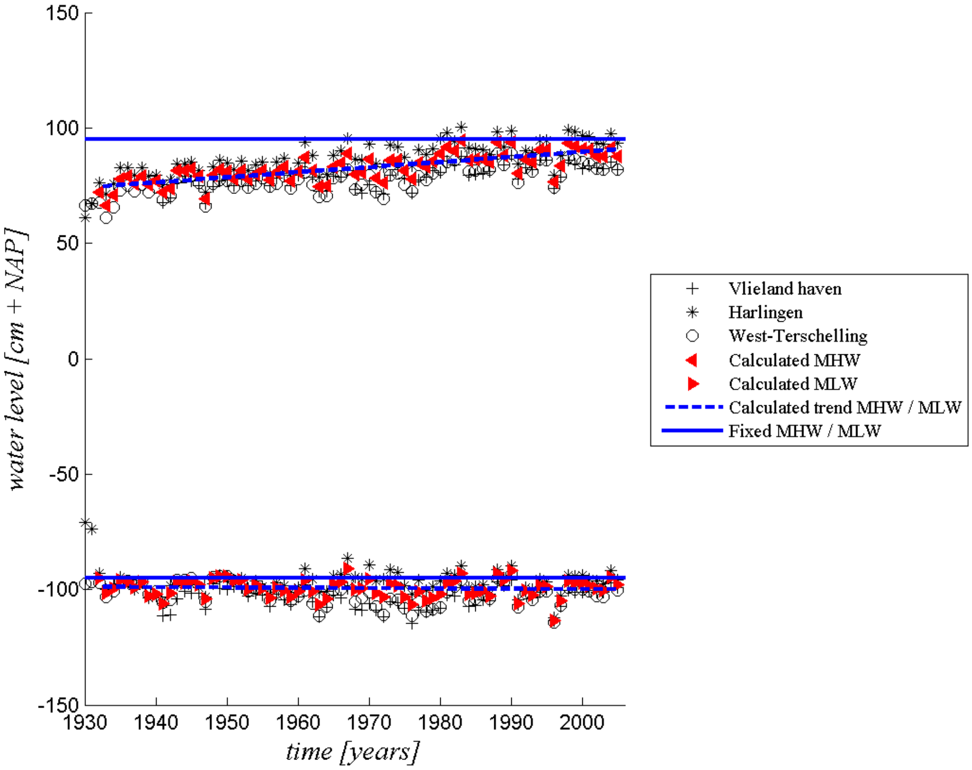


Figure 3.6: Water levels inside Vlie basin

Following the trends in calculated MHW and MLW inside the basin water levels are chosen for the different years to determine basin characteristics from the bathymetrical data.

Table 3.4 compares the fixed water levels taken from Elias et. al. (2006) with the average of the actual water levels calculated for the years in which a bathymetry is available.

Basin	**Fixed water levels**				**Actual water levels**			
	HW*	MW*	LW*	H (m)	HW*	MW*	LW*	H (m)
Marsdiep	0.825	0	-0.825	1.65	0.67	-0.09	-0.85	1.53
Eierlandse gat	0.825	0	-0.825	1.65	0.59	-0.11	-0.81	1.40
Vlie	0.95	0	-0.95	1.90	0.89	-0.08	-0.99	1.83
Amelander zeegat	1.075	0	-1.075	2.15	1.01	-0.11	-1.23	2.24
Friesche Zeegat	1.10	0	-1.10	2.20	1.00	-0.15	-1.30	2.30

Table 3.4: Comparison of fixed and calculated actual water levels

* [m NAP]

There are some significant differences between the tidal ranges used in the analysis with fixed water levels and tidal ranges representing the actual water levels in this study. The main differences can be found in the tidal range determined for Marsdiep and Eierlandse gat. Traveling along the Dutch coast from Den Helder (Marsdiep inlet) towards the East the tidal range for each basin is expected to increase because the difference between MHW and MLW at the inlets increases. Both fixed water levels and calculated actual water levels do not show this increase traveling from Marsdiep towards Eierlandse gat. The average of the calculated actual water level even decreases with respect to the calculated tidal range for Marsdiep. Marsdiep is a relatively long basin compared to the other basins in the Dutch Wadden Sea. Because of its geometry the tidal range at the back of the basin (1.84 m) is much higher than the tidal range at the inlet (1.36). Because of the large differences in tidal range over the Marsdiep basin it is to be expected that the average tidal range inside the Marsdiep basin is significantly higher than at the entrance. Because of the short length of the Eierlandse gat basin it can be expected to have an average tidal range close to the tidal range in the inlet. This could cause the average tidal range of the Marsdiep to be equal to or slightly larger than the average tidal range in the Eierlandse gat basin. This is also shown in Table 3.4. The average tidal range determined for the Eierlandse gat basin however is much smaller than expected given tidal ranges used in previous studies (Kragtwijk, 2001; van Goor, 2001; Elias et. al., 2006). Unfortunately there are no measurements available inside that basin to examine the accuracy of the water levels predicted by the model. Also applying the same method to the tidal range instead of MHW and MLW separately could lead to different results. In addition to that the relation between the water level at individual measurement stations and the average water level inside a basin is determined using bathymetrical information from 1998. Due to changes is bathymetry these relations could also change in time. This is also shown in Figure 3.5 where calculated MLW for Marsdiep increases with the same rate as MLW at measurement station Den Over. Other measurement stations inside that basin do not show such a strong increase. Examining the relation between MHW and MLW at individual measurements stations and average over a basin in time would probably lead to slightly different results in case of basins that show significant change. In this study the results presented in Table 3.4 are used including the results for Eierlandse gat. The differences in tidal ranges with respect to previous studies should be kept in mind.

Moving boundaries

One of the difficulties when analyzing the Dutch Wadden Sea is defining the boundaries between the basins. Determining boundaries between different areas of interest that do not change in time is one of the possibilities. When comparing obtained data to equilibrium relations expressing the volumes and areas of a basin in equilibrium this approach will lead to differences. Because of the adaptation process towards such an equilibrium the boundaries will move in time creating other basin areas. This creates the need to also analyze the bathymetry using boundaries that change in time.
In this study the boundary between two basins is defined as the place where two tidal waves entering through these basins meet. As a consequence the boundary is the place where the velocities are minimal. A Delft3D model (v.d. Waal, 2007) is used to simulate water movement for 8 tidal cycles using the bathymetries constructed with UCIT. Gaps in these data mainly concern the bathymetry of the Sea further offshore. This is filled with bathymetrical information of 1998 used in v.d. Waal (2007). From the results of these runs also mean velocities and standard deviation of the velocities can be calculated. Because of the tidal water motion flow direction has a large influence on the mean velocity over multiple tidal cycles at a particular position. When the velocities at that location are high, the standard deviation will be large because of the varying direction. At places where the absolute velocities are low, also the standard deviation will be low. Therefore the standard deviation (σ_{st}) can be used to determine the location of the boundaries. The determination of the boundaries with the lowest standard deviation is done visually. This influences the accuracy of the defined boundaries. Also the grid size of the model used to calculate the water motion determines the accuracy of the determined boundaries. An example of the distribution of standard deviation over the study area is given in Figure 3.7. The determined boundaries are plotted in the same figure. See appendix D for a complete overview of all bathymetries with accompanying boundaries. The Eastern boundary of the Friesche zeegat is on or near the Eastern boundary of the model. Because of this that boundary can not be determined. As can be seen from Figure 3.7 the Eastern boundary of the Amelander zeegat is not determined very accurately. This is caused by the large grid sizes used to model that region. This should be taken into account when analyzing the results.

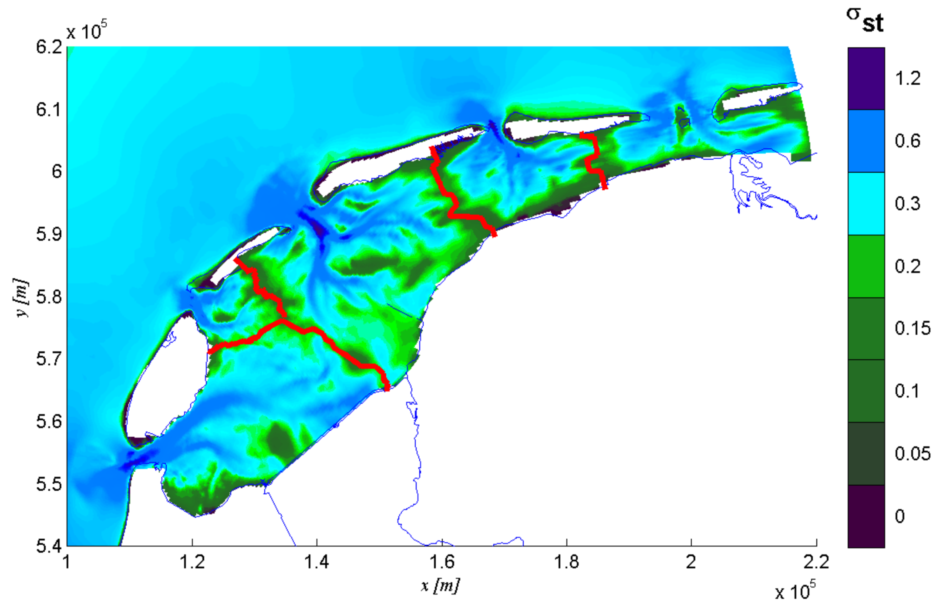


Figure 3.7: Standard deviation of the velocities for 1926 with basin boundaries

Figure 3.8 shows that the boundaries found using the minimal deviation method do not necessarily correspond with the highest points in the bathymetry.

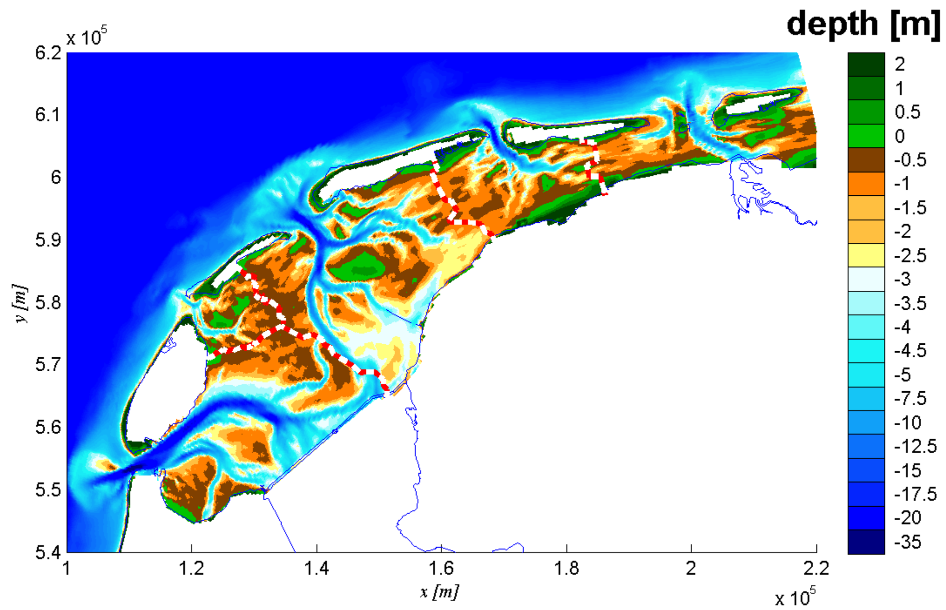


Figure 3.8: bathymetry of 1926 with basin boundaries

Comparison of hypsometric curves

Hypsometric curves in combination with water levels can be used to derive volumes and areas for the elements inside each basins. The hypsometric information already concerns hypsometric curves. For each bathymetry subtracted from UCIT hypsometric curves can be constructed using the determined boundaries, grid file and depth files of the Delft3D simulations. Resulting hypsometries can be found in Appendix F together with the hypsometric information for basins with fixed boundaries.

Flats inside the Dutch Wadden Sea are not likely to exceed a height of 5m + NAP. Consequently the cumulative areas at the highest level (5m + NAP) obtained from this hypsometric information can be considered to represent total basin surface areas of the basins. Having variable boundaries in time causes also the basin surface area to change in time. This is not the case using fixed boundaries. Consequently the cumulative at the highest level of hypsometries constructed with fixed boundaries should be constant for each basin in time. This is shown for each basin except for Vlie. Between 1982 and 1988 the cumulative area at 5m + NAP decreases in the order of ~20 km^2 (Figure 3.9). This can be caused either by area inside the basin exceeding a height of 5m + NAP or blanks in the bathymetry used to construct the hypsometries. It is possible that a small part of the basin exceeds a height of 5m + NAP. Judging from the bathymetries subtracted with UCIT (Appendix D) it seems very unlikely that this concerns an area of such dimensions. Also Figure 3.9 does not show large areas above 1m + NAP. Blanks in the information underlying these hypsometric curves would be a more plausible explanation.

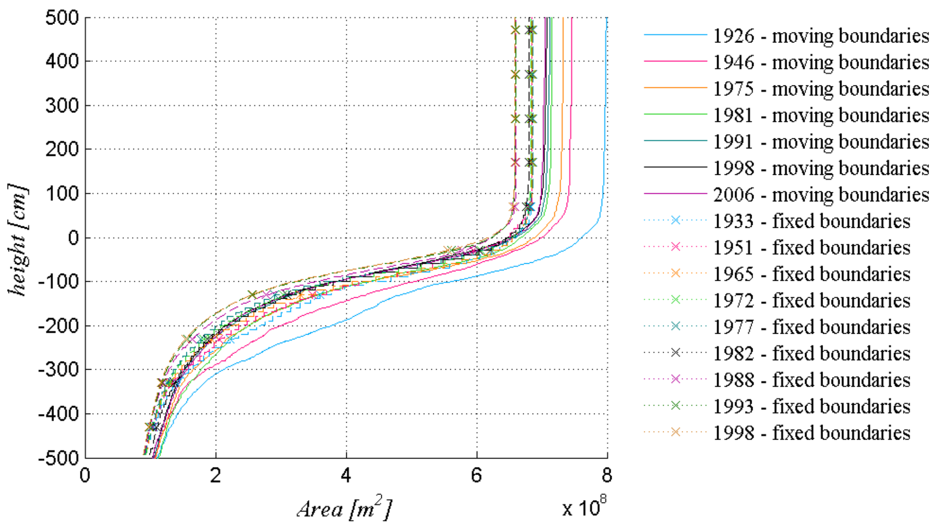


Figure 3.9: Cumulative area between -5 + NAP and 5 + NAP for Vlie basin

The cumulative wet volume under a certain level is obtained by integrating the cumulative area over the depth. Consequently the discrepancy in the total surface area of Vlie basin development in time also has its effect on the cumulative volumes determined for this basin. In case of blanks in the information this will lead to an underestimation of the wet volume. Depending on the water depth at the location of the blanks this will lead to errors in the volumes and areas determined from these hypsometric curves according to the definitions explained in section 2.2.

3.3 Results

Using definitions as explained in section 2.2 volumes and areas for all elements of the Dutch Wadden Sea are determined. This is done with the three methods mentioned above. The concluded volumes and areas are listed in appendix G. In the following paragraphs the outcome of the methods will be compared based on the equilibrium relations adopted in ASMITA.

3.3.1 Flat Areas

One of the empirical relations underlying ASMITA expresses the relative flat area as a function of the total basin surface area. This relation is part of the definition for the equilibrium flat volume.

$$\frac{A_{fe}}{A_b} = 1 - 2.5 \cdot 10^{-2} \cdot A_b^{0.5} \tag{2.5}$$

Figure 3.10 shows that the general overview does not change very much depending on the chosen method. The position of Eierlandse gat basin is remarkable. In previous studies (Eysink and Biegel (1992),van Goor (2001)), the relative flat area belonging to the Eierlandse gat was confirming relation (2.5). Elias et. al. (2006) uses the same measured data as is used in this study. Both studies show a relative flat area that is too low compared to an equilibrium defined by relation (2.5). Also the position of Marsdiep and Vlie draw the attention. Both inlets seem to disregard the equilibrium formulated by (2.5). Depending on the analyzing method the relative flat area in Marsdiep basin either stays constant in time or moves away from its equilibrium. In first instance Vlie basin seems to fulfill relation (2.5). This basin however shows a large increase causing the flat surface area to be too large relative to (2.5).

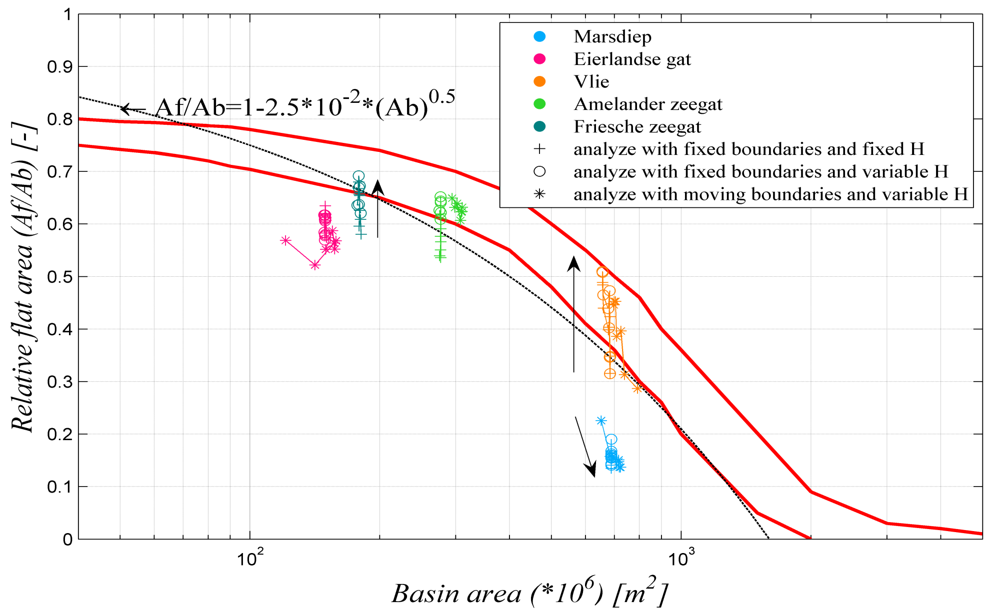


Figure 3.10: Relative flat areas measured in the Dutch Wadden Sea according to three different methods

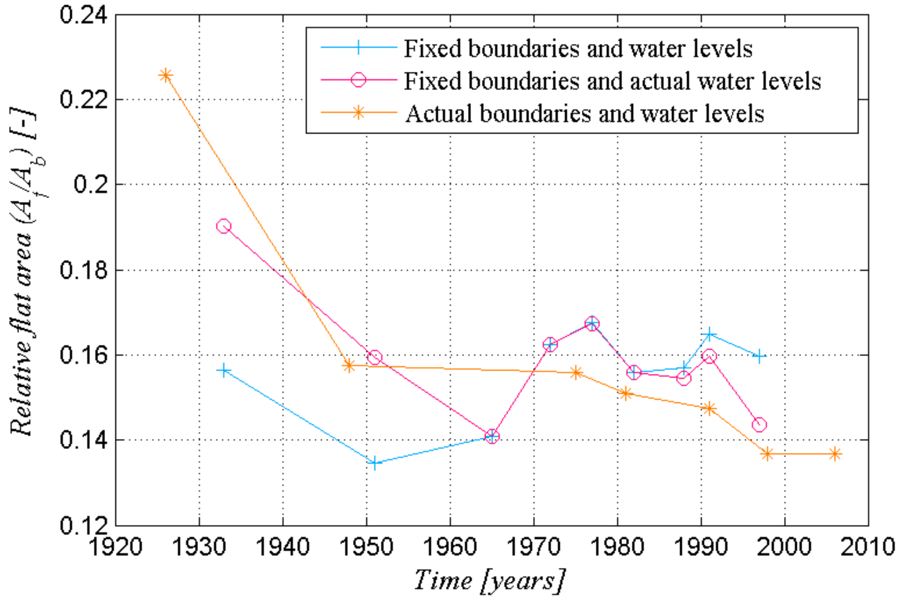


Figure 3.11: Relative flat area of Marsdiep examined with different methods

Taking a closer look at the individual systems significant differences between the analyzing methods can be observed. As an example the development of relative flat area for the Marsdiep basin is examined (Figure 3.11). Similar figures for the other basins can be found in appendix G. The difference between the two methods in which the boundaries are kept constant show the influence of actual water levels versus constant water levels in time. In both analyses the hypsometry is exactly the same. It is to be expected that at some point in time the results of the analysis using fixed water levels will approach the analysis using actual water levels. The general trend however differs for these two different methods. When analyzing with fixed water levels the relative flat area seems to be growing. The opposite is noticed when analyzing with actual water levels. This difference shows that analyzing basin characteristics for a long period in which the mean water levels significantly change it is not sufficient to assume fixed water levels. The observed decrease in relative flat area is strengthened by also taking into account the actual boundaries. Especially between 1926 and 1948 there is a large decrease in relative flat area in the Marsdiep. This can be explained by the movement of the boundaries. Figure 3.12 shows the initial movement of the boundary between Marsdiep and Vlie. In first instance Marsdiep claims a large amount of area from the Vlie basin. This concerns only channel area causing the relative flat area to decrease. Figure 3.11 shows the significant influence of taking into account both actual water levels and actual boundaries when analyzing basin characteristics. When the boundaries of a basin are more or less stable and a period is examined in which the water levels do not significantly change these effects may be neglected. This is not the case when Marsdiep is examined between 1932 and present.

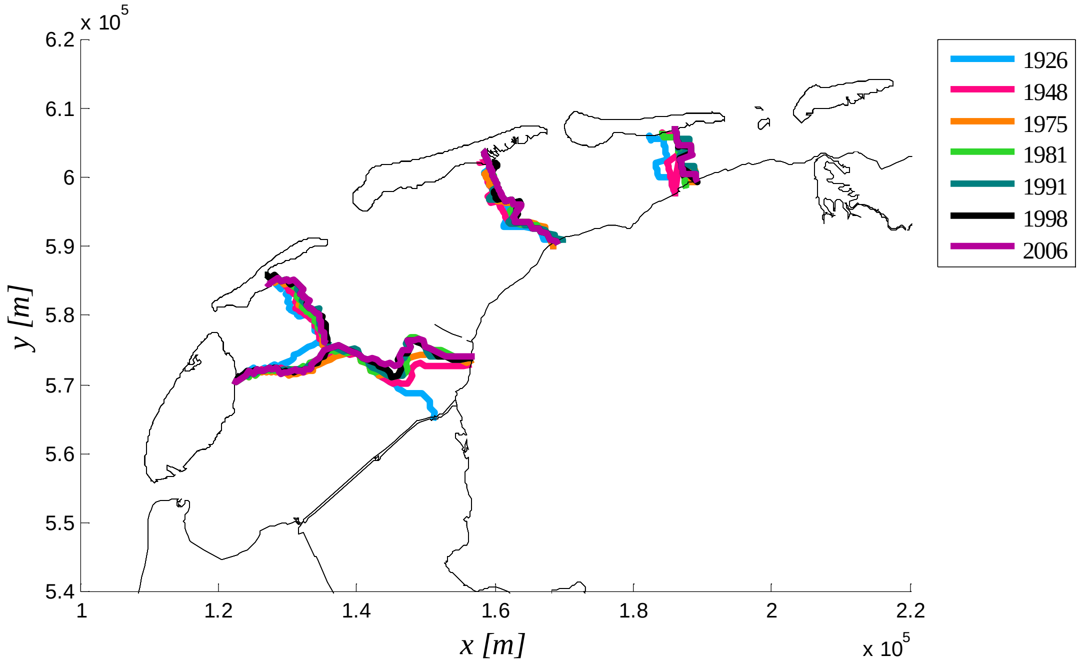


Figure 3.12: Basin boundaries between 1926 and 2006

3.3.2 Flat height

The second relation adopted in ASMITA to define the equilibrium flat volume concerns the equilibrium mean flat height. According to Eysink and Biegel (1992) this relation yields:

$$h_{fe} = \alpha_{fe} \cdot H \tag{2.6}$$

An important parameter is α_{fe}. From section 2.3.2 it is known that Eysink and Biegel (1992) also derived a relation for expressing α_{fe} as a function of the basin surface area:

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{2.7}$$

In that relation α_f is 0.41 for all inlets belonging to the Dutch Wadden Sea. Van Goor (2001) used different values for α_f in the different basins in the same area ranging from 0.38 to 0.5. From the measurements h_f / H can be calculated. Figure 3.13 compares the measurements with relation (2.7). Differences between analyzing with fixed water levels or varying water levels can be seen in almost all inlets. Except for the Ameland basin none of the basins show large differences in h_f / H analyzed with fixed boundaries compared to the analysis with moving boundaries. The basin surface area using actual boundaries is much larger compared to the surface area analyzed with fixed boundaries. A possible reason for the difference in the Ameland basin can be found in the accuracy of the Eastern boundary as explained in section 3.2.

Regardless of the analyzing method the mean flat height development of most basins become more stable in the last period. From Figure 3.13 it can be concluded that α_f = 0.41 in general describes the situation for all inlets using data of all analyzing methods. When only the data calculated with actual boundaries and actual water levels is examined it seems that (2.7) large basins are under estimated and small basins over estimated. A best fit through these data based on a linear relationship leads to relation (3.1). This is illustrated in Figure 3.14.

$$\alpha_{fe} = 0.36 - 1.24 \cdot 10^{-10} \cdot A_b \tag{3.1}$$

According to Eysink and Biegel (1992) the mean flat height is related to MHW. The amount of wave action determines the distance between the mean flat height and MHW. The basin surface area gives an indication to which extend waves are able to develop inside a basin. Including the mean fetch for an average wave direction would provide more information on the wave climate. Therefore small differences in α_f (relation (2.7)) for different basins can be expected. The difference between taking α_f = 0.41 for all basins or taking different values for α_f is shown in Figure 3.15 and Figure 3.16. Figure 3.17 compares the calculated flat height with an equilibrium based on relation (3.1). These figures are based on the data calculated with actual boundaries and actual water levels. In particular for the period between 1970 and 2006, with exception of the Marsdiep, all mean flat heights tend to be stable. These mean flat heights for the individual basins are not described by the known relation for α_{fe} (2.7). When choosing values for α_f in each separate basin the equilibrium flat height can be forced at a certain level. Consequently Figure 3.16 describes the stable situation well. Figure 3.17 shows that also relation (3.1) predicts equilibrium mean flat heights that approach the stable periods in reality better than relation (2.7).

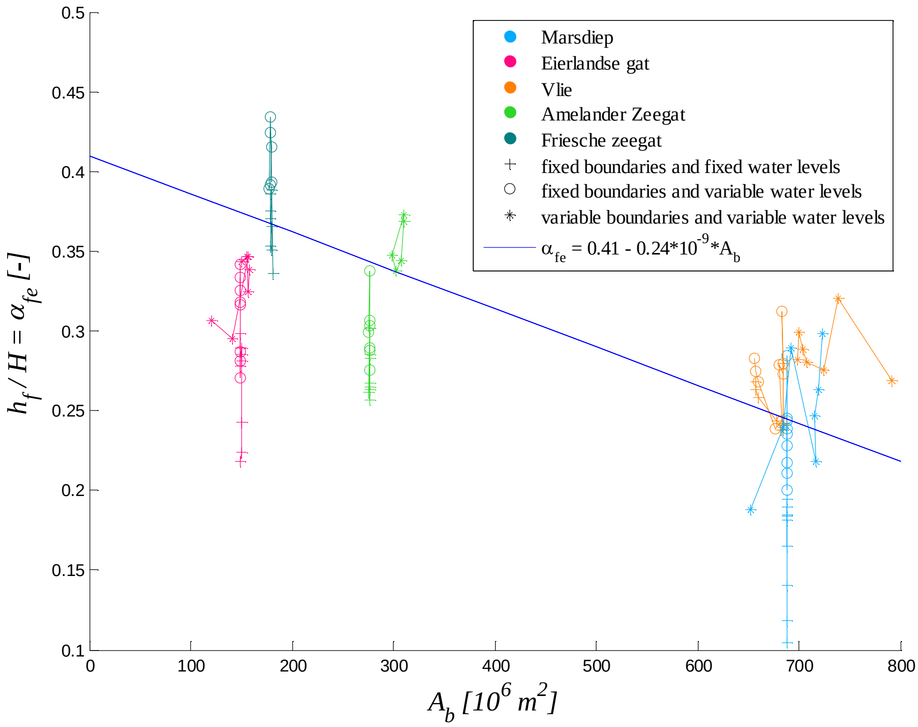


Figure 3.13: Comparison between measurements and α_{fe} according to Eysink and Biegel (1992)

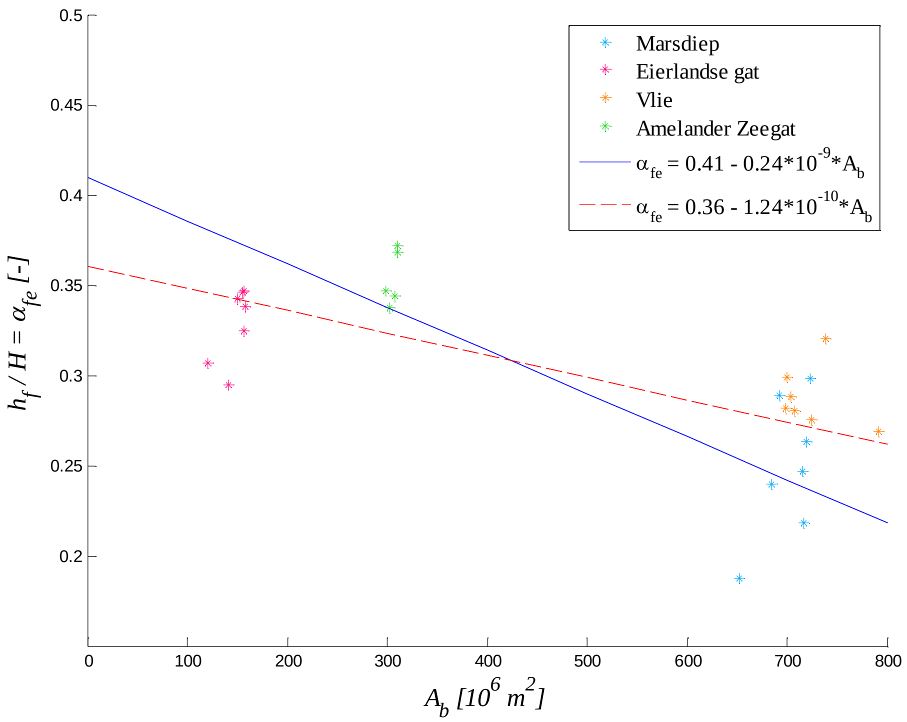


Figure 3.14: Comparison between measurements with actual boundaries and relations (2.7) & (3.1)

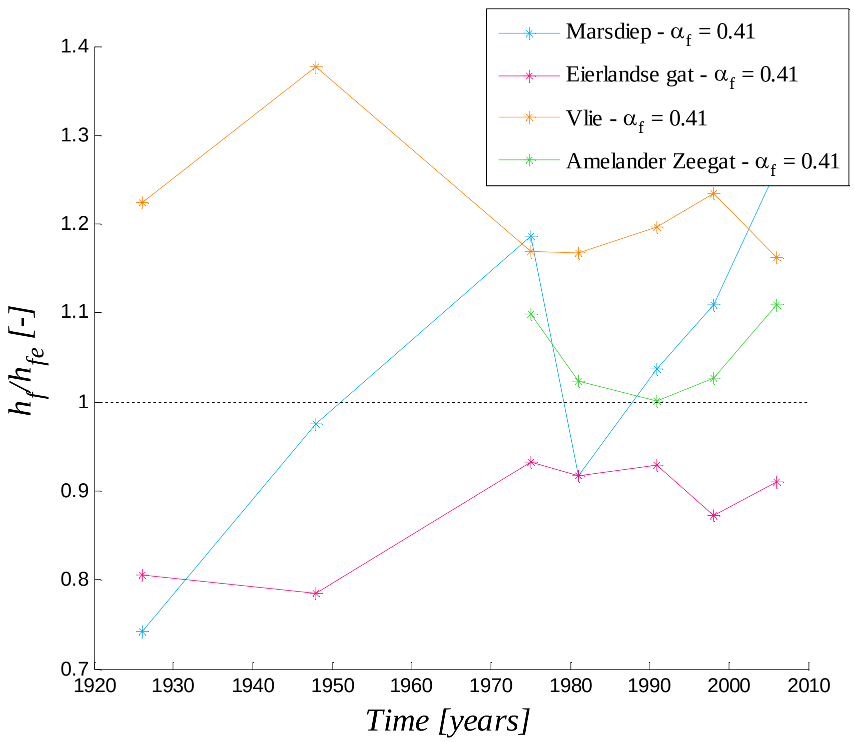


Figure 3.15: Mean flat height development in time scaled with equilibrium flat height according to Eysink and Biegel (1992)

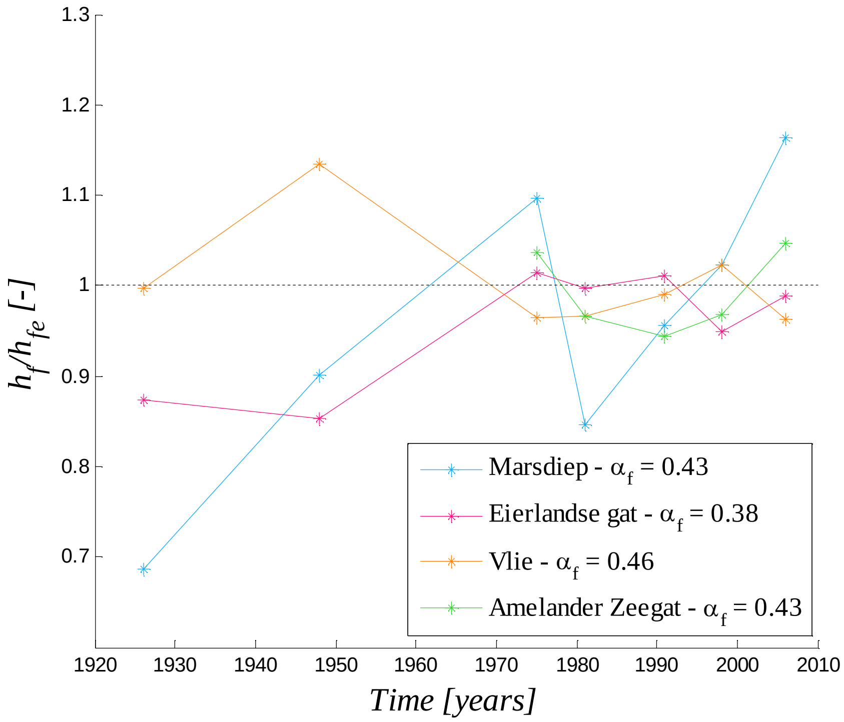


Figure 3.16: Mean flat height development in time scaled with equilibrium flat height defined for each basin individually

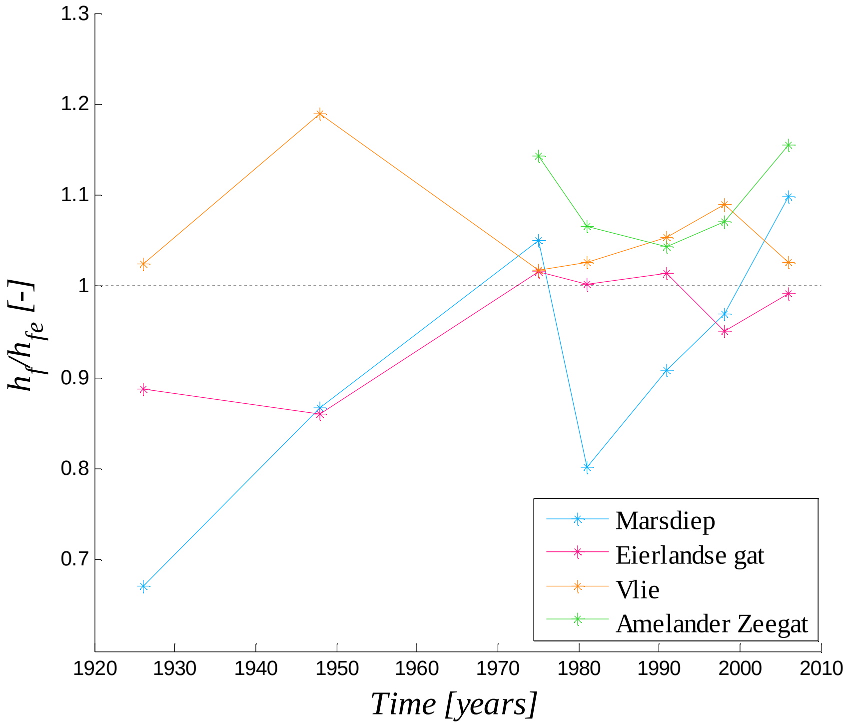


Figure 3.17: Mean flat height development in time scaled with equilibrium flat height determined with relation (3.1)

Relation (2.6) only gives an indication of the equilibrium between morphology and hydrodynamic conditions. There is no information on how the adaptation of the flat height towards that equilibrium will take place. Adaptation processes often show a logarithmic character. In that case the adaptation can be described using an expression like (3.2)

$$X = X_0 \cdot e^{\left(-\frac{t}{\tau}\right)} \tag{3.2}$$

in which:
X [-] Certain quantity
X_0 [-] The initial difference between a certain quantity and its equilibrium
t [s] Elapsed time
τ [s^{-1}] Characteristic adaptation time equal to:

$$\tau = \frac{X_0}{\Delta X_0}$$

with:
ΔX_0 Initial rate of adaptation

Applying this concept to the adaptation of the flat height gives:

$$h_{f(t)} = h_{f(0)} + \left(h_{fe} - h_{f(0)}\right)\left(1 - e^{\left(-\frac{t}{\tau}\right)}\right) \tag{3.3}$$

It is assumed that adaptation of the mean flat height after a change of the water levels takes place in a period of approximately 5 years (Eysink and Biegel, 1992). Unfortunately the frequency with which bathymetries have been measured after closure of the Zuider Sea is too low to examine this. In case this assumption is correct the time scale for adapting towards a new mean flat height is much smaller than the time scale for adaptation of the flat volume. As a consequence adaptation of the flat height towards its new equilibrium is not largely influenced by the development of the flat volume. Relation (3.3) will be used in ASMITA to describe the behavior of the mean flat height and as a result of that also the development of the flat surface areas based on the change of flat volume.

To test this relation for each basin the mean flat height is reproduced using the initial mean flat height of that basin and relation (3.3). In case of all basins the best fit was obtained using τ=10 [years]. As an example Figure 3.18 shows the measured mean flat heights and the relation for adaptation towards an equilibrium mean flat height for the Eierlandse gat. See appendix G for similar figures for other basins. In spite of the scatter in the measurements it still seems that this relationship in general describes the development of the mean flat heights for the basins of the Dutch Wadden Sea.

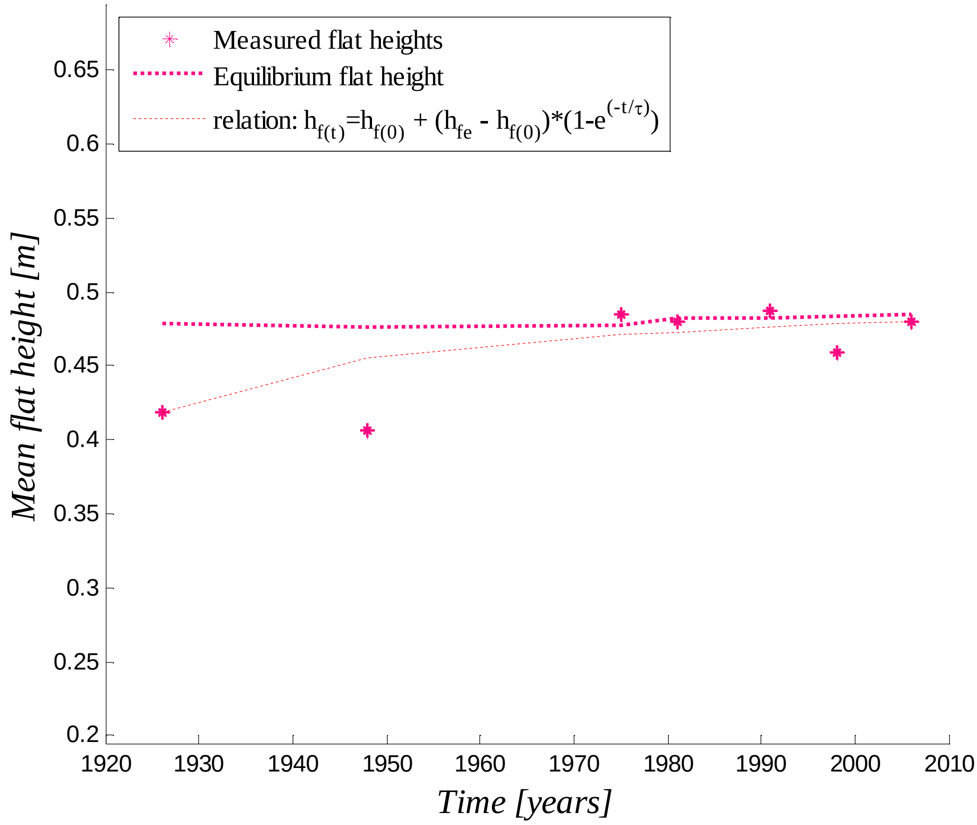


Figure 3.18: Mean flat height development Eierlandse gat compared to relation (3.3)

3.3.3 Flat volume

In ASMITA the equilibrium flat volume is obtained by multiplying the equilibrium flat surface (2.5) by the equilibrium mean flat height (2.6). This leads to relation (2.8).

$$V_{fe} = \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b} \right) \cdot A_b \cdot H \qquad (2.8)$$

with:

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \qquad (2.7)$$

Figure 3.19 shows the equilibrium flat volume for different values of α_f. Measured flat volumes are also included in this figure. The previous sections show that measured mean flat heights seem to be in accordance with the equilibrium relation formulated by Eysink and Biegel (1992). The best description is obtained when α_f is varied for each basin. The relative flat area of Marsdiep and Vlie display unexpected behavior. This is also shown in Figure 3.19. The flat volume of the Vlie basin keeps increasing while according to relation (2.8) the equilibrium has already been reached. The flat volume of the Marsdiep basin shows a small increase. To reach an equilibrium both the equilibrium flat height and equilibrium flat area have to be in equilibrium. In case of the flat surface area this can not be observed yet. Consequently the adaptation of the mean flat height towards its equilibrium does not lead to a development of the flat volumes towards the equilibrium flat volume.

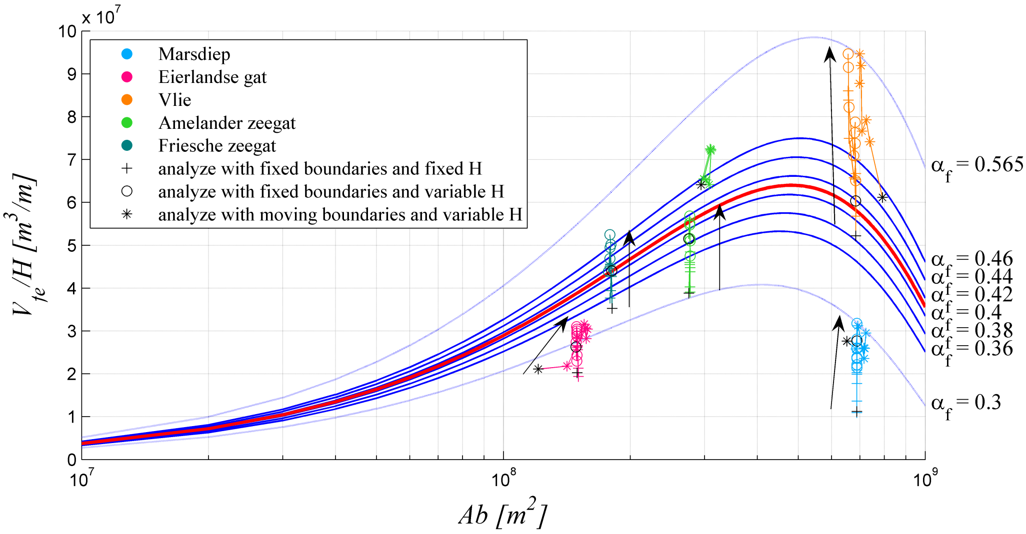


Figure 3.19: Measured flat volumes compared to relation (2.8)

3.3.4 Channel volume

Relation (2.18) is adopted in ASMITA to calculate the equilibrium channel volume as a function of the tidal prism:

$$V_{ce} = \alpha_c \cdot P^{\beta_c} \tag{2.18}$$

Measured channel volumes of all basins in the Dutch Wadden Sea and for the three analyzing methods are presented in Figure 3.20. From section 2.3.2 it follows that α_c is dependant on the shape of the basin and has to be calibrated for each basin individually. Values for the Dutch Wadden Sea used by van Goor (2001) and Kragtwijk (2001) vary between $9*10^{-6}$ and $23*10^{-6}$. Equilibrium channel volumes calculated with coefficients in this range are indicated in Figure 3.20. Regarding channel volumes most of the basins in the range of the equilibrium volumes as defined by Kragtwijk (2001) and van Goor (2001). For the Marsdiep basin Kragtwijk (2001) used $\alpha_c \approx 20*10^{-6}$. For the Vlie basin $\alpha_c \approx 9*10^{-6}$ was used. Although these two basins do not have the same shape this is a large difference. One of the conclusions of Elias et. al. (2006) is that the Marsdiep basin could still be out of equilibrium. Comparing the measured channel volumes with equilibrium channel volumes based on the coefficient of Kragtwijk (2001) gives the impression that Marsdiep is not far from equilibrium concerning channel volume. The coefficients for the equilibrium channel volume of Marsdiep and Vlie basin are further looked at in Chapter 4.

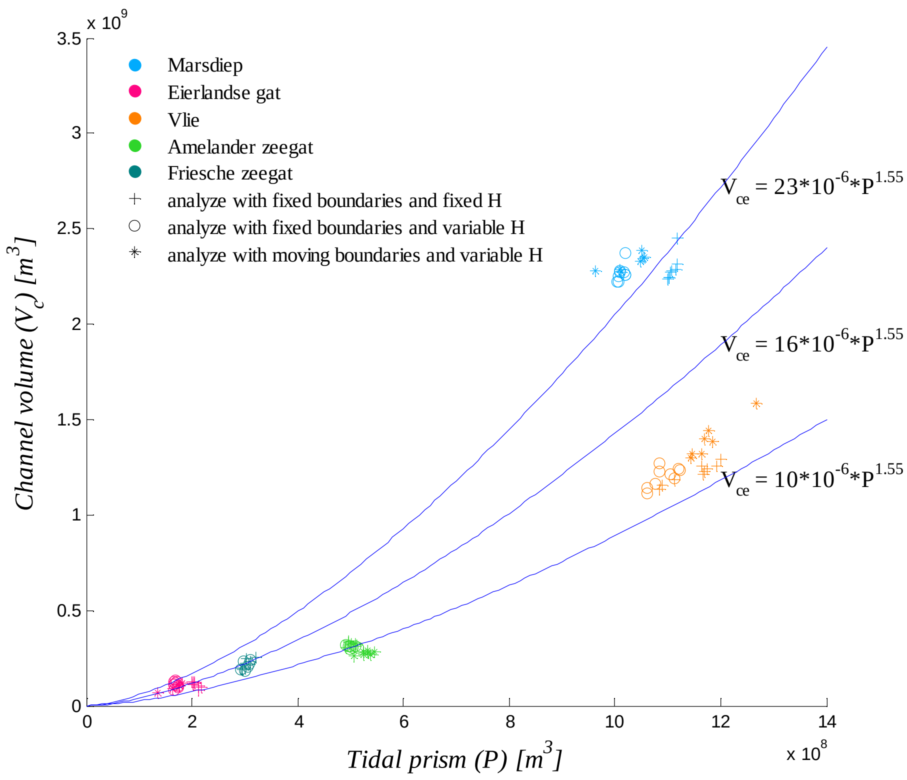


Figure 3.20: Channel volumes relative to the equilibrium relation

3.4 Basin surface areas

Based on the analysis with actual boundaries also the change of the total basin surface area in time can be examined. Figure 3.21 illustrates the movement of the boundaries between the different basins for the past 70 years. The inaccuracy of the Eastern boundary of the Amelander zeegat is visible. An initial shift of the boundary between the Marsdiep and Vlie basin can be observed. A small increase of the Eierlandse gat basin in the direction of Marsdiep and Vlie occurs in the same period. The boundary between Vlie basin and Ameland basin moves towards the East. The movement of this boundary is small compared to the movement of the other boundaries enclosing the Vlie basin. This causes the Vlie basin to decrease in time. The development of the basin surface areas between 1926 and 2006 relative to the surface areas in 1926 is summarized in Figure 3.22. Friesche zeegat is missing in this figure because of the uncertainties in the Eastern Boundary as a result of the model configuration.

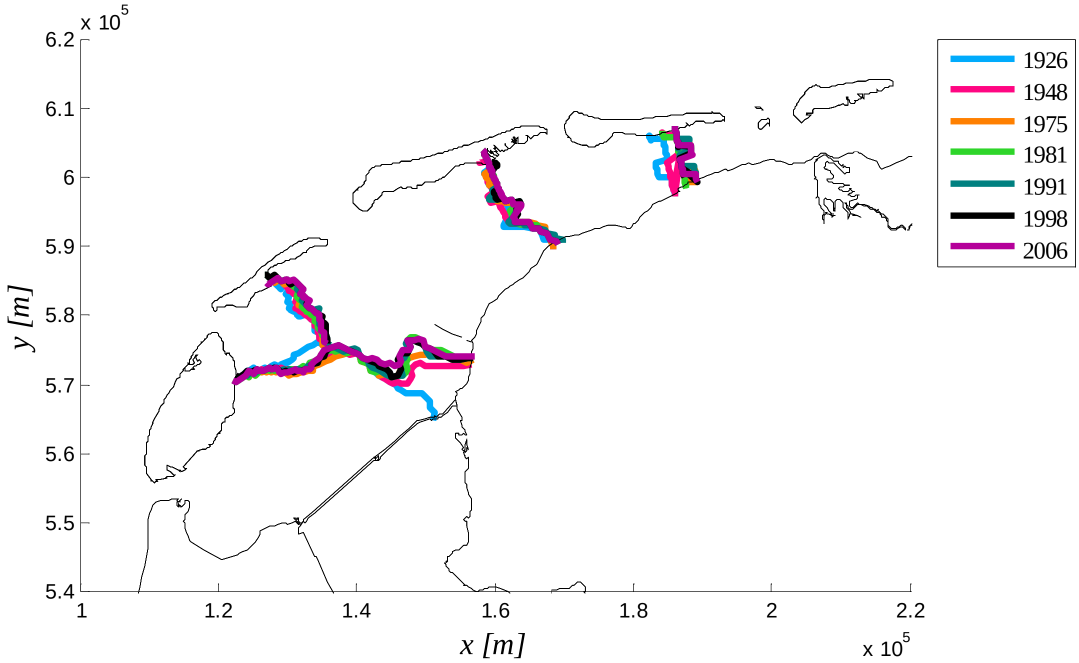


Figure 3.21: Basin boundaries between 1926 and 2006

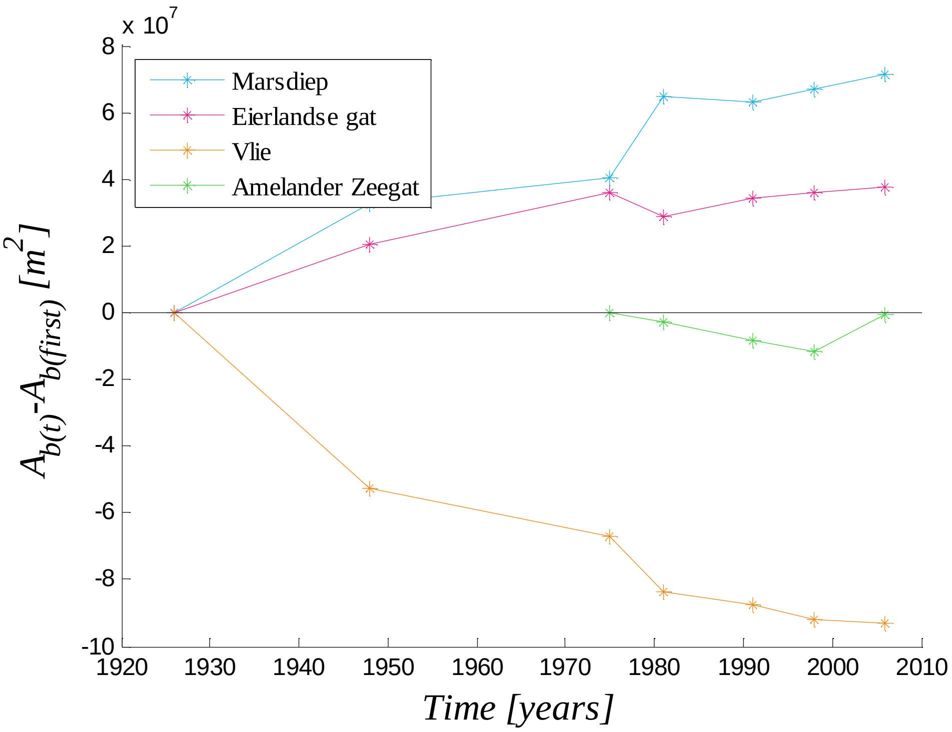


Figure 3.22: Basin surface area development Dutch Wadden Sea

Figure 3.21 and Figure 3.22 show that the adaptation process of the basin surface areas after the closure of the Zuider Sea initially is very fast. Gradually this adaptation slows down. The boundary between two basins is defined by the characteristics of these basins. Until this moment there is no relation expressing the placement or movement of a boundary based on these characteristics.

The adaptations of the Marsdiep-, Eierlandse gat- and Vlie basin all appear to have an exponential character. Figure 3.23 shows that the basin surface area adaptation scaled with the difference between the first and last measured basin areas. The developments of the individual basin areas can be approached with the following relation:

$$\Delta A_b^* = \Delta A_{b,e}^* \cdot \left(1 - e^{-dt/\tau}\right) \tag{3.4}$$

In which:

$$\Delta A_b^* = A_b(t) - A_b(1926)$$

$$\Delta A_{b,e}^* = A_{b,e} - A_b(1926)$$

Relation (3.4) by definition leads to a stable situation on the long term. Assuming the existence of an equilibrium for the Western part of the Dutch Wadden Sea this could also be expected in reality. Figure 3.23 includes this relation for each individual inlet. τ (relation (3.4)) is a measure for the adaptation time. $A_{b,e}^*$ gives an indication of the adjustment in the period between 1926 and present relative to the adjustments still needed to reach a stable basin surface area defined by (3.4). Two time scales can be identified. The Vlie and Eierlandse gat basins both have a characteristic adaptation time (τ) around 30 years. The Marsdiep basin seems to be further out of equilibrium with a characteristic adaptation time of 71 years.

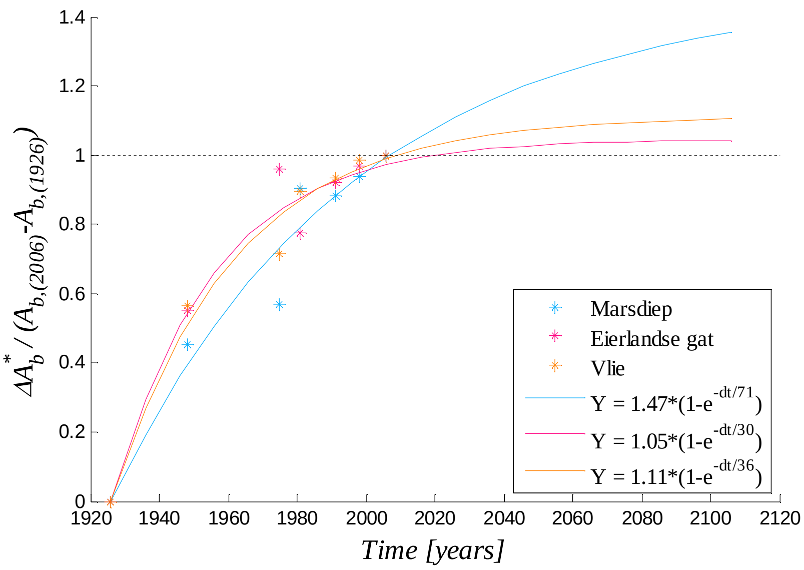


Figure 3.23: Basin surface area adaptations together with relation

3.5 Sediment Budget of the Western Dutch Wadden Sea

Next to basin characteristics also the sediment volume changes of the Western Dutch Wadden Sea can be obtained from both data sources (hypsometric data with fixed boundaries and measurement data obtained with UCIT, see also 3.1.1). It is also possible to determine sediment volume changes of the individual basins. These volume changes are caused by a combination of the altering definition of the basin boundaries in time and volume change due to sediment exchange.

3.5.1 Cumulative volume changes

Hypsometries of the cumulative volume (Appendix F) provide information on the total wet volume under a certain level. Examining the volume changes under the highest level gives the sediment volume change in the basins considered. Sediment volume changes of the Western Dutch Wadden Sea (including Marsdiep, Eierlandse gat and Vlie) with the two available sources of information are reproduced in Figure 3.24. Relative large fluctuations can be observed around the measurements of 1981 and 2006, considering the data subtracted from UCIT. The hypsometric data show similar fluctuations. This could give an indication of the accuracy of the measurements (Elias, 2006). A bathymetry representing a particular year is always a combination of measurements taken over a certain period. Besides the accuracy of the measurements itself this scattering of measurement periods also influences the calculated volume changes between different bathymetries. This leads to differences that can be observed between the two data sources. Although both sources are based upon the same measurements, the processing of the data appears to cause differences. In general similar development of the sediment volume is shown for the hypsometric data and UCIT data. One of the main differences can be found in the period between 1982 and 1987. In this period the sediment volume following from the hypsometric data shows a large increase. This can not be found in the UCIT data. A possible explanation for this difference can be found in the hypsometric curves. As discussed in section 3.2 a large difference in cumulative area at the highest level occurs between the hypsometries representing 1982 and 1987. This could lead to an overestimation of the sediment volume if the difference is caused by blanks in the data underlying these curves.

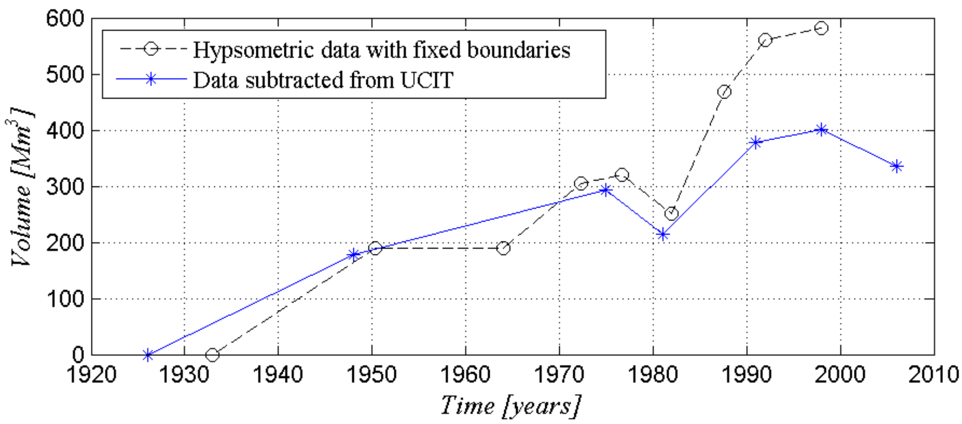


Figure 3.24: Cumulative volume changes of the Western Wadden Sea

Elias (2006) also investigated the development of the sediment volume for the Western Wadden Sea (Figure 3.25). This study is based on Rijkswaterstaat *Vaklodingen* data. Many resemblances can be observed between both data sources used in this study and concluded volume changes by Elias (2006). An exception to this is the large jump between 1982 and 1987 in the hypsometric data discussed above. This can also not be found in the results of Elias. Sediment gains according to the hypsometric data in this period are in the order of

~80 Mm^3 larger than sediment gains following from Elias (2006) and UCIT data used in this study. It can be assumed that this is caused by the unexpected decrease of the surface area in the Vlie basin (~20 km^2) discussed in section 3.2. To account for an extra sediment gain of ~80 Mm^3 the average height of this area has to be around 1m + NAP. This surface area as well as the average height are similar to the height and surface area of the *Griend*, one of the high flats inside the Vlie basin. Changes in the hypsometry above MHW are not taken into account when calculating basin characteristics according to the definitions explained in Chapter 2. Assuming the large jump in volume and surface area is caused by missing data of for example a high flat like the *Griend*, this will not have a large influence on the basin characteristics concluded from these data. The mean flat height of this area lies above MHW. The concluded sediment volume between MLW and MHW will therefore not largely be influenced by the missing data about the developments of flat area above MHW. Consequently calculated basin characteristics will not largely be influenced by these missing data. Concluded sediment volume changes however have to be corrected for this. Besides volume changes inside the basins forming the Western Dutch Wadden Sea Elias (2006) also investigated the volume changes of the ebb-tidal deltas. Figure 3.25 also shows these changes. From the data sources used in this study as well as the volume development of the Western Dutch Wadden Sea calculated by Elias (2006) a large decrease of sediment volume can be observed between 1976 and 1982. This is not compensated by a similar increase of the ebb-tidal deltas (Figure 3.25).

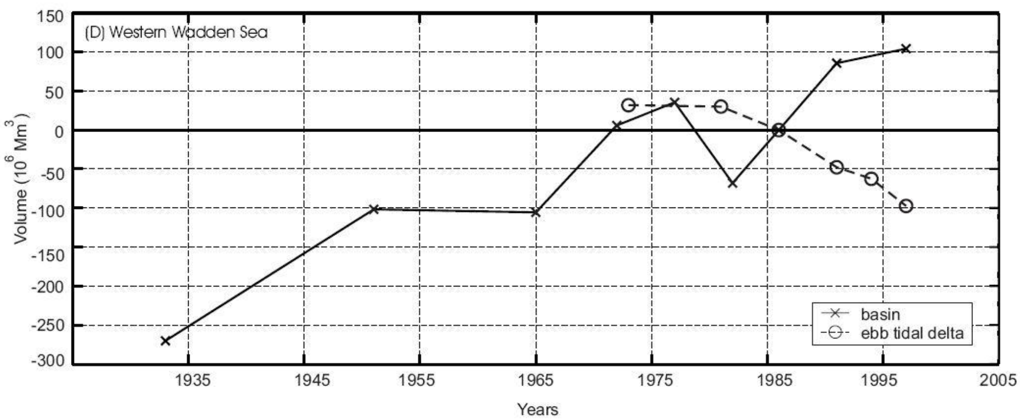


Figure 3.25: Cumulative changes of the Western Wadden Sea, taken from Elias (2006)

3.5.2 Sediment exchanges

Elias (2006) analyzed the sediment volume changes of the Western Wadden Sea as well as volume changes of the accompanying deltas. One of his conclusions is that there must have been an exchange of sediment between the basins of Marsdiep and Vlie. The individual inlets cannot be described separately as the major erosion occurs at the Marsdiep ebb-tidal delta and the main sedimentation in the Vlie basin. This means that volume change due to sediment transport consists of contributions due to exchange with the ebb-tidal delta and exchange with the adjacent basins. These two contributions cannot be isolated considering only volume changes inside the basins. Consequently the actual sediment exchange through a single inlet cannot be estimated using only bathymetric data inside the basins. Only the total sediment import or export of the three basins forming the Western Wadden Sea can be determined (Figure 3.24) assuming no sediment transport occurs over the eastern boundary towards the Ameland basin.

Dividing the volume changes by the period in which it took place gives an indication of the total sediment transport through all inlets in that period. Figure 3.26 is obtained when examining this for all periods between measurements individually.

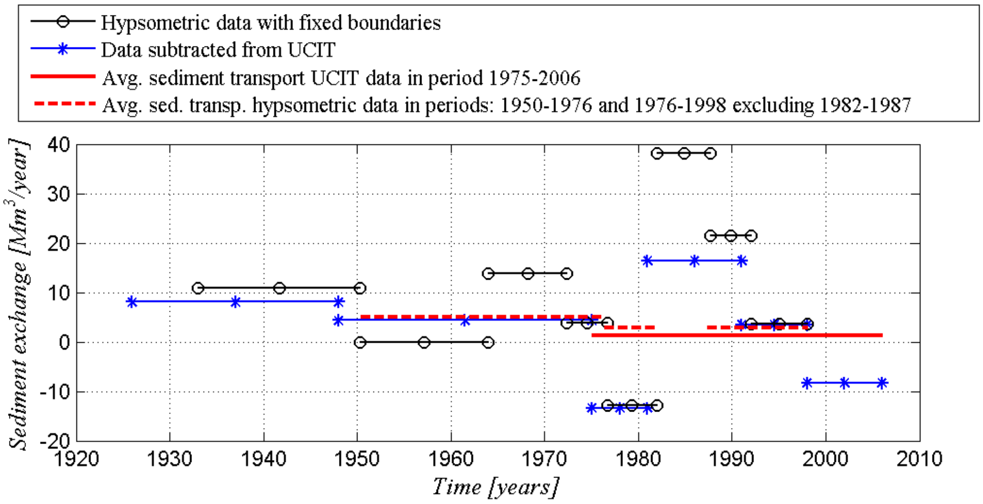


Figure 3.26: Total sediment transport through inlets of the Western Wadden Sea concluded from the cumulative volume changes (Figure 3.24)

Regarding the UCIT data relatively high export and import rates can be observed around 1981 and between 1999 and 2006. The occurrence of high sediment export (~13 Mm^3/year) followed by high import (~16 Mm^3/year) within a period of 16 years seems unlikely to occur. This could be caused by the large fluctuation of the measurements around 1998 and 2006.

The average sediment import between 1975 and 2006 concluded from Figure 3.24 based on the UCIT data amounts ~1,3 Mm^3/year. This is low according to what can be expected based on the influence of SLR. The surface area of the three basins together amounts approximately $1.55*10^9$. The amount of sediment needed to follow SLR in the order of 17 cm/century is ~2.6 Mm^3/year.

Transport rates deduced from volume changes according to the hypsometric data show similar fluctuations. The large sediment import rate (~40 Mm^3/year) between 1982 and 1987 reflects the abnormal development of the sediment volume of the Western Dutch Wadden Sea discussed above. Neglecting this period the average sediment import rate between 1976 and 1998 following from these data amounts ~2,9 Mm^3/year. This is comparable with the average sediment import rate that can be concluded from UCIT data for that period. Also the average sediment exchange rate in the preceding period (1950 – 1976) is in the same range as the average sediment import concluded from UCIT data.

Although there are large fluctuations in the measured volumes it can be concluded that both data sources used in this study show similar developments of the total sediment volume inside the Western Dutch Wadden Sea. This excludes the period between 1982 and 1987 in which a sudden change of the basin surface area and wet volume under 5m + NAP in the hypsometric information causes the concluded sediment transports to have an unrealistic value in the order of ~40 Mm^3/year. This could be caused by blanks in the data underlying the obtained hypsometric curves. From the differences between the to data sources used in this study it follows that these blanks should than have the size of the highest flat in the Vlie basin (Griend). Average sediment transport rates for the entire Western Dutch Wadden Sea solely concluded from both data sources used in this study amount: ~10 Mm^3/year between 1930 and 1950; ~4,6 Mm^3/year between 1950 and 1975; ~2,1 Mm^3/year between 1975 and 2006.

Elias (2006) concludes a total sediment import that ranges between 9 to 10 Mm^3/year for the period between 1986 and present (1997 being the latest bathymetry for the entire Western Wadden Sea included in that study). Although there is a large difference with the sediment exchange rate averaged over the period between 1975 and 2006, this conclusion can also be drawn from Figure 3.24. The large difference between those sediment transport is mainly caused by the period prior to 1982 in which a large decrease of the total amount of sediments can be observed inside the basins for all data sources. Between 1986 and 1997 the volume changes of the basins forming the Western Dutch Wadden Sea and their ebb-tidal deltas seem to be balancing each other. This does not hold for the period between 1976 and 1982 (Figure 3.25). When estimating sediment transport solely based on the volume changes of the basins this mismatch between the data of the basins and ebb-tidal deltas is not taken into account. The sediment transport averaged over the period 1986 to 1997 therefore seems to be a more reliable estimation of sediment exchanges through the inlets in reality compared to sediment exchange averaged over a longer period including measurements between 1976 and 1982. Volume changes in this period following from measurements of the volume development inside the basins do not seem to be reliable. The basin characteristics concluded in the previous sections however also contain this information. An exact reproduction of these data by the ASMITA model therefore is expected to yield sediment exchanges comparable to the sediment exchanges concluded from the data sources used in this study. The simulations will therefore be compared to the sediment exchange rates mentioned above. Differences between these sediment exchange rates and possibly more realistic estimations of the actual sediment exchange made by Elias (2006) have to be taken into account.

3.5.3 Change of basin characteristics due to movement of boundaries

Part of the area and volume changes when analyzing with actual boundaries can be directly related to the movement of the boundaries. Certain areas are claimed or lost due to the alternating definition of the boundary. The changes of area and volume due to this effect have nothing to do with physical movement of sediment. It is solely a consequence of the changed location of the boundary.

These changes can be isolated from measurements. For each moment measurements are available also boundaries are determined. With these boundaries and measurements hypsometric curves can be constructed for each basin. This can also be done for exactly the same bathymetry but with boundaries of the previous moment of available measurements. Both hypsometries can be used to derive basin characteristics. Because the bathymetry used to construct these characteristics are identical, differences between those hypsometric curves and derived basin characteristics are caused by the changed definition of the boundaries.

Consequently differences in volumes and areas are changes due to the redefinition of the boundary in that period. This can be examined for all periods of shifting boundaries. Resulting changes are reproduced in Figure 3.27.

The movement of the boundary between Marsdiep and Vlie basin occurs at a location where only channel area can be found. Changes of channel area and volume therefore mainly occur in the Marsdiep and Vlie basins (Figure 3.27). Boundaries surrounding the Eierlandse gat basin mainly cover flat area. Therefore no large changes of the channel element occur in the Eierlandse gat basin as a result of the movement of those boundaries. An increase of the flat surface area in this basin due to movement of the boundaries is balanced by a decrease of flat surface area in the Marsdiep and Vlie basins. The accompanying volume changes of the flats in Eierlandse gat on the other hand show unexpected behavior. The flat surface area between 1991 and 1998 shows a small increase. It is than to be expected that also the flat volume change in the same period is positive. In this particular period that is not the case. The opposite can be observed for the following period. This is discussed in Appendix B.

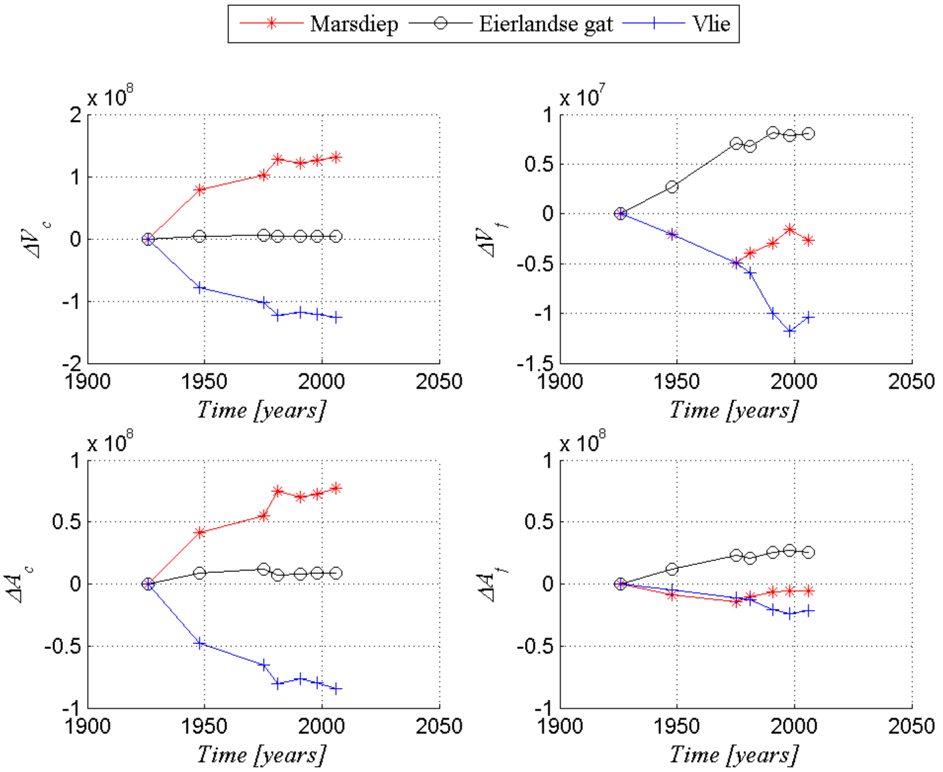


Figure 3.27: Cumulative volume and surface area changes due to movement of basin boundaries

By definition the sum of surface areas of all elements stays constant in time considering only movement of the boundaries between the basins and no changes in bathymetry. This does not hold for the sediment volume changes due to movement of the boundaries. Volumes for each basin are determined using MLW and MHW. These values differ per basin. If the boundary between two arbitrary basins (1 and 2) moves, the amount of volume gained in basin 1 is therefore not equal to the amount of volume lost in basin 2. The gained volume for basin 1 is related to MLW in that basin. The lost volume by the same movement of the boundary in basin 2 is related to MLW in this basin. This is illustrated in Figure 3.28.

Flat volume lost in basin 2 due to the movement of the boundary is equal to V_1. The volume gained by basin 1 amounts V_1+V_2.

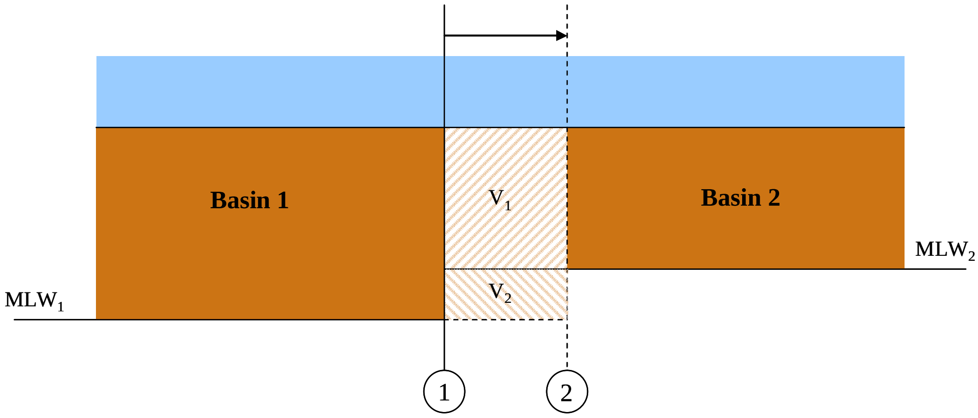


Figure 3.28: Schematization of flat volume changes due to movement of a boundary

3.6 Conclusions

- A method is presented to distinguish basins in a barrier lagoon system. When a bathymetry is known the water motion can be modelled using a process based model. The line between two inlets where the velocity deviation over several tidal cycles is minimal separates two tidal basins. Accuracy of the boundary depends on the accuracy of the model.

- In this study a conventional way of analysing tidal basins using fixed boundaries and fixed water levels in time is compared with analyses using actual water levels and actual boundaries. It can be concluded that both including actual water levels and including the movement of boundaries between basins have a significant influence on the resulting basin characteristics. This is found for example when comparing the relative flat areas for Marsdiep calculated with these results.

- According to Eysink and Biegel (1992) mean flat heights inside a basin tend to reach an equilibrium. This equilibrium can be related to MHW and is also included in the definition of the equilibrium flat volume in ASMITA. The adaptation takes place in a short period compared to the adaptation of flat volume to a new equilibrium. Using an exponential equation like (3.3) the measured flat heights can be reproduced. This will also be used in ASMITA to calculate mean flat heights and resulting flat areas given a certain flat volume. The resized surface areas can be used in the next time step to calculate sediment exchange.

$$h_{f(t)} = h_{f(0)} + \left(h_{fe} - h_{f(0)}\right)\left(1 - e^{\left(-\frac{t}{\tau}\right)}\right) \qquad (3.3)$$

- Measured channel volumes in general fulfil the relation for equilibrium channel volume included in ASMITA (2.18). One of the coefficients in that relation depends on the shape of the basin. Coefficients used by Kragtwijk (2001) would indicate that both Marsdiep and Vlie basin are not far from equilibrium. Because Elias et. al. (2006)

conclude that Marsdiep might still be developing towards its equilibrium these coefficients are re-examined while calibrating ASMITA for the Western Part of the Dutch Wadden Sea.

- Basin surface areas following from the analysis with actual basin boundaries initially change fast starting at 1926. This could be caused by the closure of the Zuider Sea forcing the Marsdiep and Vlie basin to find a new equilibrium. In time the adaptation appears to slow down. When describing this behavior with an exponential relation two time scales can be distinguished. Vlie and Eierlandse gat basins seem to have reached a near equilibrium state in terms of basin surface area. The Marsdiep basin still seems to be far out of equilibrium.

- Sediment volume changes for the Western Dutch Wadden Sea are determined for both data sources. It can be concluded that there seems to be data missing in the upper part of the hypsometric curves obtained for basins with fixed boundaries in case of the Vlie basin from 1982 until present. Whereas the majority of the missing data appears to lie above MHW this does not have a large effect on the concluded basin characteristics in that period. Volume changes concluded from these data have to be corrected for that.

- Because of sediment transport between the basins no estimation can be made of the sediment export / import through the inlet of an individual basin solely based on hypsometric information of this basins. An estimation of the sediment export or import of the Western Dutch Wadden Sea through all inlets can be made assuming no sediment transport occurs at the Eastern Boundary of the Vlie basin. Rough estimations based on the two available sources amount:

    - ~10 Mm^3/year (1930 - 1950)
    - ~4,6 Mm^3/year (1950 - 1975)
    - ~2,1 Mm^3/year (1975 - 2006)

- A large difference can be identified between the estimated sediment transport between 1975 and 2006 from the data sources used in this study and estimations by Elias (2006) for the total sediment import between 1986 and present. This difference can be explained by the different periods that are examined. Elias (2006) also investigates the volume changes of the ebb-tidal deltas. Volume changes of the basins and ebb-tidal deltas do not confirm each other between 1975 and 1986. Consequently an estimation of the sediment change based on data between 1986 and present will provide a more reliable estimation of the actual sediment transport in this period. Basin characteristics deduced for the different basins and used for calibration of ASMITA however do also contain volume changes between 1975 and 1986. In this study therefore sediment exchanges as mentioned above will be used for comparison with calculation results.

4 Implementation of adjustments in ASMITA

4.1 Introduction

In section 2.5 several adjustments are suggested to improve the long-term morphologic predictions of the Western Dutch Wadden Sea. Analysis of field data (Chapter 3) provides necessary information for their implementation. In this chapter the implementation of the adjustments in ASMITA is discussed. Chapter 5 describes the effects of these changes.

4.2 Flat area changes

Until now ASMITA only calculates volume changes. From Chapter 3 it can be concluded that also surface areas of flats and channels change in time. Including these changes in ASMITA computations is expected to lead to different sediment exchanges between the water column and bottom of an element. This leads to different volume changes as well. Relation (3.3) introduced in Chapter 3 expresses the development of the mean flat height towards its equilibrium.

$$h_{f(t)} = h_{f(0)} + \left(h_{fe} - h_{f(0)}\right)\left(1 - e^{\left(-\frac{t}{\tau}\right)}\right) \quad (3.3)$$

The step in the calculation scheme of ASMITA (Figure 2.2) where morphological change is calculated can be expanded with an extra step. This concerns a recalculation of the surface areas of each element inside the basin. In first instance only the volume changes of all elements is calculated. This provides the flat volume during that time step. Dividing this volume by the mean flat height determined with (3.3) gives the flat area at that moment (4.1).

$$A_f = \frac{V_f}{h_f} \quad (4.1)$$

Basin surface area equals the summation of channel and flat surface areas. The total surface area inside a basin is only affected by movement of the basin boundaries. This can be calculated. Consequently the new channel surface area is obtained by subtracting the newly determined flat surface area from the basin surface area.

$$A_c = A_b - A_f \quad (4.2)$$

New surface areas for the elements inside the basin are used in the next time step for determination of the sediment exchanges.

4.3 Sediment exchange between basins

The relation for determining the sediment exchange between an element and its environment (section 2.3.4) can be rewritten to:

$$\sum_m \delta_{n,m}\left(c_n^* - c_m^*\right) + \sum_m q_{n,m}\left(\varphi_{n,m}c_n^* + \varphi_{m,n}c_m^*\right) + s_n = w_{s,n}A_n\left(\gamma_n^* - c_n^*\right) \tag{4.3}$$

In which s_n denotes all exchanges between the element and the outside world:

$$s_n = \delta_{n,E}\left(c_n^* - c_{n,E}^*\right) + q_{n,E}\left(\varphi_{n,E}c_n^* + \varphi_{E,n}c_{n,E}^*\right) = c_{n,E}^*\left(q_{n,E}\varphi_{E,n} - \delta_{n,E}\right) + c_n^*\left(\varphi_{n,E}q_{n,E} + \delta_{n,E}\right) \tag{4.4}$$

and

$$\varphi_{n,m} = \begin{cases} 1 \text{ if } q_{n,m} > 0 \\ 0 \text{ if } q_{n,m} < 0 \end{cases} \rightarrow \quad \varphi_{m,n} = 1 - \varphi_{n,m}$$

Using equations (4.3), (4.4) and (2.26) a system containing n elements can be described with:

$$\frac{d\vec{V}}{dt} = c_E \mathrm{S}\left(\mathrm{W}(\vec{\gamma}^* - \vec{c}^*) + \frac{1}{c_E}\left(\left(\frac{d\zeta}{dt} - \frac{1}{2}\frac{d\vec{H}}{dt}\right)\eta\vec{a} - \vec{b}\right)\right) \tag{4.5}$$

$$\left(\mathrm{D}+\mathrm{Q}\right)\vec{c}^* + \vec{u} = \mathrm{W}\left(\vec{\gamma}^* - \vec{c}^*\right) \quad \Rightarrow \quad \vec{c}^* = \left(\mathrm{D}+\mathrm{Q}+\mathrm{W}\right)^{-1}\cdot\left(\mathrm{W}\vec{\gamma}^* - \vec{u}\right) \tag{4.6}$$

In which:

$$\mathrm{D} = \begin{pmatrix} \delta_{1,2}+\delta_{1,3}+\ldots+\delta_{1,n}+\delta_{1,E} & -\delta_{1,2} & -\delta_{1,3} & \ldots & -\delta_{1,n} \\ -\delta_{2,1} & \delta_{2,1}+\ldots+\delta_{2,3}+\delta_{2,n}+\delta_{2,E} & -\delta_{2,3} & \ldots & -\delta_{2,n} \\ -\delta_{3,1} & -\delta_{3,2} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & -\delta_{n-1,n} \\ -\delta_{n,1} & -\delta_{n,2} & \ldots & -\delta_{n,n-1} & \delta_{n,1}+\delta_{n,2}+\ldots+\delta_{n,n-1}+\delta_{n,E} \end{pmatrix}$$

$$\mathrm{Q} = -\begin{pmatrix} q_{1,2}\varphi_{1,2}+q_{1,3}\varphi_{1,3}+\ldots+q_{1,n}\varphi_{1,n} & q_{1,2}\varphi_{2,1} & q_{1,3}\varphi_{3,1} & \ldots & q_{1,n}\varphi_{n,1} \\ q_{2,1}\varphi_{1,2} & q_{2,1}\varphi_{2,1}+q_{2,3}\varphi_{2,3}+\ldots+q_{2,n}\varphi_{2,n} & q_{2,3}\varphi_{3,2} & \ldots & q_{2,n}\varphi_{n,2} \\ q_{3,1}\varphi_{1,3} & q_{3,2}\varphi_{2,3} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & q_{n-1,n}\varphi_{n,n-1} \\ q_{n,1}\varphi_{1,n} & q_{n,2}\varphi_{2,n} & \ldots & q_{n,n-1}\varphi_{n-1,n} & q_{n,1}\varphi_{n,1}+q_{n,2}\varphi_{n,2}+\ldots+q_{n,n-1}\varphi_{n,n-1} \end{pmatrix}$$

$$\mathrm{W} = \begin{pmatrix} w_{s,1}A_1 & 0 & \ldots & 0 \\ 0 & w_{s,2}A_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & 0 \\ 0 & 0 & 0 & w_{s,n}A_n \end{pmatrix} \quad ; \quad \mathrm{S} = \begin{pmatrix} \sigma_1 & 0 & \ldots & 0 \\ 0 & \sigma_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & 0 \\ 0 & 0 & 0 & \sigma_n \end{pmatrix}$$

$$\vec{a} = \begin{pmatrix} A_1 \\ A_2 \\ \ldots \\ A_n \end{pmatrix} \quad ; \quad \vec{u} = \begin{pmatrix} c_{1,E}^*\left(q_{1,E}\varphi_{E,1} - \delta_{1,E}\right) \\ c_{2,E}^*\left(q_{2,E}\varphi_{E,2} - \delta_{2,E}\right) \\ \ldots \\ c_{n,E}^*\left(q_{n,E}\varphi_{E,n} - \delta_{n,E}\right) \end{pmatrix} \quad ; \quad \vec{\gamma}^* = \begin{pmatrix} \gamma_1^* \\ \gamma_2^* \\ \ldots \\ \gamma_n^* \end{pmatrix}$$

$$\eta = \begin{pmatrix} \eta_1 & 0 & \dots & 0 \\ 0 & \eta_2 & \dots & 0 \\ \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & \eta_n \end{pmatrix} \quad ; \quad \vec{H} = \begin{pmatrix} H_1 \\ H_2 \\ \dots \\ H_n \end{pmatrix}$$

Using this formulation both the advective- and diffusive type of transport of sediments between different elements or an element and the outside world can be schematized.

Exchange of sediments from one basin towards another can only occur at the location where these two basins share the same boundary. By definition this is the watershed between those basins. It is most likely that watersheds are located at flat areas in the back of the basin. Therefore sediment exchange between two arbitrary basins in most cases will occur only between their flat elements. In case of the Marsdiep and Vlie basin this assumption is not valid. Both basins do not have flats at the location of the watershed separating Marsdiep and Vlie. Sediment exchange between those two basins can only be realized between the channel elements. To account for sediment exchange between the basins of the Western Dutch Wadden Sea in this study connections will be made between the flat elements of all basins except for the connection between Marsdiep and Vlie. This is modeled as a connection between the two channel elements. Connections are made by allowing diffusion between these elements. There is no physical background for the estimation of the horizontal exchange coefficients used to schematize this connection. During the assessment of the effect of such connections these parameters will therefore be seen as calibration coefficients.

4.4 Movement of basin boundaries

In section 2.5 it is stated that including changes of basin surface areas in time could lead to an improvement of predictions concerning morphologic development of the Western Dutch Wadden Sea with ASMITA. Basin surface areas change due to movement of watersheds. The placement of these watersheds is determined by the phase difference of tidal waves entering the basins at the entrances in combination with the velocity of the traveling tidal wave inside the basins. The traveling velocity of a tidal wave inside a basin is determined by basin characteristics and characteristics of the tidal wave itself. It would be best to include a relation in ASMITA that describes the velocity of a tidal wave inside the basin based on characteristics of that basin. In combination with a predefined phase difference at the entrances and a characteristic length-scale this could lead to an expression for placement of a watershed between two basins based on their characteristics. This also determines the change of basin surface areas. Until now no relation has been formulated expressing the change off basin surface area as a consequence of the basin characteristics. From chapter 3 it follows that watersheds are not always located at flat parts. Movement of the boundary between Marsdiep and Vlie adds channel parts from Vlie to Marsdiep.

Changes of areas and volumes of the individual elements caused by movement of their boundaries are determined in section 3.5.3. In the present study these changes will be prescribed during the simulations. This will give an indication of the influence of the movement of boundaries on computed sediment transports volumes and areas.

4.5 Calibration of coefficients

One of the suggested adjustments of ASMITA is re-calibration of all coefficients. The coefficients used in ASMITA can roughly be divided into two groups. First there are coefficients used in the equilibrium relations. The values of the equilibrium coefficients determine the final equilibrium elements tend to reach. The development towards this equilibrium is governed by the amount of sediment exchange between the elements and within an element between the water column and the bottom. This is determined by the horizontal and vertical exchange coefficients. Considerations about the estimation and/or calibration of the equilibrium coefficients for flats and channels are discussed in the following two sections. Horizontal exchange coefficients can be estimated based on the results of previous studies (van Goor (2001), Kragtwijk (2001), Buisman (1997)). This is discussed in section 4.5.3.

4.5.1 Equilibrium flat volume

As concluded in section 2.3.2 relation (2.8) has to be included in ASMITA to take into account the change of basin surface area in time.

$$V_{fe} = \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b} \right) \cdot A_b \cdot H \tag{2.8}$$

with:

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{2.7}$$

In these relations α_f is the only coefficient determining the equilibrium flat volume. This parameter can be deduced from measurements (section 3.3.2, Table 4.1). Kragtwijk (2001) calibrated ASMITA for prediction of morphologic behavior of Marsdiep and Vlie basins. Equilibrium flat volumes can be translated into α_f given the basin geometries. Resulting coefficients are included in Table 4.1. α_f-values deduced from Kragtwijk (2001) do not match the results of the analysis of field measurements. These coefficients however compensate the unexpected behavior regarding the flat surface area leading to a fair description of the development of flat volume in those simulations. Section 4.1 described the implementation of a relation for determination of the equilibrium mean flat height. This is also done based on the parameter α_f. The equilibrium mean flat height is used to recalculate surface areas inside the basin. Calibrating α_f in such a way that flat volumes are reproduced correct will lead to predicted mean flat heights and areas that deviate from measurements. This can be corrected by introducing an extra coefficient (c_{fc}) to calibrate the equilibrium flat volume without changing the equilibrium mean flat height (relation (4.7)). There is no physical background for this new correction coefficient. Because a proper estimation can be made for α_f based on analysis of field measurements, c_{fc} can be seen as a calibration parameter for the equilibrium flat volume.

$$V_{fe} = c_{fc} \cdot \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b} \right) \cdot A_b \cdot H \tag{4.7}$$

	α_f deduced from measurements	α_f used in previous studies[1]
Marsdiep	0.43	0.30
Eierlandse gat	0.38	0.38
Vlie	0.46	0.565

Table 4.1: equilibrium mean flat height coefficients deduced from measurements and used in previous studies

[1] Values for Marsdiep and Vlie are deduced from Kragtwijk (2001). α_f for Eierlandse gat is obtained from van Goor (2001)

4.5.2 Equilibrium channel volume

In section 2.3.2 it is explained that a basic form for the relation expressing channel volume relative to MSL is given by (2.12).

$$V_c = c_A \cdot c_s \cdot P \cdot L \qquad (2.12)$$

Using (2.13) this is rewritten as (2.16).

$$L = \sqrt{\frac{(P + V_f) \cdot L}{H \cdot B}} \qquad (2.13)$$

$$V_c = c_A \cdot c_s^1 \sqrt{\frac{L}{H \cdot B}} \cdot \frac{\beta_p}{\gamma_p} \cdot P^{\frac{3}{2}} = \alpha_c^* \cdot P^{\frac{3}{2}} \qquad (2.16)$$

(2.18) is adopted in ASMITA to approach (2.16).

$$V_{ce} = \alpha_c \cdot P^{\beta_c} \qquad (2.18)$$

Values for α_c in previous studies range from $8*10^{-6}$ to and $23*10^{-6}$ depending on the shape of the basin. Determining α_c is not straightforward. If a basin is assumed to have reached an equilibrium this coefficient can be calculated using the mean channel volume and tidal prism over the period it was in equilibrium. These volumes can be deduced from the bathymetry. The reactions of the basin due to small changes or the rising sea level can then be modeled. A different situation occurs when the equilibrium for a basin is unknown. Based on the same principle the equilibrium channel volume can be approached in two ways. First a way is discussed to relate the equilibrium channel coefficients (α_c) of two comparable basins. Second a method is discussed for calculating the final equilibrium situation of a basin providing the equilibrium channel coefficient for this particular basin.

Correlation of α_c between two comparable basins

An indication for the correlation between α_c-values of two comparable basins can be obtained from (2.16). Although (2.18) is not an analytic solution of (2.16) it is assumed that the influence of the shape of the basin on α_c and α^*_c is similar.

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = \frac{\alpha^*_{c,2}}{\alpha^*_{c,1}} \tag{4.8}$$

An estimation of α^*_c can be made based on basin characteristics (2.16). When the channel equilibrium coefficient of one basin is known ($\alpha_{c,1}$), this can be translated into $\alpha_{c,2}$ representing the channel equilibrium coefficient of another basin.

The characteristic channel length (L), channel width (B) and tidal range (H) can be obtained from the basin geometry. The empirical parameters β_p and γ_p are varying with the tidal prism (P). The variation of V_c due to these coefficients is very small for basins with a tidal prism larger than 160*10^6 [m^3]. Therefore it is taken as part of the constant coefficient α^*_c. β_p and γ_p can be calculated for the final equilibrium. In case of equilibrium the tidal prism (P_e, relation (4.9)) is defined by the tidal range (H), the basin surface area (A_b) and the equilibrium flat volume (V_{fe}). V_{fe} can be calculated with (2.8).

$$P_e = H \cdot A_b - V_{fe} \tag{4.9}$$

c_A (2.12) is assumed to be similar for comparable basins. This leaves only c^1_s unknown in the determination of α^*_c. To estimate this shape coefficient we have to go back to its origin. In first instance the shape coefficient c_s introduced by Eysink and Biegel (1992) follows from the integration of the cross-sectional channel area over the channel axis (4.10).

$$c_s = \frac{\int_0^L P(x)dx}{P \cdot L_c} \tag{4.10}$$

The only way to obtain relation (2.16) out of (2.12) is by expressing the flat volume (Vf, relation (2.13)) at a certain moment as a fraction of P:

$$P + V_f = (1 + a_c)P = a \cdot P \tag{4.11}$$

Substituting (4.11),(2.13) and the coefficients to transform $V_{c,MSL}$ to $V_{c,MLW}$ (relation (2.15)) into (2.12) yields:

$$V_c = c_A \cdot c_s \cdot \sqrt{a} \cdot \sqrt{\frac{L}{H \cdot B}} \cdot \frac{\beta_p}{\gamma_p} \cdot P^{\frac{3}{2}} = \alpha^*_c \cdot P^n \tag{4.12}$$

with:

$$a = \frac{H \cdot B \cdot L}{P} \tag{4.13}$$

Comparing (4.12), (4.13) and (2.14) gives:

$$c_s^1 = c_s \cdot \sqrt{\frac{H \cdot B \cdot L}{P}} \qquad (4.14)$$

This provides an expression for c^1_s. With this information it is possible to calculate $\alpha^*_{c,1} / \alpha^*_{c,2}$ for two arbitrary basins. When the equilibrium channel volume of one of those basins is known, α_c for that basin can be translated into α_c for another basin (4.8).

One of the drawbacks of this method is the need of a comparable basin for which the equilibrium is known. It is also not known whether the assumption that c_s stays constant in time is valid.

Deriving α_c from the final equilibrium channel volume

The method for translating α_c of one basin to another is based on the integration of the tidal prism over the channel axis. The same approach can also be used for calculating the final channel equilibrium volume. Starting at the back of the basin it is possible to integrate the channel cross-sectional area over the channel length for that basin in equilibrium. This provides the equilibrium channel volume. The calculation scheme for this integration is summarized in Figure 4.1 and discussed below.

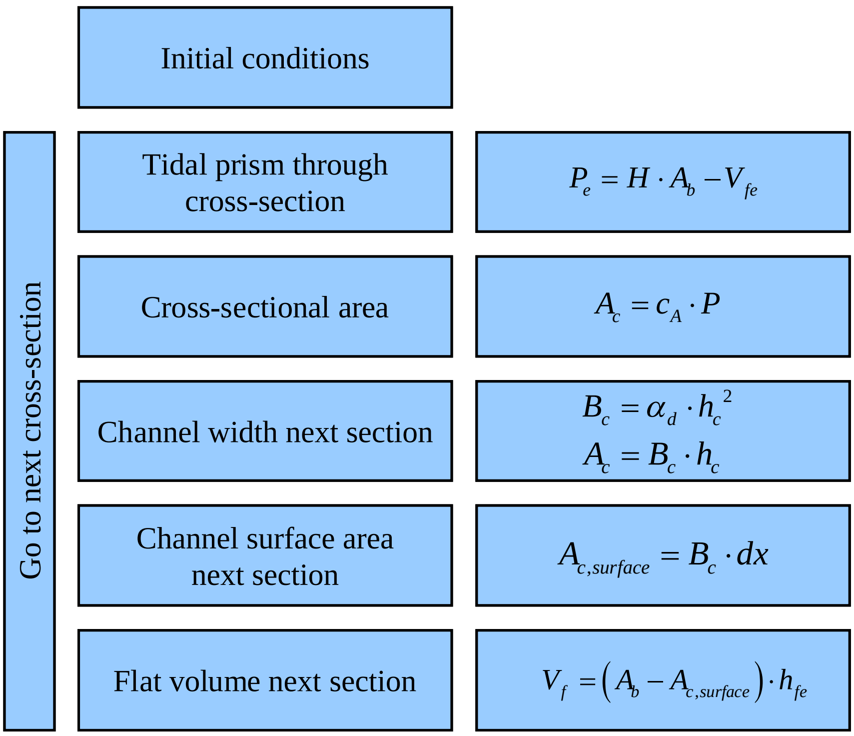


Figure 4.1: Integration scheme equilibrium channel volume

The basin is characterized in different channel sections. Each section has a characteristic channel length and width. The width of a particular channel section is the width of the area in which water is supplied and drained by that channel section. The characteristic channel length in that basin is given by the summation of the characteristic channel lengths in each section. By definition the flat height in a basin in equilibrium has adapted to its equilibrium flat height. This also holds for the back of the basin. The section at the back of the basin can be assumed to have no significant channels. For this first section the tidal prism can be calculated according to (4.9).

$$P_e = H \cdot A_b - V_{fe} \tag{4.9}$$

This provides the tidal prism that flows through a cross-section at distance dx of the back of the basin. With the tidal prism (P_e) also the cross-sectional area (A_{cr}) is known (relation (2.10)).

$$A_{cr} = c_A \cdot P \tag{2.10}$$

According to Eysink (1990) an approximate value of c_A for the Dutch Wadden sea is $7.0*10^{-5}$. To calculate the width of the channel in the next channel section a relation between the channel width (B_c) and channel depth (h_c) is necessary. Such a relation is known from Allersma (1992):

$$B_c = \alpha_d \cdot h_c^2 \tag{4.15}$$

The cross-sectional area is also the mean channel depth times the mean channel width.

$$A_{cr} = B_c \cdot h_c \tag{4.16}$$

When the width of the channel in the next cross-section is known also the channel surface area (A_c) in this section can be calculated.

$$A_c = B_c \cdot dx \tag{4.17}$$

From this the flat volume (V_f) in the next channel section can be calculated.

$$V_f = \left(A_b - A_c\right) \cdot h_{fe} \tag{4.18}$$

This provides the information to calculate the tidal prism passing the next section.

both the equilibrium channel volume and tidal prism will follow from this method. Using (2.18) α_c can then be calculated regardless of the fact whether an equilibrium for this basin or a comparable basin has been known.

$$V_{ce} = \alpha_c \cdot P^{\beta_c} \tag{2.18}$$

Besides the equilibrium channel volume this method also provides the flat volume, flat area and channel area in the final equilibrium state. It would be interesting to compare the outcomes of this method for basins with different areas and different shapes to the relation for the relative flat area deduced from Renger and Partenscky (1974) (2.5).

One of the drawbacks of this method is the uncertainty of relation (4.15) determining the correlation between mean channel width and mean channel depth. Furthermore it is assumed that the final shape of the basin and channel in equilibrium is known. The degree of meandering of the channels inside a basin as well as the chosen shape of the basin itself highly determines the channel length and distribution of the basin width over the channel length. The movement of watersheds between different basins influences the basin shapes. For a better approximation of the equilibrium state therefore also further investigation of the changing basin shapes and areas due to the movement of watersheds is needed. This method can only be used if a fair approximation of the basin shape including channel patterns can be made.

Estimated correlation between α_c values of Marsdiep and Vlie

In this study it is chosen to calculate the correlation of α_c between two basins. This information can be used in the calibration of ASMITA. A detailed description of the computation of this calibration can be found in Appendix A. The computation leads to:

$$\frac{\alpha_{c,Mars}}{\alpha_{c,Vlie}} \approx 1.41 \tag{4.19}$$

This will be kept in mind when calibrating the Marsdiep and Vlie systems including sea level rise.

The coefficients used in ASMITA can roughly be divided into two groups. First there are coefficients used in the equilibrium relations. The values of the equilibrium coefficients determine the final equilibrium elements tend to reach. The development towards this equilibrium is governed by the amount of sediment exchange between the elements and within an element between the water column and the bottom. This is determined by the horizontal and vertical exchange coefficients. Considerations about the estimation or calibration of both groups are discussed below.

4.5.3 horizontal exchange coefficients

Tidal asymmetry can lead to a net sediment transport during a tidal period. In Chapter 2 it is explained that in ASMITA this is described by a diffusion phenomenon. The diffusion coefficient (δ) represents the tide residual exchange capacity between two elements. Van Goor (2001) optimized diffusion coefficients from field data on the Zoutkamperlaag (part of the Friesche Zeegat).

The diffusion coefficient depends on the cross-section which is available for sediment exchange between the elements considered and the length between the centers of those elements. Kragtwijk (2001) concluded that the rate between different characteristic lengths can be used as a scale factor. As an example the horizontal diffusion coefficients of Zoutkamperlaag used by van Goor (2001) are scaled for Marsdiep. Scaling for Vlie and Eierlandse gat is performed in the same manner.

In general it can be said that scaling of the diffusion coefficients approximately is obtained by:

$$\delta_{mars} = \sqrt{\frac{A_{mars}}{A_{zoutk}}} \cdot \delta_{zoutk} \tag{4.20}$$

in which:

δ_{mars} [m/s] Diffusion coefficient Marsdiep
δ_{zoutk} [m/s] Diffusion coefficient Zoutkamperlaag
A [m^3] Characteristic surface area

In case of the diffusion coefficient between the outside world and delta (δ_{od}) the surface area of the delta (A_d) plays an important role. For the exchange coefficient between delta and channel (δ_{dc}) the basin area (A_b) can be used. For the diffusion coefficient between channels and flats (δ_{cf}) this can be further specified.

$$\delta_{mars} = \sqrt[3]{\frac{V_{s,mars}}{V_{s,zoutk}}} \cdot \delta_{zoutk} \tag{4.21}$$

with:

V_s [m^3] Shoal volume, defined as the total wet volume above flats and below MHW

5 Assessment of the effect of the suggested adjustments in ASMITA

5.1 Schematization of the study area in ASMITA

The Western Dutch Wadden Sea consists of three inlets with accompanying tidal basins. In ASMITA Each system is represented by three elements (Delta, channel and flat, see chapter 2). This is illustrated in Figure 5.1. Diffusion between the elements or between an element and the outside world is indicated with an arrow. This schematization also includes connections between the flats of Marsdiep and Eierlandse gat, Vlie and Eierlandse gat and between the channels of Marsdiep and Vlie. These connections are made to simulate sediment exchange between the basins (see also section 4.3 and 5.4.3).

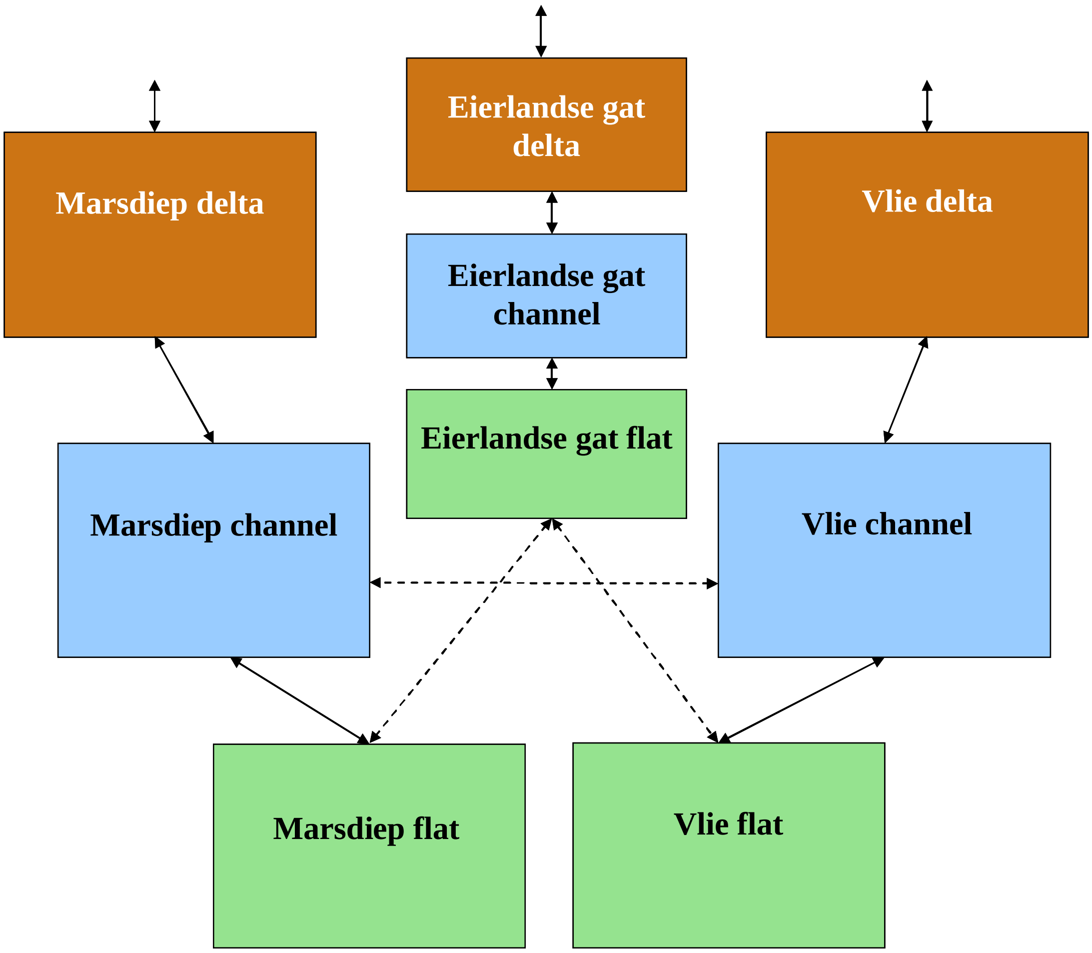


Figure 5.1: Schematization of the Western Dutch Wadden Sea in ASMITA

5.2 Input parameters

Input parameters can be divided into three groups. The first group concerns initial values and characteristics of elements and systems. This includes initial values as well as vertical exchange coefficients and tidal ranges. A second group that can be distinguished contains general parameters like the time step, overall equilibrium concentration and SLR. Next to that also horizontal exchange parameters have to be specified. This provides information about the interaction between the elements.

5.2.1 Characteristics of elements and systems

Initial Volumes and Areas

Each model has to be calibrated to measured data. Volumes and areas of elements inside the basins concluded from measured data depend on the reference levels and basin boundaries that are used. This is discussed in Chapter 3. The value of the initial channel and flat areas and volumes depends on the data used to calibrate the model. If for example the movement of the boundaries is included in model computations, also volumes and areas analyzed with moving boundaries have to be used for calibration. This will be elaborated in section 5.3.

The delta element schematizes the ebb-tidal delta outside a coastal inlet. In ASMITA it is represented by the total volume of sediments above a fictitious sea bottom, which would be there if no inlet existed (Section 2.2). Volumes and areas of the ebb-tidal deltas for each inlet have been investigated by Eysink and Biegel (1992) and Mulder (1999) and summarized by van Goor (2001) and Kragtwijk (2001). Delta Volumes and areas deduced from Kragtwijk (2001) and van Goor (2001) are reproduced in Appendix G. In this study the ebb-tidal delta volumes used by Kragtwijk (2001) and van Goor (2001) are used as initial values and for the calibration of ASMITA models. In reality the coastline has shifted landward. This causes the delta volumes to change in time due to change of the reference profile. Delta volumes used by Kragtwijk (2001) are corrected for that. Kragtwijk assesses volume developments using a model that includes a formulation to account for delta volume changes due to shifting of the reference coastal profile. Between the closure of the Zuider Sea and 1990 the coastline has displayed a landward movement. Starting in 1990 suppletions are applied to prevent the coastline from moving in landward direction. This landward movement results in a direct enlargement of the delta volume in measurements, whereas sediment that initially belonged to the coastal profile is gradually attributed to the delta volume. This is not accounted for in the present model. This has to be taken into account when judging the model results.

Tidal ranges

In ASMITA it is possible to either impose a tidal frame that is constant in time or an evolving tidal frame. Depending on the settings of the model this choice has to be made. This is further discussed in section 5.3.

vertical exchange coefficients

Buisman (1997) investigated the sensitivity of ASMITA outcomes to the used vertical exchange coefficients. It was found that the final equilibrium volumes are not largely affected by a change in vertical exchange rate. Comparable conclusions can be drawn from van Goor (2001). Nevertheless the initial behavior is influenced by the choice of w_s. Kragtwijk (2001) investigated the sensitivity of the system time scales to deviations of the vertical exchange coefficient. In this study w_s was taken between $1.0*10^{-5}$ and $1.0*10^{-4}$.

Only the two shortest time scales were affected by these changes. Results of calibrations by Buisman (1997) for this coefficient also range between $1.0*10^{-5}$ and $1.0*10^{-4}$. In this study first estimations of w_s will be taken from van Goor (2001) and Kragtwijk (2001) as presented in Table 5.1.

vertical exchange coefficient (w_s) for element:	**Marsdiep**	**Eierlandse gat**	**Vlie**
Delta	$1.0*10^{-4}$	$0.1*10^{-4}$	$1.0*10^{-4}$
Channels	$1.0*10^{-4}$	$0.5*10^{-4}$	$1.0*10^{-4}$
Flats	$1.0*10^{-4}$	$1.0*10^{-4}$	$1.0*10^{-4}$

Table 5.1: vertical exchanges used by Kragtwijk (2001) and van Goor (2001)

n-parameter

This parameter is used in the definition of the local equilibrium concentration. It is based on a sediment transport formula, which gives a non-linear relation between sediment transport and mean velocity. $n = 2$ is used in previous studies (Buisman (1997), Van Goor (2001) and Kragtwijk (2001)). This is in compliance with a third power for the sediment transport formula and will also be used in this study.

5.2.2 Horizontal exchange coefficients

Relations (4.20) and (4.21) can be used to convert optimized diffusion coefficients by van Goor (2001) to coefficients for Marsdiep, Eierlandse gat and Vlie (Table 5.2). This is believed to provide proper estimations for these coefficients. Therefore diffusion coefficients will be kept fixed at the values denoted in Table 5.2 during the calibration process.

	δ_{cf}	δ_{dc}	δ_{od}
Zoutkamperlaag	840	1290	1060
Marsdiep	992	3304	1374
Eierlandse gat	866	1510	738
Vlie	1426	2853	1565

Table 5.2: Estimated horizontal exchange coefficients

5.2.3 General input parameters

Overall equilibrium concentration

For a model that uses three elements to schematize each basin, the outside world represents the coastal and offshore regions surrounding the delta. The concentration in that region is mostly determined by the long-shore sediment transport. The magnitude of the overall equilibrium concentration (c_E) can be derived by estimating the long-shore sediment transport caused by waves. Annually this is around 1 to 2 million m^3 along the Dutch coast (Kragtwijk, 2001). Van Goor (2001) investigated the outside world equilibrium concentration for inlets along the Dutch coast. Concluded magnitudes of c_E range from $1.2*10^{-4}$ to $2.4*10^{-4}$. Also Buisman (1997) used $c_E = 2*10^{-4}$. In this study $c_E = 2*10^{-4}$ will be used.

Relative sea level rise

It is common to express sea level rise relative to the surface level of landmasses close to the sea. This relative rise is a combination of the absolute change in the ocean's surface level and subsidence of the land. Changes of the ocean surface level is a change on global scale. This can be caused by melting of glaciers and polar ice caps. Vertical movement of the land surface used as reference can occur due to tectonic effects or for example extraction of gas or oil.

Many studies have been conducted regarding relative sea level rise. According to Rakhorst (2000), measurements of the mean sea level along the Dutch coast over the past 150 years reveal a fairly constant increase of 14 to 17 cm per century. The calibration of the exchange and equilibrium coefficients is done based on volume and area measurements of the past 70 years. A sea level rise of 17 cm per century is therefore chosen for calibration of the models.

Time step (dt)

The time-step and number of time-steps have to be specified before starting a simulation. No problems have been encountered regarding the stability of the calculations and used time step. The accuracy of the results is not largely influence by the chosen time step (see also Buisman, 1997). In this study all simulations are preformed with a time-step of 25 days.

5.3 Approach

Inlets forming the Western Dutch Wadden Sea have been studied before using ASMITA. Kragtwijk (2001) examined morphologic behavior of Marsdiep and Vlie elements using a model with fixed water levels. This excludes the effect of SLR and variations of the tidal range. van Goor (2001) assessed the effect of SLR on the system of Eierlandse gat. This was done using a tidal range that was kept constant in time. To assess the effects of the adjustments on computations concerning the Western Dutch Wadden Sea all three inlets will have to be modeled simultaneously and with similar settings. For this purpose first simulations are performed excluding SLR and variation of the tidal range in time. To calibrate this model, data with fixed basin boundaries and fixed water levels are used. This basic model will be expanded with actual water levels. Calibration of the expanded model can be done based on characteristics obtained by the analysis of the measurements using fixed boundaries and actual water levels. This model will be used to assess the effects of the extensions regarding exchange over the boundaries, moving boundaries in time and recalculation of the surface areas. In this way the effect of the various adjustments is isolated. Including the movement of the boundary calls for a calibration with data including this movement as well. For the model extended with the movement of boundaries, data analyzed with actual boundaries and water levels is used. Chapter 3 describes how measurement data referred to in this section are deduced. Results of the analysis of measurements can be found in Appendix G. Tidal ranges used for calculations with fixed water levels and actual water levels are similar to tidal ranges used in Chapter 3 for analysis of the measurement data. they can be found in Appendix E. The setup of the models used to assess the effects of the suggested adjustments can be found in Appendix H.

A first impression of the accuracy of the model is obtained by comparing the calculated volumes with measurements. As explained in Chapter 3, translating volume changes of individual basins to sediment exchanges through their inlets based on measurements will not provide information on the sediment exchanges through the inlets in reality. Sediment transport over the basin boundaries has to be taken into account. A model with fixed boundaries can be compared to sediment exchanges calculated without this contribution. This will give the same information as a comparison of the calculated volumes with measurements. The main objective of this study is to improve long-term modeling of systems like the Western Dutch Wadden Sea. This is needed to get a better indication of sediment demand and transports in future. Although sediment transport through individual inlets are not determined in this study, it is possible to calculate the total sediment exchange through all inlets of the Western Dutch Wadden Sea (Chapter 3). Comparing these exchanges to total exchanges calculated by the model will give an indication of the effect of adjustments to the model. In chapter 4 a method to estimate the correlation between coefficients determining the equilibrium channel volume is presented. According to theory a calibrated model for the Western Dutch Wadden Sea including all important processes should have a factor of ~1,4 between α_c of Marsdiep and Vlie. In section 5.4 the various models will be discussed based on the three features explained above. Setup and Results of all models can be found in respectively Appendix H and Appendix I.

5.4 Influence of adjustments

5.4.1 Model with fixed water levels and fixed basin boundaries

The basic model discussed in this section is comparable to models used by Kragtwijk (2001) for long-term morphological predictions of Marsdiep and Vlie. None of the adjustments suggested is included and the water levels are simulated fixed in time. The results of this model can be compared to measurement data analyzed with boundaries and water levels kept fixed in time.

Results

Resulting development of the characteristic volumes for Marsdiep and Vlie are reproduced in Figure 5.2 and Figure 5.3. Figure 5.4 contains similar data for the Eierlandse gat. A summation of sediment exchanges through individual inlets calculated by the model (Figure 5.5) leads to the total sediment exchange through all inlets of the Western Dutch Wadden Sea (total sediment exchange). Figure 5.6 compares the total sediment exchange with conclusions drawn from measurements (Chapter 3).

α_c coefficients used in this simulation for Marsdiep and Vlie amount respectively $1,4*10^{-5}$ and $0,77*10^{-5}$. This leads to a factor of ~1,82 between those two.

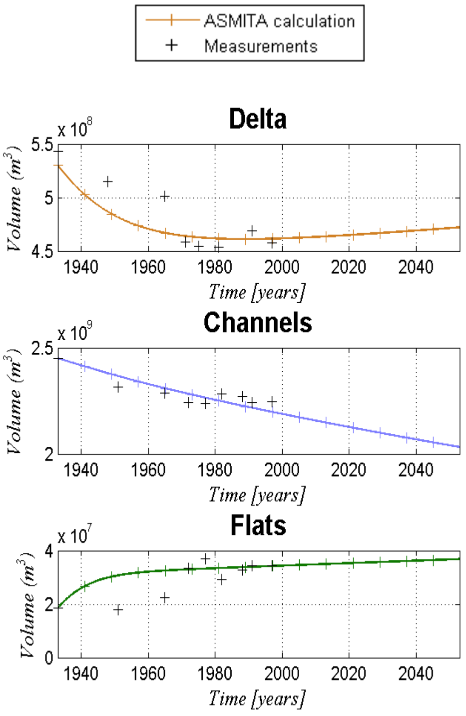


Figure 5.2: Comparison of ASMITA calculation with fixed water levels and boundaries with measurements for Marsdiep

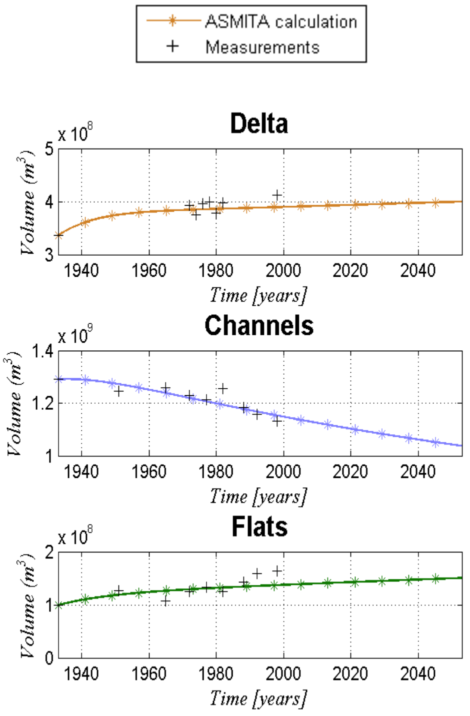


Figure 5.3: Comparison of ASMITA calculation with fixed water levels and boundaries with measurements for Vlie

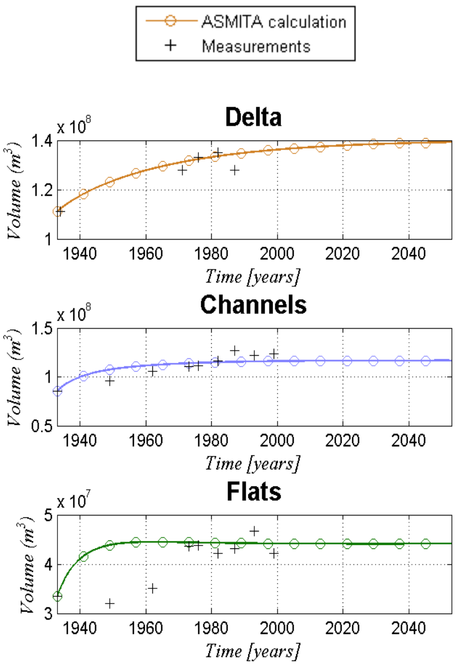


Figure 5.4: Comparison of ASMITA calculation with fixed water levels and boundaries with measurements for Eierlandse gat

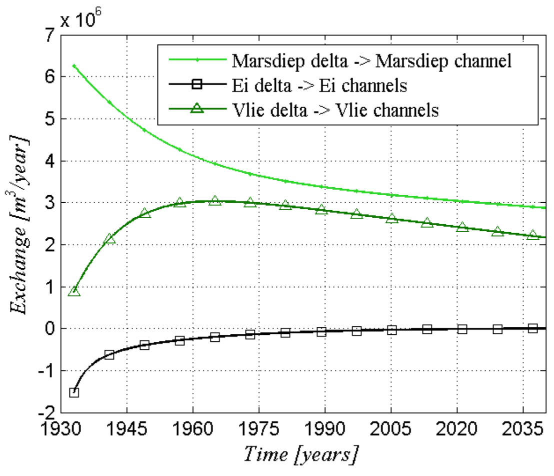


Figure 5.5: Sediment transports through individual inlets following from an ASMITA calculation with fixed boundaries and fixed water levels

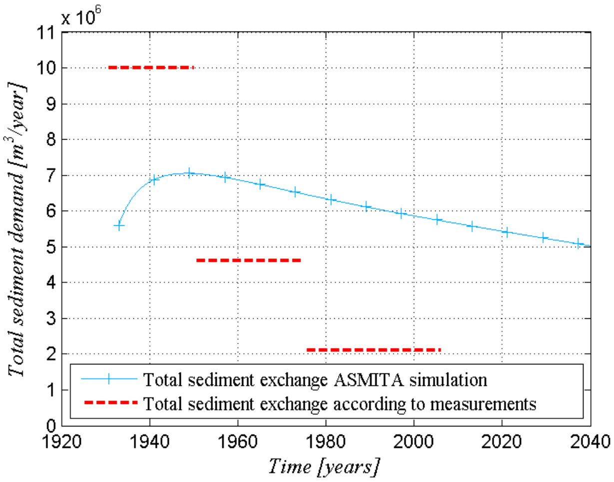


Figure 5.6: Comparison of total sediment transport through all inlets of the Western Dutch Wadden Sea between measurements and an ASMITA simulation with fixed basin boundaries and fixed water levels

Discussion

Kragtwijk (2001) studied possible behavior of a three element ASMITA model having fixed water levels and basin boundaries. This was done using a linearized version of ASMITA. The behavior of channel and delta volumes differ depending on the characteristics of the elements relative to their equilibrium. The expected morphological behavior due to different combinations of disturbances qualitatively all have similar features. First there is the possibility of an initial reaction to the disturbance, possibly overshooting the equilibrium. The initial reaction has a short time scale and is followed by an exponential like adaptation towards an equilibrium with a longer time scale. In some cases the initial reaction is small. None of the reactions show linear adaptation towards a new equilibrium in any phase. Element characteristics derived using fixed water levels and fixed boundaries do not always show developments that are in accordance with the results of Kragtwijk (2001). For example Eierlandse gat channel almost shows a linear growth between the closure of the Zuider Sea and present. The model discussed in this section has similar settings as models used by Kragtwijk (2001). Consequently similar results can be expected. It is therefore to be expected that the element characteristics will not be reproduced exactly in many cases. Improving these predictions is the main objective of this study.

The Results for Eierlandse gat (Figure 5.4) show interesting features. Measured volumes of channels and flats appear to be almost linear. As described above it is not possible to simulate this with a three element ASMITA model with these settings. In case of flat and channel volume an initial reaction (short time scale) can be observed followed by an adaptation towards an equilibrium (larger time scale). Figure 5.5 shows the effect of these initial reactions on the simulated sediment transport rates through the inlet of Eierlandse gat. The computed initial reaction of the channel element forces the basin to export a large amount of sediments in the first period. Similar to Eierlandse gat also Vlie shows a large initial growth of the sediment exchange through its inlet. The initial reactions of the Vlie delta and channels cause the sediment import into that basin to increase in first instance followed by a gradual decrease. The total sediment exchange equals the summation of the sediment transport rates through all inlets belonging to the Western Dutch Wadden Sea. Due to the initial reactions of Eierlandse gat en Vlie the total exchange displays similar behavior.

From Figure 5.6 it can be concluded that compared to measurements in first instance total sediment exchange through all inlets is underestimated. This is compensated with an overestimation in the remaining period.

The vertical exchange coefficient has an influence on the time scale of the initial behavior. As explained above the linear development of the elements of Eierlandse gat can not be modeled without an initial reaction. To reduce the effect of this behavior vertical exchange coefficients for the Eierlandse gat basin turned out to give optimal results when lowered to a value of $1{,}0*10^{-5}$. Based on studies of Buisman (1997), Kragtwijk (2001) and van Goor (2001) this is considered to be the lower limit for this coefficient.

5.4.2 Model including the effect of SLR and variations of the tidal ranges

van Goor (2001) assessed the effect of SLR on ASMITA calculations for Eierlandse gat. SLR is not the only component determining the actual water levels. Also the development of the tidal range contributes to changes of the reference levels MLW and MHW. Actual water levels (as determine in Chapter 3) in this model are approach by a combination of a constant sea level rise of (17 cm/century) for all basins and tidal ranges evolving in time specified for each basin individually. This introduces differences between the actual water levels and simulated water levels, because MSL of each basin is increasing with different rates for each basin instead of one rate of SLR. In general this method gives good approximations of the actual water levels. Comparison of actual water levels with the simulated water levels can be found in Appendix I.

Results

Figure 5.7 compares measurements analyzed using actual water levels with simulated basin characteristics for Marsdiep. Similar figures are given for Eierlandse gat (Figure 5.8) and Vlie (Figure 5.9). These results can also be found in Appendix I. Resulting sediment transports through the inlets of these basins are illustrated in Figure 5.10. Figure 5.11 gives the total sediment transport through all inlets of the Western Dutch Wadden Sea as a result of this computation.

Calibration of this model lead to new equilibrium channel coefficients. For Marsdiep $\alpha_c=16{,}5*10^{-6}$ and for Vlie $\alpha_c=8*10^{-6}$. This leads to a ratio of ~2.

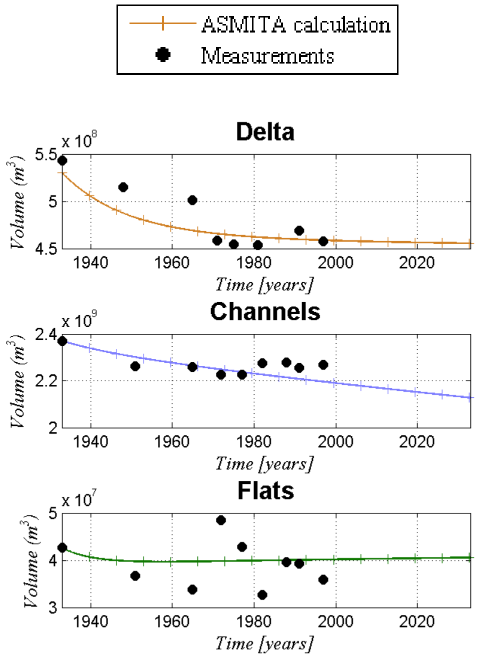


Figure 5.7: Comparison of ASMITA calculation with actual water levels and boundaries with measurements for Marsdiep

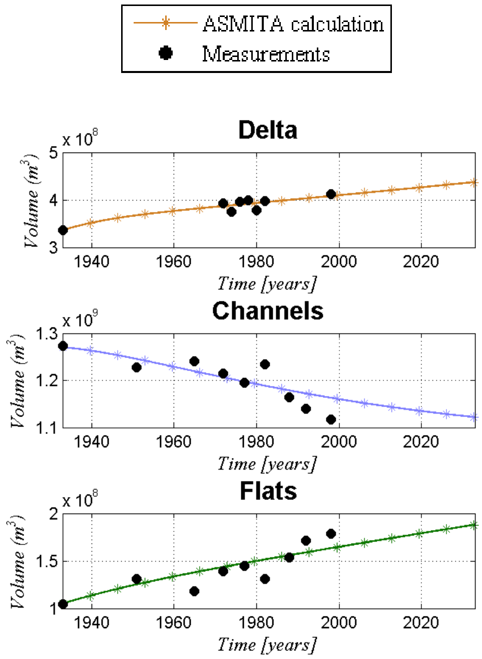


Figure 5.8: Comparison of ASMITA calculation with actual water levels and boundaries with measurements for Vlie

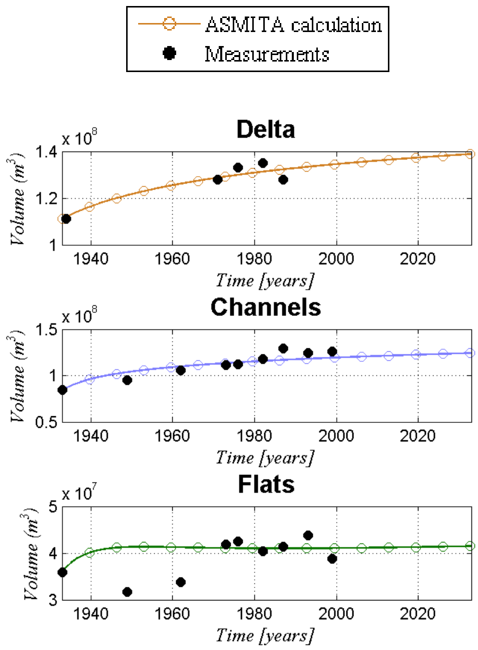


Figure 5.9: Comparison of ASMITA calculation with actual water levels and boundaries with measurements for Eierlandse gat

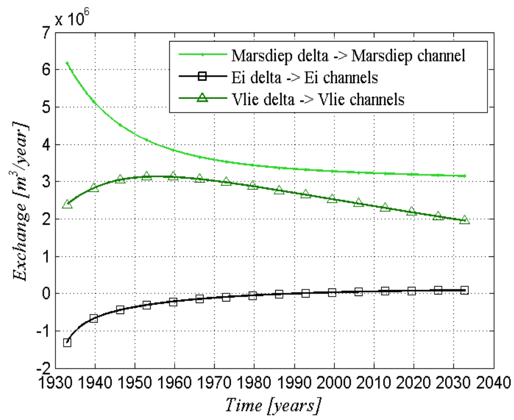


Figure 5.10: Sediment transports through individual inlets following from an ASMITA calculation with fixed boundaries and actual water levels

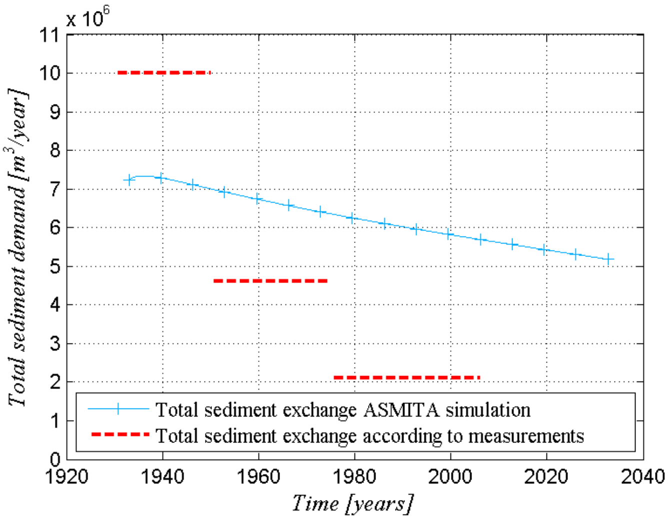


Figure 5.11: Comparison of total sediment transport through all inlets of the Western Dutch Wadden Sea between measurements and an ASMITA simulation with fixed basin boundaries and actual water levels

Discussion

Including SLR and development of the tidal ranges is expected to cause differences with respect to the basic model discussed in the pervious section. SLR as well as changes of the tidal range will affect in a direct change of the characteristic volumes. Because of the movement of the reference level MLW volumes will change. SLR will cause the channel volume to increase and the flat volume to decrease. An increasing tidal range will have the opposite effect. A secondary effect is expected to occur due to these volume changes. Volume changes of the flat elements as well as a change of the tidal range directly will influence the tidal prism. The tidal prism determines equilibrium volumes of delta and channels. The tidal ranges used for Marsdiep and Eierlandse gat also significantly differ from the tidal ranges used in the simulation with fixed water levels. Consequently the tidal prisms for these basins will be different from tidal ranges computed with a model with fixed water levels.

Effects of the differences outlined above can be observed from results. In case of Marsdiep the tidal range is smaller when simulating with actual water levels. This causes the tidal prism to be less. Volumetric data are in the same order of magnitude and show comparable characteristic behavior. To simulate such behavior the equilibrium channel volume has to be in the same order of magnitude. This is accomplished by enlarging the equilibrium channel coefficient to compensate for the smaller tidal prism. Tidal ranges used in both studies for the Vlie basin are comparable. Consequently this equilibrium channel coefficient does not differ much from the coefficient used in a model with fixed water levels. This explains the larger ratio between the equilibrium channel coefficients observed for this simulation.

Also the influence of the increasing tidal ranges in Eierlandse gat and Vlie can be observed. The simulation with fixed water levels shows a constant channel volume for Eierlandse gat after an initial adaptation (Figure 5.4). A linear increase of the tidal range also increases the tidal prism linearly. This introduces a linear growth of the equilibrium channel volume and equilibrium delta volume. Due to diffusion the growing equilibrium volume of the channel and delta of Eierlandse gat induce a linear growth of the characteristic volumes of these elements. In case of the channel volume this is still not enough to accurately simulate the measured characteristics. The same effect can be observed at the delta volume of Vlie. Because of this linear growth the initial adaptation of the Vlie delta that can be observed when simulating with fixed water levels becomes less. This has a strong effect on the computed sediment transport through the Vlie inlet. The initial import rate changes from ~0,8 Mm^3/year for the simulation with fixed water levels to ~2,4 Mm^3/year for the present situation. This reduces the initial increase of the sediment transport observed from Vlie delta towards Vlie basin. Consequently also the total sediment import into the Western Dutch Wadden Sea initially is more stable.

The model discussed in this section will be used to assess the effects of the adjustments proposed in this study.

5.4.3 Assessing the effect of sediment exchange between basins

One of the main objectives of this study is to include sediment transport between basins. According to Elias (2006b) sediment transport (~71-80 $*10^6$ m^3) must have occurred from Marsdiep basin towards Vlie between 1986 and 2004. Averaged over this period that leads to a sediment transport of ~3 Mm^3/year. As a first step to include such communication between basins in this study it is assumed that the driving forces for this transport can be modeled in the same way as sediment transport between elements within one basin. Transport has to occur over the basin boundaries. For this purpose connections are made by allowing diffusive transport between the flats of Marsdiep and Eierlandse gat, the flats of Eierlandse gat and Vlie and between the channel elements of Marsdiep and Vlie. Next to the equilibrium coefficients also the vertical exchange rates between the basins are used as calibration parameters.

Results

Figure 5.12 shows the equilibrium concentrations following from an ASMITA model including exchange over the boundaries. In this model all horizontal exchange rates between basins are set to 300 m^3/s. Figure 5.13 represents calculated sediment transport through the inlets of individual basins as well as sediment transport calculated between basins.

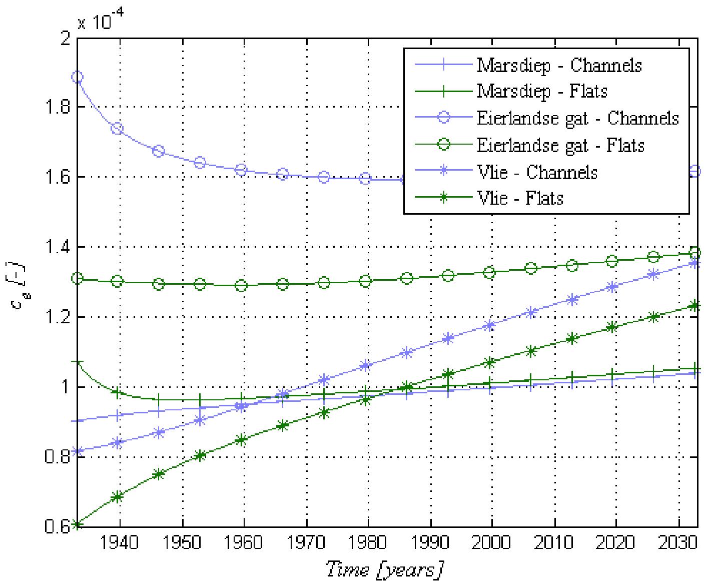


Figure 5.12: Equilibrium concentrations calculated with an ASMITA model allowing exchange over the boundaries

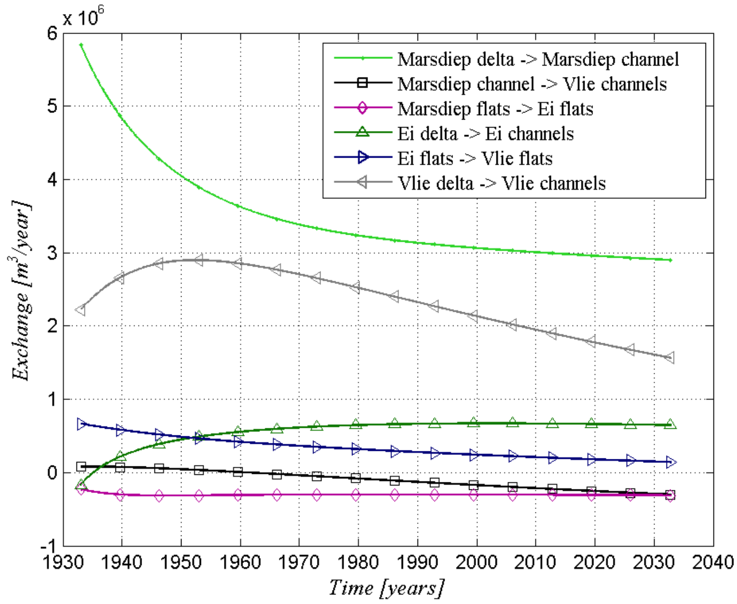


Figure 5.13: Sediment transports through individual inlets following from an ASMITA calculation with exchange over the boundaries

Discussion

The sediment transport between two elements is based on the relative deviation of those elements from their equilibrium. This is expressed in the local equilibrium concentration (relation (2.22)). When an element is in equilibrium this concentration is equal to the overall equilibrium concentration ($2*10^{-4}$ in this simulation). A local equilibrium concentration that is lower than the overall equilibrium concentration indicates the element needs sediment to approach its equilibrium volume. If two connected elements both need sediment the exchange is directed towards the element that is most out of equilibrium. Figure 5.12 shows

that in this simulation all equilibrium concentrations are beneath the overall equilibrium concentration. This means all elements are in need of sediment. Initially Vlie channel is more out of equilibrium than Marsdiep channel. This results in a sediment transport from Marsdiep towards Vlie. Due to SLR the channel elements tend to grow. This brings both channel elements more out of equilibrium. In case of Vlie this is partly compensated by the increasing tidal range. Consequently the Vlie channel will grow towards its equilibrium easier. This causes the local equilibrium concentration of Vlie channel to increase and cross the equilibrium concentration of Marsdiep. Resulting sediment exchange between both elements will be directed towards Marsdiep. This tendency is also observed during calibration. Changing the horizontal exchange coefficients between basins only alters the magnitude of this effect. No structural sediment transport could be simulated using this configuration. From this it is concluded that the suggested adjustment does not correctly model the driving forces that cause the large sediment transport from Marsdiep towards Vlie basin. Further understanding of the physics that cause this transport can lead to a better method to implement the exchange of sediments between basins. Judging from the calibration results implementation of a connection between basins by allowing diffusive exchange is not considered to be an improvement of ASMITA calculations.
This model uses delta volumes corrected for the movement of the reference coastal profile. Volume changes of the delta element due to this movement are not accounted for in the ASMITA model. Including an extra term in the relation used to compute volume changes of the ebb-tidal delta will lead to delta elements that grow relatively easier compared to this simulation. This will have an effect on the equilibrium coefficients determined after calibration. This however does not change the mechanism explained above that prevents a structural sediment transport from Marsdiep towards Vlie. Conclusions regarding the sediment exchanges between basins as modeled in this study are therefore not expected to be influenced by the absence of a term expressing the change of the delta volume due to movement of the reference coastal profile.

5.4.4 Assessing the effect of movement of the basin boundaries

Until now no relation has been formulated to express the movement of basin boundaries as a function of the characteristics of those basins. In this study the effect of such a movement on calculations performed with ASMITA is assessed by prescribing the measured volume and area changes caused by the movement of the boundary for each individual element (see also section 3.5.3). Results of these simulations will give an indication of the importance of finding and implementing a relation that expresses the movement of boundaries in time.

Results

Results of an ASMITA calculation with the prescribed volume and area changes due to movement of boundaries can be found in Appendix I. The figures below show the same results. Figure 5.14 contains a comparison between calculated volume developments and measurements analyzed with actual water levels and actual boundaries for Marsdiep. Similar figures are included for Vlie (Figure 5.15) and Eierlandse gat (Figure 5.16). Sediment transport rates through the inlets of the individual basins are presented in Figure 5.17. The total sediment import through all inlets of the Western Wadden Sea is presented in Figure 5.18. After calibration of the model equilibrium channel coefficients of α_c=22*10^{-6} (Marsdiep) and α_c=8,0*10^{-6} (Vlie) were found to best fit the measurements.

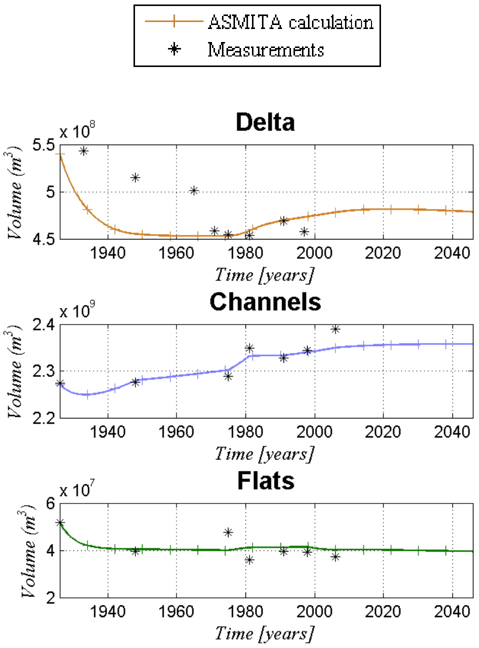


Figure 5.14: Comparison of ASMITA calculation including movement of basin boundaries with measurements for Marsdiep

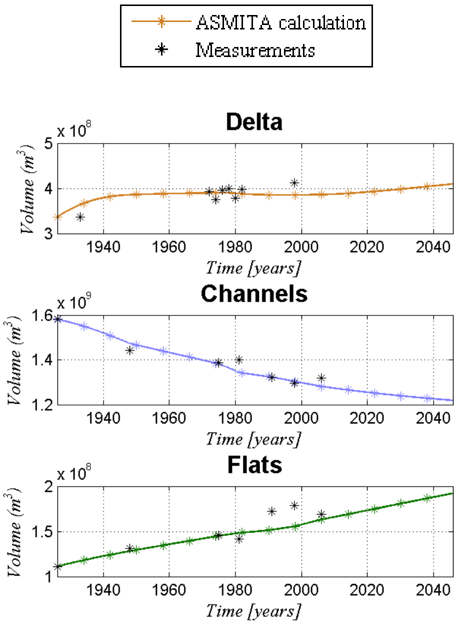


Figure 5.15: Comparison of ASMITA calculation including movement of basin boundaries with measurements for Vlie

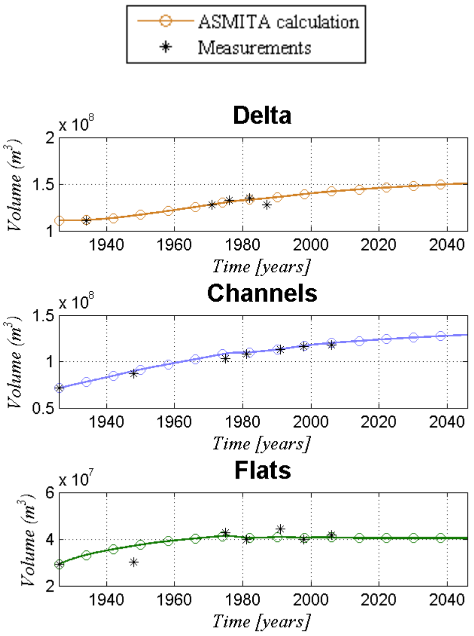


Figure 5.16: Comparison of ASMITA calculation including movement of basin boundaries with measurements for Eierlandse gat

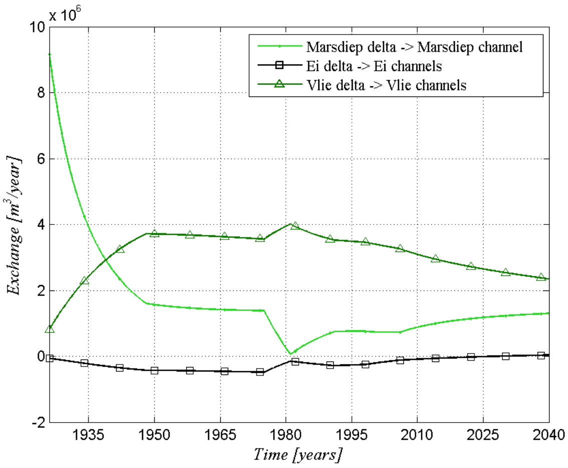


Figure 5.17: Sediment transports through individual inlets following from an ASMITA calculation with movement of basin boundaries

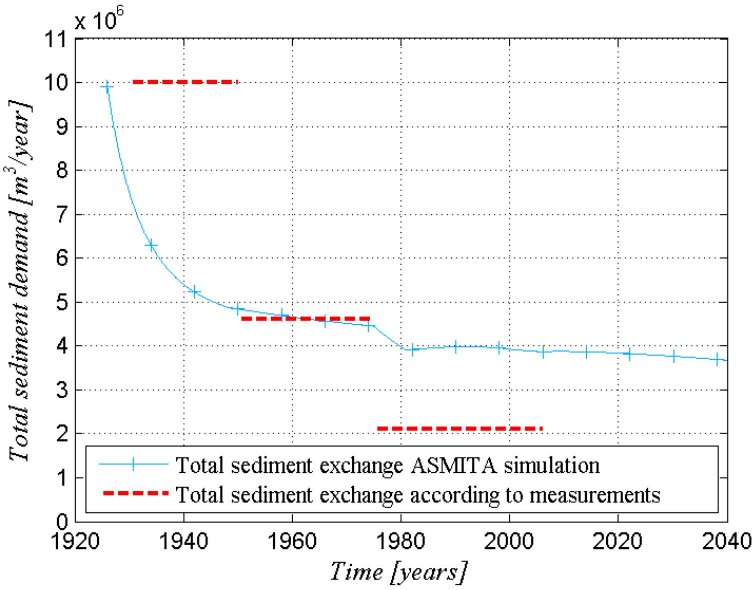


Figure 5.18: Comparison of total sediment transport through all inlets of the Western Dutch Wadden Sea between measurements and an ASMITA simulation including movement of the basin boundaries

Discussion

Movement of the boundaries has a direct and an indirect effect on the development of the basin characteristics. The direct effect is found in the amount of surface area and sediment volume that is actually added or subtracted from an element due to the moving boundaries. The secondary effect introduced by the enlargement or reduction of the tidal prism due to this movement. From the results presented above it can be concluded that this second aspect plays an important role in the prediction of future behavior of a system like the Western Dutch Wadden Sea. Movement of the basin boundaries of the Eierlandse gat mostly takes place at the flats. The flat area therefore will be directly affected by the movement of the basin boundaries. This is hardly the case for the Eierlandse gat channel element. Because of the steady growth of the basin surface area also the tidal prism grows. This is affecting the channel element as well. The almost linear development of the channel found in measurements could not be reproduced with a simulation without taking into account the movement of basin boundaries. Figure 5.16 shows that including this effect leads to a fair description of the measured development of the channel volume. The total sediment exchange calculated from the simulation results show more resemblance with measurements as well. This is partly caused by the fact that including the movement of the boundaries enables the model to simulate the behavior of Eierlandse gat more accurately. Also measured changes of the characteristics of Marsdiep and Vlie are followed more closely by the simulation results.

In all figures sudden changes can be observed. This is due to the method that is used to asses the effect of the movement of basin boundaries. The placement of basin boundaries can only be determined at moments for which measurements are available. For reasons of simplicity it is assumed that changes in the periods between those measurements can be distributed evenly over that period. Consequently the volume and area changes due to movement of the boundaries are implemented as constant rates of change in different periods. At the transition of one period to the following period a sudden change of this constant rate takes place. Sudden changes in the behavior of the calculated characteristics can therefore be expected. The morphologic behavior of an element after transition from one period towards another is discussed in Appendix C.

Judging from the results of this ASMITA model, implementation of the surface area and volume changes due to movement of basin boundaries is considered to be an improvement. Unfortunately at this moment no relation has been formulated to express future changes of the basin boundaries. It is recommended to investigate the movement of basin boundaries in time. Implementation of such a relation is expected to lead to a more accurate prediction of morphological behavior of combined systems like the Western Dutch Wadden Sea. If not available different scenarios for the movement of those boundaries can be prescribed to take into account the effect of these changes on future morphologic behavior.

The model used to assess the influence of movement of the basin boundaries does not include volume changes of the delta element due to movement of the reference coastal profile. Characteristic delta volumes used for calibration however are corrected for this movement. Including an extra term in the relation expressing volume changes adding this effect is not expected to qualitatively change the results obtained by this model. Although equilibrium coefficients will be different the gradual changes of the basin characteristics due to movement of the boundaries will be identical. This will also result in direct and indirect influence on the computed volume changes regardless of the exact values of the equilibrium coefficients.

5.4.5 Assessing the effect of re-calculation of the surface areas

It is proposed to expand ASMITA calculations with an extra calculation step to re-calculate the surface areas of basin elements. Relation (3.3) is used to calculate the development of the mean flat height towards its equilibrium. This process is assumed to take place independently of the developments of other basin characteristics. Using the calculated flat volume each time step also the accompanying flat surface area is determined. With a known basin area this also provides the channel surface area. In Chapter 3 coefficients determining the equilibrium flat height (α_f) are determined based on data analyzed with actual boundaries. Determination based on data with fixed boundaries and actual water levels lead to slightly different coefficients. The model used to assess the effect of the proposed adjustment is an expansion of the model with fixed boundaries and actual water levels discussed in section 5.4.2. α_f coefficients for this model therefore also have to be determined based on data analyzed with fixed boundaries and actual water levels. The coefficients used for this model amount:

- 0,41 for Marsdiep flats;
- 0,37 for Eierlandse gat flats and
- 0,43 for Vlie flats

Results

The adjustment considered in this section is aimed at correctly simulating the development of surface areas. The first step in this adjustment is to simulate the development of the mean flat heights. Figure 5.19 compares the simulated mean flat heights and measurements.

Calculated surface areas can be found in Figure 5.20 (Marsdiep), Figure 5.22 (Eierlandse gat) and Figure 5.24 (Vlie). Differences between the volume developments calculated with models excluding the recalculation of surface areas (section 5.4.2) and including this calculation are very small. Figure 5.21, Figure 5.23 and Figure 5.25 therefore show the difference between those runs for respectively Marsdiep, Eierlandse gat and Vlie.

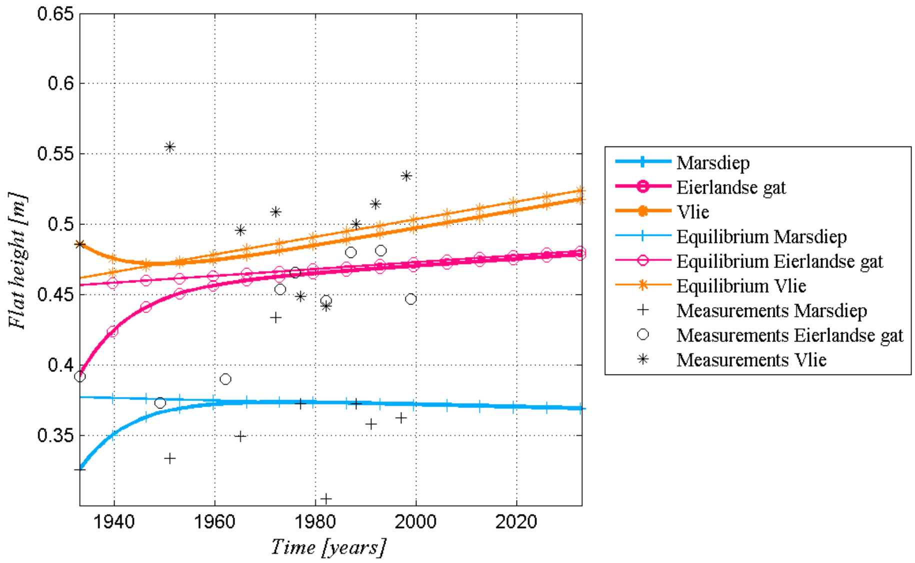


Figure 5.19: Comparison between the development of mean flat heights simulated and according to measurements analyzed with fixed boundaries and actual water levels

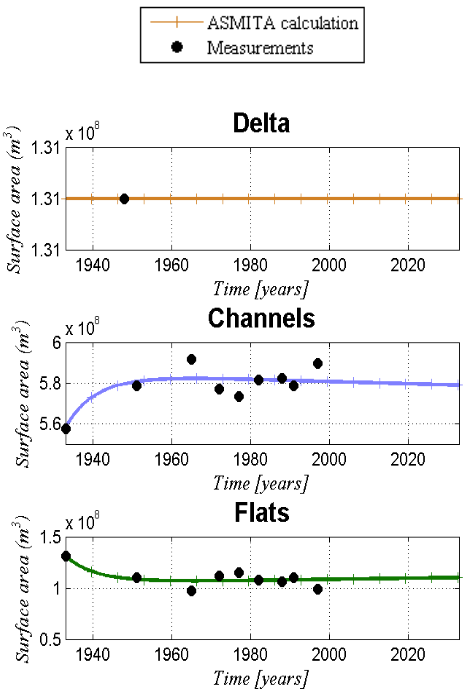


Figure 5.20: Comparison of simulated surface area developments with measurements analyzed with fixed boundaries and actual water levels for Marsdiep

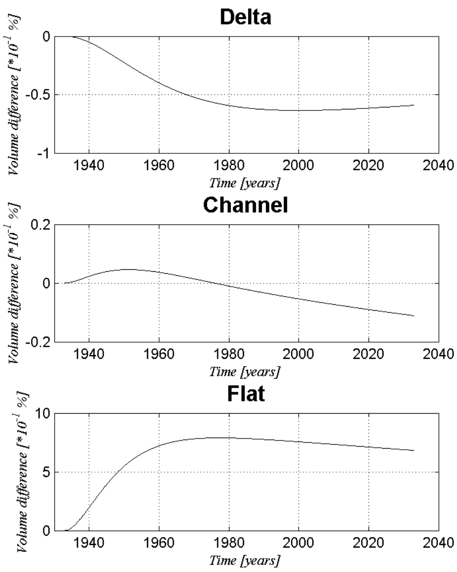


Figure 5.21: Volume difference between a simulation without surface area recalculation (section 5.4.2) and a simulation including recalculation of areas for Marsdiep

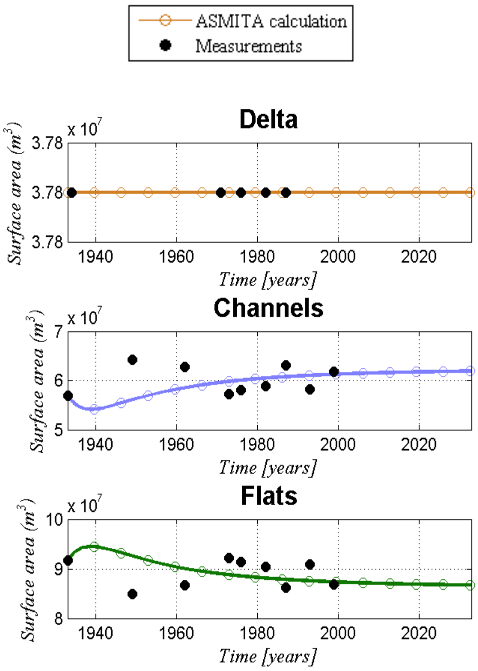


Figure 5.22: Comparison of simulated surface area developments with measurements analyzed with fixed boundaries and actual water levels for Eierlandse gat

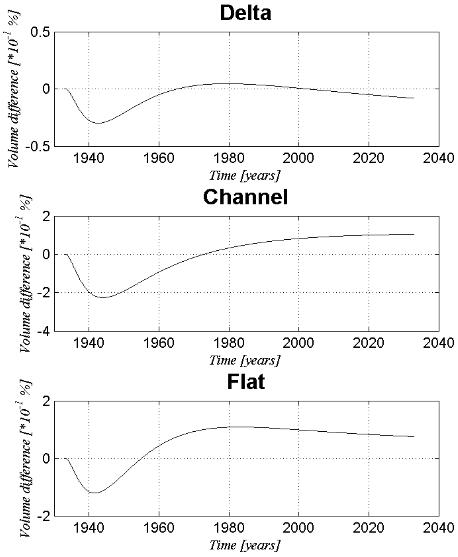


Figure 5.23: Volume difference between a simulation without surface area recalculation (section 5.4.2) and a simulation including recalculation of areas for Eierlandse gat

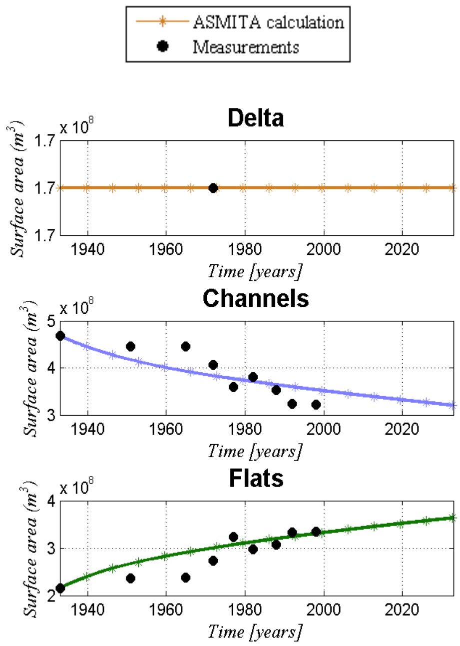


Figure 5.24: Comparison of simulated surface area developments with measurements analyzed with fixed boundaries and actual water levels for Vlie

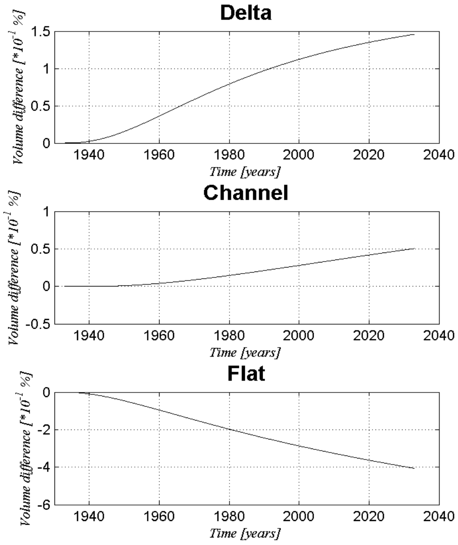


Figure 5.25: Volume difference between a simulation without surface area recalculation (section 5.4.2) and a simulation including recalculation of areas for Vlie

Discussion

The basin surface area stays constant in time. This makes the development of the mean flat height simply dependent on the tidal range. It can be calculated on beforehand using relation (3.3). Theoretically the adjustment of surface areas should have two effects. Firstly the surface areas of the elements partly determine the amount of sediment exchange between the water column and bottom of these elements. This affects the magnitude of the initial adaptation and time scale. Kragtwijk (2001) analyzed the sensitivity of system time-scales to changes of the surface areas of elements. This was done using a linearized three element model excluding the effect of changing tidal ranges and SLR. No noticeable influence of the surface areas on system time-scales was found. A second effect is introduced when also including changes of the MLW due to SLR and changes of the tidal range. SLR and changes of the tidal range in time determine the reference levels with which elements are characterized. Changes in the reference level MLW result in changes of the volumes that characterize channel and flat elements. The volume change of these elements is solely a result of the shift of this reference level. It can be calculated by multiplying the elements surface area times the shift of the MLW level. Consequently a change of the element surface areas also has an effect on the volume change of this element due to the combination of SLR and changes of the tidal range.

Both effects introduced by simulating the development of element surface areas only lead to small changes of the computed volume developments compared to the simulation without the recalculation of flat areas. Figure 5.24 and Figure 5.25 visualize the effects described above. The surface area of the Vlie flat element in this simulation grows significant. Compared to a simulation in which the surface areas are kept constant the amount of sediments lost due to the combination of SLR and changes of the tidal range is larger. This is also to be expected based on the theory explained above. Although differences of the calculated volumes can be visualized they are small compared to a simulation without recalculation of the element surface areas. Volume developments calculated with a model that includes these changes do not show differences larger than 1% compared to an identical simulation excluding the recalculation of surface areas.

With this adjustment also changes of surface areas of the elements inside the basins can be calculated. The effect of these changes appears to be minimal. A similar conclusions was drawn by Kragtwijk (2001) based on a linearized three element model excluding the effect of SLR and variations of the tidal range. The recalculation of surface areas leads to a more accurate description of reality compared to fixed surface areas in time. In spite of the minimal effect of this adjustment it is therefore still considered to be an improvement of ASMITA.

As explained in section 5.2.1, this model does not include changes of the delta volume due to movement of the coastal profile. Including this effect will lead to different equilibrium coefficients to reproduce measurements. Calculated volume changes inside the basins are not expected to be not largely influenced by these changes. Calibration of a model that includes this extra term will lead to different channel and flat equilibrium coefficients to reproduce the same measurement data. Because of this computed volume and surface area changes will be comparable. It is therefore to be expected that such an adjustment will not largely influence the conclusions drawn from this simulation.

5.5 Optimal simulation

5.5.1 Optimal model setup

Main objective of this study is to improve predictions of morphological development of barrier lagoon systems like the Western Dutch Wadden Sea. This is approached by attempting to eliminate shortcomings of the existing models. The base for this model is formed by the schematization of the three inlets as discussed in section 5.1. Suggested adjustments of ASMITA are assessed in the previous section. The adjustment implemented to include sediment exchange between basins (section 5.4.3) did not lead to satisfactory results. No constant sediment exchange from Marsdiep towards Vlie could be simulated with this adjustment. From data analysis it can be concluded that a significant amount of sediment is transported from Marsdiep towards Vlie basin (Elias, 2006b). Including the possibility of a diffusive type sediment exchange between the various basins in the combined system did not lead to this transport. For this reason the adjustment suggested in this report to include sediment exchanges between basins is not included in the optimal simulation. Second the influence of the movement of boundaries is assessed (section 5.4.4). Manually prescribing the measured changes leads to a better reproduction of measured basin characteristics. Also the total sediment import computed for all systems forming the Western Dutch Wadden Sea showed an increased similarity with measurements. Consequently this adjustment is considered to be an improvement to ASMITA calculations and implemented in the optimal simulation. Last also the influence of changes of the surface areas of individual elements in time is assessed (section 5.4.5). Although the influence on computed volume developments and sediment exchange rates is very small it is a better description of reality compared to simulations in which element surface areas are fixed in time. For this reason recalculation of element surface areas is included in the optimal simulation. All input variables of the optimal simulation are listed in Appendix H.

5.5.2 Results

Figures below contain comparisons between the simulated volume developments and measurements, sediment transport through the individual inlets and the total sediment exchange through all inlets compared with measurements. All results can be found in Appendix I. Equilibrium channel coefficients used in this simulation for Marsdiep and Vlie amount respectively α_c=2.2*10^{-5} and α_c=8*10^{-6}. This leads to:

$$\frac{\alpha_{c,Mars}}{\alpha_{c,Vlie}} = 2,75$$

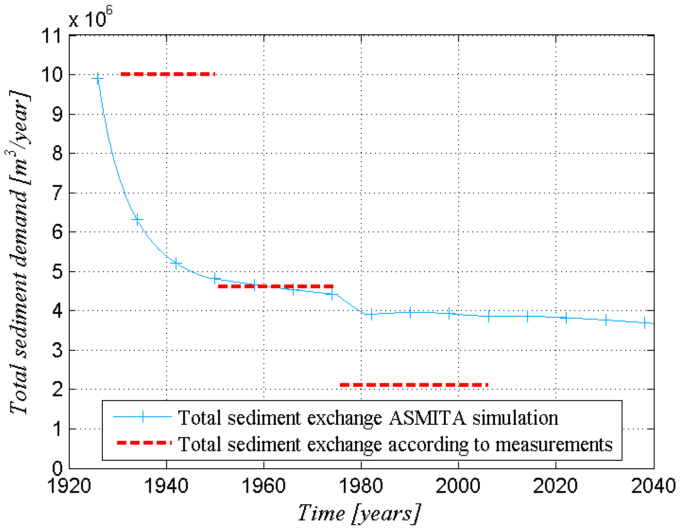


Figure 5.26: Comparison of total sediment transport through all inlets of the Western Dutch Wadden Sea between measurements and an optimal ASMITA simulation

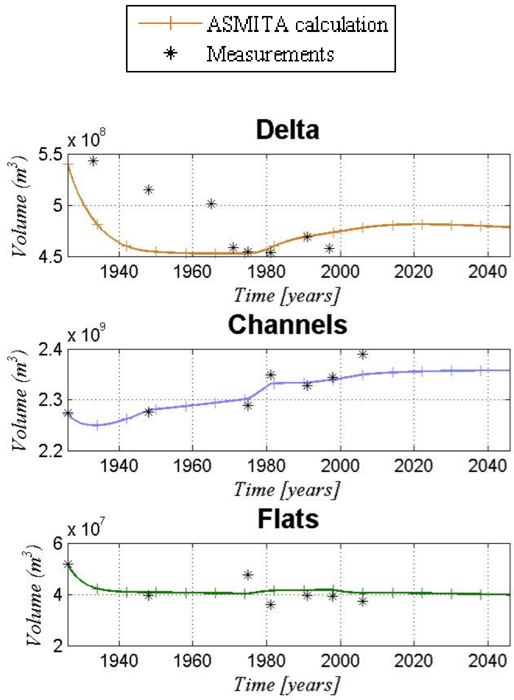


Figure 5.27: Comparison of simulated volume developments using an optimal model with measurements analyzed with actual boundaries and actual water levels for Marsdiep

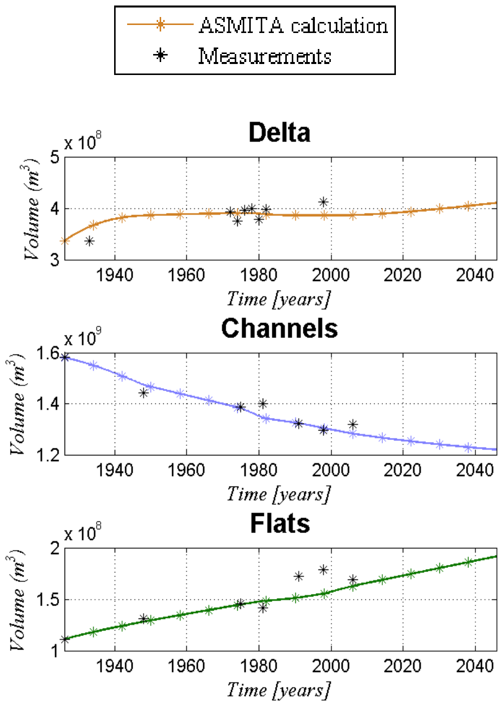


Figure 5.28: Comparison of simulated volume developments using an optimal model with measurements analyzed with actual boundaries and actual water levels for Vlie

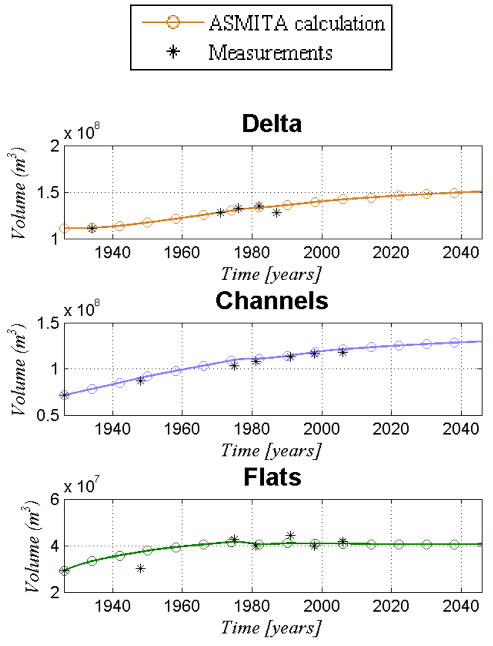


Figure 5.29: Comparison of simulated volume developments using an optimal model with measurements analyzed with actual boundaries and actual water levels for Eierlandse gat

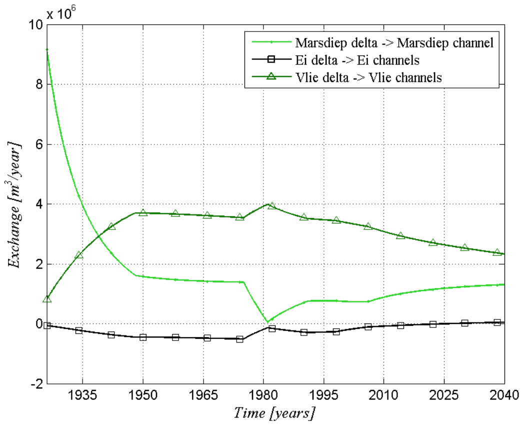


Figure 5.30: Sediment transports through individual inlets following from an optimal ASMITA calculation

5.5.3 Discussion

The optimal model is formed by a combination of the model used to assess the effect of movement of basin boundaries and recalculation of element surface areas. The latter did not have much influence on computed volume changes and sediment exchanges. Results of the optimal model are therefore expected to show similarities with the results of the model used to asses movement of basin boundaries. Some of the features that characterize the developments of volumes and sediment exchanges according to measurements and former studies however can not be reproduced with this model. According to Elias (2006b) sediment is exchanged between Marsdiep and Vlie during the period of interest (~ 4 Mm^3/year from Marsdiep towards Vlie). No adjustment is included in the optimal simulation to simulate such a sediment transport. Consequently the exchange between Marsdiep and Vlie is not present in the results. This also influences the sediment exchanges simulated through inlets of those basins.

In general the adjustments implemented in this model appear to improve predicted behavior of the elements forming the Western Dutch Wadden Sea between the closure of the Zuider Sea and present. Volume developments calculated in this simulation show many similarities with volumes calculated from measurements using actual boundaries and actual water levels. The adjustments implemented in the optimal model also cause the total sediment exchange through all inlets of the Western Wadden Sea to show more resemblances with the total sediment exchange estimated from measurements. There are however also differences between the optimal model simulation and expected behavior based on measurements. Sediment exchanges through the inlet of the Marsdiep in the present situation are estimated to be in the order of ~5-6 Mm3/year (Elias, 2006). This cannot be concluded from the results of this optimal simulation. Figure 5.30 shows a sediment import rate in the order of ~1 Mm^3/year for the Marsdiep inlet at present. This difference could be explained by the absence of sediment transport from Marsdiep towards Vlie in the model. Removing a large volume from the Marsdiep channel element will lead to an increased sediment import through the Marsdiep inlet (with a maximum of ~5 Mm^3/year, in case all transport towards Vlie is compensated by an increase of the sediment import through Marsdiep). Including sediment transport from Marsdiep channel towards Vlie channel will also affect the equilibrium channel coefficients. The ratio between the equilibrium channel coefficients of Marsdiep and Vlie channels for the optimal simulation amounts 2,75. Sediment transport from Marsdiep channel towards Vlie channel will enlarge the Marsdiep channel volume. Vlie channel volume will decrease due to the sediment that is brought from Marsdiep. To reproduce measured volumes correctly the equilibrium channel volume of Marsdiep has to be lowered compared to the optimal simulation. In case of Vlie channel the equilibrium volume will have to be increased. This will lower the ratio between those two coefficients. That is also to be expected given the theory explained in section 4.5.2.

From the results of this optimal simulation it can be concluded that the effect of the shift of hydrodynamic boundaries on the tidal prism is an important mechanism. Taking into account the influence of the movement of those boundaries on the tidal prism leads to a better understanding of characteristics and trends of the morphological development of the Western Dutch Wadden Sea between 1932 and present. It is recommended to also include the movement of basin areas in models used to predict future behavior of this and similar systems. It is therefore recommended to further investigate the movement of hydrodynamic boundaries. A relation expressing the displacement of the boundaries in time would improve ASMITA predictions. The movement of watersheds can also be included by investigating different predefined scenarios. A second conclusion can be drawn regarding predicted sediment exchanges. The optimal simulation calculates a sediment transport rate of ~4 Mm^3/year through all inlets of the Western Dutch Wadden Sea in total. ~1 Mm^3/year of this sediment exchange is transported through Marsdiep inlet. No sediment exchange is included from Marsdiep towards Vlie. Implementation of a mechanism that creates this sediment exchange is expected to lead to larger import through Marsdiep inlet and a ratio of the equilibrium channel coefficients that is closer to 1,4. This would decrease the differences between the optimal simulation and expectations based on theory (Appendix A) and measurements (Elias, 2006b). It therefore recommended to further investigate the driving forces of the sediment transport from Marsdiep towards Vlie basin. Better understanding of the mechanisms that lead to this transport could lead to a more accurate description that can be included in ASMITA to simulate such transport.

The optimal simulation is calibrated using delta volumes corrected for the movement of the coastal profile. This is not included in the model formulations. A proper optimal simulation should also include a term in the relation expressing volume changes to include delta volume change due to movement of the coastal profile. This is expected to mainly lead to differences of the calibrated equilibrium coefficients. Calibration of such a model with the same measurements is not expected to lead to different model behavior. Consequently calculated volume developments are expected to show the same behavior, only having different equilibrium coefficients. Volume changes can only be achieved by sediment exchange and changes in the reference levels. Development of reference levels inside the basins are not influenced by including a shift of the reference coastal profile. Similar volume developments will therefore also lead to comparable sediment exchanges.

6 Conclusions and Recommendations

6.1 Conclusions

The first part of this study consists of the analysis of measurements of the Western Dutch Wadden Sea. From data analysis the following conclusions can be drawn.

- Including development of the reference water levels (MLW and MHW) in the analysis of measurement data leads to different conclusions concerning the development of basin characteristics in time.
- The movement of basin boundaries in time can be included in the analysis of measurements. This appears to have a significant influence on the determined basin characteristics and observed trends in the development of these characteristics.
- Basin boundaries can be determined using a minimal velocity deviation criterium. The result of such anlysis shows that the watershed between Marsdiep and Vlie moved significantly towards the East between the closure of the Zuider Sea (1932) and present.
- The coefficient determining the flat equilibrium volume (α_f) can be determined from field measurements. This coefficient is used to describe the equilibrium mean flat height. The equilibrium flat surface area is expressed as a function of the basin surface area. From measurements it can not be concluded that the large basins in the Dutch Wadden Sea tend towards this equilibrium. In ASMITA calculations, problems caused by this fact are avoided by using an extra calibration coefficient in this relation.
- By definition the coefficient determining the equilibrium channel volume is depending on basin geometry. This means that each basin should have its own coefficient. Integration of the tidal prism along the channel axis can lead to an understanding of the shape coefficient partly determining the equilibrium. A second method has been suggested to calculate the equilibrium channel volume in the final equilibrium state.

The second part of this study is aimed at improving long-term morphologic predictions of the Western Dutch Wadden Sea using ASMITA. Several adjustments are proposed. Conclusions from the assessment of the effect of those adjustments are summarized below.

- From data analysis it follows that a strong sediment exchange from Marsdiep towards Vlie must have occurred. Allowing diffusive transport between those basins does not lead to such transports in simulation results. It is concluded that the driving mechanisms for this transport are not modeled correctly by the relations included in ASMITA to calculate sediment transport elements of one basin.
- Changes of basin characteristics due to movement of basin boundaries in time can be prescribed in ASMITA calculations. Models including those changes show more similarities between simulation results and measurements. It is concluded that the influence of movement of watersheds on the development of the tidal prism has a large influence on developments of basin characteristics.
- From analysis of field measurements a relation describing the development of mean flat heights towards their equilibrium is introduced. The development of the mean flat height is assumed to be independent of the development of other basin characteristics. Implementation of this relation in ASMITA enables the possibility to calculate development of flat and channel surface areas. The influence of changes of flat and channel surface areas in time on simulated development of characteristic volumes is assessed to be minimal.

An optimal simulation is carried out including the adjustments concerning recalculation of the surface area of basin elements and prescribed volume and area changes due to movement of boundaries. Sediment exchanges through all inlets of the Western Dutch Wadden Sea concluded from this simulation amount:

- ~7 Mm^3/year (1930 - 1950)
- ~5 Mm^3/year (1950 - 1975)
- ~4 Mm^3/year (1975 - 2006)

During the last period simulated sediment exchange through the Marsdiep inlet amounts ~1 Mm^3/year. It should be noted that this simulation does not include sediment exchange from Marsdiep towards Vlie. Sediment transport concluded from literature between Marsdiep and Vlie can be estimated around ~4 Mm^3/year for the same period. Including such sediment exchange will also increase the simulated sediment import through Marsdiep.

All models used in this study are calibrated using delta volumes that are corrected for changes of the reference coastal profile. The model formulations do not account for these volume changes of the delta element. A closed sediment balance is only obtained when including an extra term in the model formulations expressing the volume change of the delta element due to movement of the reference coastal profile. Calibration of such a model is expected to lead to different equilibrium coefficients for all basins. A model including the volume changes due to shifting of the reference coastal profile qualitatively is not expected to show different model behavior. Calibration will still be performed using the same measurement data. Volume developments will therefore show comparable characteristics. Comparable volume developments also imply similar sediment exchanges between elements inside the basin and between the delta and channel element. Due to direct volume changes of the delta element as a result of movement of the coastal profile the sediment exchange between the delta element and the outside world is expected to be different. Based on these considerations the lack of a term expressing the delta volume changes due to movement of the reference coastal profile is not expected to alter the conclusions drawn from the results of the assessment of proposed adjustments in this study. Concluded equilibrium coefficients however are expected to be different when including the extra term needed to create a closed sediment balance.

6.2 Recommendations

To improve understanding of the long-term morphologic development of combined systems like the Western Dutch Wadden Sea as well as predictions using ASMITA it is recommended to further investigate the following.

- The results of this study show that accounting for development of the reference levels (MLW and MHW) in time leads to different concluded basin characteristics and simulation results. Reference levels averaged for the individual basins are determined using relations that express the averaged reference levels as a function of measured water levels at individual measurement stations nearby. The method used in this study does not include changes of these relations in time. Changes can occur due to alterations of the basin geometries. There is a significant influence of changes of the reference levels on determined and simulated basin characteristics. It is therefore recommended to further investigate the development of reference levels in time.

- Measurement data as well as ASMITA simulations do not seem to confirm the relation used to calculate the equilibrium flat surface area. The reactions of the large basins in the Western Dutch Wadden Sea can not be explained with this relation. It is recommended to further investigate the development of flat surface areas of Marsdiep and Vlie in combination with the equilibrium relation.
- Movement of watersheds appears to have a large influence in the development of the tidal prism and therefore also the development of basin characteristics. The movement of boundaries should be included in ASMITA computations. At this momen no relation has been formulated to expres the movement of basin boundaries in time. It is reccomended to further investigate the movement of watersheds in time. Including a relation in ASMITA to take into account this effect will improve long-term morphologic predictions of the Western Dutch Wadden Sea. Further understanding of the movement of boundaries could also lead to different scenarios for this movement that can be prescribed in ASMITA computations.
- It is recommended to further investigate the measured sediment transport from Marsdiep towards Vlie. Better understanding of the mechanisms driving this exchange of sediment is necessary to include this in ASMITA calculations. ASMITA simulations including sediment exchange over the basin boundaries will have different resulting sediment exchange rates compared to the optimal simulation presented in this study.
- The models used in this study do not contain volume change of the delta element due to movement of the reference coastal profile. Calibration with delta characteristics corrected for this movement also requires a model configuration that includes this effect. It is therefore recommended to include an extra term in the relation expressing volume chnages to account for this effect.

References

Buijsman, M.C., 1997, The impact of gas extraction and sea level rise on the morphology of the Wadden Sea. Faculty of Civil Engineering, Delft University of Technology, Delft

Elias, E., Koningsveld, M. van, Tonnon, P.K., Wang, Z.B., 2006, Sediment budget analysis and testing hypotheses for the Dutch coastal system, Report Z4100, WL | Delft Hydraulics, Delft

Elias, E., 2006, Morphodynamics of Texel Inlet, IOS Press, ISBN 1-58603-676-9

Elias, E. 2006b, Morfodynamica van het Zeegat van Texel, Report TU Delft in cooperation with Rijkswaterstaat RIKZ, (in Dutch)

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, Report H1300, WL | Delft Hydraulics, Delft

Eysink, W.D. and 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, Report H1300, WL | Delft Hydraulics, Delft

Gerritsen, F., 1990, Morphological stability of Inlets and Channels of the Western Wadden Sea. Nota GWAO-90.019, Dienst getijdewateren, Rijkswaterstaat

Gerritsen, F. de Jong, H. and Langerak, A., 1990, Cross-sectional stability of estuary channels in the Netherlands, Proceedings of 22nd Coastal Engineering conference, ASCE, abstract

Goor, M.A. van, 2001, Influence of Relative Sea Level Rise on Coastal Inlets and Tidal Basins, Report Z2822, WL | Delft Hydraulics, Delft

Koningsveld, M. van, Stive, M.J.F., Mulder, J.P.M., 2004, Balancing research efforts and management needs. A challenge for coastal engineering

Kragtwijk, N.G., 2001, Aggregated scale modeling of tidal inlets of the Wadden Sea, Report Z2822, WL | Delft Hydraulics, Delft

Mulder, J.P.M., 1999, Zandbalansen van het Zeegat van Texel met het Invers Sediment Transport Model, 1931-1971, Rapport RIKZ/OS-99.116.x, Project Kust82000, Rijks instituut voor Kust en Zee/RIKZ, Rijkswaterstaat

Rakhorst, H.D., 2000, Draft Ontwikkeling van de westelijke Waddenzee. Erosie en Sedimentatie westelijke Waddenzee en aangrenzende Noordzee, 1926/1933-1982. Nota NH-ANV-2000-20. Directie Noord-Holland, Rijkswaterstaat

Renger, E. and Partenscky, H.W., 1974, Stability criteria for tidal basins, Proceedings 14th Coastal Eng. Conf., ASCE, Vol2, ch 93., pp. 1605-1618

Stive, M.J.F., Capobianco, M., Wang, Z.B., Ruol, P. and Buisman, M.C. 1998, Morphodynamics of a Tidal Lagoon and adjacent Coast. 8th International Biennial Conference on Physics of Estuaries and Coastal Seas, The Hague, September 1996, pp 397-407

Vriend, H.J. de, Dronkers J., Stive, M.J.F., Dongeren, A. van, Wang, Z.B., 1998, Coastal inlets and Tidal basins, lecture notes for course CT5303, Delft

Waal, v.d. R.J., 2007, From personal communication in preparation of the report Z4169, WL | Delft hydraulics, Delft

Walton, T.L. and Adams, W.D., 1976, Capacity of Inlet outer bars to store sand, Proceedings of 15th Coastal Eng. Conf., ASCE, Honolulu, Hawaii, p1919-1937

A Assessing the correlation of α_c between Marsdiep and Vlie

In this study the correlation between α_c for Marsdiep and Vlie is estimated. This can be used during the calibration of AMSITA. The method explained in section 4.5.2 for expressing the correlation between the channel equilibrium coefficients of two basins can be summarized as follows:

The formulation of V_{ce} adopted in ASMITA reads:

$$V_{ce} = \alpha_c \cdot P^{\beta_c} \tag{2.18}$$

The analytical formulation for the equilibrium channel volume reads (Eysink, 1992):

$$V_c = c_A \cdot c_s^1 \sqrt{\frac{L}{H \cdot B}} \cdot \frac{\beta_p}{\gamma_p} \cdot P^{\frac{3}{2}} = \alpha_c^* \cdot P^{\frac{3}{2}} \tag{2.16}$$

It is assumed that the influence of the shape of the basin on α_c is comparable to the influence on α_{c^*}. This means that the ratio two basins for these coefficients for both basins is similar:

$$\frac{\alpha_{c,2}}{\alpha_{c,1}} = \frac{\alpha_{c,2}^*}{\alpha_{c,1}^*} \tag{4.8}$$

Determination of c_s follows from:

$$c_s = \frac{\int_0^L P(x)dx}{P \cdot L_c} \tag{4.10}$$

c_s can be corrected to c_s^1:

$$c_s^1 = c_s \cdot \sqrt{\frac{H \cdot B \cdot L}{P}} \tag{4.14}$$

For a basin in equilibrium the flat volume is given by:

$$V_{fe} = \alpha_{fe} \cdot \left(\frac{A_{fe}}{A_b}\right) \cdot A_b \cdot H \tag{2.8}$$

and

$$P_e = H \cdot A_b - V_{fe} \tag{2.2}$$

These equations provide enough information to compute the correlation between α_c values of comparable basins. For this purpose basin characteristics like P, L, B, and c_s are required. Marsdiep and Vlie basins are visually divided into channel sections. It is attempted to define the channel sections in such a way that it covers part of the main channel with the flat area that is fed or drained by that part of the channel (Figure A.1).

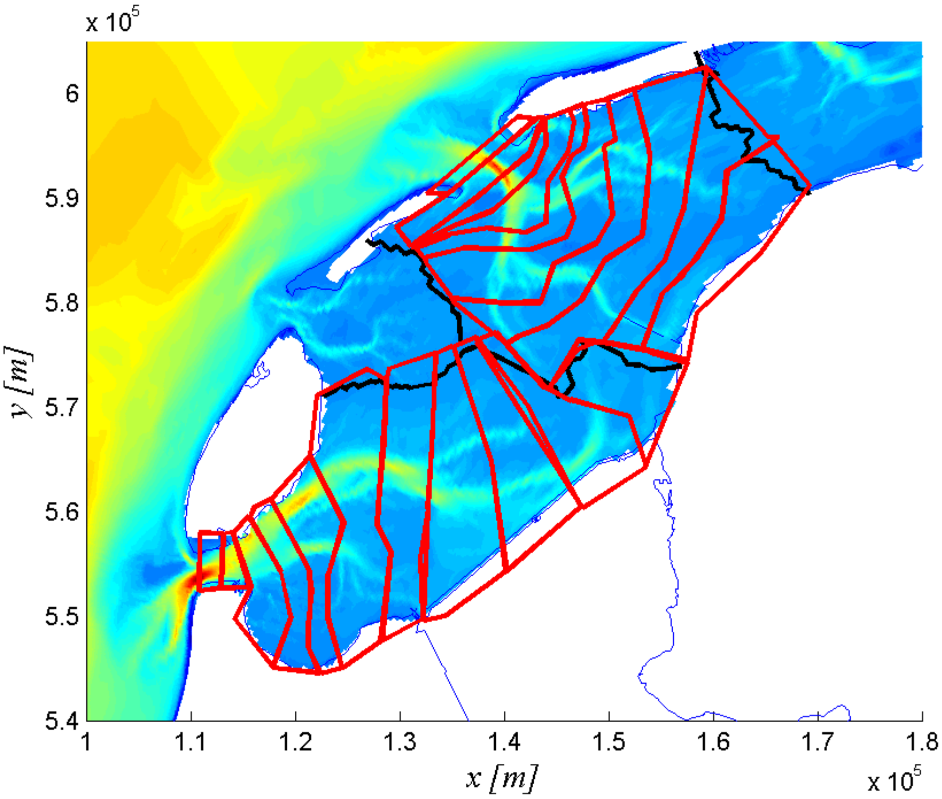


Figure A.1: Illustration of the channel sections used to define c_s

For each channel section (i) characteristics like the channel length (L_i), section width (B_i) and tidal prism that is stored in that section (P_i) are determined. Summation of the individual characteristic channel lengths of all sections in one basin provides the total characteristic channel length of that basin. The waited average of the channel widths of all sections gives the characteristic basin width. c_s can be determined from the characteristics of the individual channel sections. Based on relation (4.10) c_s can be approached by:

$$c_s = \frac{\sum_{i=1}^{n} P_i \cdot L_i}{\sum_{i=1}^{n} P_i \cdot \sum_{i=1}^{n} L_i} \tag{A.1}$$

The results for all parameters computed is presented in Table A.1. With (4.8) the correlation between α_c values of Marsdiep and Vlie yields:

$$\frac{\alpha_{c,Mars}}{\alpha_{c,Vlie}} = \frac{\alpha^*_{c,Mars} \cdot c_A}{c_A \cdot \alpha^*_{c,Vlie}} = \frac{0.104}{0.074} \approx 1.41$$

	Marsdiep	Vlie
H	1.52	1.89
$\sum_{i=1}^{n} L_i$	51828	34897
$\sum_{i=1}^{n} P_i$	$1.07*10^9$	$9.80*10^8$
$\sum_{i=1}^{n} P_i \cdot \sum_{i=1}^{n} L_i$	$5.55*10^{13}$	$3.42*10^{13}$
$\sum_{i=1}^{n} P_i \cdot L_i$	$6.07*10^{12}$	$4.10*10^{12}$
c_s	0.1095	0.1200
B	16683	26301
A_b	$6.89*10^8$	$6.57*10^8$
α_f	0.43	0.46
V_{fe}	$9.53*10^7$	$1.35*10^8$
P_e	$9.52*10^8$	$1.11*10^9$
β	0.514	0.526
γ	0.905	0.889
c_s^1	0.1286	0.1502
$\frac{\alpha_c^*}{c_A}$	0.104	0.074

Table A.1: Summarize of the results for the computation of the channel equilibrium coefficient.

B Paradoxical development of flat areas and volumes

It can be proved that if a basin gains flat area at only one location also the flat volume should increase. This does not necessarily have to be the case if simultaneously a basin increases and decreases at different locations. This is illustrated with a simple case in which a basin is considered with a high flat at the left side and a low flat on the right side (Figure B.1). Boundaries at both sides are moving. Suppose a small surface area is gained at the left side of the basin and a larger amount of surface area lost at the right side. The total change of flat surface area amounts the summation of all individual changes. In this case that would be negative. The total change of flat volume amounts the summation of all individual volume changes. Because of the height of the flats a situation could occur that the flat volume gained at the left side exceeds the flat volume lost at the right side. In that case the volume change would be positive.

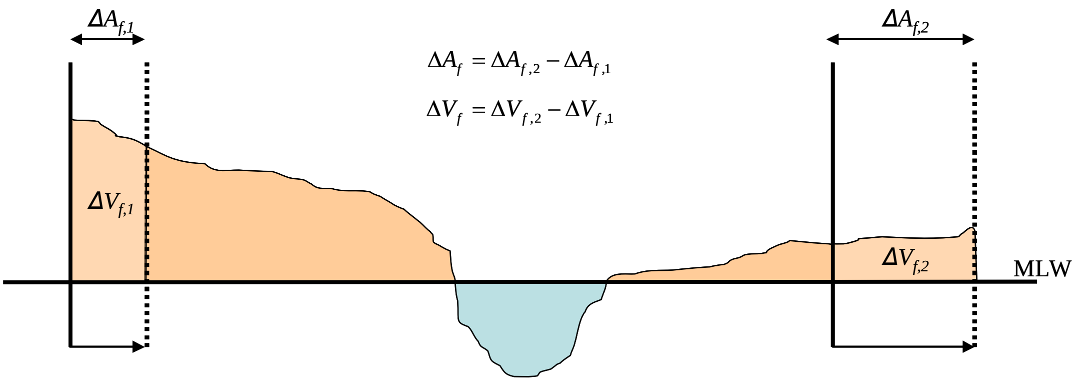


Figure B.1: Illustration of possible cause paradoxal behavior

This phenomenon could explain the unexpected flat volume changes due to movement of the boundary between 1991 and 1998 as well as between 1998 and 2006. In both periods the change of flat surface area and flat volume due to movement of the boundary show opposite signs. The period between 1991 and 1998 will be further examined.

Figure B.2 shows the boundaries surrounding Eierlandse gat for the years 1991 and 1998 on the grid used to construct hypsometric curves. Grid cells gained and lost due to the movement of the boundaries are indicated respectively yellow and brown. The areas, heights relative to MLW and sediment volumes above MLW of those grid cells are indicated in Table B.1. The surface area of the grid cells lost is smaller than the total surface area of the gained grid cells. The opposite is observed for the flat volume of those grid cells.

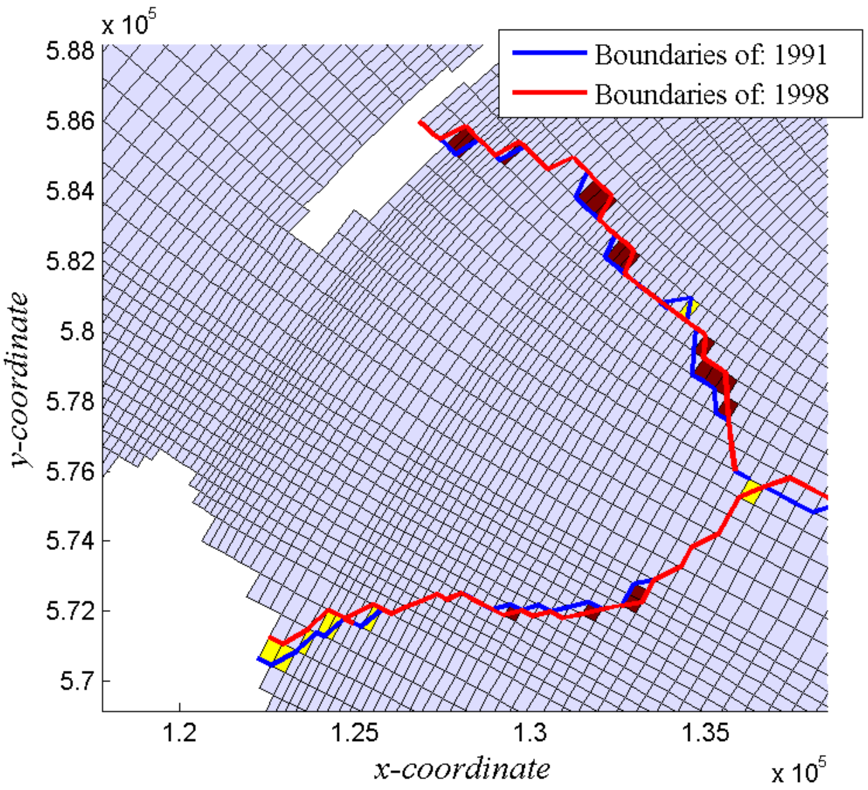


Figure B.2: Boundaries of Eierlandse gat basin for 1991 and 1998

Grid cells gained			Grid cells lost		
Surface area	Height	Sediment Volume	Surface area	Height	Sediment Volume
170636	1.018	173784	297406	1.116	331997
132891	0.957	127179	318702	1.083	345297
115682	0.886	102530	174246	1.177	205141
156014	0.395	61569	182610	1.094	199805
249121	0.219	54634	188233	1.000	188209
269091	0.184	49522	204013	0.410	83620
143251	0.227	32521	195154	0.563	109785
161998	0.170	27481	290449	0.415	120520
164087	0.315	51628			
165416	0.368	60869			
133368	0.317	42318			
204864	0.361	74019			
211305	0.443	93514			
217588	0.388	84328			
223794	0.358	80112			
159735	0.015	2338			
236799	0.206	48722			
161611	0.213	34419			
166128	0.295	48948			+
3443379		1250434	1850813		1584375

Table B.1: Contribution to area and volume changes by the individual grid cells that change basin

C Reaction of model results to sudden changes of the basin boundary movement

Volume developments are calculated using relation (2.26).

$$\frac{dV_n}{dt} = c_E \sigma_n A_n \left(w_{s,n} \left(\gamma_n^* - c_n^* \right) + \frac{\eta_n}{c_E} \left(\frac{d\zeta}{dt} - \frac{1}{2} \frac{dH}{dt} \right) \right) - \sigma_n b_n \quad (2.26)$$

Terms in this equation express the volume change due to sediment exchange between an element and its environment, volume change due to changes of the reference level MLW (caused by SLR and variations of the tidal range in time) and volume change due to dredging or dumping. Including the movement of boundaries adds a fourth term to this equation. This term expresses the volume change of elements during a particular time step as a result of the movement of the basin boundaries.

$$\frac{dV_n}{dt} = c_E \sigma_n A_n w_{s,n} \left(\gamma_n^* - c_n^* \right) + \sigma_n A_n \eta_n \frac{d\zeta}{dt} - \sigma_n A_n \eta_n \frac{1}{2} \frac{dH}{dt} - \sigma_n d_n + \frac{dV_{ab,n}}{dt} \quad (C.1)$$

SLR and changes of the tidal range in time cause a linear change of the reference water level in time. Assuming no large variations of the element surface areas this can be seen as constant contributions to the calculated volume change in time. The same holds for the schematization of the movement of basin boundaries in this study. No contributions of dredging and dumping are prescribed. Non linearity of the calculated volume developments are therefore introduced by the term that expresses sediment exchange between an element and its environment. The magnitude of this contribution depends on the difference between the local sediment concentration of an element and its equilibrium concentration. The local sediment concentration is influenced by the equilibrium concentrations of the element itself and equilibrium concentrations of other connected elements. Local equilibrium concentrations express the deviation of the characteristic volumes from their equilibrium. Volume developments calculated with equation (2.26) excluding the effect of SLR, variations of the tidal range and dredging and dumping have been characterized by Kragtwijk (2001). The influence of the nearly constant contribution of terms expressing volume change due to variations of MLW and volume change due to movement of basin boundaries acts directly and indirectly. The direct contribution is introduced by the volume change of elements due to movement of MLW and basin boundaries. The characteristic volume of an element is directly changed because it is attributed to another basin in case of movement of the basin boundaries. Direct changes of the characteristic volumes also invokes an indirect effect on calculated volume developments. Due to changes of basin characteristics also the tidal prism and thus equilibrium volumes will change. This affects local equilibrium concentrations of all elements and therefore also sediment exchange between elements. Movement of the boundaries and alterations of MLW are simulated with a constant rate in this study. This causes the basin characteristics and equilibrium volumes to evolve in time. The effect of such changes will be different from the effect of a sudden change of basin characteristics. Sudden changes of the basin characteristics (like closing of part of the basin as was done in 1932) cause the system instantly to be relatively far from equilibrium. A large initial reaction can than be expected. Gradual change of the equilibrium volumes will on the other hand result in a different trend of the calculated volume developments. This is shown using the results of the simulation used to assess the effect of changes of the basin boundary. To assess the effect of a continuous movement of basin boundaries with a constant rate the period between 1948 and 1975 is isolated. The simulation time is expended using the same volume changes due to movement of boundaries as used for this period. The effect of including the movement of basin boundaries on the observed trend becomes clear when results of this simulation for Marsdiep are compared to identical simulations with only 50% or 0% of the changes due to movement of boundaries prescribed (Figure C.1).

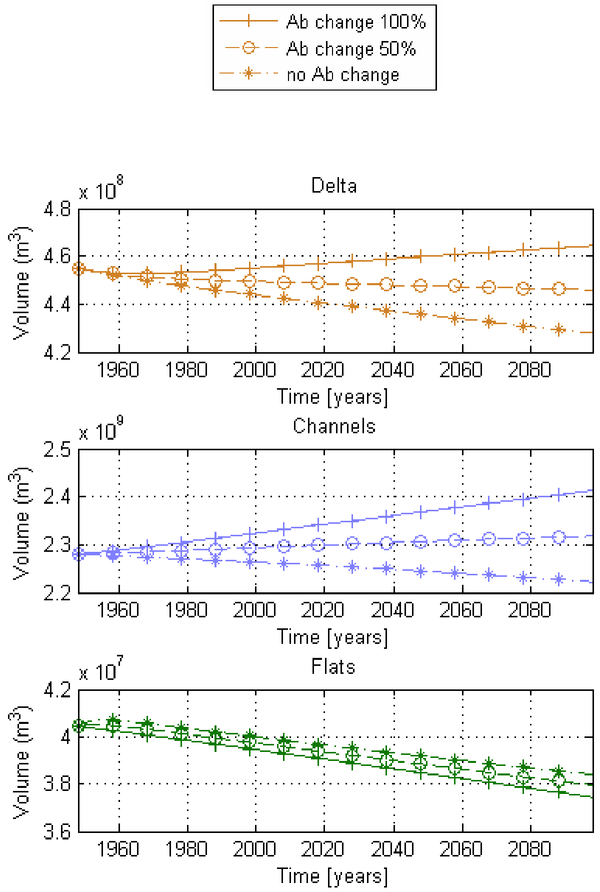


Figure C.1: Comparison of volume developments during isolated period with differen change rates of the basin boundary

Sudden changes of the rate of movement of basin boundaries will also change the observed trends in calculated volume developments. This can also be observed from the results of the simulation used to assess the influence of movement of the boundaries (see also section 5.4.4). As an example Figure C.2 shows the development of volumes of Marsdiep. The periods in which the rate of change of the basin boundaries are taken constant are clearly visible. It is striking that the first period displays a distinct non-linear adaptation as a reaction of the changed conditions whereas the following periods almost seem to adapt linear. According to the theory explained above sediment exchange between basin elements should always cause a non-linear adaptation process. Using the simulation in which the second period is isolated it can be shown that this is also the case in these simulations.

Figure C.3 shows the volume developments of Marsdiep resulting from this simulation. The period between 1948 and 1975 is indicated with a red line. The delta element shows a clear non-linear development. Also the calculated sediment transport from this run illustrated non-linearity (Figure C.5). The reactions to the evolving equilibrium volumes however are small compared to the first period. This can be explained by the relatively slow movement of the boundaries between 1948 and 1975. The following period (1975 – 1981) again shows larger adaptations. This also corresponds with the relatively fast movement of the basin boundary.

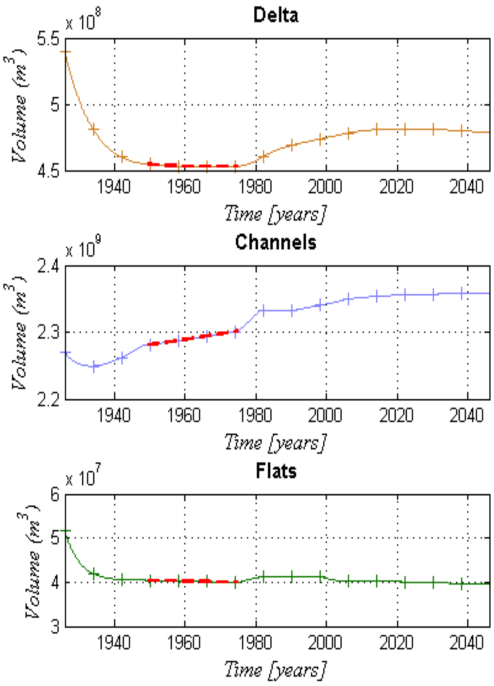


Figure C.2: Volume development of Marsdiep elements in simulation used to assess the effect of movement of basin boundaries

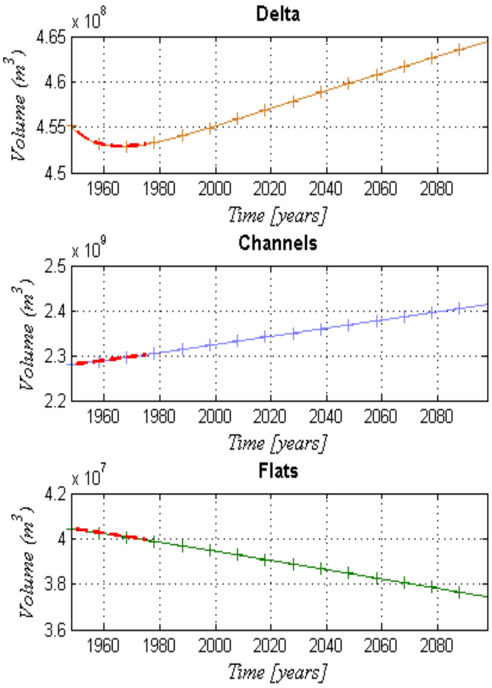


Figure C.3: Volume development of Marsdiep elements isolating initial values and model settings of 1948 in the simulation used to assess the effect of movement of basin boundaries

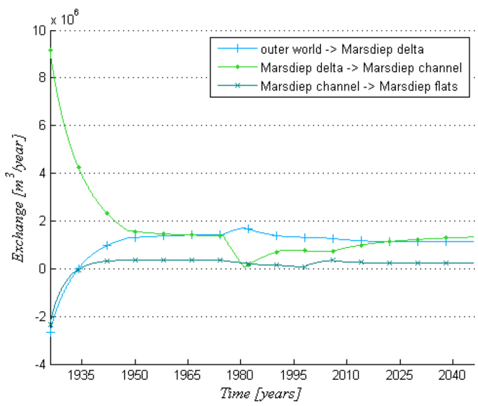


Figure C.4: Sediment transports in Marsdiep basin following from the simulation used to assess the effect of movement of basin boundaries

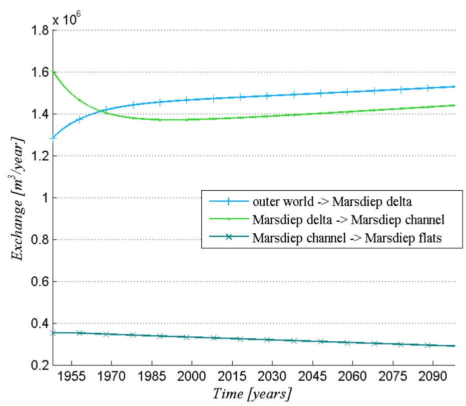
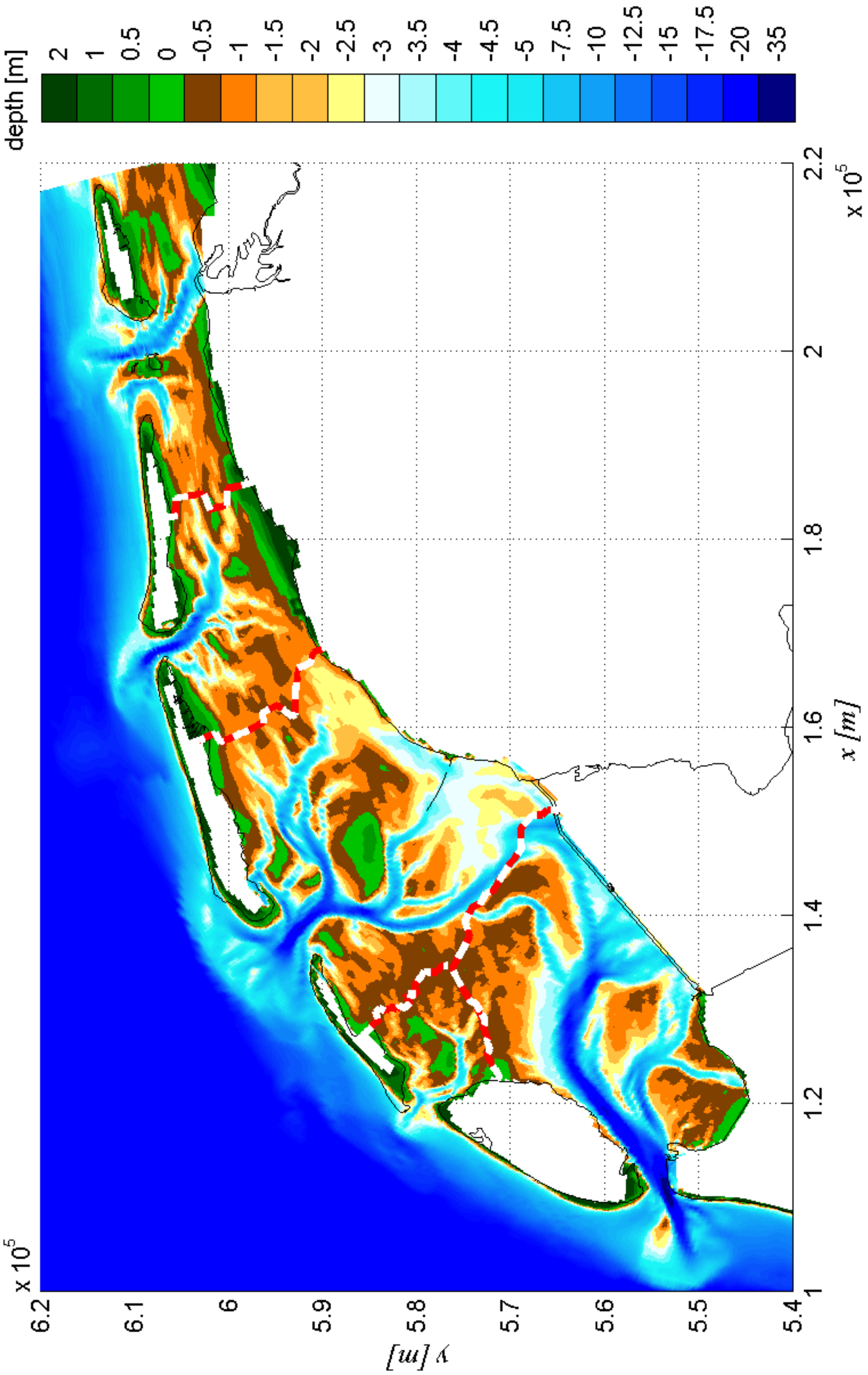


Figure C.5: Sediment tranpsorts in Marsdiep basin following from the simulation of the isolated period

D Maps of bathymetries (UCIT), chronology of the underlying data and velocity deviation used to define boundaries

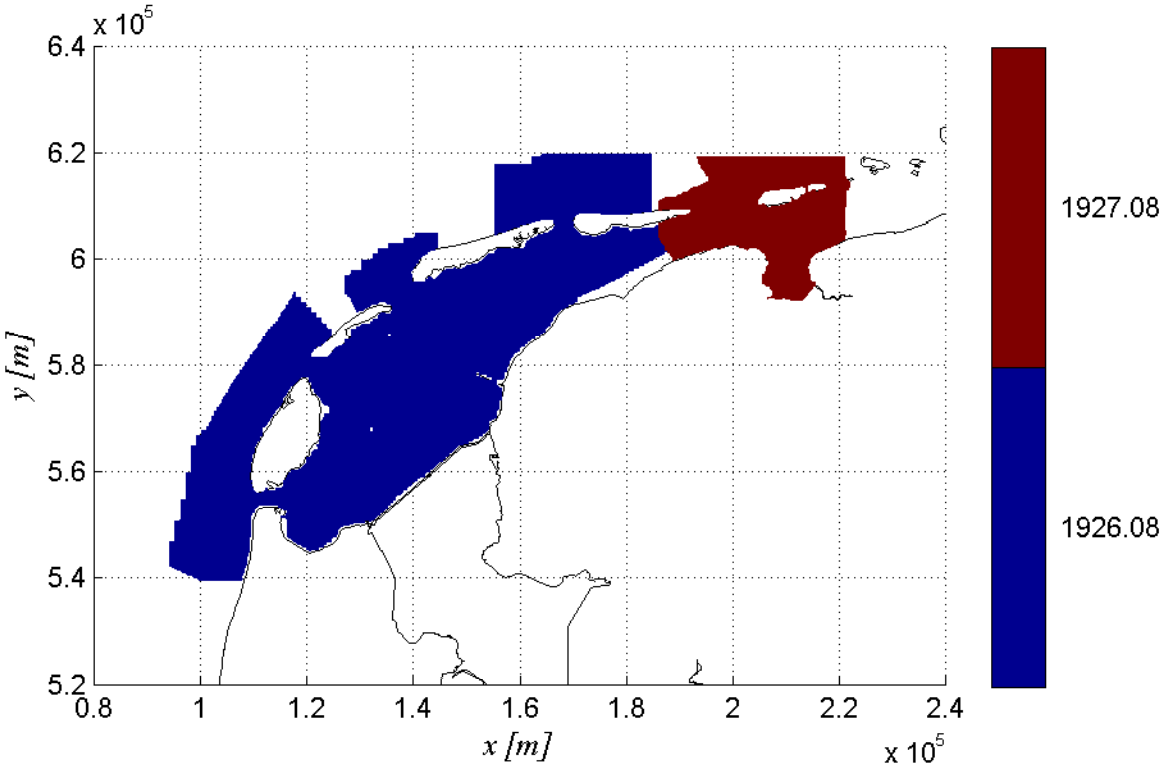


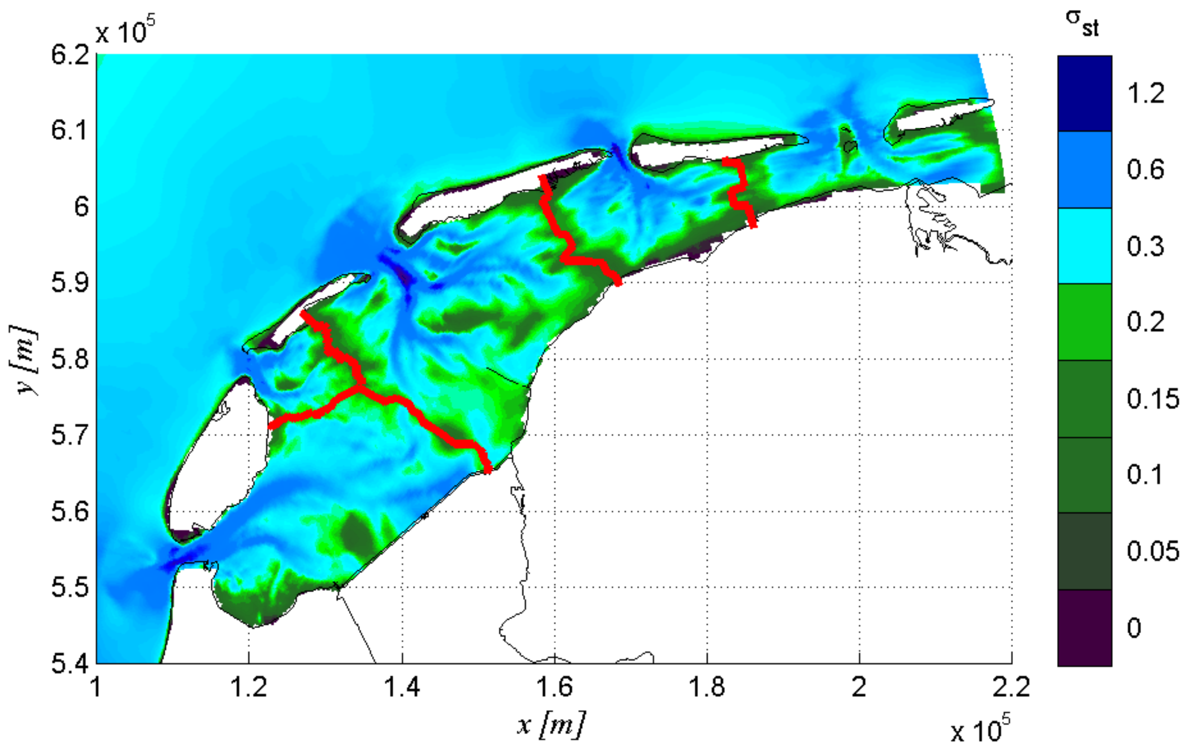
1926 bathymetry constructed with UCIT
including boundaries determined using
minimal standard deviation of the velocities

Z4169

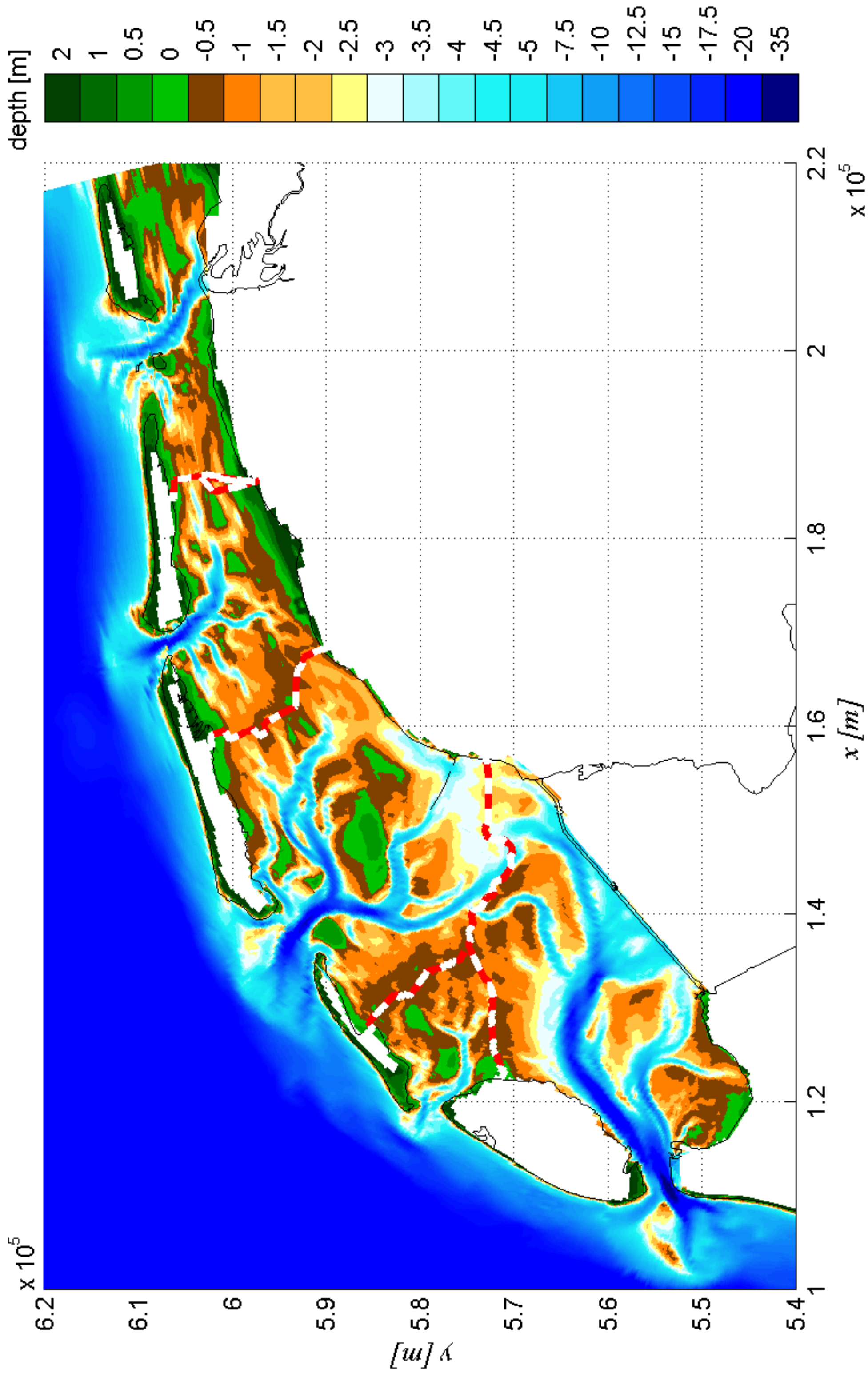
WL | DELFT HYDRAULICS

Figure: D.1

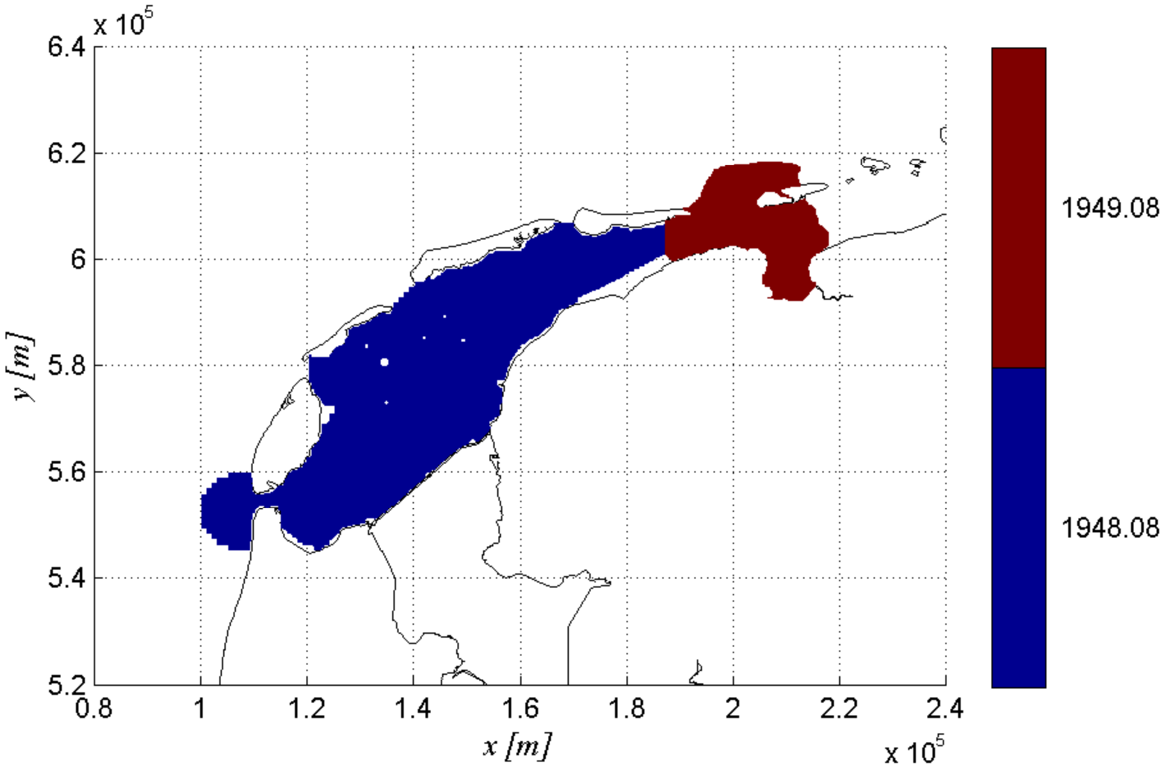


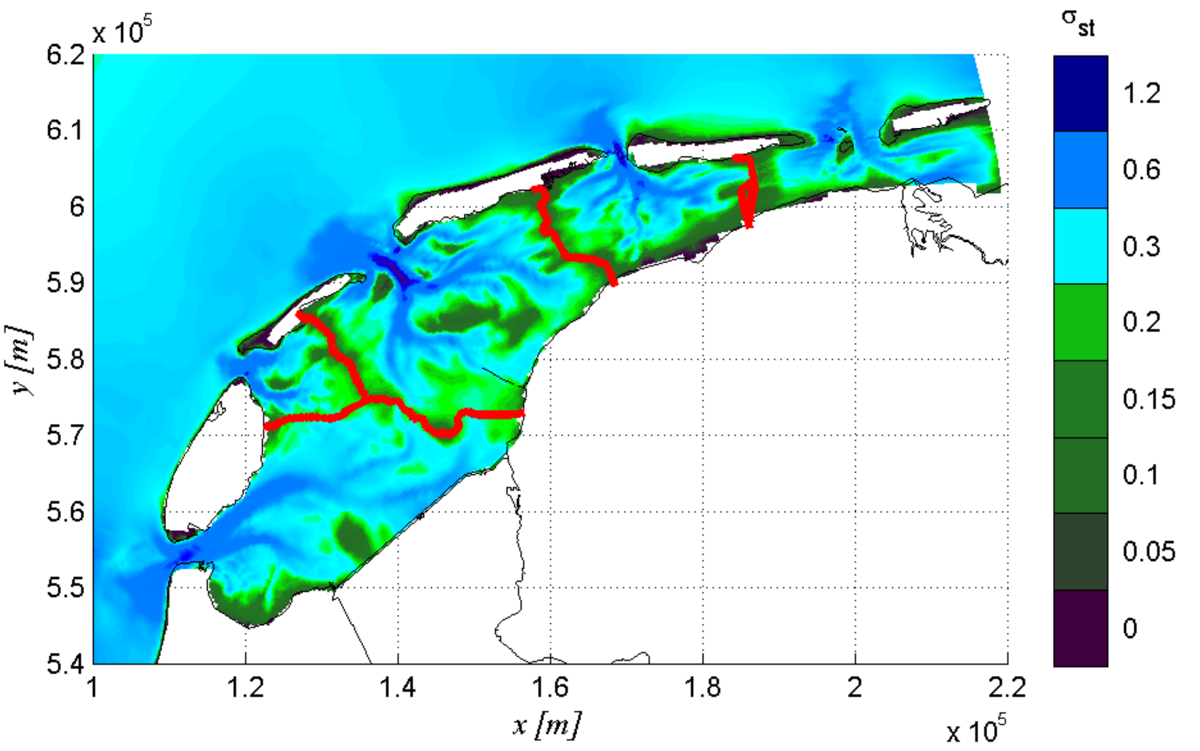


year: 1926 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.2

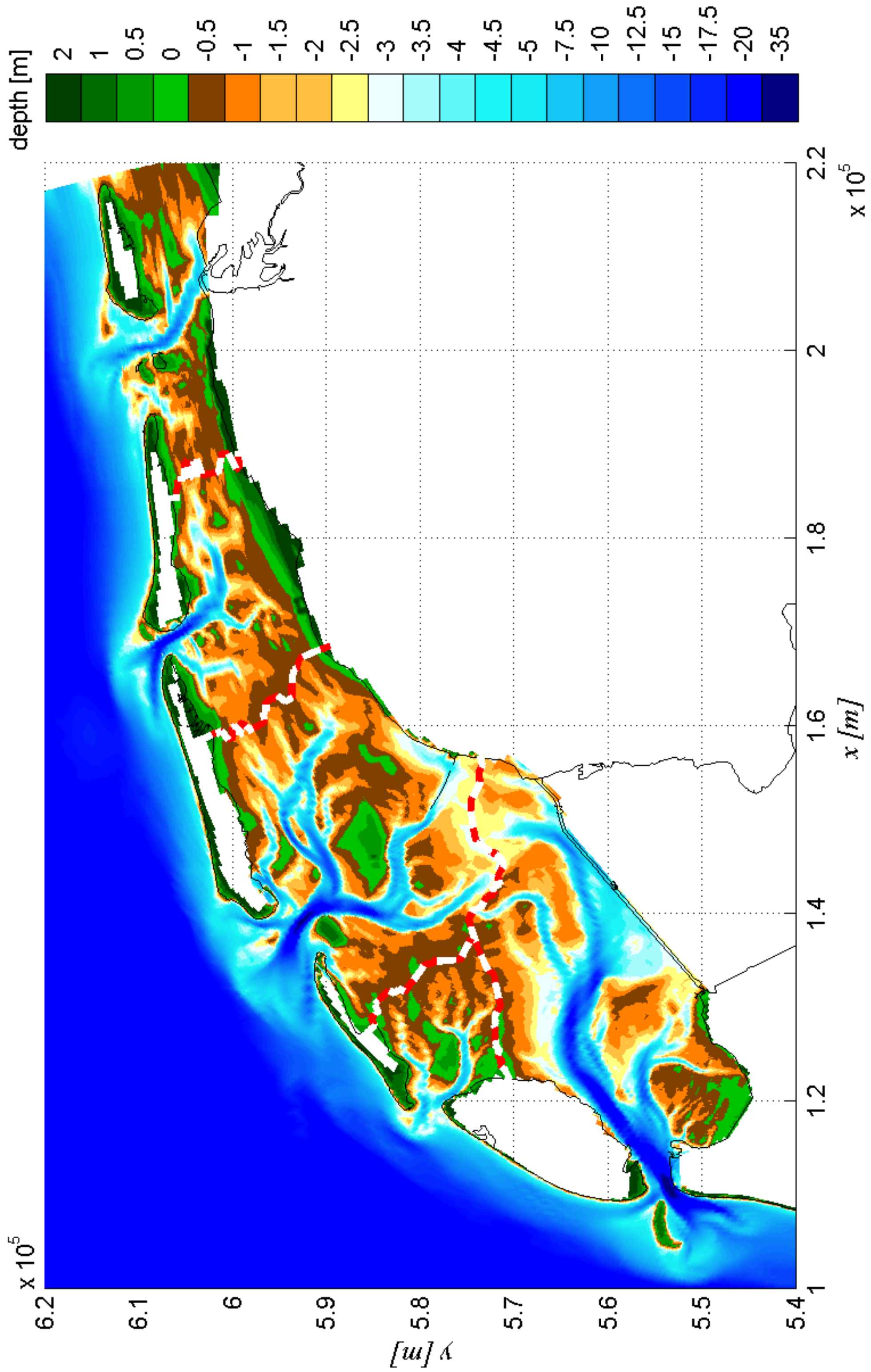


1948 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.3

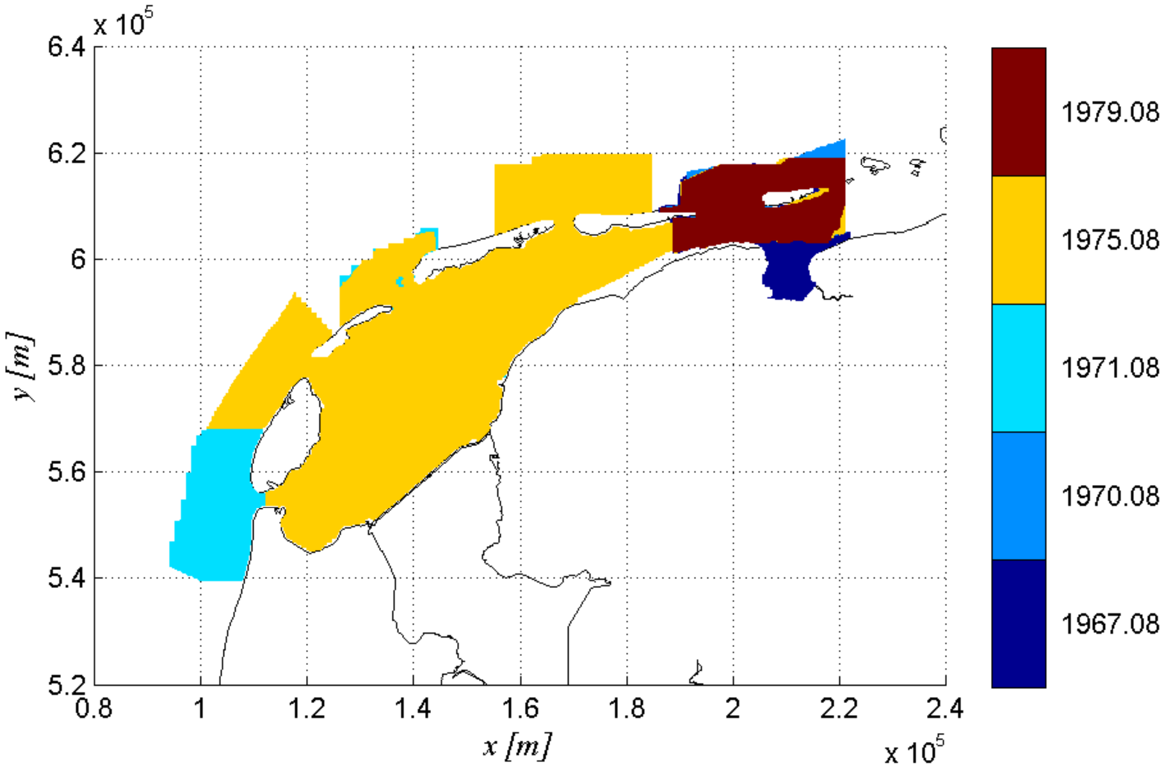


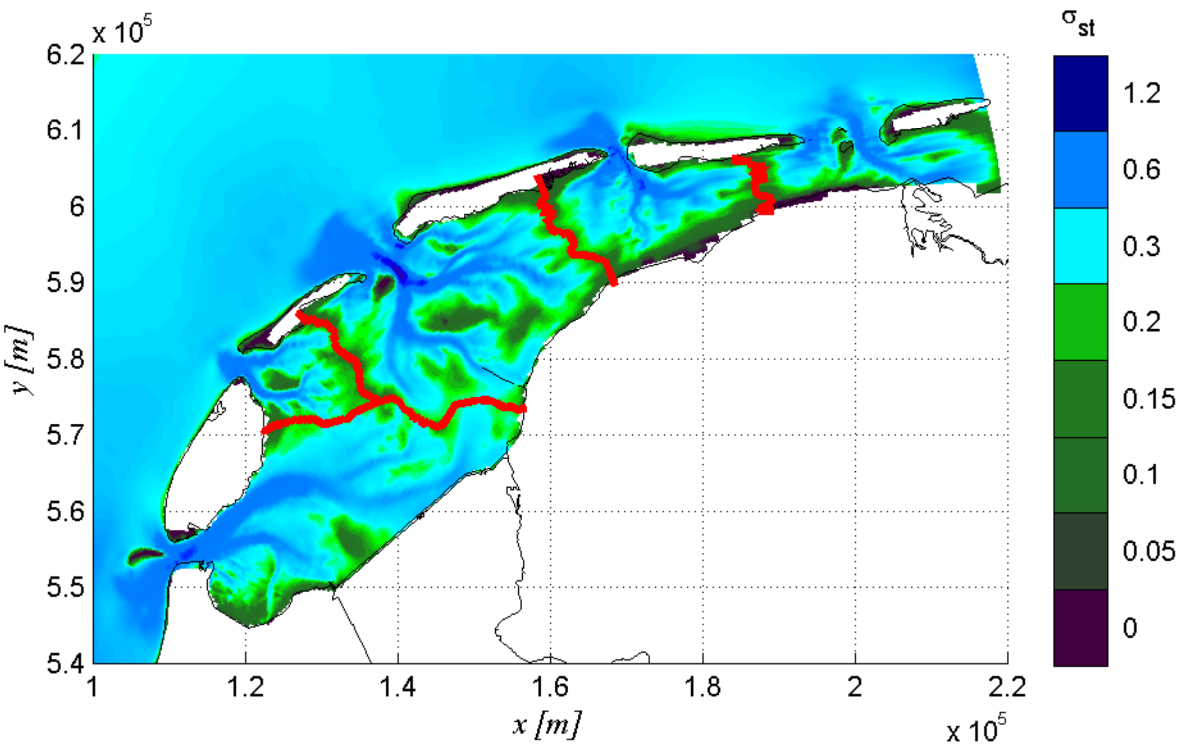


year: 1948 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.4

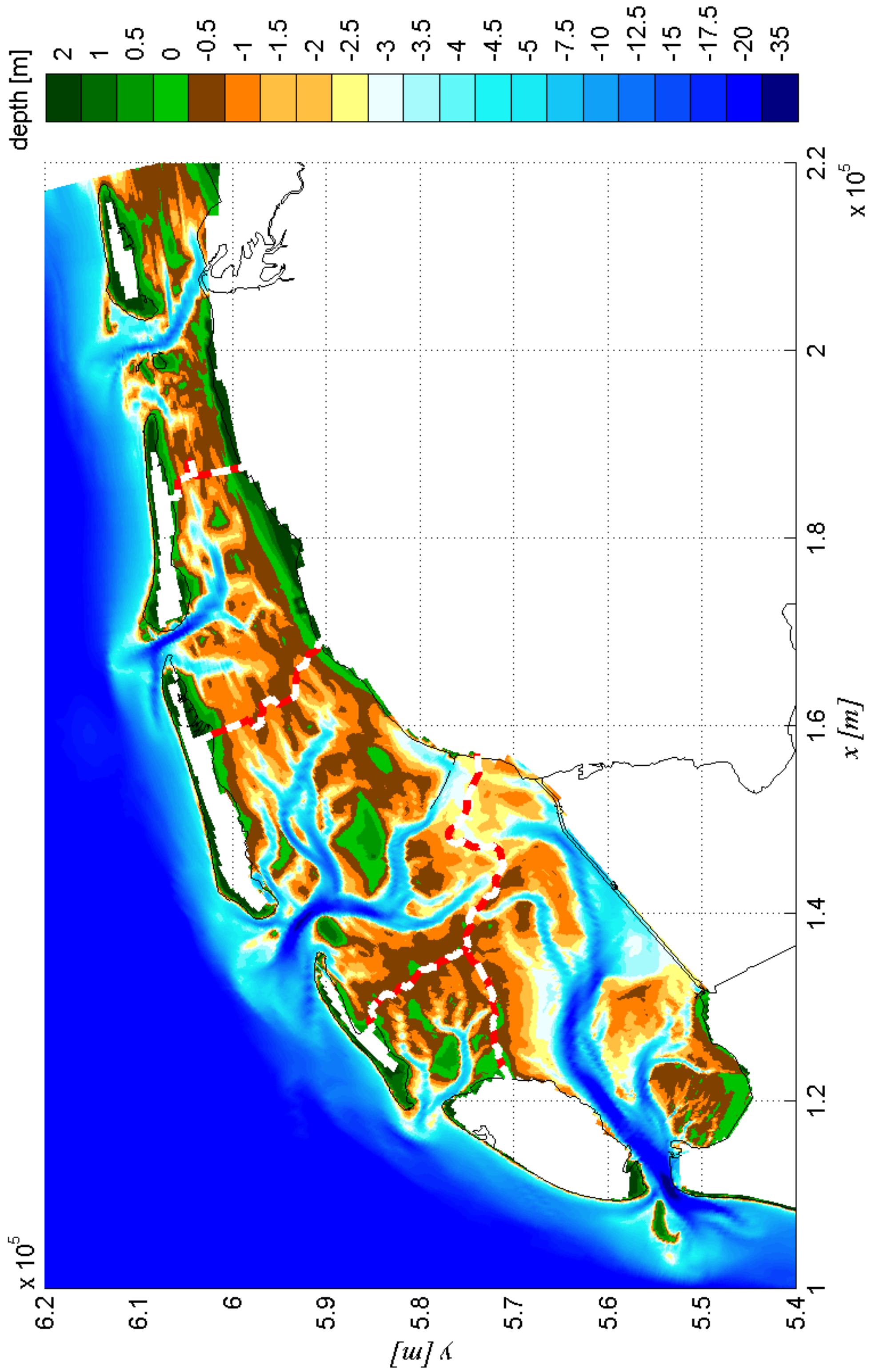


1975 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.5

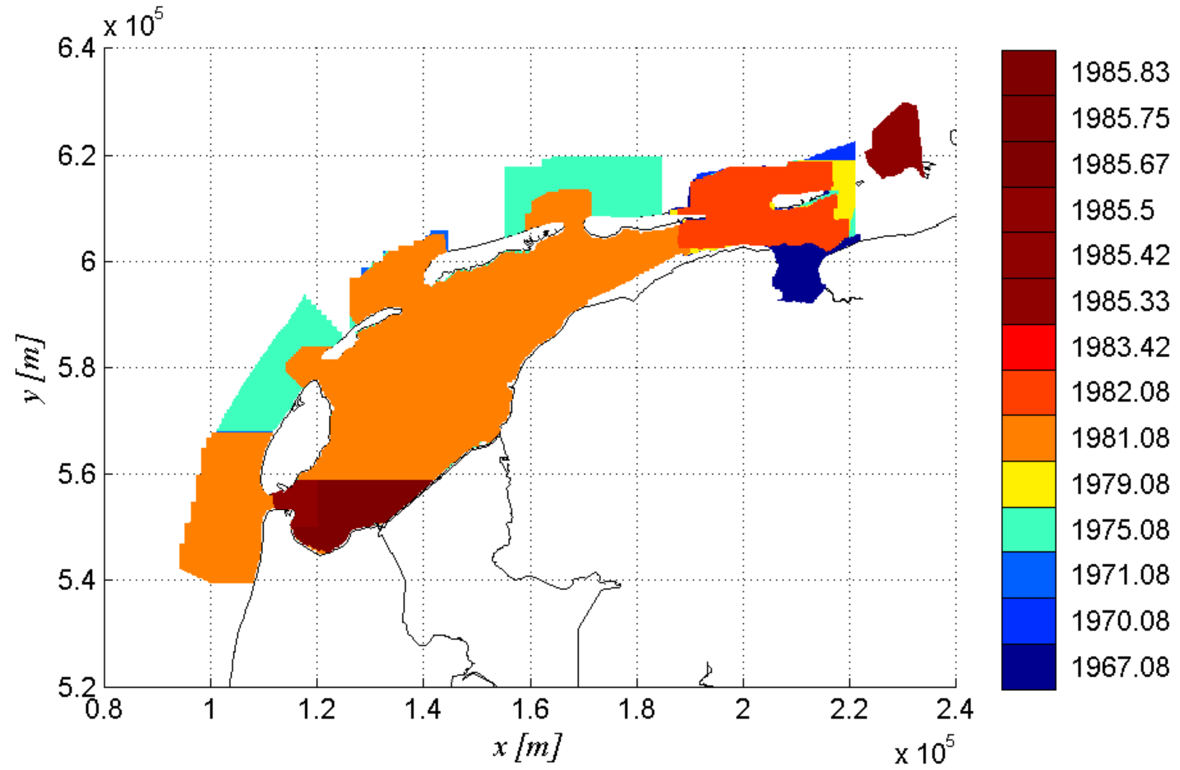


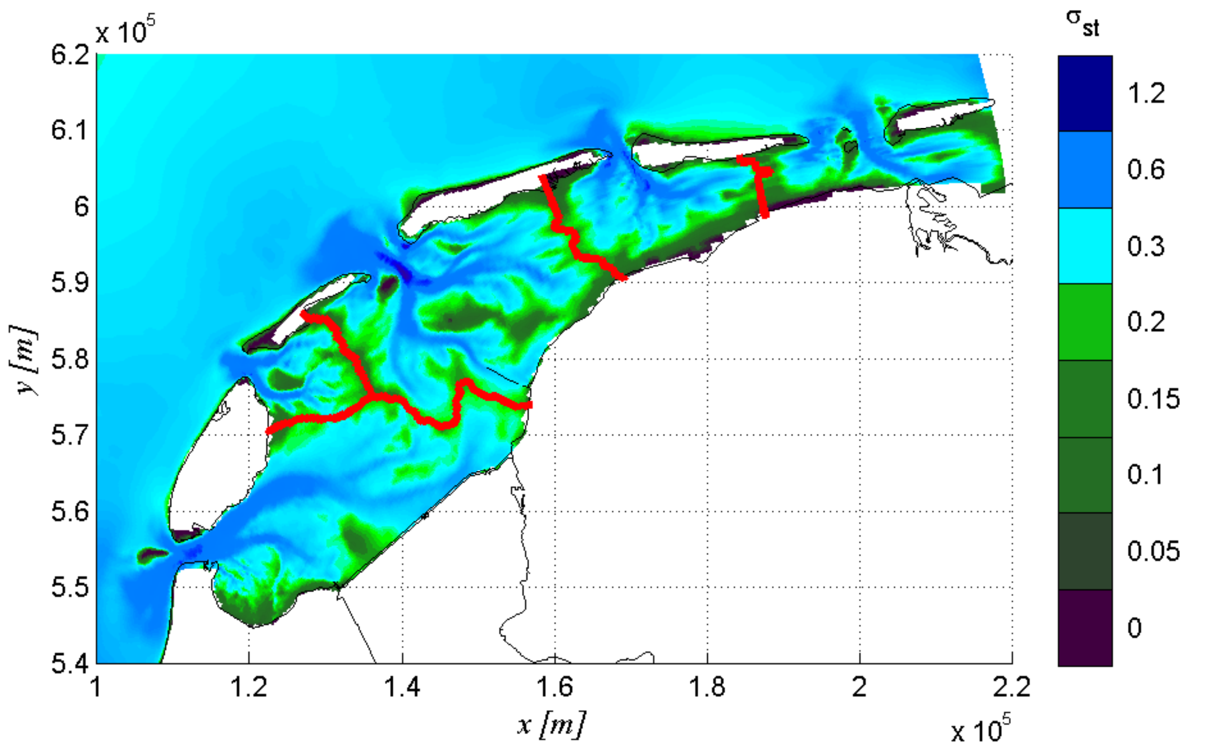


year: 1975 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.6

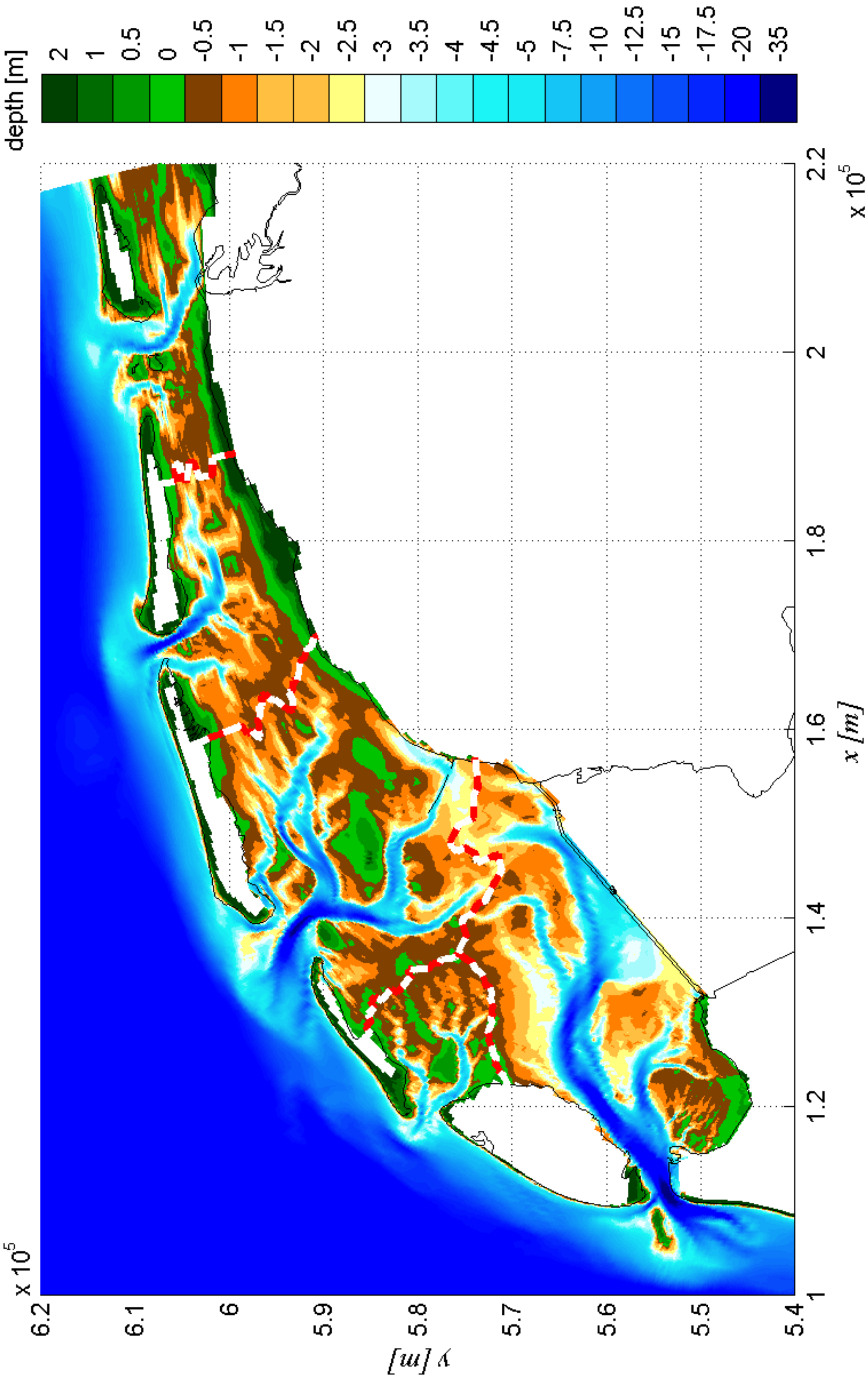


1981 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.7

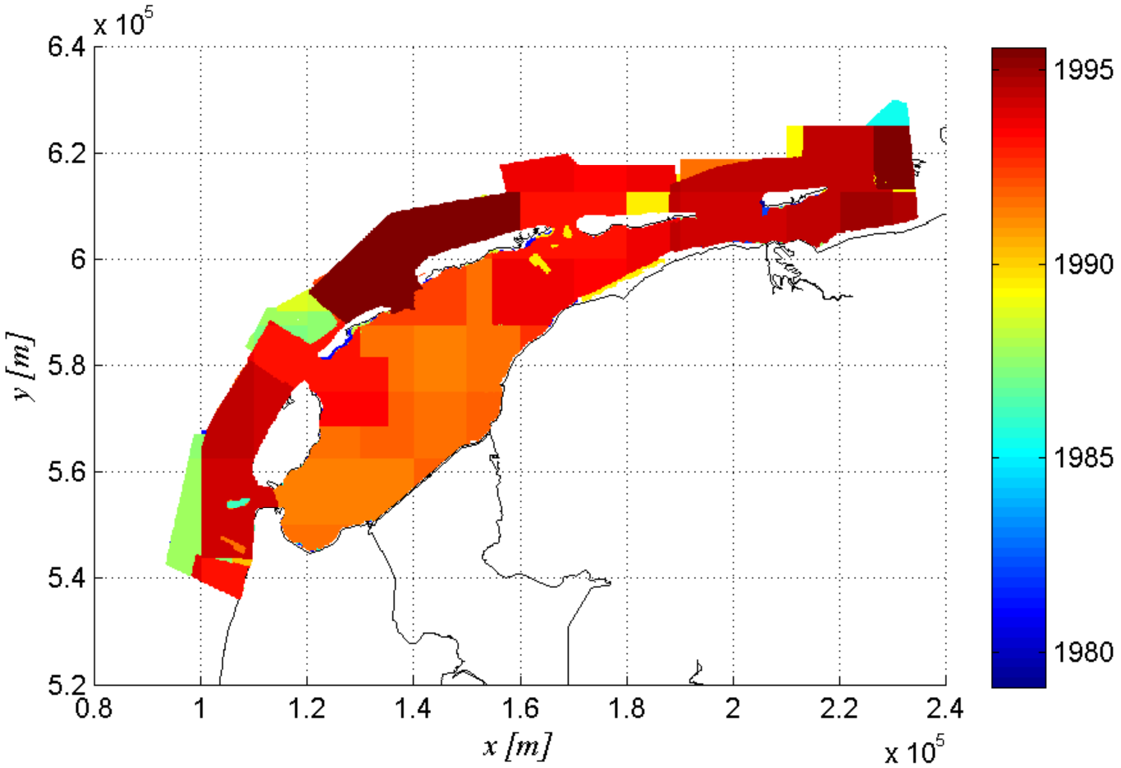


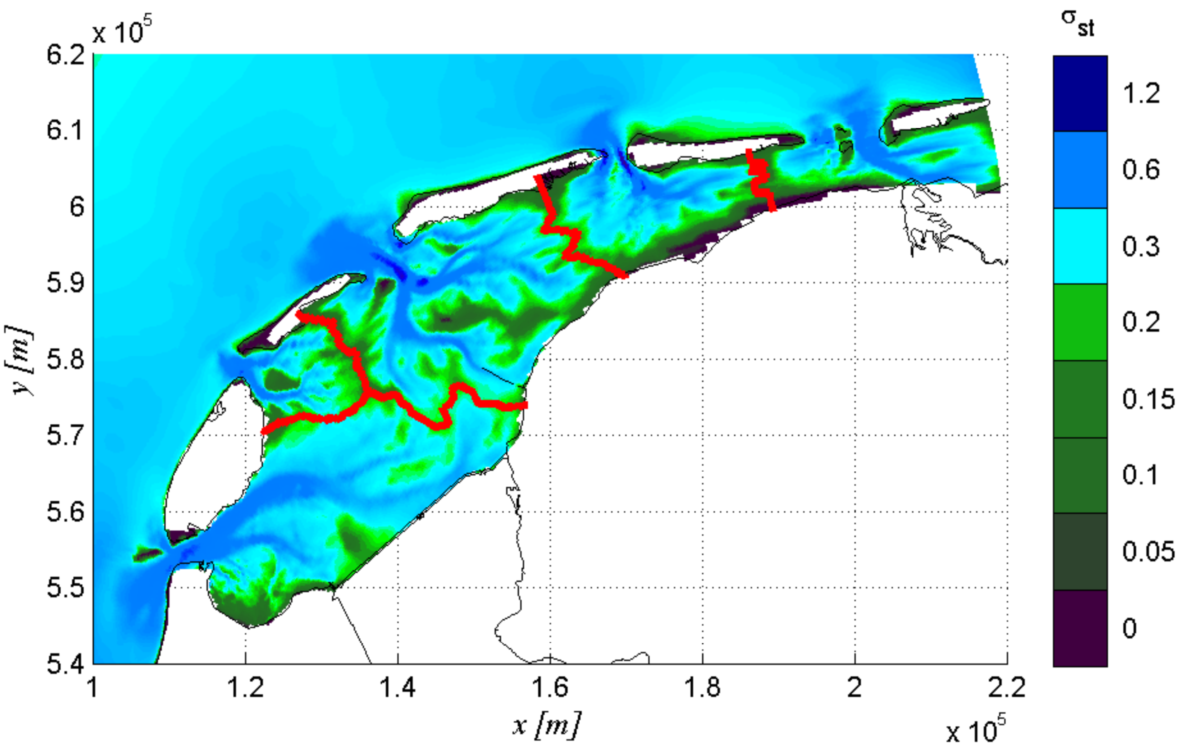


year: 1981 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.8

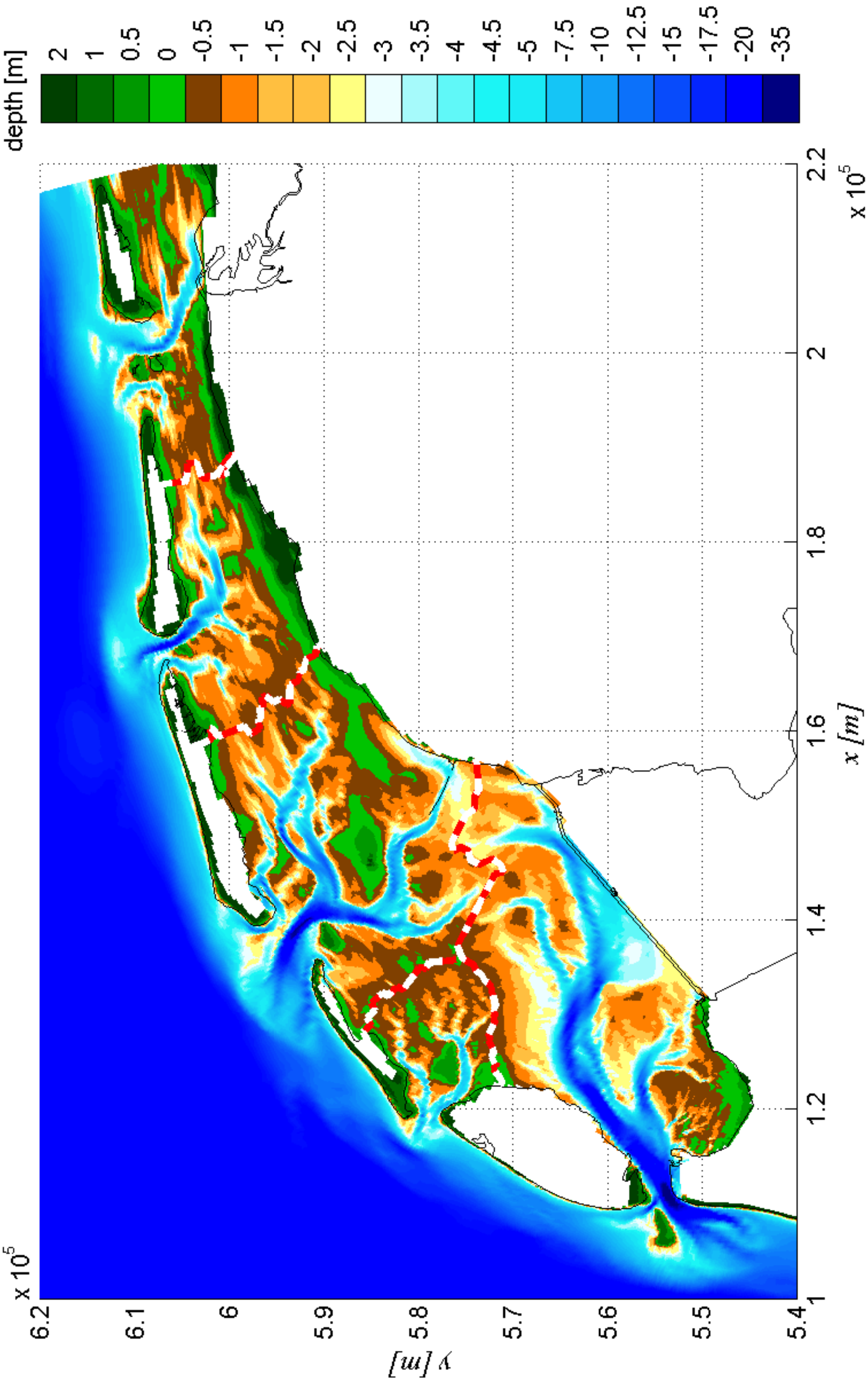


1991 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.9

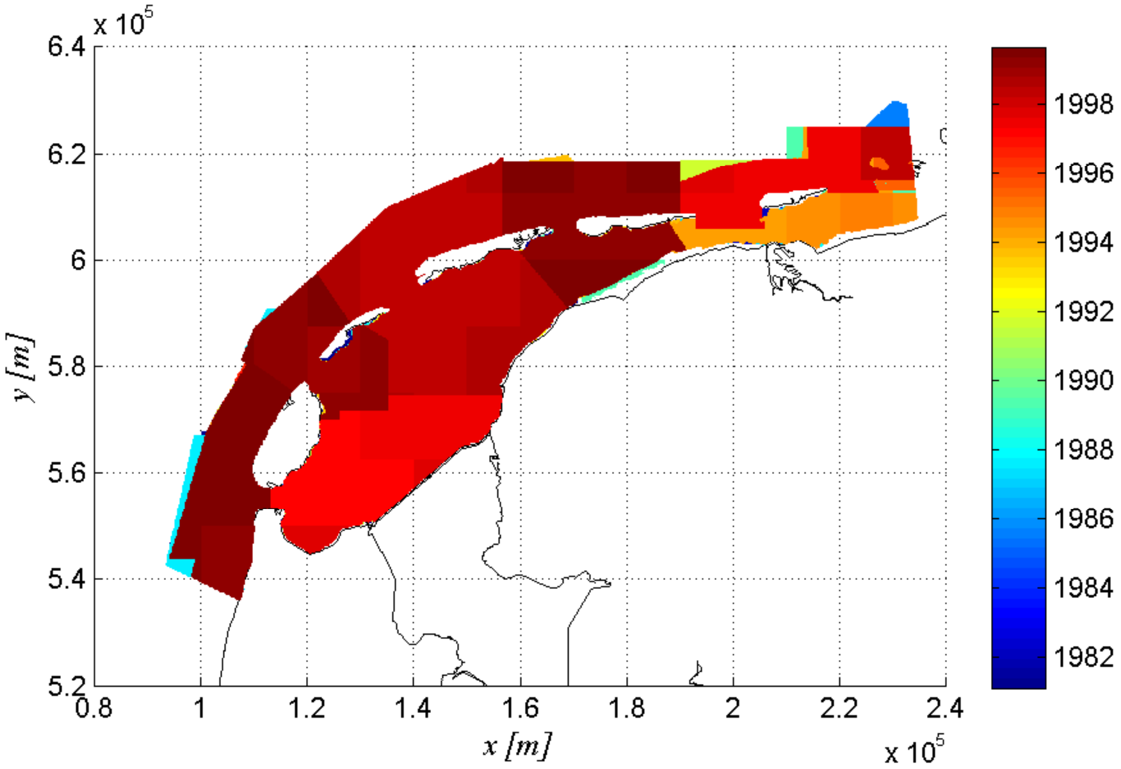


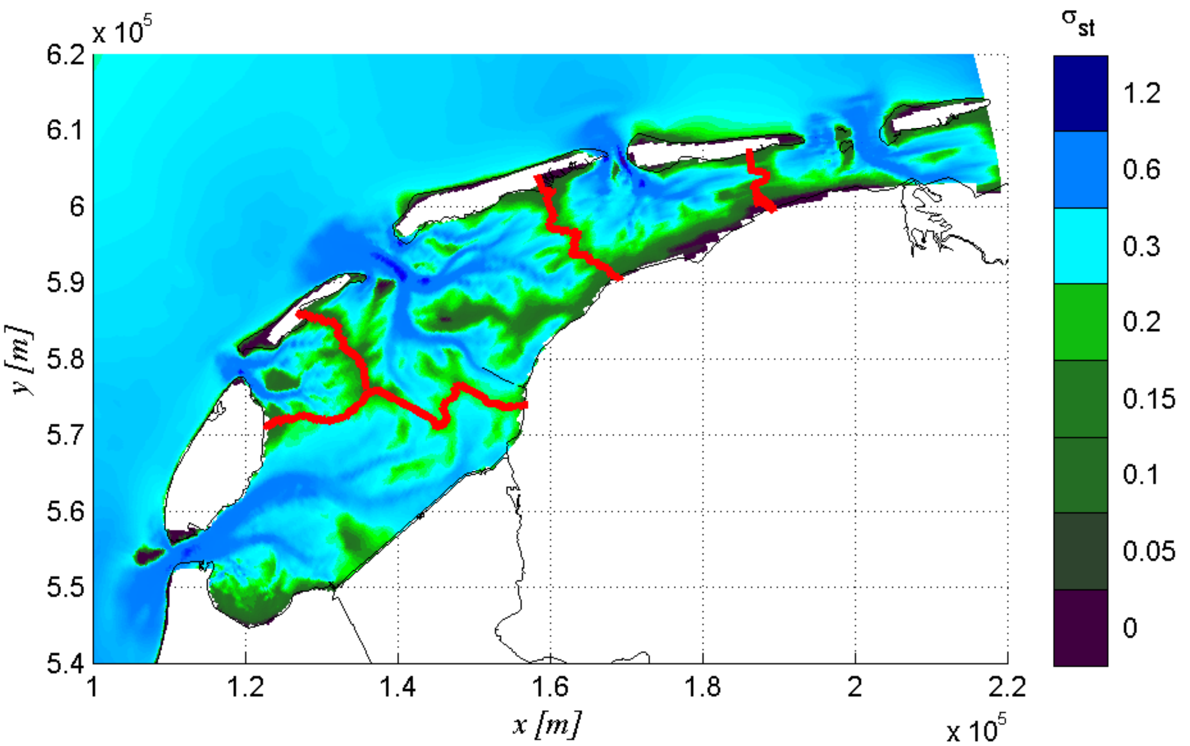


year: 1991 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.10



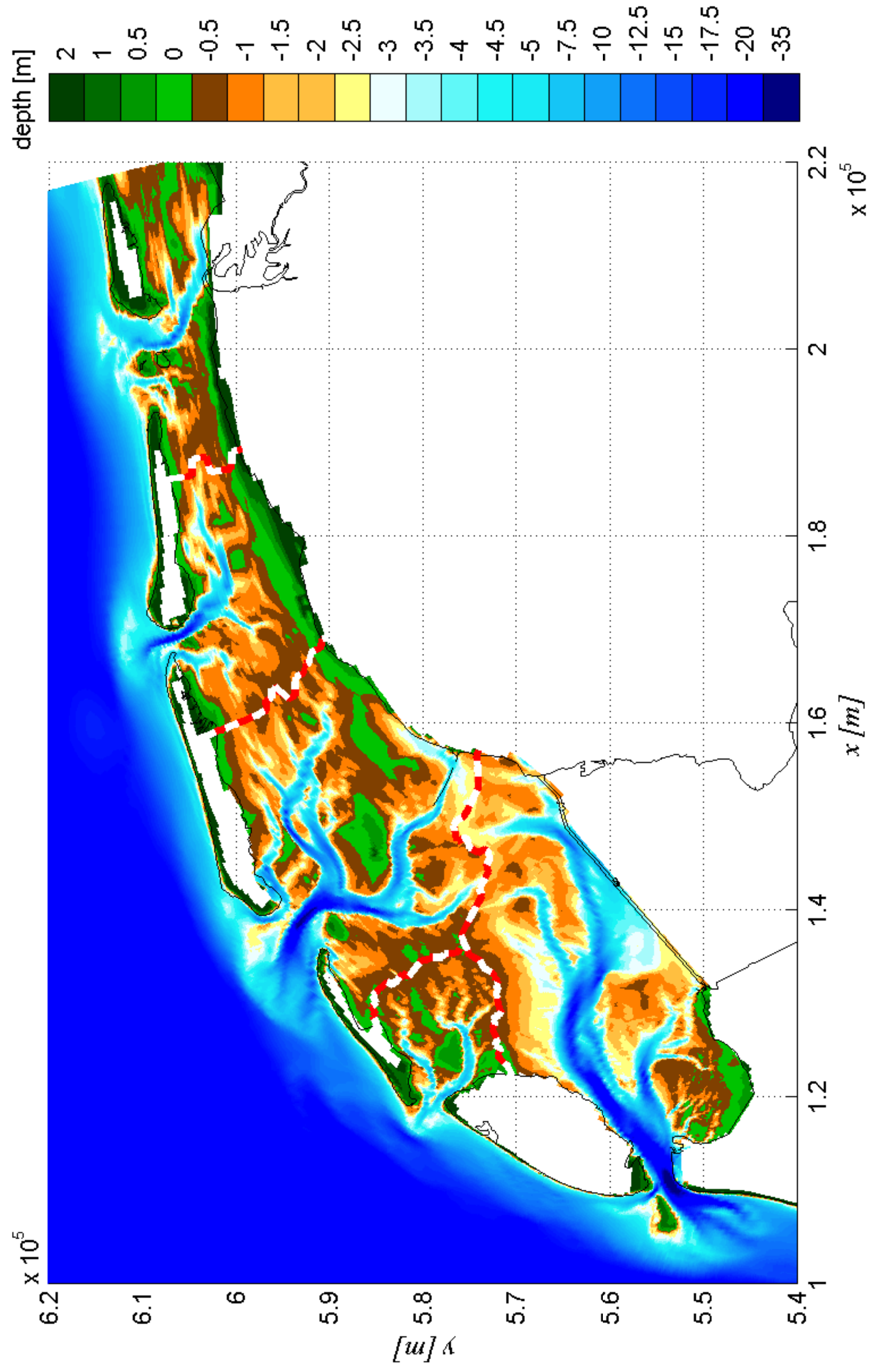
1998 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.11



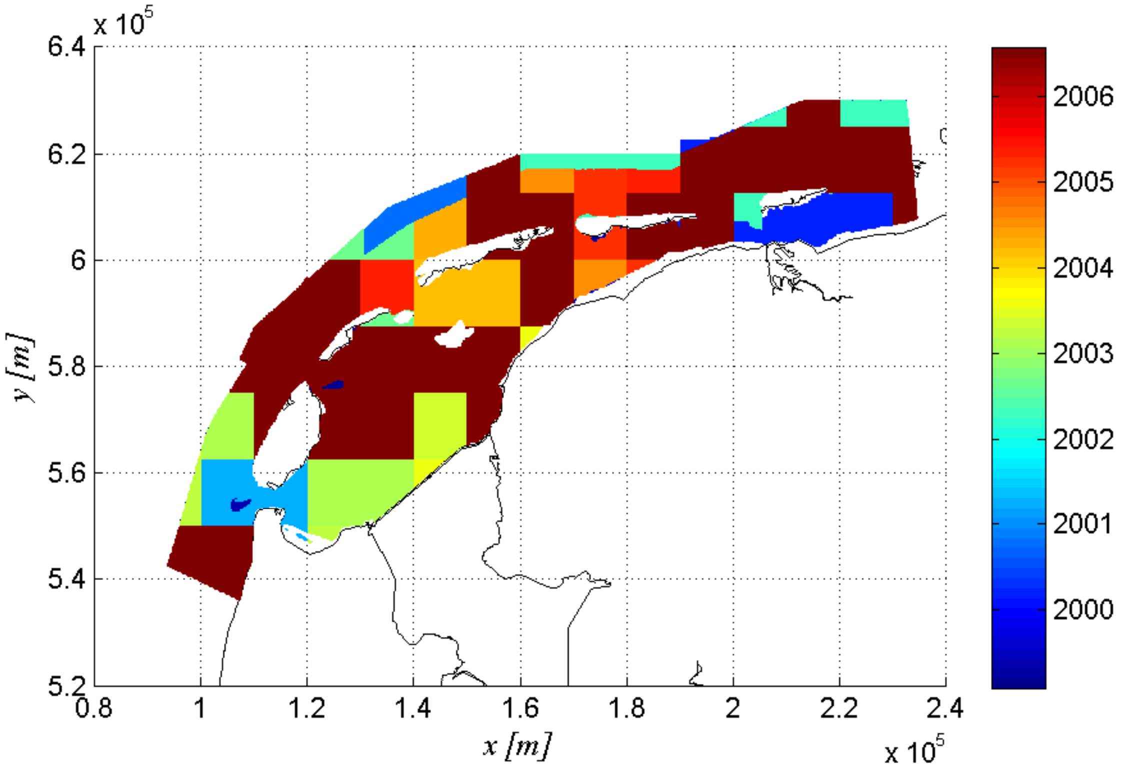


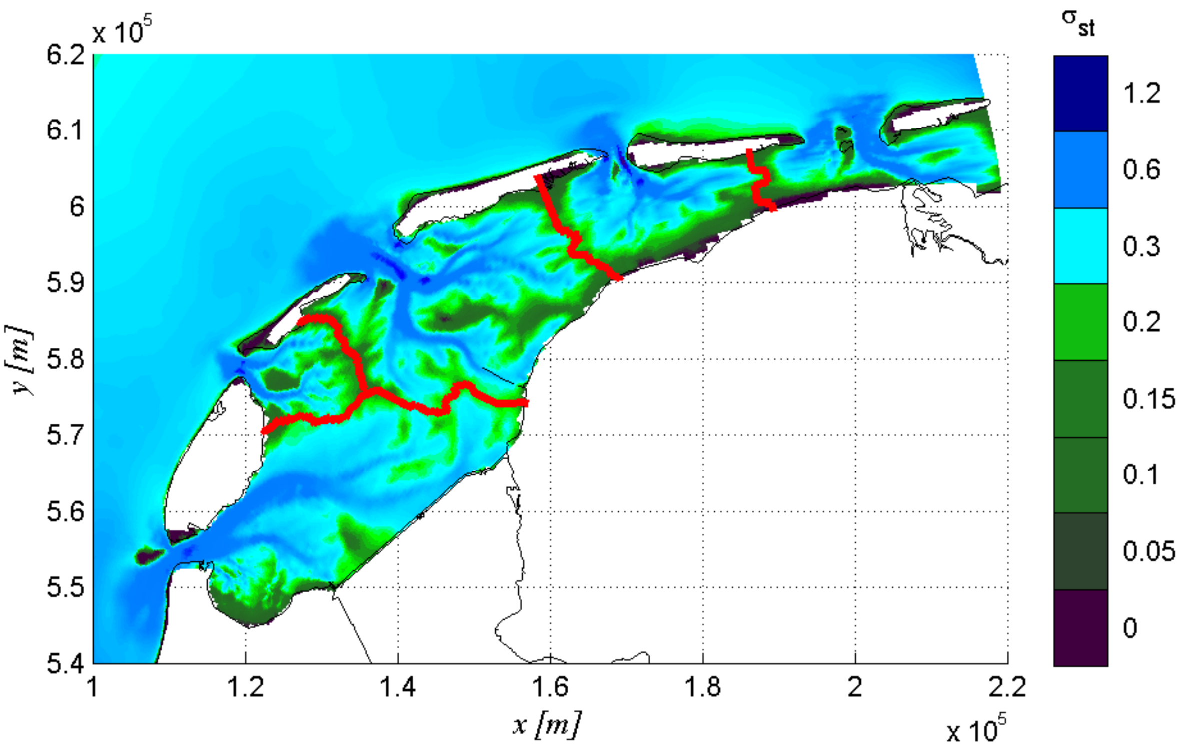
year: 1998
Chronology of measurements forming the bathymetry (upper plot)
Calculated standard deviation and boundaries (lower plot)

year: 1998 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.12



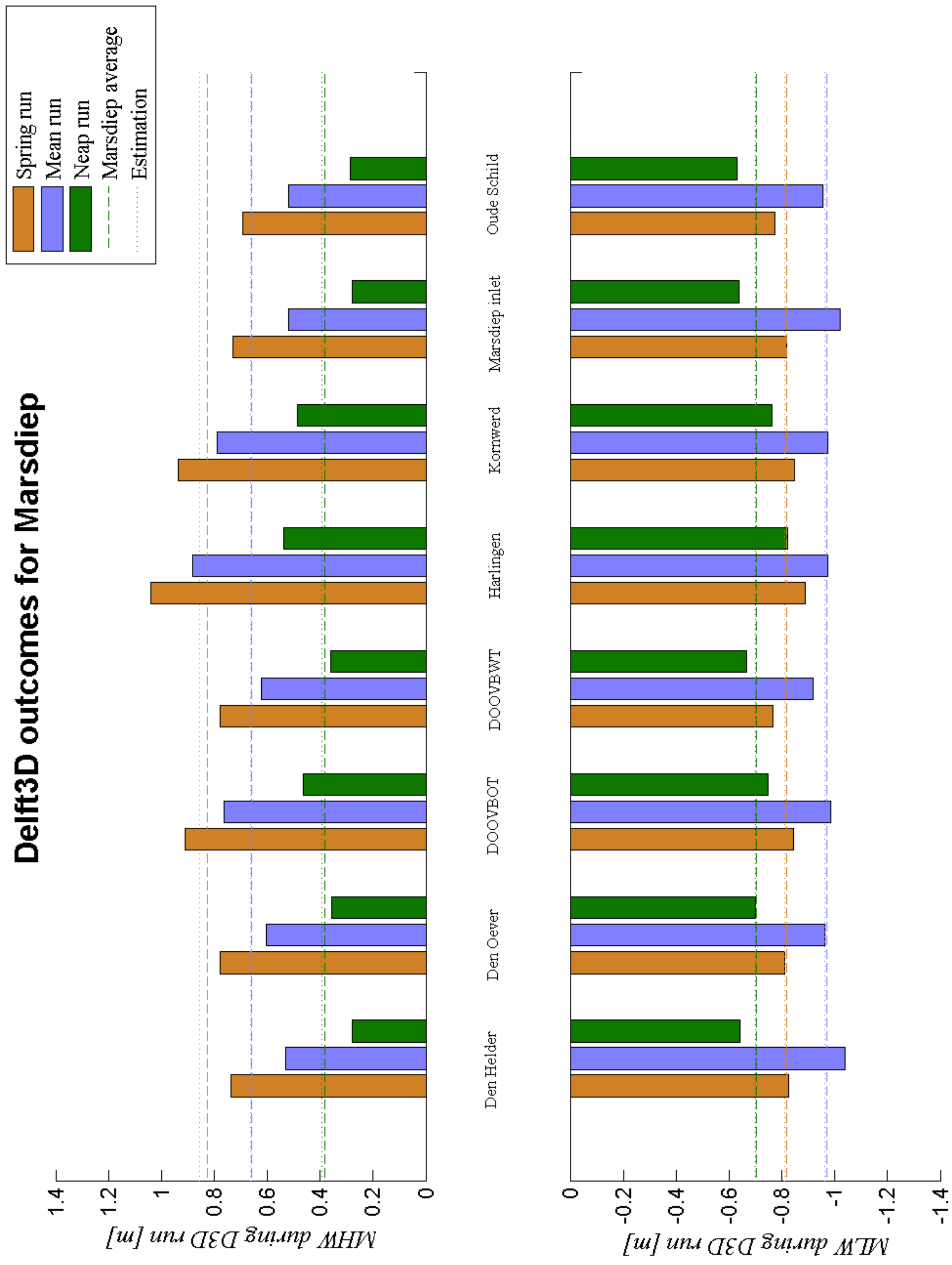
2006 bathymetry constructed with UCIT including boundaries determined using minimal standard deviation of the velocities		Z4169
WL | DELFT HYDRAULICS		Figure: D.13



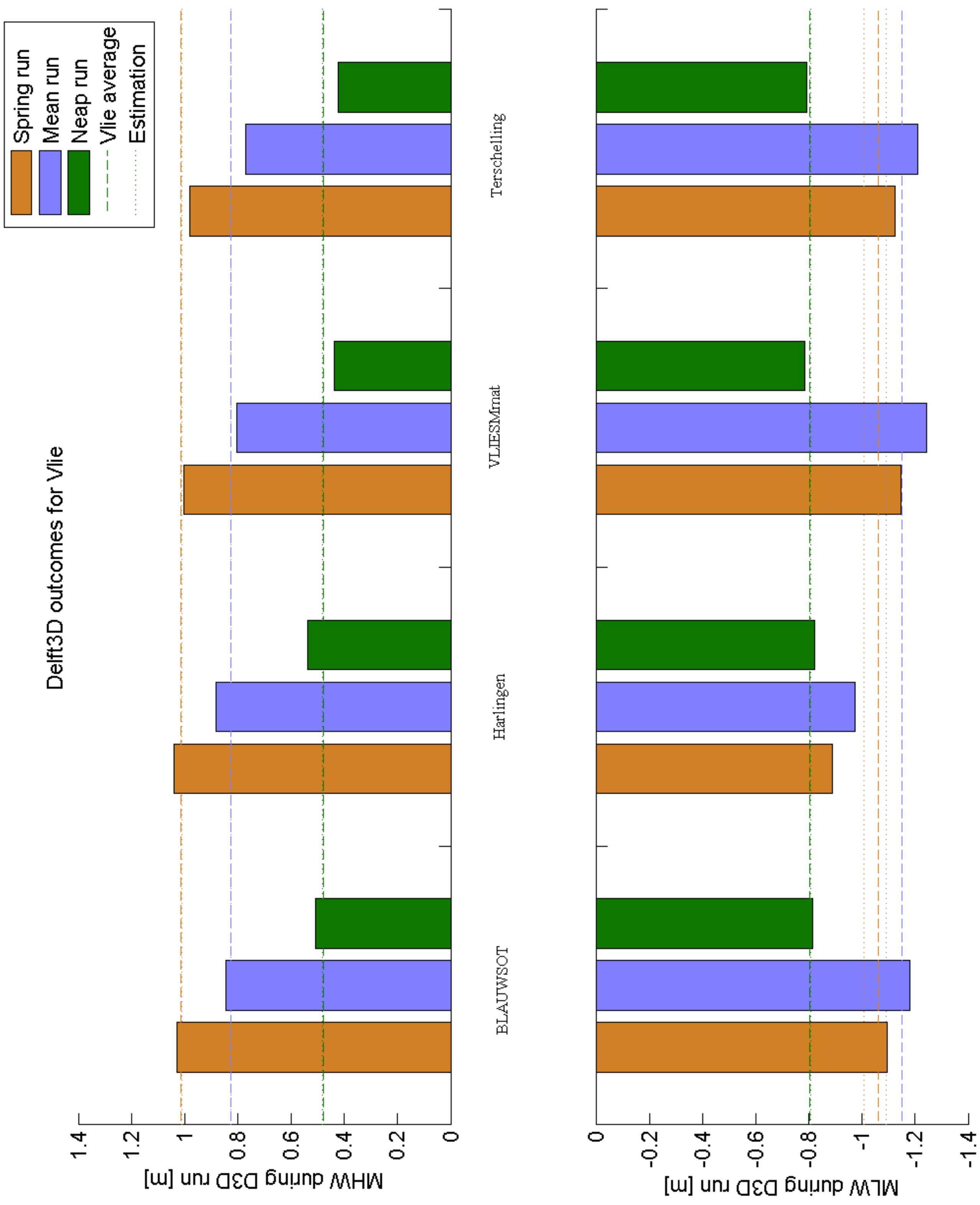


year: 2006 Chronology of measurements forming the bathymetry (upper plot) Calculated standard deviation and boundaries (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure: D.14

E Calculated actual water levels for all basins in the Dutch Wadden Sea

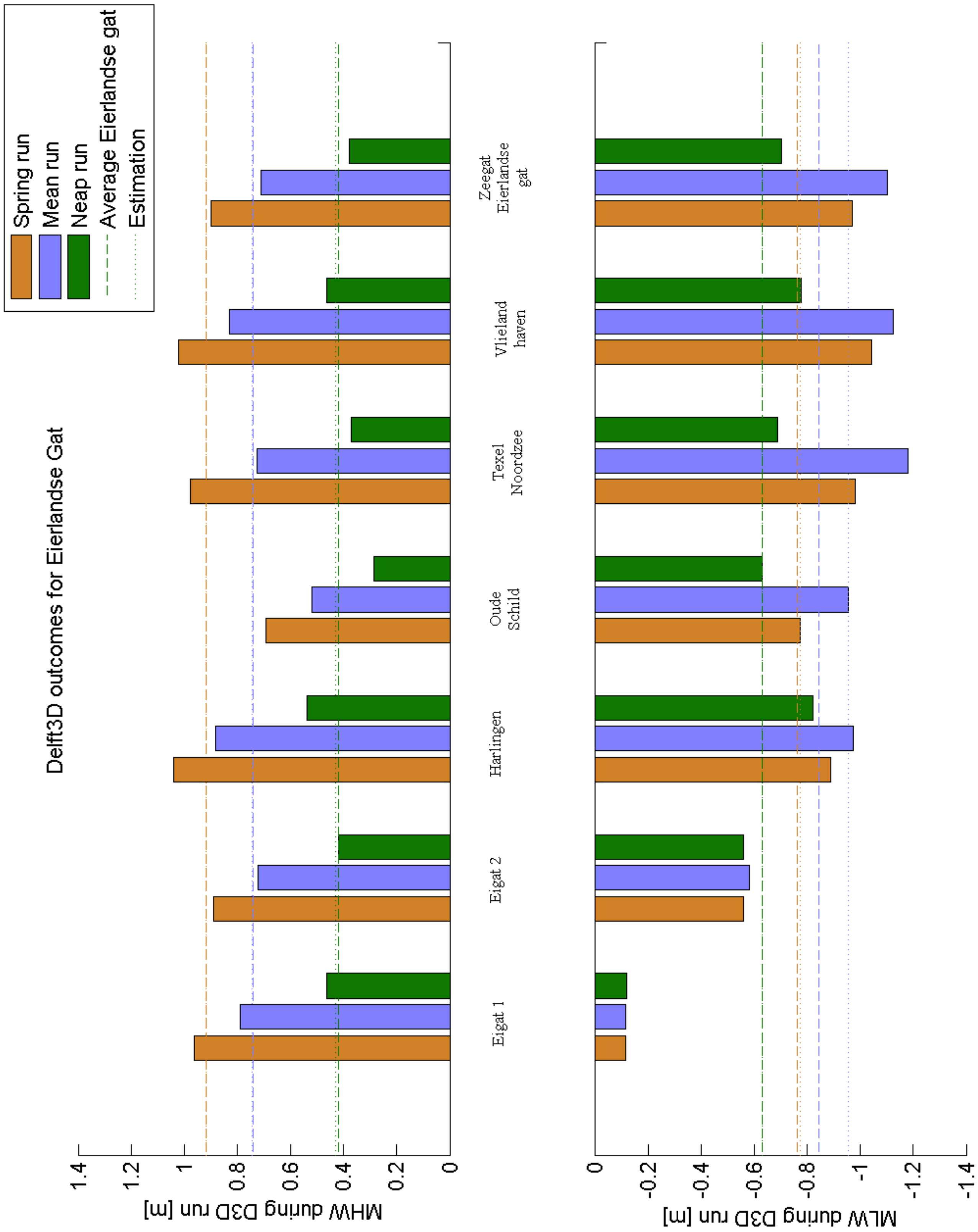


Correlation between simulated water levels at observation points and simulated average water level inside Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure E.1



Correlation between simulated water levels at observation points
and simulated average water level inside Vlie basin

Correlation between simulated water levels at observation points and simulated average water level inside Vlie basin		Z4169
WL | DELFT HYDRAULICS		Figure E.2



Correlation between simulated water levels at observation points and simulated average water level inside Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure E.3

	MLW	MHW	Tidal range
1933	-97.3	56.7	1.54
1951	-92.3	61.2	1.53
1965	-88.3	64.6	1.53
1972	-86.3	66.4	1.53
1977	-84.9	67.6	1.53
1982	-83.5	68.8	1.52
1988	-71.8	70.3	1.52
1991	-81.0	71.0	1.52
1997	-79.3	72.5	1.51
Average in time	-85.0	66.6	1.53

Table E.1: Calculated actual water levels for Marsdiep basin

	MLW	MHW	Tidal range
1933	-85.4	51.2	1.37
1949	-83.6	54.1	1.38
1962	-82.2	56.5	1.39
1973	-80.9	58.6	1.39
1976	-80.6	59.1	1.40
1982	-79.9	60.2	1.40
1987	-79.4	61.1	1.41
1993	-78.7	62.3	1.41
1997	-78.0	63.4	1.41
Average in time	-81.0	58.5	1.40

Table E.2: Calculated actual water levels for Eierlandse gat basin

	MLW	MHW	Tidal range
1933	-98.9	74.8	1.74
1951	-99.1	78.8	1.78
1965	-99.3	81.8	1.81
1972	-99.4	83.4	1.83

1977	-99.5	84.5	1.84
1982	-99.6	85.6	1.85
1988	-99.7	86.9	1.87
1992	-99.7	87.8	1.88
1998	-99.8	89.1	1.89
Average in time	-99.4	83.6	1.83

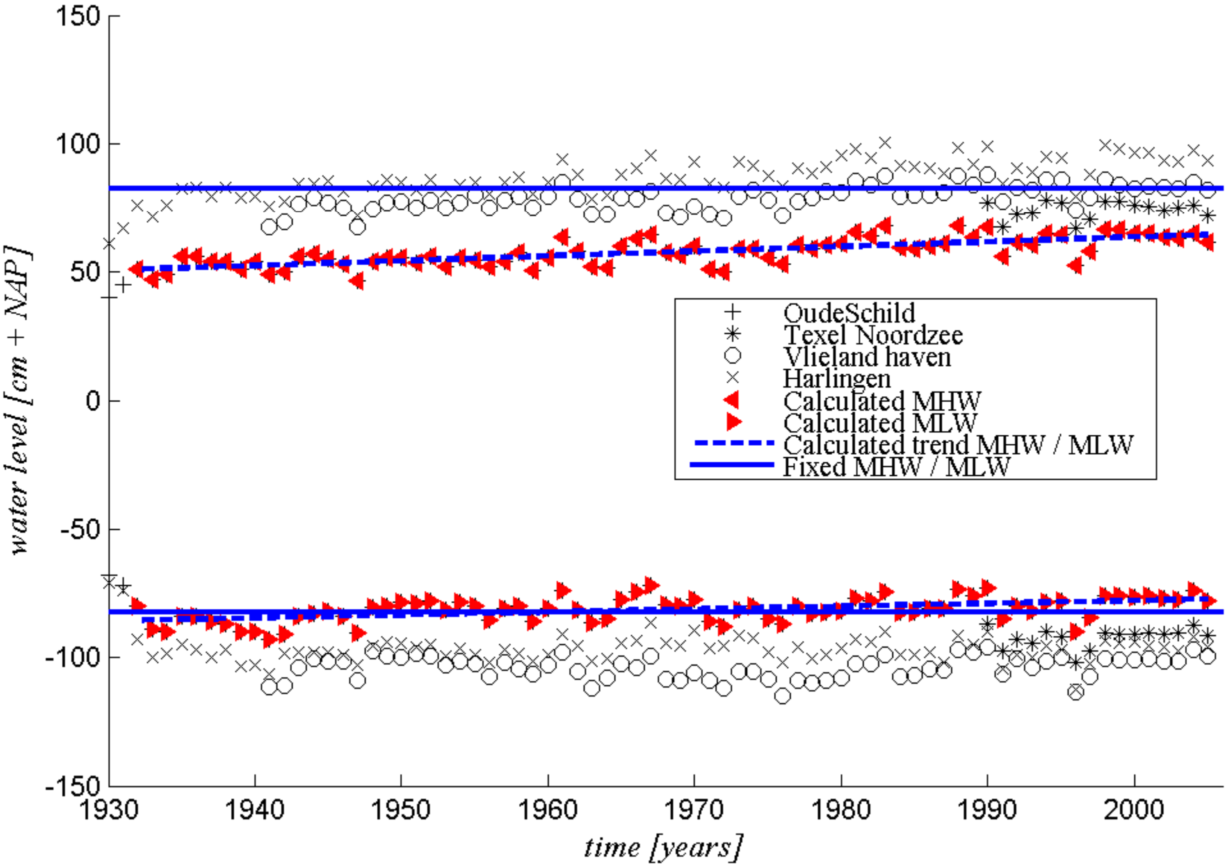
Table E.3: Calculated actual water levels for Vlie basin

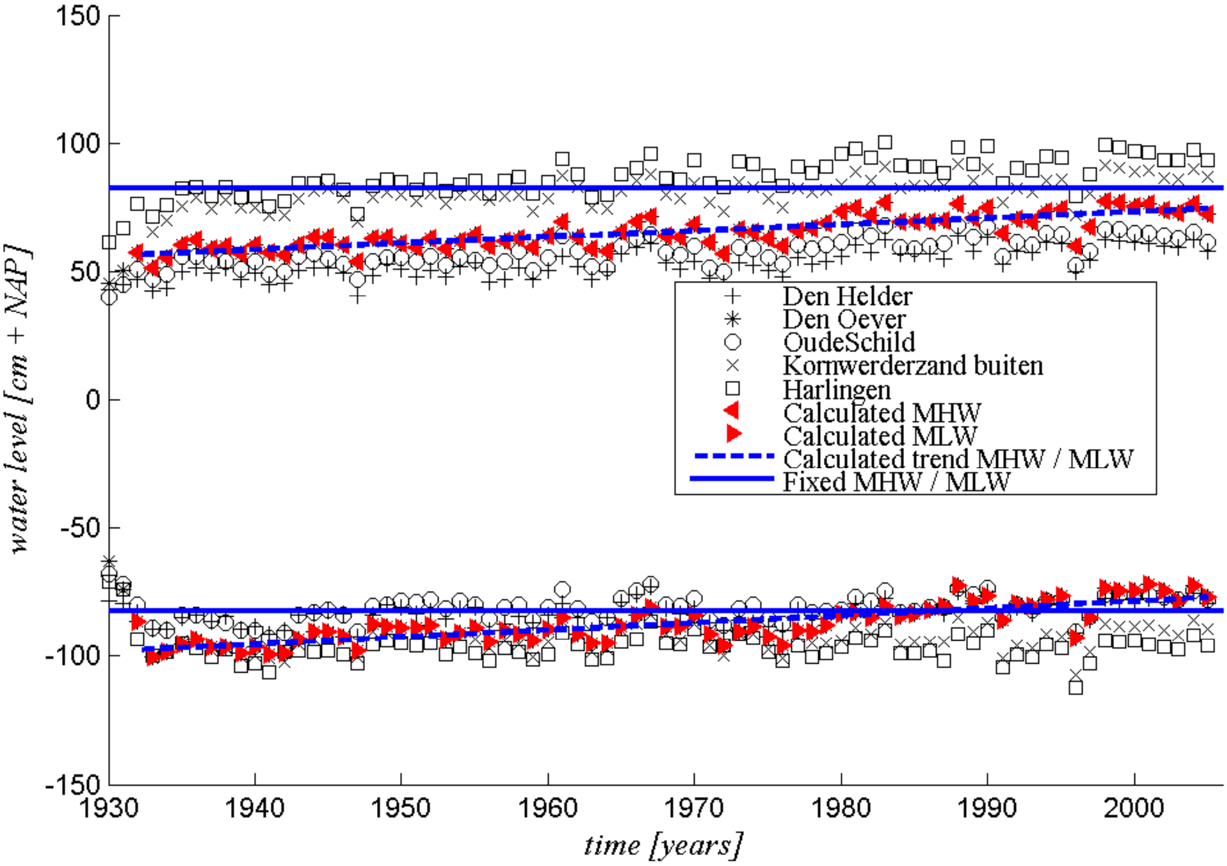
	MLW	**MHW**	**Tidal range**
1967	-125.8	97.1	2.23
1973	-124.6	98.6	2.23
1978	-123.7	100.0	2.24
1984	-122.5	101.6	2.24
1989	-121.5	102.9	2.24
1993	-120.8	103.9	2.25
1999	-119.6	105.5	2.25
Average	-122.6	101.4	2.24

Table E.4: Calculated actual water levels for Amelander zeegat

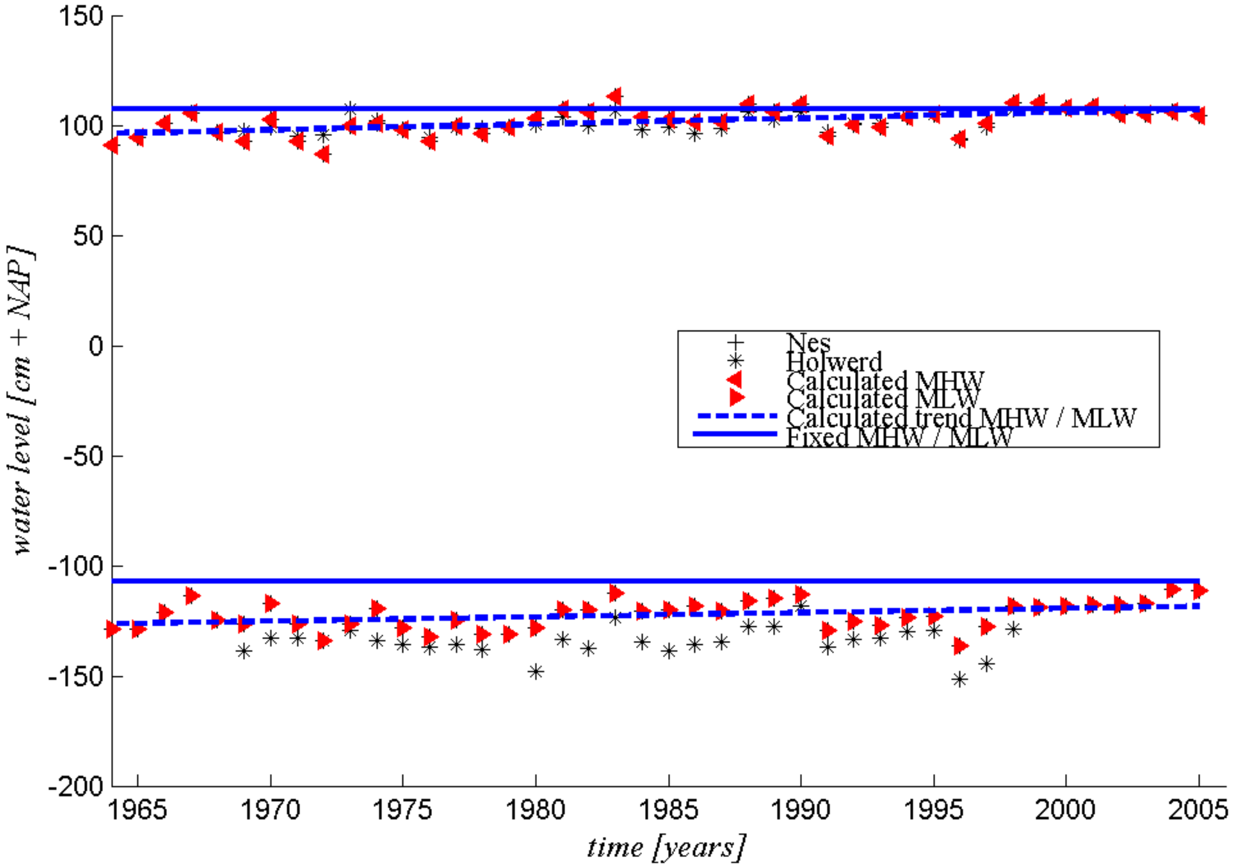
	MLW	**MHW**	**Tidal range**
1970	-131.2	96.3	2.28
1979	-130.2	99.0	2.29
1982	-129.8	99.9	2.30
1987	-129.2	101.5	2.31
1991	-128.8	102.7	2.31
1997	-128.0	104.5	2.32
Average	-129.5	100.7	2.30

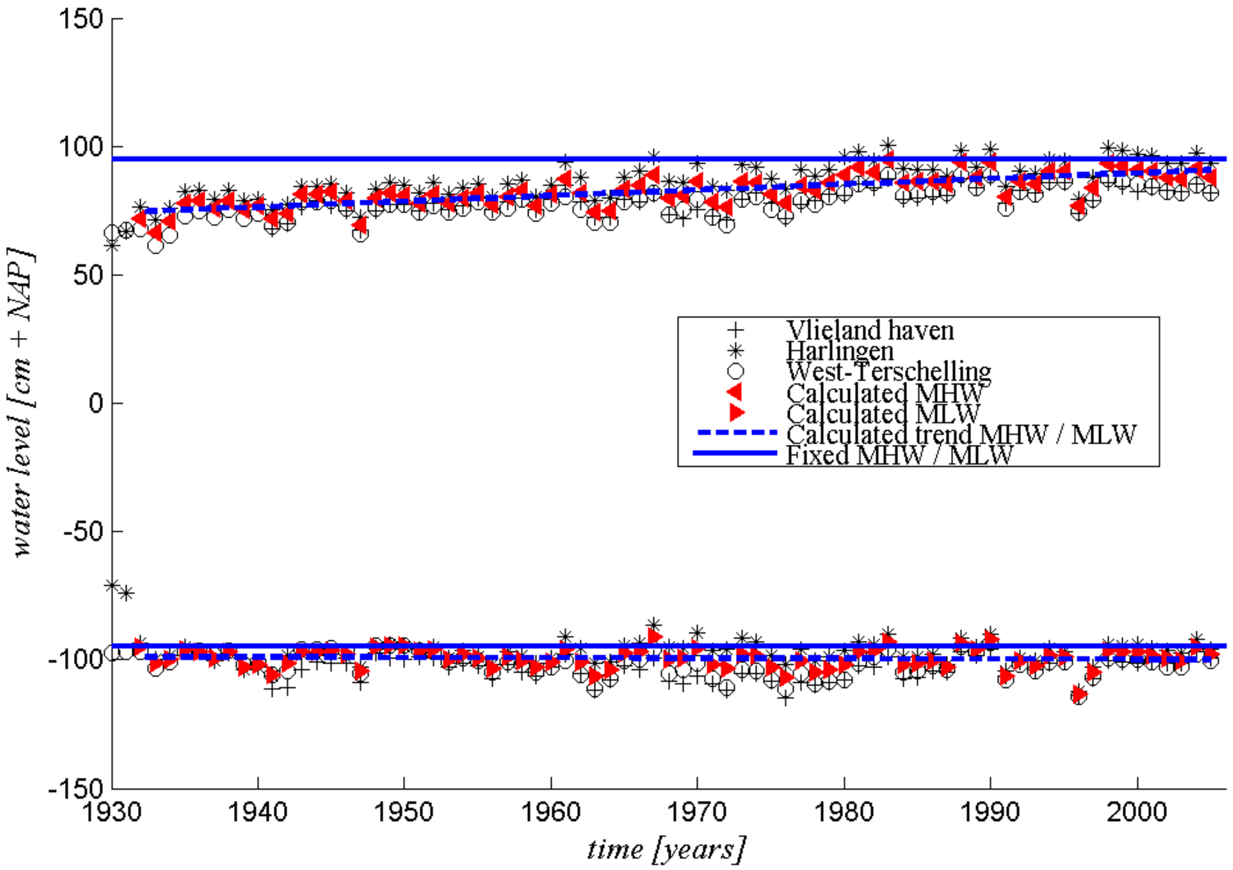
Table E.5: Calculated actual water levels for Friesche zeegat



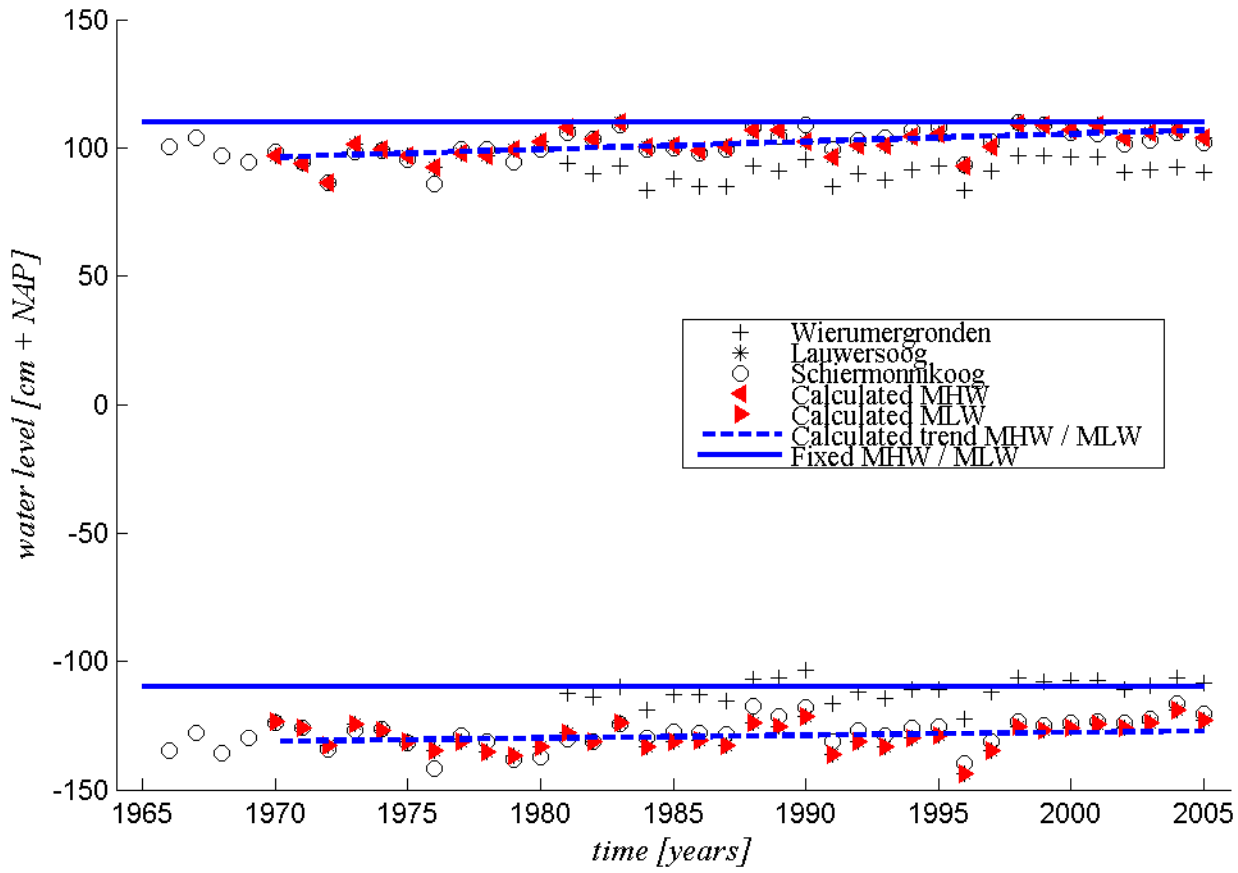


Comparison between calculated actual water levels and water levels measured at individual measurement stations for Marsdiep (upper plot) and Eierlandse gat (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure E.4



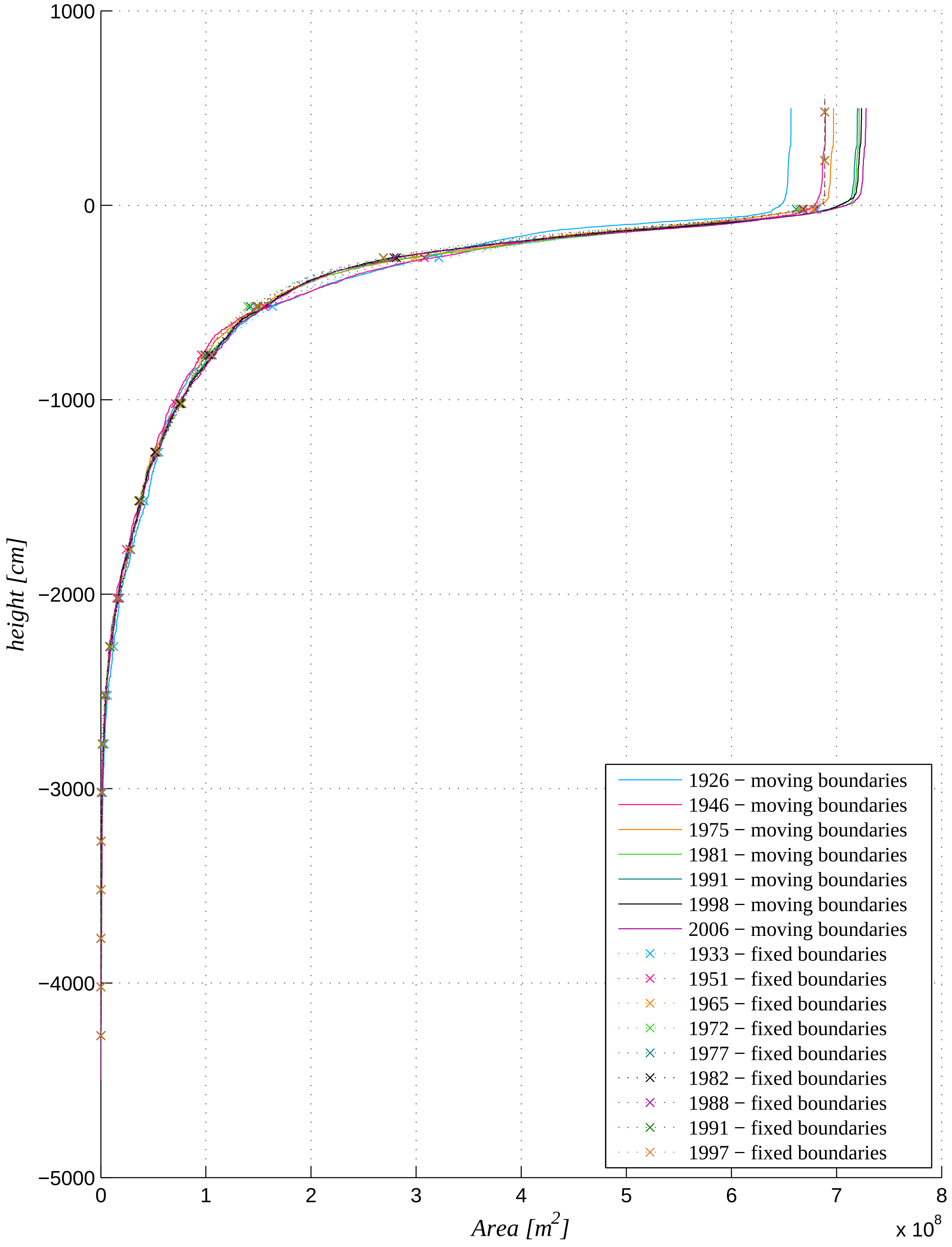


Comparison between calculated actual water levels and water levels measured at individual measurement stations for Vlie (upper plot) and Amelander zeegat (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure E.5

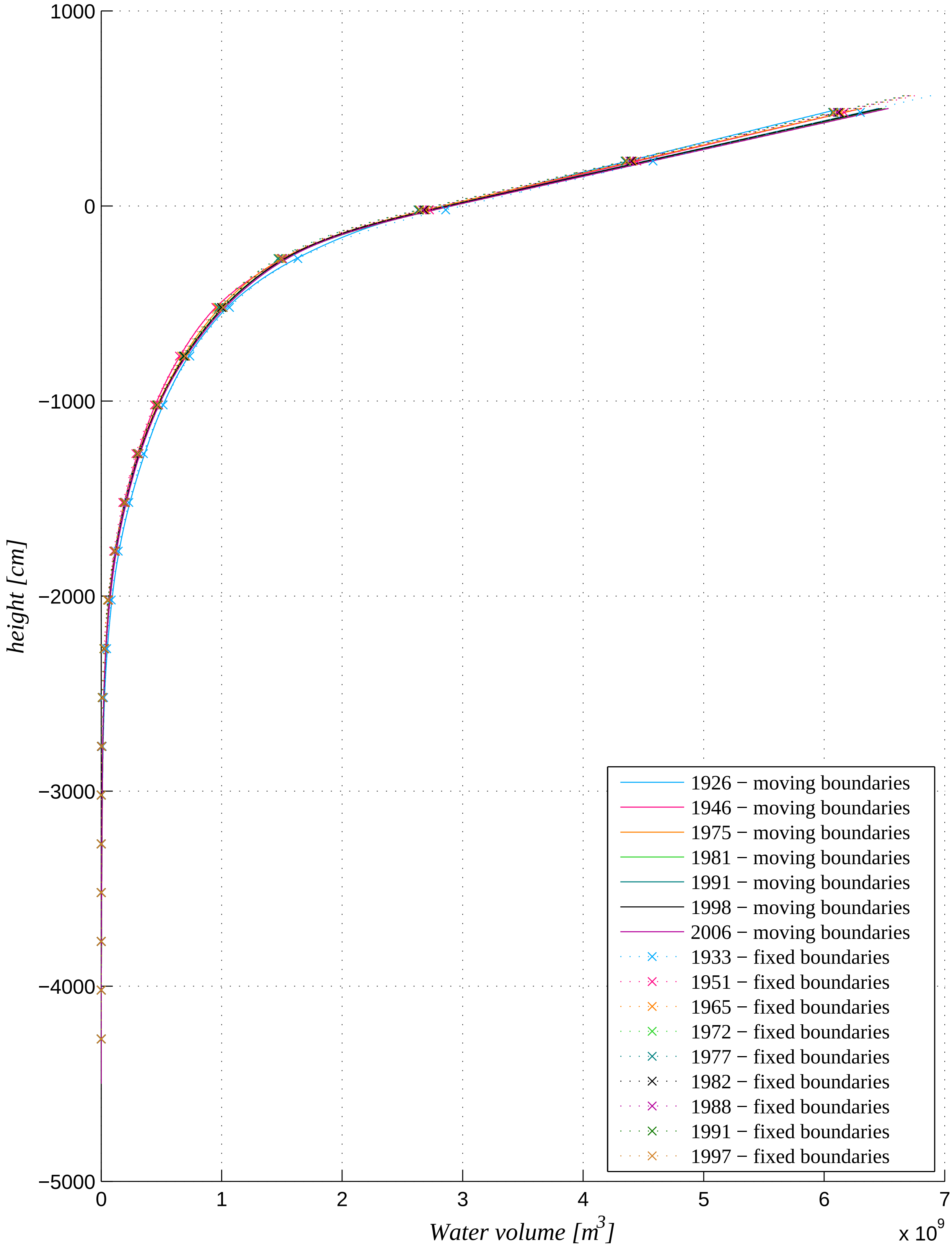


Comparison between calculated actual water levels and water levels measured at individual measurement stations for Friesche zeegat		Z4169
WL | DELFT HYDRAULICS		Figure E.6

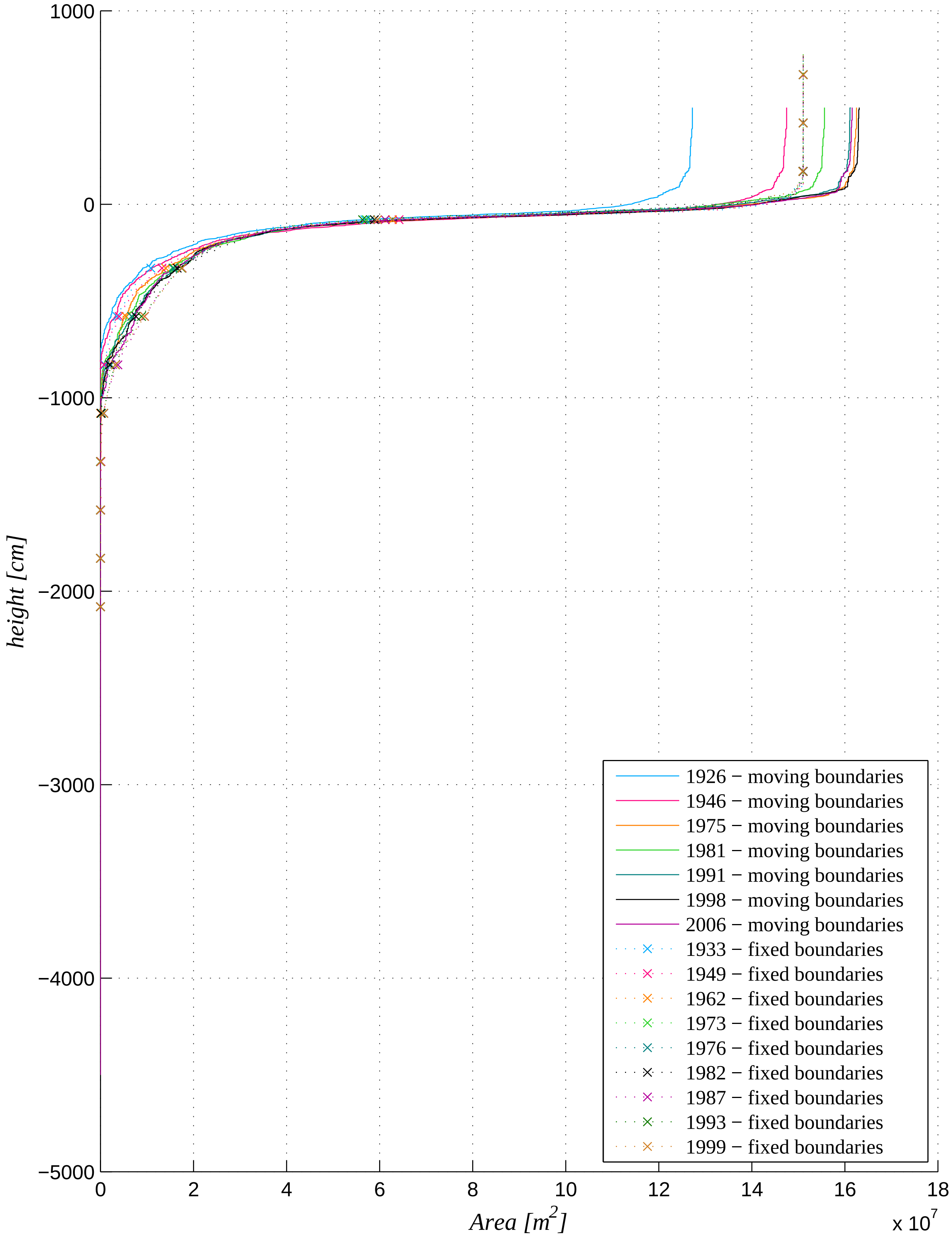
F Hypsometric curves of the basins in the Dutch Wadden Sea



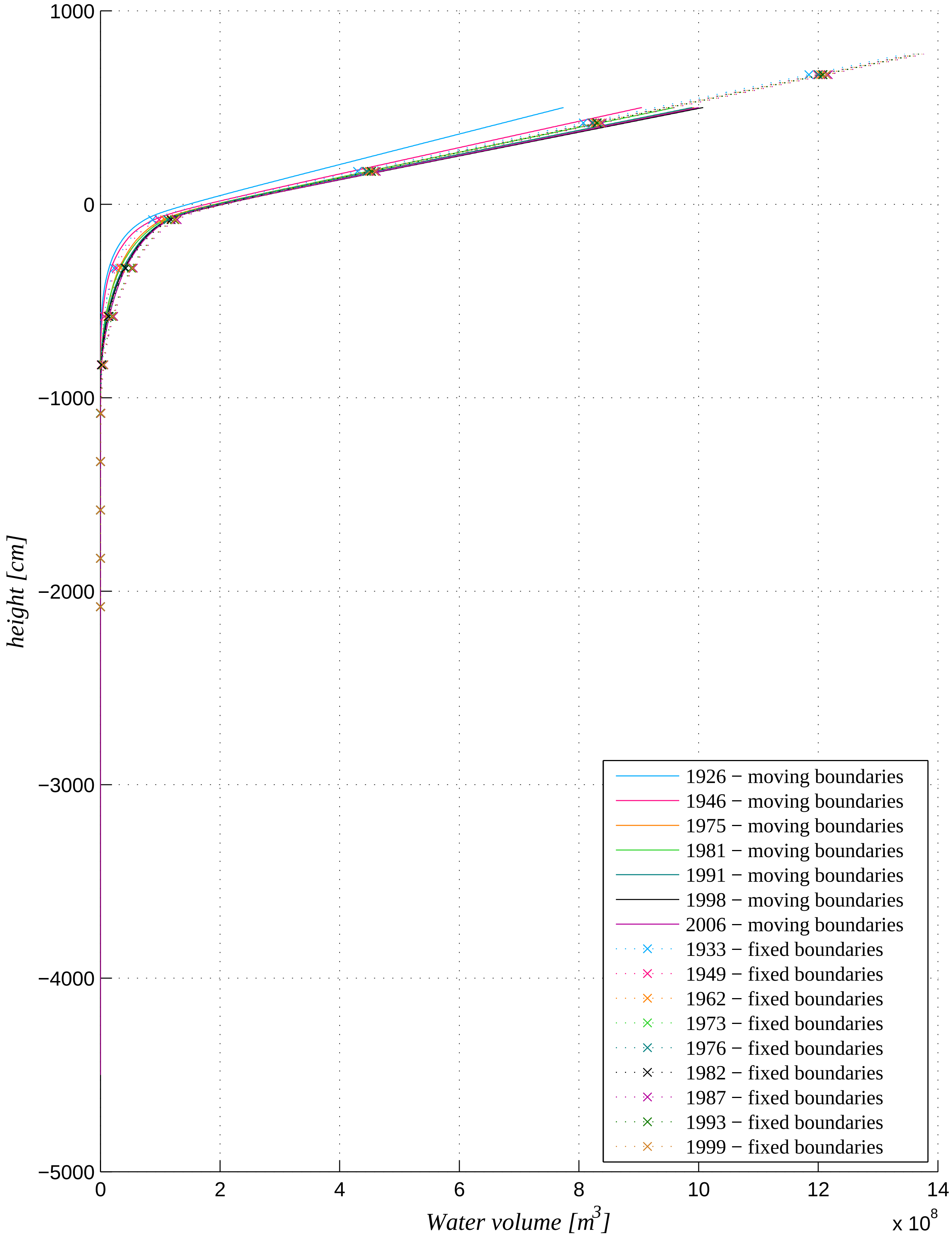
Hypsometries of the cumulative area inside Marsdiep basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.1



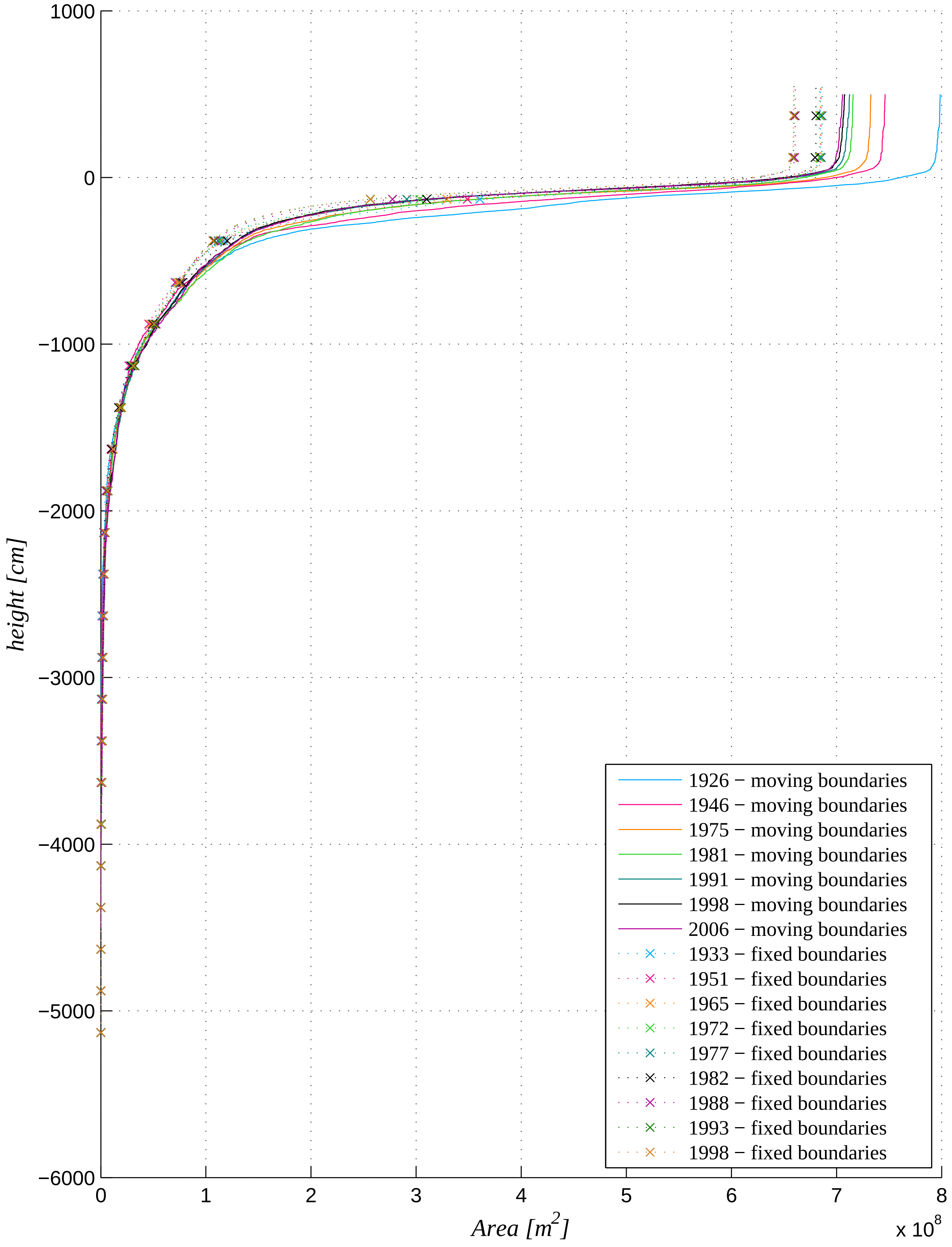
Hypsometries of the cumulative volume inside Marsdiep basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.2



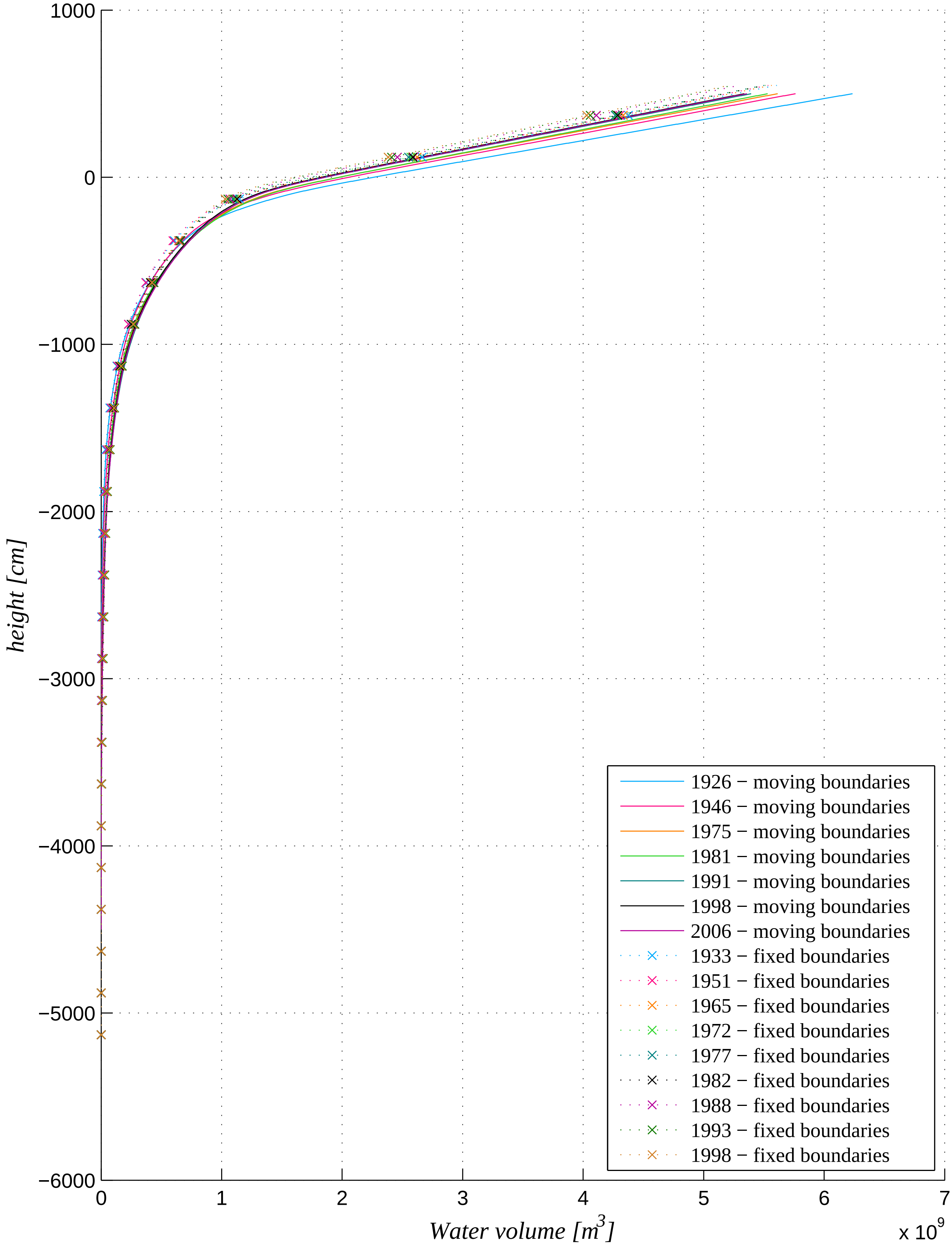
Hypsometries of the cumulative area inside Eierlandse gat basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.3



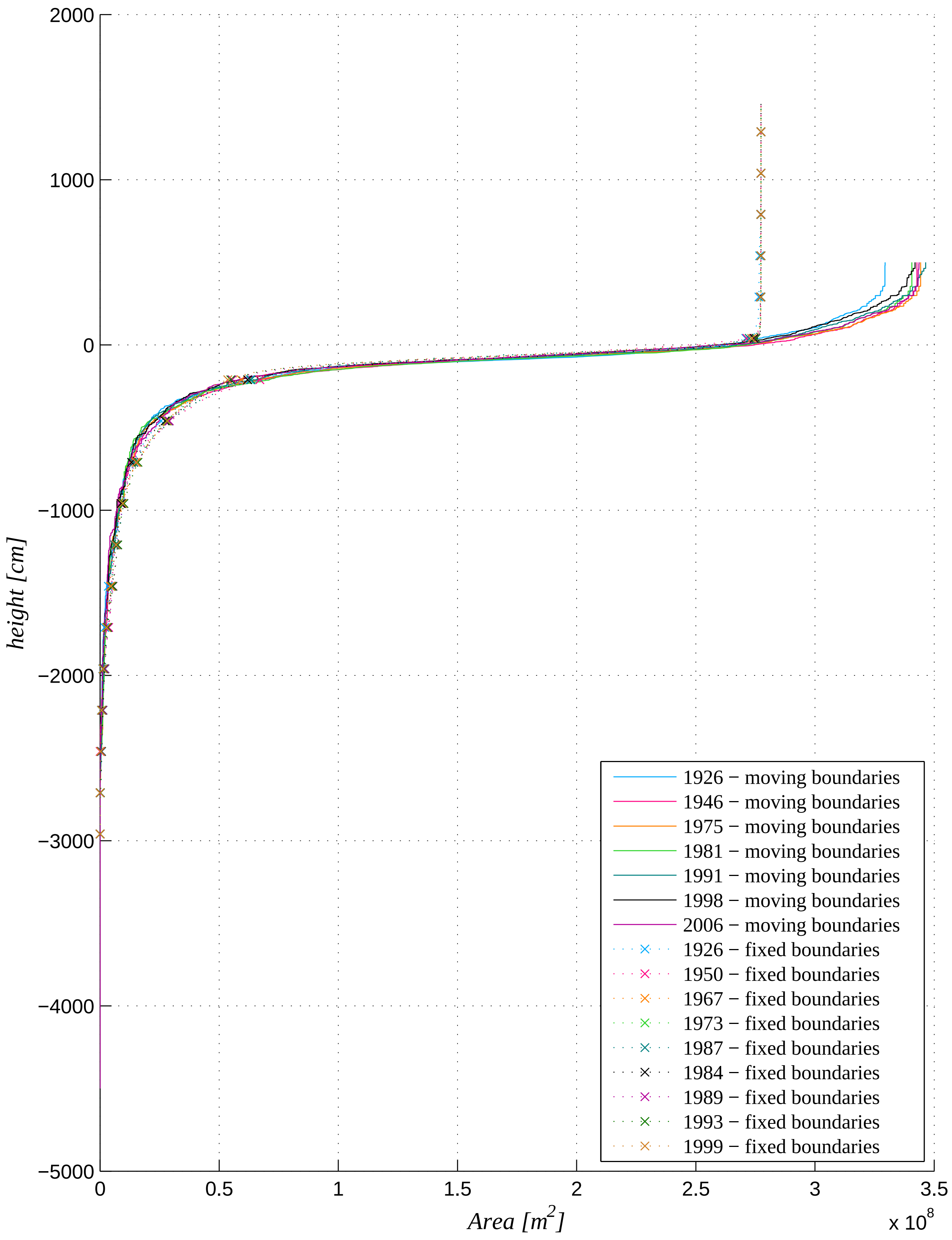
Hypsometries of the cumulative volume inside Eierlandse gat basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.4



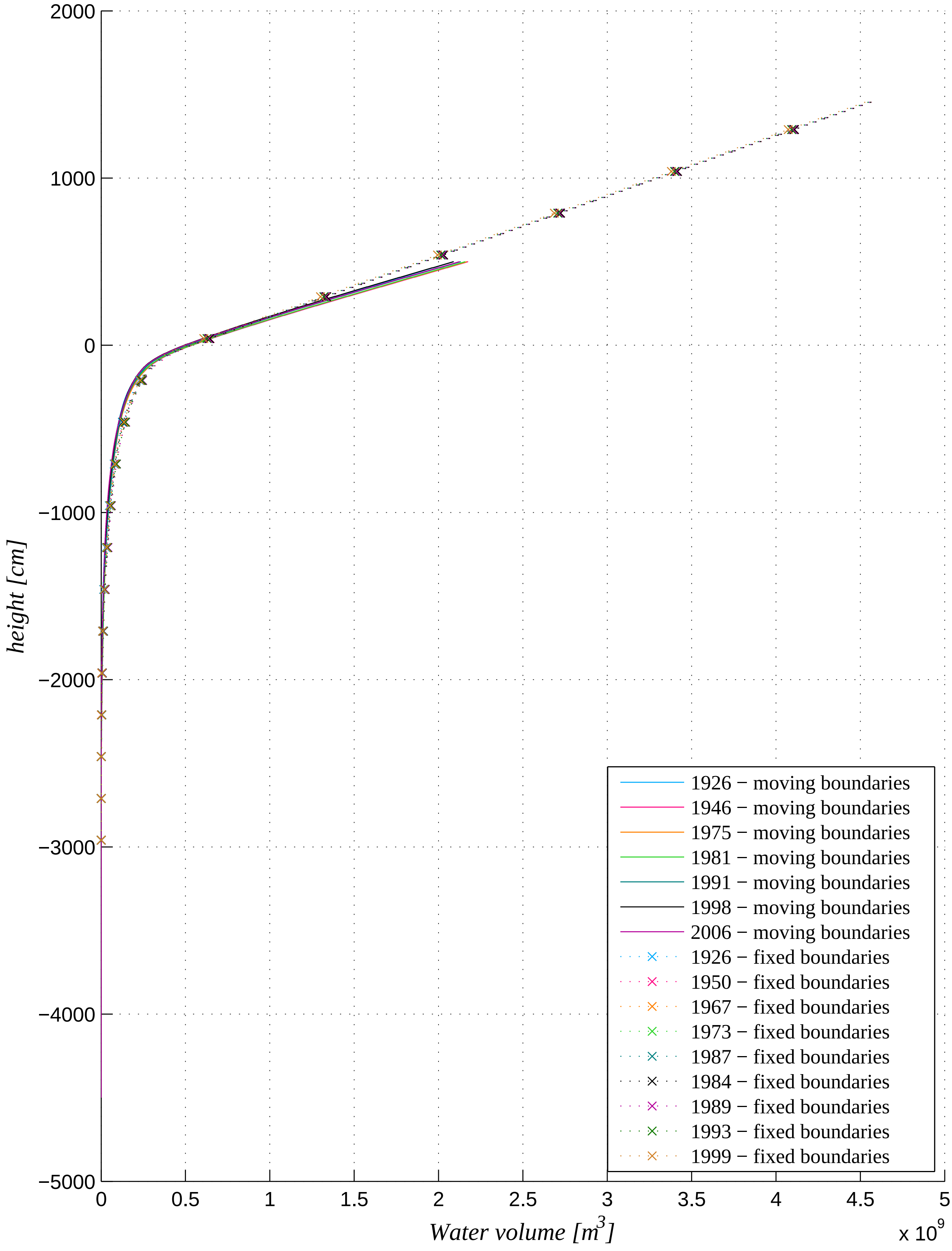
Hypsometries of the cumulative area inside Vlie basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.5



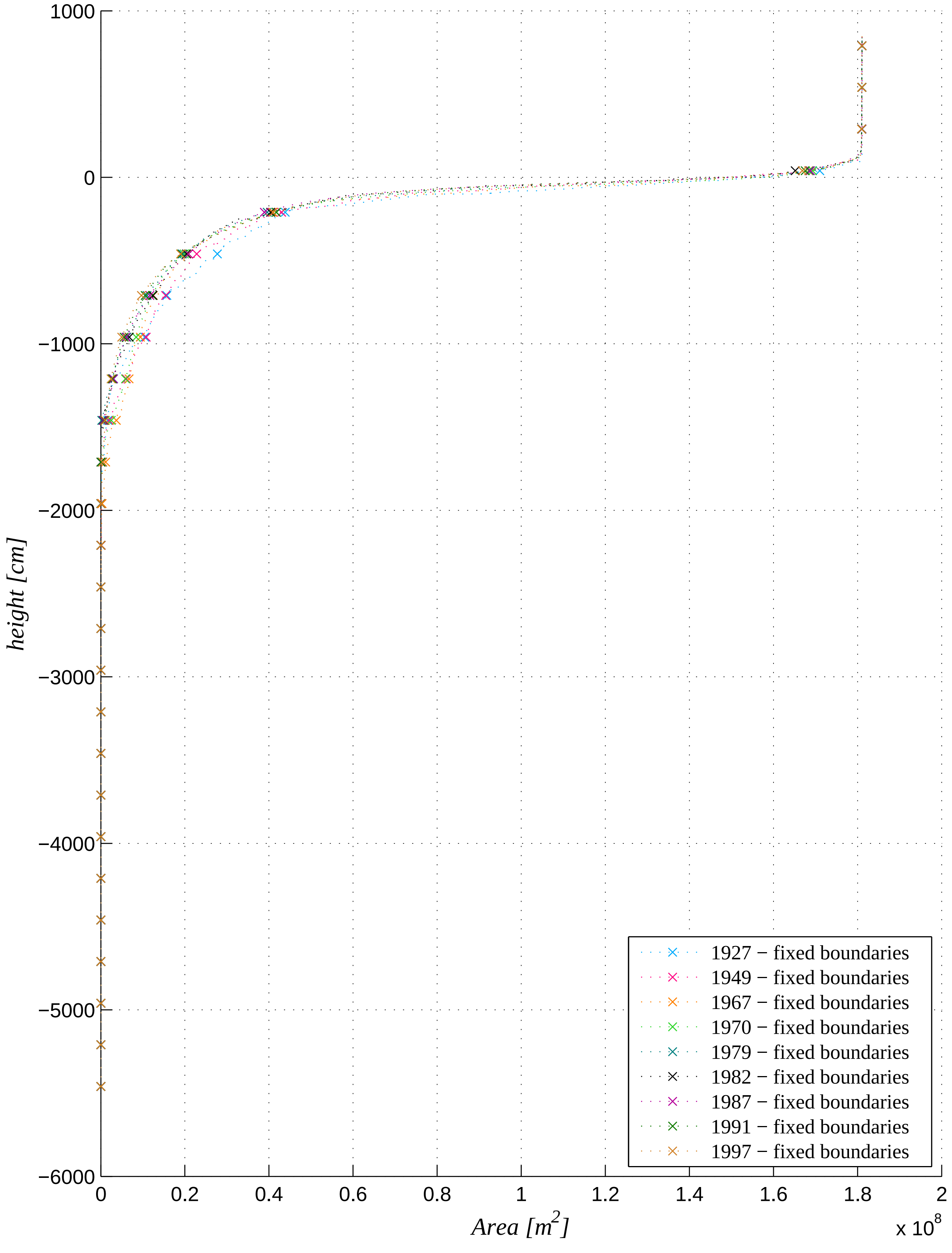
Hypsometries of the cumulative volume inside Vlie basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.6



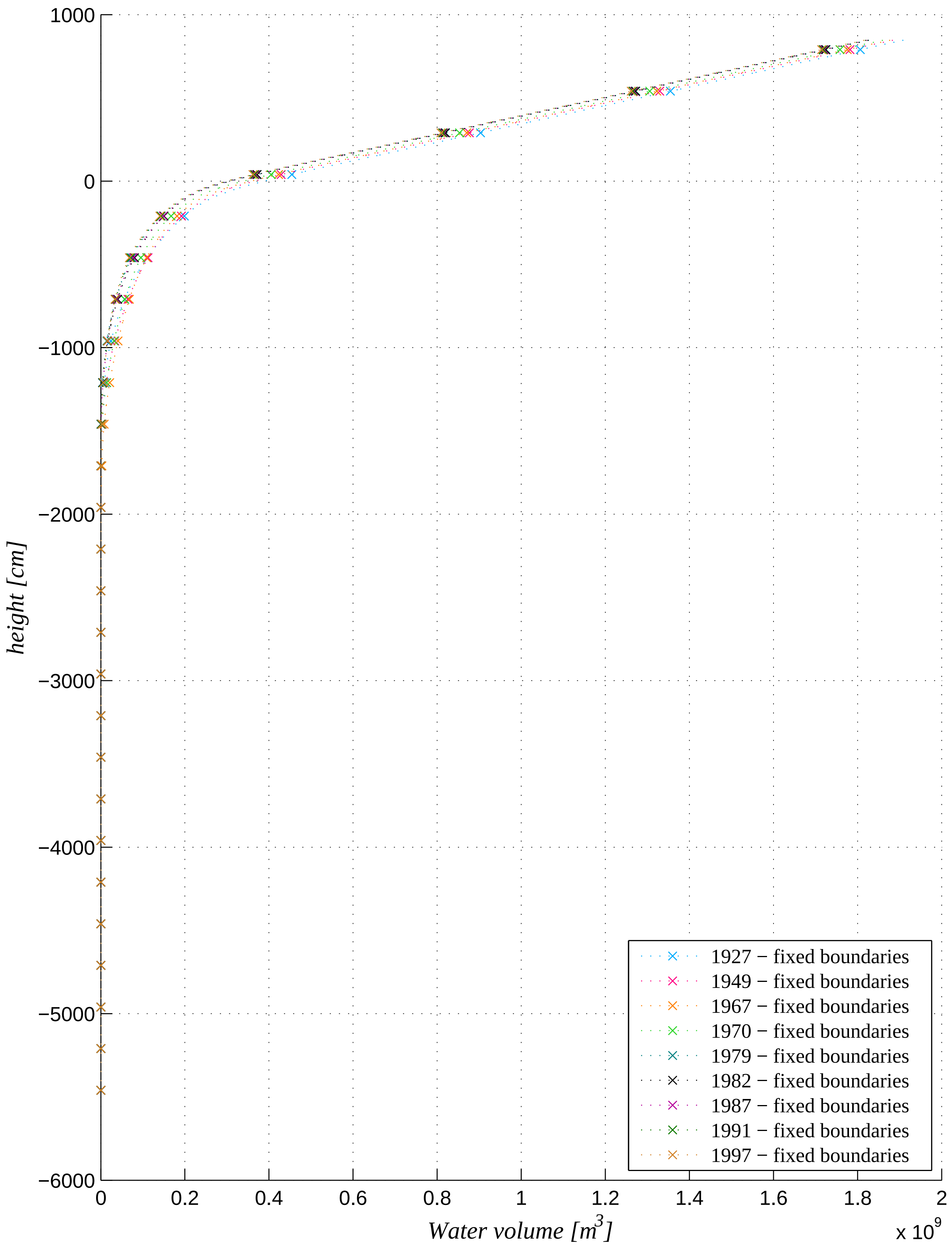
Hypsometries of the cumulative area inside Ameland basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.7



Hypsometries of the cumulative volume inside Ameland basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.8



Hypsometries of the cumulative area inside Friesche zeegat basin for various years between 1926 and 2006 using fixed and actual boundaries		Z4169
WL | DELFT HYDRAULICS		Figure F.9



Hypsometries of the cumulative volume inside Friesche zeegat basin for various years between 1926 and 2006 using fixed and actual boundaries	Z4169
WL | DELFT HYDRAULICS	Figure F.10

G Basin characteristics resulting from data analysis

Characteristics analyzed with fixed boundaries and fixed water levels

time [years]	Vc [m^3] (10^8)	Vf [m^3] (10^6)	Ac [m^2] (10^8)	Af [m^2] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1933	25,40	6,10	6,33	5,57	4,01	0,11	9,24
1951	24,07	7,14	6,35	5,34	3,79	0,13	9,23
1965	23,79	10,59	6,28	6,12	3,79	0,17	9,19
1972	23,31	19,39	6,12	7,65	3,81	0,25	9,10
1977	23,26	22,14	6,05	8,34	3,84	0,27	9,08
1982	23,71	15,85	6,19	6,98	3,83	0,23	9,14
1988	23,62	18,86	6,09	7,99	3,88	0,24	9,11
1991	23,31	20,06	6,08	8,05	3,83	0,25	9,10
1997	23,36	20,43	6,11	7,80	3,83	0,26	9,09

Table 6.1: Marsdiep: calculated basin characteristics with fixed boundaries and fixed water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1933	8,53	3,34	5,69	9,27	1,50	0,36	2,13
1949	9,61	3,20	6,42	8,64	1,50	0,37	2,17
1962	10,54	3,51	6,28	8,76	1,68	0,40	2,13
1973	11,04	4,36	5,72	9,27	1,93	0,47	2,04
1976	11,14	4,39	5,81	9,17	1,92	0,48	2,03
1982	11,62	4,22	5,89	9,11	1,97	0,46	2,05
1987	12,66	4,31	5,92	9,03	2,14	0,48	2,04
1993	12,22	4,67	5,46	9,49	2,24	0,49	2,00
1999	12,34	4,22	5,74	9,20	2,15	0,46	2,04

Table 6.2: Eierlandse gat: calculated basin characteristics with fixed boundaries and fixed water levels

time [years]	Vc [m^3] (10^9)	Vf [m^3] (10^8)	Ac [m^2] (10^8)	Af [m2] (10^8)	hc [m]	hf [m]	P [m^3] (10^9)
1933	1,29	0,99	4,68	2,16	2,76	0,46	1,20
1951	1,24	1,27	4,46	2,39	2,79	0,53	1,17
1965	1,26	1,08	4,46	2,38	2,82	0,45	1,19

1972	1,23	1,24	4,06	2,75	3,03	0,45	1,17
1977	1,21	1,33	3,94	2,90	3,08	0,46	1,17
1982	1,25	1,25	4,08	2,70	3,08	0,46	1,16
1988	1,18	1,42	3,70	2,90	3,20	0,49	1,11
1992	1,16	1,59	3,39	3,18	3,41	0,50	1,09
1998	1,13	1,63	3,36	3,21	3,37	0,51	1,08

Table 6.3: Vlie: calculated basin characteristics with fixed boundaries and fixed water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1926	31,43	8,35	12,68	14,84	2,48	0,56	5,08
1950	33,74	9,88	12,44	15,22	2,71	0,65	4,96
1967	32,22	8,66	12,01	15,68	2,68	0,55	5,09
1973	32,97	9,78	11,71	15,95	2,81	0,61	4,97
1978	32,97	9,78	11,71	15,95	2,81	0,61	4,97
1984	32,09	8,40	12,85	14,84	2,50	0,57	5,12
1989	32,27	9,41	11,34	16,36	2,85	0,58	5,01
1993	31,60	9,63	10,81	16,90	2,92	0,57	4,99
1999	30,47	10,42	10,55	17,14	2,89	0,61	4,91

Table 6.4: Amelander zeegat: calculated basin characteristics with fixed boundaries and fixed water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1927	25,72	7,76	7,60	10,50	3,38	0,74	3,21
1949	24,81	9,39	7,06	10,98	3,51	0,86	3,03
1967	23,38	8,29	7,24	10,67	3,23	0,78	3,11
1970	21,93	8,67	6,72	11,24	3,26	0,77	3,09
1979	19,35	9,45	6,22	11,75	3,11	0,80	3,01
1982	19,92	9,90	5,72	12,15	3,48	0,82	2,94
1987	19,63	9,82	5,92	11,90	3,31	0,83	2,94
1991	19,35	9,97	6,16	11,74	3,14	0,85	2,94
1997	18,99	10,03	6,11	11,81	3,11	0,85	2,94

Table 6.5: Friesche zeegat: calculated basin characteristics with fixed boundaries and fixed water levels

Characteristics analyzed with fixed boundaries and actual water levels

time [years]	Vc [m^3] (10^8)	Vf [m^3] (10^7)	Ac [m^2] (10^8)	Af [m^2] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1933	23,70	4,26	5,58	13,11	4,25	0,33	10,18
1951	22,62	3,66	5,79	10,98	3,91	0,33	10,20
1965	22,58	3,39	5,92	9,70	3,82	0,35	10,19
1972	22,24	4,85	5,77	11,18	3,86	0,43	10,03
1977	22,26	4,29	5,73	11,53	3,88	0,37	10,07
1982	22,75	3,27	5,81	10,73	3,91	0,30	10,16
1988	22,78	3,96	5,82	10,63	3,91	0,37	10,08
1991	22,54	3,93	5,79	11,00	3,89	0,36	10,08
1997	22,70	3,59	5,90	9,89	3,85	0,36	10,10

Table 6.6: Marsdiep: calculated basin characteristics with fixed boundaries and actual water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^3] (10^7)	Af [m^3] (10^7)	hc [m]	hf [m]	P [m^3] (10^8)
1933	8,42	3,59	5,69	9,17	1,48	0,39	1,67
1949	9,55	3,17	6,42	8,50	1,49	0,37	1,74
1962	10,61	3,38	6,28	8,67	1,69	0,39	1,74
1973	11,15	4,18	5,72	9,22	1,95	0,45	1,67
1976	11,26	4,25	5,81	9,14	1,94	0,47	1,66
1982	11,80	4,03	5,89	9,05	2,00	0,45	1,69
1987	12,90	4,14	6,31	8,62	2,05	0,48	1,68
1993	12,44	4,37	5,83	9,08	2,14	0,48	1,66
1999	12,64	3,88	6,18	8,69	2,05	0,45	1,71

Table 6.7: Eierlandse gat: calculated basin characteristics with fixed boundaries and actual water levels

time [years]	Vc [m^3] (10^8)	Vf [m^3] (10^8)	Ac [m2] (10^8)	Af [m2] (10^8)	hc	hf	P [m^3] (10^9)
1933	12,73	1,05	4,68	2,16	2,72	0,49	1,08
1951	12,27	1,31	4,46	2,36	2,75	0,56	1,08
1965	12,40	1,18	4,46	2,38	2,78	0,50	1,12
1972	12,14	1,39	4,06	2,74	2,99	0,51	1,10

1977	11,94	1,45	3,60	3,23	3,32	0,45	1,11
1982	12,34	1,31	3,80	2,97	3,25	0,44	1,12
1988	11,64	1,53	3,53	3,07	3,30	0,50	1,08
1992	11,39	1,72	3,23	3,34	3,52	0,51	1,06
1998	11,16	1,79	3,22	3,35	3,47	0,53	1,06

Table 6.8: Vlie: calculated basin characteristics with fixed boundaries and actual water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^8)
1967	29,43	11,48	10,28	17,21	2,86	0,67	4,98
1973	31,78	12,69	10,81	16,84	2,94	0,75	4,91
1978	30,50	11,53	9,85	17,83	3,10	0,65	5,04
1984	31,39	12,37	9,63	18,03	3,26	0,69	4,96
1989	31,49	12,29	9,63	18,03	3,27	0,68	4,98
1993	30,57	10,68	10,47	17,23	2,92	0,62	5,16
1999	30,99	11,49	9,93	17,76	3,12	0,65	5,09

Table 6.9: Amelander zeegat: calculated basin characteristics with fixed boundaries and actual water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^8)
1970	24,21	10,03	6,85	11,21	3,53	0,89	3,11
1979	23,46	11,35	6,49	11,40	3,61	1,00	2,97
1982	22,02	10,08	6,46	11,28	3,41	0,89	3,07
1987	20,73	10,81	5,92	11,96	3,50	0,90	3,04
1991	18,20	11,61	5,89	12,08	3,09	0,96	3,00
1997	18,91	12,20	5,50	12,37	3,43	0,99	2,94

Table 6.10: Friesche zeegat: calculated basin characteristics with fixed boundaries and actual water levels

Characteristics analyzed with actual boundaries and actual water levels

time [years]	Vc [m^3] (10^8)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^8)
1926	22,79	4,26	50,49	14,72	4,51	0,29	9,62
1948	22,75	3,96	57,67	10,77	3,94	0,37	10,11
1975	22,88	4,76	58,47	10,80	3,91	0,44	10,09
1981	23,49	3,60	60,85	10,82	3,86	0,33	10,56
1991	23,28	3,96	60,97	10,53	3,82	0,38	10,48
1998	23,44	3,93	62,06	9,84	3,78	0,40	10,52
2006	23,89	4,47	62,45	9,89	3,83	0,45	10,52

Table 6.11Marsdiep: calculated basin characteristics with actual boundaries and actual water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^7)
1926	7,12	2,88	5,21	6,88	1,36	0,42	13,63
1948	8,67	3,00	6,77	7,39	1,28	0,41	16,48
1975	10,36	4,28	6,84	8,84	1,52	0,48	17,61
1981	10,83	3,97	6,72	8,27	1,61	0,48	17,02
1991	11,30	4,45	6,41	9,12	1,76	0,49	17,42
1998	11,65	3,98	7,04	8,68	1,66	0,46	18,22
2006	11,79	4,32	6,84	8,99	1,72	0,48	18,13

Table 6.12: Eierlandse gat: calculated basin characteristics with actual boundaries and actual water levels

time [years]	Vc [m^3] (10^8)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^8)
1926	15,83	10,61	56,45	22,72	2,80	0,47	12,67
1948	14,43	13,14	50,75	23,15	2,84	0,57	11,78
1975	13,88	14,55	43,75	28,73	3,17	0,51	11,85
1981	14,00	14,17	43,49	27,33	3,22	0,52	11,68
1991	13,23	17,22	38,55	31,88	3,43	0,54	11,47
1998	12,97	17,89	38,29	31,66	3,39	0,57	11,43
2006	13,20	16,72	38,69	31,14	3,41	0,54	11,64

Table 6.13: Vlie: calculated basin characteristics with actual boundaries and actual water levels

time [years]	Vc [m^3] (10^7)	Vf [m^3] (10^7)	Ac [m^2] (10^7)	Af [m^2] (10^7)	hc	hf	P [m^3] (10^7)
1926	25,99	14,13	10,32	19,10	2,52	0,74	50,70
1948	28,43	16,05	11,66	19,27	2,44	0,83	52,46
1975	28,68	16,16	11,44	19,62	2,51	0,82	53,23
1981	28,51	14,36	12,10	18,65	2,36	0,77	54,48
1991	27,63	14,65	10,91	19,32	2,53	0,76	53,24
1998	26,56	14,74	11,01	18,86	2,41	0,78	52,48
2006	27,01	16,25	11,67	19,34	2,32	0,84	53,69

Table 6.14: Amelander zeegat: calculated basin characteristics with actual boundaries and actual water levels

Delta characteristics

Time [years]	Volume *10^8 [m^3]	Surface area [m^2]
1925	4.90	1.31*10^8
1933	5.43	-
1948	5.15	-
1965	5.01	-
1971	4.59	-
1975	4.54	-
1981	4.54	-
1991	4.69	-
1997	4.58	-

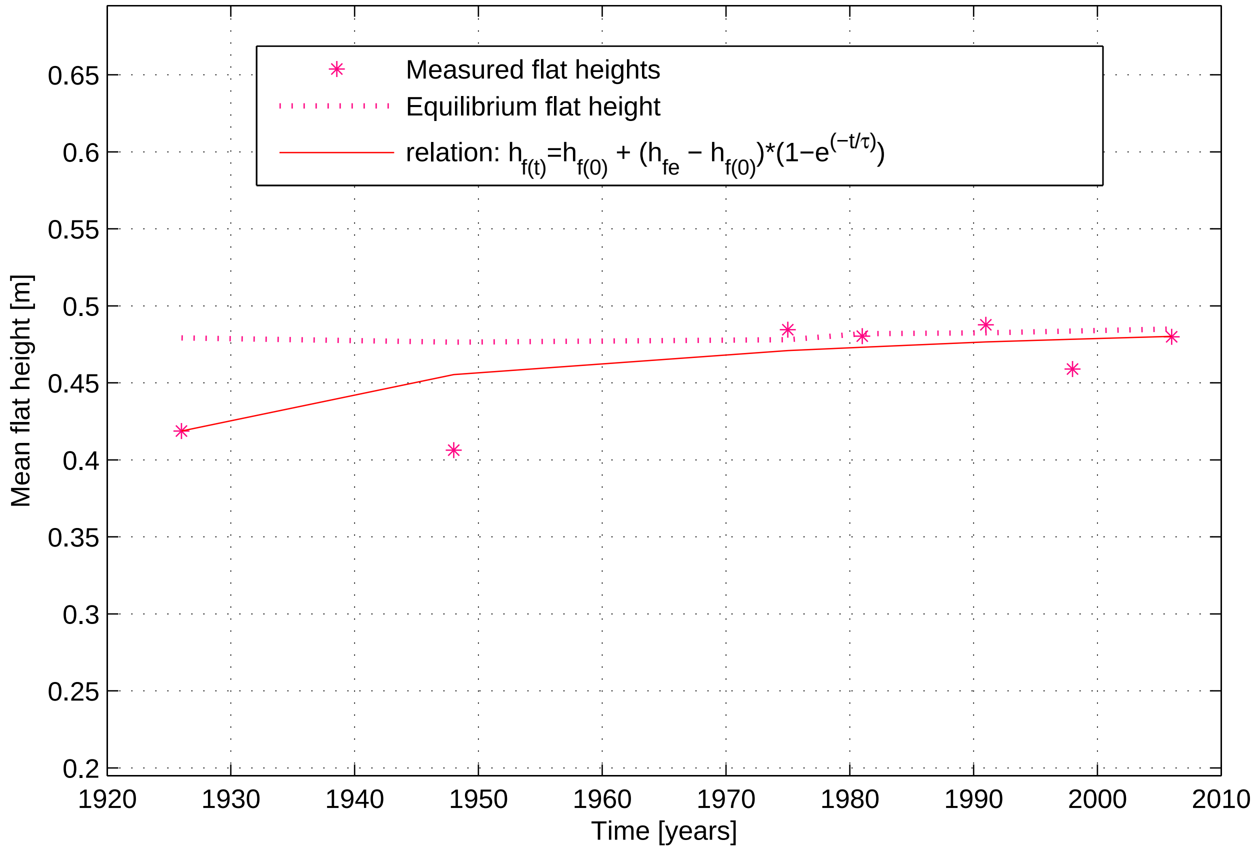
Table G.1: Marsdiep delta characteristics deduced from Kragtwijk (2001)

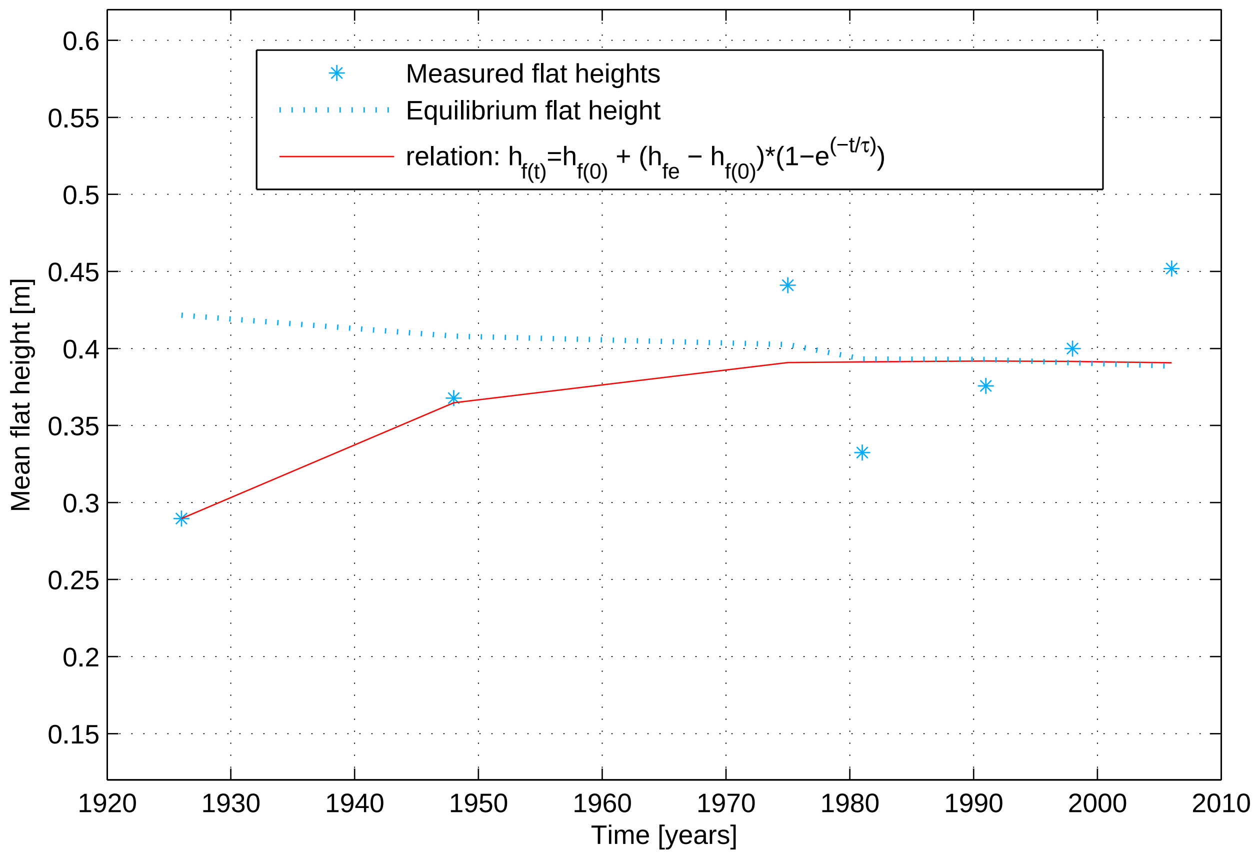
Time [years]	Volume *10^8 [m^3]	Surface area *10^7 [m^2]
1934	1.11	3.78
1971	1.28	3.78
1976	1.33	3.78
1982	1.35	3.78
1987	1.28	3.78

Table G.2: Eierlandse gat delta characteristics taken from v. Goot (2001)

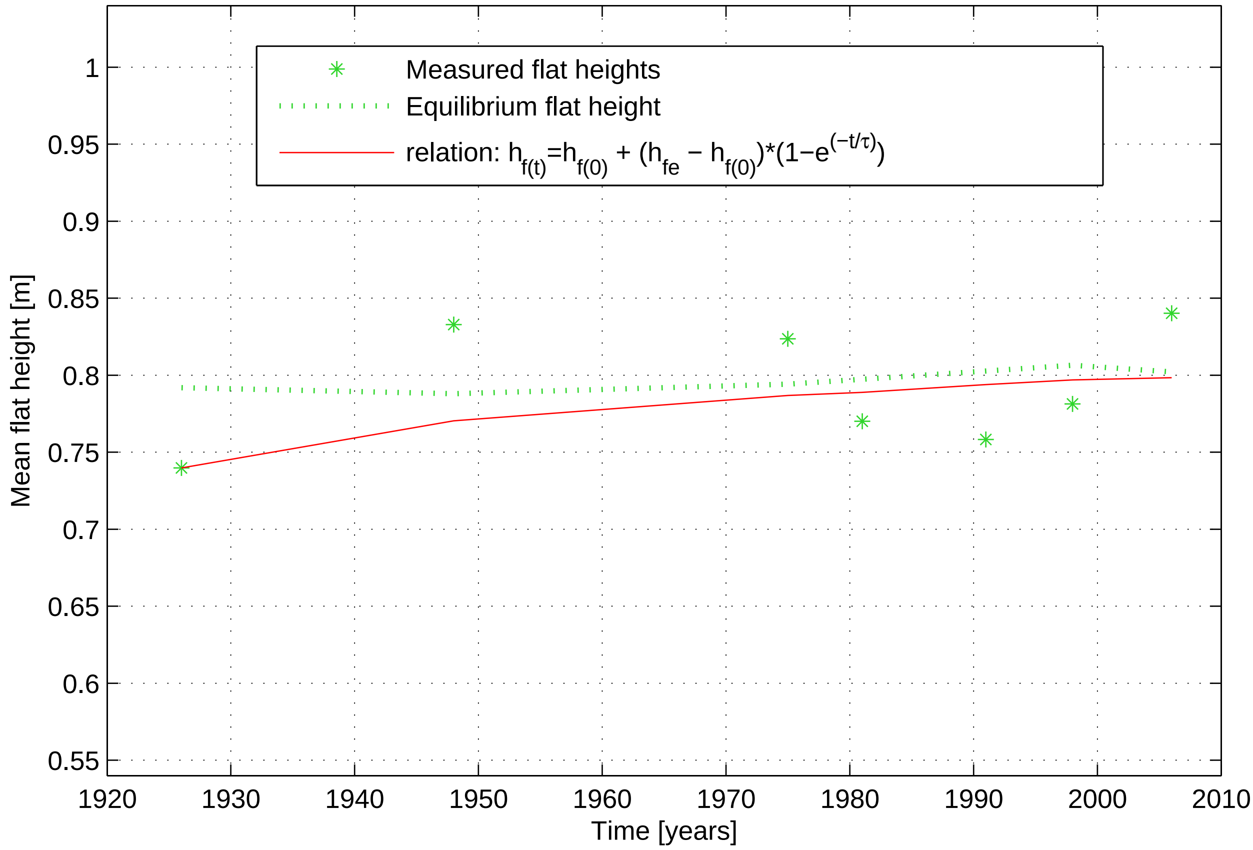
Time [years]	**Volume $*10^8$ [m^3]**	**Surface area [m^2]**
1933	3.36	$1.7*10^8$
1972	3.92	-
1974	3.75	-
1976	3.95	-
1978	3.98	-
1980	3.78	-
1982	3.98	-
1998	4.12	-

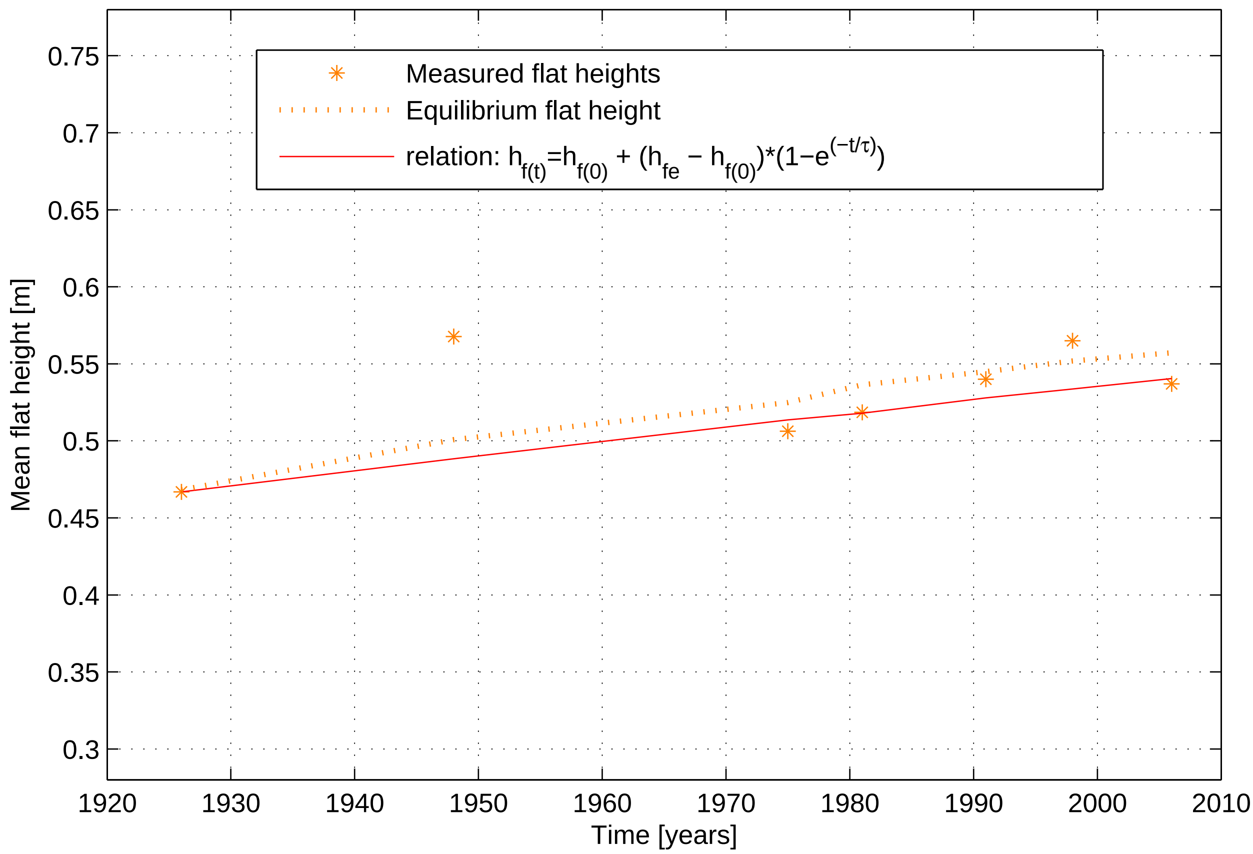
Table G.3: Vlie delta characteristics deduced from Kragtwijk (2001)



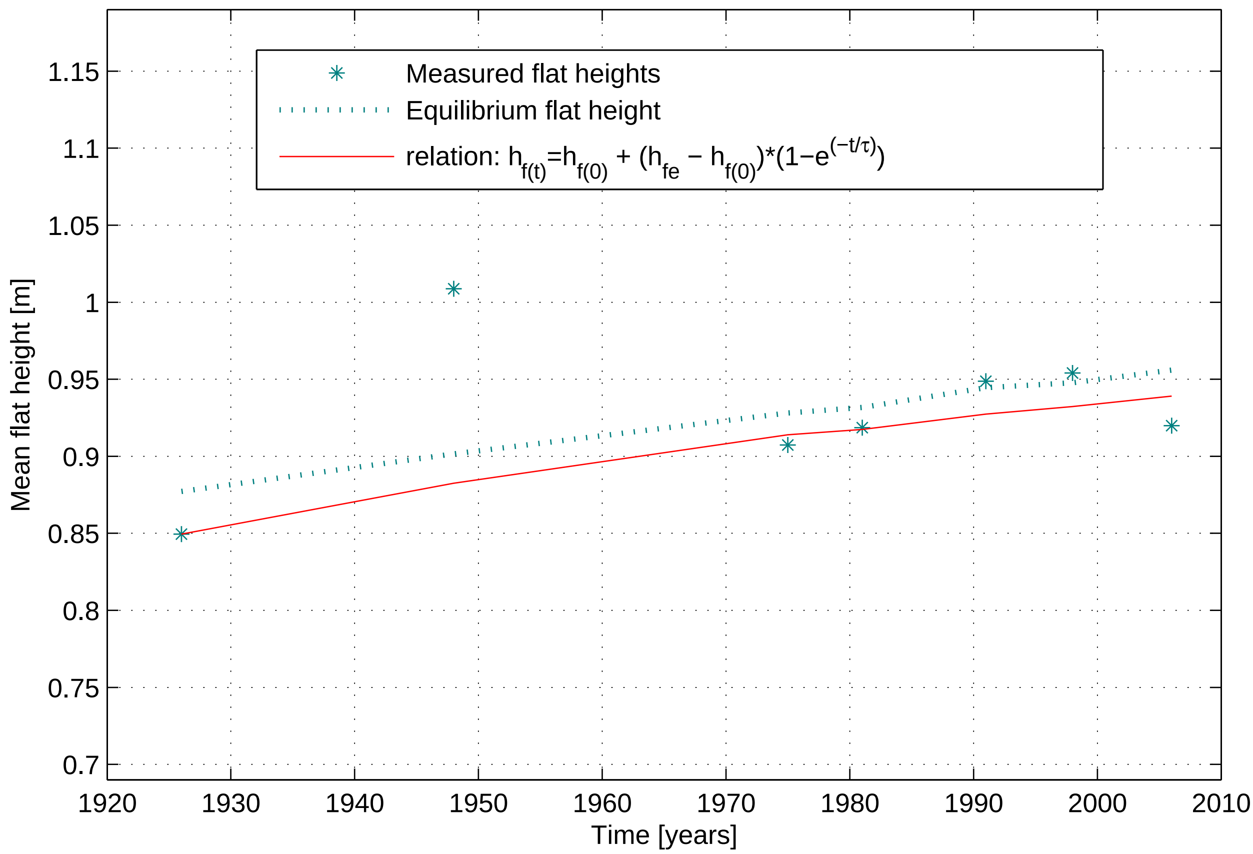


Development of flat height in time with relation 3.3 for: Marsdiep (upper plot) and Eierlandse gat (lower plot)	Z4169	
WL | DELFT HYDRAULICS		Figure G.1

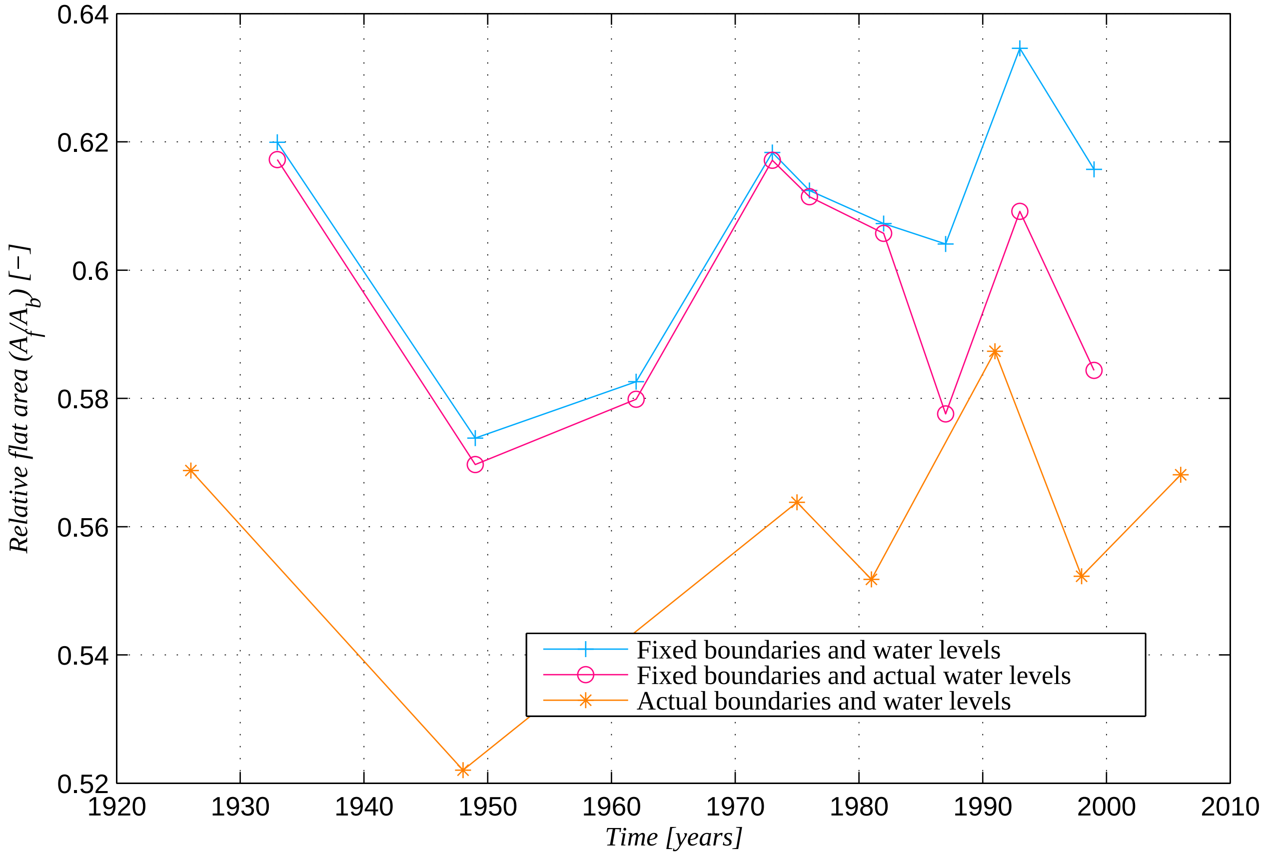


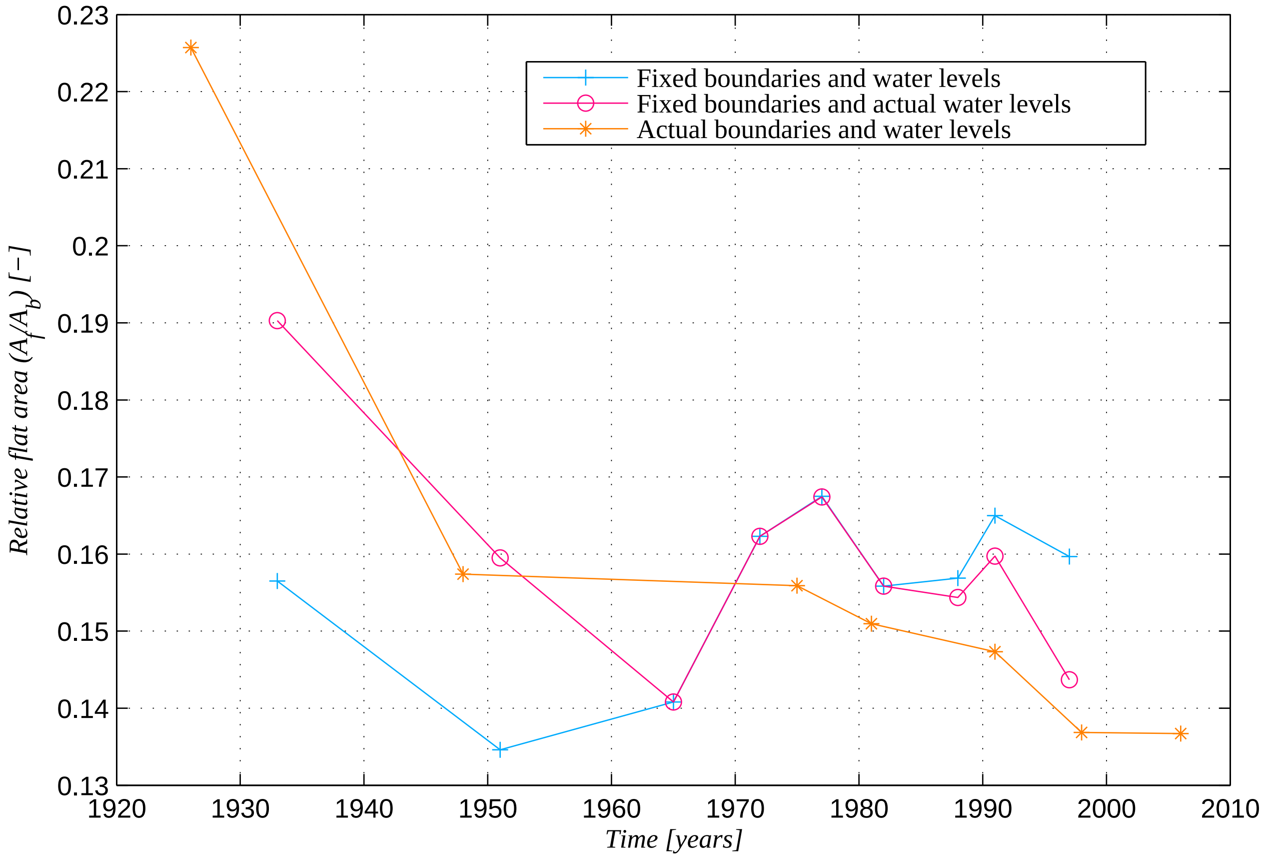


Development of flat height in time with relation 3.3 for: Vlie (upper plot) and Amelander Zeegat (lower plot)	Z4169
WL | DELFT HYDRAULICS	Figure G.2

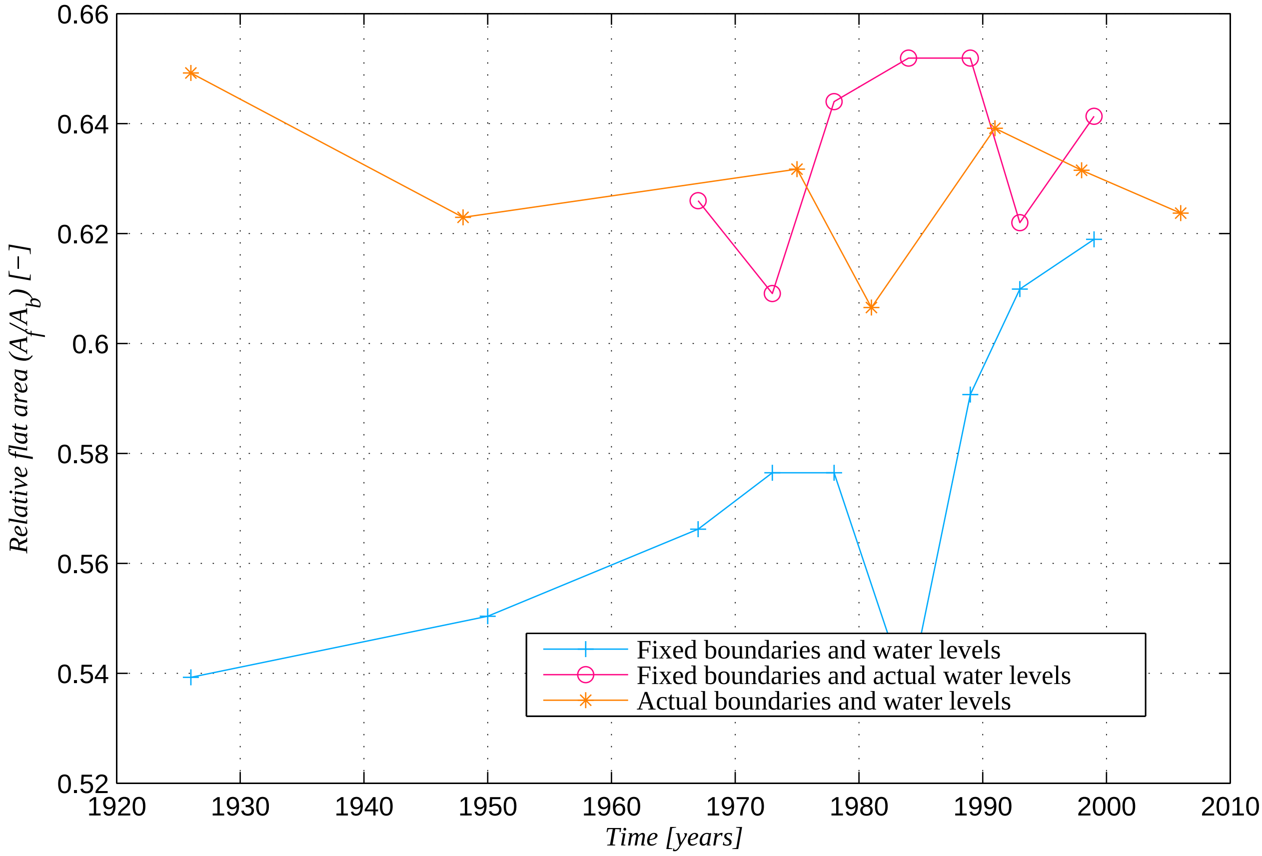


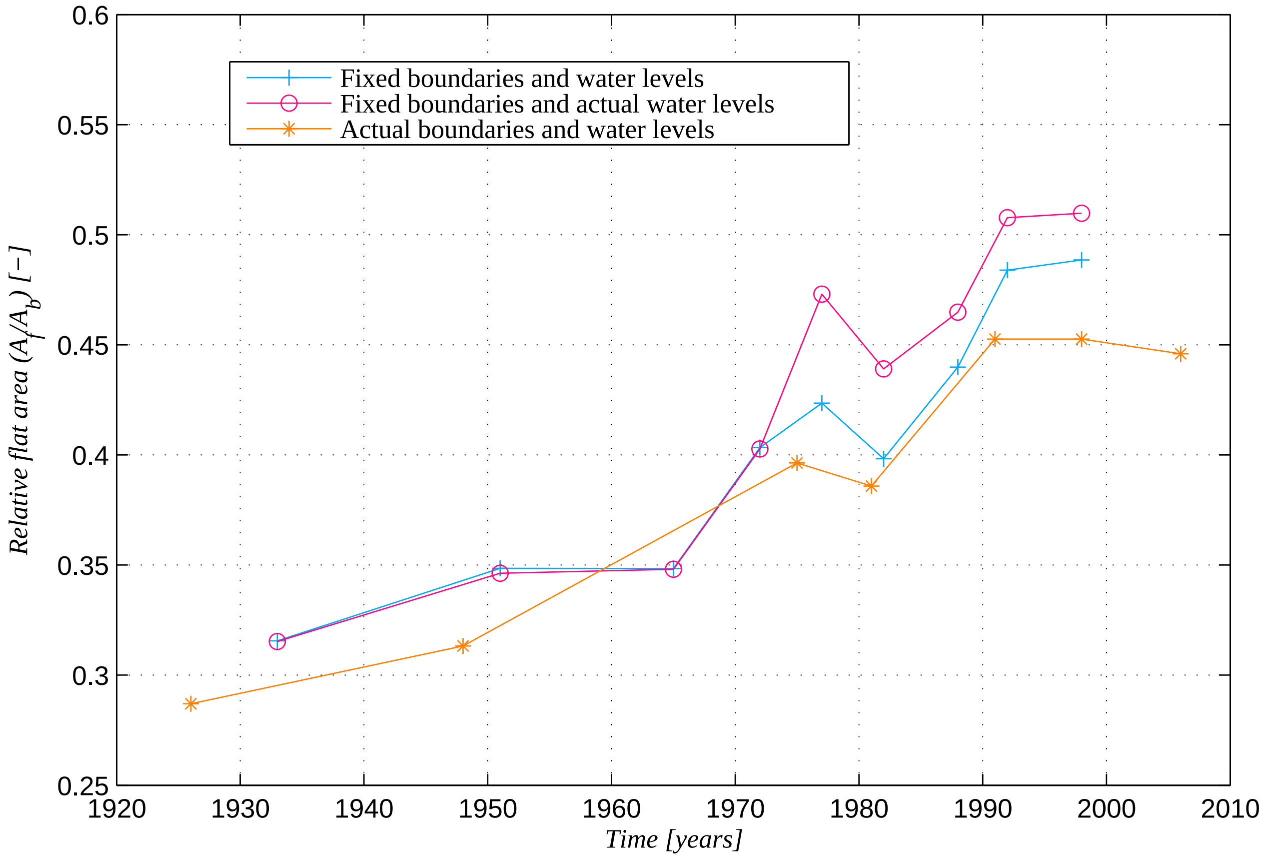
Development of flat height in time with relation 3.3 for: Friesche zeegat	Z4169	
WL | DELFT HYDRAULICS		Figure G.3



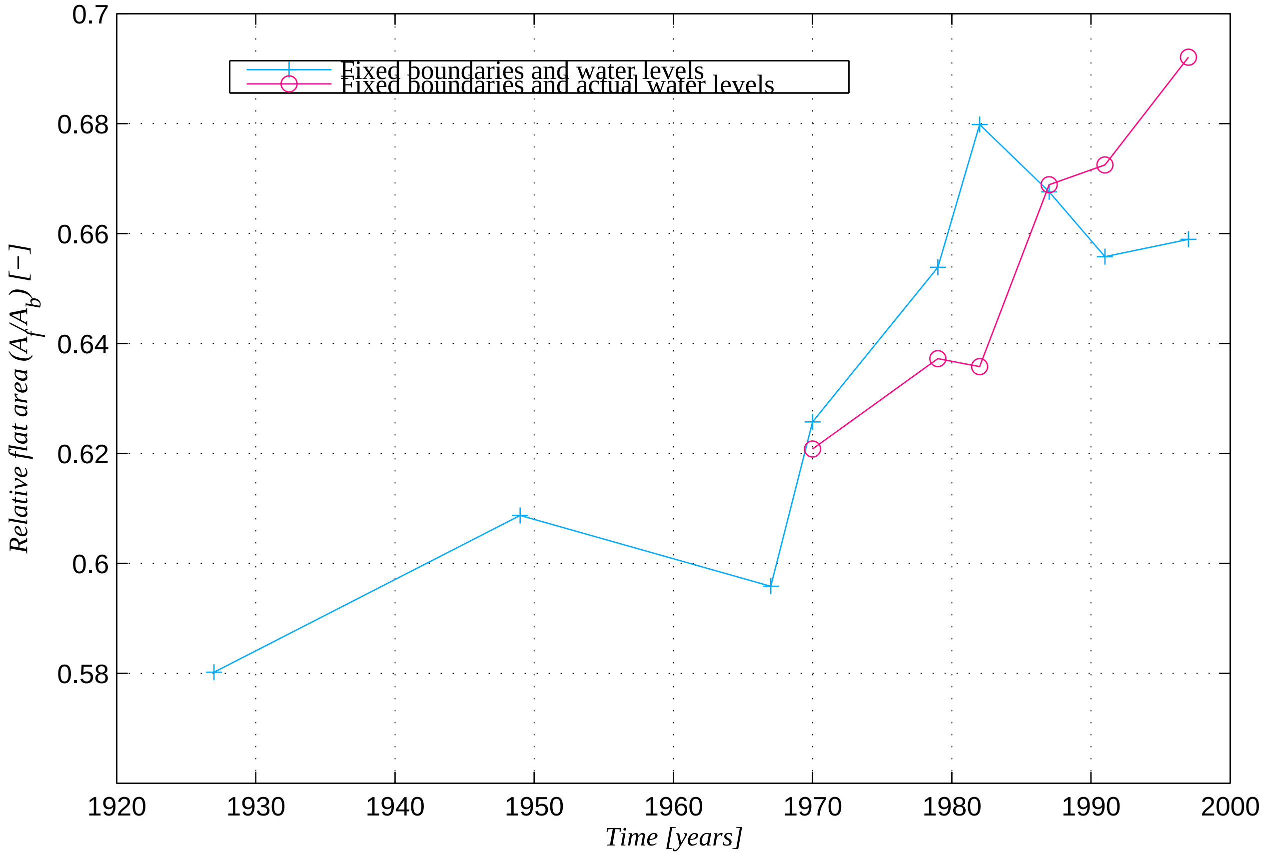


Relative area development in time of: Marsdiep (upper plot) and Eierlandse gat (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure G.4





Relative area development in time of: Vlie (upper plot) and Amelander Zeegat (lower plot)		Z4169
WL | DELFT HYDRAULICS		Figure G.5



Relative area development in time of: Friesche zeegat		Z4169
WL | DELFT HYDRAULICS		Figure G.3

H Model setup

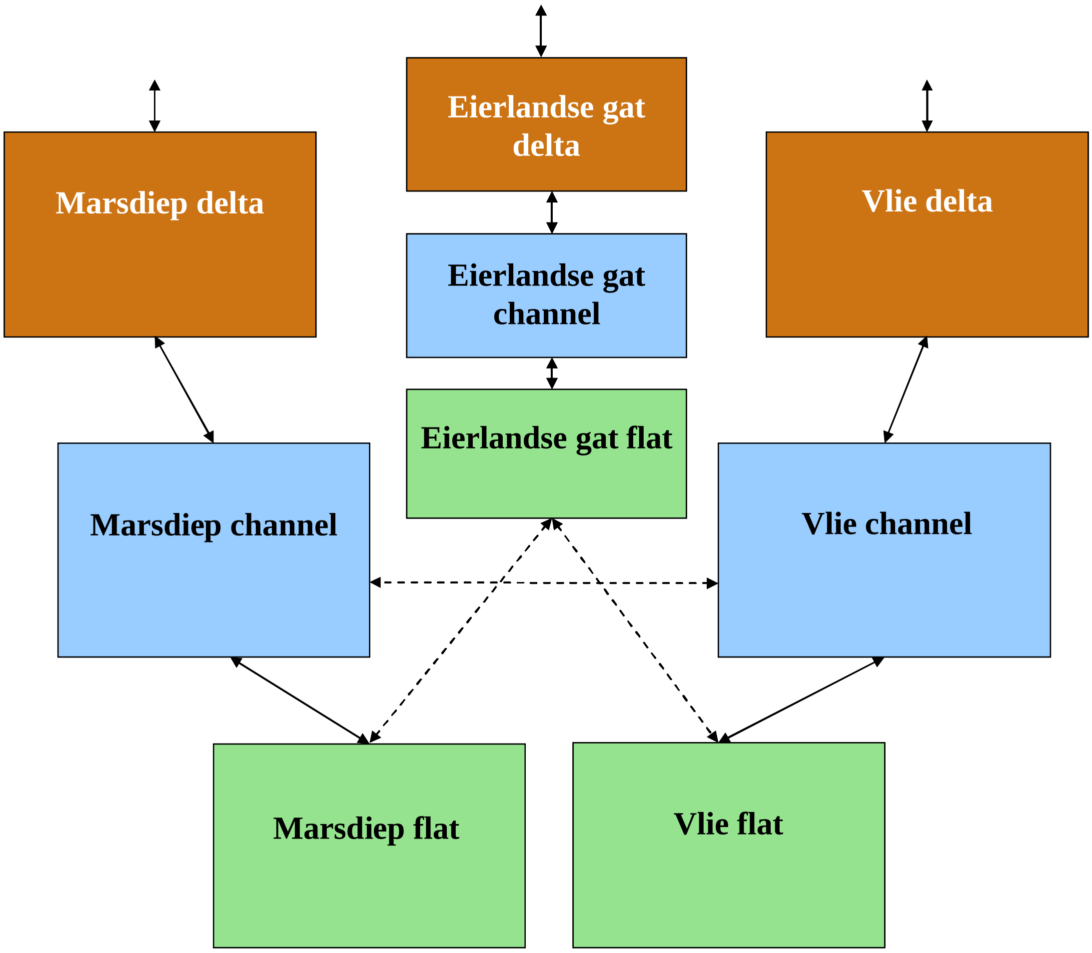


Figure H.1: Schematisation of the Western Dutch Wadden Sea used in ASMITA computation

Parameter	Marsdiep	Eierlandse gat	Vlie
$V_{d,init}$ [m^3]	$5.3*10^8$	$1.11*10^8$	$3.364*10^8$
$V_{c,init}$ [m^3]	$2.45*10^9$	$8.53*10^7$	$1.29*10^9$
$V_{f,init}$ [m^3]	$1.85*10^7$	$3.34*10^7$	$9.92*10^7$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.81*10^8$	$5.69*10^7$	$4.68*10^8$
$A_{f,init}$ [m^2]	$1.08*10^8$	$9.27*10^7$	$2.16*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.65	1.65	1.9
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.43	0.38	0.46
c_{fc} [-]	0.5	0.75	1.4
α_c [-]	$14*10^{-6}$	$15.5*10^{-6}$	$7.7*10^{-6}$
α_d [-]	$43*10^{-4}$	$85*10^{-4}$	$32*10^{-4}$

Table H.1: Model parameters of basic model exlcluding the effect of SLR and variations of the tidal ranges (see also section 5.4.1)

Parameter	**Marsdiep**	**Eierlandse gat**	**Vlie**
$V_{d,init}$ [m^3]	$5.3*10^8$	$1.11*10^8$	$3.36*10^8$
$V_{c,init}$ [m^3]	$2.37*10^9$	$8.42*10^7$	$1.27*10^9$
$V_{f,init}$ [m^3]	$4.26*10^7$	$3.59*10^7$	$1.05*10^8$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.58*10^8$	$5.69*10^7$	$4.68*10^8$
$A_{f,init}$ [m^2]	$1.31*10^8$	$9.17*10^7$	$2.16*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.54 -1.36*	1.37 – 1.73*	1.74 – 2.91*
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.41	0.37	0.43
c_{fc} [-]	0.7	0.875	2.09
α_c [-]	$16.5*10^{-6}$	$21*10^{-6}$	$8*10^{-6}$
α_d [-]	$47*10^{-4}$	$107*10^{-4}$	$36*10^{-4}$

Table H.2: Model parameters of model including actual water levels (see also section 5.4.2).

* Actual water levels used in this model are conform calculated actual water levels for the individual basins. See also Appendix E.

Parameter	Marsdiep	Eierlandse gat	Vlie
$V_{d,init}$ [m^3]	$5.3*10^8$	$1.11*10^8$	$3.36*10^8$
$V_{c,init}$ [m^3]	$2.37*10^9$	$8.42*10^7$	$1.27*10^9$
$V_{f,init}$ [m^3]	$4.26*10^7$	$3.59*10^7$	$1.05*10^8$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.58*10^8$	$5.69*10^7$	$4.68*10^8$
$A_{f,init}$ [m^2]	$1.31*10^8$	$9.17*10^7$	$2.16*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.54 -1.36*	1.37 – 1.73*	1.74 – 2.91*
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.43	0.38	0.46
c_{fc} [-]	0.6	1	1.6
α_c [-]	$17*10^{-6}$	$18*10^{-6}$	$8*10^{-6}$
α_d [-]	$47*10^{-4}$	$107*10^{-4}$	$36*10^{-4}$

Table H.3: Input parameters of model used to assess the effect of exchange over basin boundaries (see also section 5.4.3)

* Actual water levels used in this model are conform calculated actual water levels for the individual basins. See also Appendix E.

Parameter	Marsdiep	Eierlandse gat	Vlie
$V_{d,init}$ [m^3]	$5.4*10^8$	$1.11*10^8$	$3.36*10^8$
$V_{c,init}$ [m^3]	$2.27*10^9$	$7.12*10^7$	$1.58*10^9$
$V_{f,init}$ [m^3]	$5.164*10^7$	$2.93*10^7$	$1.11*10^8$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.01*10^8$	$5.21*10^7$	$5.64*10^8$
$A_{f,init}$ [m^2]	$1.51*10^8$	$6.86*10^7$	$2.276*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.54 -1.36*	1.37 – 1.73*	1.74 – 2.91*
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.43	0.38	0.46
c_{fc} [-]	0.5	0.8	1.95
α_c [-]	$22*10^{-6}$	$19.7*10^{-6}$	$8*10^{-6}$
α_d [-]	$41*10^{-4}$	$108*10^{-4}$	$33*10^{-4}$

Table H.4: Input parameters of model used to assess the effect of movement of the basin boundaries (see also section 5.4.4)

* Actual water levels used in this model are conform calculated actual water levels for the individual basins. See also Appendix E.

Parameter	**Marsdiep**	**Eierlandse gat**	**Vlie**
$V_{d,init}$ [m^3]	$5.3*10^8$	$1.11*10^8$	$3.36*10^8$
$V_{c,init}$ [m^3]	$2.37*10^9$	$8.42*10^7$	$1.27*10^9$
$V_{f,init}$ [m^3]	$4.26*10^7$	$3.59*10^7$	$1.05*10^8$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.58*10^8$	$5.69*10^7$	$4.68*10^8$
$A_{f,init}$ [m^2]	$1.31*10^8$	$9.17*10^7$	$2.16*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.54 -1.36*	1.37 – 1.73*	1.74 – 2.91*
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.41	0.37	0.43
c_{fc} [-]	0.7	0.875	2.09
α_c [-]	$16.5*10^{-6}$	$21*10^{-6}$	$8*10^{-6}$
α_d [-]	$47*10^{-4}$	$107*10^{-4}$	$36*10^{-4}$
τ_{hf} [years]	10	10	10

Table H.5: Input parameters of the model used to assess the effect of recalculation of surface areas (see also section 5.4.5)

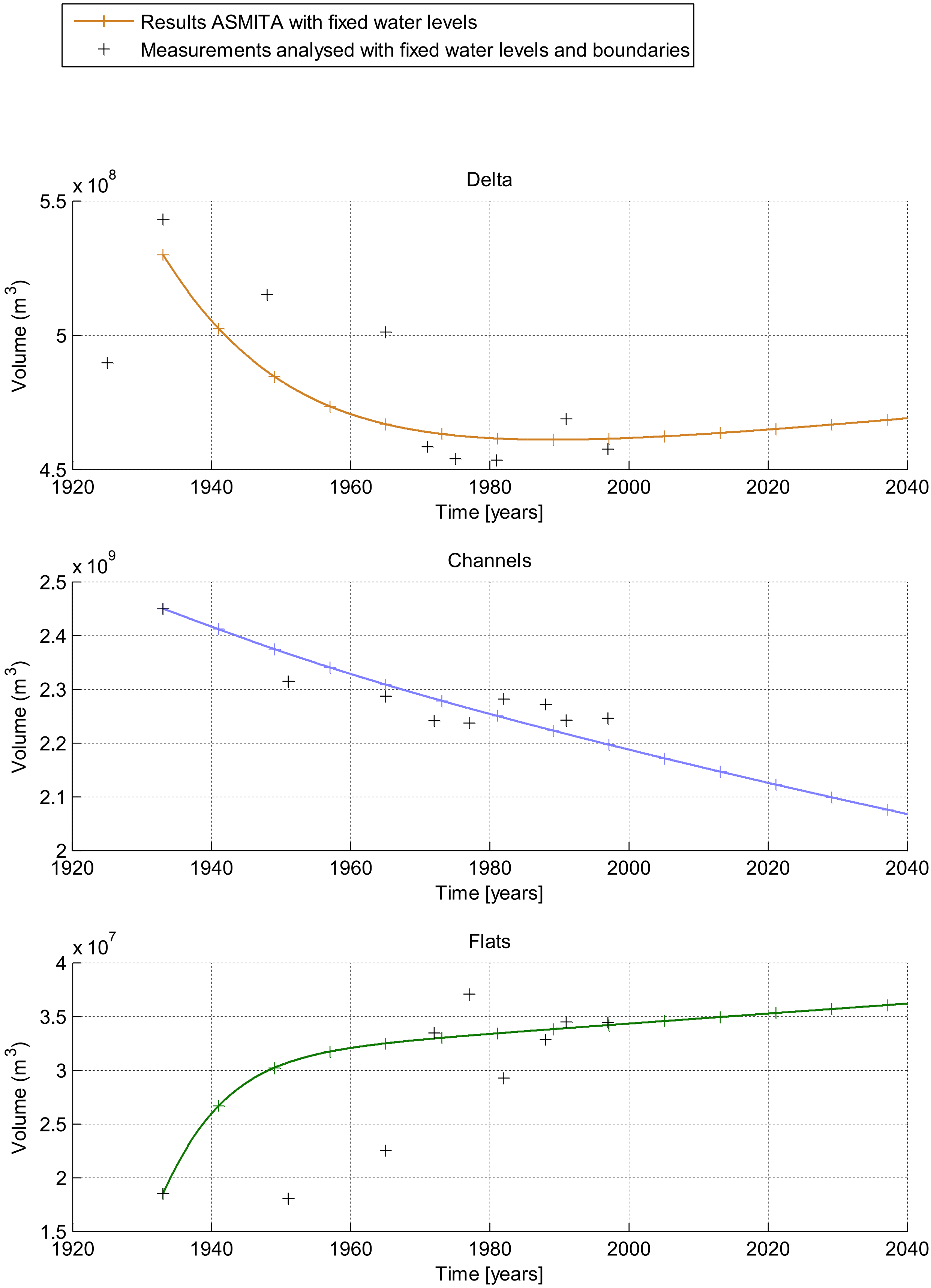
* Actual water levels used in this model are conform calculated actual water levels for the individual basins. See also Appendix E.

Parameter	Marsdiep	Eierlandse gat	Vlie
$V_{d,init}$ [m^3]	$5.4*10^8$	$1.11*10^8$	$3.36*10^8$
$V_{c,init}$ [m^3]	$2.27*10^9$	$7.12*10^7$	$1.58*10^9$
$V_{f,init}$ [m^3]	$5.164*10^7$	$2.93*10^7$	$1.11*10^8$
$A_{d,init}$ [m^2]	$1.31*10^8$	$3.78*10^7$	$1.7*10^8$
$A_{c,init}$ [m^2]	$5.01*10^8$	$5.21*10^7$	$5.64*10^8$
$A_{f,init}$ [m^2]	$1.51*10^8$	$6.86*10^7$	$2.276*10^8$
c_E [-]	$2*10^{-4}$	$2*10^{-4}$	$2*10^{-4}$
w_{sf} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sc} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
w_{sd} [m/s]	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-4}$
n [-]	2	2	2
H [m]	1.54 -1.36*	1.37 – 1.73*	1.74 – 2.91*
δ_{cf} [m^3/s]	980	840	1300
δ_{dc} [m^3/s]	2450	1290	2560
δ_{do} [m^3/s]	1550	1060	1770
α_f [-]	0.43	0.38	0.46
c_{fc} [-]	0.5	0.8	1.95
α_c [-]	$22*10^{-6}$	$19.7*10^{-6}$	$8*10^{-6}$
α_d [-]	$41*10^{-4}$	$108*10^{-4}$	$33*10^{-4}$

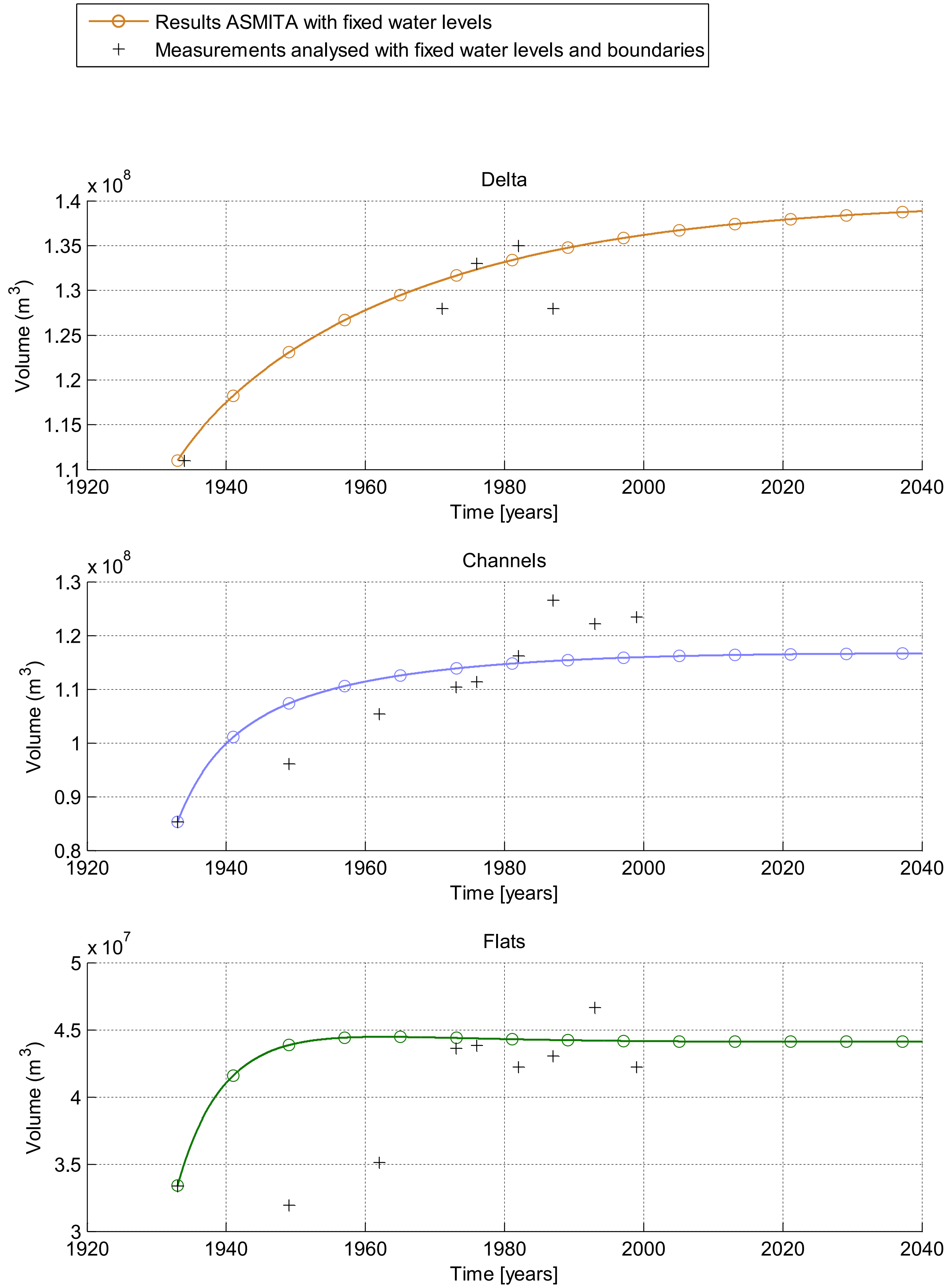
Table H.6: Input parameters of optimal simulation (see also section 5.5)

* Actual water levels used in this model are conform calculated actual water levels for the individual basins. See also Appendix E.

I Model results

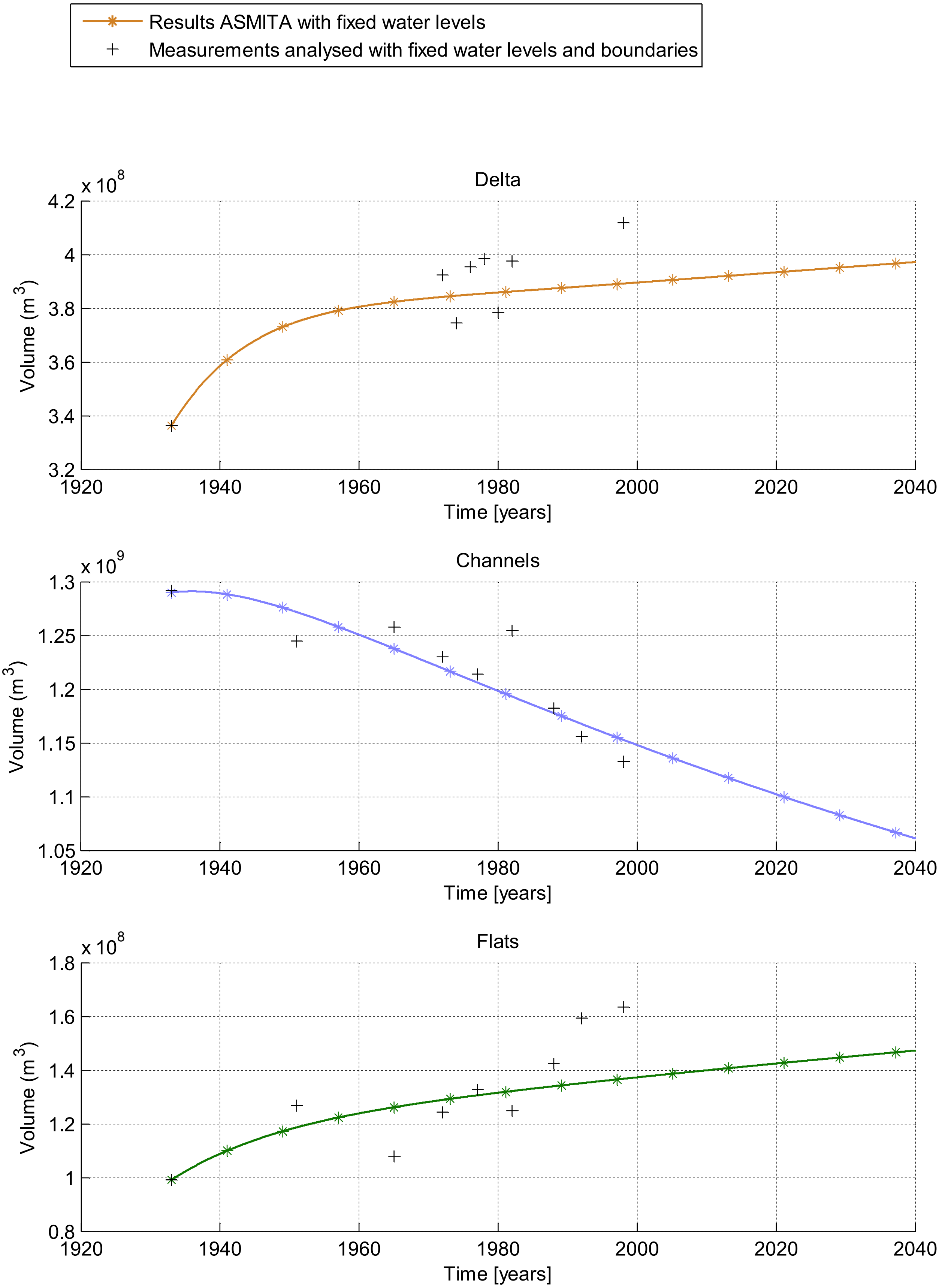


Comparison between measurements and simulation results of a model with fixed boundaries and actual water levels for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.1

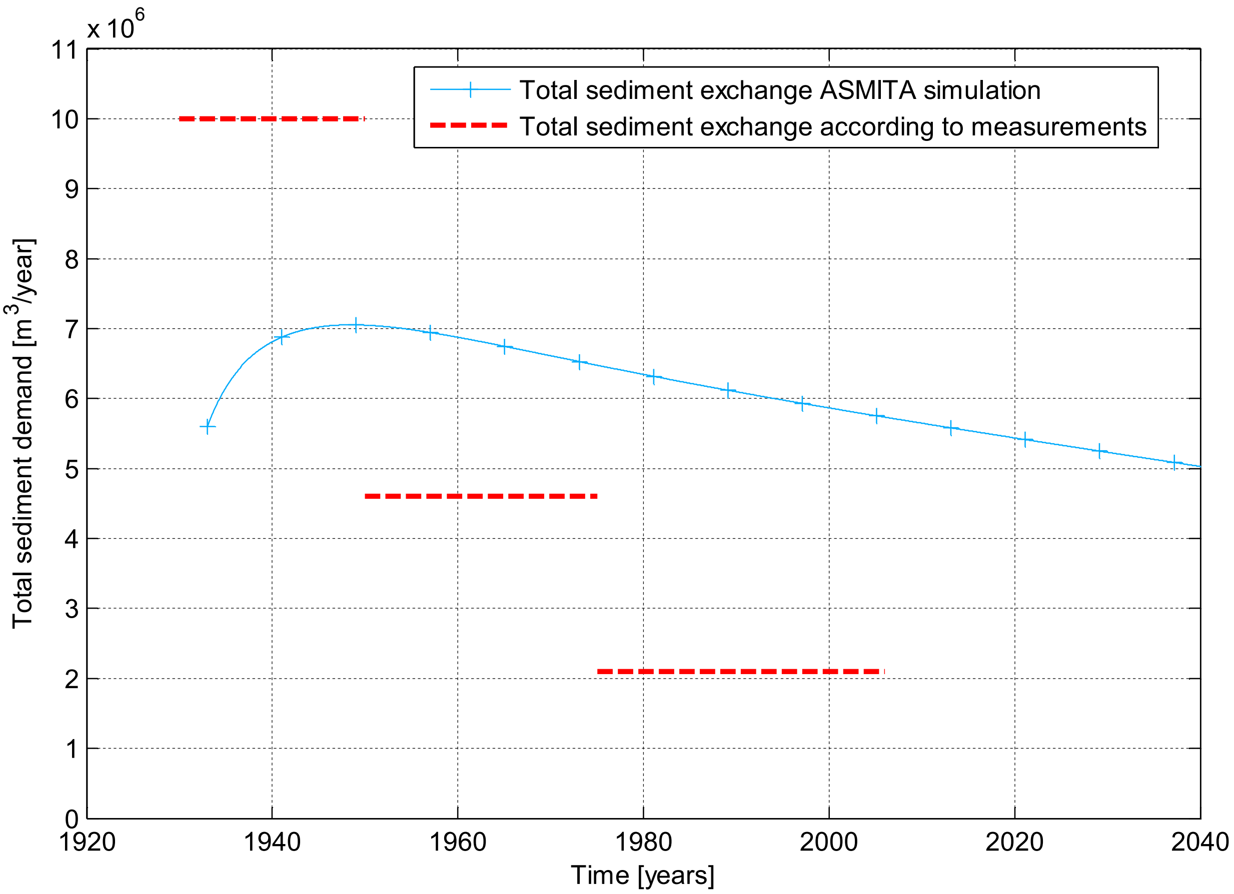


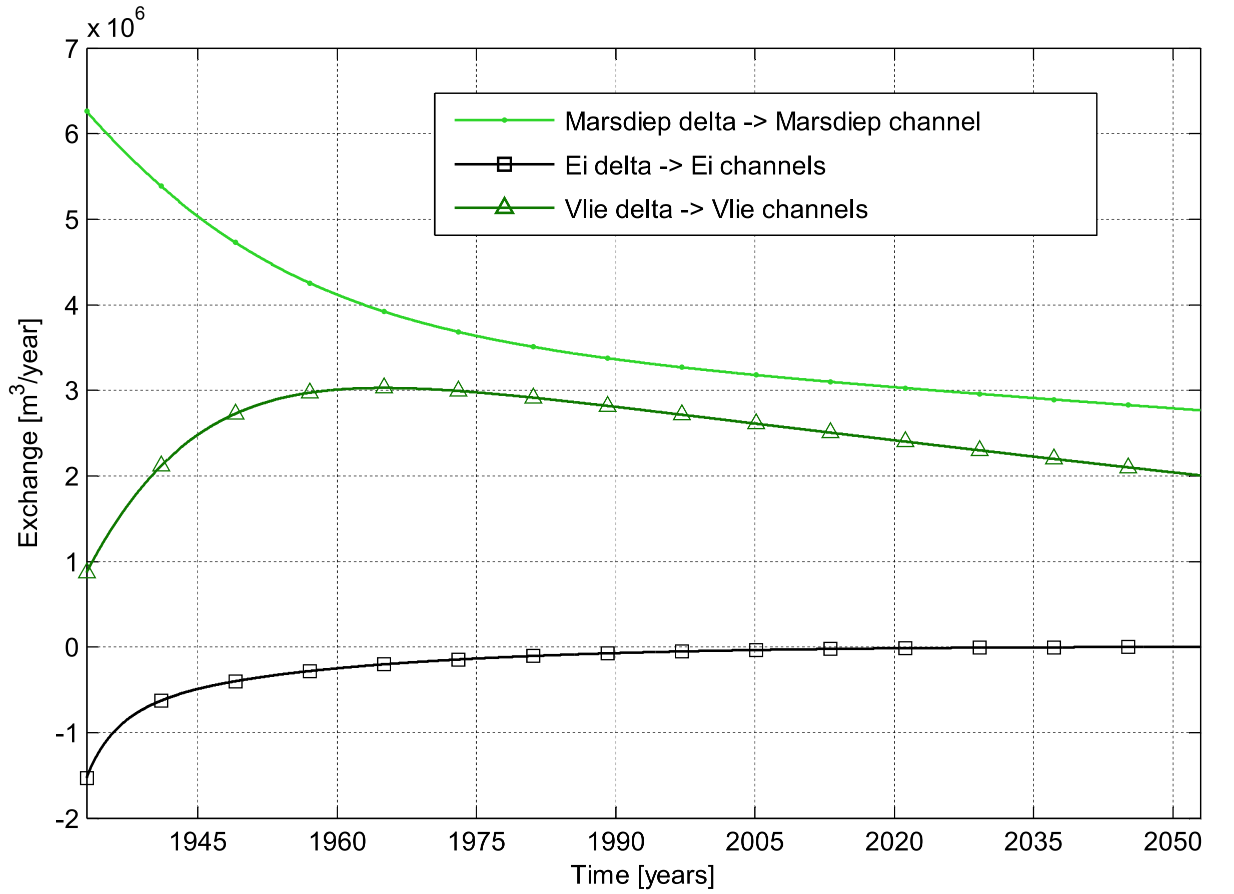
Comparison between measurements and simulation results of a model with fixed boundaries and actual water levels for Eierlandse gat

Comparison between measurements and simulation results of a model with fixed boundaries and actual water levels for Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure I.2

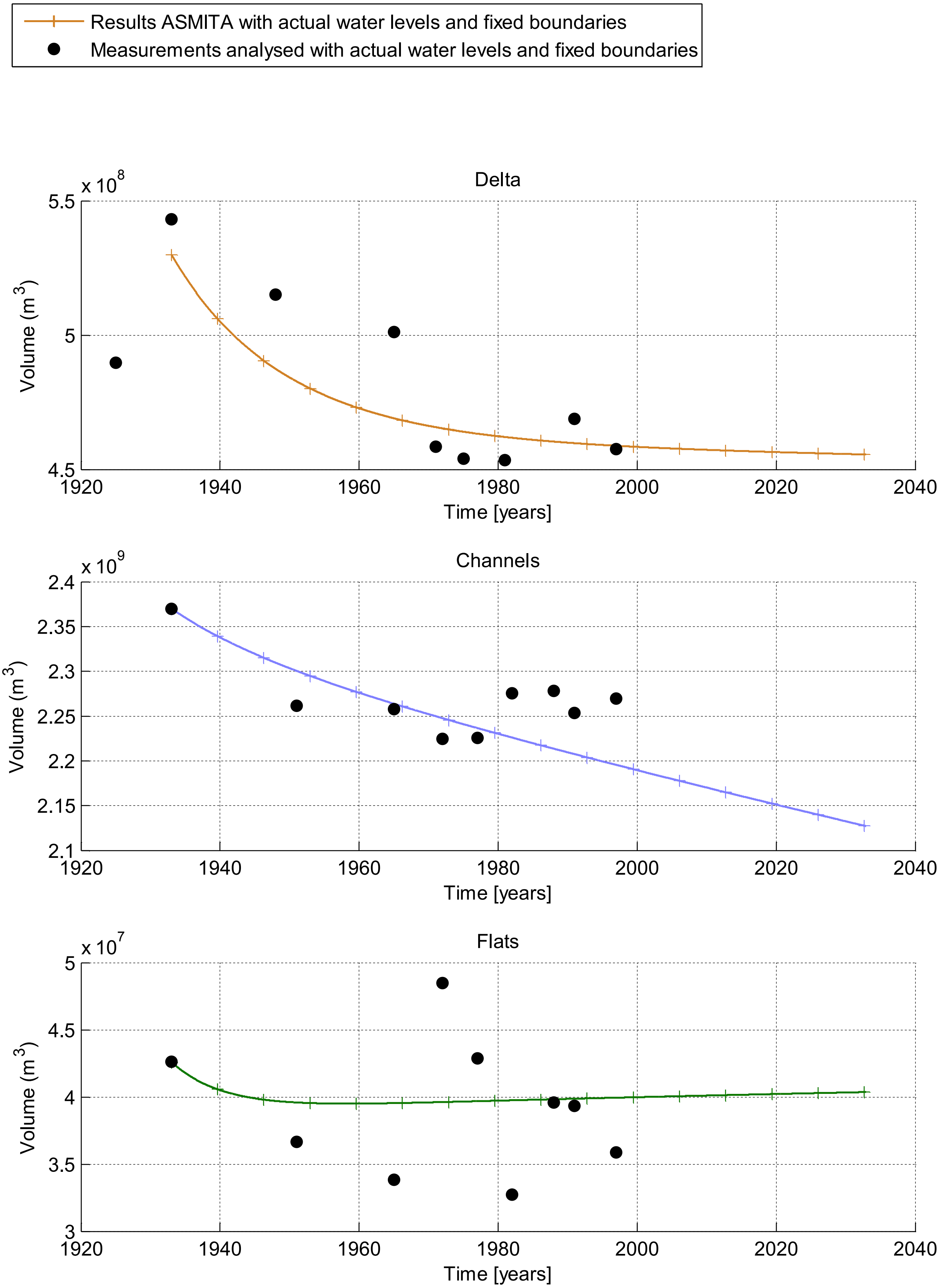


Comparison between measurements and simulation results of a model with fixed boundaries and actual water levels for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.3

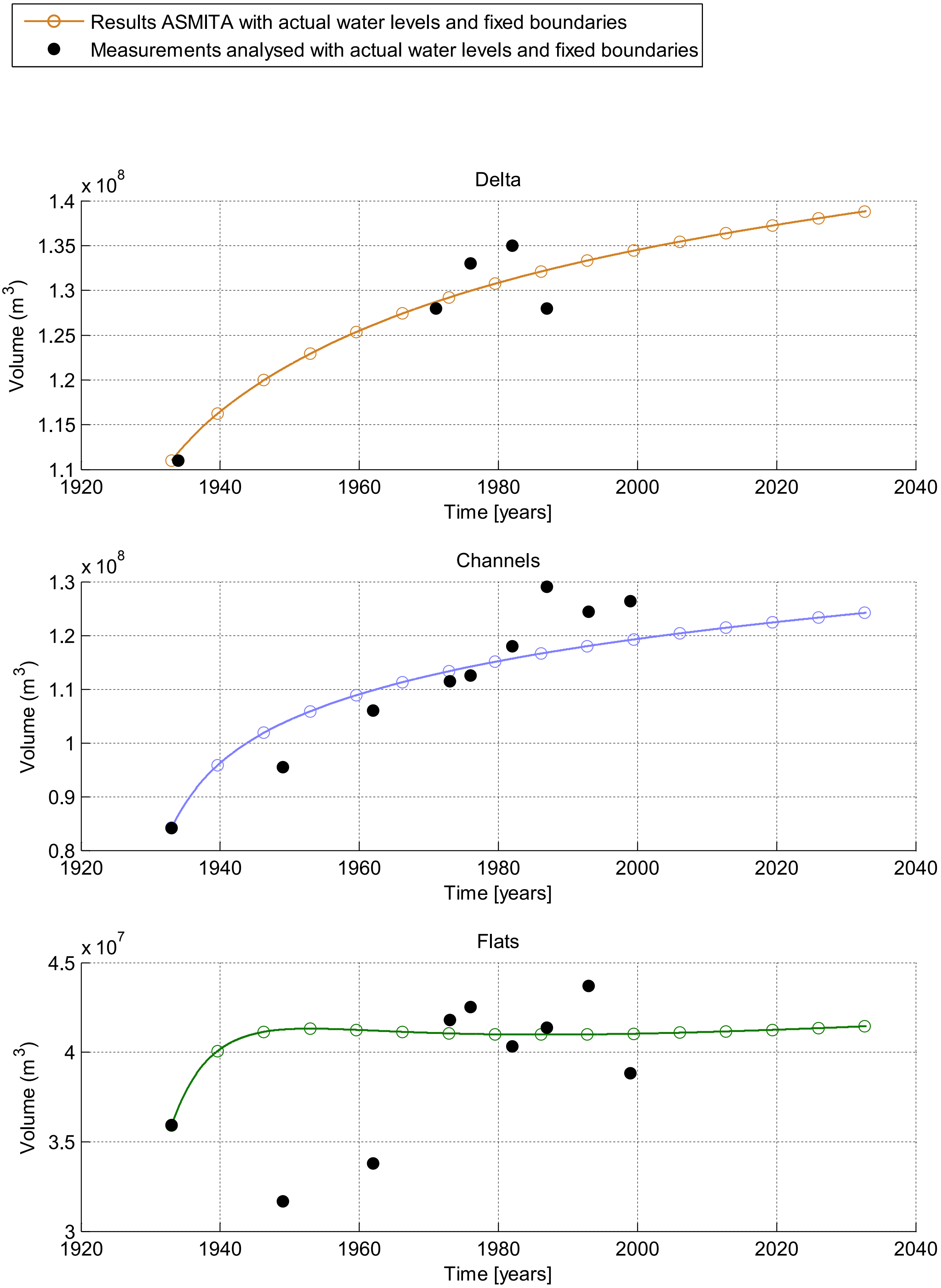




Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation with fixed water levels and fixed boundaries (section 5.4.1)		Z4169
WL | DELFT HYDRAULICS		Figure I.4



Comparison between measurements and simulation results of a model with actual water levels and fixed boundaries (section 5.4.2) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.5

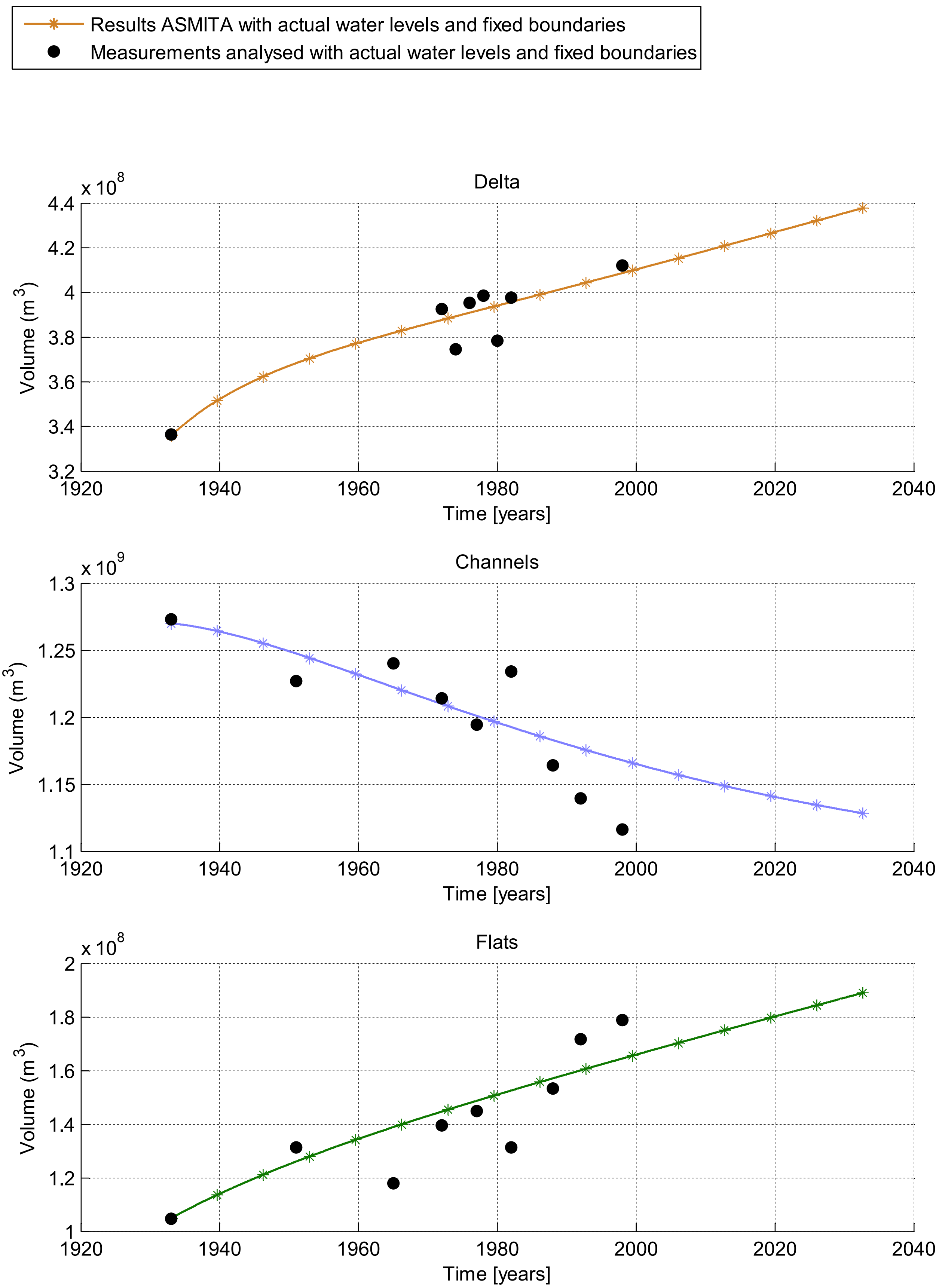


Comparison between measurements and simulation results of
a model with actual water levels and fixed boundaries (section 5.4.2)
for Eierlandse gat

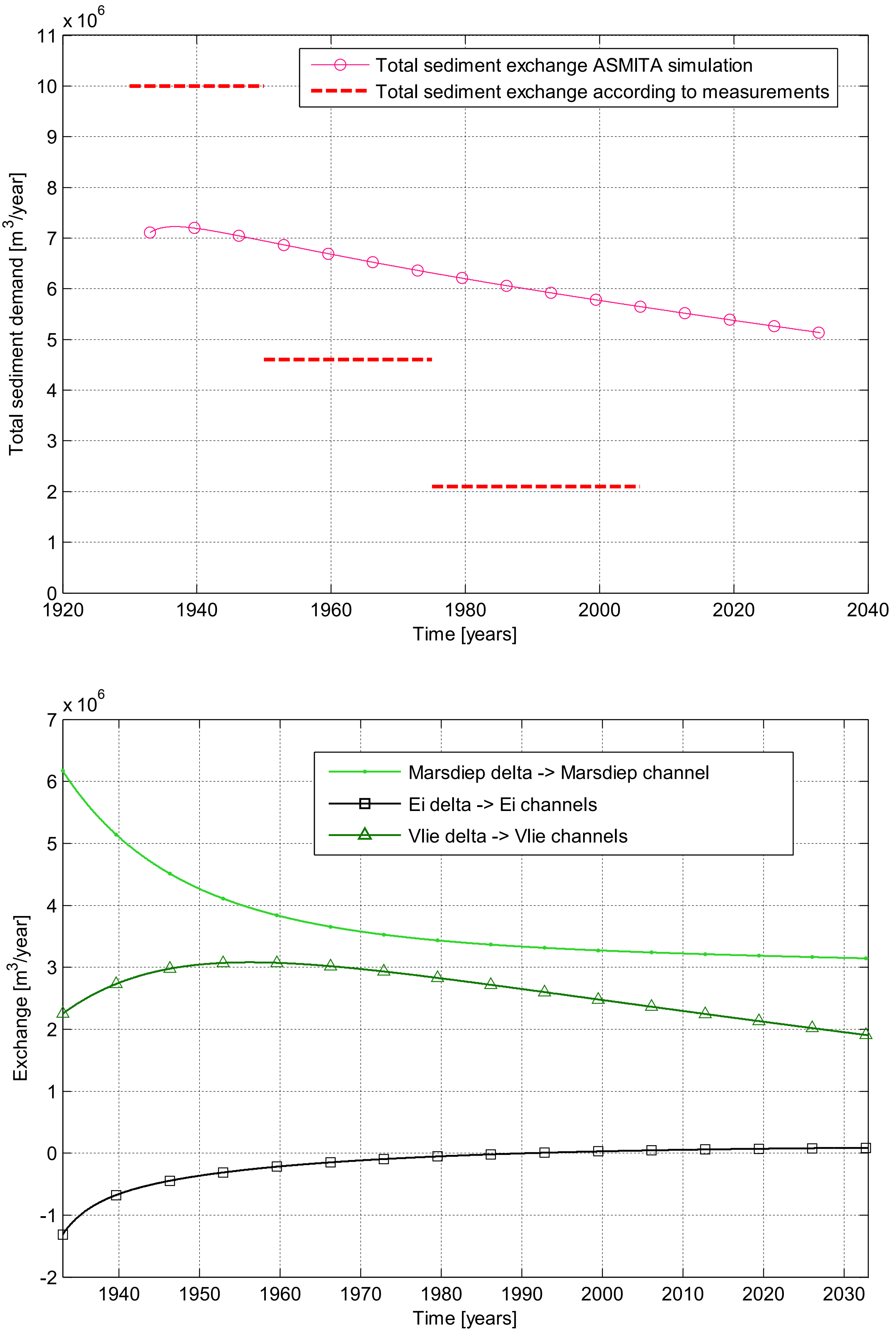
Z4169

WL | DELFT HYDRAULICS

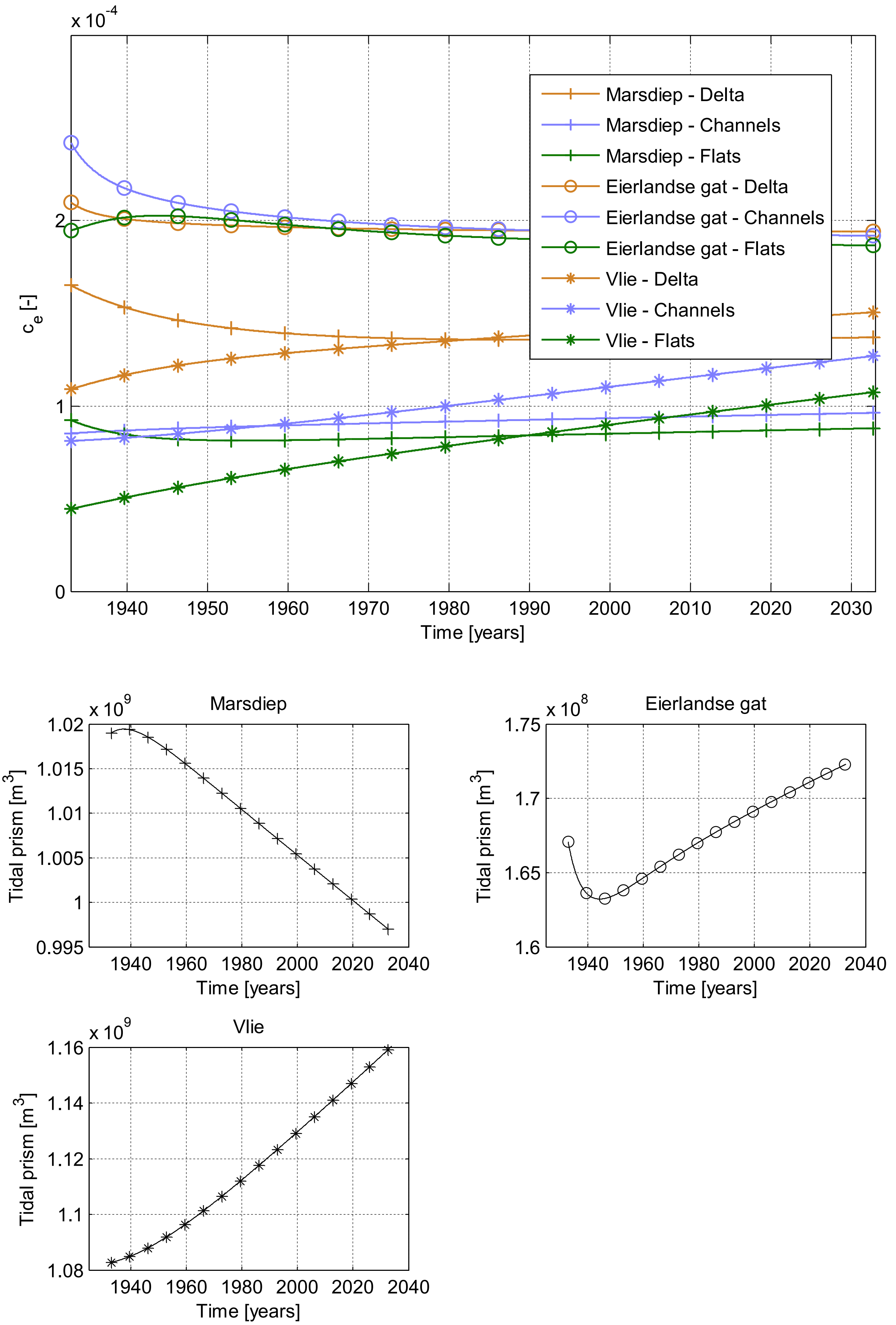
Figure I.6



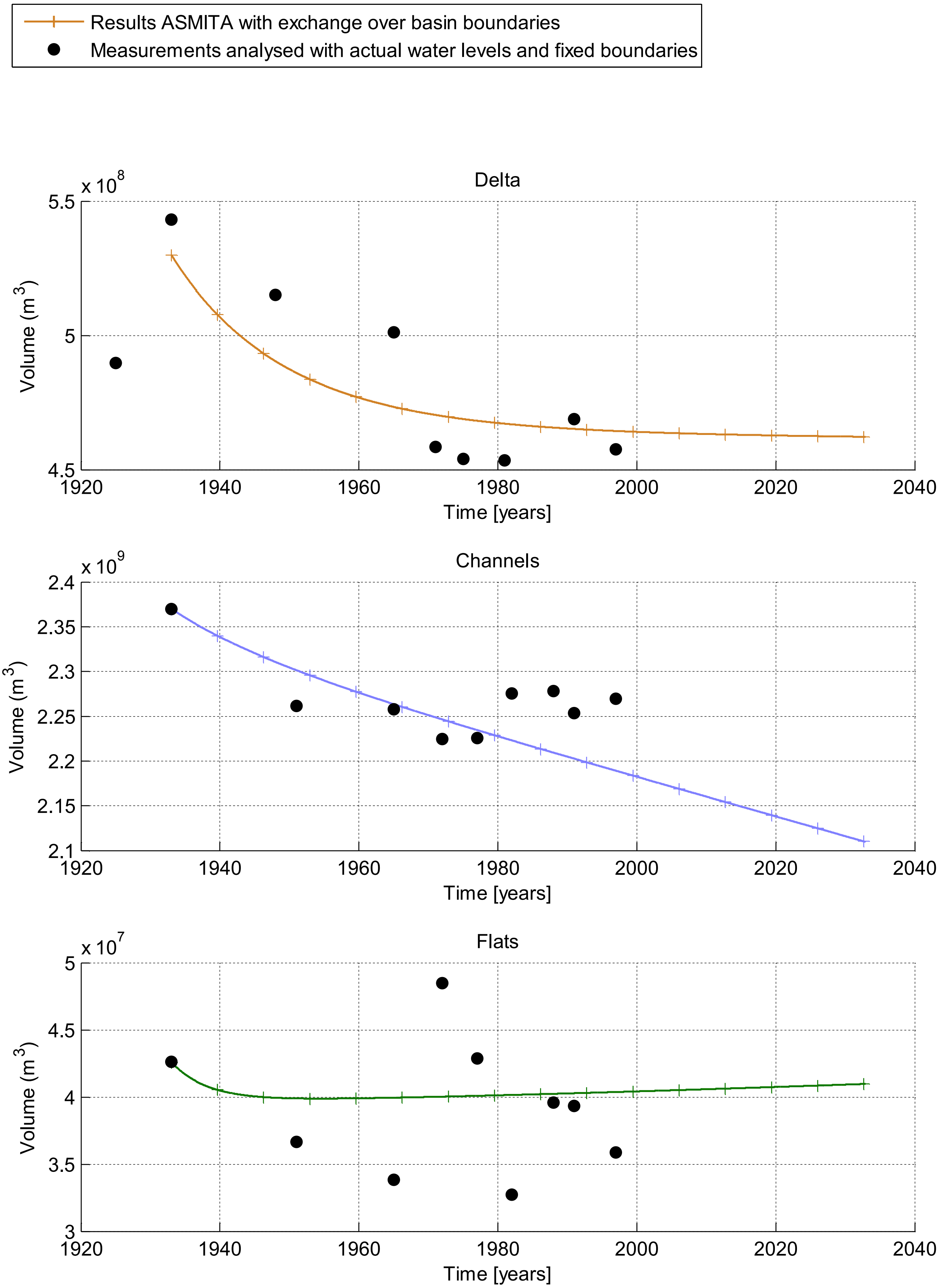
Comparison between measurements and simulation results of a model with actual water levels and fixed boundaries (section 5.4.2) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.7



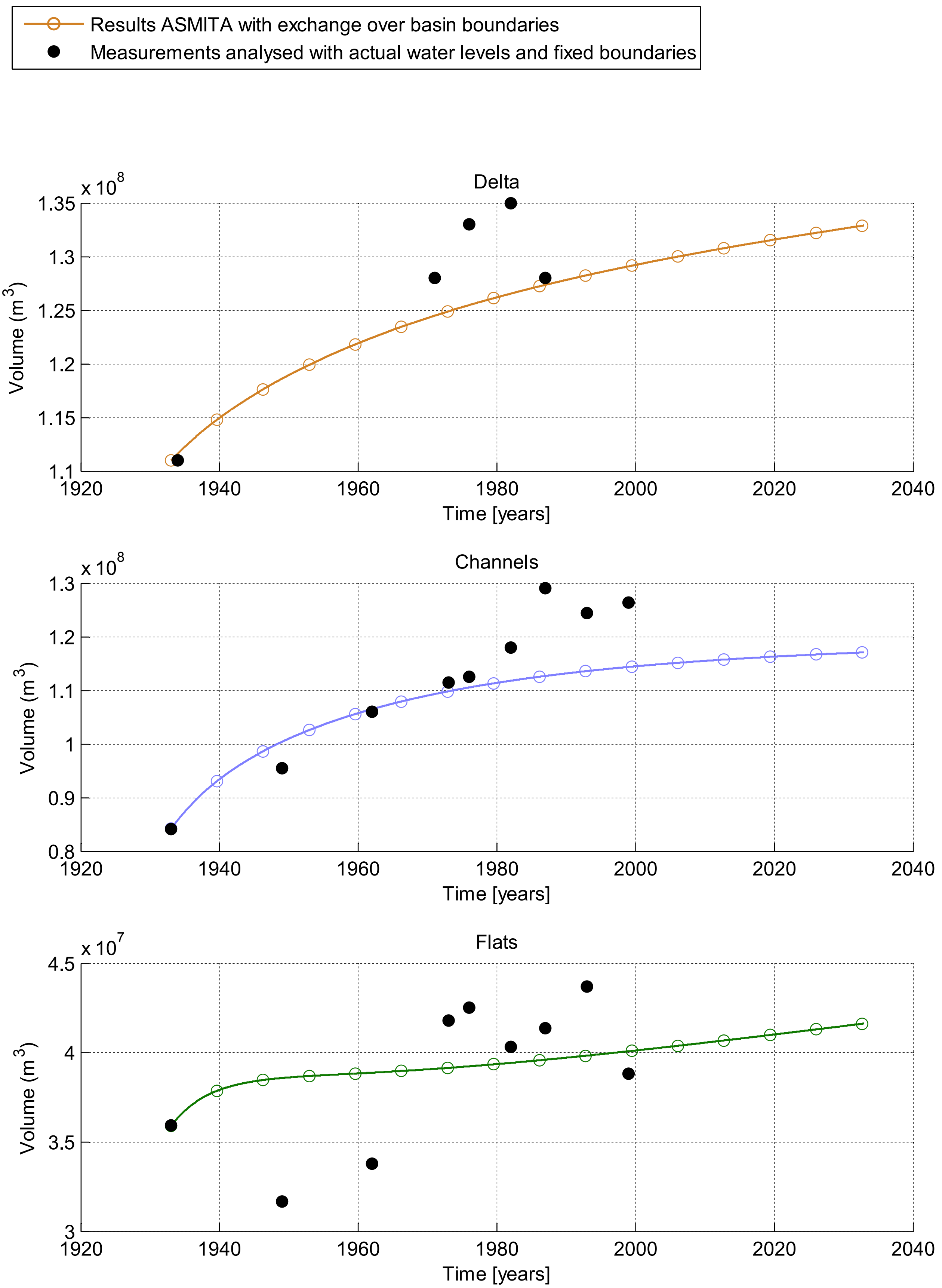
Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation with actual water levels and fixed boundaries (section 5.4.2)		Z4169
WL | DELFT HYDRAULICS		Figure I.8



Calculated equilibrium concentrations (upper plot) and development of tidal prisms (lower plots) when simulating with a model with actual water levels and fixed basin boundaries		Z4169
WL | DELFT HYDRAULICS		Figure I.9



Comparison between measurements and simulation results of a model with exchange over basin boundaries (section 5.4.3) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.10

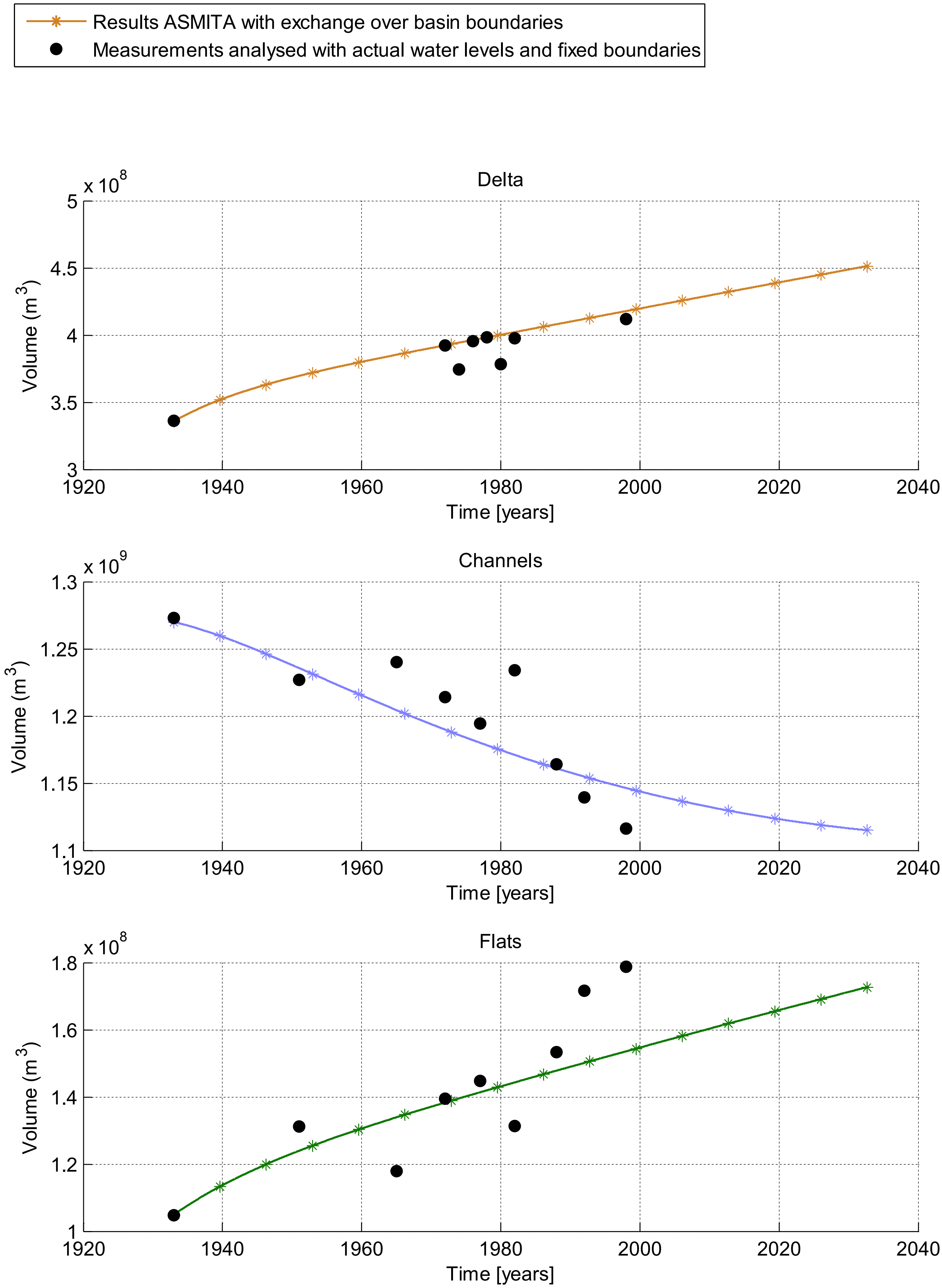


Comparison between measurements and simulation results of
a model with exchange over basin boundaries (section 5.4.3)
for Eierlandse gat

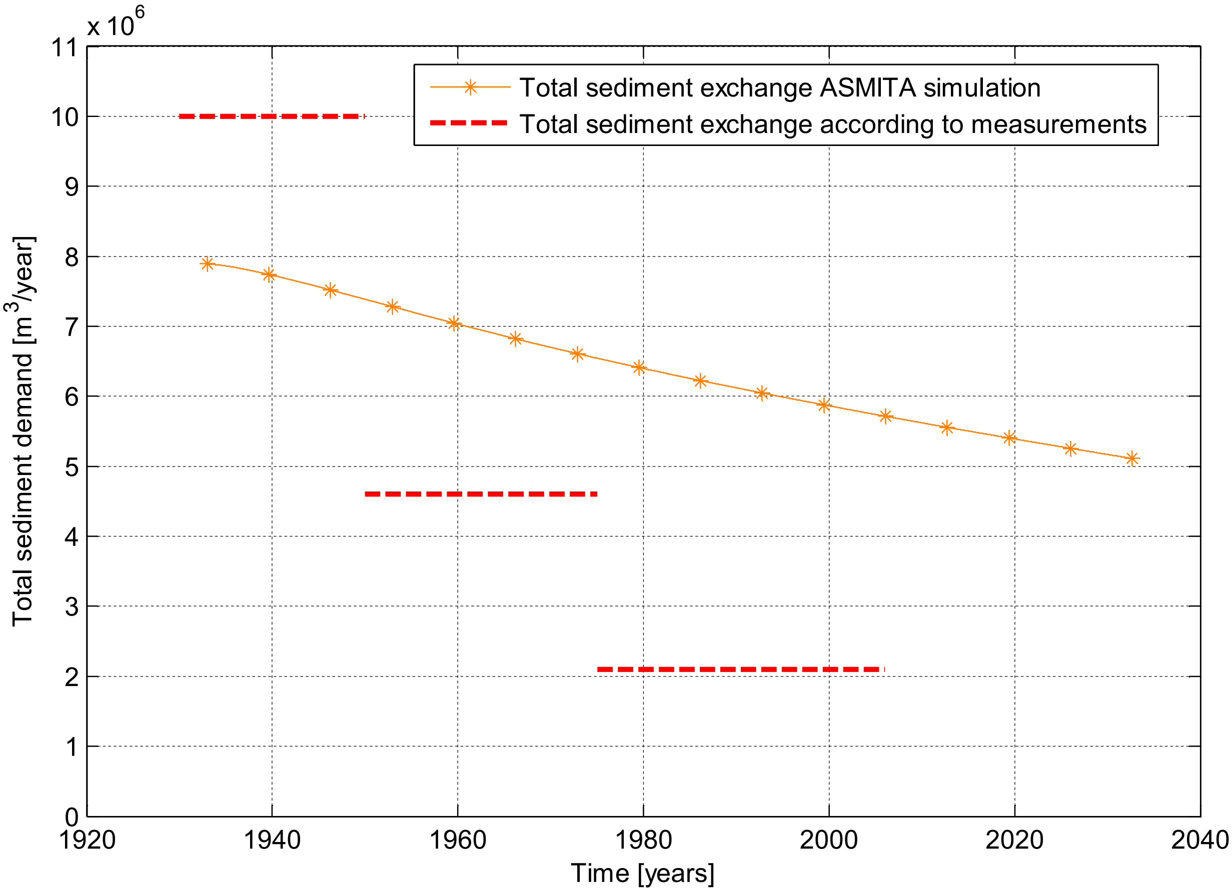
Z4169

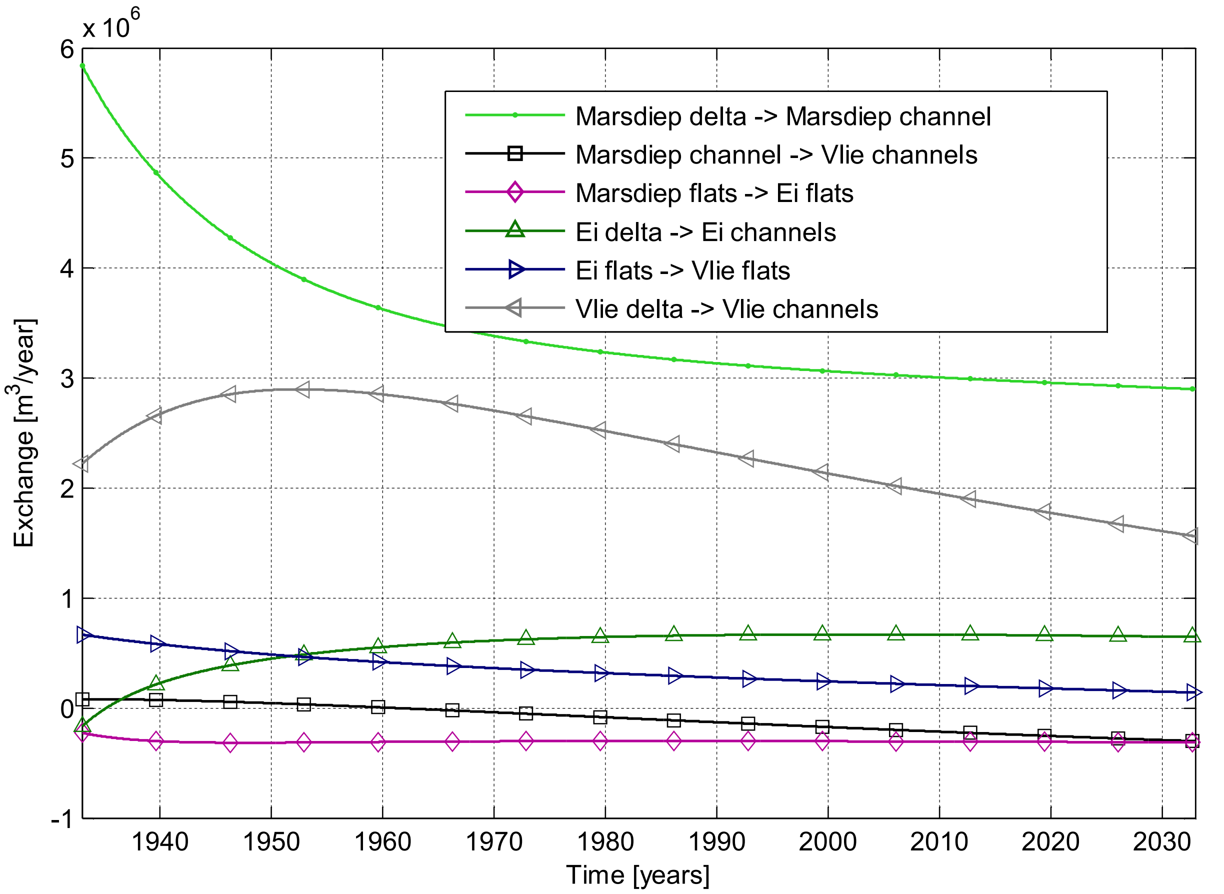
WL | DELFT HYDRAULICS

Figure I.11

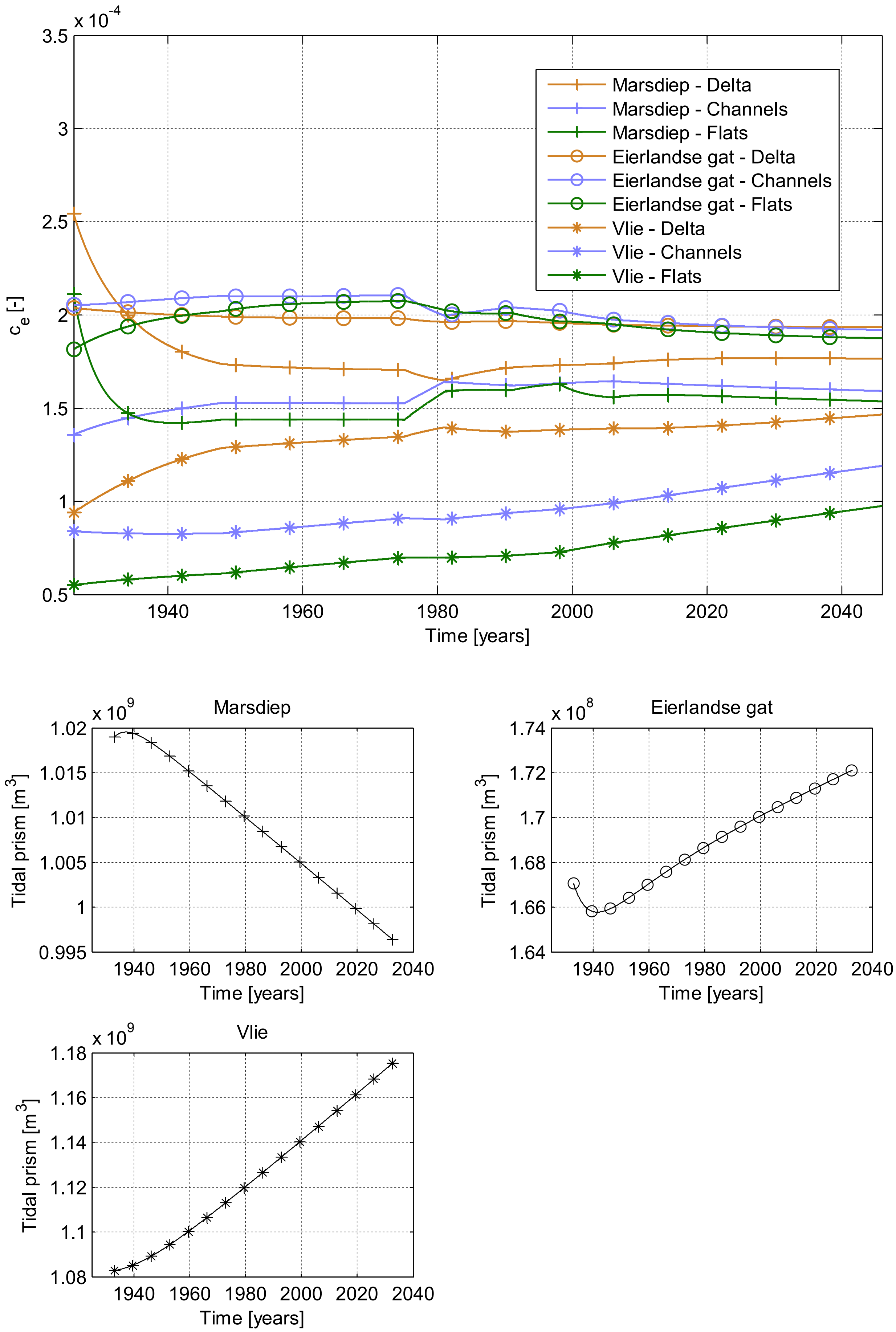


Comparison between measurements and simulation results of a model with exchange over basin boundaries (section 5.4.3) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.12

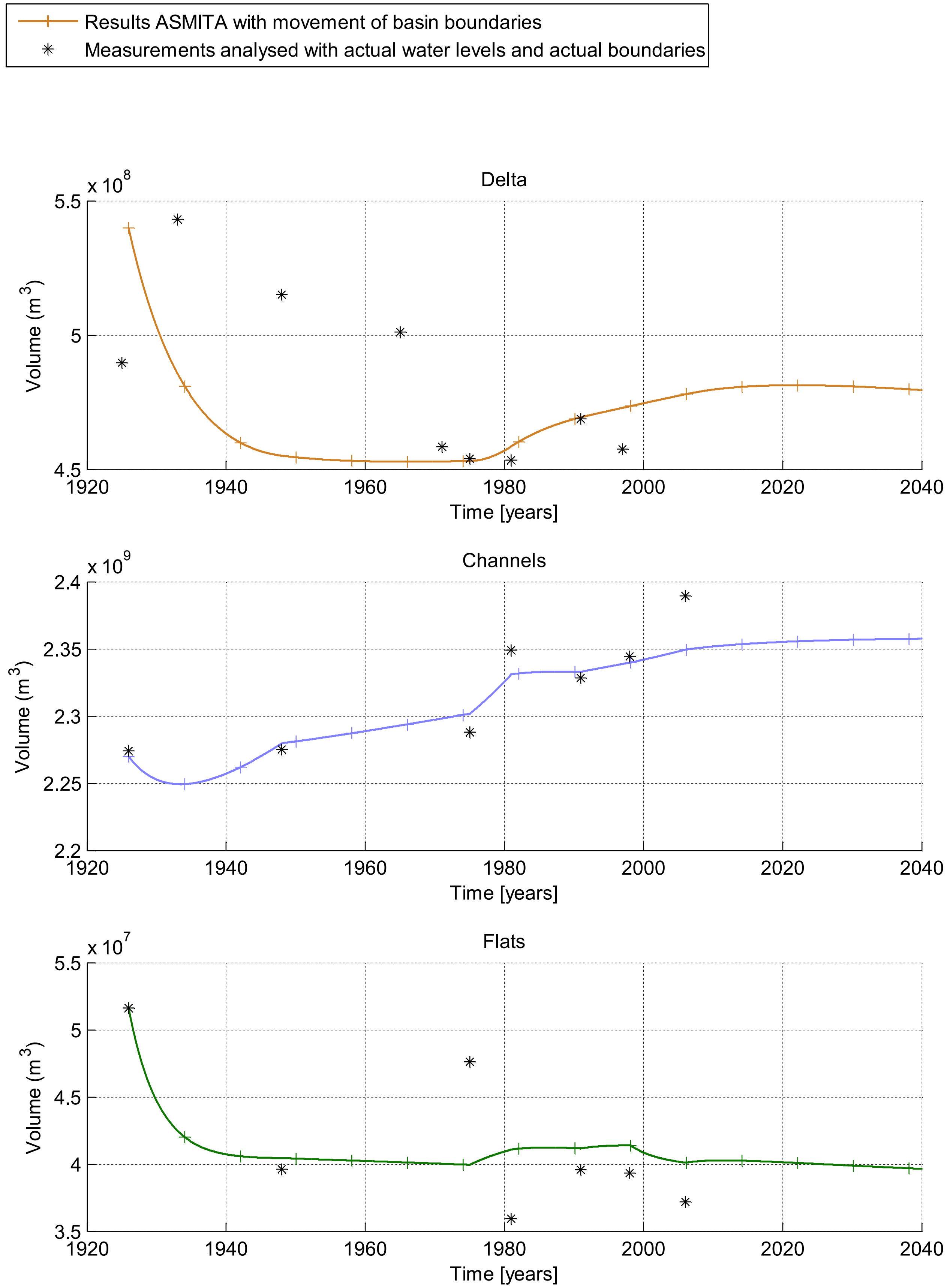




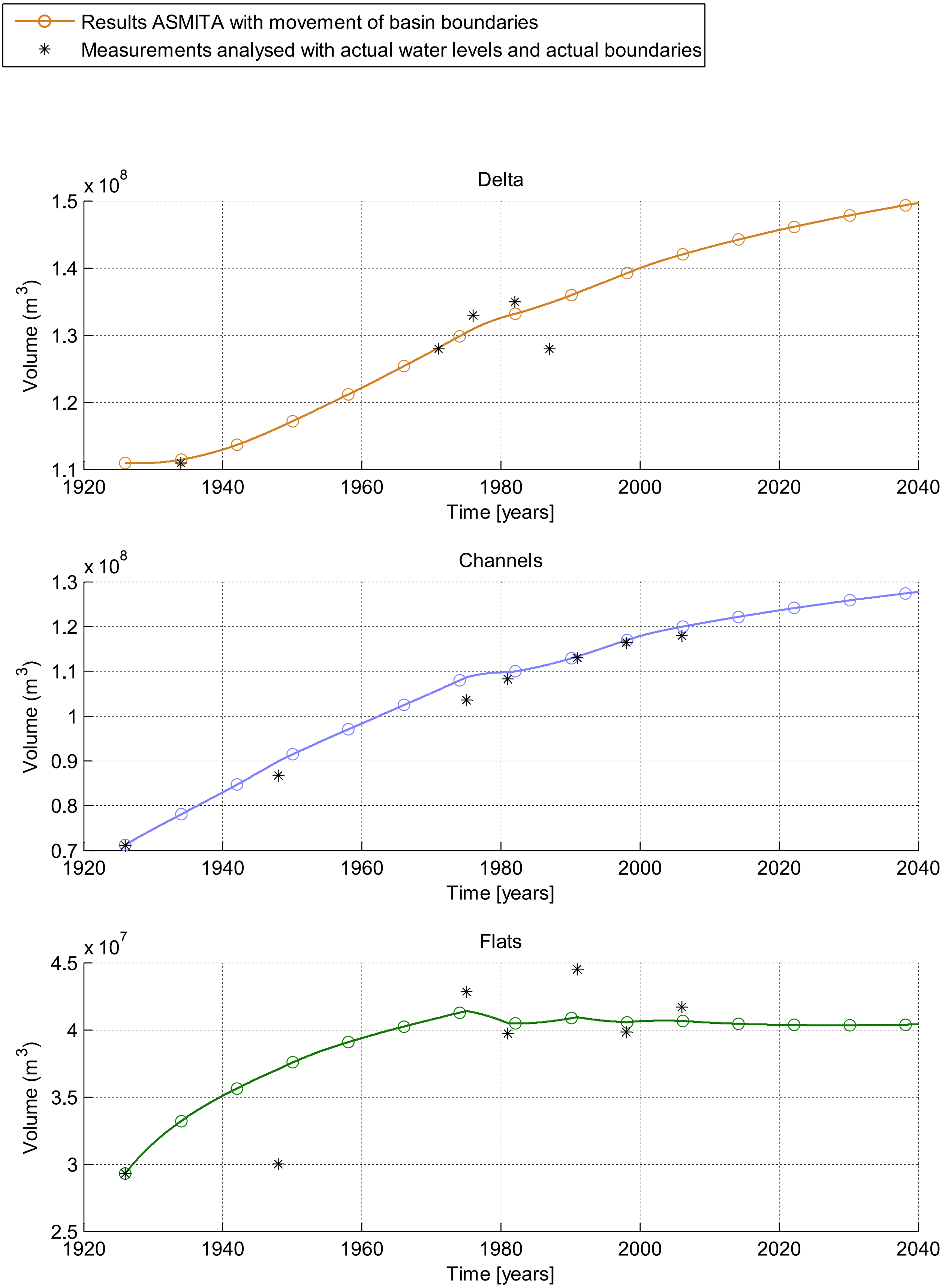
Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation with exchange over basin boundaries (section 5.4.3)		Z4269
WL | DELFT HYDRAULICS		Figure I.13



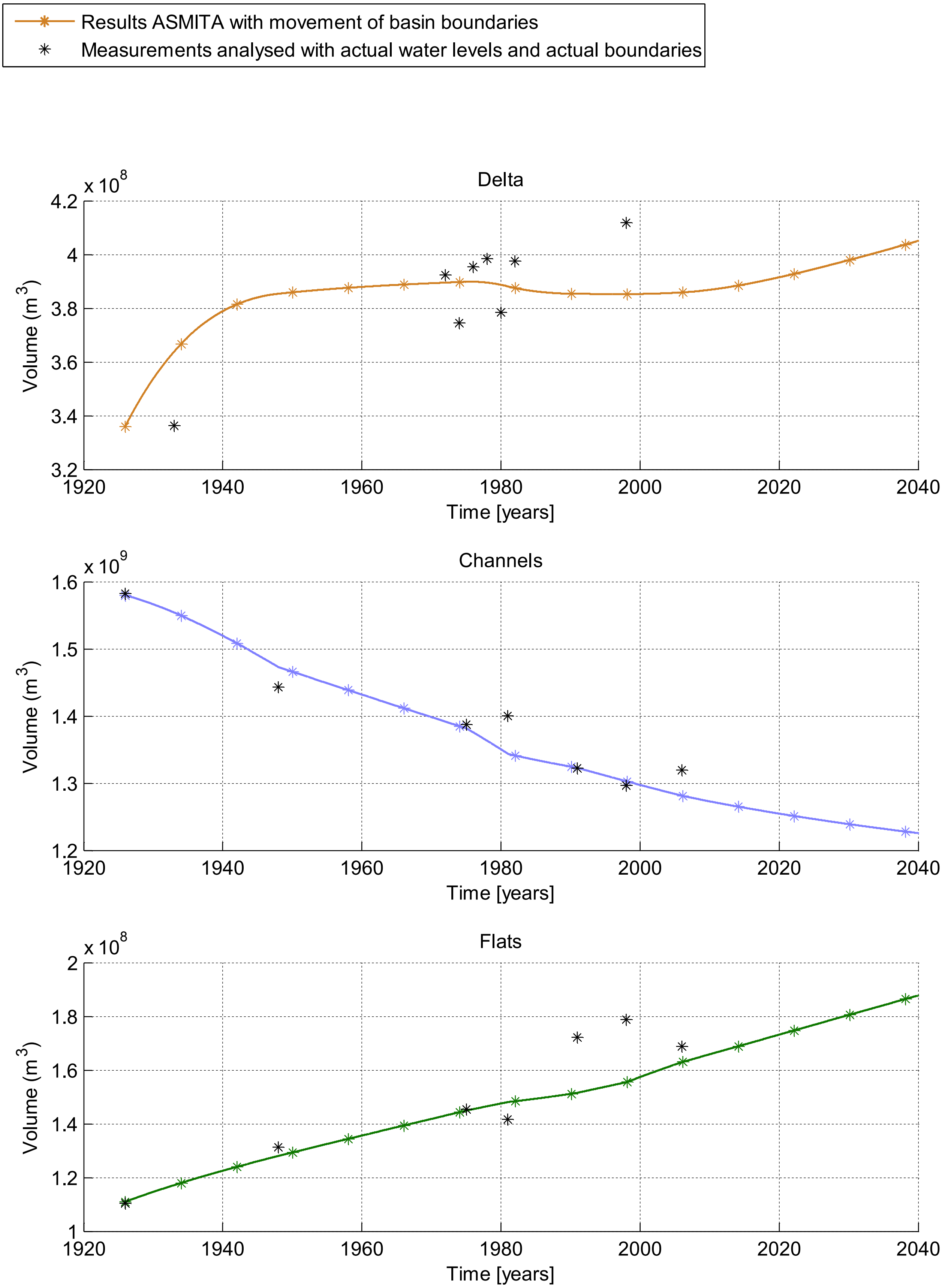
Calculated equilibrium concentrations (upper plot) and development of tidal prisms (lower plots) when simulating with a model that includes sediment exchange over basin boundaries		Z4169
WL | DELFT HYDRAULICS		Figure I.14



Comparison between measurements and simulation results of a model with actual water levels and basin boundaries (section 5.4.4) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.15



Comparison between measurements and simulation results of a model with actual water levels and basin boundaries (section 5.4.4) for Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure I.16

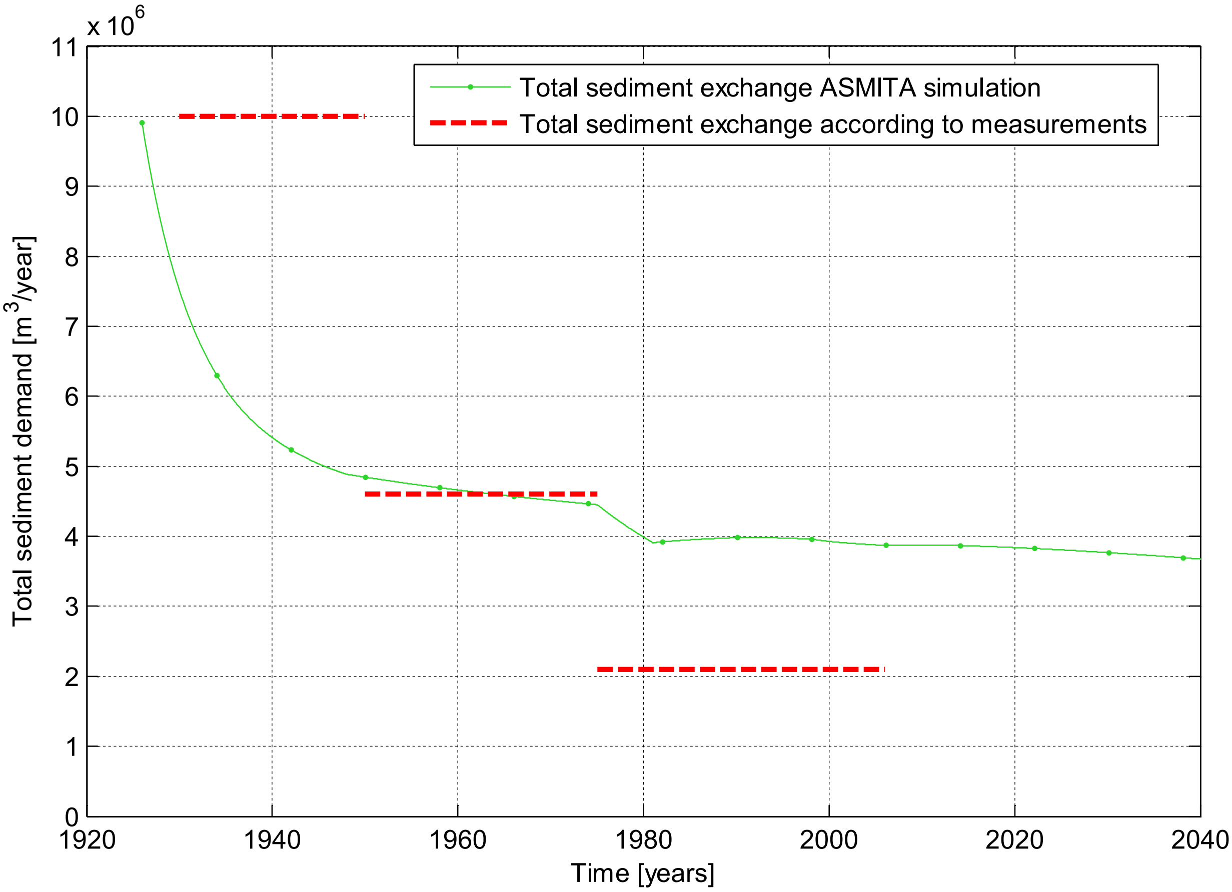


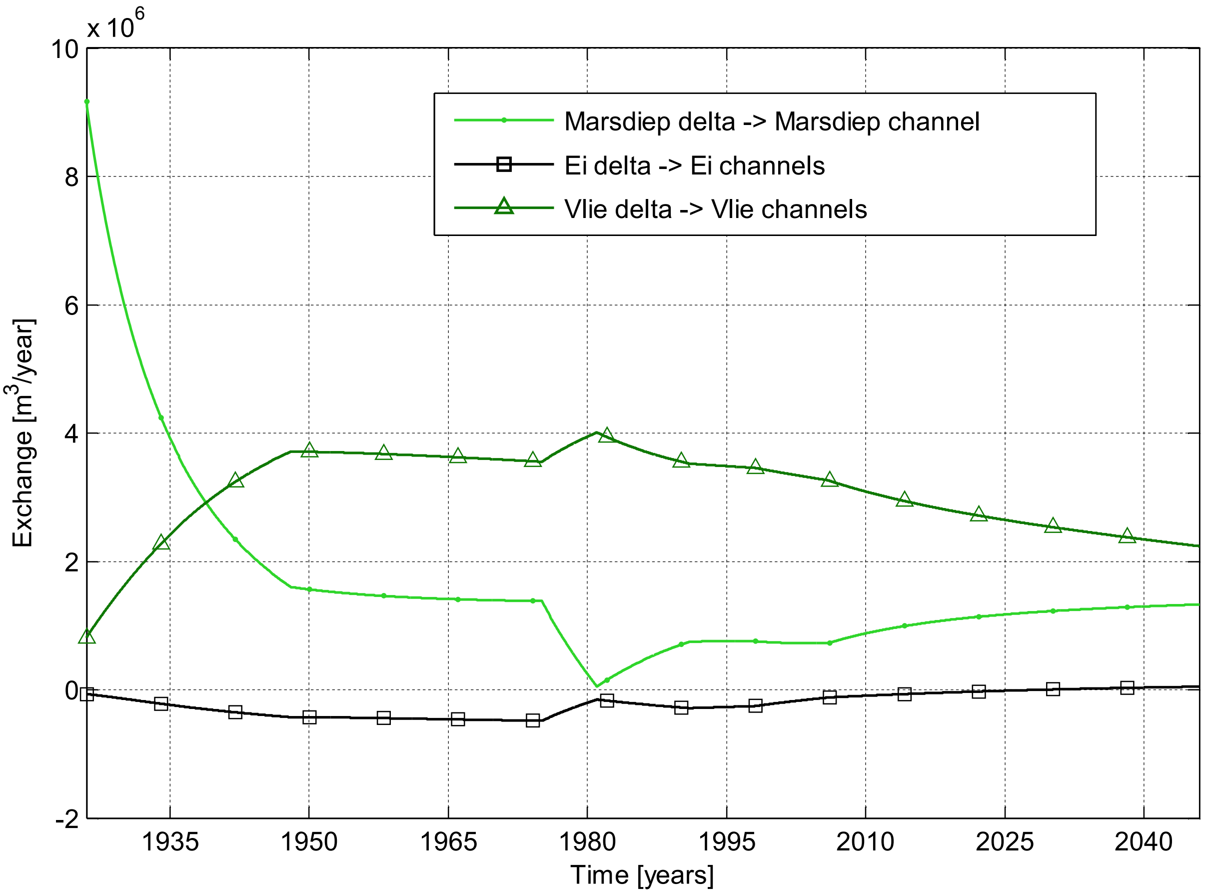
Comparison between measurements and simulation results of
a model with actual water levels and basin boundaries (section 5.4.4)
for Vlie

Z4169

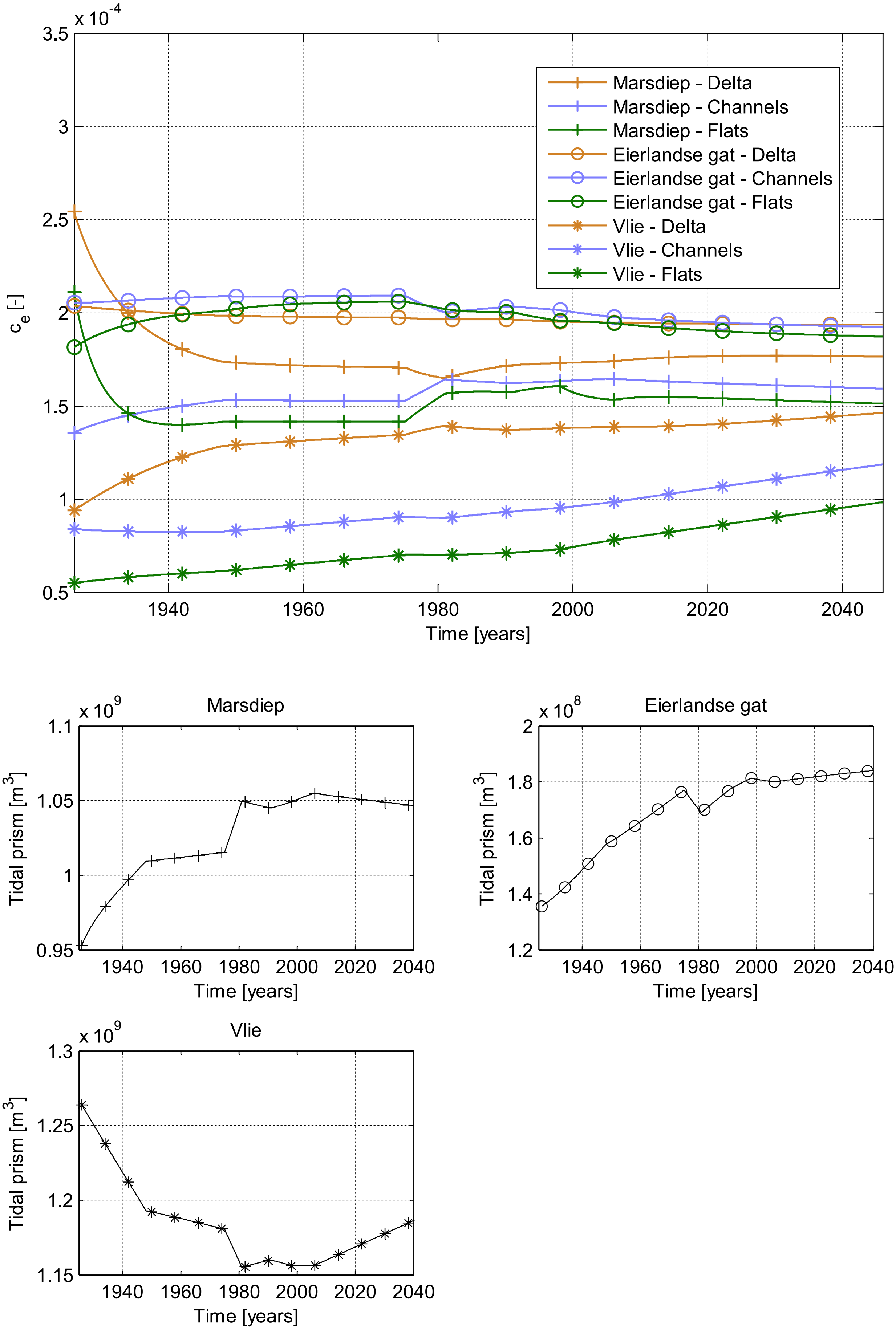
WL | DELFT HYDRAULICS

Figure I.17

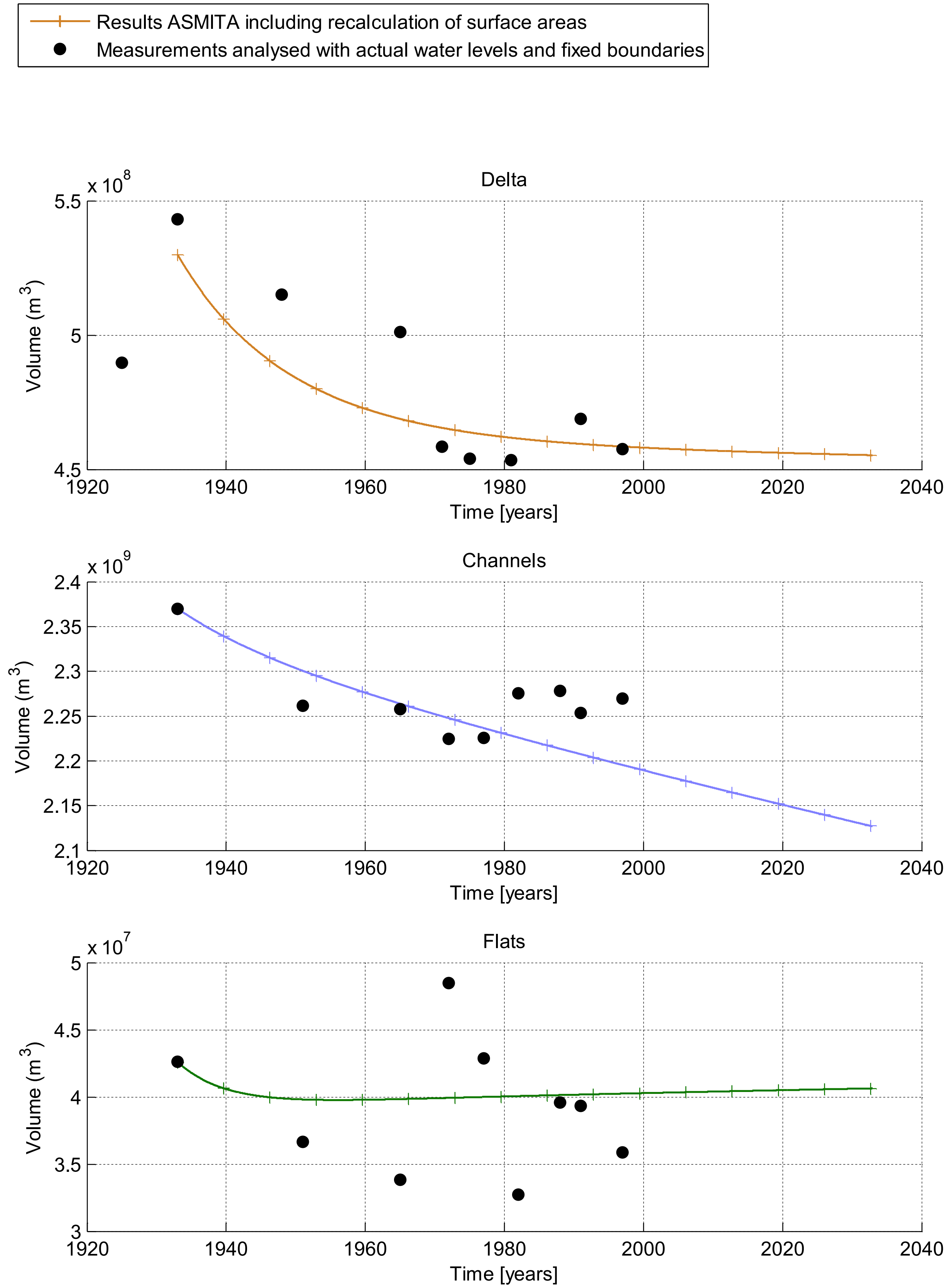




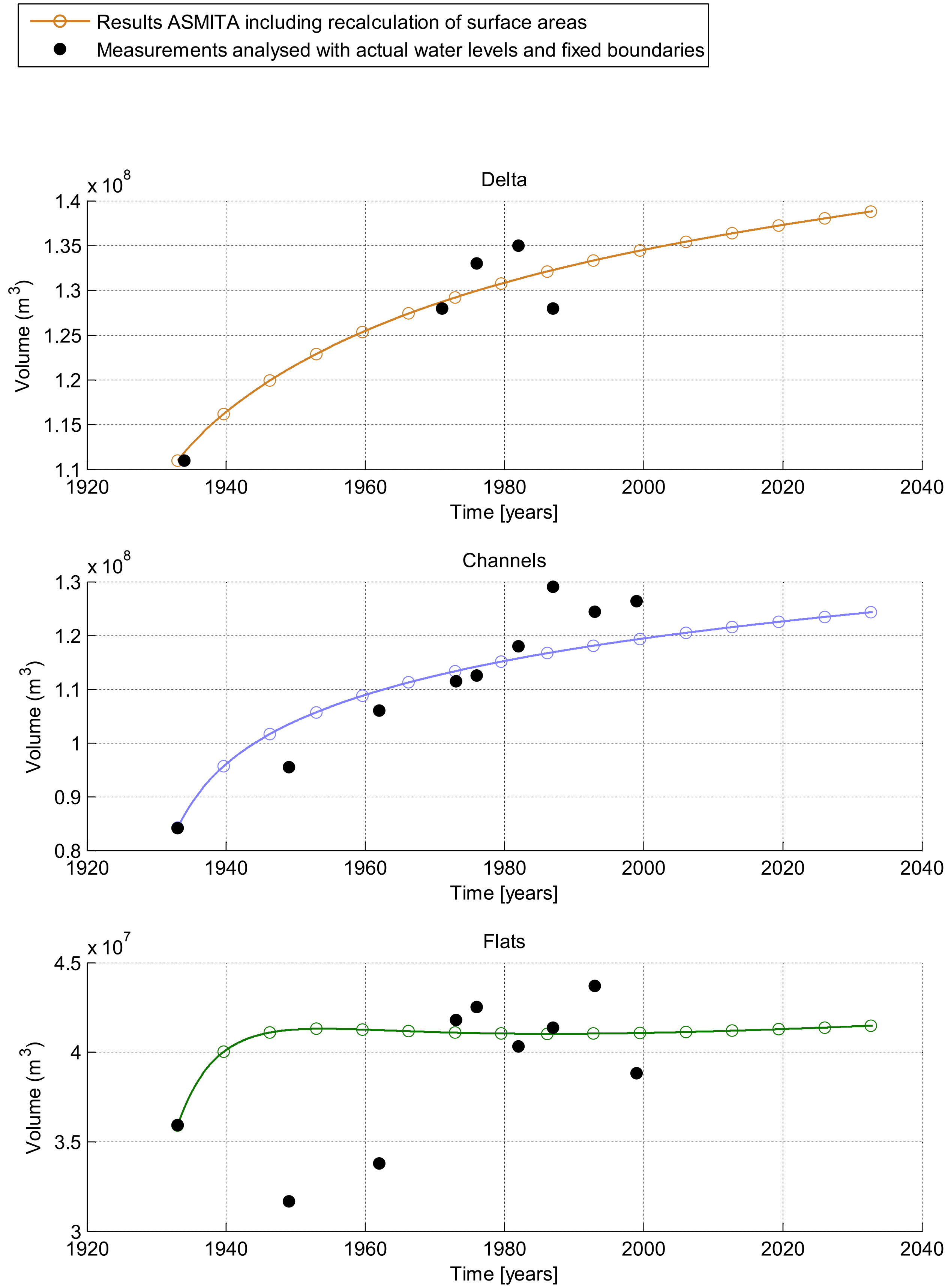
Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation including movement of basin boundaries (section 5.4.4)	Z4169
WL | DELFT HYDRAULICS	Figure I.18



Calculated equilibrium concentrations (upper plot) and development of tidal prisms (lower plots) when simulating with a model that includes movement of the basin boundaries		Z4169
WL | DELFT HYDRAULICS		Figure I.19



Comparison between measurements and simulation results of a model including recalculation of element surface areas (section 5.4.5) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.20

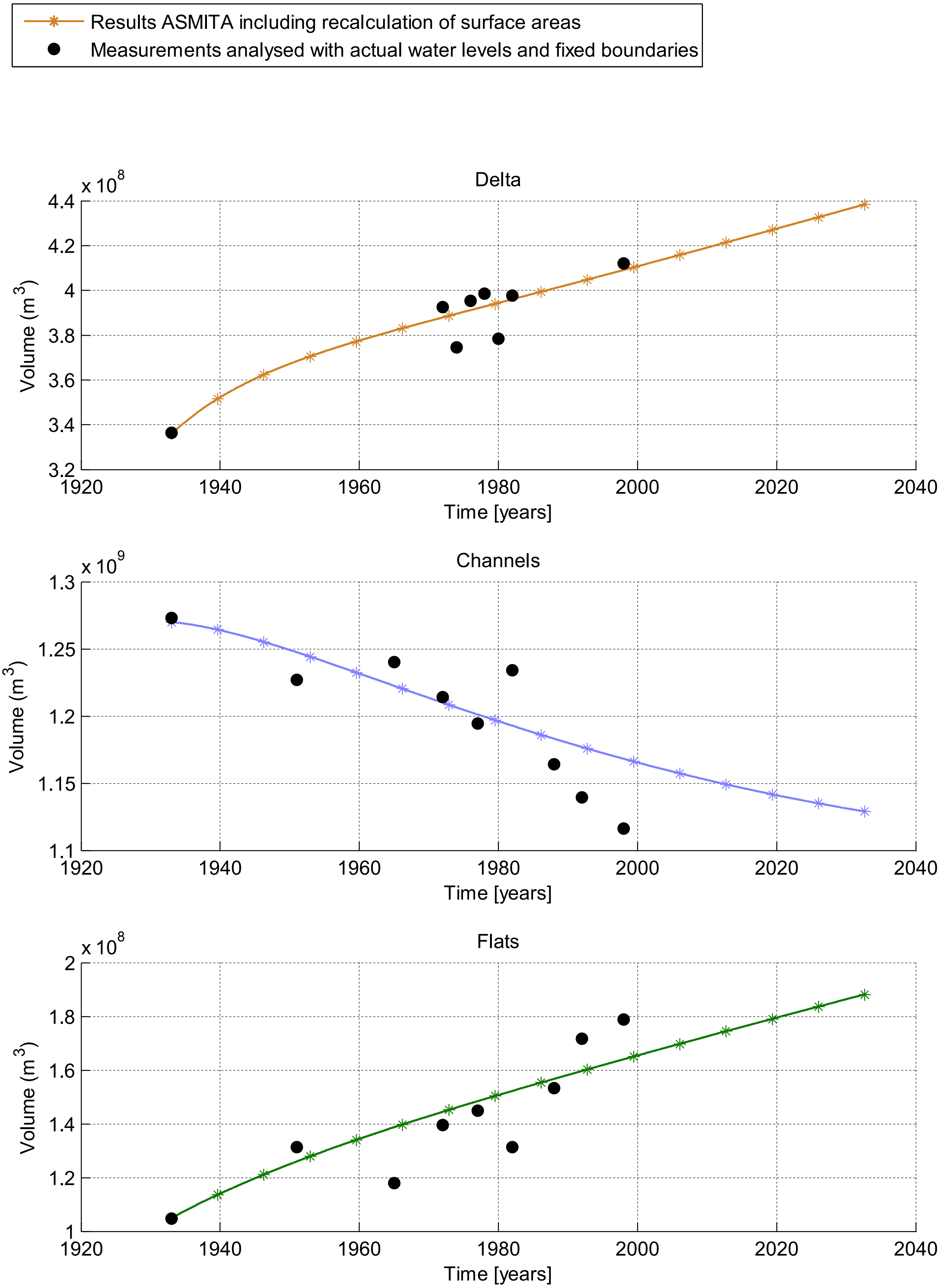


Comparison between measurements and simulation results of
a model including recalculation of element surface areas (section 5.4.5)
for Eierlandse gat

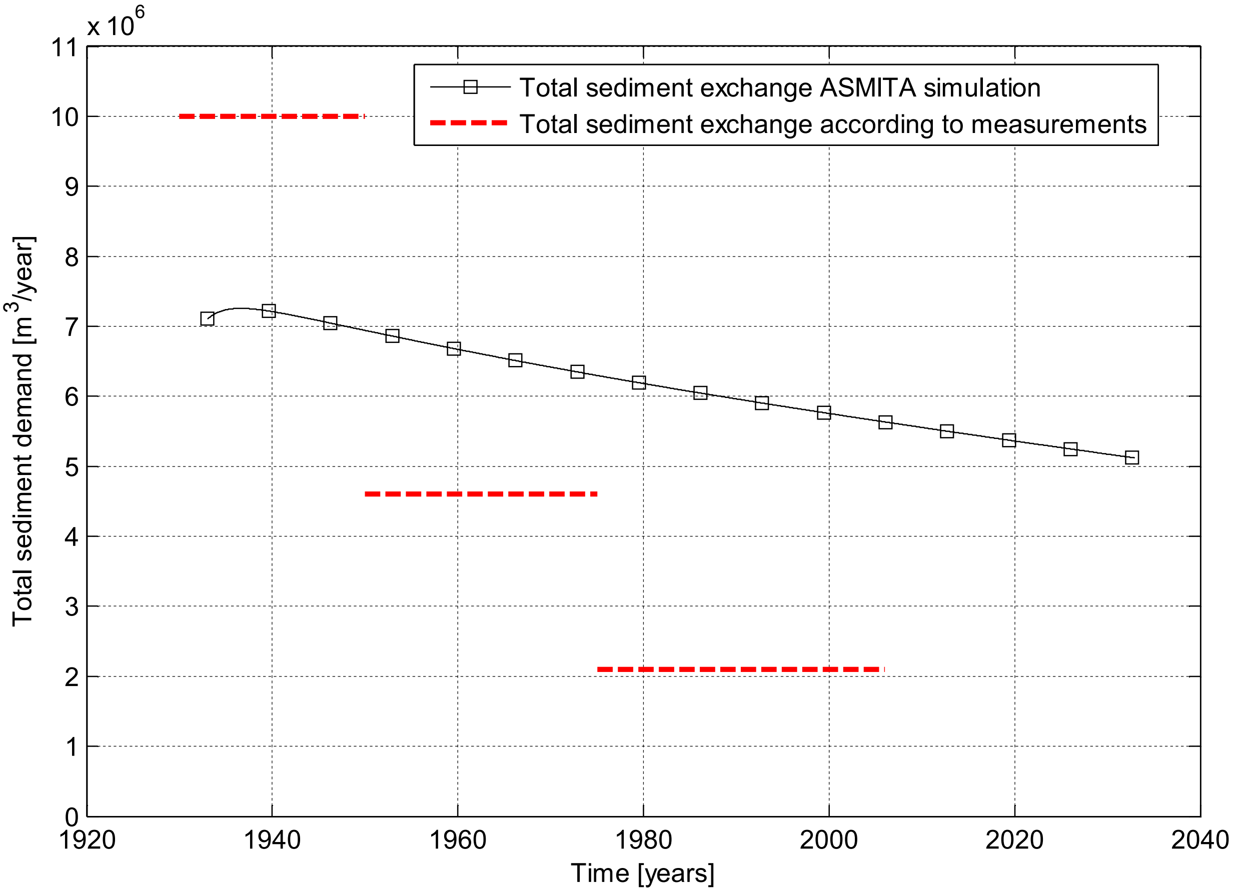
Z4169

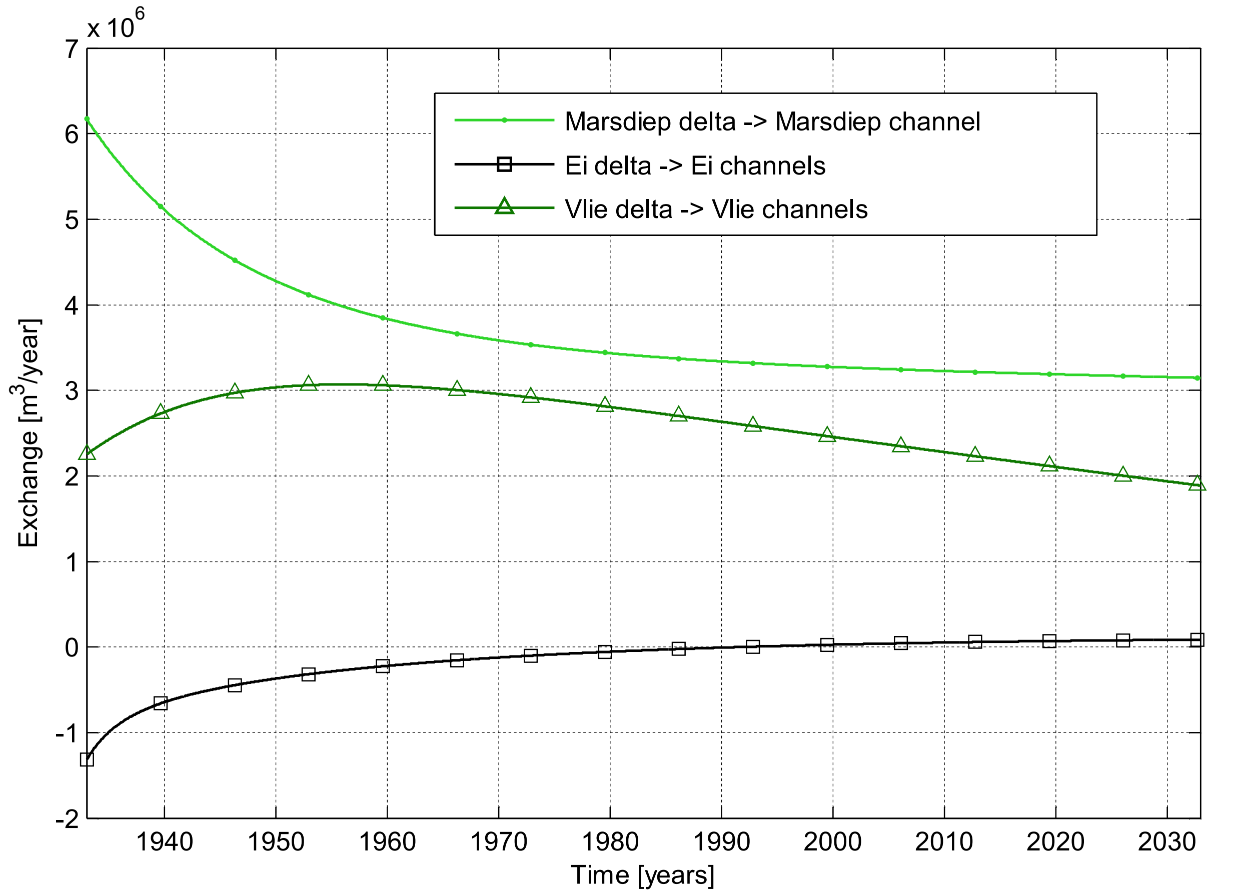
WL | DELFT HYDRAULICS

Figure I.21

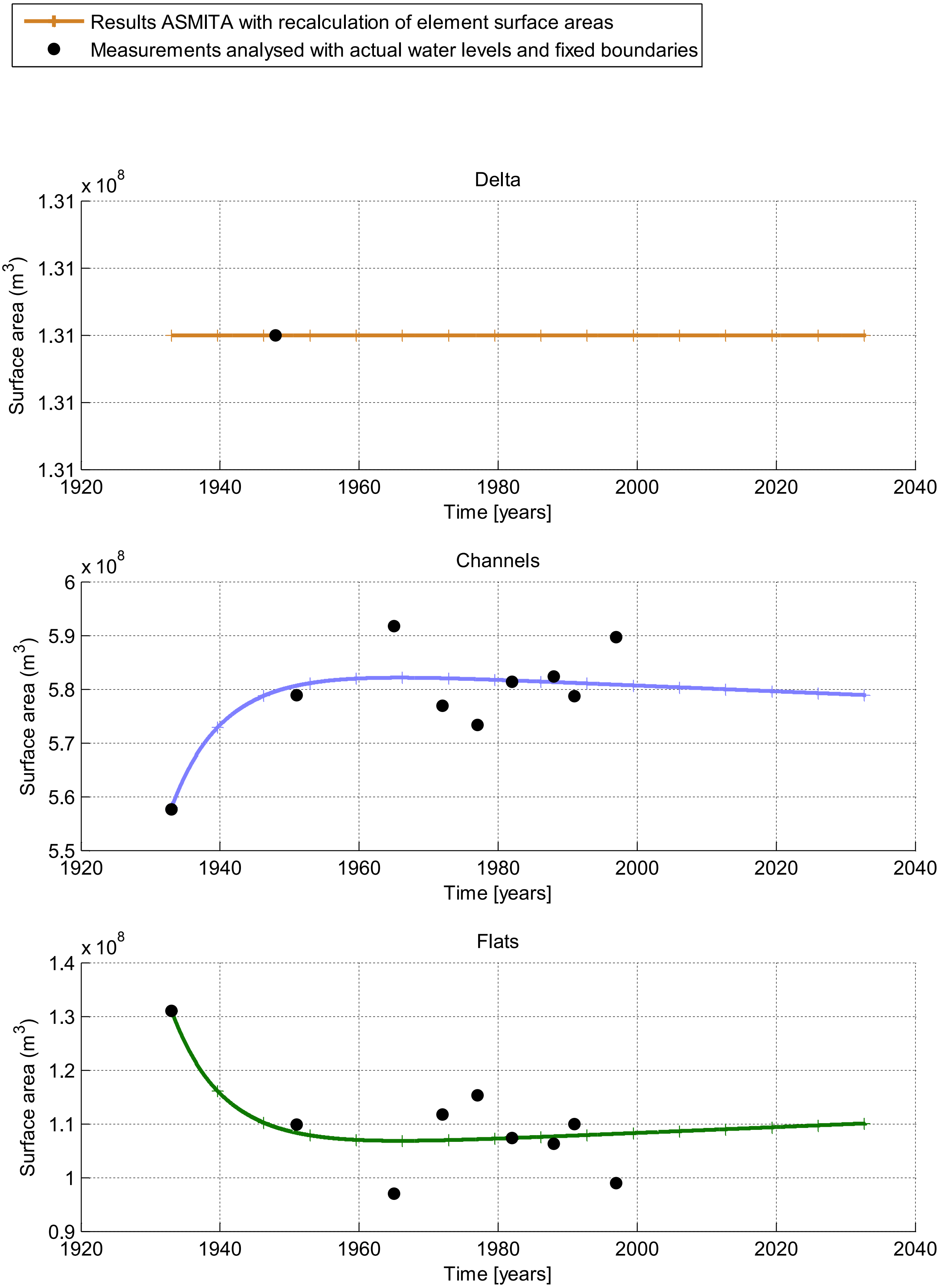


Comparison between measurements and simulation results of a model including recalculation of element surface areas (section 5.4.5) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.22

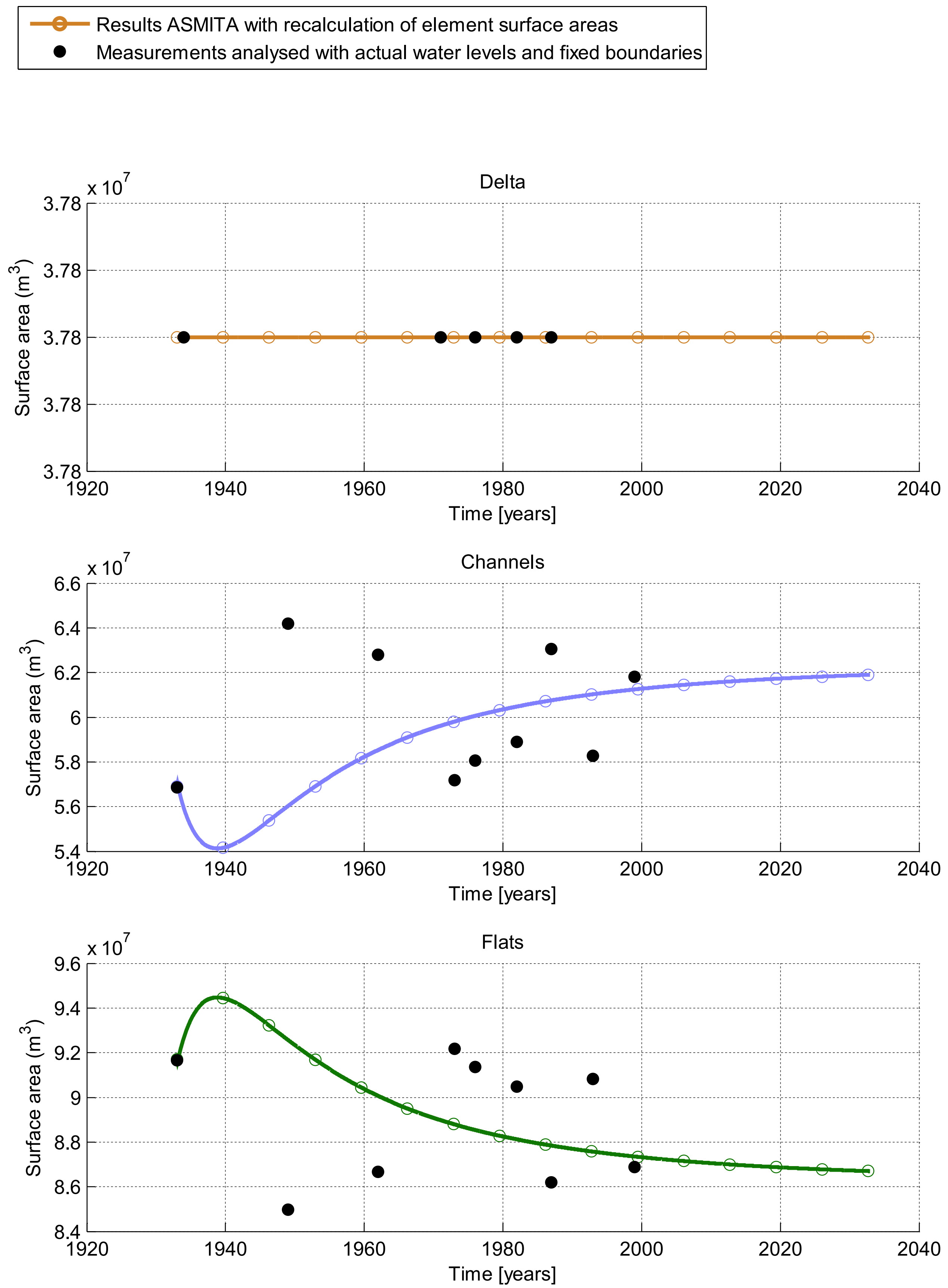




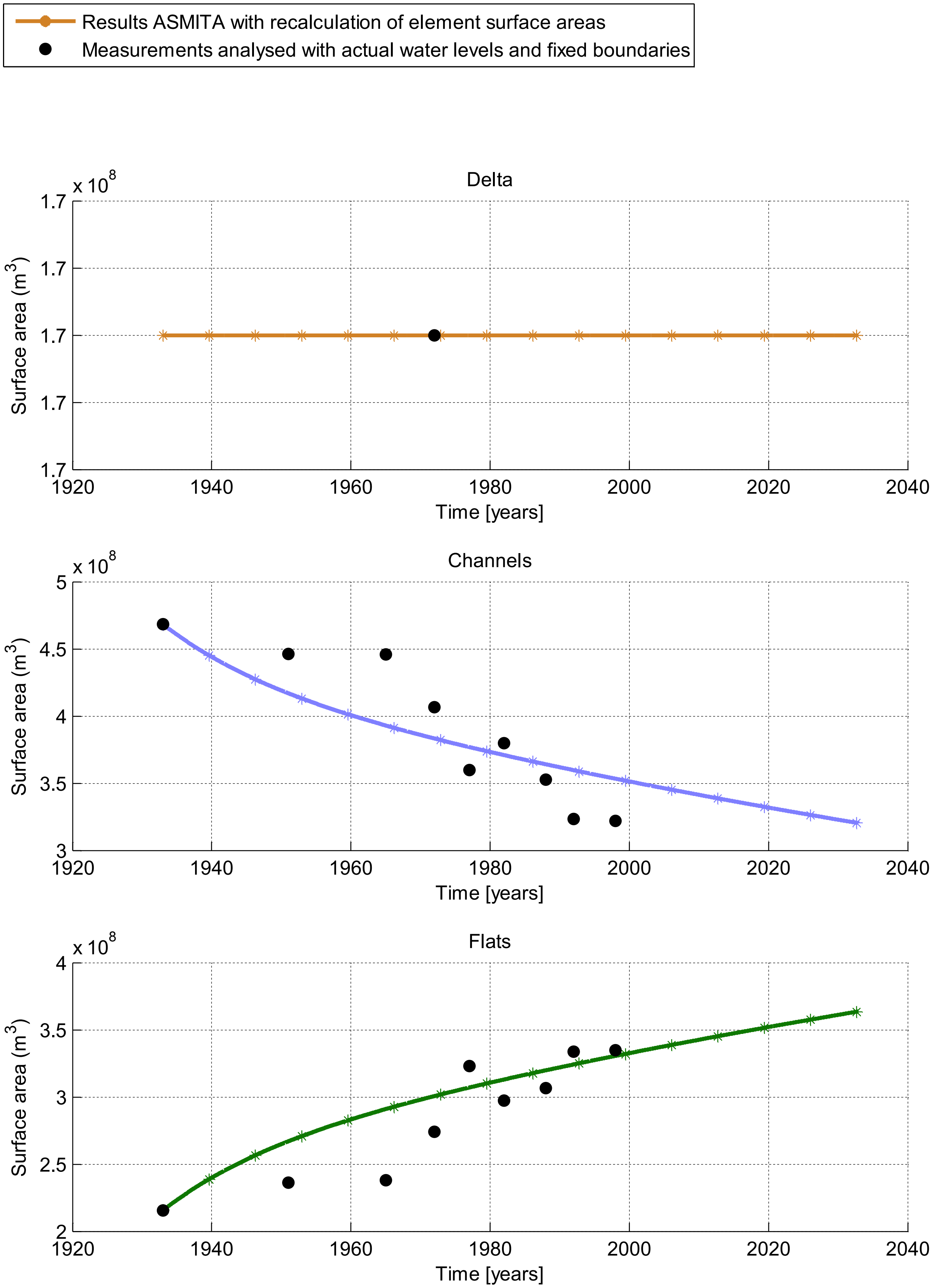
Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation with recalculation of element surface areas (section 5.4.5)		Z4160
WL | DELFT HYDRAULICS		Figure I.23



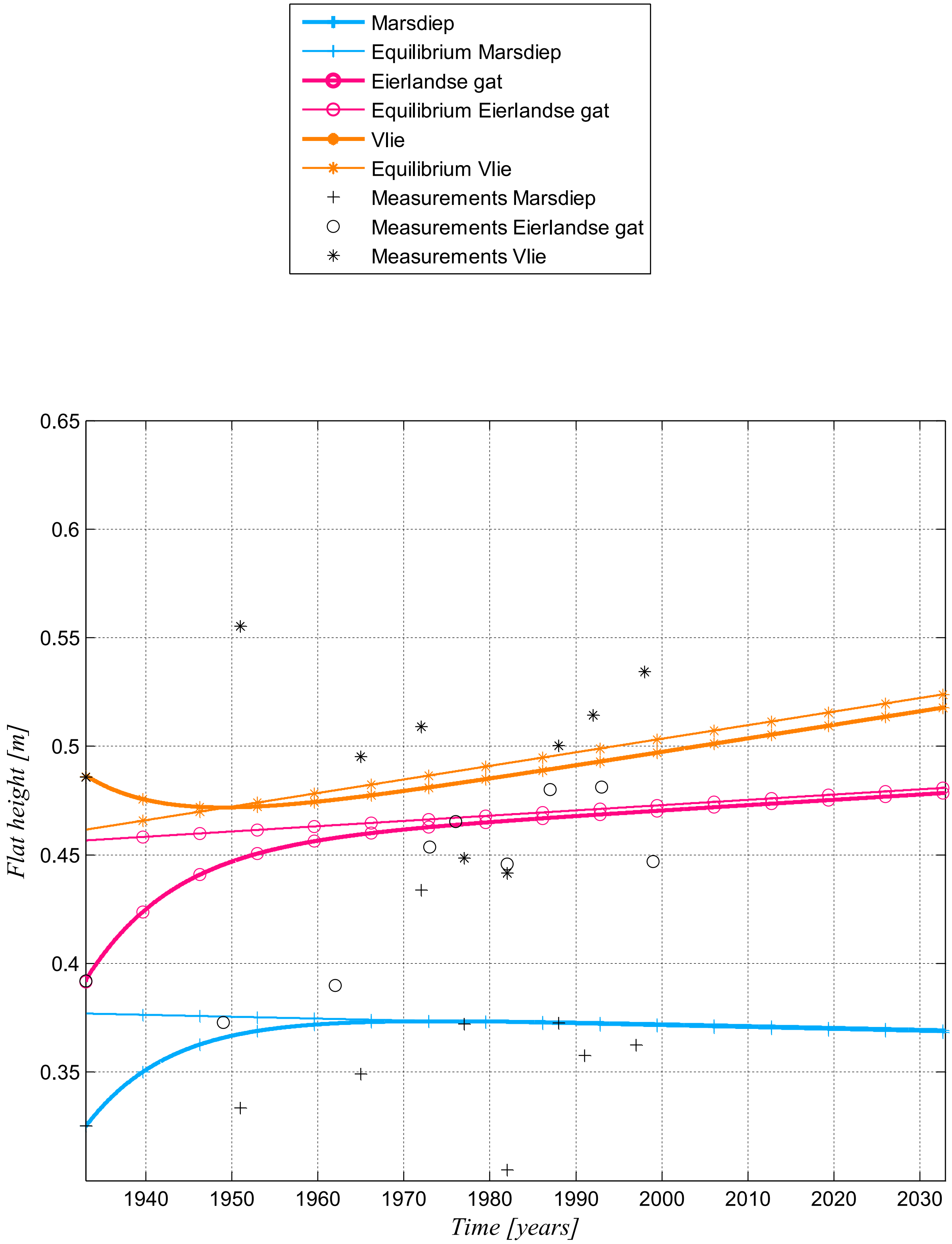
Comparison between measurements and simulation results of a model with recalculation of element surface areas (section 5.4.5) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.24



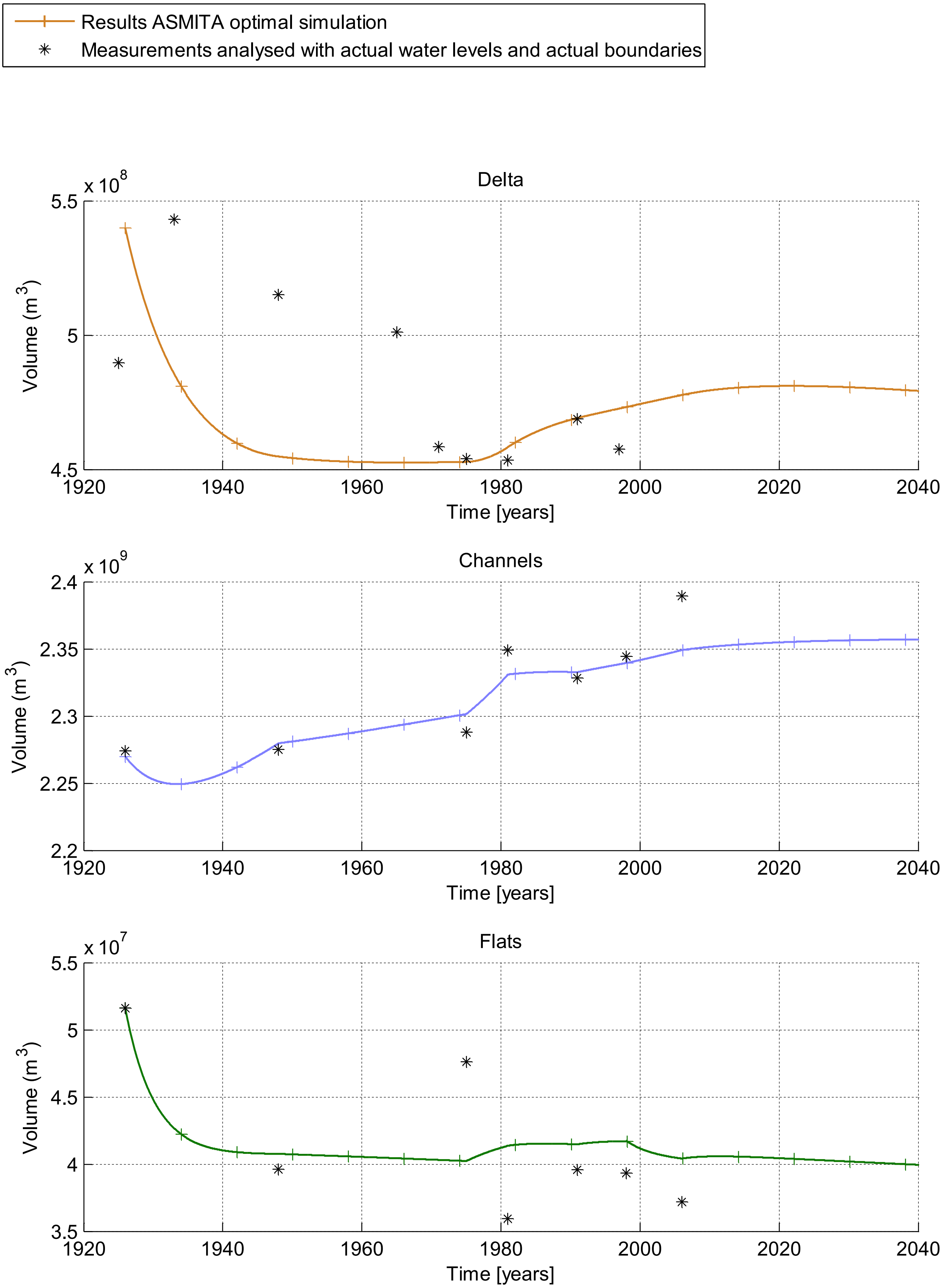
Comparison between measurements and simulation results of a model with recalculation of element surface areas (section 5.4.5) for Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure I.25



Comparison between measurements and simulation results of a model with recalculation of element surface areas (section 5.4.5) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.26



Comparison between measured mean flat heights and mean flat height developments calculated by the model used to assess the effect of recalculation of surface areas (section 5.4.5)		Z4169
WL | DELFT HYDRAULICS		Figure I.27

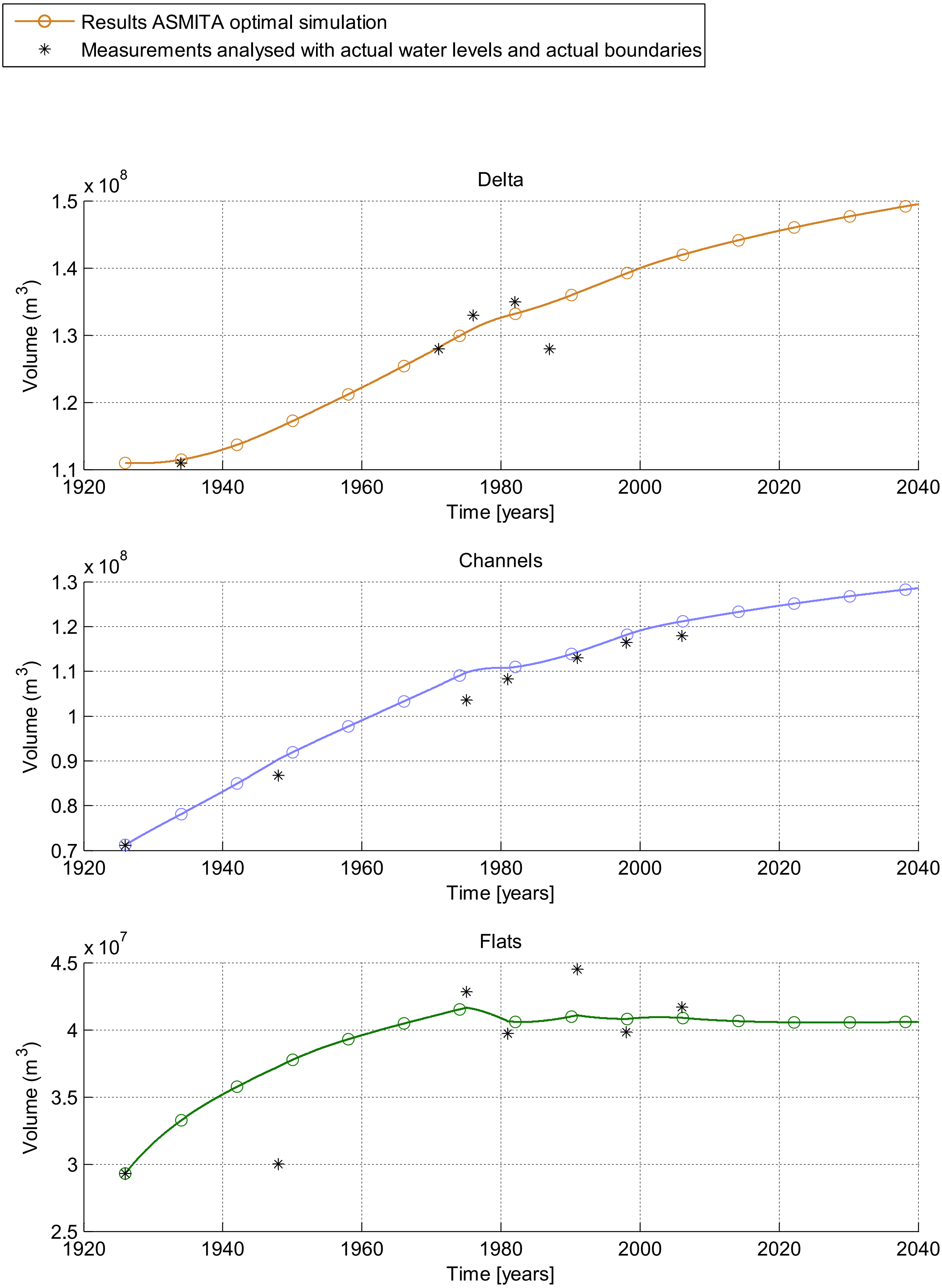


Comparison between measurements and simulation results of a model with optimal configuration (section 5.5) for Marsdiep

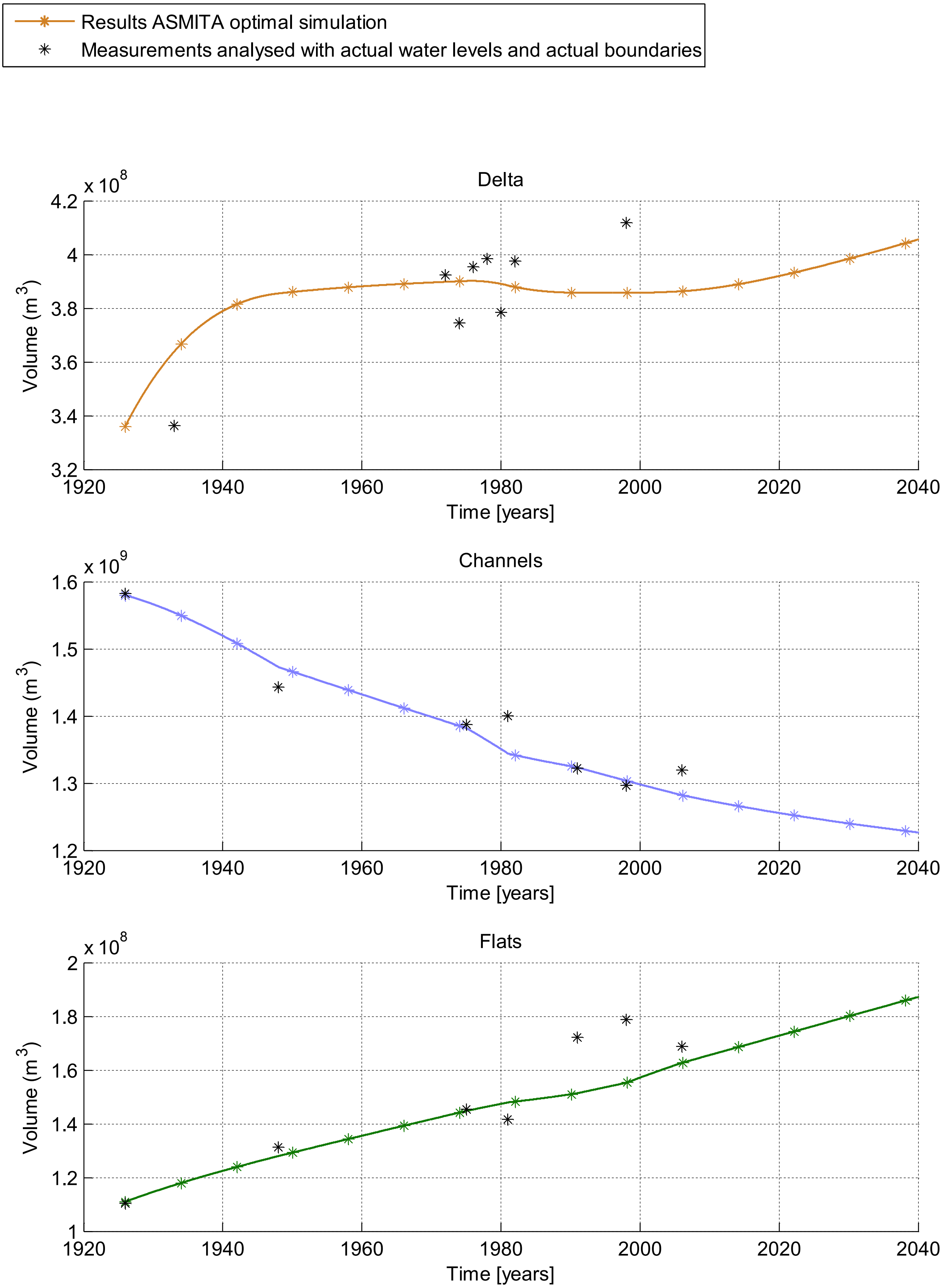
Z4169

WL | DELFT HYDRAULICS

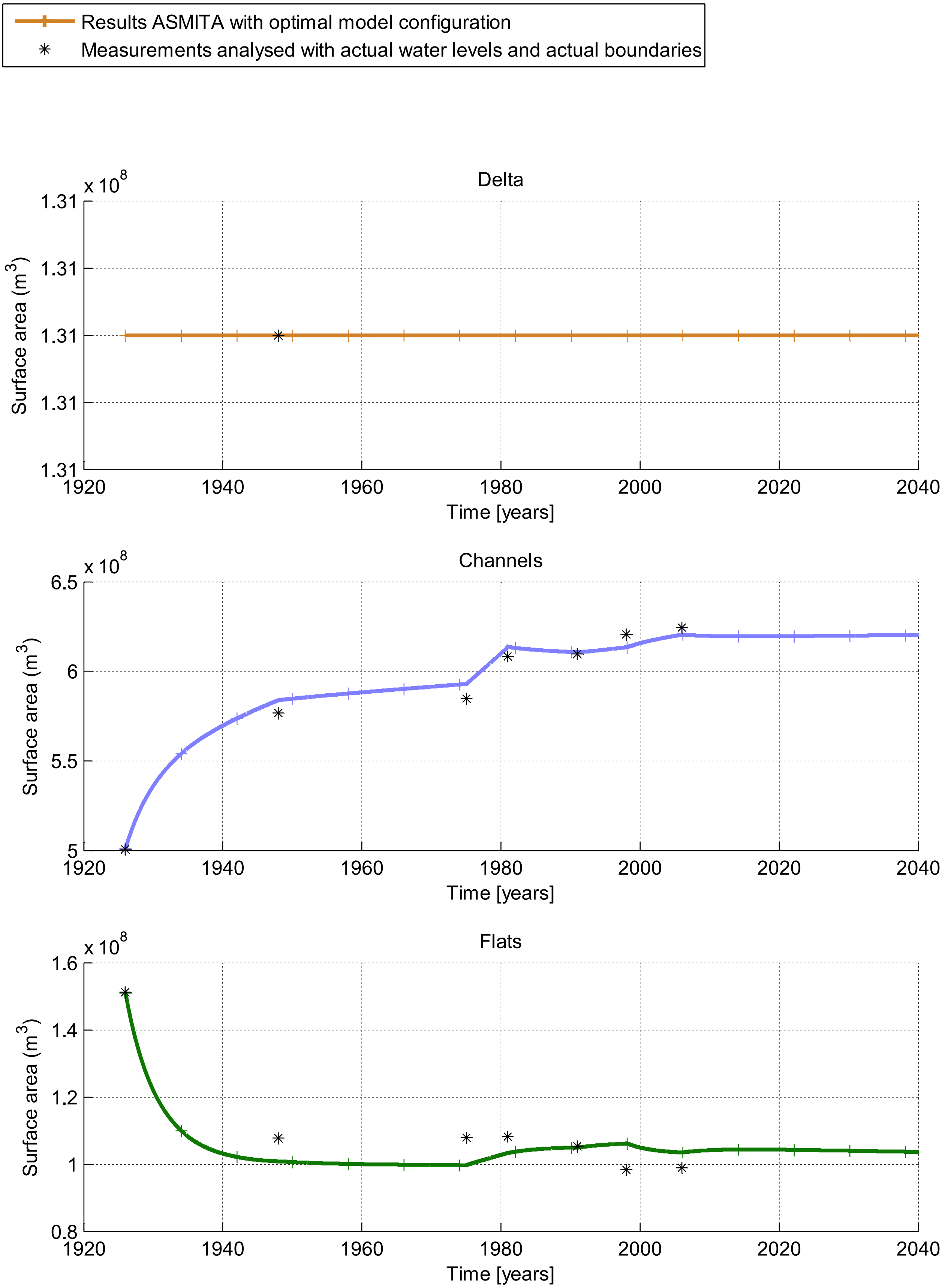
Figure I.28



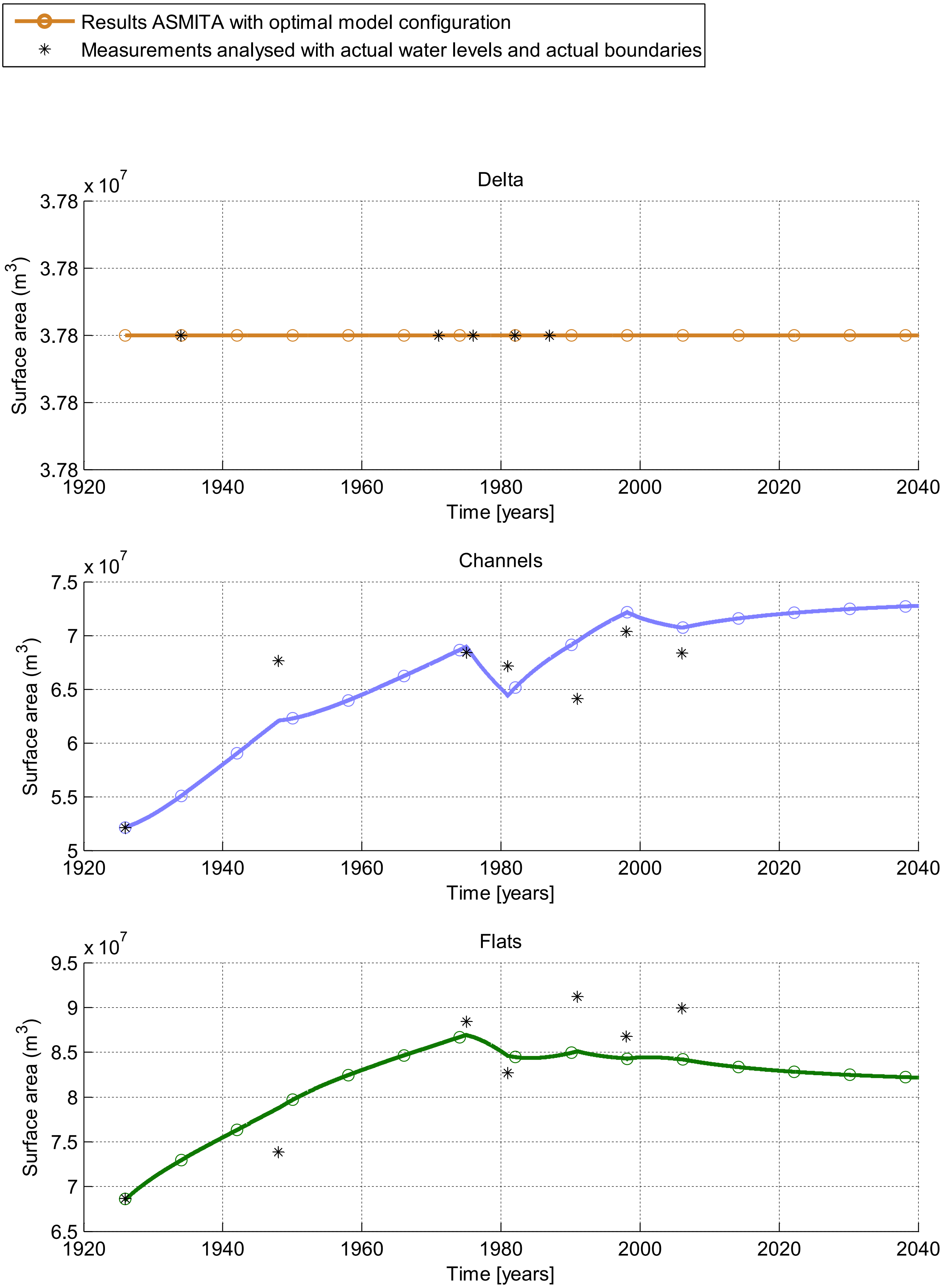
Comparison between measurements and simulation results of a model with optimal configuration (section 5.5) for Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure I.29



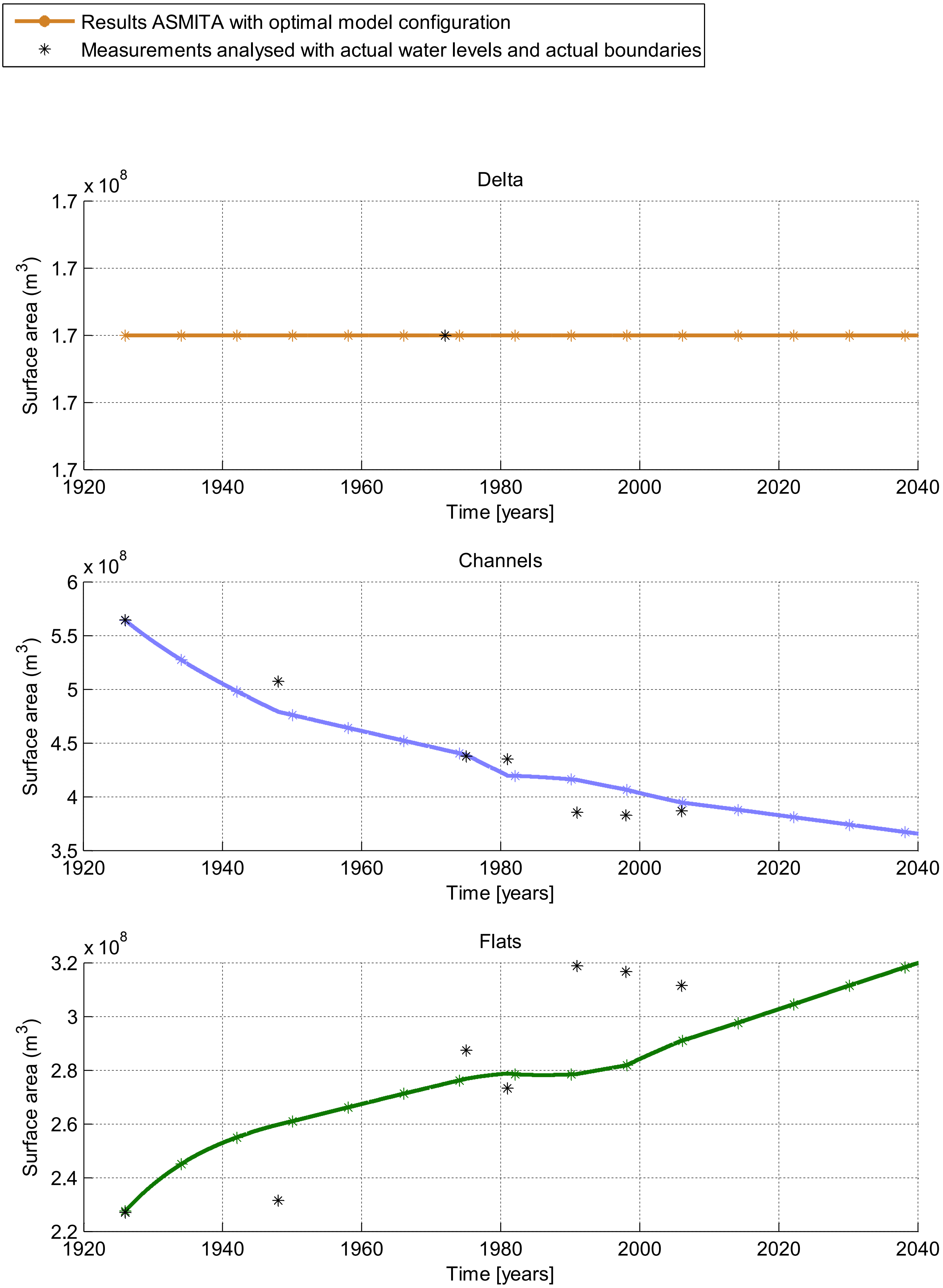
Comparison between measurements and simulation results of a model with optimal configuration (section 5.5) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.30



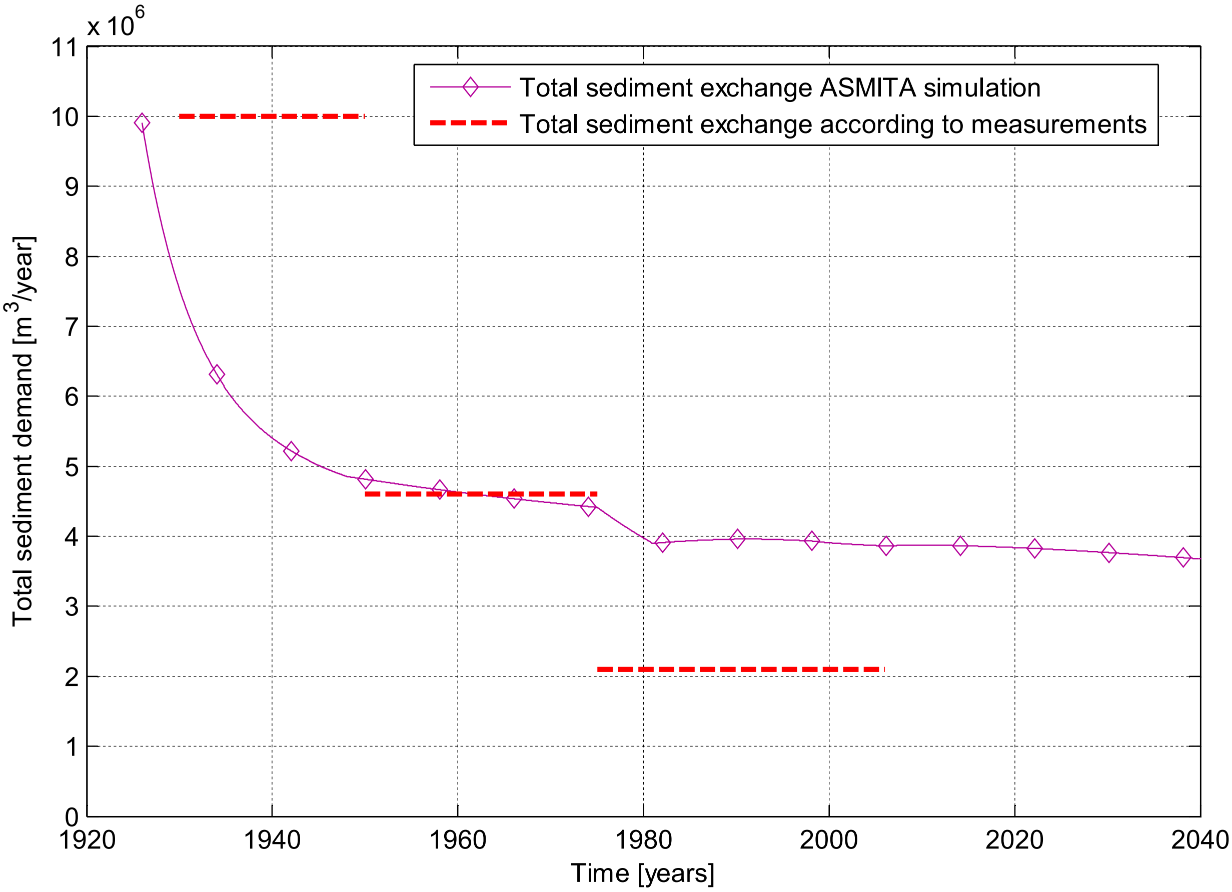
Comparison between measurements and simulation results of a model with optimal cofiguration (section 5.5) for Marsdiep		Z4169
WL | DELFT HYDRAULICS		Figure I.31

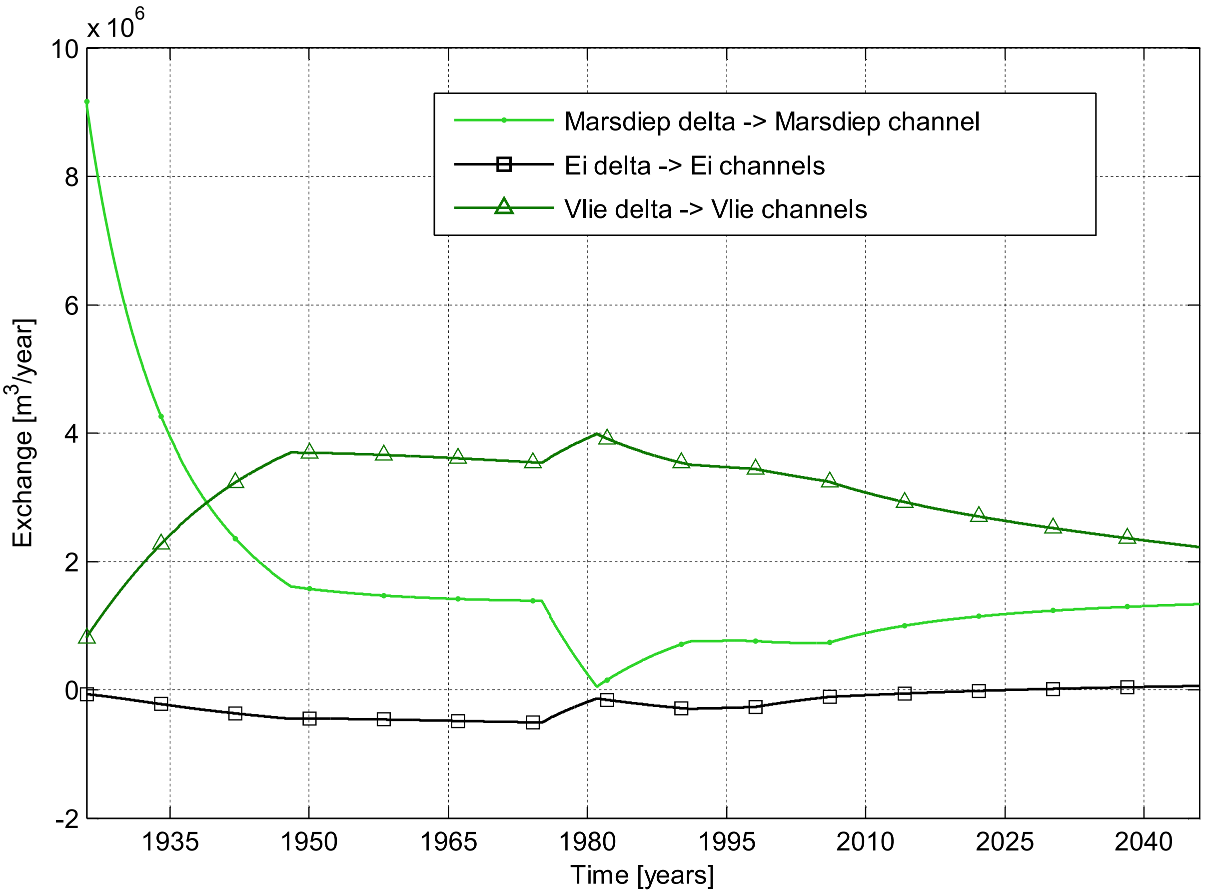


Comparison between measurements and simulation results of a model with optimal cofiguration (section 5.5) for Eierlandse gat		Z4169
WL | DELFT HYDRAULICS		Figure I.32



Comparison between measurements and simulation results of a model with optimal cofiguration (section 5.5) for Vlie		Z4169
WL | DELFT HYDRAULICS		Figure I.33



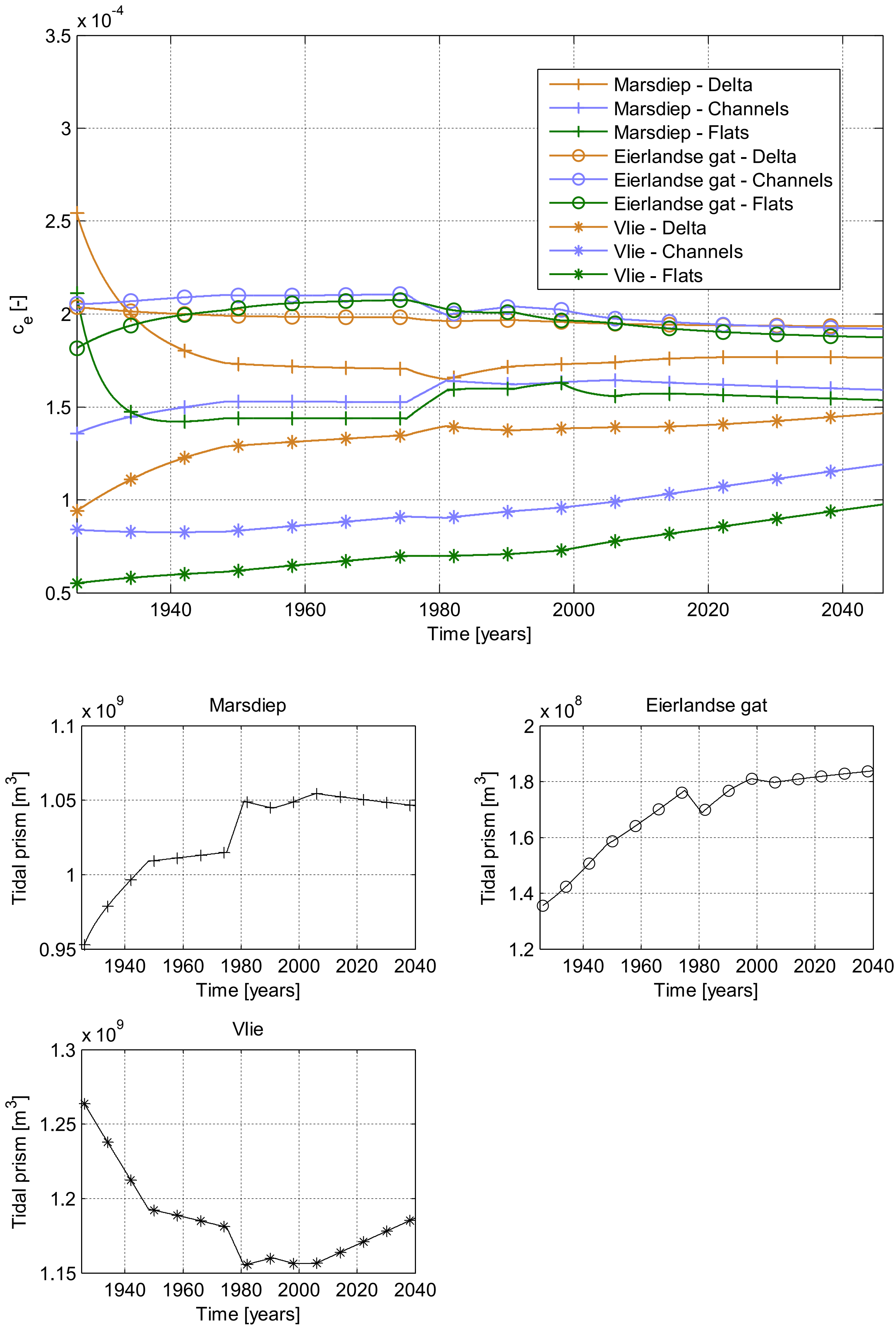


Simulated sediment exchanges (lower plot) and comparison between calculated sediment demand and measured volume changes (upper plot) for a simulation with optimal configuration (section 5.5)

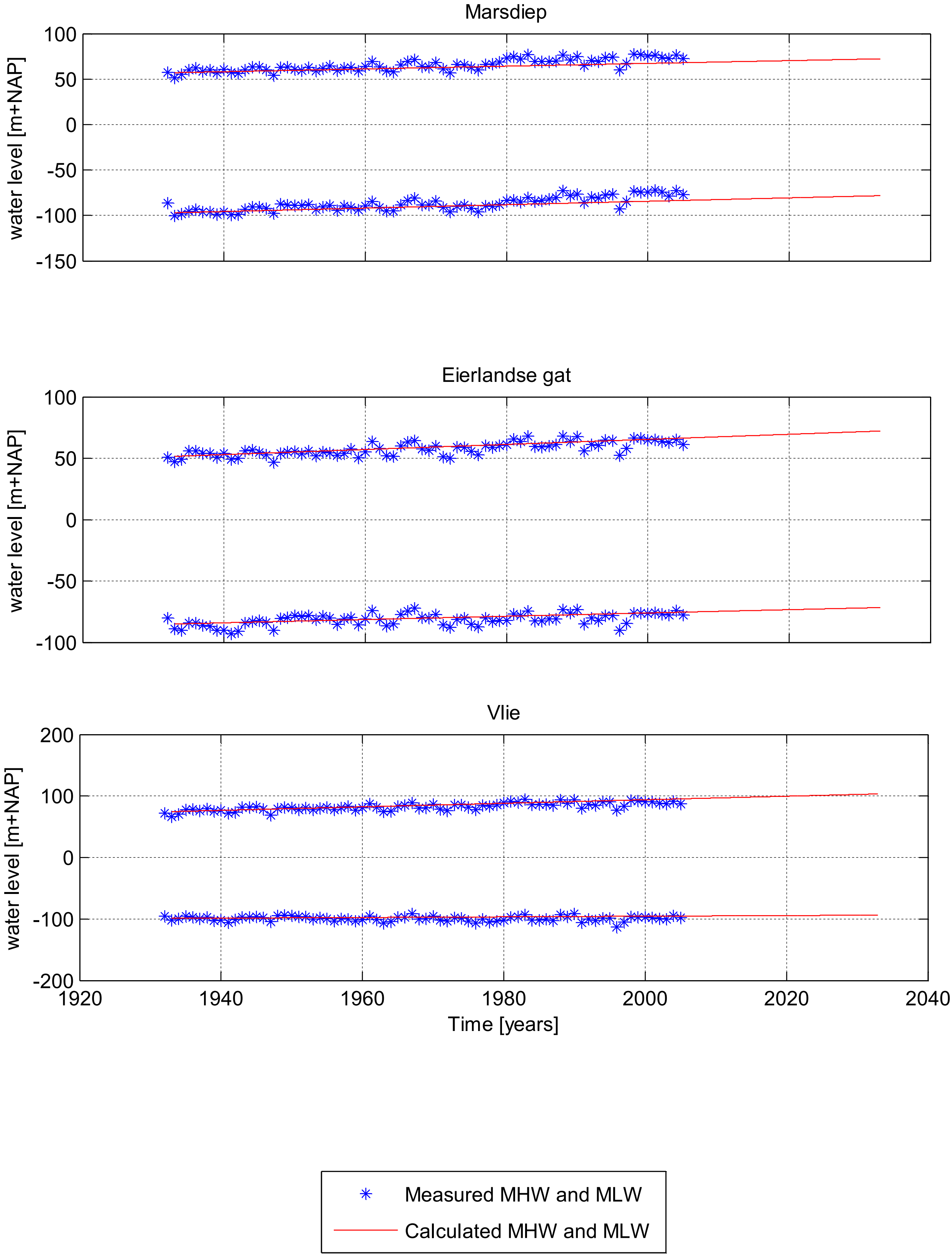
Z4169

WL | DELFT HYDRAULICS

Figure I.34



Calculated equilibrium concentrations (upper plot) and development of tidal prisms (lower plots) when simulating with a model with an optimal configuration		Z4169
WL | DELFT HYDRAULICS		Figure I.35



Comparison between actual water levels and water levels simulated in all models that include actual water levels		Z4169
WL | DELFT HYDRAULICS		Figure I.36