Prepared for:

Rijkswaterstaat RIKZ

Long-term interaction between the Dutch coast and the tidal basins

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Zheng Bing Wang
Edwin Elias
Christophe Briere

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CLIENT:	Rijkswaterstaat RIKZ
TITLE:	Long-term interaction between the Dutch coast and the tidal basins

ABSTRACT:

Rijkswaterstaat is responsible for the maintenance of the coastal foundation. More insight into the interaction between the tidal basins in the Wadden Sea and the Western Scheldt and the coast is very important for the management of the Dutch coast. This study aims to answer the following research questions:

- How do the developments of the tidal inlets on the long-term look like?
- What are the possible effects for the sand-balance of the Dutch coast?
- Which processes govern the developments?
- What are the influences of the development on the coast erosion of the island-heads and on the sand nourishment requirement for the coast maintenance?

The Western Scheldt is deepening due to export of sediment and sand mining. It is expected that the export will continue in the coming period, with an order of magnitude of 1 Mm^3/year. The development of this estuary has only limited effect on the sand-balance of the Delta Coast. Ignoring the export from this estuary in considering the coastal maintenance would be justified. Tidal asymmetry is commonly identified as an important mechanism influencing the residual sediment transport. For the Western Scheldt this seems not to be the case. The change from import to export near Vlissingen-Breskens cannot be explained by the initial transport modelling of tidal transport.

The Wadden Sea basins are importing about twice the amount of sediment than required for compensating sea-level rise, due to the human interferences. The impact of the closure of the Zuiderzee will still be influencing the development of the system for centuries. The total sediment demand for restoring the morphological equilibrium of the Marsdiep-Vlie system is estimated to be in the order of 1000 million m^3. The import forms an important item for the sand-balance of the Dutch coast. Under accelerated sea-level rise this import will even increase in the future, although the increase will be less than proportional to the rate of sea-level rise.

REFERENCES:

VER	AUTHOR		DATE	REMARKS	REVIEW		APPROVED BY	
1	Z.B. Wang				J.A. Roelvink			
2	Z.B. Wang				J.A. Roelvink		T. Schilperoort	

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Samenvatting

Rijkswaterstaat is verantwoordelijk voor het in stand houden van het kustfundament; de hoeveelheid zand in de kustzone tussen de NAP-20 m dieptelijn en de landwaartse rand van de duinen moet op niveau worden gehouden t.o.v. stijgend zeeniveau. Recente studies laten zien dat er een grote import van zand is naar de Waddenzee, terwijl er voor de Westerschelde een discrepantie lijkt te bestaan tussen de gemeten export van het estuarium en het zandverlies in het mondinggebied. Meer inzicht in de interactie tussen de getijdenbekkens in de Waddenzee en de interactie van Westerschelde met de aanliggende kust is van cruciaal belang voor een effectief beheer van de Nederlandse kust.

Het doel van deze studie het vergroten van inzicht in de lange-termijn ontwikkeling van de zeegaten Marsdiep en Westerschelde. Hierbij worden de volgende onderzoeksvragen behandeld:

- Hoe ziet de lange termijn ontwikkelingen van de zeegaten er over langere tijdschalen uit?
- Wat zijn de mogelijke effecten voor de zandbalans van de Nederlandse kust?
- Welke processen sturen de ontwikkelingen?
- Welke invloed hebben de ontwikkelingen op de kustachteruitgang van de eilandkoppen en op de suppletiebehoefte voor het kustonderhoud?

Om deze vragen te beantwoorden worden zowel proces-gebaseerde als gedrag-georiënteerde modellen gebruikt. Dit vormt tevens een eerste aanzet tot het overbruggen van de kloof tussen de empirische kennis en proceskennis, alhoewel de processen en mechanismen voor lange-termijn ontwikkelingen van zeegaten en estuaria nog steeds niet volledig worden begrepen.

De Westerschelde verdiept door export van sediment (ondanks zeespiegelstijging) en sedimentonttrekking t.g.v. zandwinning. De verwachting is dat de export zal doorgaan in de komende periode, met een orde van grootte van 1 miljoen m^3 per jaar (geldend voor alle beschouwde scenarios van zeespiegelstijgingsnelheid). De belangrijkste onzekerheid in deze schatting betreffen toekomstige menselijke ingrepen binnen het estuarium zoals verdere verdieping van de vaargeul, de bagger- en stortstrategie, en het zandwinningsbeleid.

De sedimentuitwisseling tussen bekken en kustgebied is een orde van grootte kleiner dan het sedimentverlies in het voordeltagebied (1 miljoen m^3 per jaar versus 10 miljoen m^3 per jaar). Daarom kan gesteld worden dat de ontwikkeling van de Westerschelde slechts een beperkt effect heeft op de grootschalige zandbalans van de voordelta. Gezien de kleine volumes, en omdat de uitwisseling op dit moment positief is voor de kust (export), lijkt het niet meenemen van sediment toevoer van de Westerschelde naar de kust een gerechtvaardigde (veilige) keuze.

Getijasymmetrie wordt gewoonlijk beschouwd als een belangrijk mechanisme voor het netto sedimenttransport. In het Westerschelde estuarium lijkt dit echter niet het dominante mechanisme te zijn. Korte-termijn proces-gebaseerde modellering waarbij amplituden en fasen van de dominante getijcomponenten langs de open-zeerand zijn gevarieerd, geven slechts een geringe invloed op de zandtransporten in het estuarium; de omslag van import naar export bij Vlissingen-Breskens kan niet met deze methode worden verklaard. In het

oostelijke deel van het estuarium (ten oost van Hansweert) zijn de verschillen wat groter. De de amplitude van M2 is hier toegenomen en de amplitude van M4 afgenomen door verdieping van de Westerschelde. De model resultaten geven een duidelijke verandering in het horizontale getij (snelheden) waardoor hier minder sediment import optreedt.

De Waddenzee bekkens laten een sediment import zien die groter is dan benodigd ter compensatie van zeespiegelstijging. Ongeveer het helft van de huidige import is nodig om zeespiegelstijging te compenseren. De rest van de import is nog steeds het gevolg van aanpassin aan de menselijke ingrepen uit het verleden (voornamelijk Afsluiting van de Zuiderzee). Bij de huidige zeespiegelstijging zal het effect van de afsluiting van de Zuiderzee de ontwikkeling van het systeem nog eeuwen (200 - 400 jaar) beïnvloeden. Op basis van de transportcapaciteit (het importerend vermogen) zou gemiddeld de Nederlandse Waddenzee niet dieper worden bij een versnelling van de zeespiegelstijging tot 40 cm/eeuw, als er voldoende sediment beschikbaar is. Bij een zeespiegelstijgingsnelheid van 100 cm/eeuw zullen Marsdiep en Vlie niet meer in staat zijn een dynamisch evenwicht te bereiken. Zonder rekening te houden met zeespiegelstijging, wordt de totale sedimenthonger voor het herstel van het morfologische evenwicht van het Marsdiep-Vlie systeem geschat in de orde van 1000 miljoen m^3 (tussen 500 en 1500 miljoen m^3); in deze eerste schatting zitten echter nog vele onzekerheden.

Door de grote volumes vormt de import van zand naar de Waddenzee bekkens een belangrijkere onderdeel in de zandbalans van de Nederlandse kust. De totale import is ongeveer gelijk aan het huidige kustsuppletie volume. Bij versnelde zeespiegelstijging zal deze import zelfs verder toenemen alhoewel de toename minder dan evenredig met de snelheid van zeespiegelstijging zal zijn.

Summary

Rijkswaterstaat is responsible for the maintenance of the coastal foundation; the amount of sand in the coastal zone between NAP-20 m depth-line to the landward boundary of the dune has to be kept at level with respect to the rising sea-level. Recent studies show that a large sand import into the Wadden Sea exists, while for the Western Scheldt a discrepancy exists between the measured sand export of the estuary and a decreasing ebb-tidal delta. More insight into the interaction between the tidal basins in the Wadden Sea and the Western Scheldt and the coast is very important for the management of the Dutch coast. A good understanding of the sources and sink terms in the sediment budget is essential for a successful maintenance strategy.

In this study we aim to answer the following research questions:

- How do the developments of the tidal inlets on the long-term look like?
- What are the possible effects for the sand-balance of the Dutch coast?
- Which processes govern the developments?
- What are the influences of the development on the coast erosion of the island-heads and on the sand nourishment requirement for the coast maintenance?

To answer these questions process-based (Delft3D) and behaviour-oriented models (ASMITA) are used to bridge the gap between empirical knowledge and process knowledge even though the processes and mechanisms for long-term development of the inlets and estuaries are still not fully understood.

The Western Scheldt is deepening due to export of sediment (despite sea-level rise) and sediment extraction due to sand mining. It is expected that the export will continue in the coming period, with an order of magnitude of 1 million m^3 per year, applicable for all considered scenarios of sea-level rise rates. The most important uncertainty here concerns the development of the human interferences within the estuary: possible further deepening of the navigation channel, dredging and dumping strategy, and sand mining policy. The development of the Western Scheldt has only limited effect on the sand-balance of the Delta Coast. The exchange between this basin and the coast area is an order of magnitude smaller than the sediment loss in the Delta Coast area (about 1 million m^3 per year versus about 10 million m^3 per year). As this exchange at present is an export (thus a positive item for the coast) and it is expected to remain so in the coming period, ignoring it in considering the coastal maintenance would be justified.

Tidal asymmetry is commonly identified as an important mechanism influencing the residual sediment transport. For the Western Scheldt this seems not to be the case. Amplitudes and phases of the higher frequency tidal components at the open sea boundary seem to have little influence on the development of the lower estuary according to the short-term process-based modelling; the change from import to export near Vlissingen-Breskens can not be explained by this method. In the upper estuary (east of Hansweert) the amplitude of M2 has increased and the amplitude of M4 has decreased due to the deepening of the Western Scheldt. Similar to the change in the vertical tide (water levels), a clear change in the horizontal tide (velocities) can be observed causing less import of sediment.

The Wadden Sea basins are importing more sediment than required for compensating sea-level rise. About half of this import is needed to compensate for sea-level rise, the additional

import is still due to the human interferences. Under the present sea-level rise the impact of the closure of the Zuiderzee will still be influencing the development of the system for centuries (200 – 400 years). On average the Dutch Wadden Sea will not become deeper even if the relative sea-level rise accelerates to about 40 cm/century and sufficient sediments are available. For a sea-level rise rate of 100 cm/century Marsdiep (and Vlie) will not be able to reach a dynamic equilibrium. The total sediment demand for restoring the morphological equilibrium of the Marsdiep-Vlie system is estimated to be in the order of 1000 million m^3 (between 500 and 1500 million m^3) without taking into account sea-level rise, although many uncertainties exist in the estimation.

The import to the Wadden Sea basins forms a more important item for the sand-balance of the Dutch coast. The total import is about equal to the coastal nourishment at present!. Under accelerated sea-level rise this import will even increase in the future, although the increase will be less than proportional to the rate of sea-level rise.

Contents

Appendices

1 Introduction

1.1 Background

Rijkswaterstaat is responsible for the maintenance of the coastal foundation. This means that the amount of sand in the coastal zone between NAP-20 m depth-line to the landward boundary of the dune has to be kept at level with respect to the rising sea-level. For the determination of the required maintenance it is important to estimate the various losses. In the Northern part of the coast the sand import to the Wadden Sea plays an important role. In the Southern part especially the sand exchange with the Western Scheldt is an important component. For both tidal basin systems the sediment exchange with the adjacent coast is poorly understood.

Recent studies (Elias, 2006a, 2006b, Elias et al, 2006) show that the sand-import to the Wadden Sea is still very large. For the Western Scheldt there seems to be a discrepancy between the sand export determined from the sand-balance of the estuary and the decreasing ebb-tidal delta (indicating sand import to the estuary). More insight into the interaction between the tidal basins in the Wadden Sea and the Western Scheldt and the coast is very important for the management of the Dutch coast (Figure 1.1).

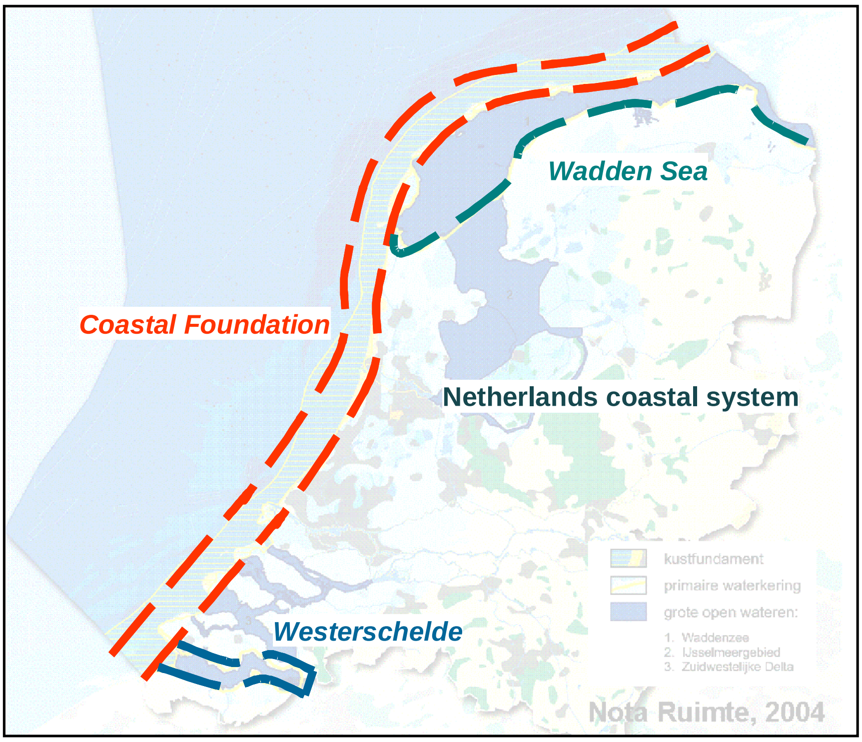


Figure 1.1 Coastal system of the Netherlands: a sand sharing system consisting of Coastal Foundation, Wadden Sea and Western Scheldt (after Mulder et al, 2007).

1.2 Problem analysis

1.2.1 Tidal inlets and the Dutch Coast

The present coastal management policy of Rijkswaterstaat is to maintain the position of the coast line (indicated by BCL = Basal Coast Line) and to maintain the coastal foundation. The position of the coast line is indicated by the so called Basal Coast Line (BCL), see KUSTNOTA (1990). The coastal foundation is defined as the area between the landwards edge of the dunes (or dikes) and the NAP-20 m depth line. The maintenance of both is in principle realized by sand nourishment. The maintenance of the coastal foundation means that sufficient sand need to be nourished in order to keep pace with sea-level rise and compensate loss of sand from the coastal foundation area. The nourishment requirement is thus determined by the effect of the sea-level rise and the total loss of sand through the boundaries. The effect of the sea-level rise is easy to be determined if the rate of the sea-level rise is known. Sea-level rise in the future depends on the climate change and is uncertain. Therefore we will consider various scenarios of sea-level rise rate in the study. If the Dutch coast is considered as a whole the possible losses at the following boundaries are relevant: South boundary at the border with Belgium, Northeast boundary at the border with Germany, sea boundary at the NAP-20 m depth line, land boundary along the dune-foot (/dike-foot) and the tidal inlets, i.e. mouths of the tidal basins. In this study we will especially focus on the last component of the losses, viz. the exchanges with the tidal basins.

The most important tidal basins along the Dutch coast are those in the Wadden Sea (Marsdiep, Eierlandsegat, Vlie, Amelanderzeegat, Friesche Zeegat and Eems-Dollard) and the Western Scheldt (the only open one in the Delta region). The sediment exchange between these tidal basins and the coast depends on the morphological development in the basins. The long-term, large scale developments in the basins are influenced by the relative sea-level rise and the human interferences. Various studies into the long-term morphological developments of the tidal basins have already been carried out. For each of the tidal basins mentioned above, an ASMITA model has already been set up. For the two important basins Marsdiep en Western Scheldt, recently more questions arose concerning the development of the import/export at the mouth. For Marsdiep the question concerns in how far the morphological equilibrium has been recovered after the closure of Zuider Sea. For the Western Scheldt uncertainties concerning the future development arose after the observation of the turning from import to export at the mouth in the nineteen-nineties. Therefore we will especially pay our attention to these two tidal inlets in this study.

For Marsdiep as well as Western Scheldt a similar research question can be formulated. The main question is what are the effects of the sand import to the basins for the adjacent coast? To answer this main question the following sub-questions need to be answered:

- How much sand is still needed to achieve a possible morphological equilibrium?
- How does the equilibrium look like?
- Is there sufficient sand available to achieve the equilibrium and where does it come from?
- What are the possible measures to restrict the loss of sand along the coast?

1.2.2 Scenarios of future developments

Depending on the available and required amounts of sand there are roughly four possible scenarios concerning the future development:

1. There is sufficient sand buffer along the adjacent coast for achieving the natural equilibrium in the tidal basins.
2. There is insufficient sand available, but the tidal basins achieve equilibrium because of large scale sand nourishment.
3. There is insufficient sand available and no equilibrium is achieved, a ‘drowned’ system develops.
4. There is sufficient sand available, but no equilibrium is achieved, a ‘drowned’ system develops.

For the prediction of the future development three different sea-level rise rates (20, 60, and 100 cm/century) will be considered.

1.3 Objectives

The objective of the study is to obtain insight into the long-term development of the tidal inlets Marsdiep and Western Scheldt. Concrete research questions to be answered are:

- What do the developments of the tidal inlets on the long-term look like?
- What are the possible effects on the sand-balance of the Dutch coast?
- Which processes govern the developments?
- What are the influences of the developments on the coastal erosion of the island-heads and on the sand nourishment requirement for the coastal maintenance?

1.4 Set up of the study

1.4.1 General approach

Because of the large temporal and spatial scales of the sediment exchange between the tidal basins and the coast and the relatively small temporal and spatial scales of the relevant physical processes and the human interference like sand nourishment, we will make use of process-based modelling (with Delft3D) as well as behaviour-oriented modelling (with ASMITA). Bridging the gap between the empirical knowledge and the process knowledge is one of the objectives we want to achieve.

Establishing morphological equilibrium by sediment exchange between a tidal basin and the coast is a very long term development. Such long-term development can be modelled relatively easily and fast with ASMITA. The results will give insight into the amount of sand needed for the future equilibrium and the large-scale features of the system for different scenarios of sea-level rise.

With Delft3D process-based modelling can be carried out in order to gain more insight into the relevant processes and mechanisms, and to analyse the effects of changes in the system in more detail. Delft3D modelling will be carried out for various situations concerning the bathymetry. Not only the real bathymetry (based on available field surveys) but also predicted bathymetries for future situations will be used. The construction of future bathymetries is based on ASMITA results.

1.4.2 Project organisation

Because of the fundamental character of the study the project has been carried out by WL | Delft Hydraulics in co-operation with universities by implementing four MSc-projects into the study. In total four MSc-theses have been produced within the frame work of the present project, by students from Delft University of Technology, UNESCO-IHE and Southampton University. An overview of the four MSc-projects is given in the following table.

Title thesis	Student	University	Supervising professor
1	Pieter van Geer	TU Delft	M.J.F. Stive
2	Ali Dastgheib	UNESCO-IHE	J.A. Roelvink
3	Robert-Jan van de Waal	TU Delft	H.J. de Vriend
4	Annelies Bolle	Southampton	C. Amos

The team at WL | Delft Hydraulics has further carried out additional research and has integrated the results from the various sub-studies in order to achieve the objective of the project.

1.5 Acknowledgment

The study has benefited very much from the many meetings with the four MSc-students involved together with their supervisors from the universities / institutes. Especially the valuable contributions from Ir. J.R. de Ronde of RIKZ, Ir.M. Van der Wegen & Prof.dr.ir.J.A. Roelvink from IHE are gratefully acknowledged.

2 The Dutch coastal system

2.1 The Dutch coastal system

2.1.1 System description

In this report we frequently use the terms *coastal foundation* and *coastal system*. These terms are introduced for the Dutch coast and illustrated in Figure 2.1. Their definitions are as follows (see e.g. Nederbragt, 2005):

Coastal foundation. The Dutch coastal foundation is defined as the area enclosed by the following boundaries:

- On the sea side the smoothed (continuous) NAP -20 m depth-line.
- On the land side it extends to all the dune areas and the sea dikes. In areas with extended dunes the boundary is the landwards edge of the dunes. In areas with narrow dunes and with hard sea defences the boundary is extended landwards with the space needed for 200 year sea-level rise.
- On the southwest the border with Belgium.
- On the Northeast the border with Germany.

Coastal system. This is the coastal foundation plus the large open waters which are connected to the coast. Thus the coastal foundation does not include the tidal basins but the coastal system does.

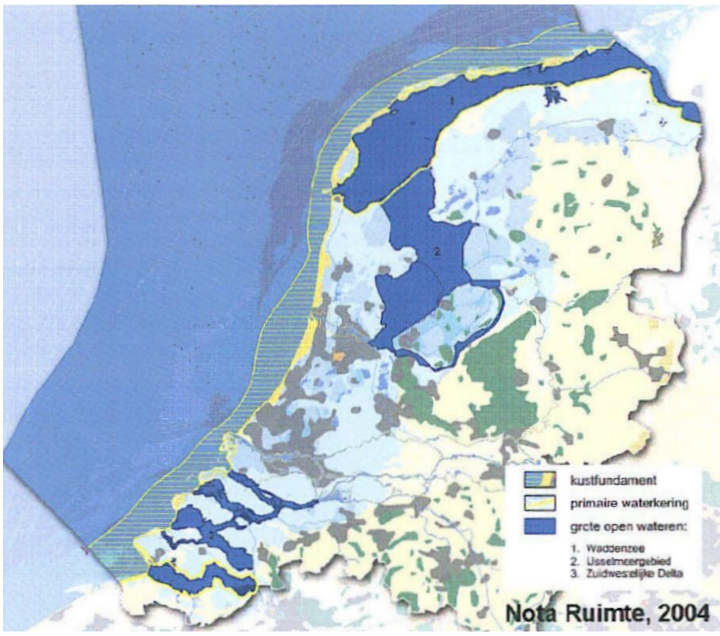


Figure 2.1 Dutch coastal system and coastal foundation (after Nederbragt, 2005)

The Dutch coastal system can roughly be divided into three areas with distinct morphologic features (Fig. 2.1). The closed Holland coast forms the central part, extending over a length of nearly 120 km. This continued coastline of beaches and dunes is slightly curved with a main orientation of NNE to SSW. In the south the over 4 km long breakwaters near Hoek van Holland and the continuously dredged entrance channel to Rotterdam harbour limit the sand bypassing from the estuary-dominated Delta coast, forming an almost closed boundary (Van Rijn, 1995).

During the last centuries the natural behaviour of the Holland coast was increasingly distorted by the construction of coastal defence structures such as groins (Hoek van Holland - Scheveningen, Petten - Den Helder), seawalls (Petten, Scheveningen, Den Helder) and harbour breakwaters (Hoek van Holland, Scheveningen and IJmuiden). Presently, the behaviour of the Holland coast is best described as naturally undisturbed (no inlets) but largely influenced by man-made structures (Wijnberg, 2002). Since 1990 the coastline is maintained primarily by beach, foreshore and dune nourishments, which requires large efforts. Up to 2000 over 30 million (M) m^3 of sand had been nourished along the Holland coast; in total over 100 Mm3 along the entire coast (Roelse, 2002). Detailed descriptions of the Holland coast, its development, behaviour and governing processes, can be found in Hoozemans and van Vessem (1990), Van Rijn (1995) and Wijnberg (1995). The surface area of the coastal foundation is about 4170 km^2.

In the north, Texel Inlet forms the transition from the Holland coast to the barrier islands of the Wadden Sea. Today, the Dutch Wadden Sea system consists of a series of 6 tidal inlet systems (Texel Inlet, Eierlandse Gat Inlet, Vlie Inlet, Ameland and Pinkegat Inlet, Frisian Inlet, and Eems-Dollard Inlet). As indication of the sizes the surface areas of the important tidal basins are given in Table 2.1. The associated barrier islands separate a large tidal flat area (over 2500 km^2 at low tide) from the North Sea forming a unique and important habitat for numerous species of fish, mammals and birds. The Dutch inlets consist of relatively large ebb-tidal delta shoals, narrow and deep inlet channels, and extensive systems of branching channels, tidal flats and salt marshes in the back-barrier basins. The change in coastline orientation from South-North to West-East along the Wadden Sea islands relates to the underlying Pleistocene morphology.

Table 2.1 Areas of tidal basins

Basin	Area (10^6 m^2)
Western Scheldt	270
Marsdiep	655
Eierlandse gat	158
Vlie	715
Amlanderzeegat	276
Friesche Zeegat	155

The Delta coast consists of a series of islands separated by estuaries. With the exception of the Western Scheldt closed or semi-closed barriers dammed these estuaries during the last decades such as the well-known storm-surge barrier in the Eastern Scheldt (1976-1986). The Dutch part of the Western Scheldt river basin equals around 1000 km^2 and is tidally dominated. The meso to macro-tidal regime is characterised by a mean tidal range of 3.8 m at Vlissingen increasing to 5.2 m at Antwerp due to the funnel-shape of the estuary. River inflow is small (< 1%) compared to the tidal prism of 2 x 10^9 m^3. Due to the importance of the river for shipping to Antwerp, human interventions play an important role in the morphodynamic development of the estuary. Almost continuous dredging (and dumping) is needed to maintain navigability in the channels.

2.1.2 Importance of tidal basins

Tidal lagoons and estuaries, collectively named tidal basins, interrupt a large part of the world's shorelines with their associated coastal inlets. Compared to the morphodynamic behaviour of uninterrupted coastlines and of rivers, the morphodynamic behaviour of tidal basins is a degree more complex and less well understood. These systems are important for both ecological (e.g. for marine life, birds) and for socio-economic reasons (harbours, inland waterways, recreation, resource exploitation, etc.). Also, there are strong indications (Stive et al., 1991) that the morphological response of tidal basins to natural and human interventions has an impact on the coastal sediment budget which is large compared to that of interventions along an uninterrupted coast. As an example consider the impact of sea-level rise on a coast adjacent to a tidal basin compared to that on an uninterrupted coast. Under the assumption that a tidal basin establishes morphodynamic equilibrium in following the rate of sea-level rise shoreline recession of the adjacent coast can be expressed as follows (Stive and Wang, 2003):

$$c_{pr} = \frac{\partial MSL}{\partial t}\frac{L_p}{H_p} + \frac{\partial MSL}{\partial t}\frac{A_b}{H_p L_{ac}} \qquad (2\text{-}1)$$

where c_{pr} is the profile recession;
$\partial MSL/\partial t$ is the rate of sea-level rise;
L_p is the active cross-shore profile length;
H_p is the active cross-shore profile depth;
A_b is the tidal basin area;
L_{ac} is the length of the adjacent coast impacted.

In the above equation the first term on the right-hand side expresses the Bruun effect (Bruun, 1962) and the second term expresses the basin effect. The Bruun effect is exceeded by the basin effect as soon as:

$$A_b > L_p L_{ac} \qquad (2\text{-}2)$$

Typical orders of magnitude for L_p and L_{ac} are 1 km and 10 km respectively, so that basin areas larger than O (10 km^2) cause an extra impact on shoreline recession rates which exceeds the direct impact due to the Bruun effect. All the tidal basins along the Dutch coast are larger than this size, and thus have important effect on the development of the coast.

Specifically for the Dutch coastal system a similar argument can also be made by comparing the (horizontal) area of the coastal foundation and the area of the tidal basins. As shown in Figure 2.1 the total area of the tidal basins in the Wadden Sea and the Western Scheldt is comparable to the area of the coastal foundation. For keeping pace with the sea-level rise the amount of sediment needed in the whole coastal system can be estimated as the product of the area of the system and the sea-level rise rate, thus

$$D_{tot} = D_f + D_b = A_{fun}\frac{\partial MSL}{\partial t} + A_b\frac{\partial MSL}{\partial t} \qquad (2\text{-}3)$$

Herein

D_{tot} = total sediment demand due to sea-level rise
D_f = sediment demand of the coastal foundation
D_b = sediment demand in the tidal basins
A_{fun} = horizontal area of the coastal foundation

Although this is a very rough estimate without taking into account the delayed response of e.g. the tidal basins to sea-level rise, it does indicate the importance of the tidal basins. For the present sea-level rise rate of 18 cm/century D_f is estimated at 7.5 million m^3 per year and D_b at about 5 million m^3 per year (Nederbragt, 2005).

2.1.3 Coastal management policy

The targets and strategy of the Dutch coastal management policy are formulated in a series of government document (Kustnota's).

Since 1990 the maintenance of the position of the coastline has been a coastal management target. For this purpose the Basal Coastline has been defined, which is not allowed to be exceeded in the landwards direction by the momentary coastline. Since 2000 the maintenance of the deeper coastal water up to the NAP -20 m depth-line is added as target. This means that the whole outer part (seawards of the dune-foot at about NAP +3 m) of the coastal foundation needs to be maintained, i.e. compensating any loss and the effect of sea-level rise.

The strategy of the maintenance is to use as much as possible soft measures in the form of sand nourishment. Hard measures in the form of coastal structures are only considered if it is really necessary.

The present practice is that 12 million m^3 sand is nourished along the Dutch coast each year. For the allocation of the nourishment first the development of the momentary coastline is analysed. Nourishment is carried out at locations where the BCL is endangered. For this purpose about 6 million m^3 nourishment per year is required. The remaining 6 million m^3 is used for maintaining the deeper part of the coastal foundation. For the lateral distribution under water nourishment is carried out as much as possible because it is relatively much cheaper. Beach nourishment is only carried out at locations where it is really necessary.

It is noted that the maintenance of the tidal basins is not included as a target in the present coastal management policy, although the losses of sand due to the imports to the basins are considered in the determination of the required nourishment. However, maintaining the whole coastal system, thus including the tidal basins, are already under consideration for the future coastal management policy (Nederbragt, 2005, see also the internet site http://ucit.wldelft.nl/ucit/display/KvdNLK/Kenniskaart).

2.2 Historical development

2.2.1 Determination of nourishment requirement

The present nourishment amount of 12 million m^3 per year is based on the analysis of Mulder (2000), who has determined in detail the sand losses from the coastal foundation. Nederbragt (2005) reanalyzed the losses by setting up a conceptual model for the Dutch coastal system. He made the assumption that the total effect of the transports at the seawards boundary and the two boundaries at the borders with Belgium and Germany is negligible compared to the effect of sea-level rise. The nourishment required for compensating the sea-level rise in the whole coastal system can then simply be calculated according to Eq. (2-3). For the sea-level rise rate of 18 cm/century this results in 12.5 million m^3 per year. This figure is close to the 12 million m^3 per year determined by Mulder (2000). However, Nederbragt also points out another important item of loss, viz. sand mining of at least 5 million m^3 per year in the coastal foundation area and at least 8 million m^3 per year if the whole coastal system is considered.

Elias (2006a, 2006b) carried out an extensive and detailed study of the Texel Inlet (Marsdiep) and came to the following conclusions:

- The hypothesis of the cyclic behaviour of the ebb-tidal delta of this inlet, based on the observations in the past (Sha, 1989) is no longer valid.. No cyclic development has occurred on the scale of the inlet system after the construction of Helderse Sea-defense that stabilised the southern embankment of the inlet gorge. An important lesson is thus that we cannot fully rely on the knowledge of the past for future predictions.
- The tidal basin still needs a large amount of sand to recover morphological equilibrium. The Texel inlet and the Vlie inlet form a coupled morphological system and the effect of the closure of the Zuiderzee is still far from damped out.
- There is still sufficient sand and sediment transport capacity available for importing sediment into the basin. As a result the ebb-tidal delta and adjacent coasts endure severe sand losses, presently estimated at 5 to 6 million m^3 per year.

The large sediment transports into the basin point to the fact that sediment losses from the coastal foundation due to the import by the tidal basins can exceed the amount needed for the basins to keep pace with the sea-level rise. From the analysis of Elias et al (2006) it is concluded that this is applicable for the Dutch Wadden Sea as a whole. The sediment budget analysis (see Figure 2.2) based on the trend in the recent 15 years shows that the annual sediment import to the Dutch Wadden Sea (Marsdiep, Eierlandse Zeegat, Vlie, Amlanderzeegat and Friesche Zeegat together) is about 12 million m^3 per year at present. Based on the trend in a longer period Nederbragt (2005) calculated the annual import to these basins to be 7.5 million m^3 per year. Although the two analyses show different results, both values are much more than the amount required for compensating the sea-level rise of 18 cm/century. The total of these five basins is about 1960 km^2, so the annual import needed for keeping pace with the present sea-level rise is about 3.5 million m^3 per year. The results thus indicate that the coastal foundation (which does not include the tidal basins) is not maintained by the present nourishment of 12 million m^3 per year.

Figure 2.2 also illustrates the sediment budget changes along the entire Dutch coast.. The development of the Delta area is remarkable. Despite of the nourishment of 2.8 million m^3

per year this whole delta coast is losing about 9 million m^3 sand per year. The total loss is thus in the order of 12 million m^3 per year. This loss cannot be explained by the exchange with the tidal basins, of which only the Western Scheldt is really open. The behaviour of this sub-system is still subject of study and not understood yet. However, if this loss is indeed true it means that the nourishment requirement for maintaining the coastal foundation is even larger.

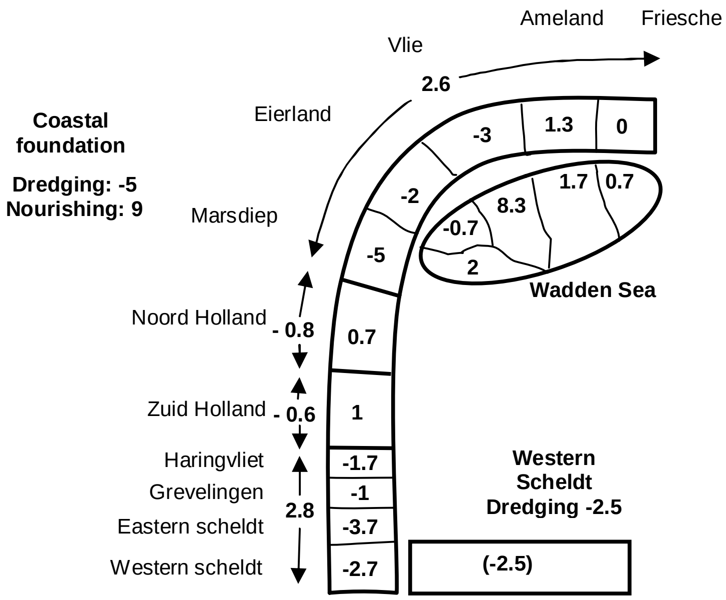


Figure 2.2 Sediment budget of the Dutch coastal system (after Elias et al, 2006), based on trend in the period 1990-2005.

2.2.2 Human interferences

Major modifications have been carried out in the Dutch coastal system over the last decades (centuries). Studies by Elias (2006) have shown that the ongoing adaptation to closure of the Zuiderzee, 75 years ago, still plays a dominant role in the morphodynamic evolution of the Western Wadden Sea. Due to the importance of human interventions we present an overview of the dominant interferences in this section.

For the present behaviour of the Wadden Sea area the most important interventions are the closure of the Zuiderzee (1925-1932) and the closure of the Lauwerszee (1969). The study of Elias (2006a, 2006b) showed the impact of the closure of the Zuiderzee. Vast amounts of sediment were imported into the remaining basin, a process that is still far from damped out at present. Land subsidence due to gas mining might increase the sediment demand of the Wadden Sea in the (near) future. Along the barrier coasts of the Wadden Islands maintaining the Coastal Foundation brings in sediments into the system. It is unclear how this surplus sediment influences the system. However, the natural process of barrier island retreat to maintain equilibrium with rising sea-levels is no longer possible by keeping the coastline at the 1990 position.

During the last centuries the natural behaviour of the Holland coast was increasingly distorted by the construction of coastal defence structures such as groins (Hoek van Holland - Scheveningen, Petten - Den Helder), seawalls (Petten, Scheveningen, Den Helder) and harbour breakwaters (Hoek van Holland, Scheveningen and IJmuiden) see Table 1-1. Presently, the behaviour of the Holland coast is best described as naturally undisturbed (no inlets) but largely influenced by man-made structures (Wijnberg, 2002). Since 1990 the coastline is maintained primarily by beach, foreshore and dune nourishments, which requires large efforts. Up to 2000 over 30 million (M) m3 of sand had been nourished along the Holland coast; in total over 100 Mm3 along the entire coast (Roelse, 2002). Detailed descriptions of the Holland coast, its development, behaviour and governing processes, can be found in Hoozemans and van Vessem (1990), Van Rijn (1995) and Wijnberg (1995).

The harbour moles of Ijmuiden (and to a lesser extent Scheveningen) play an important role in the morphodynamic system as they extend through the surf zone (where most of the sediment transport takes place). Thereby they make an artificial separation of the coastal zones to the south and north. The frequent dredging of the entrance channels further limits the sand exchange (Van Rijn, 1995).

Additional major interferences are the Maasvlakte 2 and various coastal development projects.

Table 2.2: Overview most important engineering works along the Holland coast (based on Van Rijn, 1995; Wijnberg, 1995)

	Location	**Period**	**Spatial scale**
Seawalls:			
Helderse Seawall	km 0 - km 1.1	1721	tip of North Holland
		1956	extension
Hondsbossche and	km 20 - km 26	1500/1872/1954 1969	6 km alongshore
Pettemer Seawall Scheveningen	km 102	1896 - 1909	140 m alongshore, total length 2.5 km
Groins			
	km 0.4 - km 31	1838 - 1935	
	km 98 - km 118	1776 - 1930	
Harbour Moles			
Ijmuiden	km 55/56	1865 -1879	length 1.5 km
		1962 - 1967	length 2.3 (N) - 2.8 km (S)
Scheveningen	km 102	1900 -1908	0.25 km
		1968 - 1970	0.65 km (N)- 0.5 km (S)
Hoek van Holland	km 118	1864 - 1874	1.8 km
		1968 - 1972	4.2 km
Discharge Sluice			
Katwijk	km 86	1807	
		1984	increased capacity

The morphodynamics of the Delta Coast are dominated by the Delta Works projects. All of the inlets, except the Western Scheldt, were closed or semi-closed. The closing of the inlets reduced the sediment supply to near-zero. The morphodynamics of the Delta area are dominated by a redistribution of the sand in the system.

The only remaining inlet, Western Scheldt, is so largely influenced by dredging and dumping activities that it is difficult to determine the remaining natural dynamics.

2.2.3 Development of the inlets

Sediment imports into the basins of the Wadden Sea account for a significant loss in the sand-budget of the coastal foundation. At present this loss is estimated at 12 million m^3 per year (Elias et al, 2006). Sediment demand by the basin is expected to increase if sea-level rise accelerates. It is possible that this leads to larger sediment imports if the hydrodynamics in the basin adjust to accommodate a larger transport capacity. In numbers, the import / export of about 1.5 million m^3 per year at the mouth of the Western Scheldt estuary is of lesser importance to the total sand-budget.

Besides the importance of the basins for the sand budget, the basins themselves form important economic and ecological areas. In particular, the inter-tidal flats form habitats for many kinds of flora and fauna. To maintain the shoal areas it is important that the basins can keep pace with relative sea-level rise. If the import is less than the area of the basin multiplied by the rate of sea-level rise the basin will become deeper and it will generally mean that loss of inter-tidal flats takes place. In this sense the exchange between the basins and the coast has opposite effects to the ecological functioning of the basins than to the coastal foundation. In the Wadden Sea area the import to the basins at present is more than needed for compensating the effect of sea-level rise. For the coastal foundation this extra sediment import forms an (negative) item of loss of sand. In the Delta Coast area there are two tidal basins left, the Eastern Scheldt and the Western Scheldt. The Eastern Scheldt practically does not exchange sand with the coast any more. As a consequence the sand-demand to recover to morphological equilibrium, caused by the structure of the storm surge barrier, cannot be fulfilled and the inter-tidal flats in the basin are under pressure of erosion. Also for the Western Scheldt the overall sediment balance is negative, in the sense that the import at the mouth cannot compensate the effect of sea-level rise and especially of sand mining in the estuary.

It is noted that the maintenance of the tidal basins is not included in the coastal management policy at present, although it is already considered for future policy (Nederbragt, 2005, http://ucit.wldelft.nl/ucit/display/KvdNLK/Kenniskaart). This means that for determining the nourishment requirement the development in the tidal basins themselves is not considered. Only the import to the basin is considered as an item of loss for the coastal foundation. Given the important ecological function of the tidal basins and the possible acceleration of sea-level rise it is worthwhile to consider the whole coastal system instead of the coastal foundation, thus consider including the tidal basins in the coastal management policy.

2.3 Future Perspectives

2.3.1 General remarks

In this section preliminary predictions are presented for the various scenarios of the future development of the Dutch coastal system. Three scenarios of sea-level rise rate are considered, 18, 60 and 100 cm/century. Concerning the nourishment requirement we follow in the first instance the present coastal management policy, i.e. only maintaining the coastal foundation, but then we also considered the situation if the whole coastal system including the tidal basins need to be maintained.

The predictions here are preliminary in the sense that they are based on the available data and knowledge and by simple extrapolation to the future situation. In addition of providing a first answer to the management questions the exercise here is also meant to identify the uncertainties and remaining questions.

2.3.2 Development of the tidal basins

The tidal basins form a part of the coastal system. The key to the development of the basins is the import / export of sand to / from the basins. It is an important item for the sand-budget of the coastal foundation and it is also an indicator for the large scale morphological development in the basins self.

According to the recent analysis by Elias et al (2006) the total import to the tidal basins is about 12 million m^3 per year. This is much more than the amount required for compensating the effect of the sea-level rise. According to Nederbragt (2005) the total import needed for compensating the 18 cm/century sea-level rise is about 5 million m^3 per year. Apparently, the 7 million m^3 per year extra import is due to the response to the large scale human interferences in the basins in the past.

The distinction between the response to the sea-level rise and to the human interferences is used for making predictions of future development for different rates of sea-level rise. The argument for the preliminary prediction is that the import needed for responding to the sea-level rise will adjust to the different rates of sea-level rise, but the import to the human interference will not. If the sea-level rise remains at the present rate of 18 cm/century then the import needed for compensating its effect will remain at about 5 million m^3 per year. The 7 million m^3 per year extra import will gradually decrease and eventually vanish when the dynamic morphological equilibrium in the basins is restored, or in other words when the disturbances caused by the large scale human interferences in the past are damped out. The remaining question is how long this damping will take place. If the sea-level rise is going to accelerate, the import for compensating the sea-level rise will gradually increase from the present 5 million m^3 per year to a new level which is proportional to the rate of sea-level rise, thus 16.7 million m^3 per year for 60 cm/century and 27.8 million m^3 per year for 100 cm/century. The 7 million m^3 per year extra import due to the interferences in the past will gradually decrease to zero. An additional remaining questions is now what is the time needed for the system to adjust to the accelerated sea-level rise. It is further noted that the time needed for damping out the disturbance caused by the interferences in the past will be shorter for a higher sea-level rise rate, because the dynamic equilibrium at faster sea-level rise will have a deeper basin, i.e. less sediment required for achieving it. The predictions are summarised in the following table.

Table 2.3 Preliminary prediction of import to the tidal basins

slr rate (cm/century)	import for slr (M m^3/year)	import due to interferences	total import (M m^3/year)	remaining questions
18	5	7 ➔ 0 (T_1)	12 ➔ 5	time scale T_1
60	5 ➔ 16.7 (T_2)	7 ➔ 0 (T_3)	12 ➔ 16.7	time scales T_2 and T_3
100	5 ➔ 27.8 (T_4)	7 ➔ 0 (T_5)	12 ➔ 27.8	time scales T_4 and T_5

2.3.3 Nourishment requirement coastal foundation

Considering the sand-budget the nourishment requirement for maintaining the coastal foundation can be considered as consisting of the following items:

1. **Amount for compensating sea-level rise**. This item can simply be calculated as the product of the horizontal area of the coastal foundation and the rate of sea-level rise. For the present rate of 18 cm/century Nederbragt (2005) estimated this item to be about 7.5 million m^3 per year. It will thus be 25 million m^3 per year for 60 cm/century and 42 million m^3 per year for 100 cm/century.
2. **Import to the tidal basins**. This item is predicted in the previous sub-section (see table 2.1).
3. **Sand extraction**. According to Nederbragt (2005) the sand extraction from the coastal foundation area due to sand mining in the recent past is at least 5 million m^3 per year. It is noted that this item will be dependent on the coastal management policy in the future. The fact is that every cubic meter extracted needs to be compensated by one cubic meter nourishment if the coastal foundation has to be maintained.
4. **Loss or gain due to transport through other open boundaries**. In the analysis of Nederbragt (2005) it is hypothesised that the Dutch coastal system can be considered as a closed system. This hypothesis implies that the total transport through the other open boundaries of the coastal foundation except the tidal inlets can be neglected. This hypothesis to be supported by the trend of development in the past. However, by taking only the recent period for the trend analysis Elias et al (2006) comes to an additional loss in the coastal foundation area of about 8 million m^3 per year. This loss mainly occurs in the Delta coast area and in the other two parts (coast of Holland and Wadden Sea coast) there is a small gain. Apparently there is considerable uncertainty concerning this item of loss. Furthermore, it is unknown how this item will be influenced by the rate of sea-level rise and other factors (e.g. the coastal nourishment strategy).

In summary the predictions are as follows:

Table 2.4 Effect of sea-level rise on the coastal foundation

slr rate (cm/cent.)	due to slr (Mm^3/yer)	to basin (Mm^3/yer) based on Nederbragt (2006)	to basin (Mm^3/yer) based on Elias et al (2006)
18	7.5	7.5 → 5	12 → 5
60	25	7.5 → 16.7	12 → 16.7
100	42	7.5 → 27.8	12 → 27.8

It is remarkable to note that the computed nourishment requirement for the present rate of sea-level rise is higher than the 12 million m^3 per year according to the present coastal management policy. This is even the case if the lower limit of the calculated amount is considered (15 million m^3 per year). The difference is caused by two reasons. First, in the calculation of Mulder (2000) the extraction due to sand mining (5 million m^3 per year) is not taken into account. Second, the import to the tidal basins is estimated by Mulder (2000) to be lower than that according to the analysis of Elias et al (2006) and Nederbragt (2005). Compared to the higher limit there is another difference, viz. Mulder (2000, and also Nederbragt, 2005) neglected the transports through the other open boundaries than the tidal inlets.

2.3.4 Uncertainties and questions

Although the prediction of the nourishment requirement for the coastal foundation in the previous subsection is only preliminary, it already gives a good indication about the uncertainties and remaining questions.

The results appear to be very sensitive to the sea-level rise rate. This means that the uncertain rate of sea-level rise is an important element in the uncertainty concerning the nourishment requirement in the future. However, this uncertainty will further not be considered in the present study and the three rates will be considered as different scenarios. For a given scenario of the sea-level rise, the first item, i.e. the amount for compensating the sea-level rise, can be accurately determined with little uncertainty.

Also the import to the tidal basins depends on the rate of sea-level rise, but for this item there are also other uncertainties and questions involved. As already indicated in Table 2.1 questions remain about the various time scales on which the basins will develop from the present state to the future dynamic equilibrium. Note that each of the time scales indicated in the table can be different for each basin. Question can also be asked what the dynamic equilibrium of each basin looks like and it can even be asked if such an equilibrium exists. Another question is if the basins can be separately considered or they should be considered as a coupled system for the Wadden Sea case. All these questions and uncertainties are the subject of the present study and will be treated in the following chapters.

The item extraction in the form of sand mining can be considered as uncertain in the future as well. However, this item can be controlled by the coastal management itself. It is thus recommended to integrate the coastal nourishment and the sand mining together in the coastal management policy.

Table 2.2 indicates that there is also a considerable uncertainty concerning the item erosion due to transport through the boundaries other than the tidal inlets. Trends of development determined by taking different periods give quite different results. It is not clear which result is more reliable as future prediction. Especially the observed development in the Delta Coast area is not fully understood yet. Furthermore, questions can also be asked in how far this item will be dependent on the sea-level rise rate and on the coastal nourishment strategy as it may change e.g. the shape of the coast profiles. These uncertainties and questions will not be considered in the present study but will be the subjects of study in the VOP research programme (generic coastal research programme).

The reasoning up to now is made from the point of view of maintaining the coastal foundation. This is in line with the present coastal management policy. However, if the sea-level rise will accelerate the delayed import for compensating the faster sea-level rise will result in morphological development in the tidal basins which can be negative for especially the ecological functioning of the basins. This can be the reason that the whole coastal system rather than only the coastal foundation is considered in the future coastal management policy. If e.g. the ecological functioning of the tidal basins needs to be maintained and/or restored as well it will result in quite different nourishment requirement and nourishment strategy.

3 Western Scheldt Estuary

3.1 Introduction

The Western Scheldt (Figure 3.1) is the only estuary still exchanging sediments with the Delta Coast. Using the Delft3D model, Bolle (2006) analysed the historic reversals in sediment exchange between estuary and the coast. More insight in the fluctuating sediment exchange was obtained by analysis of existing sediment budget studies (section 3.2). The study of Bolle (2006) and additional simulations are summarised in section 3.3. Semi-empirical modelling results and predictions of future development are represented in 3.4 and 3.5 respectively.

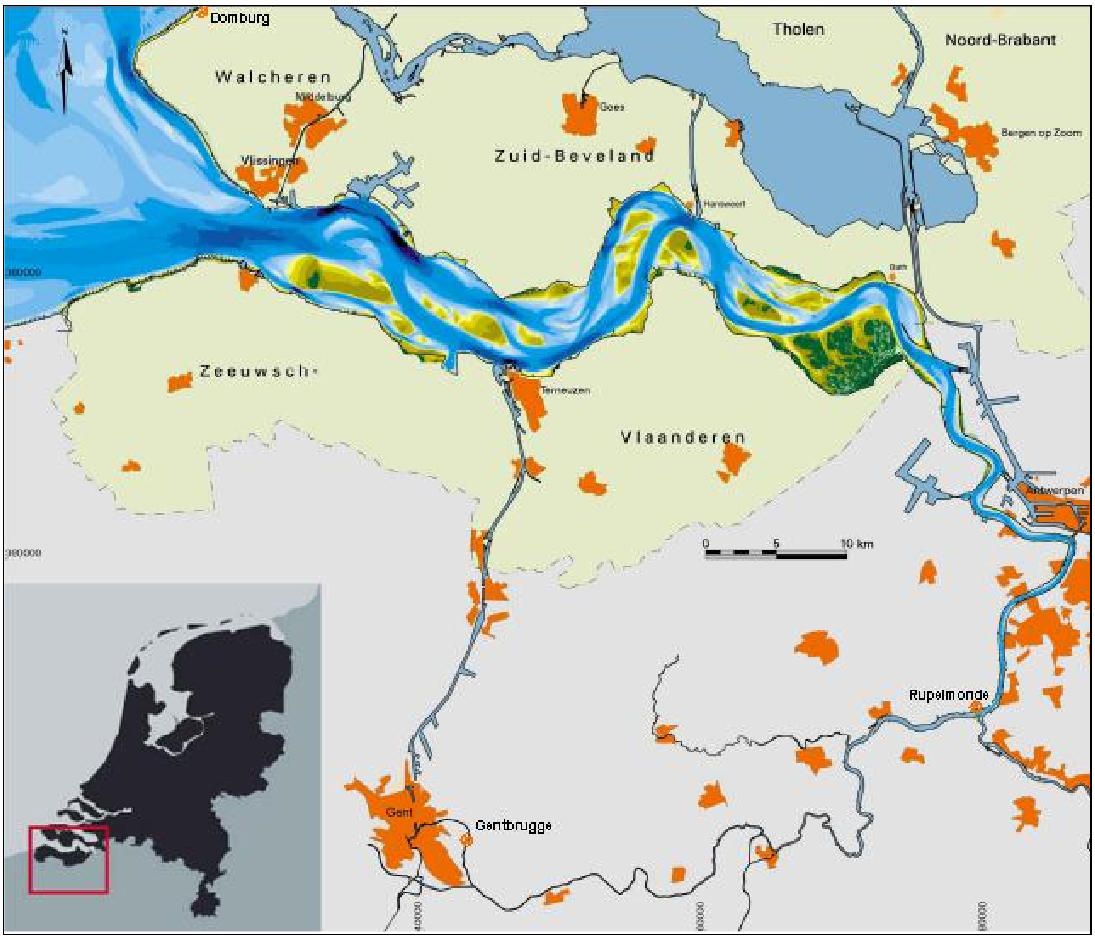


Figure 3.1 The Scheldt estuary from Gent to the Western Scheldt mouth

3.2 Sediment budget studies

In the study of Uit den Bogaard (1995) the Western Scheldt was divided into 7 budget areas; six covering the “river”, and a 7^{th} domain for the Land of Saeftinge The analysis covers the period 1955 – 1993 in 5 year intervals. To close the balance area it is assumed that the sediment transport near Antwerp is zero. The results for import / export at the downstream end of the estuary (cross-section Vlissingen – Breskens) are shown in Figure 3.3.The two lines represent different analysis methods for synchronising the bathymetric data. The bathymetry in the estuary is measured by echo sounding during the whole year, which implies that not all parts of the estuary are measured at the same moment. In order to make the sand balance analysis the bathymetry for each year is translated to January 1. For this extrapolation two methods were used, the linear interpolation (depth at a certain points is determined by interpolation using the first measurement before the date and the first measurement after the date) and the trend line methods (based on a trend line determined using more measurements around the date). The considerable differences between the results related to the two methods indicate that the import / export shows the significant uncertainties faced in sediment-budget analysis.

For both methods similar trends can be observed, although magnitudes differ considerably. In the past the Western Scheldt might have evolved from a sediment exporting system to a sediment importing system (prior to 1960). A maximum sediment import occurred around 1970. Ever since the sediment import values decreased. During the last decade a sediment export occurs. This turn from import to export has been reproduced by semi-empirical modelling (see section 3.4) but not by process-based modelling (section 3.3) until now.

The accuracy of the results from such a study depends on the quality of the bathymetric maps and the reliability of the data concerning dredging and dumping.

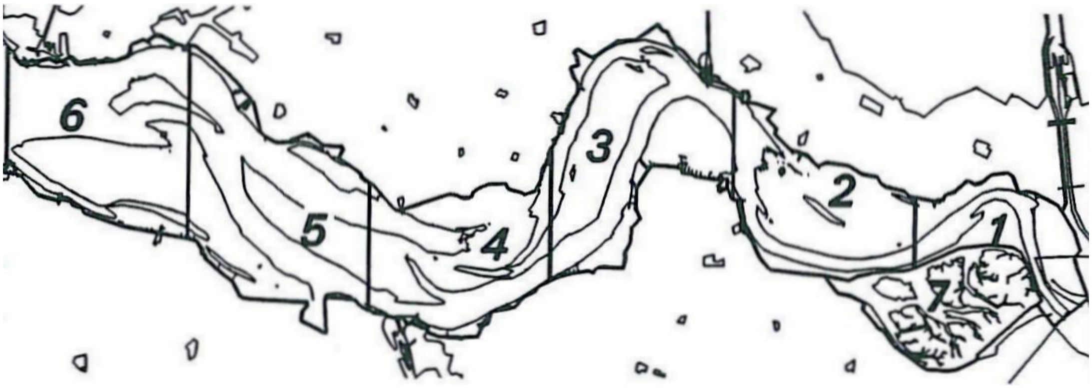


Figure 3.2 Budget areas used in the study of Uit den Bogaard (1995)

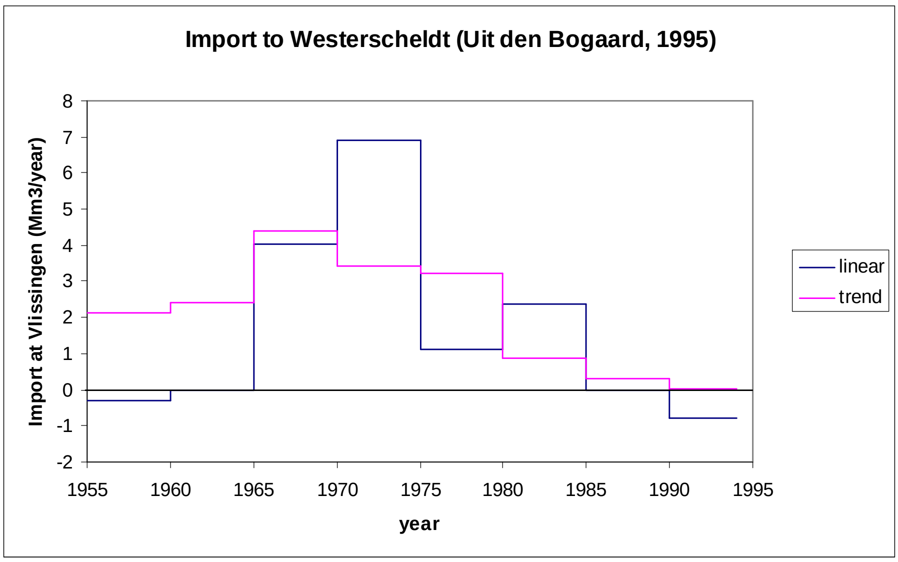


Figure 3.3 Sediment transport at Vlissingen from Uit den Bogaard (1995), positive = import

The recent study of Nederbragt and Liek (2004) expanded the analysis with recent observations (up to 2001). In addition the mouth area was also accounted for. The balance areas are based on coherent morphological units rather than a practical division based on the sounding maps (see Figure 3.4). The morphological units shown in this figure are macro and meso cells (Winterwerp et al, 2001). A similar zero exchange at Antwerp was assumed to be present. Figure 3.5 illustrates the sediment exchange over the Vlissingen-Breskens cross-section. Similar to Uit den Boogard, a change in sediment import to sediment export was observed in the early 1990's. The addition of recent data shows that the trend of sediment export continues up to present.

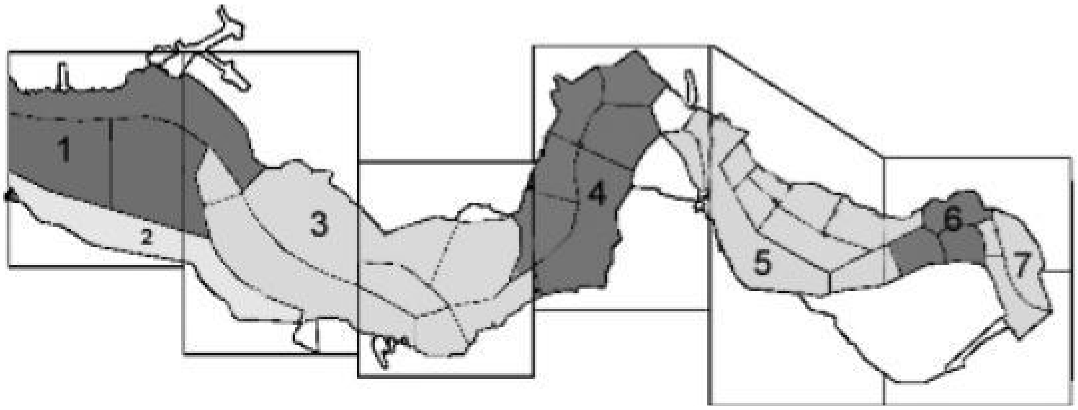


Figure 3.4 Schematisation used by Nederbragt and Liek (2004)

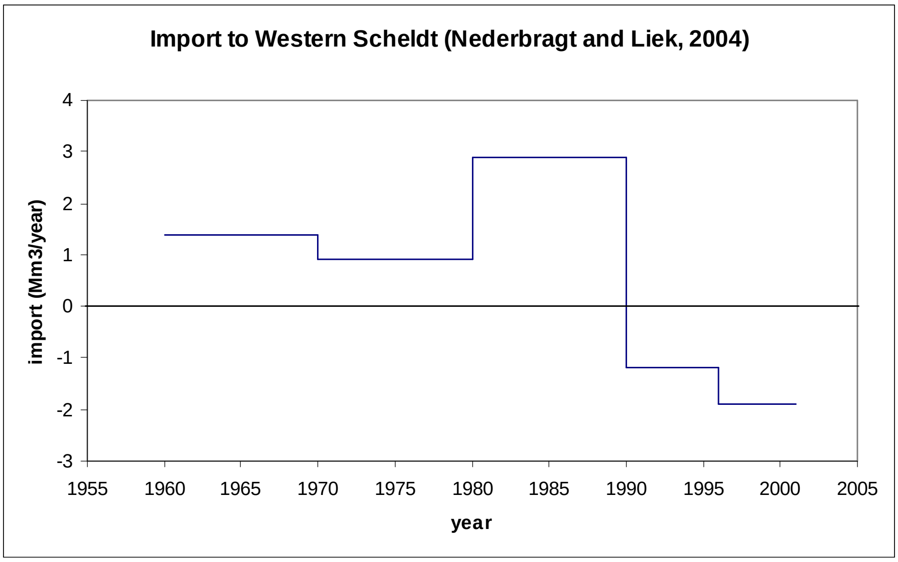


Figure 3.5 Sediment transport at Vlissingen from Nederbragt and Liek (2004), positive = import

Haecon (2006) further expanded the sediment budget with the Lower Zeescheldt up to Schelle (Figure 3.6). It is assumed that the sand transport at Schelle is zero (the results of the analysis show that the transport at the Border between The Netherlands and Belgium cannot be neglected (see Figure 3.7). This has the consequence that the transport determined at the mouth of the Western Scheldt is different than the previous results (Figure 3.8). Taking into account the transport at the upstream end of the Western Scheldt has the consequence that the turning from import to export at the mouth occurs later.

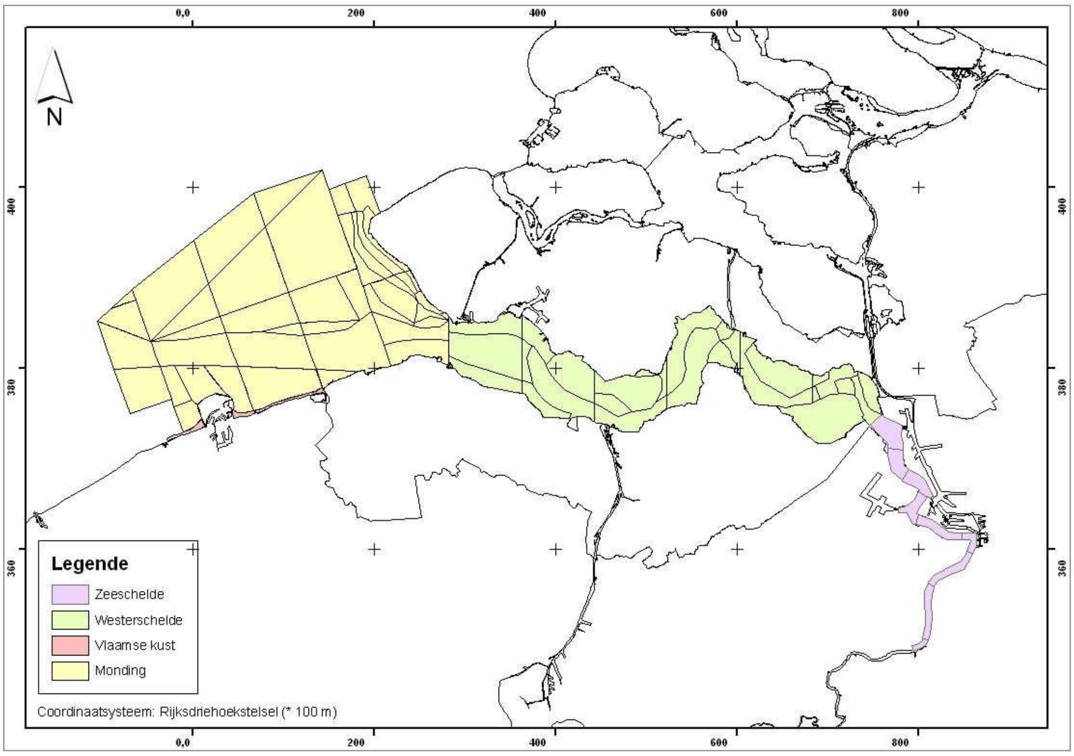


Figure 3.6 Study area and schematisation in the Haecon (2006) study

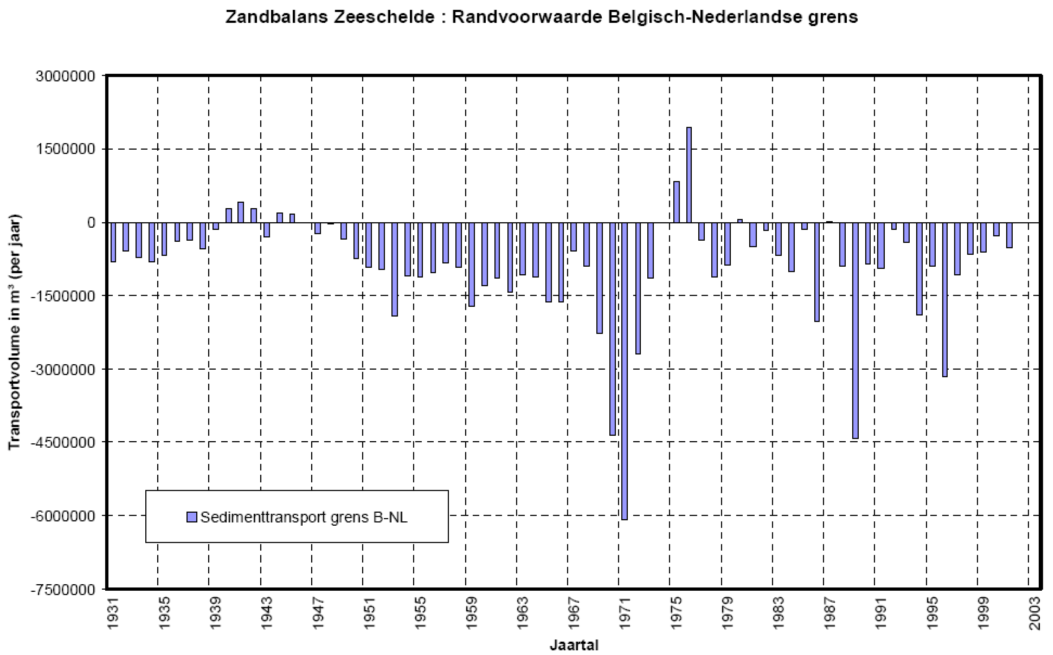


Figure 3.7 Sediment transport between Zeeschelde and Western Scheldt determined by Haecon (2006), Positive = downstream directed

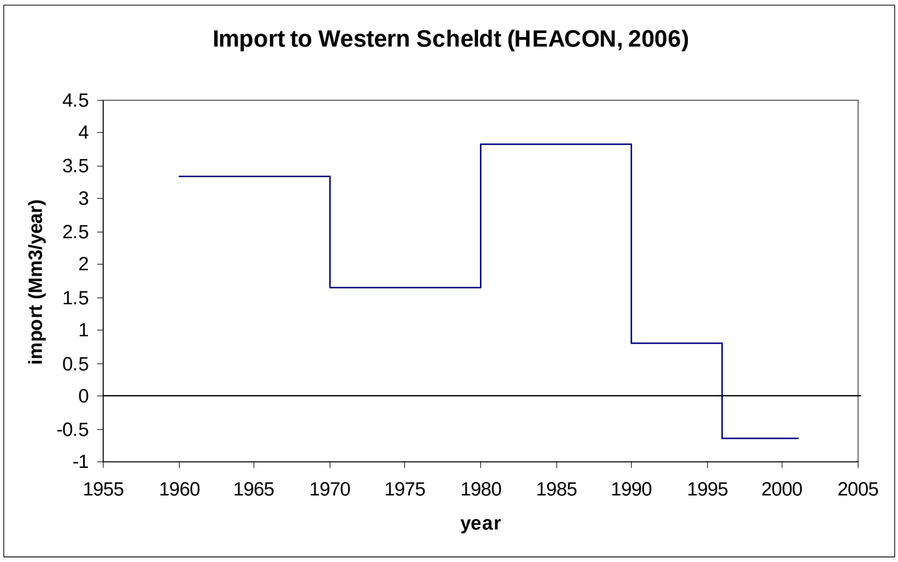


Figure 3.8 Sediment transport at Vlissingen from Haecon (2006), positive = import

Plotting the results for sediment import at the mouth of the estuary for the three studies (Fig. 3.9) shows a similar trend of decreasing sediment import and a recent change to sediment export. However, the discrepancies in absolute values between the studies (that are in the range of larger than the import/export values) make it difficult to determine the import / export accurately. To obtaining further understanding of the import to export transition is objective of the study of Bolle (2006).

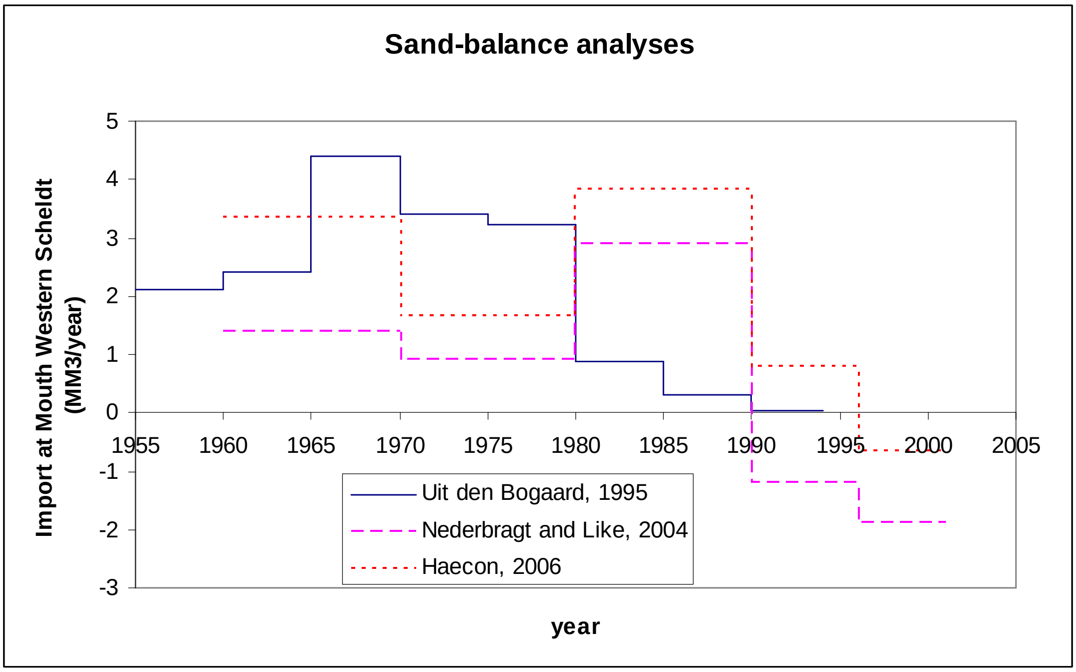


Figure 3.9 Comparison between the results from the three sand-balance analyses

3.3 Process-based modelling and considerations

Groenendaal (2005) used the WAQUA model and a model schematisation based on the set up of the ZEEKENNIS project to simulate the 2DH tidal flow in the estuary. A morphological tide with a period of 24 h 50 m is used as an open-sea boundary condition based on Kuijper et al. (2004). The sediment transport field is calculated from the flow using a simple power law ($s \propto u^n$). Bathymetries representative for the years 1968, 1972 and 2002 have been implemented using similar open-sea forcing and parameter settings. The interaction of the tide with the varying bathymetry does not reproduce the observed sediment transport reversal in the mouth of the estuary. Possible explanations for this discrepancy include: (1) inaccuracy in the sand balance analyses (unlikely as 3 sand balances show a similar trend), (2) the interaction of bathymetry and tidal flow is not representative for the sediment transport and large scale development of the estuary (other relevant processes such as wind, waves and density flow not taken into account), (3) the power-law formulation for sediment transport is not sufficiently accurate, and (4) the short-term simulations cannot reproduce a long term trend..

Within the framework of the present project Bolle (2006) elaborated on the study of Groenendaal (2005) using a more sophisticated sediment transport relation (Van Rijn 1993). Delft3D is used instead of WAQUA. A 2DH approach is followed assuming that the estuary is well-mixed. The flow solver itself is similar to the WAQUA model, however The Van Rijn transport option in Delft3D calculates the bed-load transport and the suspended transport each time step. The suspended transport is modelled by solving the advection-diffusion equation for the sediment concentration taking into account possible important effects of relaxation in time and space. For each of the bathymetries of 1970, 1983 and 2002 30 different simulations have been carried out (see Appendix A) to solve and understand the sediment transports for each of the bathymetries. Among others, these simulations include sensitivity analysis on forcing constituents, and extensive analysis of tidal asymmetry has been made. Below, the results of Bolle (2006) are translated in terms of the research questions:

Is there a change in tidal asymmetry over the years? How do changes in the bathymetry modify the tidal asymmetry?

Does the asymmetry of the vertical tide determined from the model agree with the asymmetry derived from field measurements?

By applying similar boundary conditions on the different bathymetries the bathymetry induced modification of the tide can be determined. A deviation between modelled and measurements amplitudes and phases of the main tidal constituents in the downstream stations exist. However, for sediment transport it is not the absolute values of the constituents that are most important. For example, tidal asymmetry driven transport depends on the amplitude ratio and phase differences between the M2 and M4 constituent. The modelled evolution of these amplitude ratios and phase differences within the estuary are well represented.

The trends in the different parameters describing the tidal asymmetry are well reproduced, making the DELFT3D model of the Western Scheldt a valuable tool to study the influence of distortion of the tidal propagation by the changing bathymetry and the resulting sediment transport.

How does the asymmetry of the vertical tide in the estuary change over the years?

The asymmetry of the vertical tide changes between 1970 and 2002 (see Figures 3.10 – 3.12). Largest differences occur in the eastern part of the Western Scheldt between Hansweert and Bath. There the amplitude ratios M_4/M_2 and M_6/M_2, and the phase differences $2\varphi_2$-φ_4 and $3\varphi_2$-φ_6 decrease significantly in the eastern part of the Western Scheldt (Macro cell 6, see Figure 3.4) between 1970 and 2002. Since the M4 is generated by bed friction, the decrease is most likely related to dredging and the resulting deepening of the flood and ebb channels.

A second change occurs west of macro cell 4, where the M_4/M_2 amplitude ratio decreases whereas the M_6/M_2 ratio increases. The phase difference $3\varphi_2$-φ_6 clearly increases between 1970 and 2002. The relative phase difference $2\varphi_2$-φ_4 remains constant.

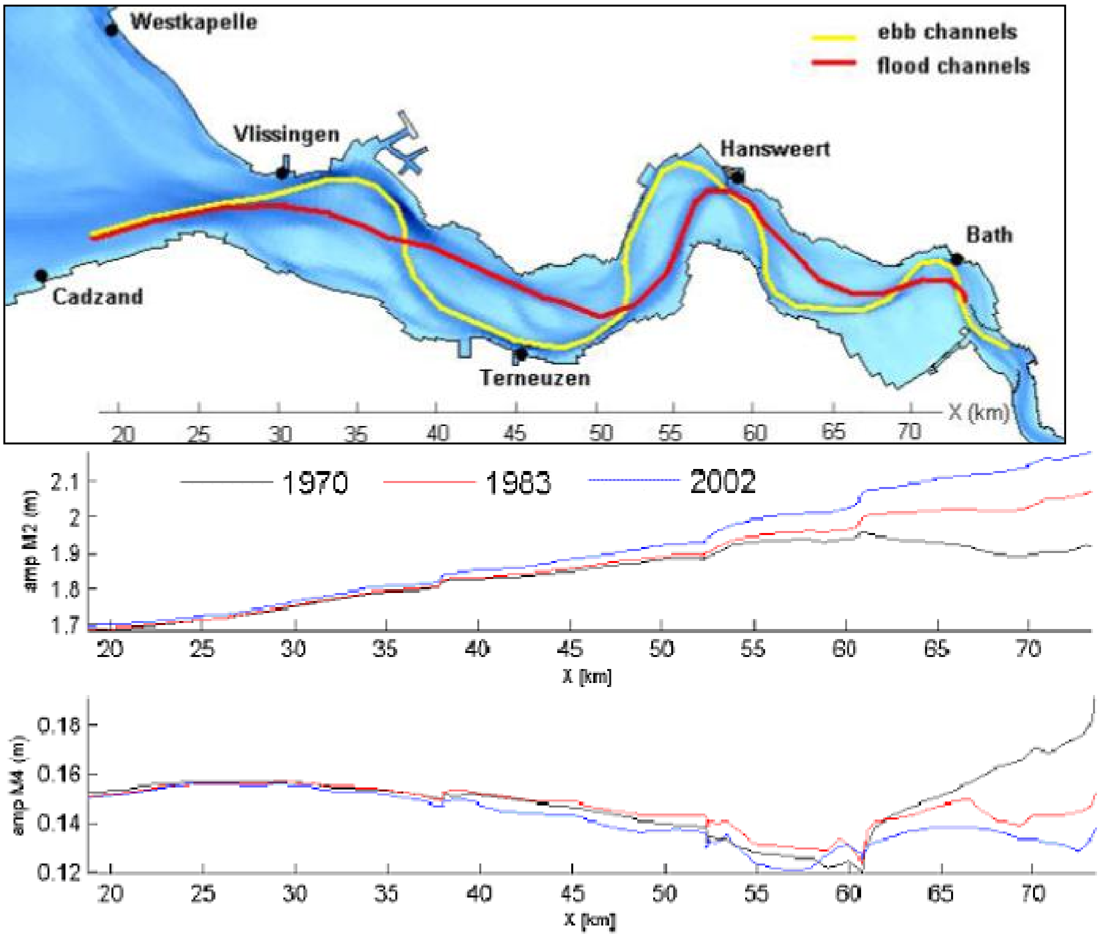


Figure 3.10 Variation of the amplitudes of M2 and M4 along (the ebb channel of) the estuary in the three differnet years.

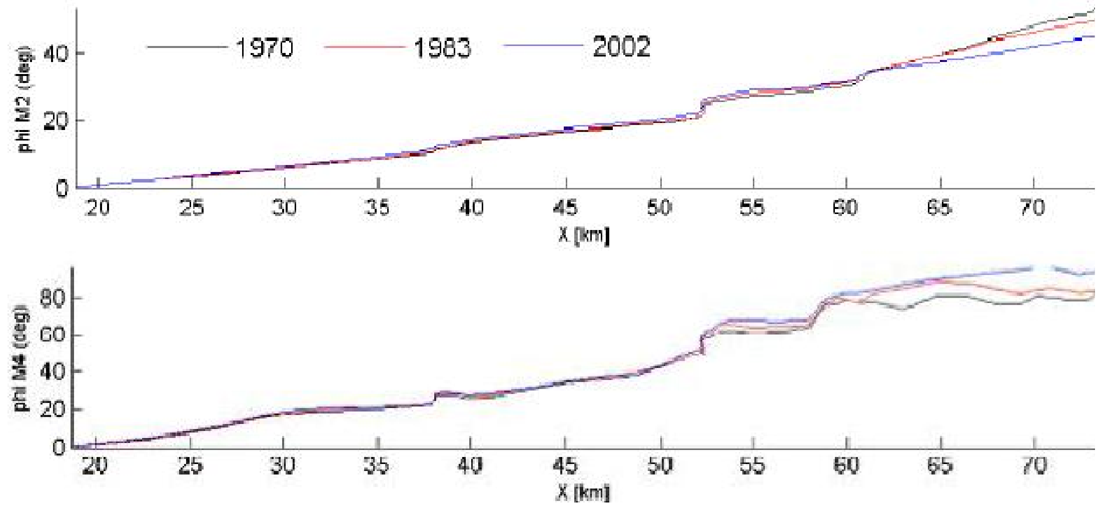


Figure 3.11 Variation of the phases of M2 and M4 along (the ebb channel of) the estuary in the three differnet years.

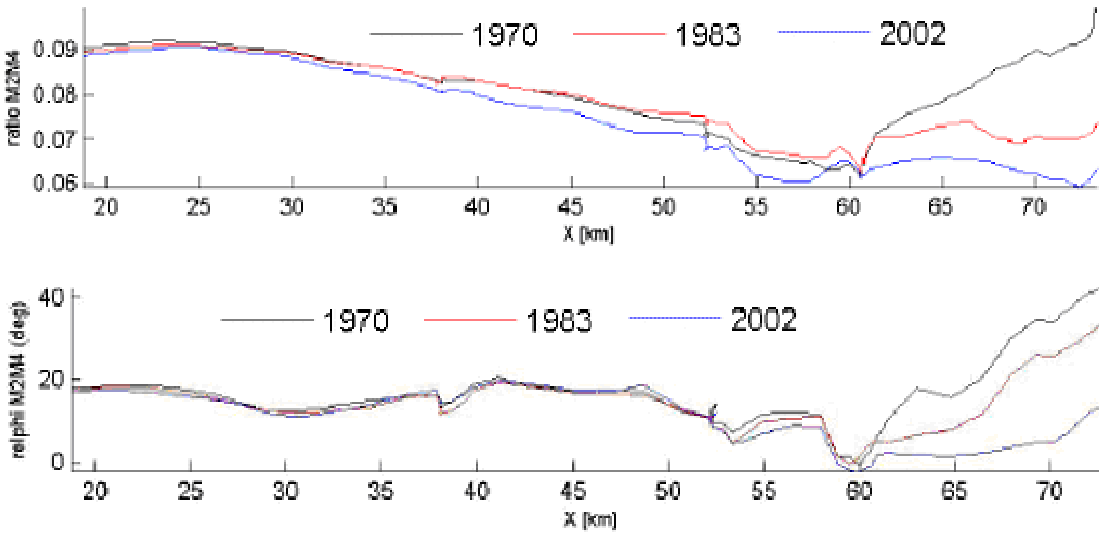


Figure 3.12 Amplitude ratio M4/M2 and phase lag 2M2-M4 along the estuary in different years.

How does the asymmetry of the horizontal tide in the estuary change over the years?

Similar to the change in vertical asymmetry, a clear change in the horizontal tide can be observed between 1970 and 2002. Largest changes occur between Hansweert and Antwerp. The amplitude ratio M_6/M_2 increases, and the ratio M_4/M_2 and the phase differences $2\varphi_2$-φ_4 and $3\varphi_2$-φ_6 decrease. Downstream from Hansweert the ratio M_6/M_2 and the phase difference $3\varphi_2$-φ_6 decreases, while no clear trend can be observed in the ratio of the M_4/M_2 amplitude and its relative phase differences $2\varphi_2$-φ_4.

Deepening of a channel leads to a decrease of the amplitude ratio M_6/M_2 (cell 3 and 4) and M_4/M_2 (cell 4, 5 and 6). The phase difference $3\varphi_2$-φ_6 is continuously increasing in macro cells 3, 4 and 5, only the amount of increase is influenced by the changes in bathymetry.

Sedimentation in a channel gives rise to an increase of the phase difference $2\varphi_2$-φ_4 (cell 3 and 4) and an increase of the amplitude ratio M_4/M_2 (cell 4). Apart from the last finding, similar reactions of the vertical tide to a modified bathymetry where found.

Is there a relation between the changes in the tidal asymmetry and the import/export of sediments at the mouth?

A clear relation between tidal asymmetry and import/export at the estuary mouth cannot be observed. The main changes in tidal asymmetry occur eastward of Hansweert. Changes near Vlissingen are small. The changes eastward of Hansweert show the clear relation between bathymetric change, tidal asymmetry and residual sediment transport.

Which changes in the bathymetry have influenced the tidal asymmetry the most?

Both the analysis of the vertical and the horizontal tide indicate that the deepening of channels leads to a decrease of the amplitude ratios M_6/M_2 and M_4/M_2. Sedimentation in a channel gives rise to an increase of the phase difference $2\varphi_2$-φ_4 and the amplitude ratio M_4/M_2 of the horizontal tide. Both evolutions of the bathymetry are in most cases due to human interventions. Dredging, dumping and sand mining occur throughout the estuary and induce important bathymetric changes. These clearly have an impact on the tidal asymmetry in the estuary.

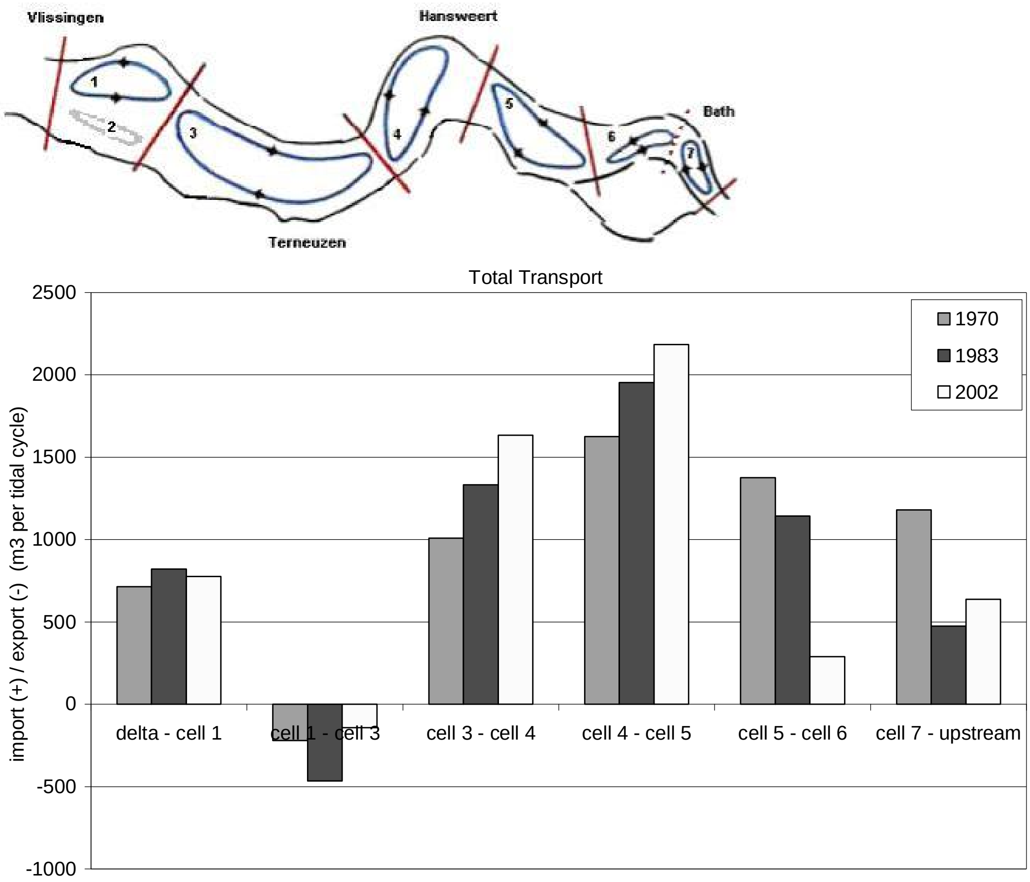


Figure 3.13 Caluculated total residual sediment transport for different years

Does the residual transport derived from the model agree with previous sand balances?

The calculated total (bed-load + suspended load) residual sediment transport through various cross-sections in the estuary for the three different years is shown in Figure 3.13.

In the central part of the Western Scheldt we do observe an increasing transport eastward transport (as reported in Stikvoort et al. 2003). This increase indicates that locally the residual transport has been influenced by the tide-bathymetry interaction.

Looking at the inlet mouth, we must conclude that the change from import to export is not reproduced in the model. In fact the export is not simulated by the model at all. When only bed-load is considered in the Van Rijn approach, an increasing seaward transport is found from cell 3 towards cell 1. On the borders of cell 3&4 and 5&6, a decrease of the upstream transport is noticed. The import from the mouth towards cell 1 is also clearly smaller in 2002 compared to the other two years. However, even for bed-load only, no export at the mouth occurs.

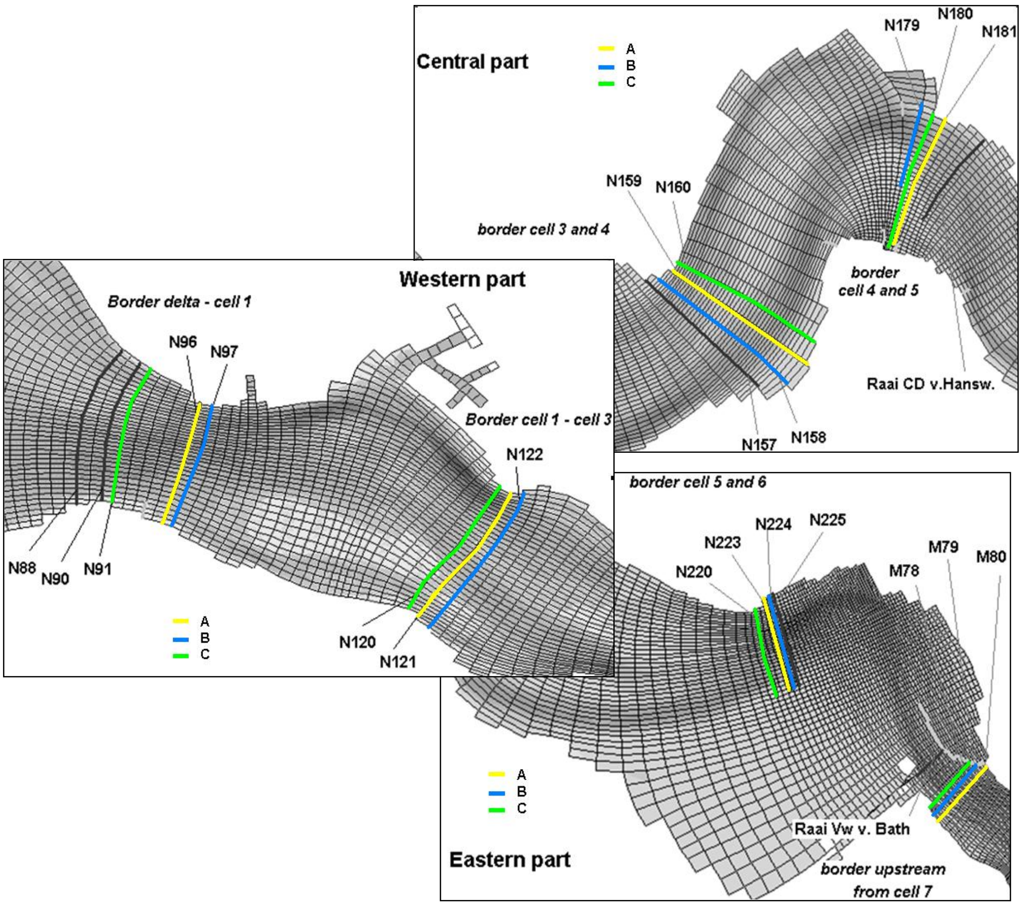


Figure 3.14 Locations of the different cross-sections

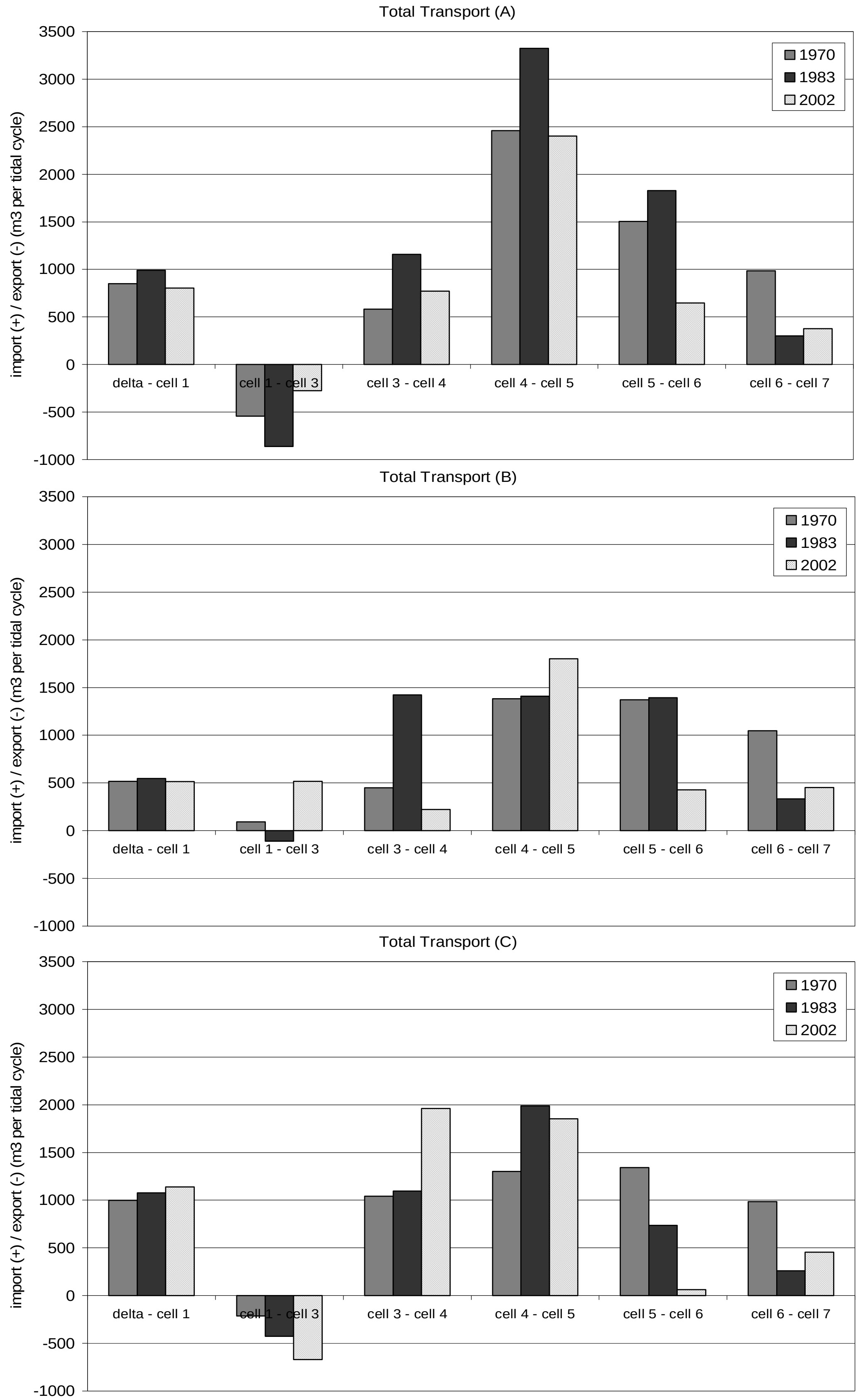


Figure 3.15 Residual sediment transport between the cells using different cross-sections as boundaries between the cells (see Figure 3.14)

Are bed-load and suspended-load transports following different trends?

By using the Van Rijn transport formulation an estimate of the separate contributions of the bed load and suspended load can be obtained .The bed-load transports appear to be only accounting for 3% of the total transport. This applies for the momentary transport as well as the residual transport.

Both the bed and suspended load follow a similar trend, with major transports in the channels. The bed load transports are a direct (non-linear) relation to the velocity field. The suspended loads are solved by the advection diffusion equation.

Although the driving mechanisms for suspended load and bed-load are not fully the same, the residual transport patterns in the model are very similar. However, as seen from the sand balance derived from the model, bed-load and suspended load don't follow exactly the same evolution. A clear increase in eastward directed transport in the central part of the Western Scheldt is found for the suspended load, whereas for bed-load only this evolution is absent. Apparently the relaxation effect for the suspended load has significant influence on the residual sediment transport.

Can different transport formulations influence the results significantly?

Comparison of the results of Engelund Hansen and Van Rijn formulation for the sediment transport shows similar patterns for the residual transport. Magnitudes differ with transport rates for Engelund Hansen typically 30 - 50% lower compared to Van Rijn.

Note that this comparison is not really valid as both models use default settings and are not calibrated on observed transport rates. For a fair comparison both models need to be calibrated (so matching transport rates are obtained), only then an objective comparison of the transport patterns and rates is allowed.

Which characteristics of the bottom geometry are responsible for the import/export of sediments at the Western Scheldt mouth?

The change from import to export at the mouth is not reproduced in the model. The question can therefore not be answered by the results of this study. Possibly this can be explained by three different reasons:

- Insufficient accuracy in forcing of the model. In this study irregularities in the water level upstream form Hansweert were found for the 1970 situation. A solution would be to calibrate the model again and to improve the schematisation of the most upstream part.
- Sediment transport due to interaction of the tide with the bathymetry isn't representative for the residual sediment transport. Also non-tidal mechanisms such as estuarine circulation, wind and waves can contribute significantly to the transports in a tidal inlet. These mechanisms haven't been included in the model for this study.
- The effect of human interventions might be underestimated and dominate over the natural changes.

Further research is needed to determine the influence of all these different processes (See recommendations).

Which are the mechanisms governing the sediment exchange between the Dutch coast and the tidal basin Western Scheldt?

The change from import to export at the mouth is not reproduced in the model. Therefore it is difficult to draw conclusions on the sediment exchange mechanisms. It might be concluded that tide-topography interaction alone is not the primary actor in the inlet mouth. More processes need to be added to reproduce observed trends. The increasing eastward transport in the central part of the Western Scheldt due to changes in bathymetry is well represented in the model. This increase shows that the changes in the residual transport are (at least) locally influenced by the interaction of bathymetry and tide.

The fact that bathymetry and tide have a clear relation in the eastern part of the Schelde might be related to the difference in bathymetry. In the eastward part of the estuary channels form a relative larger contribution than in the western part. In the channel dominated section (changes in) tidal asymmetry seems to dominate the transports. The change in tidal asymmetry can be related to the modification of bathymetry by dredging activities.

In the Western part transports on the shoals are more pronounced, responsible for generating complex residual circulations. Here tidal asymmetry does not provide a clear indication of changes in export regime. Important contributions to the residual transports such as wind and waves need to be accounted for if residuals are dominant mechanisms. The change from import to export could be related to dredging activities. Dumping of sand distorts the natural state and larger then average sediment transports take place to restore the natural state (a process similar to accelerated erosion of beach nourishments). By dredging the channel it becomes larger and sediment transport capacity decreases. Larger sediment transport rates and a larger along channel transport capacity could result in a sediment exporting system

In addition the large changes in the Voordelta and the various human interventions could have resulted in a decreased sediment supply to the estuary.

However, the absence of export in the 2002 situation indicates that some factors are still missing. Possibly wind and waves are important for the residual transport as well. Their influence hasn't been investigated in this study. Further research is needed to identify the relative importance of the different mechanisms. Furthermore, question also arises if the initial transport determined in the present study, which can be influenced by e.g. errors in the bathymetry schematisation, is representative for the real transport. Long-term simulations should thus also be considered in the future study.

Not all the simulations have been analysed and reported in the report of Bolle (2006). A complete overview of all simulations and some additional analyses are given in Appendix A. In Appendix B a specific analysis to the influence of the downstream boundary condition (the tidal forcing) is carried out by comparing the results of the simulations in which the tidal constituents in the downstream boundary condition have been varied. It appears that the results are only sensitive to the amplitude of the M_2 tide. The amplitude and phases of the higher frequency components M_4 and M_6 at the open sea boundary appear to have little influence on the results (See Figures 3.16, 3.17 and 3.18). Specifications of the depicted runs are given in the following table.

Table 3.1 Overview of the different model runs with the modified downstream boundary conditions.

Overview of the simulations						
Run ID	**Harmonic constituents at the downstream boundary**					
	M_2		**M_4**		**M_6**	
	Amplitude	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**
18	reference situation		reference situation		reference situation	
20	+25%	ref.	ref.	ref.	ref.	ref.
21	+50%	ref.	ref.	ref.	ref.	ref.
23	ref.	ref.	+50%	ref.	ref.	ref.
24	ref.	ref.	ref.	ref.	+25%	ref.
25	ref.	ref.	ref.	ref.	+50%	ref.
29	ref.	ref.	ref.	ref.	ref.	+50%
ref. = reference situation (identical to the settings of run 18)						

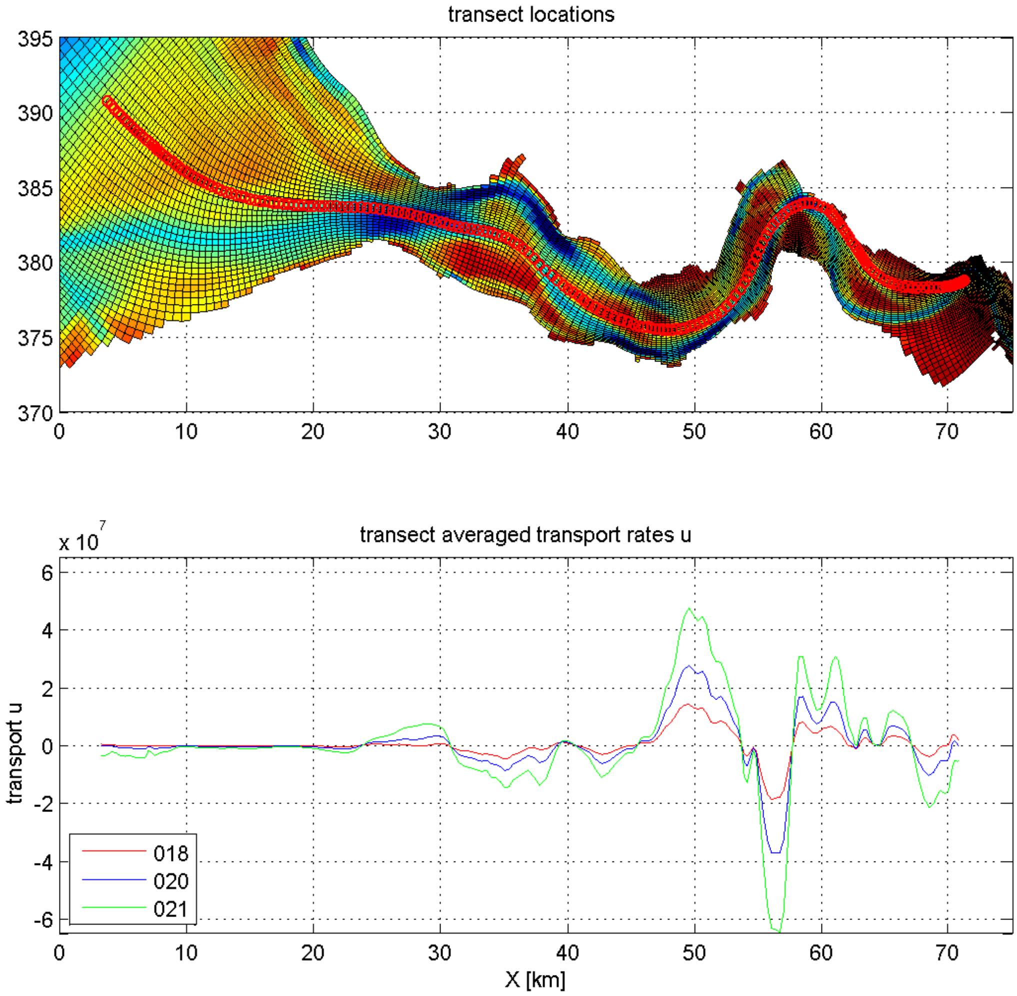


Figure 3.16 Computed longitudinal transport from the various runs (in m^3/s per transect cross-section width)

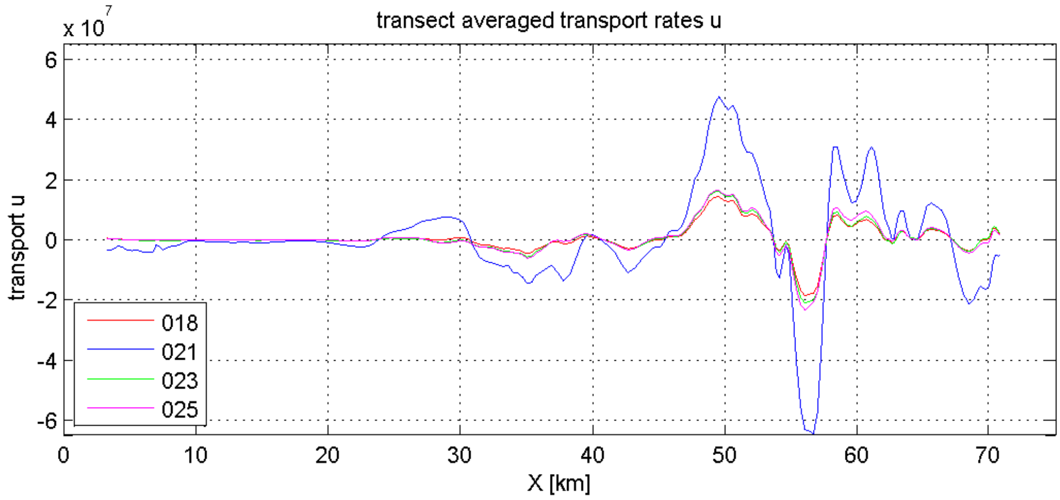


Figure 3.17 Computed longitudinal transport from the various runs (in m^3/s per transect cross-section width)

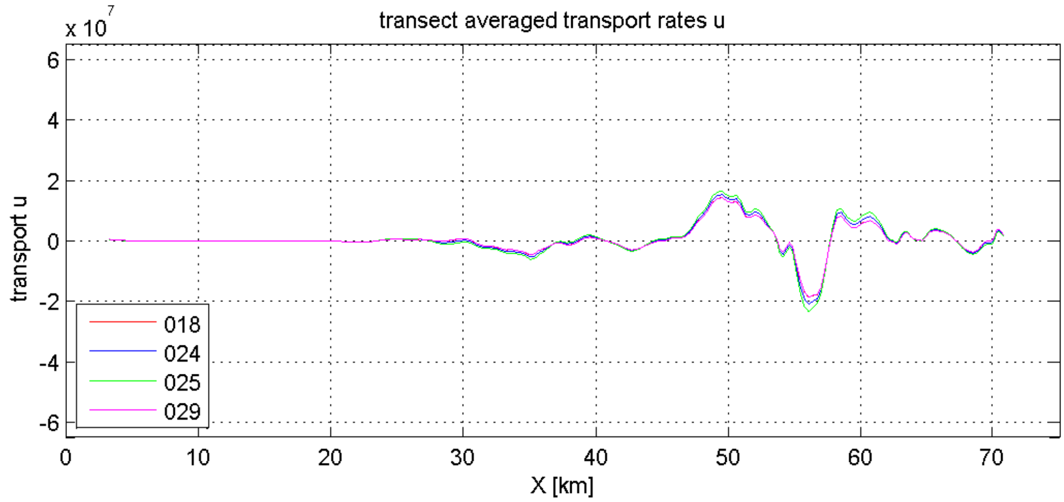


Figure 3.18 Computed longitudinal transport from the various runs (in m^3/s per transect cross-section width)

Long-term simulations with the same software and similar model set-up appear to be able to reproduce the characteristic channel-flat structures in the estuary (Hibma, 2004, Van der Wegen, 2006). The results of Van der Wegen (2006) suggest that the morphological development approaches a state satisfying the neutral tidal asymmetry condition defined in the literature, but the residual transport at the mouth is not zero at that state.

That the process-based modelling is not able to simulate the turning from import to export at the mouth of the estuary seems to suggest that there are still some shortcomings of the applied model. If we compare the circulation cells as defined in Literature with the zero-crossings in residual sediment transport rates then we observe a reasonable correspondence in the upper estuary (cells 4 and 5) and limited correspondence in the lower estuary (1 to 3). The upper estuary is also the area were we can see a clear correspondence in bathymetric change and tidal asymmetry. In this area tides are likely the dominant process and the model seems to capture the essential of the estuary change reasonably well. In the lower estuary no clear correlation between bathymetric change and tidal transports is observed. This is likely due to non-tidal contributions such as wind and waves that play a more important role in this wider part of the estuary.

Hypothesis, with tides only we create an initial channel-shoal pattern. In the wider lower estuary non-tidal processes play an increasingly important role in alterations of the macro-scale channel-flat structures.

This agrees with the results from the study on the basis of the field observations by Wang et al (1999, 2002). The relation between the observed historical morphological changes and the changes of the tidal asymmetry agree well with the theories reported in the literature, but the change of the residual sediment transport cannot be explained from the change of the tidal asymmetry.

Another issue is the functioning of the mouth area, the large funnel-shape area outside the cross-section Vlissingen-Breskens. It is not clear if this area should be considered as a part of the estuary itself or it should be considered as the ebb-tidal delta. For the management purpose this part belongs to the coastal area and it is a part of the coastal foundation. Therefore the mouth of the estuary is defined at the cross-section Vlissingen-Breskens in the present study.

3.4 Semi-empirical modelling

Semi-empirical modelling is often applied for modelling long-term morphologic development. The basic principle of these models is that residual sediment transport occurs in the direction of the gradient of sediment demand. Various studies have used the ESTMORF and ASMITA models for the Western Scheldt estuary (Wang and Van Helvert, 2001; Jeuken et al., 2002; Wang, 1997; Meangbua, 2003; Kemerink, 2004). Both ESTMORF and ASMITA are capable of reproducing the transport reversal from import to export. The modification of the strategy for dumping dredged material after the second deepening of the navigation channel was identified as the main mechanism.

ESTMORF was originally specially developed for the Western Scheldt Estuary. An overview of the model development and the first applications of the model is given by Wang and Van Helvert (2001). Recently Jeuken et al (2002) and Kemerink (2004) expanded the studies by taking into account sea-level rise. Sea-level rise has shown to have a smaller impact on the import / export at the mouth, than the dredging (including sand mining) and dumping strategy in the estuary. The rate of sea-level rise only influences the magnitude of the residual sediment transport, but not its sign; at the mouth of the estuary export is predicted for all sea-level rise scenarios considered with export magnitudes increasing at higher sea-level rise rates. Jeuken et al. (2002) report that the export at the present rate of sea-level rise (20 cm/century) is about 1.5 million m^3 per year (Figure 3.19) and it increases to 1.7 million m^3 per year if the sea-level rise accelerate to 60 cm per century (Figure 3.20). Kemerink (2004) reports similar results.

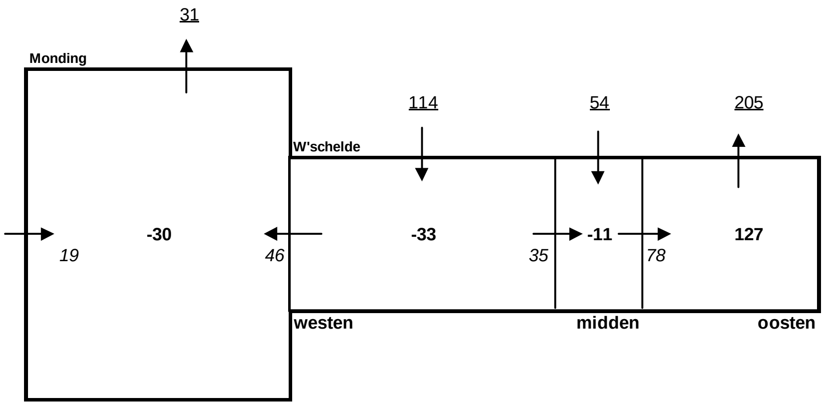


Figure 3.19 Sand balance for the whole period 1999-20**30** simulated by ESTMORF for the situation of continuing dredging & dumping strategy and slr = 20 cm /century

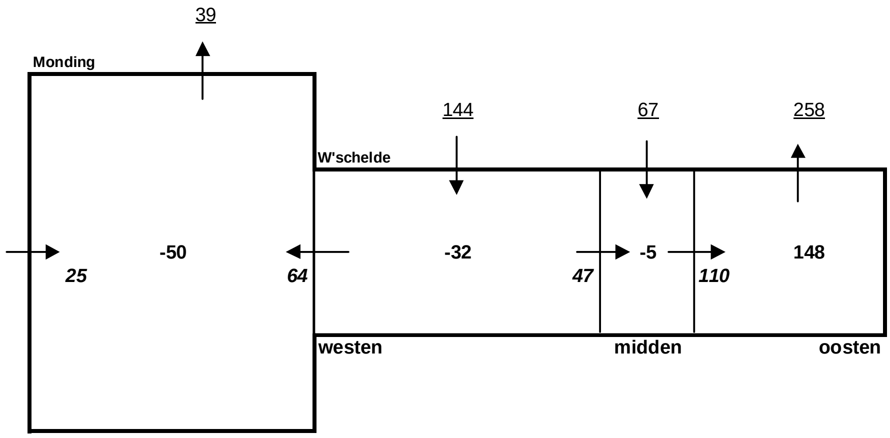


Figure 3.20 Sand balance for the whole period 1999-20**38** simulated by ESTMORF for the situation of continuing dredging & dumping strategy and slr = 60 cm/century. Note that the period covered is different than in Figure 3.19.

ASMITA modelling of the Western Scheldt estuary and its mouth area were intiated by Wang (1997), and further elaborated by Meangbua (2003) who extended the ASMITA-Western Scheldt model by including the Mouth area of the Eastern Scheldt. The results of the Meangbua model simulations were implemented in the NL-Coast model (a PonTos-ASMITA hybrid, see Steetzel and Wang, 2004 & Wang et al, 2006 for details).

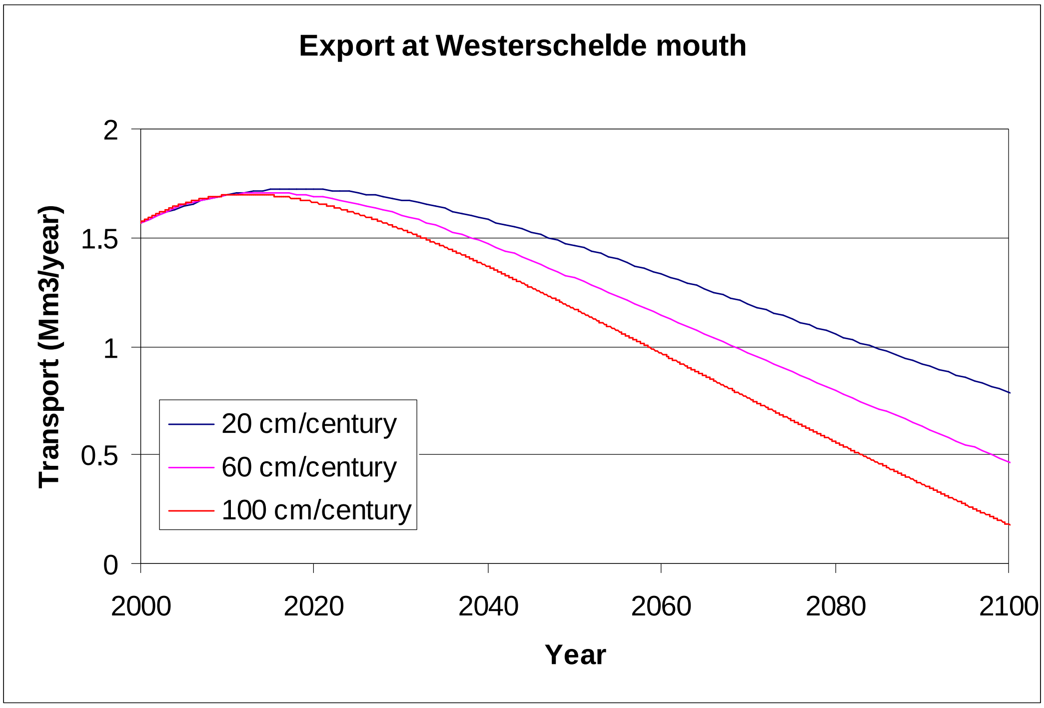


Figure 3.21 Sediment transport from estuary to mouth area at Vlissingen simulated by ASMITA model (Negative = import)

ASMITA results (Wang et al, 2006) for sediment transport in the estuary mouth for three sea-level rise scenarios are shown in Figure 3.21. In these simulations it is assumed that the present dredging and dumping strategy including sand mining will remain the same in the future. Similar to ESTMORF export at the mouth is modelled. However, ASMITA predicts a decreasing trend and on the long-term a switch to sediment import (estimated to take around 150 years). In addition export decreases with increasing sea-level rise. This response is opposite to the increasing rates predicted by ESTMORF. These differences are related to the tidal propagation in the estuary that is not included in ASMITA. In ESTMORF it is predicted that the tidal range in the estuary increases, the tidal wave propagation accelerates and tidal prism increases.

The semi-empirical modelling using ESTMORF and ASMITA reveals the fact that sea-level rise causes a sediment demand not only in the Western Scheldt Estuary but also in the mouth area. As the mouth area is even much larger than the estuary in size the sediment demand due to sea-level rise in the mouth area is much larger than that in the estuary.

To improve the ASMITA model predictions, future modifications include:

- Implementing the results of the recent sand balance analysis (Nederbragt and Liek, 2004, Haecon, 2006). This task has not been completed as reliable data dredging/dumping volumes are not yet available for the entire system.
- Implement the feedback of changes in forcing and tidal propagation.

Real improvement of the semi-empirical modelling is hampered at this stage by two major knowledge deficiencies. To really improve the ASMITA schematisation we need to understand the interaction between Western Scheldt and Delta coast (that appears to be relatively unimportant), and we need more understanding of the process responsible for the observed dynamics.

3.5 Prediction and evaluation

As the process-based modelling is still unable to explain the development of the import / export at the estuary mouth, the predictions can best based on the semi-empirical modelling. The export at the mouth of the Western Scheldt estuary is calculated in the order of 1.5 million m^3 per year. Both ESTMORF and ASMITA predict that the influence of the rate of sea-level rise on the export is limited. Moreover, the two models predict opposite influences of accelerated sea-level rise on the import. ESTMORF predicts a small increase and ASMITA predicts a small decrease due to higher sea-level rise rate. Concerning the development in time ASMITA predicts a decrease of the export on the long-term, and the export will turn to import again over about 150 years. This feature is not predicted by ESTMORF, although it should be remarked that the simulation period of ESTMORF computations are much shorter. Based on these considerations it is concluded that the most reasonable prediction is that the export will be in the order of magnitude of 1 million m^3 per year in the coming century, applicable for all considered rates of sea-level rise.

From the reasoning above it becomes clear that the prediction contains significant uncertainties. As processes and mechanisms of the historical development are not understood yet, the two semi-empirical models do not produce the same results, and the process-based modelling failed to reproduce export at the mouth, there is much uncertainty related to the prediction method. Another category of uncertainties is due to the development within the estuary self. The model results indicate that the management of the dredging and dumping activities in the estuary has strong influence on the import / export at the mouth of the estuary. The future development of this management is uncertain and depends on e.g. whether or not the navigation channel will be further deepened. However, from the point of view of coastal management, the uncertainty in the prediction of the import / export at the mouth of the Western Scheldt is not very important. The magnitude of this import / export is relatively small compared to the changes in the Delta Coast area. As reported in Chapter 2, the analysis of the historical development suggests that the whole Delta Coast area is losing sand with a rate in the order of magnitude of 10 million m^3 per year. The exchange with the Western Scheldt is thus only a small item in the balance of the Delta Coast area. For the coastal management understanding the other uncertainties in this balance is thus much more important. The import / export at the mouth is more important for the development within the estuary it self.

For the development of the Delta Coast it is important to understand what has caused the large loss of sediment from this area. A remaining question is also whether or not this loss needs to be compensated. In the present practise this loss is not compensated by nourishment. For the development of the estuary itself it is important to understand the development of the exchange at the mouth in the past, in order to make better predictions for the future development. Therefore it is recommended to carry out more research concerning the observed large loss in the Delta Coast area and to do more study in order to understand the historical development of the sediment exchange between the Western Scheldt and the coast.

Furthermore, it is noted that the sediment demand in the mouth area of the Western Scheldt caused by sea-level rise is much more than that in the estuary itself. The horizontal surface area (at mean sea level) of the estuary is about 270 km^2, and that of the mouth area is about 770 km^2. For the present rate the sea-level rise causes a sediment demand of about 0.5 million m^3 per year in the estuary and about 1.2 million m^3 per year in the mouth area.

4 Wadden Sea basins

4.1 Introduction

The Dutch Wadden Sea consists of a series connected tidal basins (Figure 4.1). The present study focuses on the Marsdiep basin. However, as the recent studies and also all the MSc-projects carried out in the present study indicate that this tidal basin cannot be considered in isolation, the whole western part of the Dutch Wadden Sea, consisting of the three basins Marsdiep, Eierlandsegat and Vlie, is considered integrally.

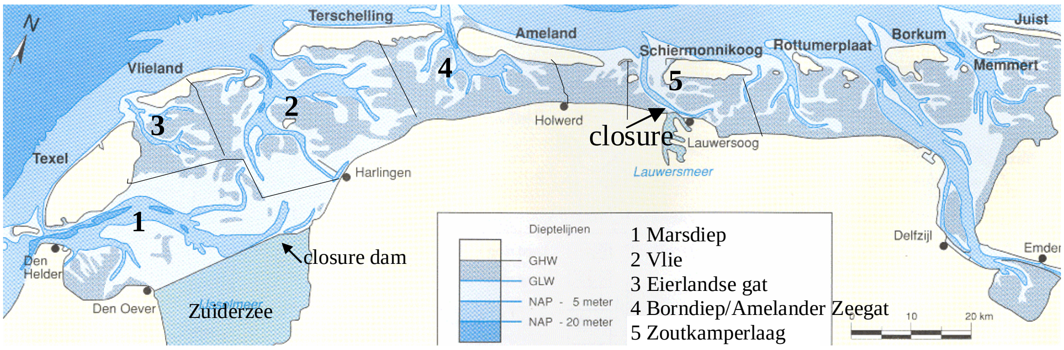


Figure 4.1 The Dutch Wadden Sea, with approximately tidal watersheds

Three MSc-projects have been carried out (Dastgheib, 2007, Van Geer, 2007, Van de Waal, 2007). The results and findings are summarised and evaluated in section 4.2. The sediment demand of the system is analysed in 4.3 by considering the morphological equilibrium. In 4.4 the future development including the corresponding uncertainties is considered.

4.2 Summary subtasks

4.2.1 MSc-projects

The MSc-projects have the common objective to understand the interaction between the tidal basins Marsdiep and Vlie in the Western part of the Dutch Wadden Sea.

Van der Waal (2007) uses Delft3D to improve understanding of the processes and mechanisms influencing the sediment exchange between the tidal basins and the coast. Predictions of future sediment transport rates are obtained by modelling present as well as future situatuions by changing the bathymetry in the model. The future bathymetry is constructed on the basis of predictions from the long-term semi-empirical modelling, carried out by Van Geer (2007) foccuses on the sediment demand of the system by analysis of historical data and by improving the ASMITA modelling for the inlets.

Another study on the long-term morphological development is carried out by Dastgheib (2007), but then using process-based modelling with simplified schematisations of the driving forces etc..

The three MSc-projects are complementary for understanding the behaviour of the system.

In the following three subsections each of the three MSc-projects is summarised, followed by an integrated evaluation in 4.3.5.

4.2.2 Short-term process-based modelling (Van der Waal 2007)

The research by Van de Waal (2007) focuses on the influence of the forcing mechanisms wind, waves and tides. Secondly, simulations with future bathymetries have been made to asses the impact on sediment exchange through the inlets (see Figures 4.2, 4.3 and 4.4). The main findings of the study are summarised below:

Forcing processes

First the importance of the three driving forces for sediment transport is investigated by comparing the results from three kinds of runs: with only tide, with tide and waves, with tide, wind and waves. The following conclusions have been drawn from the comparison:

- Due to tidal forcing Texel inlet imports sediment, Eierlandsegat and Vlie inlet export sediment.
- The direct influence of waves is most pronounced at the ebb-tidal delta area, where most of the wave energy is dissipated.
- A spatially varying water level set-up as a result of the large-scale wind forcing creates residual flow between the basins that is in the same order of magnitude as the tidal residual flow. In addition set-up affects the storage area in the basins, increasing the tidal velocities in the inlets.
- Indirect effects of waves are the generation of a residual flow between the basins, and the reduction of the tidal range. Effects are larger for increasing wave-heights. The direction of the residual flow depends on the angle of incidence of the wave.
- The modelled transport of sediments between the basins is limited, and shows little reaction to a change in the forcing.
- The sediment transport through the Vlie inlet appears to be very much dependent on the effect of wave height and wavedirection. With only tide the inlet is exporting sediment, including waves changes this to importing sediment.

Based on these conclusions it is necessary to include all three driving processes in the modelling for determining the residual sediment transport. A schematised wave climate with the corresponding wind forcing is used.

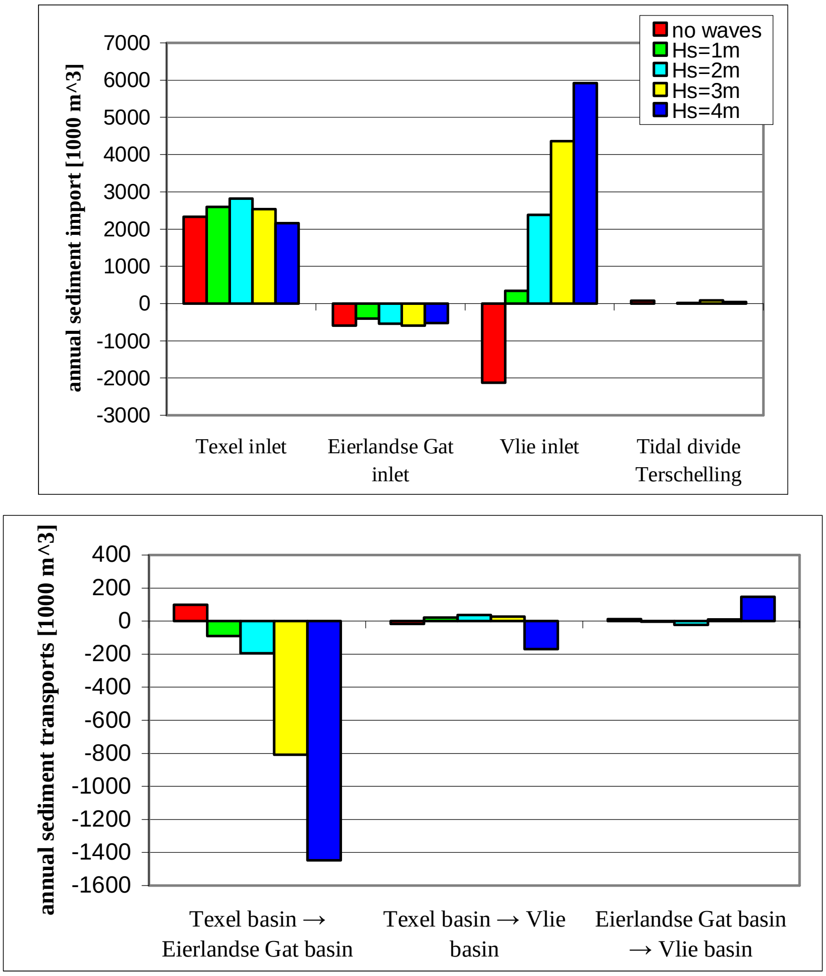


Figure 4.2 Influence of wave height on the residual sediment transport. Upper panel: Tide-averaged sediment imports through the inlets and over the tidal divide “Terschelling”, Lower panel: Tide-averaged sediment transports over the tidal divides. In all simulations wave come from Northwest.

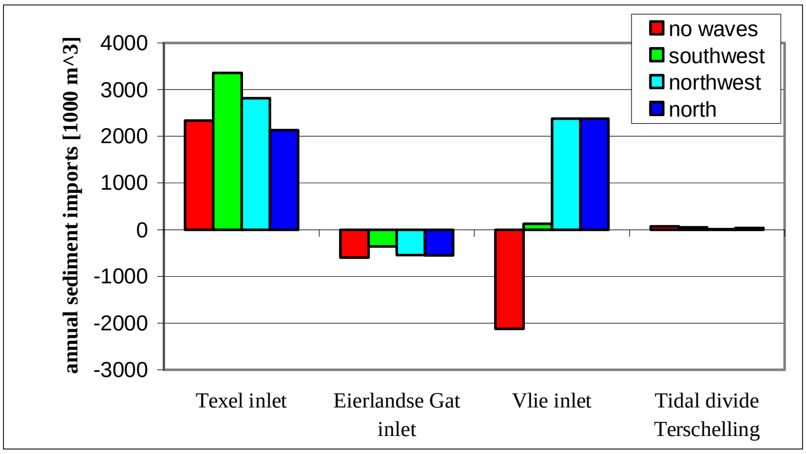


Figure 4.3 Influence of wave direction on the sediment transport rates through the inlets. Significant wave height is 2 m in all simulations.

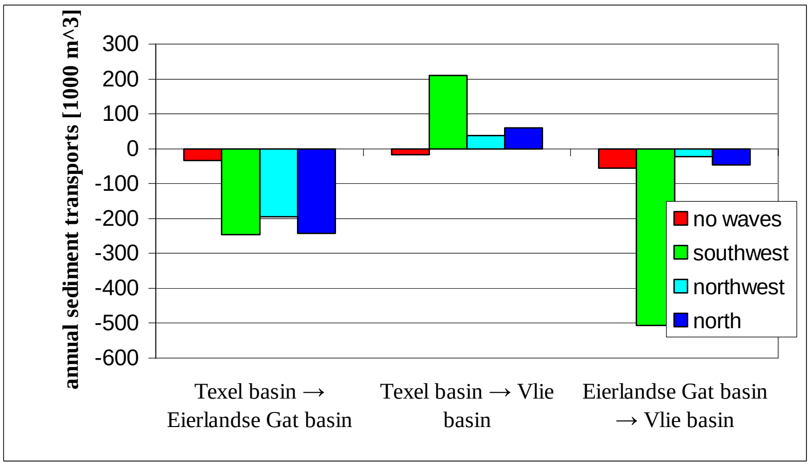


Figure 4.4 Influence of wave direction on sediment transports over the tidal divides. Significant wave height is 2 m in all simulations.

Bathymetric influence

Model simulations with various hypothetical (future) bathymetries have been carried out in order to obtain more insight into the impact of the morphological impact on the residual sediment transport. First a simulation with the 1998 bathymetry is carried out. This simulation is used as reference for comparison with the simulations with adjusted bathymetries. Due to the restrictions of the models the results of this simulation do not fully agree with reality (the total sediment import through the three basins is lower than the observed data and sediment transport between the basins is absent), but for the comparison of model results it is considered sufficient accurate. The results from this run (see Figure 4.5) can be summarised as follows:

- With the bathymetry of the year 1998 the Western Wadden Sea has an import rate of 6.3 Mm^3/yr. This volume is divided over the three inlets. 3.8 Mm^3/yr is imported through the Texel inlet, 0.7 Mm^3/yr through the Eierlandse Gat inlet and 1.9 Mm^3/yr through the Vlie inlet. These figures are not the same as those according to the observations (Elias, 2006, Eilas et al, 2006) but they are of the correct order of magnitude. The observations suggest a total import through the three inlets of about 10 million m^3 per year.
- The annual transports between the basins are marginal compared to the transport through the inlets. The imported sediments through each inlet are therefore deposited in its own basin. This does not agree with the observations as reported by Elias (2006), who suggests that large amount of sediment is transported from Marsdiep to Vlie. Apparently the present model is unable to accurately simulate the transport around the tidal watersheds, probably due to the missing of the dynamics of the storms in the simulations.

The morphodynamic model results of Van der Waal shows a discrepancy with reality. The observed patterns of sedimentation-erosion in the basin, especially near the tidal watersheds, are not reproduced and excessive erosion dominates the inlet channels. An important conclusion from this study is that modelling the sediment transports in the basin and inlet is a major challenge. Due to the large area and the complicated bathymetry high-resolution models are needed. Computational time restrictions necessitate to some crude assumptions such as a 2DH approach and the use of a single bed fraction. Especially this last assumption might be an important factor in the underestimated transport rates in the basin. More research is needed to improve this part of the modelling. It might be useful to place measurement frames at the tidal divides to get some real time data for model validation. Due to the model limitations we cannot present clear conclusions on governing processes and mechanisms yet.

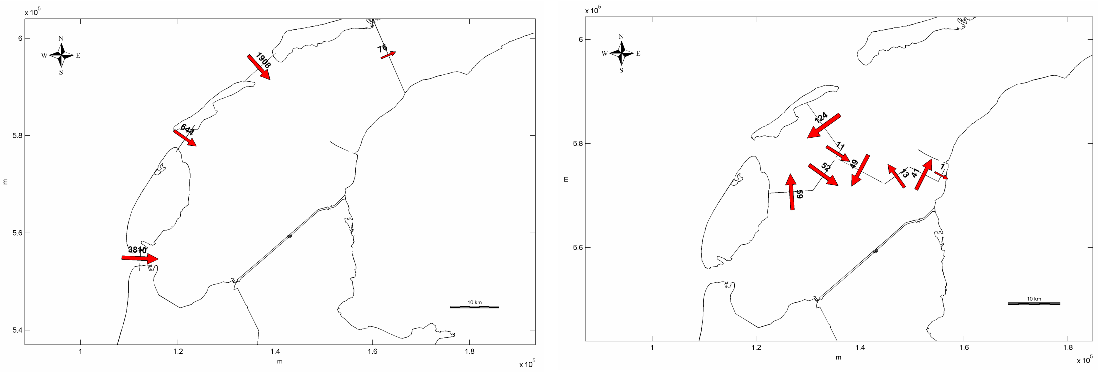


Figure 4.5 Calculated residual sediment transport though the inlets (left) and the tidal divides (right), for the 1998 bathymetry.

One of the concerns is that the large import of especially Marsdiep continues to reduce the size of the ebb tidal deltas. This can increase coastal erosion of the adjacent sections considerably, since the ebb tidal deltas form a natural breakwater reducing the wave-energy on the adjacent coastal section. In addition a reduced ebb-delta volume can decrease sediment supply to the coast and basin.

To investigate the effects of a "no ebb-delta situation" a simulation is carried out with an adjusted bathymetry where the three ebb tidal deltas in the model were removed. The following conclusions have been drawn from the results of this simulation:

- When the ebb-tidal deltas are removed, the inlets are more exposed to the incoming waves. This increases the wave action in the direct vicinity of the inlets, and subsequently the sediment transport magnitudes.
- Due to the larger wave action in the inlets, more sediment is imported around the tips of the barrier islands. In other words, due to the larger wave action the tips of the islands are eroded, and the sediment is transported towards the inlet.
- The effect of the removal of the ebb-tidal deltas on sediment transport in the model is limited. The transport in the basins is not influenced as in the model the coastlines can erode freely; the reduced sediment availability from the ebb-tidal delta is counter balanced by additional erosion of the coast. In reality transport rates are expected to decrease as erosion of the coast is limited by coastal protection works.

To investigate the existence of a morphological equilibrium state additional simulations have been made. Bathymetries were estimated on the basis of the empirical relations of Van Geer (2007). Main conclusions of this exercise (see Figure 4.6):

- The sediment transport rates through the inlets react strongly to the addition of sediments in the basins. The reaction depends on the amount of sediments and the location where they are placed.
- The Marsdiep basin suffers the largest shortage of sediment. The amount of sediment required to achieve equilibrium according to the empirical relations is $1220*10^6 m^3$. When this amount sediment is added to the bathymetry of the year 1998, the transport rate through the inlet changes to an export of $265*10^3 m^3/yr$. This is a small amount

compared to the initial import of $3810*10^3 m^3/yr$. This is an indication that the basin volume is close to its equilibrium.

- The added volumes in the Eierlandse Gat and Vlie basin are in the order of 10% compared to the added volume in the Texel basin. Especially in the Vlie basin, which has a comparable surface area, it is a significant difference. Yet the response of the sediment transports through these inlets is just as distinct, if not even more distinct, as the reaction of the transports through the Texel inlet. The initial imports quickly change into export. The explanation of these strong reactions lies in the location of the added sediments. In the two basins, the majority of the added sediments are placed in the ebb-channels. This induces a restriction of the cross-sectional area in these channels, which implies an increase in the velocity. The channels are ebb-dominant and the export during ebb increases considerably. Another explanation can be that this is an initial response of the model to the wrongly adjusted (distribution of the added sediment) bathymetry.
- The added sediments induce little additional transport of sediments over the tidal divide.

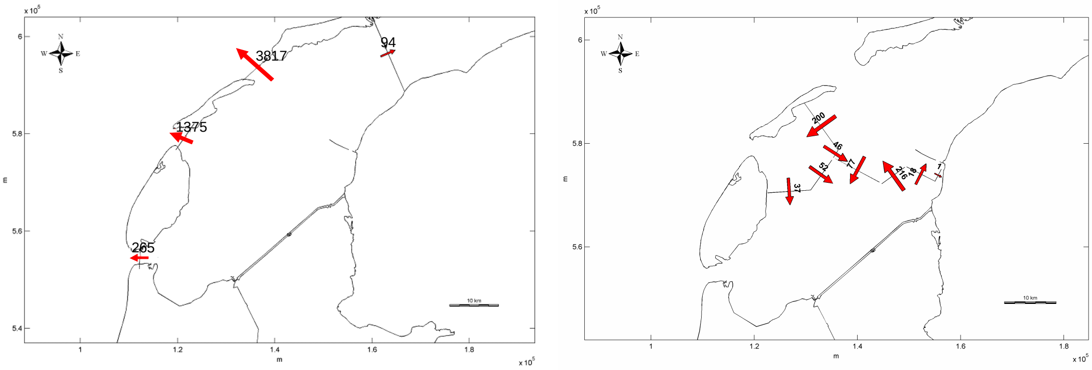


Figure 4.6 Calculated residual sediment transport though the inlets (left) and the tidal divides (right), for the estimated equilibrium bathymetry.

The results from the runs do not give exclusive answer to the research question concerning the morphological equilibrium. A number of possible causes can be identified: (1) a major limitation is short timescale of the model simulations. Therefore the model captures an initial response that not necessarily represents long term trends, (2) apparently the constructed bathymetry does not represent the equilibrium configuratiuon according to the model. It seems to suggest that the sediment demand is less than estimated from the applied equilibrium relations. Probably this is because the morphological equilibrium and equilirium bathymetry ae determined for the three basins seperately. This assumption might be invalid as also supported by the results from the simulation in which the tidal divides have been closed (using thin dams, resulting in isolated basins), which appear to differ considerably from those from the reference simulation (see also Elias et al, 2006).

4.2.3 Long-term process-based modelling

Dastgheib (2007) uses the Delft3D model in a ‘simplified’ mode, to simulate the morphological changes of the Western Wadden Sea for a period of 2100 years. To enable these long-term simulations forcing is limited to tides. Sensitivity simulations using different initial conditions are performed and the morphodynamic response analysed. The main parameters of the tidal basins are calculated and checked with existing empirical equilibrium relations in literature. It is shown that such a process based model can reach a more or less stable (dynamic-equilibrium) state in these basins. However, the end bathymetry is strongly dependent on the initial condition and model forcing. The results need to be interpreted carefully. Figure 4.7 shows the simulated bathymetry starting from a flat schematised initial bathymetry. Figure 4.8 shows how the end bathymetry (after 2100 years) depends on the initial condition.

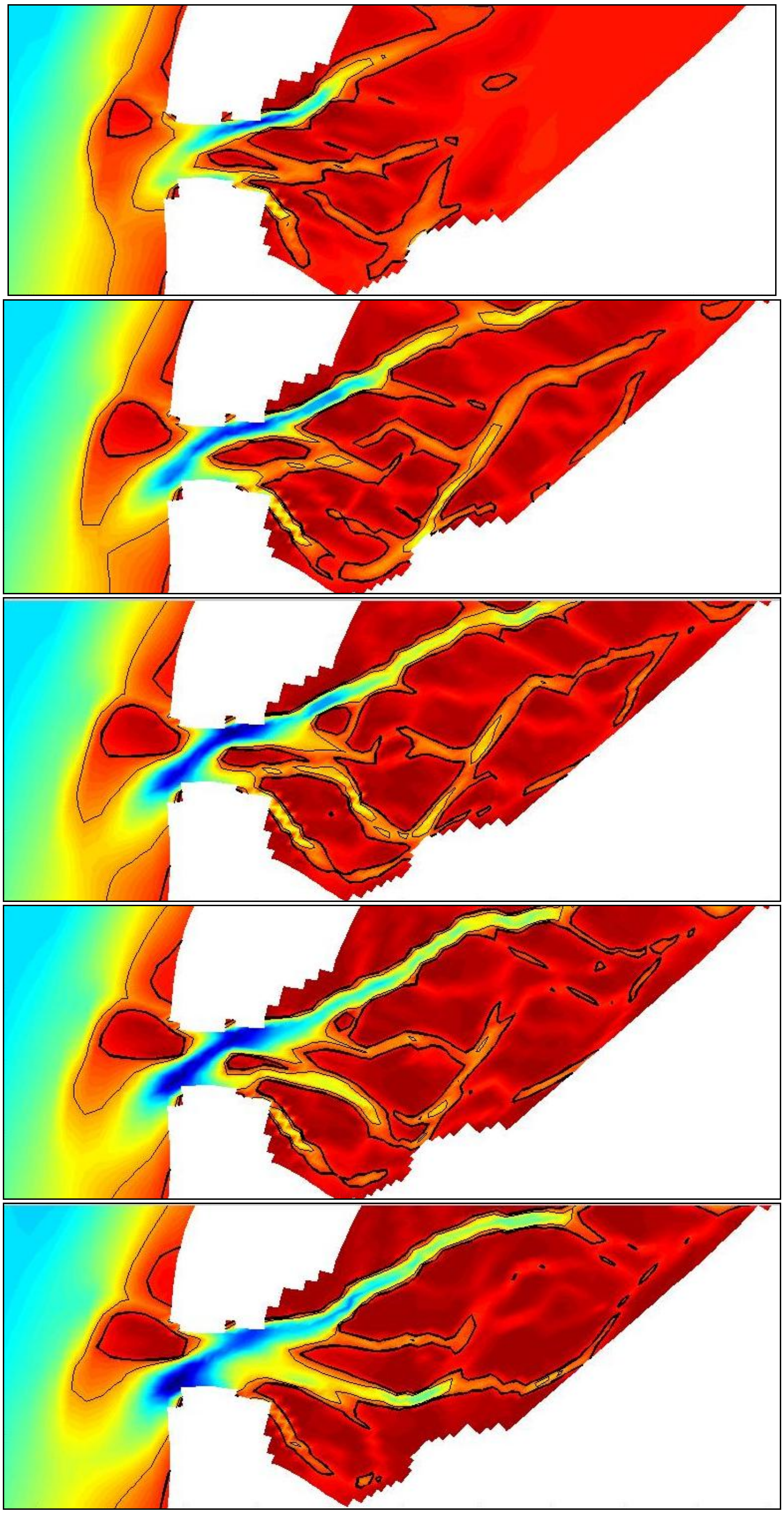


Figure 4.7: Evolution of Marsdiep Basin and its ebb-tidal delta, in morphological years of 120,400,800,1200, and 2100 for simulation L02: Starting from flat schematised bathymetry with averaged depth equal to 4.54 m, forced by M2, M4 and M6.

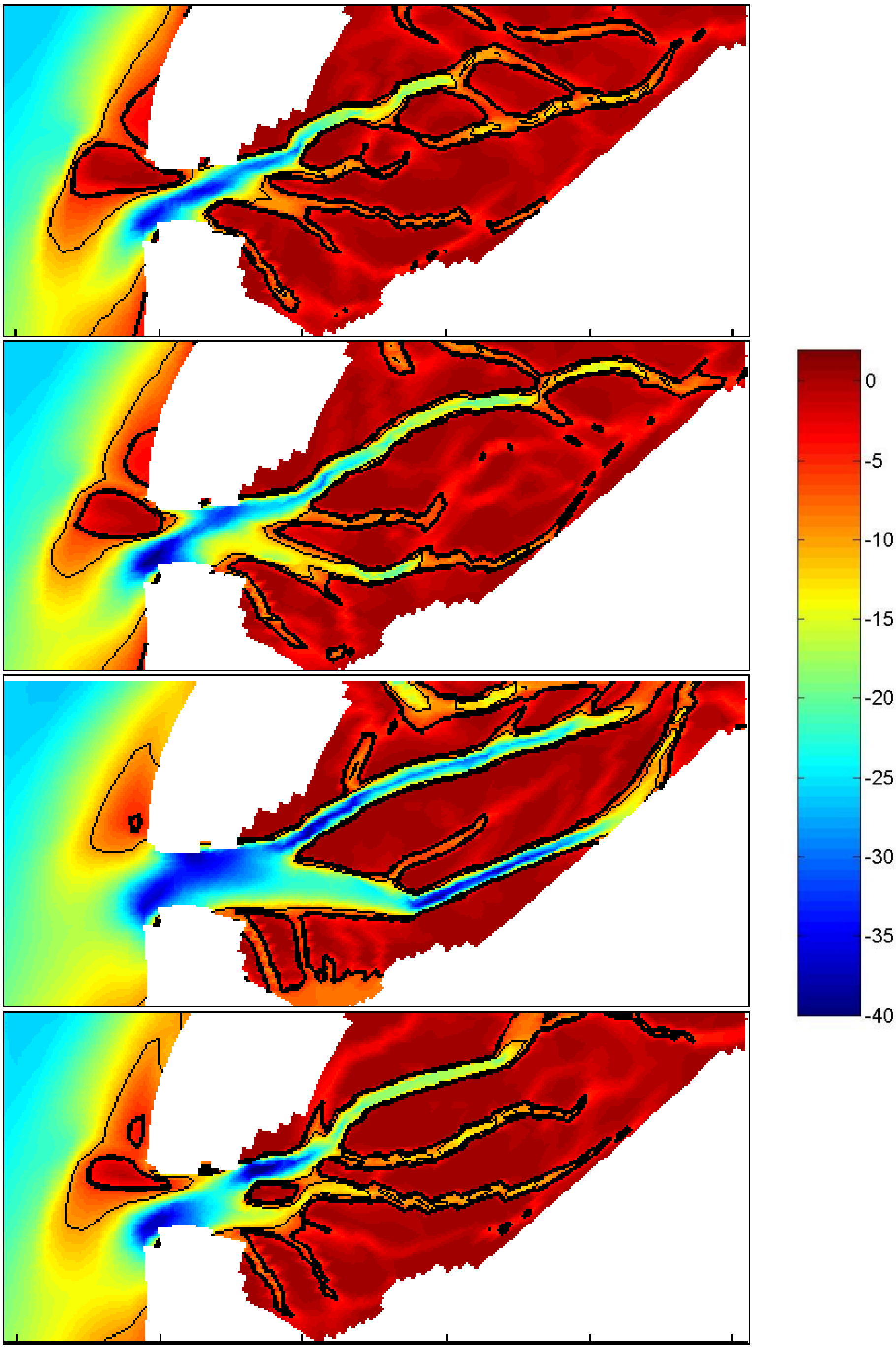


Figure 4.8: Bathymetry of Marsdiep after 2100 years of morphological modeling in different simulations (from up to down L01 (flat initial bathymetry with depth=3.62 m),L02 (flat initial bathymetry with depth=4.54 m), L03 (flat initial bathymetry with depth=8.0 m) and L04 (sloping initial bathymetry)

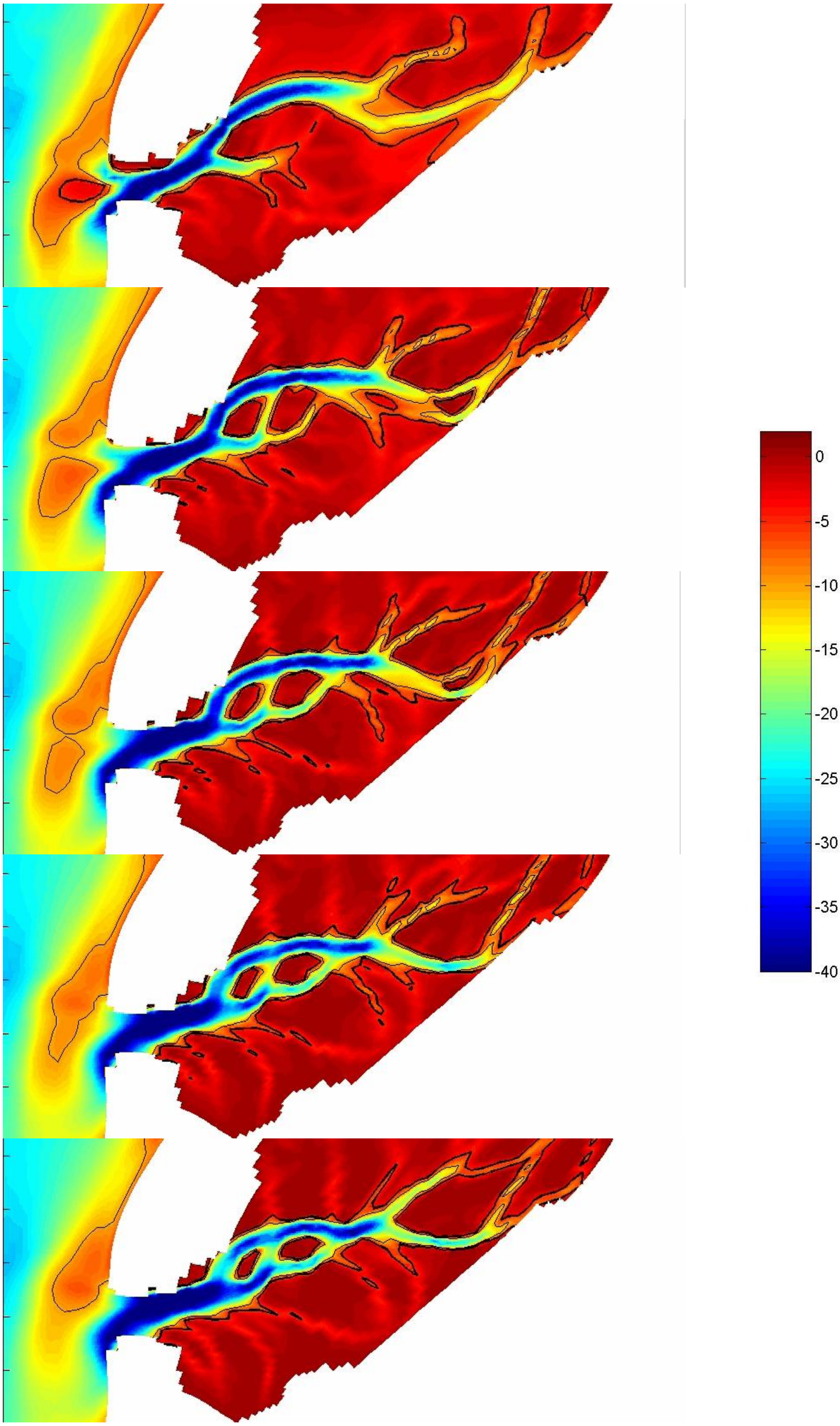


Figure 4.9: Results after 120,400,800,1200, and 2100 years starting from 1998 bathymetry

Simulations starting with measured bathymetries (see Figure 4.9) show an eastward expansion of the basins, similar to the observations.

An important conclusion from this study is that ‘simplified’ process -based models can evolve to a morphodynamic equilibrium state. This equilibrium shows large similarities with suggested relations in literature concerning the relative area of inter-tidal flat and the relation for neutral tidal asymmetry. However, the results differ considerably from the empirical relation between the channel volume and the tidal prism reported in the literature.

In the Western Dutch Wadden Sea M_4 and M_6 components of the tide are very important in simulating the morphological behaviour of tidal basins and it can not be modelled with the tidal force based on M_2 only.

Translating the results of Dastgheib (2007) to the research questions:

Can a mega-scale stable situation of the Marsdiep Basin be predicted using schematized long-term morphological modelling and given constant boundary conditions?

The Delft3D model schematisation used in this study could not simulate a single mega-scale equilibrium state for the entire Western Wadden Sea. Equilibrium states were observed, but these are dependent on the initial and boundary conditions.

How much sand is needed to import to Marsdiep to reach this hypothetical stable morphological situation and is this amount of sediment available?

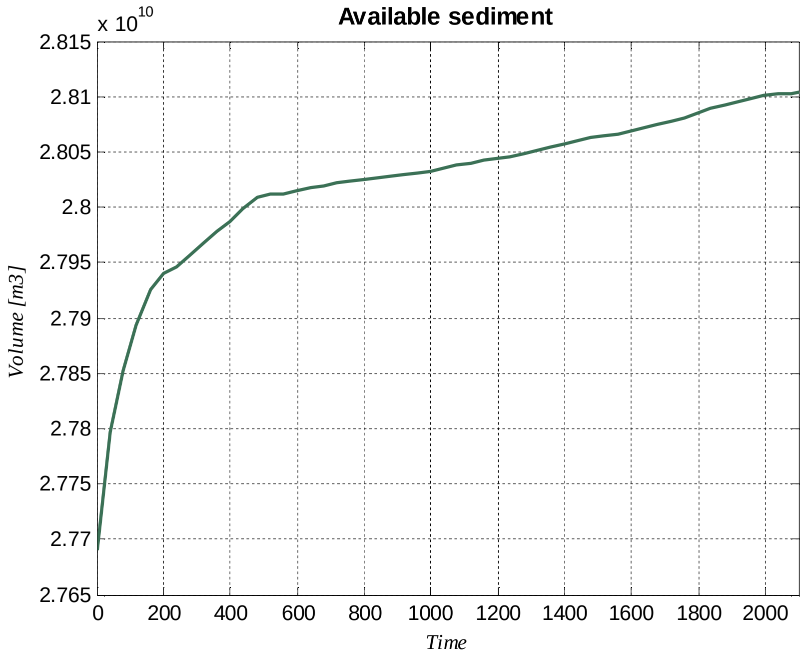


Figure 4.10 Development of the amount of sediment in the basin

The Marsdiep basin imports about 400 Mm^3 during 2100 years of simulation (Figure 4.10), assuming that the simulation with the initial real bathymetry (1998 bathymetry) is accepted as a good representative of the *mega-scale* stable (equilibrium). The main portion of the sediment import – 300 Mm^3 occurs during the first 300 years with a maximum rate of about 3 Mm^3 per year over the first 40 year. Note this is tidally driven transport only. According to Elias (2006a, 2006b) another 3 Mm^3/year is imported due to non-tidal driving forces.

What is the effect of nearby basins in the Wadden Sea, especially the Vlie Basin, on the morphology of the Marsdiep Basin?

Generally the changes in the boundaries of different tidal basins in a multi-inlet tidal system such as Dutch Wadden Sea play a significant role in determining the basin characteristics.It is shown that the effect of neighbouring basins on each other can be interpreted as varying of the boundaries of basins. From this point of view Marsdiep basin is stretching eastward and gaining some area from Vlie, while Vlie is also expanding towards the east.

For simulations with a flat initial bathymetry, Mardiep, Eierlandsegat and Vlie develop in similar rates. In reality Vlie and Marsdiep are considerably larger than Eierlandse Gat. This discrepancy might be caused by neglecting bed stratification. In reality erosion-resistant Keileem layers occur at the tidal divides between Marsdiep and Eierlandse Gat, these layers hamper the development of the inlet considerably.

Is the result of schematized long-term morphological modelling of Marsdiep Basin in agreement with empirical models?

In this study it is shown that the results of the process-based model follow the empirical equilibrium equations for flat characteristics and relative flat area qualitatively, while the results are in good agreement with the equilibrium suggested based on Friedrichs and Aubrey graph (Figure 4.11). However, the cross-sectional areas of the channels and the shapes of the hypsometric curves do not agree with the empirical relations and observations (Figure 4.12).

Some interesting results include:

1. Without geological constraints all inlets develop to a more-or-less similair shape. In reality this is not possible due to the precense of erosion resistant layers. This plausibly explains the discrepancy with the 'real' eierlandse gat.
2. In Vlie inlet a two-channel system develops of smaller size. In reality Vlie inlet developed with Lake Flevo attached. The large storage volume allowed the inlet to substain a single, large inlet channel. When we let Vlie develop with the present setting (bounded by the Friesland coastline) Vlie inlet cannot develop a wide single system.
3. Marsdiep forms the largest inlet channel. This might indicate a future dominace of Marsdiep over Vlie inlet (presently these inlets are about the same size). .

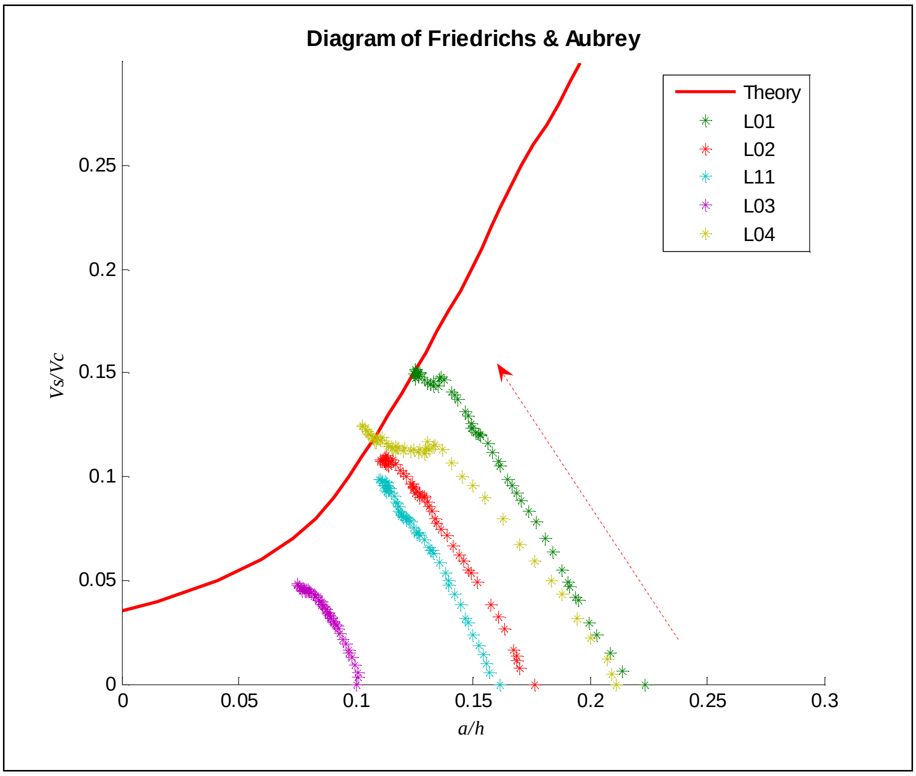


Figure 4.11: Friedrichs and Aubrey diagram for modeled Marsdiep with different initial condition, the arrow shows the direction of changes during the time

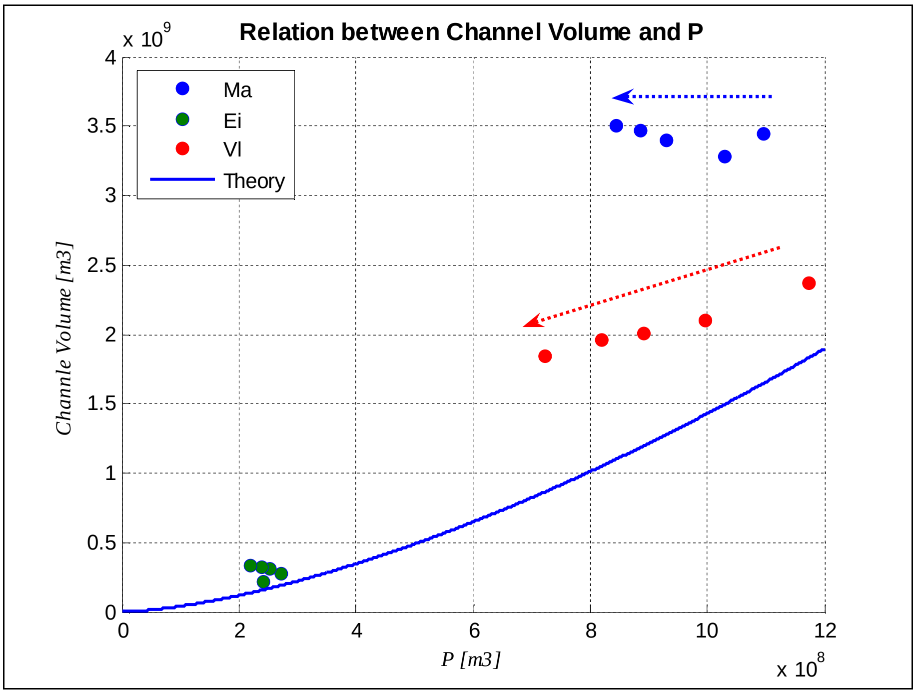


Figure 4.12:Relation between channel volume and tidal prism, considering varying boundaries

4.2.4 Long-term semi-empirical modelling

The work carried out by Van Geer (2007) can be divided into three parts: data analysis, analysis on the empirical relations and improvement / extension of the ASMITA modelling.

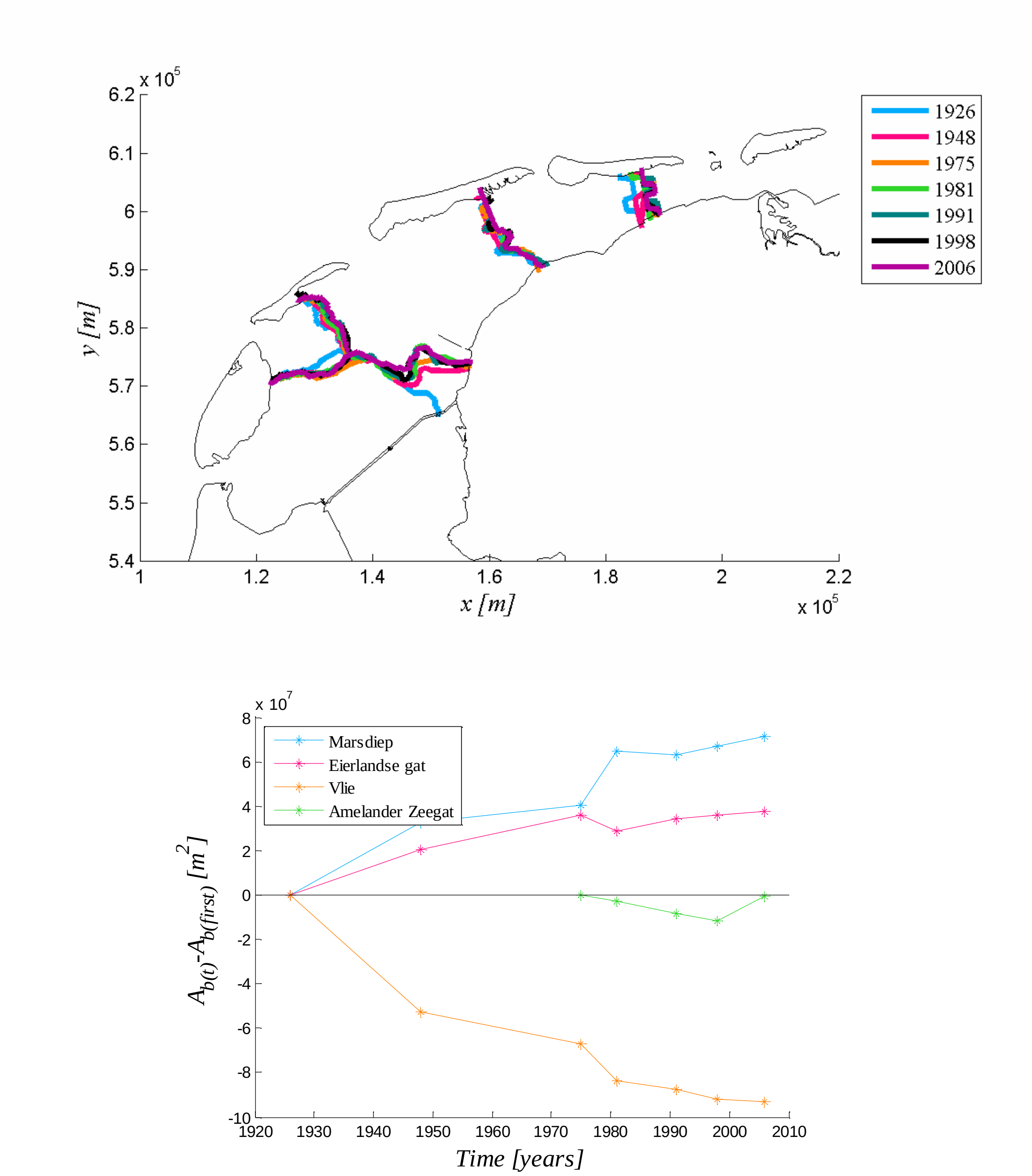


Figure 4.13 Development of the positions of tidal divides (top) and the corresponding changes of the areas of the various basins (bottom)

From the data analysis the following conclusions are drawn:

- The boundaries between the basins are not fixed. After the closure of the Zuiderzee the Marsdiep basin becomes larger at the cost of the Vlie basin (Figure 4.13). Also the Eierlandsegat basin has become larger. The part that moved from the Vlie basin to the Marsdiep basin is mainly deep water area (old channels) which is classified as channel according to the used definition.

- The tidal frame in a basin is not fixed. Besides that the mean sea level rises the tidal range is changing as well. The tidal range in the Vlie has increased and that in the Marsdiep has decreased since the closure of the Zuiderzee.
- Both points influence the results of the data analysis and the modelling of the tidal inlets (see Figure 4.14).

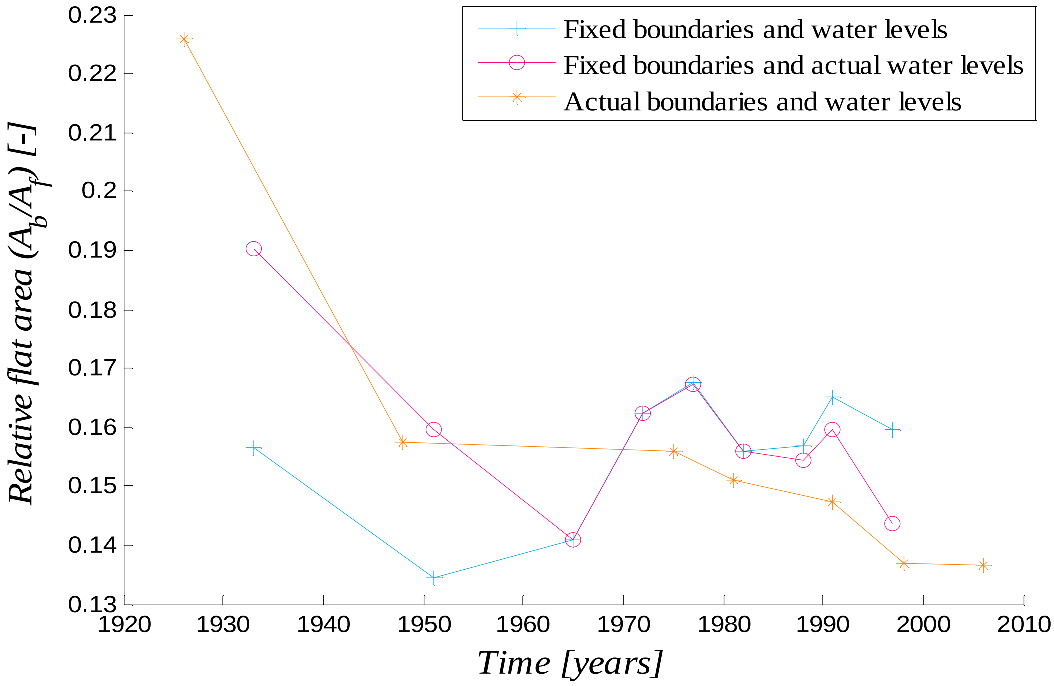


Figure 4.14: Relative flat area of Marsdiep examined with different methods

Analysis of the empirical relations in the literature leads to the following conclusion:

- The coefficients in these empirical relations are theoretically not constant for all basins. They should depend on e.g. the shape of the basin.

Four improvements / extensions of the ASMITA modelling have been attempted:

4. improve the empirical relations for the morphological equilibrium;
5. implementing time-varying areas for the inter-tidal flat and the channel in the basin;
6. implementing time-varying basin sizes, or moving boundaries between the basins;
7. implementing sediment transport through the basin boundaries.

Hindcasting simulations show that especially taking into account the movable basin boundaries have large influence on the model results. In figure 4.15 the calculated total sediment imports to the three basins from the various simulations are shown. In the basic (1) run the three basins are considered as isolated and no sea-level rise nor change of the tidal range is taken into account. Then the following simulations have been carried out by extending the model simulation by adding various features step by step. It should be noted that the results shown in this figure are preliminary as the study of Van Geer (2007) is not finished yet.

The movable basin boundaries are indeed more realistic, but no usable relation between the (change of) basin areas and the available parameters in the ASMITA model has been found. Therefore this aspect can only be used in hindcasting simulations but not in prediction simulations for the time being. .

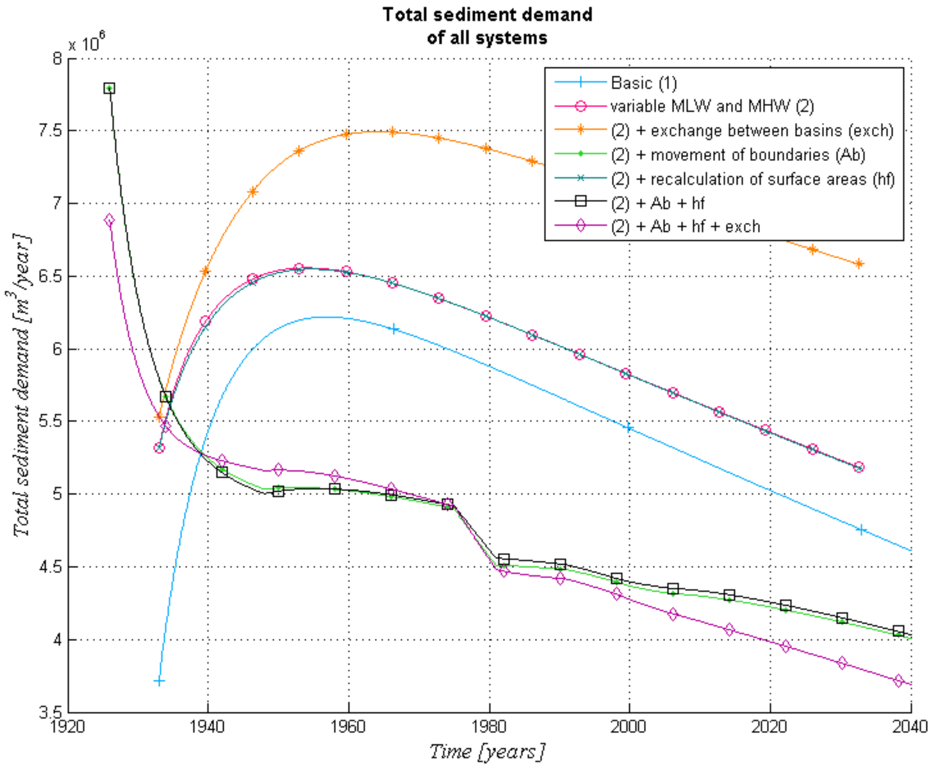


Figure 4.15 Simulated total sediment import to the three basins Marsdiep, Eierlandse Gat and Vlie.

4.2.5 Integrated conclusions

Common findings:

- The Western Part of the Dutch Wadden Sea is still not in equilibrium, not in the absolute sense, nor in the dynamic equilibrium (following sea-level rise). The effect of the closure of Zuiderzee is still far from damped out. This is a confirmation of the conclusion from the recent study of Elias (2006).
- The tidal basins in the Wadden Sea cannot be considered as isolated, but they should be considered together as a whole system. The boundaries between the basins (the tidal watersheds) are not fixed and exchanges of water and sediment occur through these boundaries.

Although these qualitative conclusions can be commonly drawn from the three studies using different methods, the quantitative results supporting these conclusions can differ considerably depending on the methods used.

Concerning the first conclusion, two detailed questions can be asked:

1. How far does the present state still deviate from the equilibrium state? How much sediment is still required to achieve the morphological equilibrium? The results from the long-term process-based modelling (Dastgheib, 2007) suggest that this sediment demand of Marsdiep is about 400 million m^3. Van der Waal (2007) calculates the sediment demand in the Marsdiep to be about 1200 million m^3, i.e. 3 times larger if he uses the equilibrium relations derived from the analysis by Van Geer (2007) as a starting point. It should be noted that both approaches suffer from the fact that the sizes of the basins become uncertain in the future. In the long-term simulation the extension of the Marsdiep basin continues even after 2100 years and the Vlie basin also extends to the east. It is questionable how far this is realistic. In the calculation using empirical relations the present sizes of the basins are used, which is surely not realistic.
2. How long will it take for establishing the morphological equilibrium? Or what is the morphological time scale? The long-term simulations suggest that the system is still developing even after 2100 years. However, the major part of the sediment demand (more than 250 of the 400 million m^3) is imported into the Marsdiep basin in the first 300 years. The transport simulations of Van de Waal (2007) suggest that the total import into the Western part of the Dutch Wadden Sea at present is about 6 million m^3 per year, of which about 4 million m^3 per year is through the Marsdiep inlet. This also suggests a morphological time scale of 200 to 300 years.

Concerning the second conclusion the following questions can be asked:

1. How fast is the movement of the tidal watershed between e.g. Marsdiep and Vlie? The results based on observations in the past (Van Geer, 2007) and predictions based on the long-term morphodynamic simulations are compared with each other in the following figure. The observations show that the Marsdiep basin has enlarged with about 80 km^2 in the last 80 years, i.e. about 1 km^2 per year (See Figure 4.16, right panel). The long-term simulation predicts an enlargement of about 100 km^2 in the coming 2100 years, i.e. about 0.05 km^2 per year (Figure 4.16, left panel). It must thus be concluded that this development is very uncertain. Note that the boundaries are based on hydrodynamics here rather than morphology.

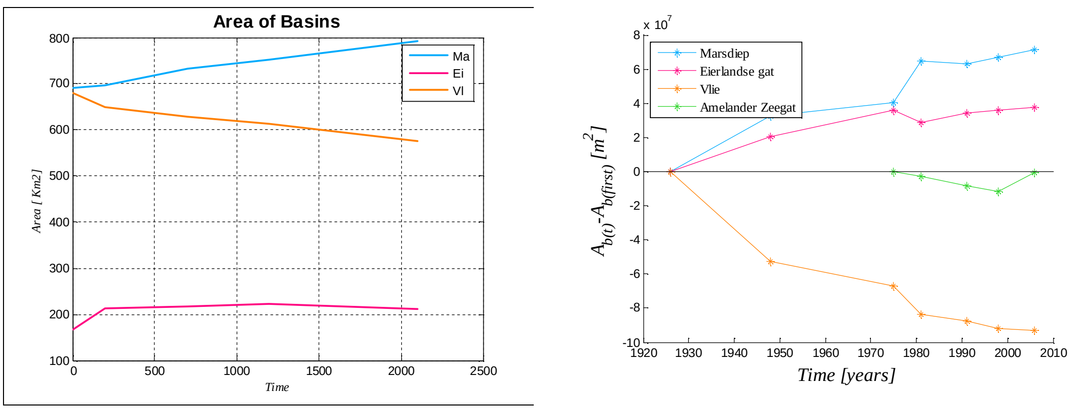


Figure 4.16 Results of the development of the size of the basins. Left: prediction based on long-term morphodynamic simulation (Dastgheib, 2007). Right: calculation based on observed bathymetries (Van Geer,2007).

2. Is there an end state for the basin sizes? The results of the long-term simulations suggest that the development continues even after 2100 years. However, it should be pointed out

that the used model does not take into account any possible restrictions such as the Pollendam at Harlingen.

Other lessons learned:

- The morphological development in the basins depends on the sediment availability. The long-term simulations with different initial bathymetric conditions all end at a state in which the basins satisfy e.g. the symmetric-tide condition of Friedrichs and Aubrery (1988), suggesting equilibrium. However, the total amounts of sediment in the basins, or the averaged water depths in the basins at the end depend strongly on the initial condition. This suggests that the development of the tidal basins, thus also the imports to the basins will be dependent on the coastal management strategy, as it will influence the availability of sand to be imported into the basins; the nourishment requirement will be dependent on the nourishment policy itself.

4.3 Morphological equilibrium

4.3.1 Single basin

Within a tidal basin two morphological elements are distinguished, viz. the inter-tidal flat and the channel. For both elements empirical relations are available for defining the morphological equilibrium.

For the inter-tidal flat there are two empirical relations, one for its area and one for its height.

$$\frac{A_{fe}}{A_b} = 1 - 2.5 \cdot 10^{-5} \cdot A_b^{0.5} \tag{4.1}$$

in which:

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

$$h_{fe} = \alpha_{fe} \cdot H \tag{4.2}$$

in which H is tidal range and according to Eysink (1990)

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} \cdot A_b \tag{4.3}$$

with α_f=0.41.

The equilibrium volume of the inter-tidal flat, i.e. the sediment volume between LW and HW, is thus per definition:

$$V_{fe} = A_{fe} h_{fe} \tag{4.4}$$

The channele volume is defined as the water volume under LW in the basin. Its equilibrium value is related to the tidal prism as follows:

$$V_{ce} = \alpha_c P^{1.55} \tag{4.5}$$

The tidal prism P is the wet volume in the basin between LW and HW, thus

$$P = A_b H - V_f \tag{4.6}$$

Using these equations the morphological equilibrium of a tidal basin can be determined from two parameters, the total basin area A_b and the tidal range H. As indication for the sediment demand in a basin one can use the total wet volume of the basin under HW:

$$V_b = V_c + P \tag{4.7}$$

The difference between the actual value of V_b and its value at equilibrium is the amount of sediment a basin needs to achieve equilibrium, i.e. the sediment demand of the basin.

4.3.2 Two-basin system

As concluded from all three MSc-projects, the tidal basins in the Wadden Sea cannot be considered as isolated basins, because the adjacent basins exchange water and sediment with each other and because the boundaries between the basins (tidal watershed) are not fixed in time. This introduces extra uncertainties concerning the morphological equilibrium and the sediment demand of the basins. Here this is illustrated by considering a two-basin system like the Marsdiep-Vlie system.

Consider two adjacent and inter-linked tidal basins with a fixed total basin area:

$$A_{b1} + A_{b2} = A_b = \text{constant} \tag{4.8}$$

Consider first the situation that the tidal ranges in the two basins are the same:

$$H_1 = H_2 = H \tag{4.9}$$

As the boundary between the basins is movable the area of each basin can vary between zero and the A_b, thus

$$0 \le \beta = \frac{A_{b1}}{A_b} \le 1 \tag{4.10}$$

For each division between the two basins, i.e. for each value of β between 0 and 1, the equilibrium volume of the inter-tidal flat, the corresponding tidal prisms and the equilibrium volume of the channel can be calculated for each basin, using the equations in the previous subsection. As an example for the tidal prisms we have:

$$P_1 = \beta\left(1-\alpha_{fe} + 2.5\cdot10^{-5}\alpha_{fe}\sqrt{\beta}\sqrt{A_b}\right)A_b H$$
$$P_2 = \left(1-\beta\right)\left(1-\alpha_{fe} + 2.5\cdot10^{-5}\alpha_{fe}\sqrt{1-\beta}\sqrt{A_b}\right)A_b H \tag{4.11}$$

So for the total tidal prism in the two basins we have:

$$\frac{P_1+P_2}{A_b H} = \left(1-\alpha_{fe}\right) + 2.5\cdot10^{-5}\alpha_{fe}\sqrt{A_b}\left[\beta^{1.5}+\left(1-\beta\right)^{1.5}\right] \tag{4.12}$$

Similar relations can be derived for the wet volumes under HW in the two basins and for the two basins together we have:

$$\frac{V_{b1}+V_{b2}}{A_b H} = F\left(A_b,\beta\right) \tag{4.13}$$

From Equation (4.12) it becomes clear that the total tidal prism is maximum when the two-basin system becomes a single basin, and it is minimum when the two basins are equal in size. The same behaviour applies for the total wet volume under HW. This is illustrated in Figure 4.17, which shows the results calculated using the values of the Marsdiep-Vlie system concerning the total basin area and the tidal range. Note that the difference between the two extreme cases (β=0 and β=0.5) concerning the sediment demand can be very large as shown by the figure.

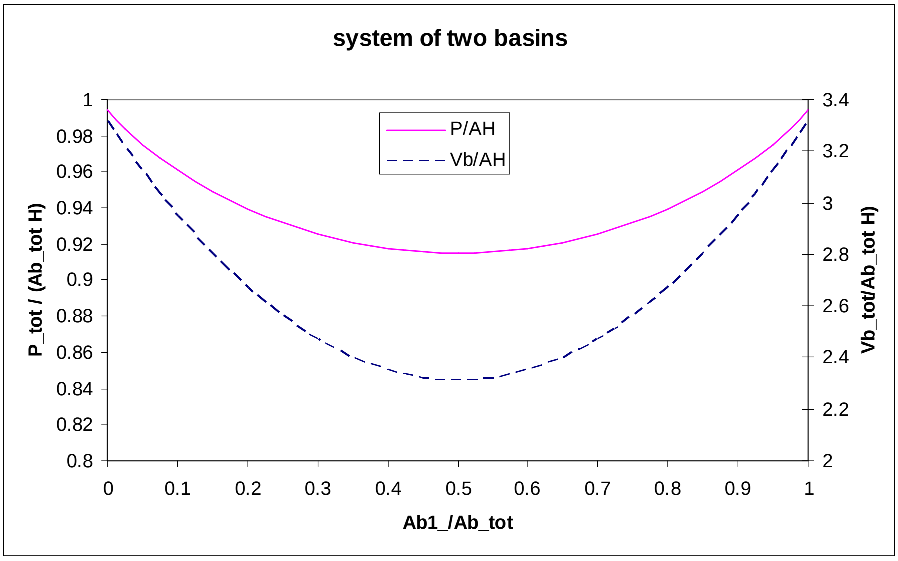


Figure 4.17 The total tidal prism and the total (wet) volume under HW of a two-basin system. Used values: A_b=1370 km^2, H=1.8 m, α_c=10^{-5} m$^{-0.55}$

In reality the tidal ranges in the two basins are not always the same, as the Marsdiep-Vlie case clearly illustrates. Also for such a case the same calculations can be carried out, see Figure 4.18 in which the tidal range in basin 1 (representing Marsdiep) is taken as 1.52 m and for basin 2 (representing Vlie) is taken as 1.89 m, following Van Geer (2007). The minimum value of the total tidal prism as well as of the total wet volume under HW now occurs at a larger value of β (>0.5), i.e. when the Marsdiep basin is larger than the Vlie basin. For making both parameters dimensionless (see Eq. 4.12 & 4.13) the averaged value of the two tidal ranges is used.

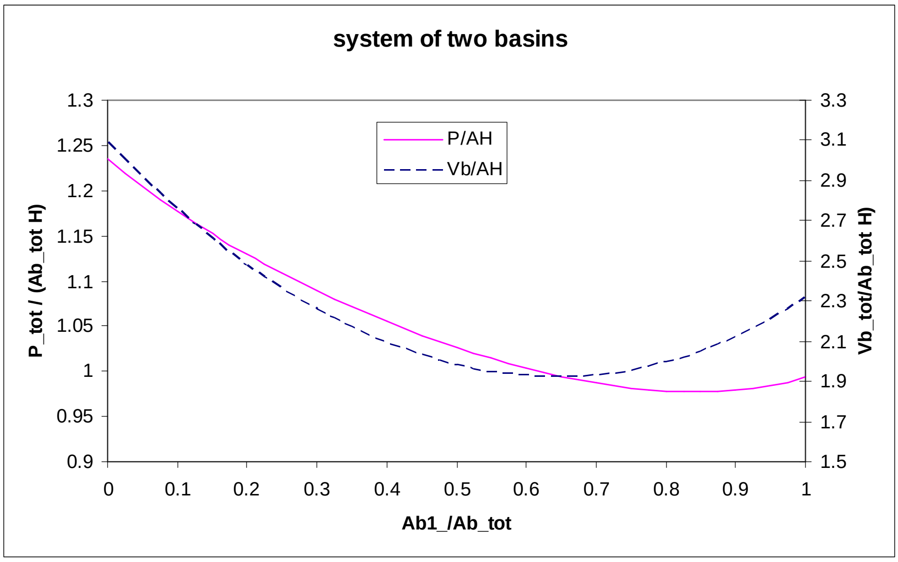


Figure 4.18 The total tidal prism and the total (wet) volume under HW of a two-basin system. Used values: A_b=1370 km^2, H_1=1.52 m, H_2=1.89 m, α_c=10^{-5} m$^{-0.55}$

As mentioned above, the total wet volume is an indication of the sediment demand. As example, the sediment demand using the results shown in Figure 4.5 with respect to the initial condition in 1970 concerning the volumes of the inter-tidal flats and the channels as reported by Steetzel and Wang (2003), is shown in the following figure. Note that those values are related to slightly different values of the tidal ranges, but the figure gives a good indication. The sediment demand is maximum when the total equilibrium wet volume in the two basins is minimum. For the system under consideration this will occur when the Marsdiep basin is slightly larger than the Vlie basin. At present the Marsdiep basin is still smaller than the Vlie basin but the Marsdiep basin is increasing in size at the cost of the Vlie basin. The system is thus developing towards a situation with larger sediment demand.

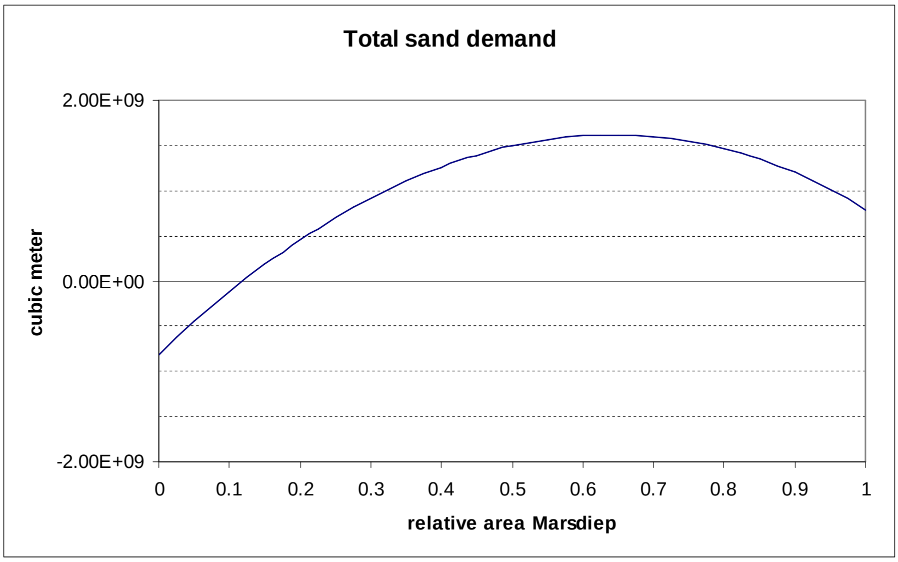


Figure 4.19 The total sediment demand. Used values: A_b=1370 km^2, H_1=1.52 m, H_2=1.89 m, $\alpha_c=10^{-5}$ $m^{-0.55}$

The total sediment demand in such a two-basin system depends thus on the location of the tidal watershed between them, or the area distribution between the two basins. Question arises then what is the most likely end situation when morphological equilibrium is established. As an attempt to answer this question the 'shortest way' hypothesis is put forward here. Consider the sediment demands in the two basins as the two components of a vector in a two-dimensional space, then this hypothesis says that the system will end at such an area division between the two basins that the length of this vector is minimal. It is called 'shortest way' because this is the state to which the system probably needs the least time to achieve. This reasoning implies the assumption that this state represents a stable morphological equilibrium. In Figure 4.20 the sediment demands in the two basins are plotted separately, as well as the length of the defined vector. The 'shortest way' hypothesis suggests that the system will end at a situation in which Marsdiep has an area which is 60% of the total area of the system. This is near the state that the total sediment demand is maximum (see Figure 4.19). The present development seems in the direction to this state.

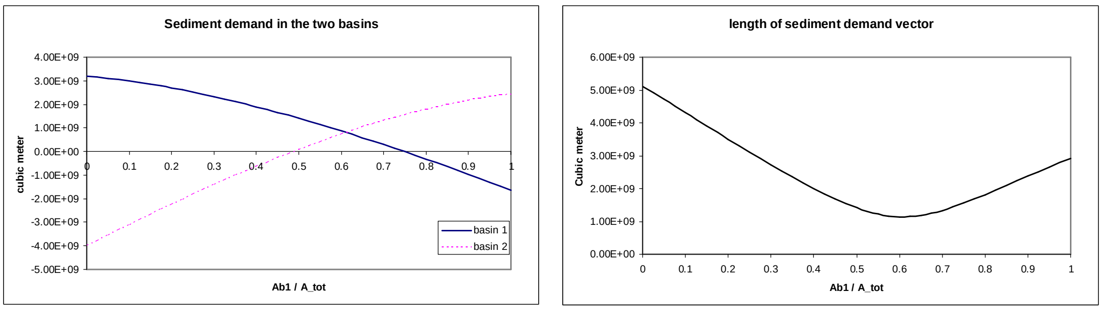


Figure 4.20 Sediment demand of the two-basin system. Left: sediment demand in the two basins. Right: length of the vector with the sediment demands of the two basins as components.

4.3.3 Influence of sea-level rise

The considerations in the previous two subsections do not take into account the influence of the sea-level rise. This means that the determined sediment demand in the basins is purely due to the human interferences in the past. In reality sea-level rise occurs, so the observed morphological development in the past should be considered as a combination of the responses of the system to sea-level rise and to human interferences (especially the closure of the Zuiderzee).

The response of a tidal basin to sea-level rise can best be studied with the long-term semi-empirical model ASMITA (see Van Goor et al, 2003, Stive and Wang, 2003). Sea-level rise causes a disturbance of a tidal basin with respect to its morphological equilibrium as it makes the tidal basin on average deeper (increases the channel volume and decreases the flat volume). As response the basin imports (more) sediment in order to compensate the effect of the sea-level rise. When the (extra) import exactly balances the sea-level rise, a dynamic equilibrium of the basin is achieved. A dynamic equilibrium can only happen after a long time in which the sea-level rise rate is constant and below a critical level and there is no human interference. At the dynamic equilibrium the basin is deeper than at the (absolute) equilibrium according to the empirical relations, i.e. with larger channels and less (lower and smaller) inter-tidal flat. The deviation between the dynamic equilibrium and the (absolute) equilibrium is larger at higher rate of sea-level rise.

In Figures 4.21 through 4.23 the simulated sediment exchanges between the three tidal basins and the coast are depicted. The simulations are based on the ASMITA models with parameter settings used by Wang et al (2006). For each inlet three simulations with different rates of sea-level rise are carried out. The case with 20 cm/century can be considered as the continuation of the present rate, whereas the two cases with 60 and 100 cm/century are two scenarios of accelerated sea-level rise. In addition, the hypothetical case of no sea-level rise is presented as well in the figures. In the simulations the change of the sea-level rise rate occurs in 2000.

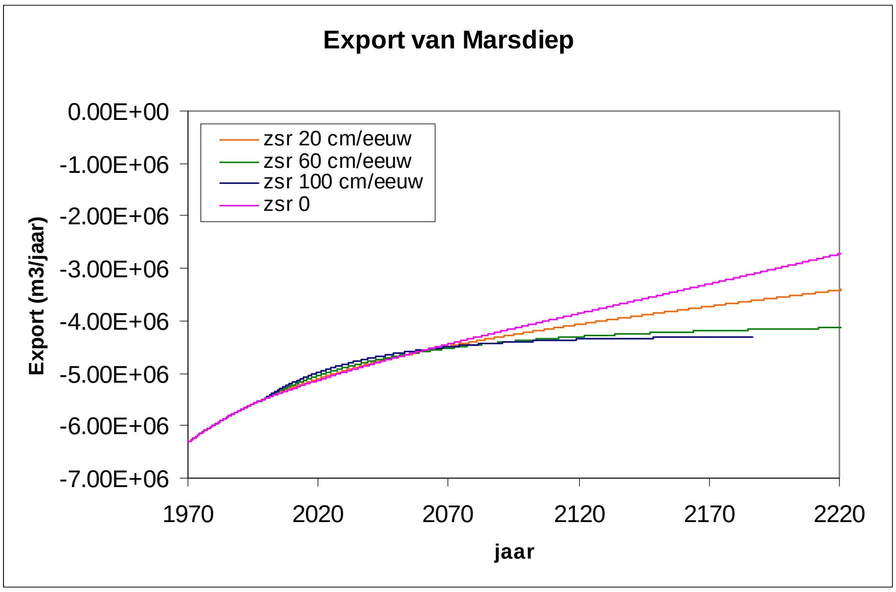


Figure 4.21 Simulated sediment exchange between Marsdiep and the coast, negative =

import

It is interesting to note that the response of Marsdiep to the accelerated sea-level rise is quite different than the responses of the two other inlets. At a higher sea-level rise rate the Marsdiep basin achieves the dynamic equilibrium earlier, whereas the other two basins achieve the dynamic equilibrium later at a higher rate of sea-level rise. The reason is that the Marsdiep is much deeper at present than its (dynamic) equilibrium, so the dynamic equilibrium corresponding to a higher sea-level rise rate is closer to the present situation. Comparison between the Eierlandse gat and Vlie shows that the time scale related to the adjustment to accelerated sea-level rise is larger for a larger basin.

It is remarkable to note that the import to Marsdiep at the end of the simulation with 100 cm/century sea-level rise is lower than the import at present. This is due to the fact that the ebb-tidal delta is then also drowned. For the first 70-80 years the rate of sea-level rise does not have much influence on the import to this basin.

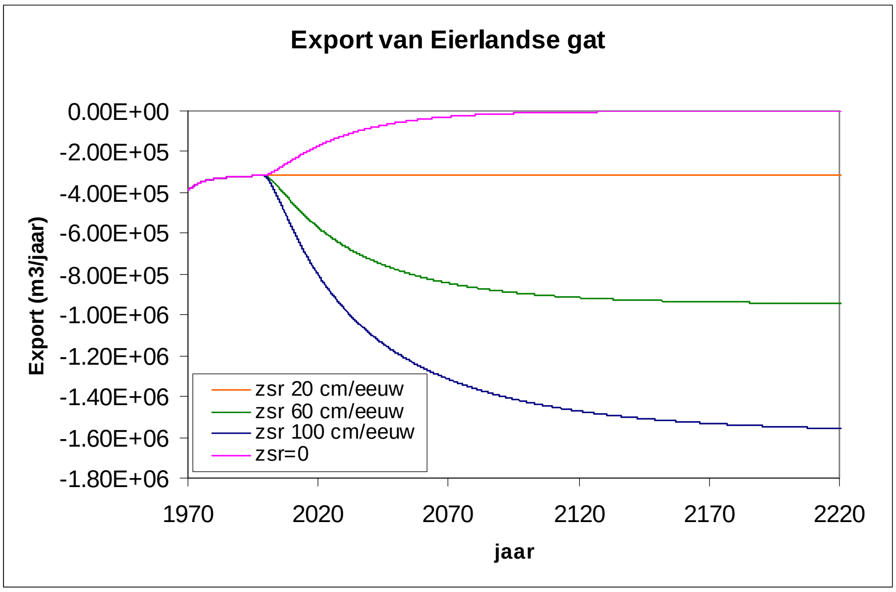


Figure 4.22 Simulated sediment exchange between Eierlandse gat and the coast, negative = import

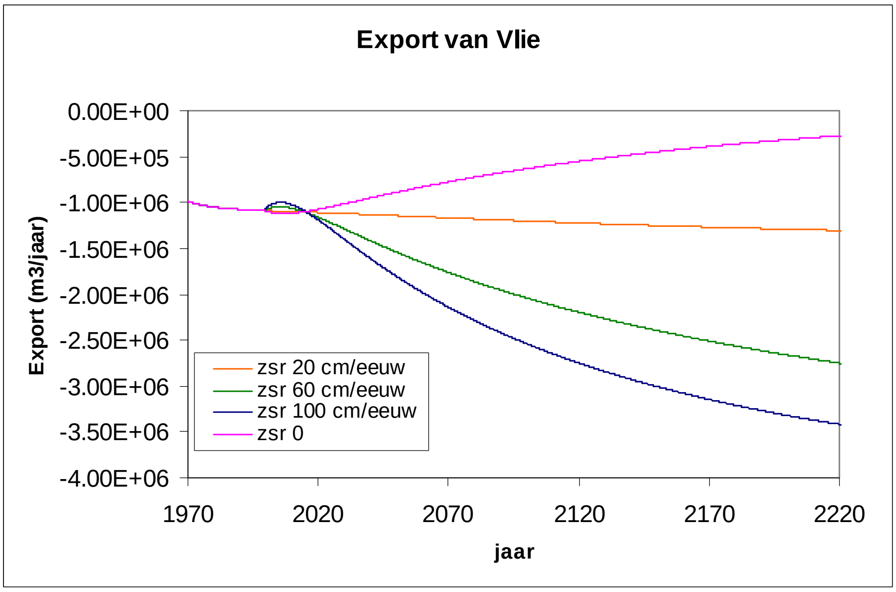
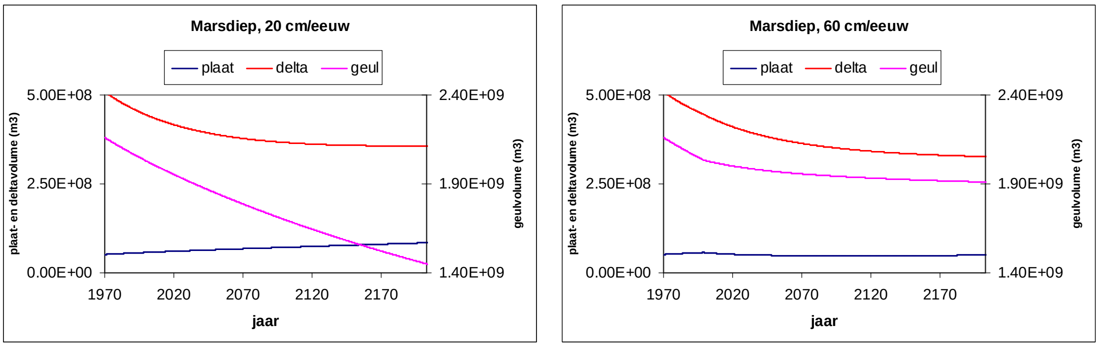
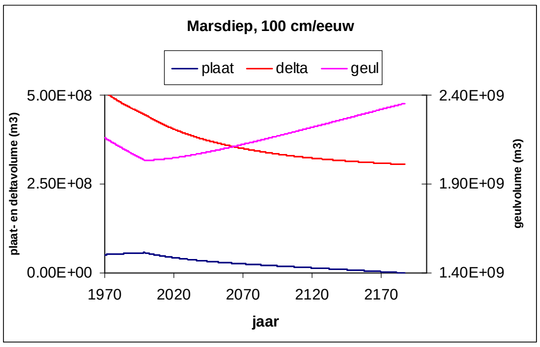


Figure 4.23 Simulated sediment exchange between Vlie and the coast, negative = import

It is also noted that 100 cm/century exceeds the critical level of sea-level rise rate for Marsdiep. This is the reason why the line corresponding to this sea-level rise rate in Figure 4.21 does not continue to the end. This is better illustrated in Figure 24, in which the development of the three morphological elements is shown for the three scenarios. For a sea-level rise rate equal to 100 cm/century the volume of the inter-tidal flat in the basin decreases to zero at around 2170. After this time the results of the simulation is no more realistic as the simulation has been working with negative flat volume since then. Also for the Vlie basin the 100 cm/century sea-level rise exceeds the critical rate, but the drowning (inter-tidal flat disappears) happens much later. Due to the morphological pit caused by the closure of Zuiderzee the Marsdiep basin has become more vulnerable to sea-level rise.

These results clearly indicate that the development within the basin can have serious impact on the ecological system if sea-level rise will accelerate. The most important negative effect of accelerated sea-level rise will probably be in the tidal basins rather than to the coast. The accelerated sea-level rise will not cause significant increase of the sediment import to Marsdiep, so the most important effect to the coast will be the drowning of the ebb-tidal delta. The drowned ebb-tidal delta will provide less protection to the coast against erosion.





For the case that the sea-level rise rate is 100 cm/century the volume of the inter-tidal flat in the basin becomes negative in around 2170. This means that the rate of sea-level rise exceeded the critical value.

Figure 4.24 Development of the Marsdiep inlet system at different sea-level rise rates. Change of sea-level rise rate starts in 2000

4.4 Future development

With the results of the research presented in the previous sections the prediction of the future perspective as given in Chapter 2 can be improved for the following aspects:

- The sand import to the tidal basins for compensating accelerated sea-level rise will be less than as presented in Table 2.3, especially for the highest rate. This is not only because that the system need time to adjust to the higher rate of sea-level rise, but also because the import will be transport-capacity limited when sea-level rise exceeds a critical rate. As shown in Figure 4.7, the import to the Marsdiep basin end at a rate of about 4.5 million m^3 per year for the sea-level rise rate of 100 cm/century, instead of the 6.55 million m^3 per year required fro compensating the sea-level rise. A consequence for this is that the basin will be drowned causing serious impact to the ecological system.
- Simply multiplying the total basin area with the rate of sea-level rise for determining the nourishment requirement related to the tidal basins as done in Chapter 2 following Nederbragt (2005) is thus too much a simplification. In addition there is another reason that this way of working is not fully correct. As shown in Figure 2.1, for the Eems-Dollard estuary only the Dutch part is taken into account. If the development of this estuary is taken into account then the restriction of the country border here should not be used.
- Indications can be given for the time scales in Table 2.3. It is clear that these time scales depend on the size of the basins and also on the specific situation concerning the human interferences in the past. For Marsdiep they have the magnitude of several centuries. For specific predictions one can best apply the ASMITA modelling.

- Due to the large morphological time scales of the tidal inlets and due to the effect of the human interferences in the past, the import to the basins in the first decades will not be much influenced by the rate of sea-level rise.
- A better view can now be given for the uncertainties of the sediment demand due to the human interference in the past. For the Marsdiep case the following sources of uncertainties exist:
  - The amount of sediment needed to achieve equilibrium is uncertain and in the range 0.5 to 1.5 billion m^3.
  - The development of the multi-basin system, especially the development of the locations of the tidal watersheds.
  - Rate of sea-level rise, as it determines dynamic equilibrium state of a basin. However, the rate of sea-level rise will not influence the import to Marsdiep significantly in the first 50 years.

  It is further noted that these three aspects may also interact with each other. The empirical relations depend on the shape of a basin and thus on the location of the tidal watersheds, and the location of the tidal watersheds may also be influenced by the rate of sea-level rise.

5 Conclusions and recommendations

5.1 Answers to research questions

What do the developments of the tidal inlets in the long term look like?

The Western Scheldt is exporting sediment at present despite sea-level rise and sediment extraction due to sand mining. The estuary is thus becoming deeper on average. Although the processes and mechanisms causing the sediment export are not yet fully understood, it is expected that the export will continue in the coming period, with an order of magnitude of 1 million m^3 per year, applicable for all considered scenarios of sea-level rise rates. The most important uncertainty here concerns the development of the human interferences within the estuary: possible further deepening of the navigation channel, dredging and dumping strategy, and sand mining policy.

At present the Wadden Sea basins are importing more sediment than required for compensating sea-level rise: the Dutch Wadden Sea is becoming shallower. The import can compensate more than twice the present rate of sea-level rise meaning that on average the Dutch Wadden Sea will not become deeper even if the relative sea-level rise accelerates to about 40 cm/century. The additional import is still due to the human interferences in the past. The effect of the closure of the Zuiderzee is still far from damped out. This interference 75 years ago has been and will be influencing the development of not only Marsdiep but also the other adjacent basins, especially Vlie. This probably also applies to the closure of the Lauwerszee, although this closure has not been the subject in the present study.
An important feature is the easterly movement of the watershed between Marsdiep and Vlie. The developments of the tidal basins cannot be isolated from each other as the boundaries between the adjacent basins are not fixed in time. At present Marsdiep is increasing in size at the cost of Vlie. This development has the consequence that the total sediment demand of the Marsdiep-Vlie system is increasing. This development probably will end until marsdiep reaches the size of 60% of the total area of the two basins together (Vlie thus the 40%). At this area-distribution the total sediment demand of this two-basin system is the highest, but this state probably costs the shotest time to reach as the length of the vector with the sediment demands in the two basins as components is then minimal. In the present situation Marsdiep reaches 48 % of the total area of the two basins together.

For long-term morphological development the tidal basins cannot be considered as isolated but should be considered together as a system. The total sediment demand for restoring the morphological equilibrium of the Marsdiep-Vlie system is estimated to be in the order of 1000 million m^3 (between 500 and 1500 million m^3) without taking into account sea-level rise, although many uncertainties exist in the estimation. An important uncertainty is related to the movement of the tidal watershed between the basins. At the moment sand transport through the inlet of the Marsdiep is estimated at 5-6 Million m^3 per year. About half of this is due to sea-level rise and half of it is due to the effect of the closure. Under the present sea-level rise the impact of the closure of the Zuiderzee will still be influencing the development of the system for centuries (200 – 400 years). If the sea-level rise is going to accelerate the import to the basins will increase, but the increase will be less than proportional to the rate

of sea-level rise. A consequence of this is that an extreme fast sea-level rise will have serious impact in the basins.
For a sea-level rise rate of 100 cm/century Marsdiep as well as Vlie will no more be able to reach a dynamic equilibrium, and will drown on the long term, if no special measures will be taken.

What are the possible effects for the sand-balance of the Dutch coast?

The development of the Western Scheldt has only limited effect on the sand-balance of the Delta Coast. The exchange between this basin and the coast area is an order of magnitude smaller than the sediment loss in the Delta Coast area (about 1 million m^3 per year versus about 10 million m^3 per year). As this exchange at present is an export (thus a positive item for the coast) and it is expected to remain so in the coming period, ignoring it in considering the coastal maintenance would be justified.

The import to the Wadden Sea basins forms a more important item for the sand-balance of the Dutch coast. Due to the human interference in the past the Wadden Sea at present is importing more sediment than needed for compensating the effect of sea-level rise. The total import to the basins Marsdiep, Eilerlandse Zeegat, Vlie, Amlanderzeegat and Friesche Zeegat is about 12 million m^3 per year according to Elias et al (2006) and 7.5 million m^3 per year according to Nederbragt (2005). About 5 million m^3 per year is due to sea-level rise, the other part (7 – 2,5 million m^3 per year) is due to human interference. The total import is about equal to the coastal nourishment at present!!.
Under accelerated sea-level rise this import will even increase in the future, although the increase will be less than proportional to the rate of sea-level rise.

Which processes govern the developments?

The long-term development of the Wadden Sea basins and the Western Scheldt will be influenced by human interferences in the past and future, and also sea-level rise plays a role.

For the Wadden Sea basins it has been concluded that all three driving processes for hydrodynamics and sediment transport, i.e. tide, wind and waves, are important for the development. Waves increase sediment availability and sediment transport capacity. Wind and setup are especially important for generating residual flow and transports between the inlets. This statement probably also applies for the Western Scheldt although this is not directly concluded from the present study as the wind and waves have not been taken into account for this system in the present study. However, as the process-based modelling with tide alone failed to explain the reversal of the residual sediment transport at the estuary mouth, the results indirectly suggest that the other driving processes are important as well.

Tidal asymmetry is commonly identified as an important mechanism influencing the residual sediment transport. For the Wadden Sea basins this has been confirmed by the results of the present study. Process-based modelling, both the long-term and short-term, reveals that it is essential to take into account the higher frequency tidal components (especially M4) in the open sea boundary condition. For the Western Scheldt this seems not to be the case. Amplitudes and phases of the higher frequency tidal components at the open sea boundary seem to have little influence on the development in the estuary according to the short-term process-based modelling. Furthermore, the relation between the residual sediment transport and the asymmetry of the vertical tide in this estuary is also less clear. A possible explanation for this discrepancy is that the basins in the Wadden Sea are short basins whereas the Western Scheldt estuary and its mouth area form a long basin (with respect to the tidal wave length).

What are the influences of the development on the coastal erosion of the island-heads and on the nourishment requirement for the coast maintenance?

The influence of the development of the Western Scheldt is limited. The relatively small export from the estuary is expected to have a positive but not significant effect on the erosion of the island-heads, and on the nourishment requirement.

For the Wadden Sea coast the import to the basins forms the most important item for the nourishment requirement for the coast maintenance. The influence on the erosion of the island-heads can well be indicated by the development of the ebb-tidal delta. The results of the process-based modelling suggest that the ebb-tidal deltas function as protection against wave attack to the island-heads by waves. The ebb-tidal deltas are predicted to decrease in size on long-term.
In one of the long-term runs the Noorderhaaks has completely disappeared. Expection is that such a drastic change is not to be expected although a significant reduction is quite possible, resulting in higher wave attack on the nearby coast.

5.2 Additional conclusions

Coastal Foundation

- With a coastal nourishment of 12 million m^3 per year the objective of maintaining the coastal foundation at the present rate of sea-level rise is not fully achieved. The reasons for this are
  (1) the sediment import to the tidal basins in the Wadden Sea is almost double the mount due to to sea-level rise. This is due to human interferences in the past like the closure of the Zuiderzee;
  (2) extraction due to sand mining;
  (3) other losses (through the open water boundaries of the coastal foundation) : John: Ik zou dit punt weglaten of duidelijk uitleggen wat je hier mee bedoelt.
- Without special measures accelerated sea-level rise will have negative effect on the tidal basins as well as to the coast. For the basins the most important negative effect will be loss of inter-tidal flat area. For the coast of the Wadden Islands the most important effect will be increased erosion due to increased import to the basins and due to the decreased protection by the drowning ebb-tidal delta.
- The coastal management policy itself will also influence the development of the coastal system, especially because the availability of sand will influence the import to the tidal basins. This means that the coastal maintenance strategy itself will influence the nourishment requirement, if only the coastal foundation (instead of the whole coastal system) is maintained as in the present coastal management policy.

Wadden Sea

- Without constraints all basins develop to a sort of similair shape and ratio of channels and shoals. Marsdiep inlet seems to dominate over Vlie inlet. Vlie inlet still is a large inlet as it formed having a large drainage area (Lake Flevo, Zuiderzee). Without this storage Vlie inlet develops to a smaller inlet; starting from scratch the Vlie inlet is even too wide to sustain a single inlet channel and two smaller channels develop. In the long-term we expect the Vlie inlet to decrease in size as Marsdiep dominates. Marsdiep is capable of substaining a wide, deep single inlet and the basin develops similairly but into a much larger system.
- Due to the morphological sink caused by the closure of the Zuiderzee Marsdiep is more vulnerable to sea-level rise than a other basins of similar size e.g. Vlie. If the rate of sea-level rise will exceed the critical level the Marsdiep basin will be drowned earlier.
- The sediment transport through the Vlie inlet appears to be very much dependent on the effect of wave height and wavedirection. With only tide the inlet is exporting sediment, including waves changes this to importing sediment.

Western Scheldt

- Going from east to west the value of import/export along the Western Scheldt is highly variable (see e.g. fig. 3.16). By only analising a cross-section a wrong picture of the changes can be derived.
- Due to the deepening of the Western Scheldt the amplitude of M2 has increased and the amplitude of M4 has decreesed. Similar to the change in the vertical tide (waterlevels), a clear change in the horizontal tide (velocities) can be observed. Largest changes occur between Hansweert and Antwerp.
- Due to the decreese of M4 and the phaseshift of M4 relative to M2 the tidal asymmetry has decreased, causing less import of sediment east of Hansweert
- In the western part of the Western Scheldt hardly any changes in M4 and tidal assymetry occur. The change from import to export near Vlissingen-Breskens cannot be explained this way.
- The Delft3D model schematization is not capable of reproducing the change from import to export, in fact the export near Vlissingen is not simulated at all.
- The increasing eastward transport in the central part of the Western Scheldt due to changes in bathymetry is well represented in the delft 3D model
- The empiricle model ESTMORF is capable of reproducing the change from import to export
- Another issue is the functioning of the mouth area, the large funnel-shape area outside the cross-section Vlissingen-Breskens. It is not clear if this area should be considered as a part of the estuary itself or it should be considered as the ebb-tidal delta.
- In case of sea-level rise the sandhunger of the mouth can cause sedimenttransport from the Western Scheldt itself to the mouth of it. The sediment demand in the mouth area of the Western Scheldt caused by sea-level rise is much more than that in the estuary itself. The horizontal surface area (at mean sea level) of the estuary is about 270 km^2, and that of the mouth area is about 770 km^2. For the present rate the sea-level rise causes a sediment demand of about 0.5 million m^3 per year in the estuary and about 1.2 million m^3 per year in the mouth area.

- The influence of the rate of sea-level rise on the export is limited.

5.3 Recommendations

- Consider the maintenance of the (ecological) functioning of the tidal basins in the coastal management policy. This is especially relevant for accelerated sea-level rise.
- Integrate sand mining and coastal maintenance in the decision making.
- Do not treat the country borders as hard boundaries, especially in the Eems Estuary.
- Consider alternative nourishment methods, especially for the Wadden Sea region:
  - For stimulating sediment import in to a tidal basin in the Wadden Sea, for decrasing the sand demand and / or compensating accelerated relative sea-level rise, nourishment on the ebb-tidal deltas can be considered (Kluyver, 2006, Van Koningsveld et al, 2007).
  - The so called “Sand-Motor” can be used in the northern part of Noord-Holland. A yearly sand suppletion ,near e.g. the Pettemer Seawall, can fullfill three goals :
    1) Strenghtening the coast and increasing safety near the pettemer SeaWall
    2) After being transported to the north it will give protection to the coast near Egmond,
    3) Finally the sand will be transported into the Wadden Sea and feed its sand-hunger (on the long term?).

The present study has not only led to answers but also to new research questions. A list of the recommended research is not given here but reference is made to the four MSc-theses (Bolle, 2006, Dastgheib, 2007, Van Geer, 2007, Van de Waal, 2007). In addition it can be recommended to carry out validations of the tools applied in the study, especially the process-based models for both the Western Scheldt and the Wadden Sea basins

For the Wadden Sea case this will require:

- improving the present model settings by a better representation of the basin and implementing multi-sediment fractions;
- calibration of the flow velocities in the basin and the sedimentation-erosion pattern
- take the ‘realistic” modelling to longer time scales in order to avoid the initial effect caused by schematisation errors of e.g. bathymetry in the model.

For the Western Scheldt a thorough study is required to understand the development of the sediment exchange between the estuary and its mouth area. The following activities are recommended in such a study:

- Analyse the uncertainties and inaccuracies of the sand-budgets.
- Further analysis of the model results (by comparing the model results with the field data for various periods) to inventory the shortcomings of the used models.
- Carry out a sensitivity study with a coarse model,
  - Looking at tidal asymmetry in connection to the outer boundaries. In the present model no relation was found between changes in the tidal asymmetry at the boundary and the import/export within the Western Scheldt
  - Looking at the impact of the upper boundary condition. We know that the upper boundary condition at Schelle is not correct, but we do not know if this has an impact on the import/export of the system.

   - Looking at the impact of dredging/dumping in an exaggerated way. At the moment one of the hypotheses is that the dredging/dumping strategy has caused the change from import to export.
   - Looking at the impact of sea level rise on import/export
- Carry out a desk study in order to identify the possible causes of the turn from import to export at the mouth of the estuary. Look inside as well as outside the estuary, using fact inventory as well as conceptual / theoretical analysis, in order to set up a conceptual model for the historical development of the large scale sand-balance.
- Improve the process-model. The conceptual model from the desk study should be used as guide. The model needs to be improved by implementing a better representation of the upstream boundary condition, such that the tidal propagation in the estuary is well reproduced for the complete period. Therefore seriously consider using the recently developed 1D-2D/3D coupling.
- Repeat the modelling study of Bolle (2006) with the improved model. Pay also attention to the empirical relations used in the semi-empirical models (which do reproduce the turn of sediment exchange) during the analysis of the model results.
- Implement the obtained knowledge in the operational models for the estuary.

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A Additional report of Bolle

A.1 Simulations

Simulations with the DELFT3D-model of the Western Scheldt were performed with the bathymetries of the years 1970, 1983 and 2002 as described in the main report. The Table below gives an overview of all the simulations with their respective settings.

Table A.1: Overview of the simulations performed with the DELFT3D-model of the Western Scheldt.

Run ID	Simulation time step (minutes)	Simulation period (days)	Time step history file (minutes)	Time step map file (minutes)	Sediment transport	Morphological update during simulation	Morphological factor	Comments
Bathymetry 2002								
1	1	5	10	150	-	-	-	test
2	1	5	10	150	-	-	-	
3	1	5	5	60	-	-	-	
4	1	5	10	150	EH	yes	120	
5	1	5	10	150	VR	yes	120	
6	1	5	10	150	-	-	-	limited amount of observation points
7	1	5	10	150	-	-	-	extra observation points in the channels
8	1	5	10	60	EH	no	1	
9	1	5	10	60	VR	no	1	
10	1	2	1	60	VR	no	1	
11	1	2	1	60	EH	no	1	
12	1	5	10	60	EH	yes	1	only 4 days simulated, cross_adapted2.crs
13	1	5	10	60	VR	yes	1	only 4 days simulated, cross_adapted2.crs
14	1	5	10	20	EH	yes	1	only 4 days simulated, cross_adapted2.crs
15	1	4	10	20	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
16	1	52	10	120	VR	yes	1	his-files for entire simulation period, map files only for the first 5 days, cross_adapted2.crs, obs_ebb_flood.obs
17	1	40	10	120	VR	yes	1	cross_adapted2.crs,
18	1	4	10	10	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
19	1	4	10	10	EH	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
20	1	4	10	10	VR	yes	1	amplitude M_2 +25%, cross_adapted2.crs, obs_ebb_flood.obs
21	1	4	10	10	VR	yes	1	amplitude M_2 +50%, cross_adapted2.crs, obs_ebb_flood.obs
22	1	4	10	10	VR	yes	1	amplitude M_4 +25%, cross_adapted2.crs, obs_ebb_flood.obs
23	1	4	10	10	VR	yes	1	amplitude M_4 +50%, cross_adapted2.crs, obs_ebb_flood.obs
24	1	4	10	10	VR	yes	1	amplitude M_6 +25%, cross_adapted2.crs, obs_ebb_flood.obs
25	1	4	10	10	VR	yes	1	amplitude M_6 +50%, cross_adapted2.crs, obs_ebb_flood.obs

26	1	4	10	10	VR	yes	1	phase M_4 +25%, cross_adapted2.crs, obs_ebb_flood.obs
27	1	4	10	10	VR	yes	1	phase M_4 +50%, cross_adapted2.crs, obs_ebb_flood.obs
28	1	4	10	10	VR	yes	1	phase M_6 +25%, cross_adapted2.crs, obs_ebb_flood.obs
29	1	4	10	10	VR	yes	1	phase M_6 +50%, cross_adapted2.crs, obs_ebb_flood.obs
30	1	5	10	20	VR	-	-	only water movement, obs_ebb_flood.obs
Bathymetry 1983								
1	1	0.2	10	150	-	-	-	test
2	1	5	10	150	-	-	-	
3	1	5	5	60	-	-	-	
4	1	5	10	150	EH	yes	120	
5	1	5	10	150	VR	yes	120	
6	1	5	10	150	-	-	-	extra observation points in channels
8	1	5	10	60	EH	no	1	
9	1	5	10	60	VR	no	1	
12	1	5	10	60	EH	yes	1	cross_adapted2.crs
13	1	5	10	60	VR	yes	1	cross_adapted2.crs
14	1	4,7	10	20	EH	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
15	1	5	10	20	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
18	1	4	10	10	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
19	1	4	10	10	EH	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
30	1	5	10	20	VR	-	-	only water movement, obs_ebb_flood.obs
Bathymetry 1970								
2	1	5	10	150	-	-	-	
3	1	5	5	60	-	-	-	
4	1	5	10	150	EH	yes	120	
6	1	5	10	150	-	-	-	extra observation points in channels
8	1	5	10	60	EH	no	1	
9	1	5	10	60	VR	no	1	
10	1	5	10	60	EH	yes	1	
12	1	5	10	60	EH	yes	1	cross_adapted2.crs
13	1	5	10	60	VR	yes	1	cross_adapted2.crs
14	1	5	10	20	EH	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
15	1	5	10	20	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
16	1	5	10	20	VR	yes	1	cross_adapted2.crs, obs_ebb_flood_1970.obs
18	1	4	10	10	VR	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
19	1	4	10	10	EH	yes	1	cross_adapted2.crs, obs_ebb_flood.obs
20	1	5	10	20	VR	yes	0	cross_adapted2.crs, obs_ebb_flood_1970.obs
30	1	5	10	20	VR	-	-	only water movement, obs_ebb_flood.obs
31	1	5	10	20	VR	-	-	only water movement, obs_ebb_flood.obs
Transport formulation: EH = Engelund Hansen, VR = Van Rijn								

The results described in the main report originate from a number of different simulations. Since during the research more requirements came up, simulations with slightly different or more detailed output were made. A summary of the simulations used in every chapter of the main report is given in Table 1-2. A short explanation of their characteristics and differences with previous simulations is given as well.

Table A.2: Summary of the simulations used in every chapter of the main report.

Chapter	Year		
	2002	**1983**	**1970**
5. Tidal Asymmetry			
5.1 Applicability of the Model	2 & 7	2 & 6	2 & 6
	Runs 6 and 7 differ from run 2 by the amount of observation points present in the model. No sediment transport was simulated.		
5.2 Vertical Tidal Asymmetry: * Along-channel variation	30	30	30
	Run 30 has the same settings as run 2 and 6/7, however in run 30 a high number of observation points has been selected in the flood and ebb channels through the entire Western Scheldt. No sediment transport was simulated.		
5.3 Horizontal Tidal Asymmetry			
* Tidal ellipses	7	6	6
	Observation points are present in the centre of the flood and ebb channel in all the macro cells. No sediment transport was simulated.		
* Along-channel variation	30	30	30
	Run 30 has the same settings as run 2 and 6/7, however in run 30 a high number of observation points has been selected in the flood and ebb channels through the entire Western Scheldt. No sediment transport was simulated.		
6. Sediment Transport			
6.1 Residual Sediment Transport Patterns	18 & 19	18 & 19	18 & 19
	Run 18 uses the Van Rijn transport formulation. Suspended load and bed-load can be distinguished. Run 19 uses the Engelund Hansen formulation for the total load. During both runs morphological changes are allowed. The map files are saved for one tidal cycle, in this way the residual transport can be plotted directly in DELFT3D.		
	8 & 9	8 & 9	8 & 9
	Run 9 uses the Van Rijn transport formulation, run 8 the Engelund Hansen. No morphological changes where allowed during the simulation, which resulted in local peaks in the sediment transport. However no peaks in the velocities could be found. This phenomenon is described more in detail in Chapter 3 of this report.		
6.2 Tidally Averaged Bed-load Transport	7	6	6
	Observation points are present in the centre of the flood and ebb channel in all the macro cells. No sediment transport has been simulated. The formula of Van de Kreeke and Robaczewska has been applied to calculate the bed-load transport.		
6.3 Sand Balance Derived from the Model	18 & 19	18 & 19	18 & 19

	Run 18 uses the Van Rijn transport formulation. Suspended load and bed-load can be distinguished. Run 19 uses the Engelund Hansen formulation for the total load. During both runs morphological changes are allowed.

Table 1-3 gives an overview of the different files with the specification of the cross-sections for which output is saved. The files with the selected observation points are summarised in Table 1-4.

Table A.3: Overview of the different specified cross-sections.

File	Specification
crs-file	
kustzui6.crs	The cross-sections as defined in the original model.
cross_adapted.crs	All the cross-sections from kustzui6.crs together with additional sections in the ebb and flood channels of every macro cell. These additional observation points were selected for the analysis of the horizontal tide in the different macro cells.
cross_adapted2.crs	All the cross-sections from cross_adapted.crs together with additional sections between the different macro cells. These cross-sections were required for the calculation of the sand balance from the model.

Table A.4: Overview of the different specified cross-sections.

File	Specification
obs-file	
kustzui6.obs	The observation points as defined in the original model.
obs_in_channels.obs	All the observation points from kustzui6.obs together with additional observation points in the centre of the ebb and flood channels of every macro cell. These additional observation points were selected for the analysis of the horizontal tide in the single points.

obs_ebb_flood.obs	All the observation points from obs_in_channels.obs together with a chain of observation points in the ebb and flood channels throughout the entire Western Scheldt. (With obs_ebb_flood_1970.obs specific for 1970 since important channel movements occurred afterwards.) These files contain the points which are used for the along-channel analysis of the vertical and horizontal tide.

A.2 Evolution of the Water Level through the Estuary

A.2.1 Findings

In Chapter 5 of the main report the vertical tidal asymmetry in the Western Scheldt has been studied. Comparison was made between the results from the model with the bathymetries of the years 1970, 1983 and 2002. No sediment transport was simulated in these cases.

The comparison of the M_2 tidal constituent derived from the model results and the observations in the different stations brought to light that the amplitude at the station Bath is lower than in Hansweert in the case with the bathymetry of the year 1970. Also for the validation of the model (Kuijper et al., 2004) with the bathymetry of the year 1972 a slightly lower value was found in Bath compared to Hansweert. The comparison of the amplitude of M_2 in the different measurement stations along the estuary derived from the observations (filled symbols and line) and the model results (2000 = calibration & 1972 = validation performed by Kuijper et al. (2004) and 1970, 1983 and 2002 which are the recent model results (as described in the main report)) is shown in Figure 2-1.

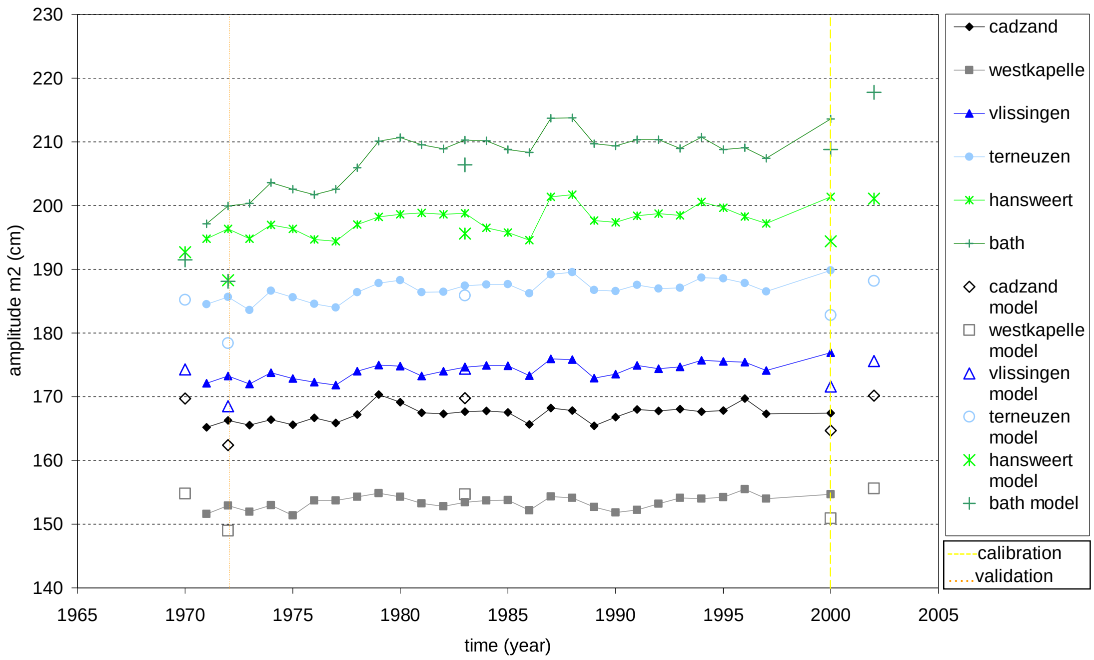

Figure A.1: Comparison of the amplitude of M_2 in the different measurement stations along the estuary derived from the observations (filled symbols and line) and the model results (2000 = calibration & 1972

= validation performed by Kuijper et al. (2004) and 1970, 1983 and 2002 which are the recent model results).

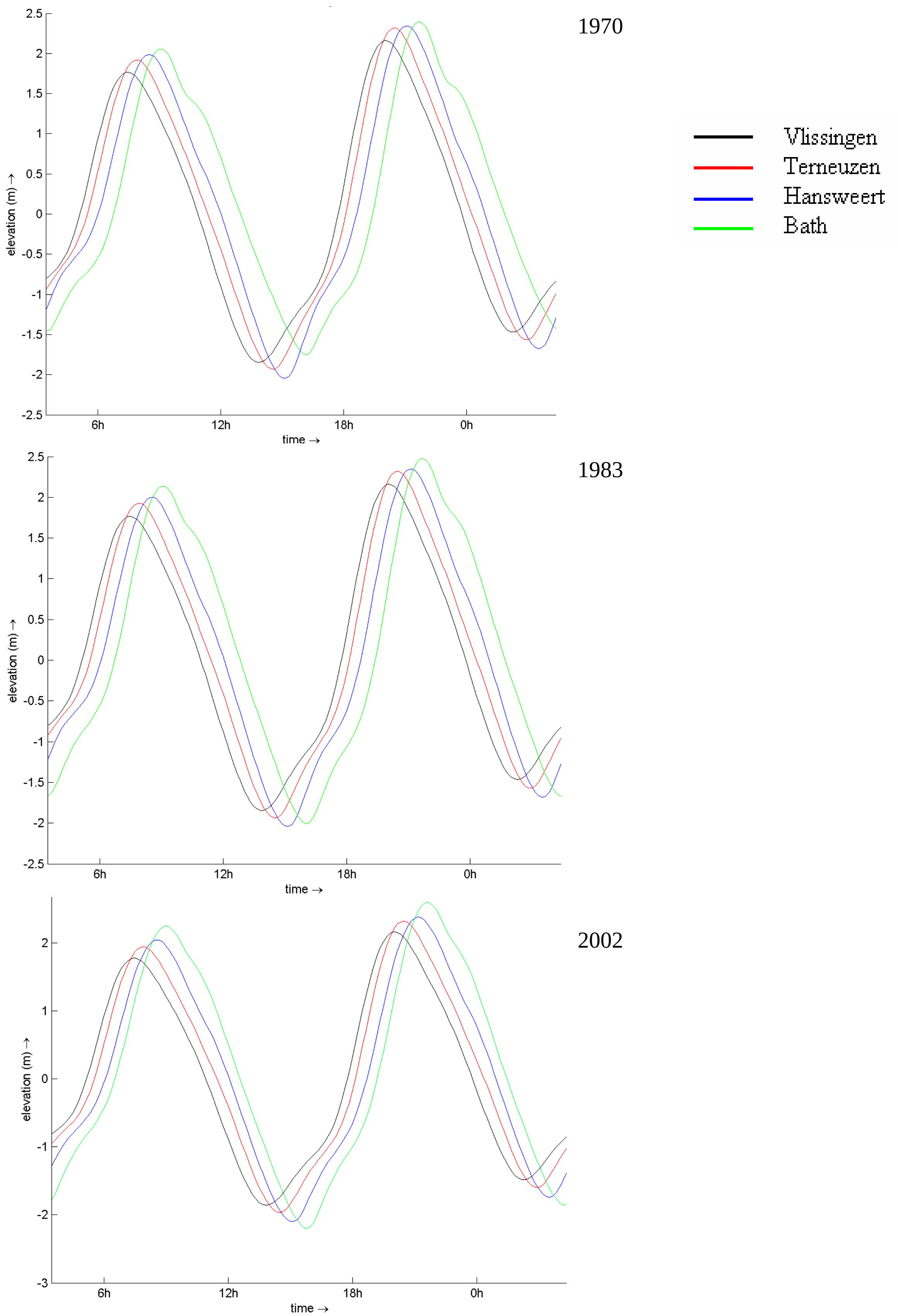

Figure A.2: Water level in the stations Vlissingen (black), Terneuzen (red), Hansweert (blue) and Bath (green) in the models with bathymetry of the years 1970 (top), 1983 (middle) and 2002 (bottom).

A closer investigation of the evolution of the water level through the estuary shows that whereas the continuing increase upstream from Hansweert is reproduced in the model for the years 1983 and 2002, the water level starts decreasing form Walsoorden in the 1970 model. This evolution can be seen in Figure 2-2.

In reality the mean tidal range increases between Vlissingen and Antwerpen (from around 3.8 to 5.2 m) and decreases again (to around 1.9 m) near Gent (Kuijper et al., 2004). Since the model results for 1970 show a decrease of the amplitude upstream from Walsoorden, the hydrodynamics are not correctly represented in the model for the part of the estuary upstream from Hansweert.

A.2.2 Recommendations

If one needs the model to represent the reality very accurate, the upstream part of the estuary should be looked at again in detail. Whereas the 2002 configuration produces the expected results, the correspondence with field data becomes worse for bottoms which differ more.

Possible reasons can be:

- A difference in tidal storage volumes. The bathymetric data probably doesn’t have the same accuracy in 1970 as in 2002. Therefore it could be that for example the shoals in the upstream part are not accurately represented, and hence the tidal propagation differs from reality.
- Wrong bed roughness.
- Wrong upstream boundary conditions.

A new calibration and validation of the model could improve the model behaviour upstream.

A.3 Comparison of Water Levels for Different Model Settings

A.3.1 Findings

The comparison of the tidal constituents of the model results with field data has been done for simulations without sediment transport. This is described in Chapter 5.1 of the main report. However, when exactly the same model is run with sediment transport and morphological changes are allowed during the simulation, the water level differs.
Figure 3-1 shows in dark colours the water level at the stations Vlissingen, Terneuzen, Hansweert and Bath from the simulation without sediment transport, whereas the light colours show the results with sediment transport and morphological changes. It can be seen that near Vlissingen the difference between the two simulations is small, whereas going upstream the difference amounts to 30-40 cm.

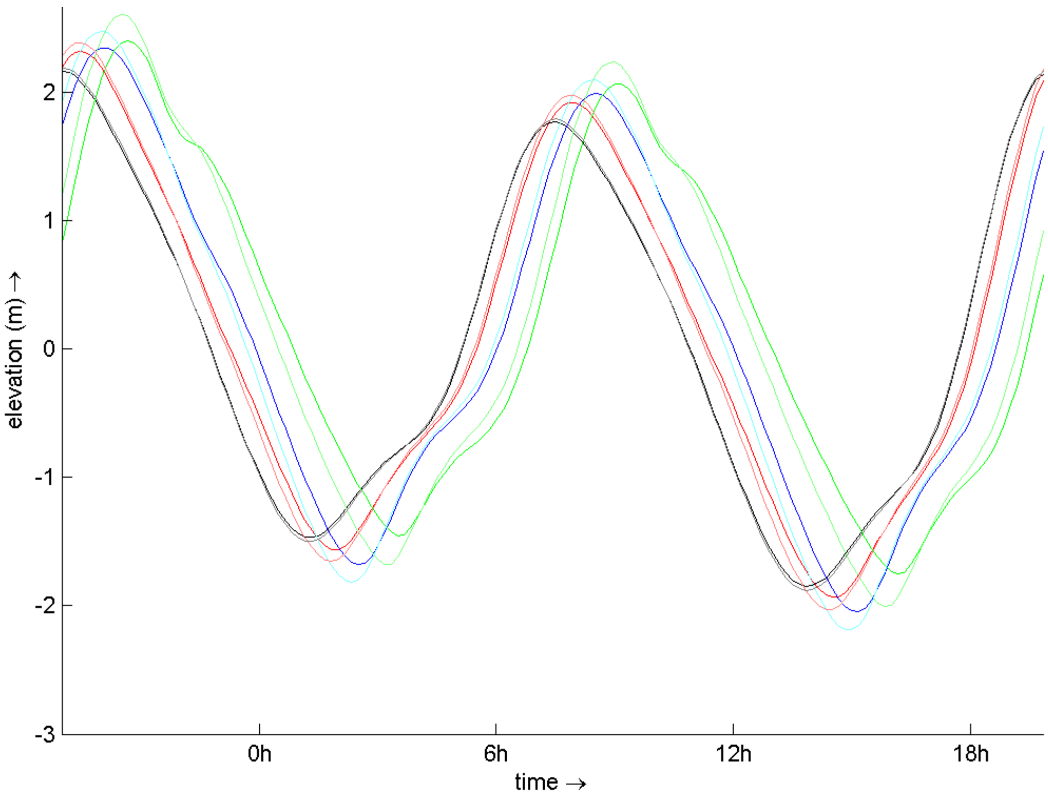

Figure A.3: Comparison of the water level at the stations Vlissingen (black), Terneuzen (red), Hansweert (blue) and Bath (green) from the model results for 1970 without sediment transport (run 002, dark colours) and with sediment transport (run 018, light colours).

A.3.2 Explanations

To see whether the sediment transport formulation or the morphologic changes are responsible for the difference in water levels, comparison has been made between:

A. Simulations without sediment transport (for example run 006 for the year 1970).
B. Simulations with sediment transport, with morphologic update (for example run 018 for the year 1970).
C. Simulations with sediment transport, but without morphologic update (for example run 009 for the year 1970).
D. Simulations with sediment transport, with morphologic update, but with the morphological factor equal to 0. In this way the bathymetry isn't updated (for example run 020 for the year 1970).

The calculated water levels for simulations C and D give the same results as the simulations without sediment transport (case A). When morphological update is allowed (with morphological factor > 0) the water level increases. Therefore the morphological changes are held responsible for the difference in water levels.

Choice of the Settings for the Simulations with Sediment Transport

For the study of the tidal asymmetry in the Western Scheldt, allowing morphologic changes is not necessary since only short-term simulations are performed. The interest is only in the transport accompanying a certain bathymetry, therefore only 5 days were simulated. One tidal cycle is selected for the analysis at the end of this period, the days before are simulated to exclude the spin-up of the model.

However there has been chosen to allow morphologic changes during the simulation since without these adaptations, peaks in the transport trough a cross-section across a channel remained present during the entire simulation period. An example from this phenomenon (run 008 for the year 1970) is shown in Figures 3-2, 3-3 and 3-4.

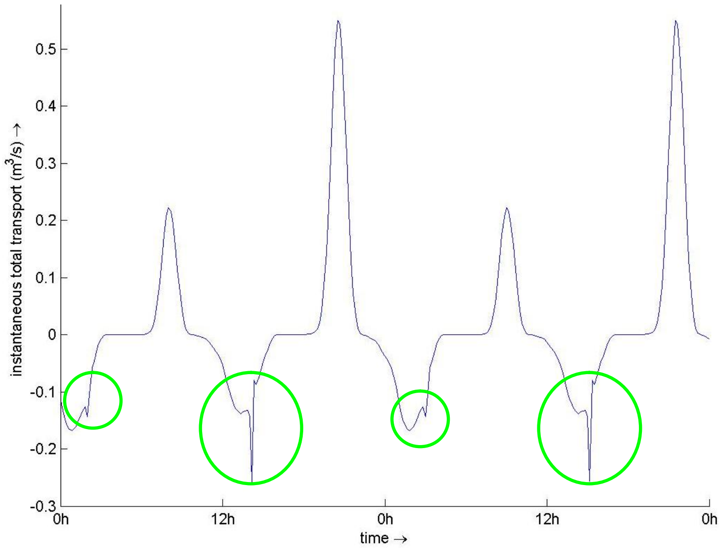

Figure A.1: Sediment transport through cross-section N159 during two tidal cycles. The peaks in the transport are marked with green circles (from run 008 for the year 1970).

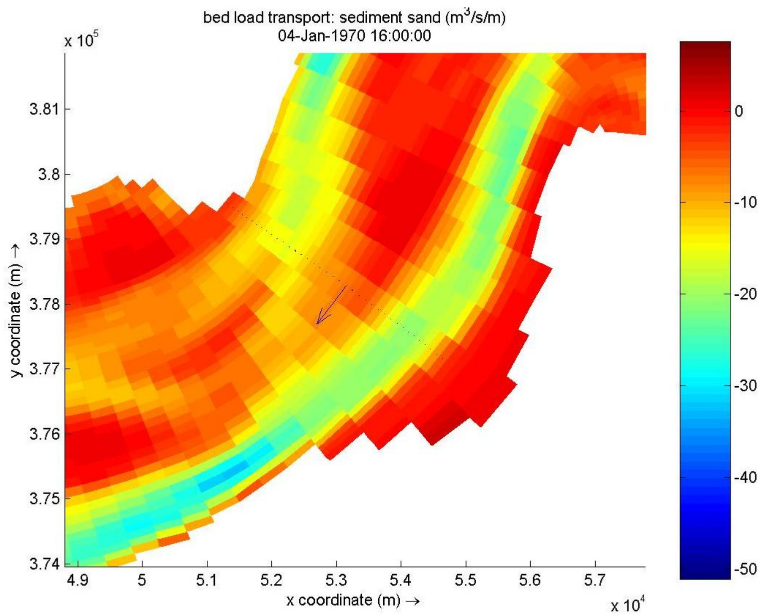

Figure A.2: Sediment transport through cross-section N159 on 04/01/1970 at 16h (from run 008 for the year 1970).

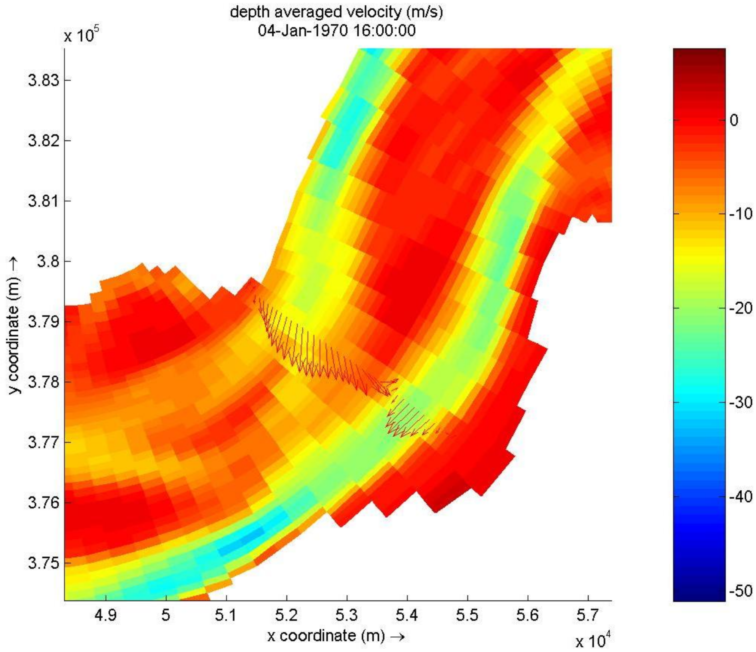

Figure A.3: Depth averaged velocity through cross-section N159 on 04/01/1970 at 16h (from run 008 for the year 1970).

In many cases the peaks are decisive for the transport direction of the residual transport through a cross-section (during one tidal cycle), which resulted in different residual transport directions between macro cells. However, the velocity through the same cross-section is smooth and doesn't show any irregularities. No explanation for the peaks could be found in the velocities.

Since the simulations are short-term (5 days), the morphological changes are assumed to be neglectable. Therefore the calculations of the sediment transport accompanying a certain bathymetry in the previous study are based on the simulations with morphological changes. However as can be seen on Figure 3-5 (area north of the Verdronken land van Saefthinge), this assumption is not everywhere completely true. In the upstream part, significant erosion/sedimentation occurs at the borders of the channels. Especially near the upstream model boundary important morphological changes occur. More towards the mouth almost no changes take place. This effect is clearly visible in the water levels shown on Figure 3-1.

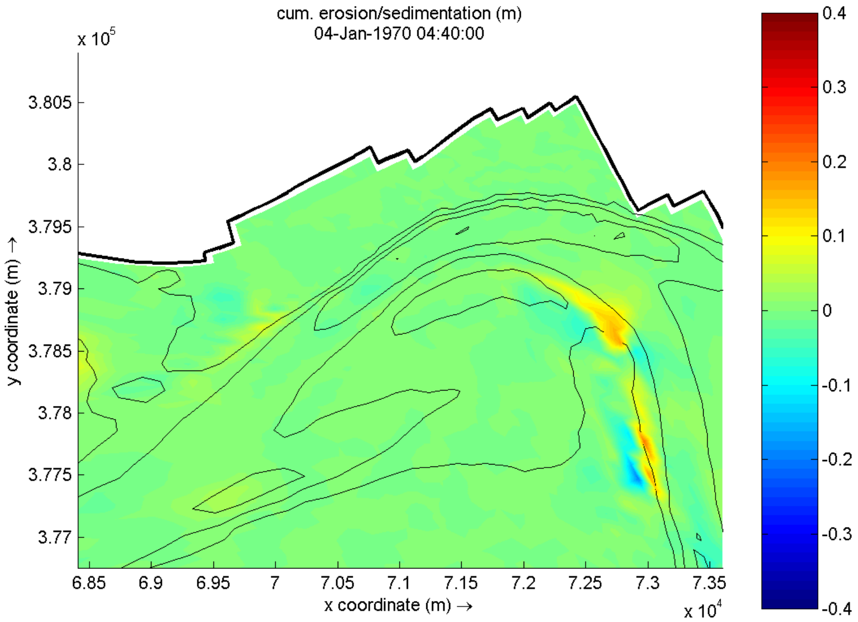

Figure A.4: Cumulative erosion/sedimentation after 4 days as found in run 018 for the year 1970 in the area north of the Verdronken land van Saefthinge. The contour lines of the initial bathymetry are shown in black.

A.4 Modified Boundary Conditions

A.4.1 Method

The tidal asymmetry inside the estuary is influenced by the asymmetry of the tide at the seaward boundary of the estuarine system (Dronkers, 1986, 1998; van der Spek, 1997). It is likely that the asymmetry of the vertical tide at a certain station is influenced by the asymmetry of the tide in the section downstream (Wang et al., 2002).

Therefore model runs have been performed with modified boundary conditions. The separate influence of 25 and 50% increase of the amplitude of the M_2, M_4 and M_6 tidal constituents and the phase of M_4 and M_6 can be deducted from these simulations. The model settings for all the different runs are shown in Table 4-1. An overview of the different runs with the modified boundary conditions is given in Table 4-2, the list with the bch-files with the modified boundary conditions are shown in Table 4-3.

The reference situation is model run 18, which is the Western Scheldt model with the bathymetry of the year 2002 and the morphological tide with duration of 25 hours as selected by Kuijper et al. (2004). The applied transport formulation is Van Rijn (2003) and morphological update is allowed during the simulation.

Table A.1: Model settings for the simulations with the modified downstream boundary conditions.

Model settings	
Simulation time step	1 minute
Simulation period	4 days

Output history	every 10 minutes during the entire simulation period
Output map file	every 10 minutes during 1 tidal cycle
Sediment transport formulation	Van Rijn (2003)
Morphological factor	1
Observation points	measurement stations and points along the ebb and flood channels
Boundary conditions - upstream - downstream	 - discharges, harmonical boundary conditions - harmonical boundary conditions as before, however now with varying amplitudes and phases for M_2, M_4 and M_6 in the different runs

Table A.2: Overview of the different model runs with the modified downstream boundary conditions.

Overview of the simulations						
Run ID	**Harmonical constituents at the downstream boundary**					
	M_2		**M_4**		**M_6**	
	Amplitude	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**
18	reference situation		reference situation		reference situation	
20	+25%	ref.	ref.	ref.	ref.	ref.
21	+50%	ref.	ref.	ref.	ref.	ref.
22	ref.	ref.	+25%	ref.	ref.	ref.
23	ref.	ref.	+50%	ref.	ref.	ref.
24	ref.	ref.	ref.	ref.	+25%	ref.
25	ref.	ref.	ref.	ref.	+50%	ref.
26	ref.	ref.	ref.	+25%	ref.	ref.
27	ref.	ref.	ref.	+50%	ref.	ref.
28	ref.	ref.	ref.	ref.	ref.	+25%
29	ref.	ref.	ref.	ref.	ref.	+50%
ref. = reference situation (identical to the settings of run 18)						

Table A.3: Overview of the bch-files for the different runs.

Run ID	bch-file
18	102.bch
20	102(M2+25p).bch
21	102(M2+50p).bch
22	102(M4+25p).bch
23	102(M4+50p).bch
24	102(M6+25p).bch
25	102(M6+50p).bch
26	102(phi4+25p).bch
27	102(phi4+50p).bch
28	102(phi6+25p).bch
29	102(phi6+50p).bch

A.4.2 Recommendations

The model results from the simulations with the modified boundary conditions still have to be analysed. By increasing the amplitude of one of the tidal constituents, the relative contribution of this component to the tide augments. Since the amplitude of the M_2, M_4 and M_6 tidal constituents influence the strength of the tide asymmetry, changes in the tide-driven sediment transport are to be expected as well. Modifying the phase of M_4 and M_6 can change the flood/ebb dominance in a certain region.

By comparing all the different scenarios to the reference situation (which is the bathymetry of the year 2002 in combination with the original morphological tide and sediment transport according to Van Rijn (2003)), the specific influence of each modification can be identified. Not only the magnitude of the phases and amplitudes of the tidal constituents at the different stations (Westkapelle, Cadzand, Vlissingen, Terneuzen, Hansweert and Bath) should be compared, but also the evolution of the different components through the estuary as done previously for the comparison between the years 1970, 1983 and 2002 as presented in the main report.

Both the changes in the vertical tide (water levels) and the horizontal tide (velocities and discharges) should be investigated. All scenarios should be compared with the reference situation.

A.5 Interventions in the Sea Scheldt

Haecon (2006) constructed a sand balance for the Western Scheldt estuary including the Sea Scheldt. Based on data of the amounts of dredging and dumping in the Sea Scheldt (Figure 5-1) the exchange of sediments across the upstream boundary of the Western Scheldt has been determined. The transported volumes across the Belgian-Dutch border are shown in Figure 5-2.

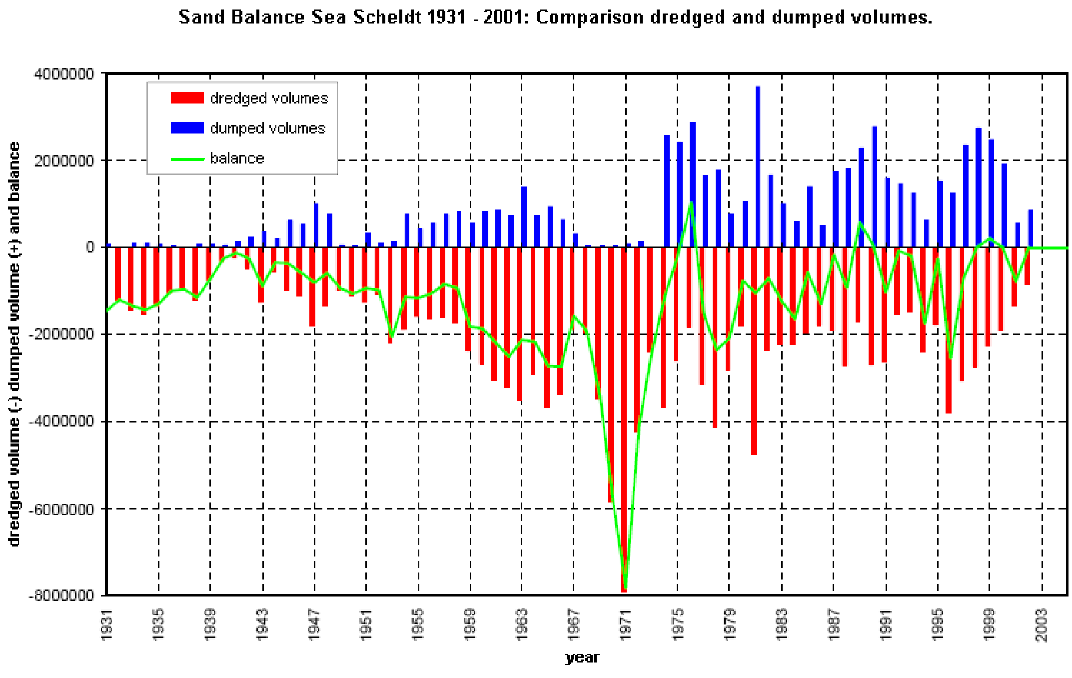

Figure A.5: Dredged and dumped volumes for the Sea Scheldt in the period 1931 - 2001 (Haecon, 2006).

With the DELFT3D-model of the Western Scheldt the sediment transport belonging to the bathymetry of the years 1970, 1983 and 2002 has been calculated. This is described in Chapter 6.3 of the main report. The outcomes for the sediment transport across the borders of the different macro cells as derived from the model are shown in Figure 5-3. A positive value represents import or eastward transport, a negative value stands for export or westward transport.

It can be seen that the model results show the same trend in the transport across the upstream boundary of the Western Scheldt as the transport derived from the sand balance by Haecon (2006) (See Figure 5-2). In 1970 a lot of sediments are transported upstream, whereas for 1983 and 2002 this amount is much smaller. This indicates that the transport across this boundary is mainly governed by the sediment demand of the Sea Scheldt.

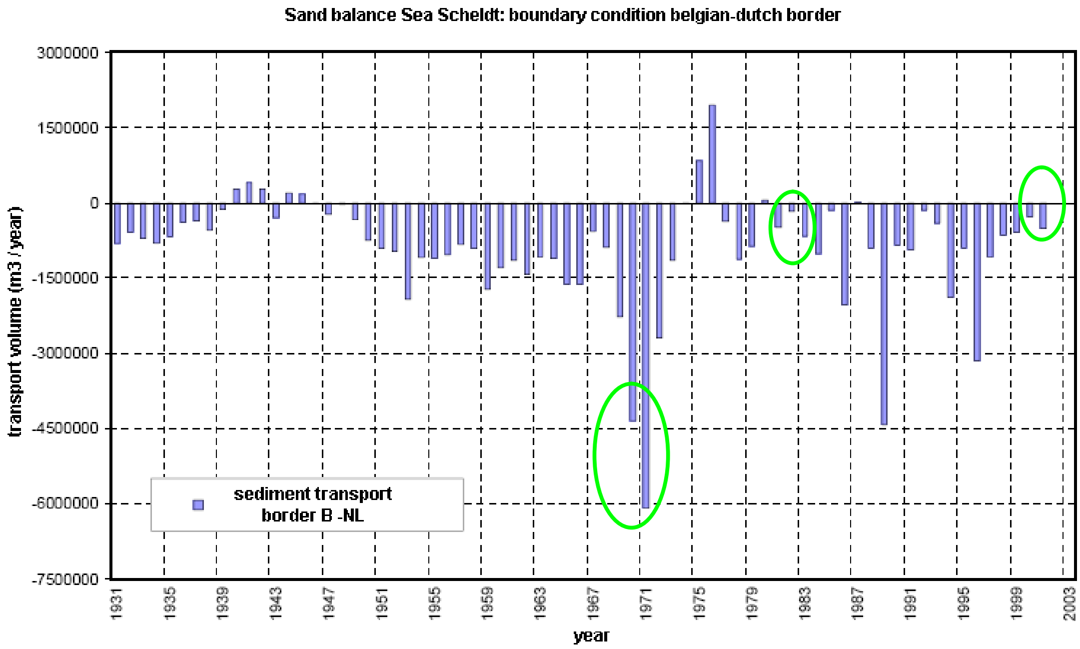

Figure A.6: Sand balance of the Sea Scheldt: boundary condition at the Belgian-Dutch border (Assumption of no transport near Rupelmonde; - = transport towards Belgium) (Haecon, 2006).

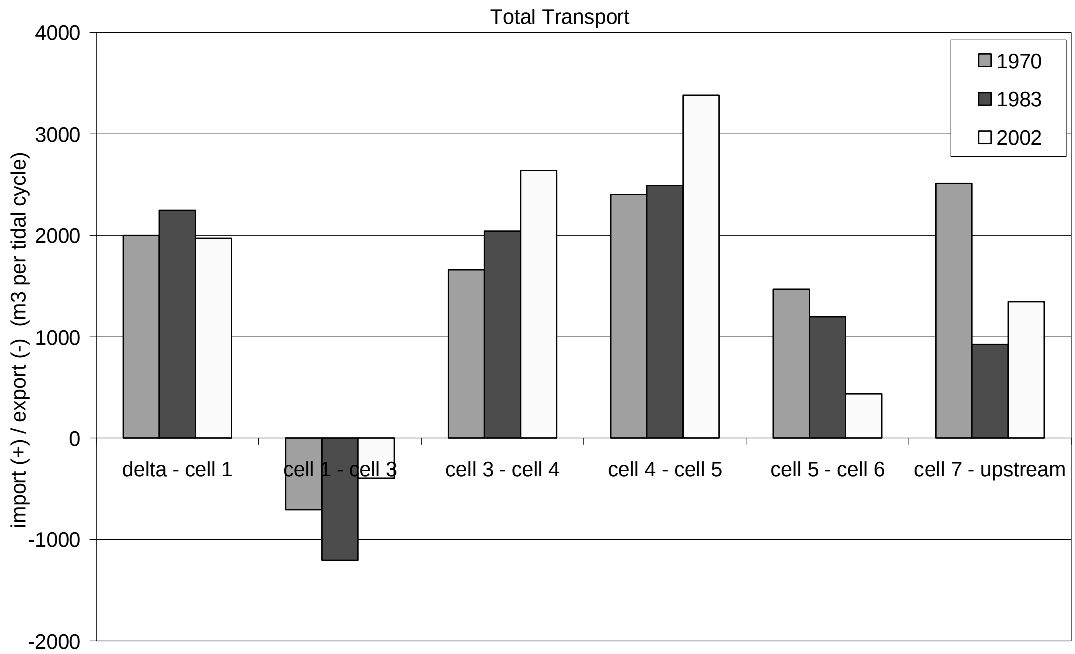

Figure A.7: Transport across the borders of the macro cells in the Western Scheldt in m^3/tidal cycle for the total, bed-load and suspended transport according to the Van Rijn formulation (+ = import or transport to the east, - = export or transport to the west) as calculated with the DELFT3D-model (See description in the main report).

A.6 Sand Balance Derived from the Model

A.6.1 Method

In the main report a sand balance has been derived from the DELFT3D-model results, which quantifies the erosion and sedimentation of sand under influence of the tide-driven sediment transport occurring for a certain bathymetry. This is described in Chapter 6.3. For this balance the Western Scheldt division into macro cells (Winterwerp et al., 2000) is used with a few adaptations (Figure 6-1).

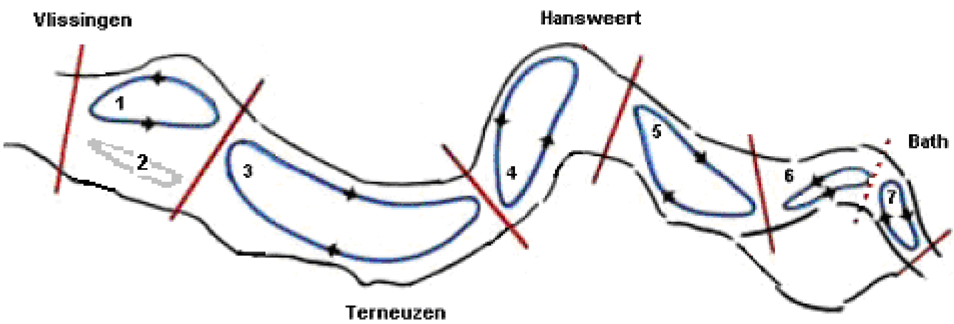

Figure A.8: Division of the Western Scheldt in cells for the sand balance. The blue loops are macro cells, the grey one is a meso cell. The red full lines represent the borders between the compartments used in the sand balance (Schematical representation after Nederbragt and Liek (2004)).

The volume change within a compartment during one tidal cycle is calculated as follows:

$$\Delta V = V_{sb} - V_{lb} \qquad \text{Equation 6.1}$$

where V_{sb} = the volume sediments passing through the seaward cell boundary during one tidal cycle (in m^3)
V_{lb} = the volume sediments passing through the landward cell boundary during one tidal cycle (in m^3)
ΔV = the volume change within the cell during one tidal cycle (in m^3)

The sand balance in the main report is based on the average transport trough several cross-sections at the borders of the macro cells. This was done to eliminate the influence of the differences in transport between subsequent cross-sections.

The influence of the selection of the cross-sections on the calculated transports and erosion or sedimentation within the different macro cells is described in this chapter. One is reminded that the simulations performed for this study are short-term. The results are described for one tidal cycle only. The results from run 019 for the years 1970, 1983 and 2002 with the total sediment transport calculated according to Engelund Hansen are used in this Chapter.

A.6.2 Single cross-section

Selected cross-sections

In this section, the sand balances derived from three different sets of single cross-sections between the macro cells are compared. The selected cross-sections for cases A, B, and C are shown on Figure 6-2 and summarised in Table 6-1.

Table A.4: Selected cross-sections in the model for the sand balances A, B and C.

Location	A	B	C
seaward border cell 1	N96	N97	N91
cell 1 – cell 3	N121	N122	N120
cell 3 – cell 4	N159	N160	N158
cell 4 – cell 5	N181	N180	N179
cell 5 – cell 6	N223	N224	N220
upstream border cell 7	M80	M79	M78

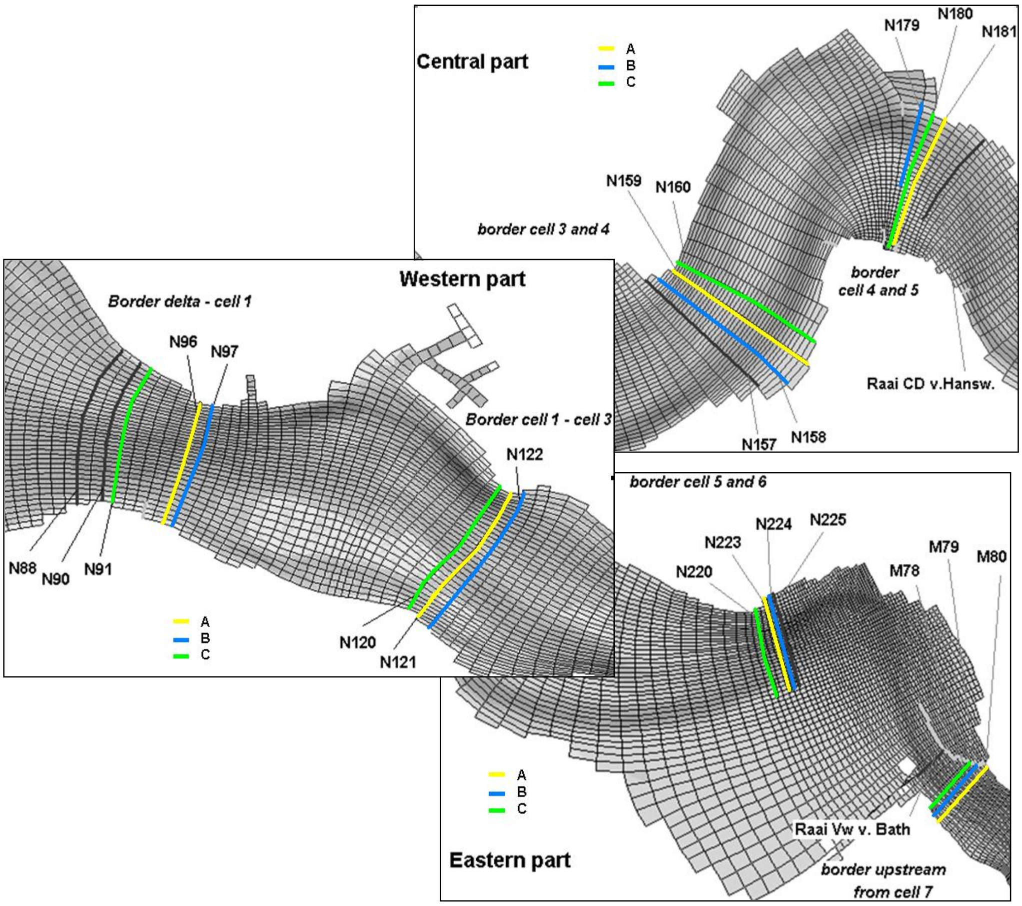

Figure A.9: Location of the cross-sections in the Western Scheldt.

Results

Figure 6-5 shows the evolution of the transport between the macro cells from 1970 to 2002 for respectively the three different selections of cross-sections (A, B, and C). The numeric values are summarised in Table 6-2.

There can be noticed that in most cases, the transport direction through subsequent cross-sections is the same, however on the border between cells 1 and 3 import (positive value) is found for 1970 and 2002 for selection B, whereas in cases A and C there is always export (negative value).

Although in general (with exception from the border between cell 1 and 3) the transport direction is identical for selections A, B, and C, the magnitude can differ significantly. Standard deviations go from 4% up to 90% of the average value of the three different selections. The differences are small at the upstream boundary of macro cell 7 (between 4 and 12%), but vary highly elsewhere, for example on the border between cell 3 and 4 (from 14 up to 90% of the average value).

Table A.5: Sediment transported through a cross-section (m^3 / tidal cycle) for the years 1970, 1983, and 2002 for different selections of cross-sections (A, B, and C).

Sediment transported through a cross-section (m^3 / tidal cycle)

Location	Year	A	B	C	Average	Standard Deviation	St. Dev. (% of average)
seaward border cell 1	2002	803	515	1140	819	313	38
	1983	990	547	1077	871	284	33
	1970	851	517	999	789	247	31
cell 1 - cell 3	2002	-274	516	-670	-143	604	-423
	1983	-862	-110	-426	-466	378	-81
	1970	-544	93	-212	-221	318	-144
cell 3 - cell 4	2002	771	223	1961	985	888	90
	1983	1159	1424	1096	1226	174	14
	1970	582	449	1042	691	311	45
cell 4 - cell 5	2002	2403	1802	1854	2019	333	16
	1983	3325	1409	1987	2240	982	44
	1970	2459	1381	1301	1714	646	38
cell 5 - cell 6	2002	646	428	62	379	296	78
	1983	1828	1393	735	1318	550	42
	1970	1503	1371	1342	1406	86	6
upstream border cell 7	2002	378	451	456	428	44	10
	1983	301	333	261	298	36	12
	1970	986	1048	986	1007	36	4

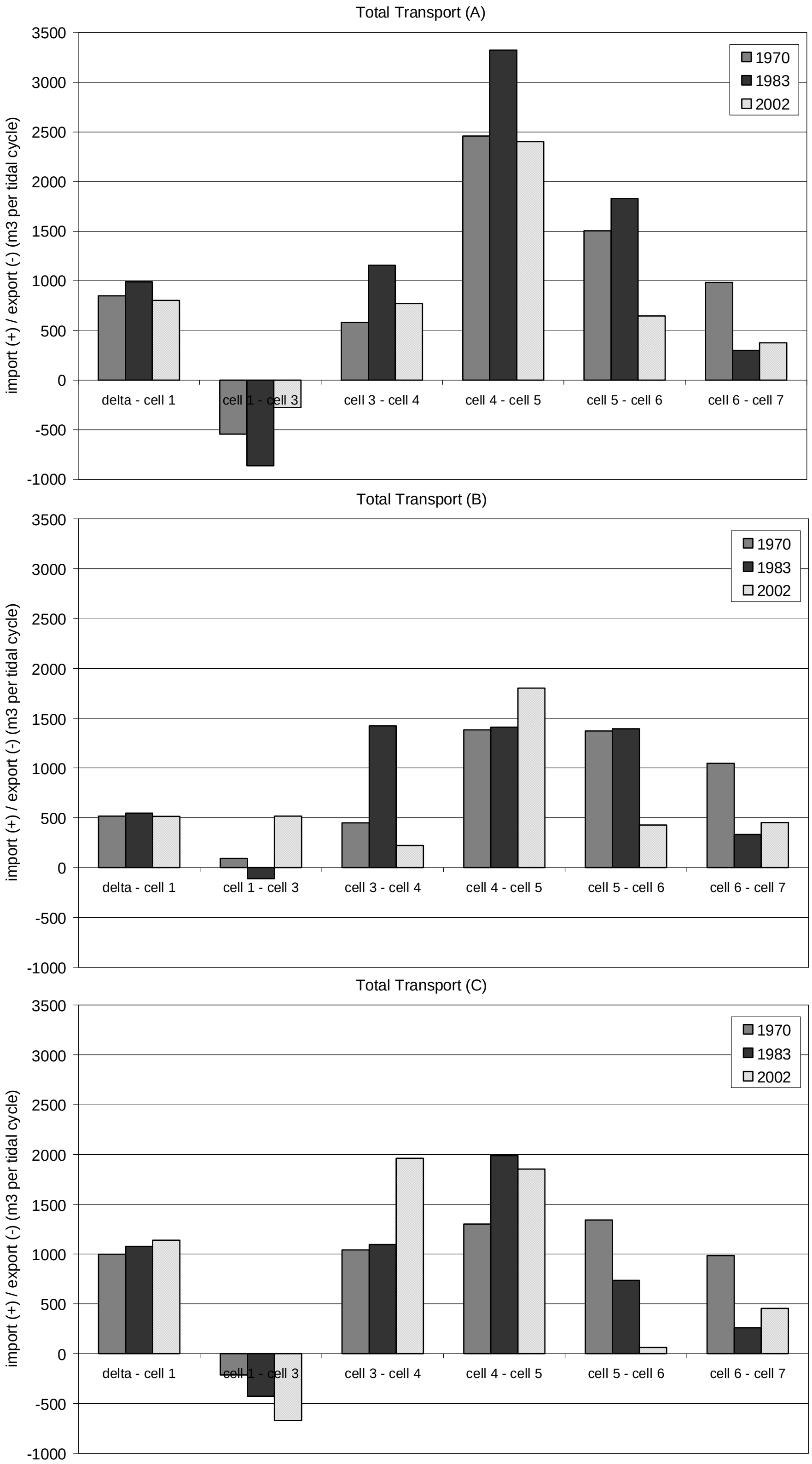

Figure A.10: Evolution of the transport between the macro cells from 1970 to 2002 for respectively the selection of cross-sections A, B, and C.

On Figure 6-3 it can be seen that apart from at the upstream border of cell 7, the trend in the transport over the years 1970, 1983, and 2002 depends on the selection of the cross-sections.

The volume changes in every macro cell for the three different selections during one tidal cycle are given in Table 6-3 and visualised in Figure 6-4.

Comparing selection A, B, and C, changes in sedimentation/erosion are found in every macro cell. Also the magnitude highly differs between the different selections: from 14% of the average value up to more than 100% in a couple of cases (See Table 6-3).

Concerning trends between the different years, only in macro cell 5 increased sedimentation is found in the three different cases. In all other macro cells the trend depends on the selected cross-sections.

Table A.6: Erosion (-) or sedimentation (+) in the macro cells (m^3 / tidal cycle) for the years 1970, 1983, and 2002 for the selections A, B, and C of cross-sections.

Erosion (-) or sedimentation (+) in the macro cells (m^3 / tidal cycle)							
Location	**Year**	**A**	**B**	**C**	**Average**	**Standard Deviation**	**St. Dev. (% of average)**
cell 1+2	**2002**	1077	-1	1810	962	911	95
	1983	1852	657	1502	1337	614	46
	1970	1395	425	1211	1010	515	51
cell 3	**2002**	-1045	292	-2631	-1128	1463	-130
	1983	-2020	-1533	-1522	-1692	285	-17
	1970	-1126	-356	-1254	-912	486	-53
cell 4	**2002**	-1632	-1578	107	-1034	989	-96
	1983	-2166	14	-891	-1014	1095	-108
	1970	-1877	-932	-259	-1023	813	-79
cell 5	**2002**	1756	1373	1792	1641	232	14
	1983	1497	17	1252	922	793	86
	1970	956	10	-41	308	561	182
cell 6+7	**2002**	269	-23	-394	-49	332	-672
	1983	1527	1060	474	1020	528	52
	1970	517	324	356	399	103	26

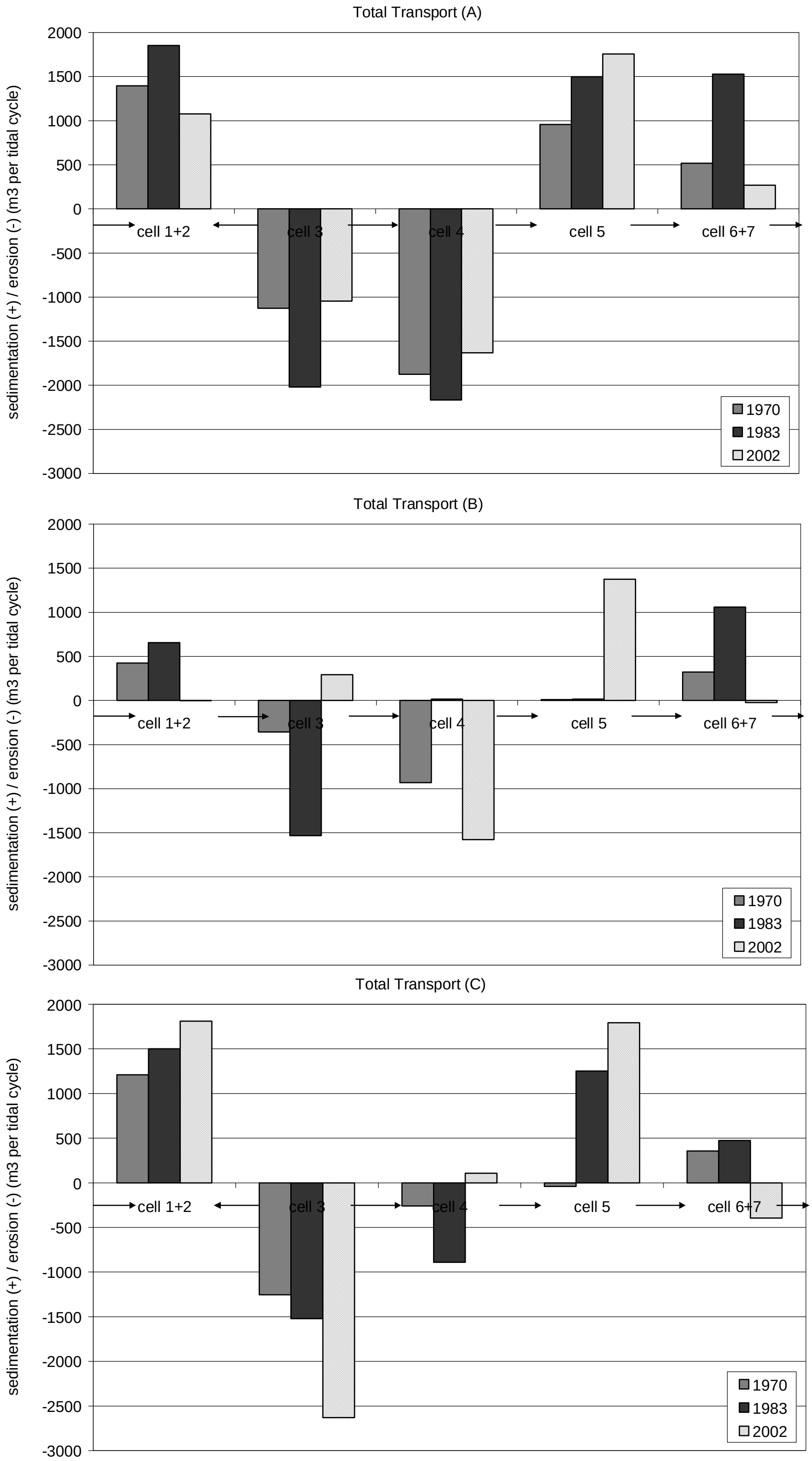

Figure A.11: Evolution of the sedimentation/erosion in the macro cells from 1970 to 2002 for the selections of cross-sections A, B, and C.

A.6.3 Average of Subsequent Cross-sections

Selected cross-sections

This section considers the effect of the choice of several cross-sections to define one boundary between two macro cells. Instead of using the transport through one single cross-section at the border, the averaged transport in the border area will be considered.

The first part discusses the results for three combinations of the averaged transport through two nearby located cross-sections (case D, E, and F). Next the results based on the averaged transport from three or more cross-sections are examined (G and H). An overview of the different cases is presented in Table 6-4.

Table A.7: Description of different selections for the sand balances based on the average transport of several cross-sections.

Selection	Description
D	average of selections A and B
E	average of selections A and C
F	average of selections B and C
G	average of selections A, B and C
H	as defined in the main report

Results

Table 6-5 shows the comparison of the averaged transport between the macro cells of selections D, E, and F. This is also visualised in Figure 6-5.

It can be seen from the Table below that the difference between the three selections is much smaller compared to the transports through a single cross-section as described in Section 6.3.1.
The transport direction is the same for the three cases in all years with exception from case D across the border between cell 1 and 3 in the year 2002.
On Figure 6-5 there can be seen that both at the seaward (cell 1) and landward (cell 7) boundary the trends found in the three cases are identical. In the other cells there is resemblance between two of the three cases.

Table A.8: Sediment transported through a cross-section (m^3 / tidal cycle) for the years 1970, 1983, and 2002 for different selections of cross-sections (D, E, and F).

Sediment transported through a cross-section (m^3 / tidal cycle)							
Location	**Year**	**D**	**E**	**F**	**Average**	**Standard Deviation**	**St. Dev. (% of average)**
seaward border cell 1	**2002**	659	971	827	819	157	19
	1983	769	1033	812	871	142	16
	1970	684	925	758	789	123	16
cell 1 - cell 3	**2002**	121	-472	-77	-143	302	-212
	1983	-486	-644	-268	-466	189	-41
	1970	-226	-378	-60	-221	159	-72
cell 3 - cell 4	**2002**	497	1366	1092	985	444	45
	1983	1291	1127	1260	1226	87	7
	1970	516	812	746	691	156	23
cell 4 - cell 5	**2002**	2102	2128	1828	2019	166	8
	1983	2367	2656	1698	2240	491	22
	1970	1920	1880	1341	1714	323	19
cell 5 - cell 6	**2002**	537	354	245	379	148	39
	1983	1610	1281	1064	1318	275	21
	1970	1437	1423	1357	1406	43	3
upstream border cell 7	**2002**	414	417	453	428	22	5
	1983	317	281	297	298	18	6
	1970	1017	986	1017	1007	18	2

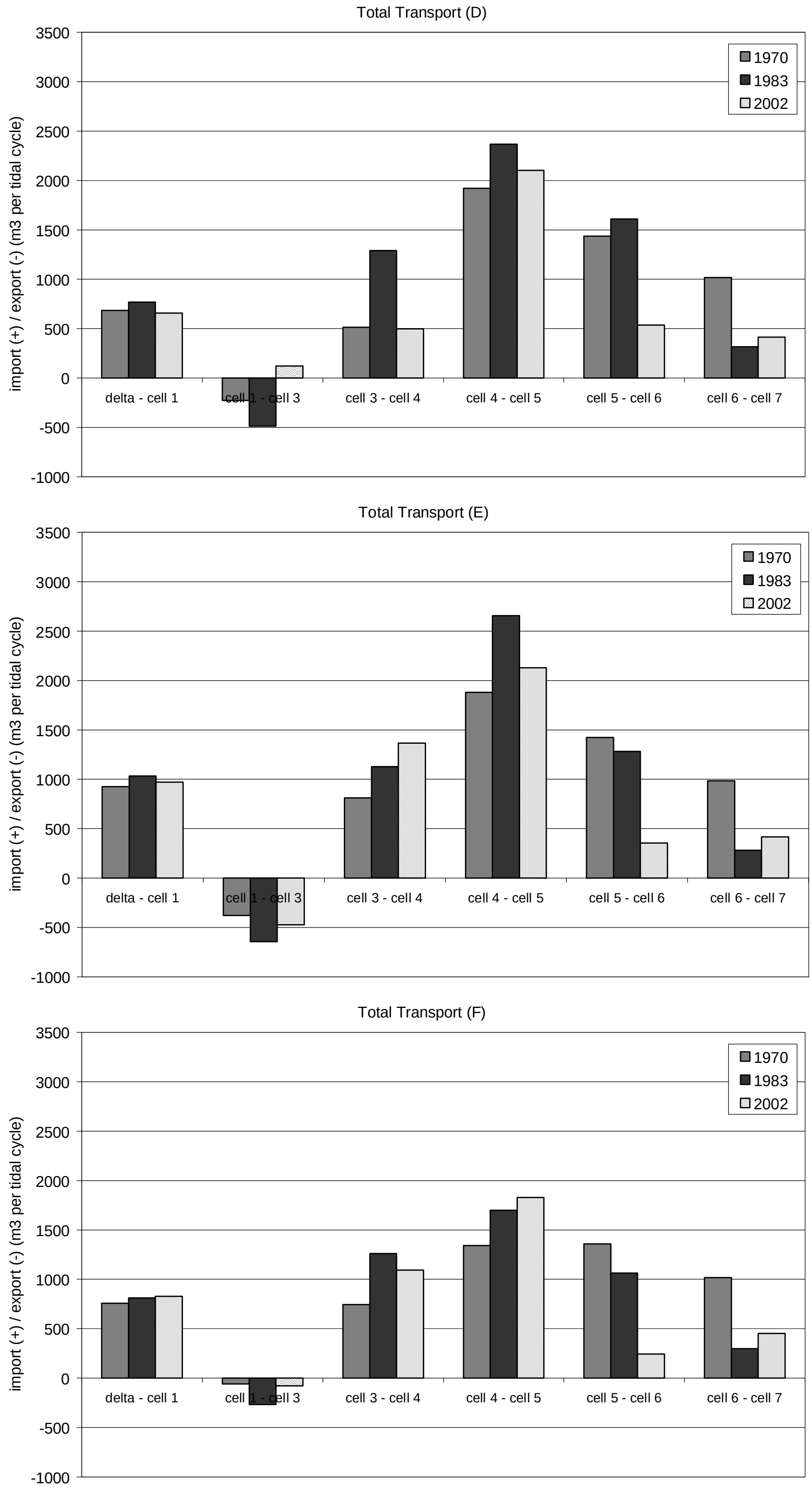

Figure A.12: Evolution of the transport between the macro cells from 1970 to 2002 for respectively the selections D, E, and F of cross-sections.

Concerning sedimentation or erosion within the macro cells, the same comparison as for the transports has been made. The numeric values are given in Table 6-6; the graphs are presented in Figure 6-6.

As found for the transport, also for the erosion/sedimentation the difference between the three cases D, E and F are smaller than those between A, B, and C (See Table 6-6, respectively 6-3). Apart from macro cell 7 in case D for the year 2002, the same evolution (erosion or sedimentation) is found for the three cases.
The trends over the years are identical in macro cells 1 and 5 for cases D, E, and F. For the trends in the other macro cells there is resemblance between two of the three cases.

Table A.9: Erosion (-) or sedimentation (+) in the macro cells (m^3 / tidal cycle) for the years 1970, 1983, and 2002 for the selections of cross-sections D, E, and F.

Erosion (-) or sedimentation (+) in the macro cells (m^3 / tidal cycle)							
Location	**Year**	**D**	**E**	**F**	**Average**	**Standard Deviation**	**St. Dev. (% of average)**
cell 1+2	**2002**	538	1443	904	962	456	47
	1983	1254	1677	1080	1337	307	23
	1970	910	1303	818	1010	258	26
cell 3	**2002**	-376	-1838	-1169	-1128	732	-65
	1983	-1777	-1771	-1528	-1692	142	-8
	1970	-741	-1190	-805	-912	243	-27
cell 4	**2002**	-1605	-762	-735	-1034	495	-48
	1983	-1076	-1528	-438	-1014	548	-54
	1970	-1404	-1068	-596	-1023	406	-40
cell 5	**2002**	1565	1774	1583	1641	116	7
	1983	757	1374	634	922	397	43
	1970	483	457	-16	308	281	91
cell 6+7	**2002**	123	-63	-208	-49	166	-336
	1983	1293	1000	767	1020	264	26
	1970	420	437	340	399	52	13

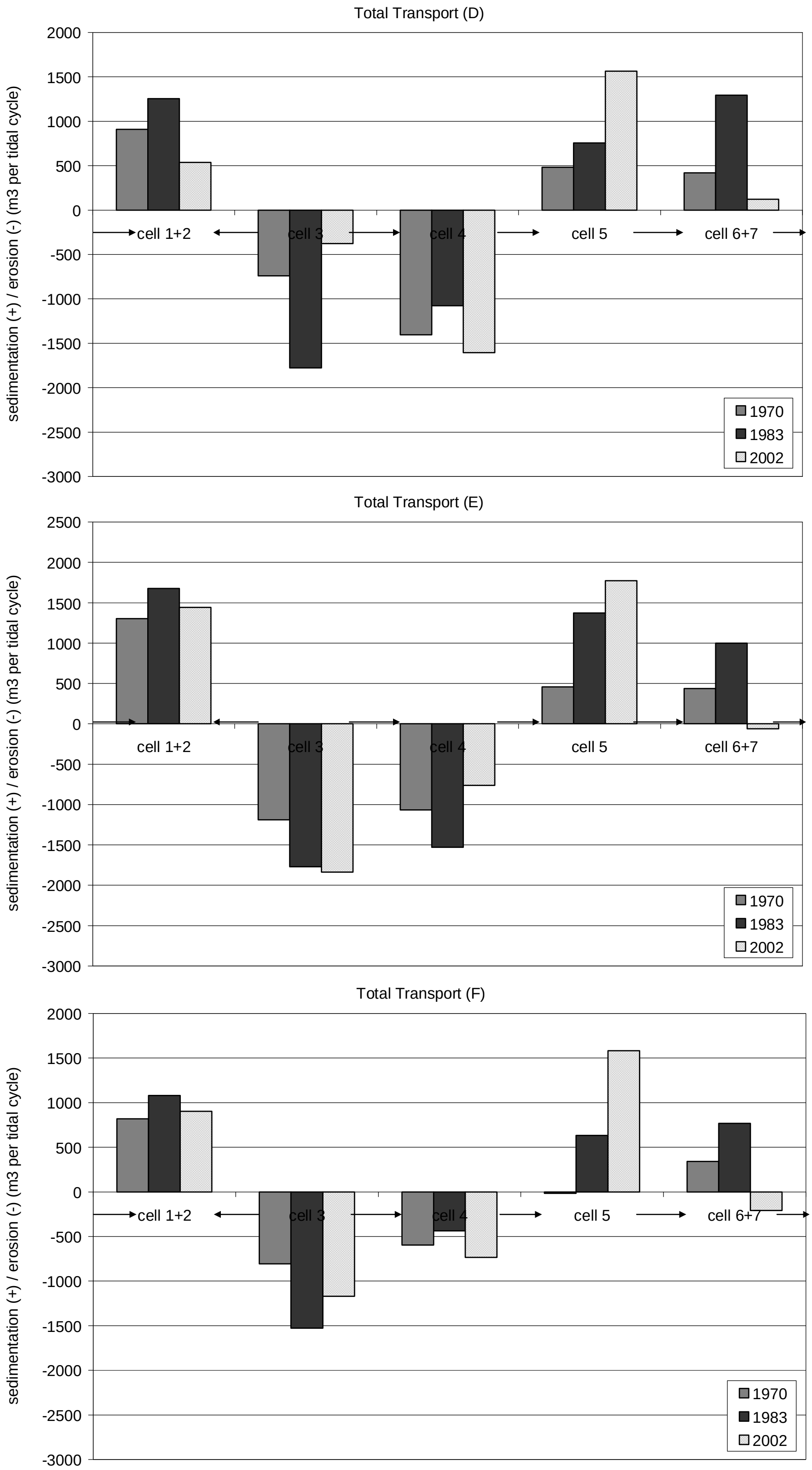

Figure A.13: Evolution of the sedimentation/erosion in the macro cells from 1970 to 2002 for the selections of cross-sections D, E, and F.

Since averaging the transport from two nearby located cross-sections gives smoother results than using single cross-sections, two more cases are examined hereafter:

- Case G: based on the selection of three cross-sections between subsequent macro cells. This is the average of cases A, B and C.
- Case H: based on the average of at least three cross-sections at each border. This case corresponds with the one applied in the main report.

From the graphs in Figures 6-7 (case G) and 6-8 (case H) there can be noticed that both cases show the same trends for the evolution of the transport between the macro cells with exception from the borders of macro cell 4, where the transport in 1983 is clearly higher in case G compared to case H.
The transport is orientated in the same direction for both cases, and similar trends for erosion/sedimentation come out.

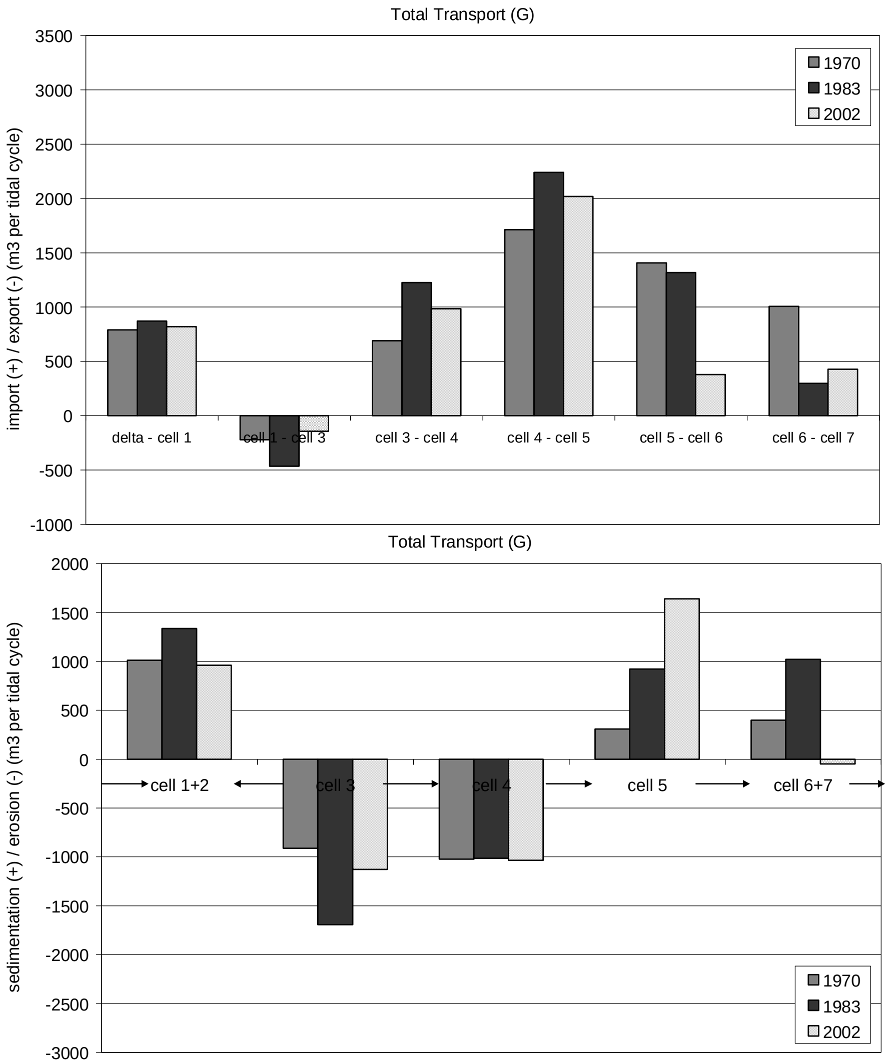

Figure A.14: Evolution of the sediment transport at the borders and the sedimentation/erosion in the macro cells from 1970 to 2002 for selection G of the cross-sections (= average of A, B, and C).

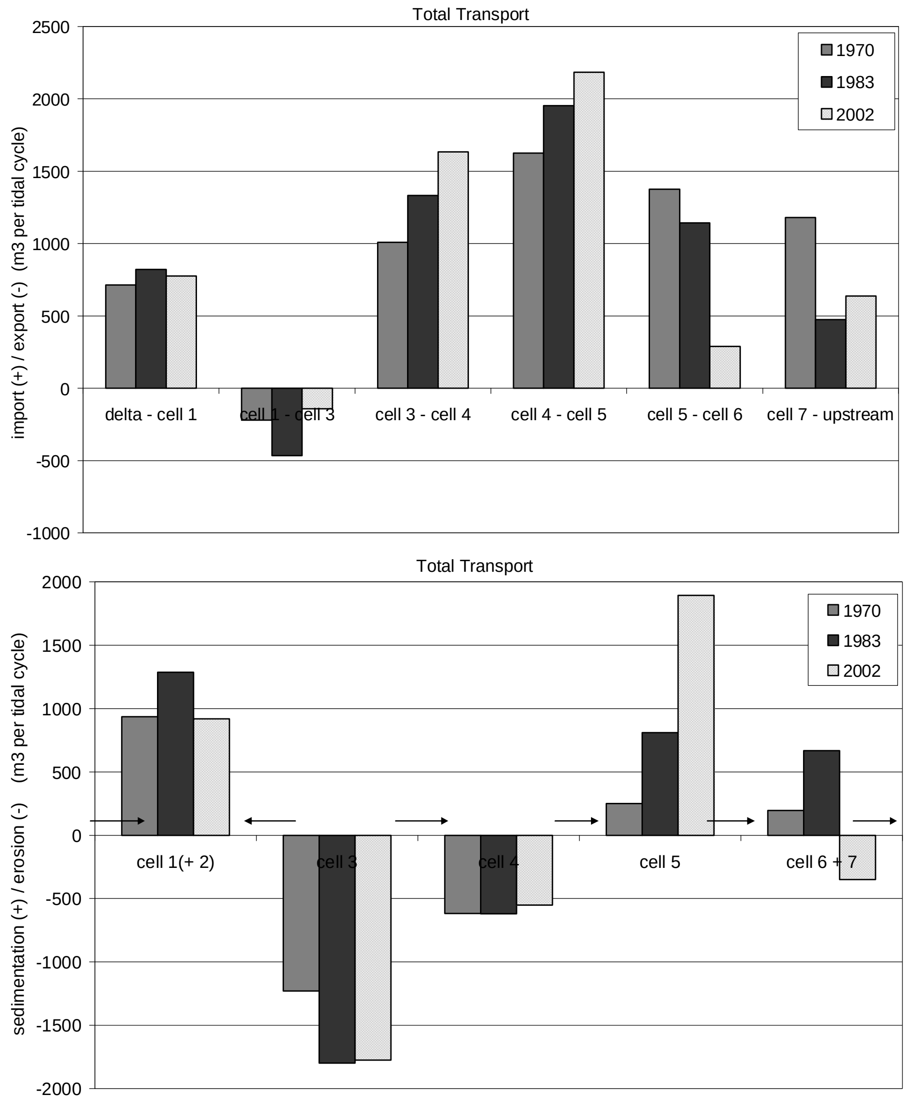

Figure A.15: Evolution of the sediment transport at the borders and the sedimentation/erosion in the macro cells from 1970 to 2002 for selection H of the cross-sections (= defined as in the main report).

Table 6-7 compares the sediment transport derived from the model for cases G and H. The comparison for the amounts of erosion or sedimentation in each macro cell is presented in Table 6-8. The difference between cases G and H is several times smaller than those between D, E, and F (See Table 6-5 and 6-6) which where based on the averaged transport of two cross-sections at each border.

Although there are still some differences between cases G and H, these selections show that the addition of another cross-section, or the choice of different cross-sections is less decisive for the final result as more cross-sections are included. Local irregularities are smoothened by the averaging over several cross-sections.

Table A.10: Sediment transported through a cross-section (m^3/tidal cycle) for the years 1970, 1983, and 2002 for the selections of cross-sections G and H.

Location	Year	G	H	Average	Standard Deviation	St. Dev. (% of average)
seaward border cell 1	**2002**	819	777	798	30	4
	1983	871	822	846	35	4
	1970	789	715	752	53	7
cell 1 - cell 3	**2002**	-143	-143	-143	0	0
	1983	-466	-466	-466	0	0
	1970	-221	-221	-221	0	0
cell 3 - cell 4	**2002**	985	1633	1309	458	35
	1983	1226	1333	1279	75	6
	1970	691	1009	850	225	26
cell 4 - cell 5	**2002**	2019	2184	2102	116	6
	1983	2240	1953	2096	203	10
	1970	1714	1626	1670	62	4
cell 5 - cell 6	**2002**	379	290	334	63	19
	1983	1318	1142	1230	125	10
	1970	1406	1376	1391	21	2
upstream border cell 7	**2002**	428	638	533	149	28
	1983	298	474	386	124	32
	1970	1007	1181	1094	123	11

Table A.11: Erosion (-) or sedimentation (+) in the macro cells (m^3/tidal cycle) for the years 1970, 1983, and 2002 for the selections of cross-sections G and H.

Location	Year	G	H	Average	Standard Deviation	St. Dev. (% of average)
cell 1+2	**2002**	962	919	940	30	3
	1983	1337	1287	1312	35	3
	1970	1010	936	973	53	5
cell 3	**2002**	-1128	-1776	-1452	458	-32
	1983	-1692	-1798	-1745	75	-4
	1970	-912	-1230	-1071	225	-21
cell 4	**2002**	-1034	-551	-792	342	-43
	1983	-1014	-620	-817	279	-34
	1970	-1023	-618	-820	286	-35
cell 5	**2002**	1641	1894	1767	179	10
	1983	922	810	866	79	9
	1970	308	251	279	40	14
cell 6+7	**2002**	-49	-349	-199	212	-106
	1983	1020	668	844	249	30
	1970	399	195	297	144	49

A.6.4 Conclusions

Regarding residual sediment transport determined from short-term simulations for one tidal cycle, selecting the transport through one single cross-section can highly influence the results. Between two subsequent cross-sections, not only the sediment transport magnitude can differ, but even the transport direction.

The results showed also that as more cross-sections are included, the final result depends less on the selection of the different cross-sections or the addition of another cross-section.

Therefore it is advisable to define a border area at the location of interest and to calculate the averaged transport through this area. In this way local irregularities will be smoothened and more general valid transport directions and magnitudes are obtained.

A.7 References

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B Influence of boundary conditions on the sediment exchange between Dutch Coast and the Western Scheldt

B.1 Introduction

In the framework of the study “Interaction between the long-term developments of the Dutch coast and the tidal basins Marsdiep and Western Scheldt” which is undertaken by WL|Delft Hydraulics in the Netherlands, and which is commissioned by the RWS National Institute for Coastal and Marine Management (RWS RIKZ), the objective is to gather and supply information, services and advice concerning the sustainable use of coasts and seas and the protection of the land against tidal flooding.

The Western Scheldt tidal basin is one of the most important basins along the Dutch Coast. Changes from import to export at the mouth was noticed in the nineties, inducing uncertainty about the future developments, and necessitating more detailed studies of this area. Among others, RIKZ of Rijkwatersaat commissioned a study concerning the exchange of sediment between the Dutch coast and the Western Scheldt (Bolle, 2006).

The study enabled to identify the mechanisms governing the import/export of sediments at the mouth of the Western Scheldt. Although the principal forcing factors in well mixed estuaries are the astronomical tide, the meteorological factors and the river flow (Wang et al., 1999), only the evaluation of the relative importance of the tide-driven sediment transports has been investigated. First of all, the part of the Western Scheldt between Rupelmonde and Hansweert is considered as partially mixed (Verlaan, 1998). Therefore the influence of density differences on the water movement and water levels is small (Technische Scheldecommissie, 1984) and has been neglected in the study. The importance of wind and waves has not been investigated, although they can contribute significantly to the transports in a tidal inlet (Elias et al., 2006).

In this previous study, the DELFT3D-model has been used to study the interaction between the bathymetry and the tide in the Western Scheldt. Three bathymetries have been used (1970, 1983 and 2002). The trends in the different parameters describing the tidal asymmetry were reproduced well enough to give confidence in the model results and to be able to compare them with other related data. However, the change from import to export at the mouth was not reproduced in the 2002 model. On the other hand, the increasing transport from west to east as found by Stikvoort et al. (2003) in the central part of the Western Scheldt was well represented in the model.

The non-ability of the model to reproduce the change from import to export at the mouth has been explained based on the following reasons:

- Insufficient accuracy in the forcing of the model. In the study irregularities in the water level upstream form Hansweert were found for the 1970 situation.
- Sediment transport due to interaction of the tide with the bathymetry isn’t representative for the residual sediment transport. Also non-tidal mechanisms such as estuarine

circulation, wind and waves can contribute significantly to the transports in a tidal inlet. These mechanisms haven't been included in the model for the study.

- The effect of human interventions might be underestimated and dominate over the natural changes.

Further simulations have been performed to address the first point, by calibrating the model boundaries again and, hence by improving the schematisation of the most upstream part. Results of these simulations are analyzed in this report.

Chapter 2 concerns are summary of the characteristics of the study area and of the insights given by previous studies. Chapter 3 describes the modeling approach (model and simulations undertaken). Finally, chapter 4 concerns the analysis of the results.

B.2 Study area

B.2.1 Characteristics

The total surface of the Western Scheldt basin (Figure B.1) is around 21000 km^2, from which 1000 km^2 is located on Dutch territory (Kramer, 2002).

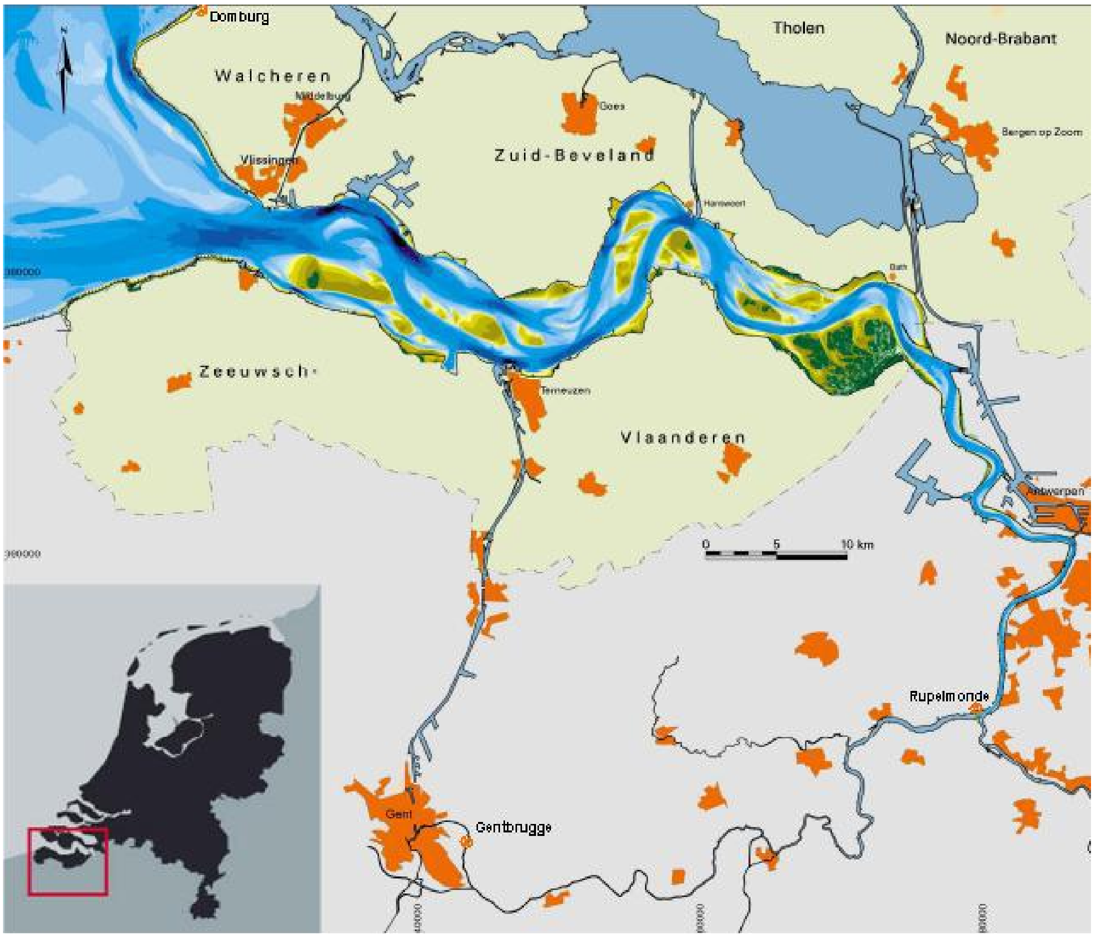

Figure B.1 The Scheldt estuary from Gent to the Western Scheldt mouth (after Groenendaal, 2005).

Hydrodynamics

The tides in the estuary are dominantly semi-diurnal. The tidal prism is in the order of 2.2 x 10^9 m^3 at Vlissingen, 0.2 x 10^9 m^3 at the Belgian-Dutch border and 0.1 x 109 m3 at Antwerpen (Verlaan, 1998). The mean tidal range increases between Vlissingen and Antwerpen from 3.8 to 5.2 m and decreases again to 1.9 m near Gent. The vertical tide is asymmetric and flood-dominant. This effect increases going upstream: the ratio between the rise and fall time of the tidal wave decreases from 0.88 at Vlissingen to 0.75 at Rupelmonde and 0.39 at Gent (Kuijper et al., 2004). Describing the hydrodynamic characteristics of the mouth, Dumon et al. (2006) noticed that the measured tidal amplitudes at sea are smaller than those in the Western Scheldt, which confirms the theory of the amplification of the tide in a funnel shaped estuary. Kornman et al. (2000) noticed an increase of the tidal range in the mouth of 4% per century. This is possibly caused by the combination of sea level rise, the interventions related to the Delta-plan and/or the anthropogenic impact within the Western Scheldt estuary (Dumon et al, 2006).

The mean river outflow is about 120 m^3/s or 5 x 10^6 m^3 of water per semi-diurnal tide. This is less than 1% of the tidal prism of about 2 x 109 m3 (Wang et al., 2002). Therefore the influence of density differences on the water movement and water levels is small (Technische Scheldecommissie, 1984).

The wave height and the wave period decrease eastwards along the Western Scheldt. Whereas at the most seaward location (Schouwenbank which is located 25 km northwest from Domburg) the mean wave height is 1.1 m, the remaining wave height at Bath is only 20% of this value. The wave period decreases from around 4 to 5 seconds at the seaward end to around 2 seconds near Bath (Gautier and Van De Boomgaard, 2003). The hydrodynamic characteristics of the mouth were recently described by Dumon et al. (2006). They analysed the data from the measurement networks “Meetnet Vlaamse Banken” from the Flemish government and “Zege Meetnet” from Rijkswaterstaat in the Netherlands.

Concerning the wind, Dumon et al. noticed that on the Vlakte van de Raan 40% of the time the direction is S-SW to SW-W. Also the highest wind speed comes from these directions. The eastern sector is the most unusual direction. The wind speed is significant higher at sea: at Westhinder the wind speed can be the double compared to Zeebrugge. Also the average wind speed on the Vlakte van de Raan is lower than at locations more to the north. This is explained by the orientation of the coastline which makes the wind from the most important S and SW directions to be more disturbed near the coast than at sea.

Morphologies

The Western Scheldt is a coastal plain estuary in the classical sense: the estuary is tide-dominated with a meso- to macro-tidal regime according to the classification of Dyer (1997). It has a funnel-shaped geometry, where the estuarine width reduces from about 6 km near the mouth, via 2-3 km near Bath to less than 100 m near the estuary head. The width-averaged depth decreases from 15 m at Vlissingen to only 3 m near Gent (Wang et al., 2002).

The meandering channel system of the Western Scheldt shows a regular repetitive pattern of ebb and flood channels. Van Veen (1950) classified this as a braided pattern. Lateral boundaries are formed by dikes and bank-protection measures. Bars are found at the seaward side of the ebb channels and at the landward side of the flood channels. The major transport occurs in the main ebb and flood channels. Winterwerp et al. (2000) used a chain of macro-cells (ebb- and flood channels) and meso cells (connecting channels) to schematize the channel system. In the Western Scheldt mouth the "Scheur/Wielingen" is clearly the main channel and is east-west directed. Another important channel is the "Oostgat" which shorts the Western Scheldt and the North Sea. The function of the shoal area the Raan as breakwater is very important for the coast behind and the entrance of the Western Scheldt (Dumon et al., 2006). The Raan forms a buffer between the sea climate and the Western Scheldt mouth, and weakens the incoming hydrodynamic patterns (waves and currents). Over the shoal area no dominant current direction is present.

Morphological changes

The Western Scheldt evolved from the Honte, a tidal channel which has been expanding landward since the early middle Ages. It gradually took over the function of the Eastern Scheldt which was the original mouth of the river Scheldt. In the 14^{th} century the Western Scheldt had scoured enough to become the new shipping route to the port of Antwerpen. In the 17^{th} century, the Western Scheldt had become a large tidal basin. During the following centuries the connections with the Eastern Scheldt and the large branches along the southern shore of the estuary silted up and were consecutively dammed in the 19^{th} and 20^{th} century. From 1800 to 1997, the channels Wielingen and Spleet evolved to one main channel: Scheur. The channel of the Walvisstaart became wider and more important. These changes are related to the evolution of the channels and shoals in the western part of the Western Scheldt, which determine the direction of the ebb-tidal flow as described by Peters (2006). The intertidal storage decreased from 295 km^2 in 1650 AD to 104 km^2 in the recent Western Scheldt (van der Spek, 1997). The configuration of the main ebb and flood channels remained unaltered in most locations since approximately 1930. However a general steepening of the bathymetry is noticed since 1955. This is indicated by the increases of the shoal area (+20% or 800 ha between 1955 and 1980) and the decrease of the sub-tidal area (-35% between 1955 and 2002) (Kuijper, 2004). Upstream of Antwerpen the geometry of the estuary remained stable. Nowadays the Western Scheldt resembles a classical funnel shaped estuary. The "Verdronken land van Saefthinge" is the only remaining substantial intertidal marsh (van der Spek, 1997).

The morphologic changes in the mouth and in the estuary are also related to a lot of different factors of which the tides, the geology and the human interventions are the most important (Peters, 2006). Apart from almost continuous dredging, dumping and sand mining in the estuary, bank protection measures have been placed at the border of a number of channels (Peters et al., 2003). The morphological evolution of the mouth is also affected by human interventions. The expansion of the port of Zeebrugge (1972-1985), with the construction of the breakwaters and the dumping of large amounts of dredged material northwest of the Vlakte van de Raan, has certainly an influence on the estuarine dynamics although the exact impact can hardly be estimated (Peters, 2006; Port of Zeebrugge, 2006). Also other edifices such as the delta-plan with the storm-surge barrier on the Eastern Scheldt (build between 1976 and 1986) have possibly affected the Western Scheldt mouth area.

B.2.2 Previous studies

Nederbragt and Liek (2004) concluded from their sand balance study that, since 1955, alternating periods with sand import and export occur. The Western Scheldt became exporting since the 90's from the previous century. On average, the export was 1.5 Mm^3/year over the period 1990-2001. The sediment transport from the east to the west has increased since 1997. The Western Scheldt combined with the mouth also shows an exporting trend over the period 1990-1996.

Duin (2005) performed a trend analysis on the data from the sand balance from Walburg (2006). He found that both the Western and the Eastern Scheldt delta show a significant erosion trend (due to natural transports) over the period 1973-1997 of respectively 2.7 and 1.1 Mm^3/year. Recently the sand balance of the Western Scheldt has been updated by Haecon (2006). They expanded the previously developed sand balance model of Nederbragt and Liek (2004) on the landward side with the Sea Scheldt to Rupelmonde and on the western side with the area between Zeebrugge and the Western Scheldt mouth. They included all data for the period 1955-2004. Their sand balance of the Sea Scheldt shows that the assumption in the previous balances of no transport across the Belgian-Dutch border is not valid. Between 1955 and 2004 a yearly import in the Sea Scheldt of 1.1 million m^3 occurs, although there is a strong fluctuation. By considering the transport towards the Sea Scheldt, the change from import to export near Vlissingen takes place several years later (in 1997) compared to the previous balance (in 1990). This agrees with the findings of Nederbragt and Liek (2004).

The import/export of sediment near Vlissingen is presumably a natural reaction of the estuarine system on a number of factors: the modified dumping strategy and the further deepening of the navigation channel by which the current and transport patterns can be influenced (Haecon, 2006). Jeuken et al. (2004) suggest that the change from sand-importing to sand-exporting system has its origin in the western and central part of the Western Scheldt. An explanation for this change is yet unknown, but possibly the cut-off around 1950 of the channel bend in the central part (near Hansweert) and the displacement of the navigation channel from the ebb towards the flood channel around 1980 have influenced this process (Kuijper et al., 2004). The exchange may be further affected by the change in sand mining, dredging and dumping strategy since 1998 (Dauwe, 2001):

- dredging in both eastern and western parts of the Western Scheldt
- relocation of the sand mining activities from the western to the eastern part
- limitation of the dumping locations in the eastern part and expansion of the dumping locations in the western part.

B.3 Modelling approach

B.3.1 The model

The two-dimensional, depth averaged hydrodynamic model of the Western Scheldt used in this study, has been derived from the Kustzuid model within the framework of the study "Long-term vision Scheldt estuary" (Winterwerp et al., 2000) as described by van der Kaaij et al. (2004). The utilised software is DELFT3D (WL|Delft Hydraulics, 2005). The model includes the lower Sea Scheldt downstream from Rupelmonde, the Western Scheldt, and the

Voordelta which is the Western Scheldt mouth region. A curvilinear grid has been applied (Figure B.2). The dimensions from the grid cells vary between 800x800 m^2 at the open sea to 150x250 m^2 within the estuary. In this way a high computational efficiency is obtained by prescribing a high resolution in the area of interest, in combination with a low resolution far away at the open model boundaries (Kuijper et al., 2004).

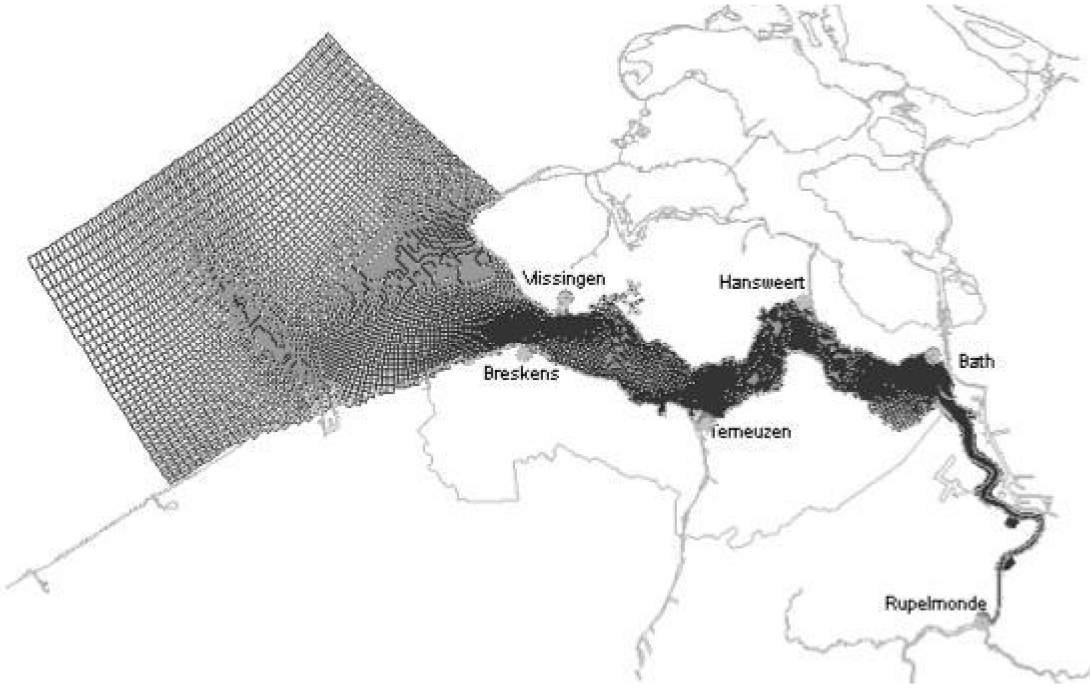

Figure B.2 Morphologic, curvilinear grid of the Western Scheldt model in DELFT3D.

The open sea boundaries of the model are forced by means of Riemann boundary conditions, i.e. a combination of water levels and velocities. At the open river boundary near Rupelmonde discharges are prescribed. The bed friction is taken from the Scalwest model and is expressed as a Manning roughness with values varying between 0.02 and 0.04 $s/m^{1/3}$ (Kuijper et al., 2004). The sediment grain size is taken uniform at 0.2 mm which is representative for the medium to fine sands in the Western Scheldt (Wang et al., 2002).

The calibration and verification of the hydrodynamic and morphodynamic model are described by van der Kaaij et al. (2004) and Kuijper et al. (2004). The calibration of the hydrodynamic model was carried out for the years 2000, 2001 and 2002 with the bathymetry of the year 2001. Water level, velocity and discharge measurements are used for the calibration over the period 19-21/06/2000. For the verification of this model the year 1972 was selected, which is during the first deepening of the navigation channel. The bathymetry was adapted to the 1972 situation and time series for the boundary signal at both the sea and river boundary where constructed based on tidal predictions. The roughness schematisation has been kept the same as during the calibration. During the calibration of the morphodynamic model Kuijper et al. (2004) selected a morphological tide in such a way that during ebb and during flood the computed sediment transport through a cross-section near Vlissingen is similar to the average ebb and flood transport for a complete spring-neap tidal cycle. They found that the computed bed level changes where almost identical compared to the runs with an entire spring-neap cycle.

B.3.2 Simulations

The tidal asymmetry inside the estuary is influenced by the asymmetry of the tide at the seaward boundary of the estuarine system (Dronkers, 1986, 1998; van der Spek, 1997). It is likely that the asymmetry of the vertical tide at a certain station is influenced by the asymmetry of the tide in the section downstream (Wang et al., 2002).

Therefore model runs have been performed with modified boundary conditions. The separate influence of 25 and 50% increase of the amplitude of the M_2, M_4 and M_6 tidal constituents and the phase of M_4 and M_6 can be deducted from these simulations. The model settings for all the different runs are shown in Table B.1. An overview of the different runs with the modified boundary conditions is given in Table B.2.

The reference situation is model run 18, which is the Western Scheldt model with the bathymetry of the year 2002 and the morphological tide with duration of 25 hours as selected by Kuijper et al. (2004). The applied transport formulation is Van Rijn (2003) and morphological update is performed during the simulation (morphological factor set to 1.0).

Table B.1 Model settings for the simulations with the modified downstream boundary conditions.

Model settings	
Simulation time step	1 minute
Simulation period	4 days
Output history	every 10 minutes during the entire simulation period
Output map file	every 10 minutes during 1 tidal cycle
Sediment transport formulation	Van Rijn (2003)
Morphological factor	1
Observation points	measurement stations and points along the ebb and flood channels
Boundary conditions - upstream - downstream	 - discharges, harmonical boundary conditions - harmonical boundary conditions as before, however now with varying amplitudes and phases for M_2, M_4 and M_6 in the different runs

Table B.2 Overview of the different model runs with the modified downstream boundary conditions.

Overview of the simulations						
Run ID	**Harmonical constituents at the downstream boundary**					
	M_2		**M_4**		**M_6**	
	Amplitude	**Phase**	**Amplitude**	**Phase**	**Amplitude**	**Phase**
18	reference situation		reference situation		reference situation	
20	+25%	ref.	ref.	ref.	ref.	ref.
21	+50%	ref.	ref.	ref.	ref.	ref.
22	ref.	ref.	+25%	ref.	ref.	ref.
23	ref.	ref.	+50%	ref.	ref.	ref.
24	ref.	ref.	ref.	ref.	+25%	ref.

25	ref.	ref.	ref.	ref.	+50%	ref.
26	ref.	ref.	ref.	+25%	ref.	ref.
27	ref.	ref.	ref.	+50%	ref.	ref.
28	ref.	ref.	ref.	ref.	ref.	+25%
29	ref.	ref.	ref.	ref.	ref.	+50%
ref. = reference situation (identical to the settings of run 18)						

B.4 Results

This chapter discusses the influence of the modified boundary conditions on the tide-driven sediment transports. The first part intends to describe the residual (tidally-averaged) transports over different sections of the Western Scheldt. The second part describes the residual main sediment transport directions in the estuary together with the erosion/sedimentation in the different macro cells as determined in the sand balance derived from the model. This leads to conclusions about the contribution of the tide-driven sediment transport to the import/export of sediments at the river mouth.

B.4.1 Methodology

Using the formulation of Van Rijn (1993), the computation of the sediment transports enables the description of the residual transport patterns. The transport rates are computed as the integral of the instantaneous transport over one tidal cycle, and thus corresponds to the difference between the ebb- and flood-transport, ie. the tidally-averaged component. This is calculated directly with DELFT 3D for one morphological tide. Only the tide-driven sediment transport is computed, since no wind, waves or density currents are taken into account.

The sand balance derived from the model in this study quantifies the erosion and sedimentation of sand under influence of the tide-driven sediment transport occurring for the 2002 bathymetry. For this balance the Western Scheldt division into macro cells (Winterwerp et al., 2000) is used with a few adaptations (Figure B.3): macro cell 1 and meso cell 2 form one entity, as well as macro cells 6 and 7. The latter entity is formed because it is not possible to define cross-sections between these two cells to determine the sediment exchange between them due to the orientation of the grid in this part of the Western Scheldt.

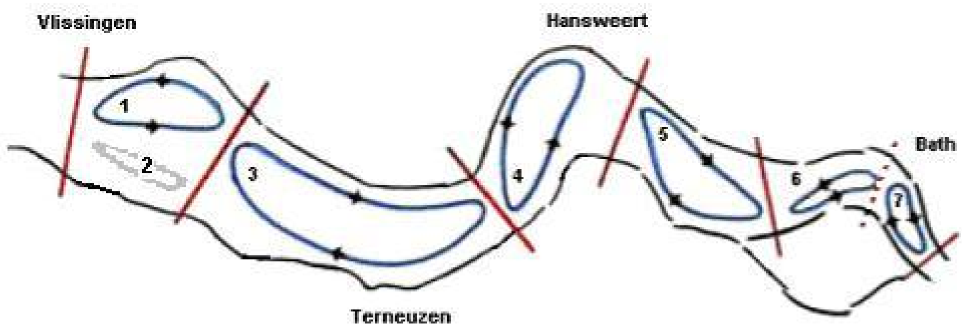

Figure B.3 Division of the Western Scheldt in cells for the sand balance. The blue loops are macro cells, the grey one is a meso cell. The red full lines represent the borders between the compartments used in the sand balance (Schematical representation after Nederbragt and Like, 2004).

The volume change within a compartment during one tidal cycle is calculated as follows:

$$\Delta V = V_{sb} - V_{lb}$$

where V_{sb} = the volume sediments passing through the seaward cell boundary during one tidal cycle (in m^3)
V_{lb} = the volume sediments passing through the landward cell boundary during one tidal cycle (in m^3)
ΔV = the volume change within the cell during one tidal cycle (in m^3)

Landward transport is counted positive, seaward transport negative. Therefore erosion will be represented by a negative volume change and sedimentation by a positive value. Calculating the sand balances using the transport between macro cells through different cross-sections representing a cell boundary can give different values. For that reason, the averaged transports through 3 different sets of single cross-sections between the macro cells are computed. The selected cross-sections for cases A, B, and C are shown on Figure B.4 and summarised in Table B.3.

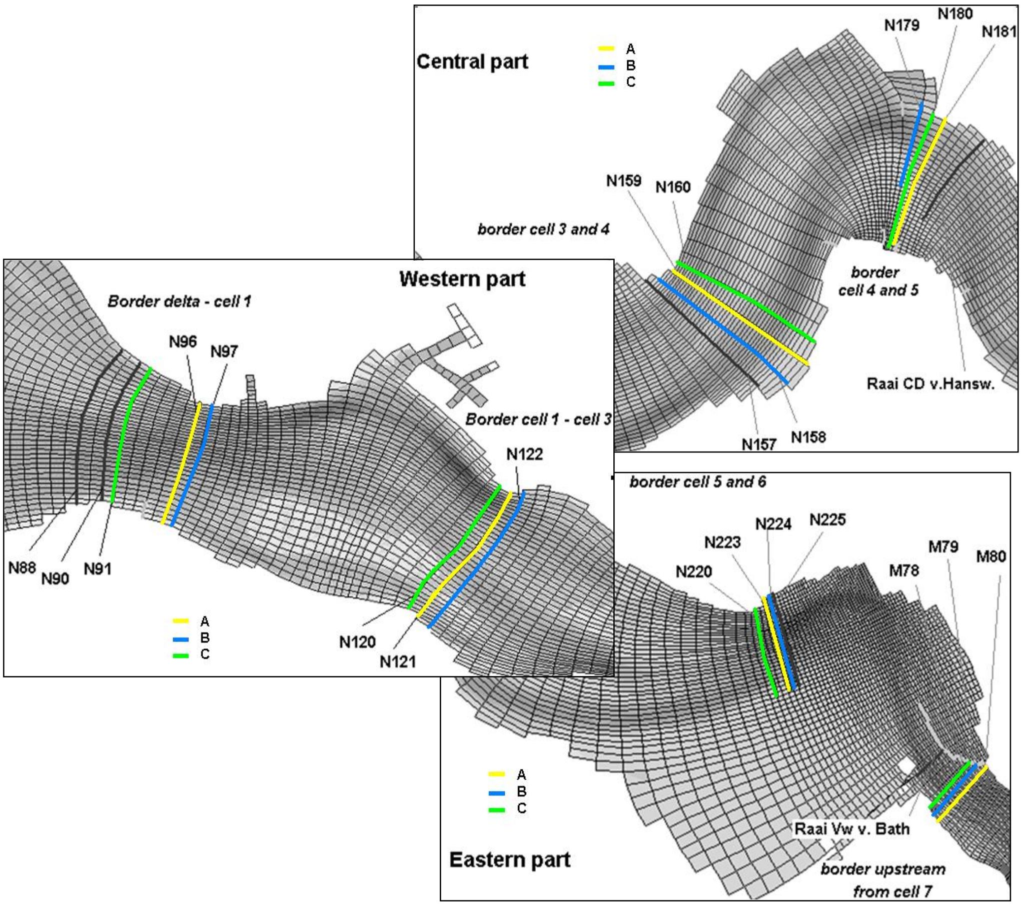

Figure B.4 Location of the cross-sections in the Western Scheldt.

Table B.3 Selected cross-sections in the model for the sand balances A, B and C.

Location	A	B	C
seaward border cell 1	N96	N97	N91
cell 1 – cell 3	N121	N122	N120
cell 3 – cell 4	N159	N160	N158
cell 4 – cell 5	N181	N180	N179
cell 5 – cell 6	N223	N224	N220

upstream border cell 7	M80	M79	M78

B.4.2 Analysis

Sediment transports are computed for one ebb-flood cycle. Erosion and sedimentation volumes are deduced from the transport rates obtained between the cells.

Total transports

Based on Test 18 (reference run with no modified boundary conditions and transport formulation from Van Rijn, 1993), the sand balance exhibits an import pattern at the mouth, as shown on Figure B.5. Sedimentation occurs in cells 1+2, because of transports directed from both the mouth and from the cell 3. Eastwards, the Western Scheldt exhibits an importing pattern. This transport from west to east was described by Stikvoort et al. (2003) as increasing in the central part of the Western Scheldt during the last decades, and is well represented in the model. On the other hand, the export of sediments at the mouth, described by Stikvoort et al. (2003), is not reproduced by the model. However, Bolle (2006) showed that the modelled import from the mouth towards the cell 1 is smaller in 2002 compared to the other two years. A high variability is noticed considering the different sets A, B, C of cross-sections.

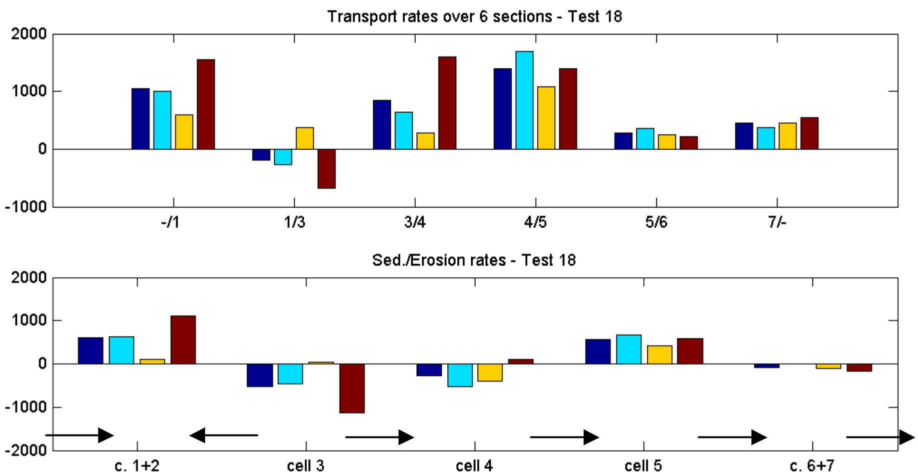

Figure B.5 (a) Transport rates over the cross-sections delimiting the studied cells. A positive value denotes an eastward transport, whereas a negative value denotes a westward transport. For each section, rates are plotted for the set A (light blue), B (yellow) and C (red). The main value is also plotted (dark blue). (b) Sedimentation/erosion rates in the cells of the Western Scheldt for the same selected sets of cross-sections.

Figure B.6 and Figure B.7 describe the cumulative- (ebb-flood cycle) sediment transports obtained for Test 20 to 29 over different cross-sections. All runs exhibit an import behaviour from the middle of Western Scheldt to the landward direction, i.e. over sections 3/4, 4/5, 5/6 and 7/upstream. Modification of the M4 and M6 components of the boundary conditions do not induce significant changes over these cross-sections, whereas increased transports are associated with modification of the amplitude of the M2 component (Test 20 and 21). In the mouth (delta to cell 3), modification of the boundary conditions induces more changes as described in Figure B.7. Over the section delta/cell 1, modification of the amplitudes of the M4 and M6 components influence slightly the sediment transports. Still, significant changes are noticed when modifying the amplitude of the M2 component. Results depend strongly on the selected set of cross-sections. This is particularly the case for Tests 20 and 21 where a high variability is noticed in the mouth (from the delta to the cell 4) between set B and set C. Moreover, differences are systematic over the cross-section 1/3, with eastward and westward transports for sets B and C, respectively.

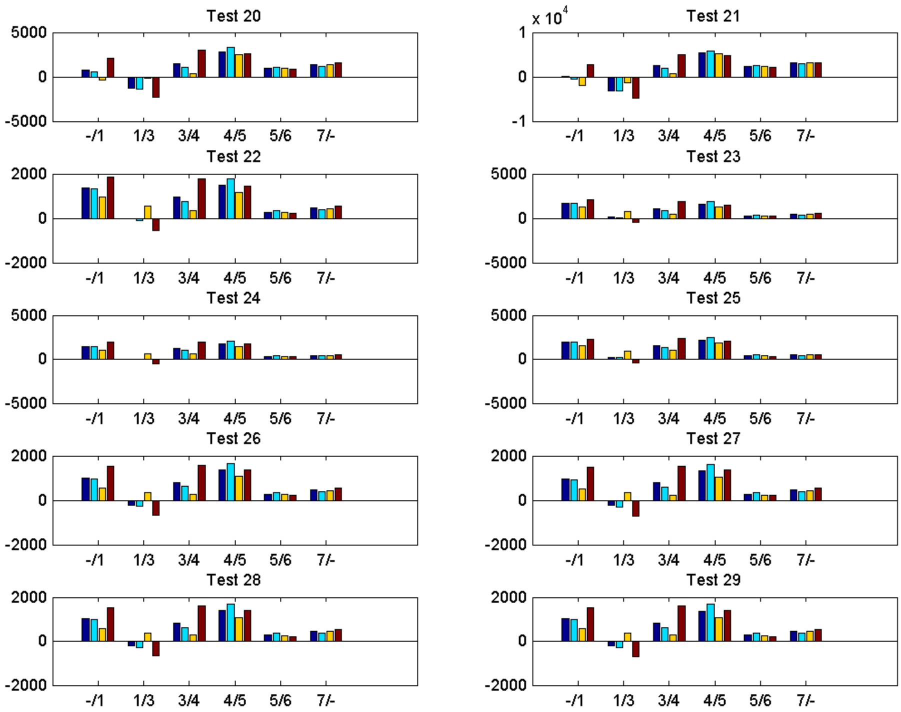

Figure B.6 Transport rates over different cross-sections plotted for Test 20 to Test 29.

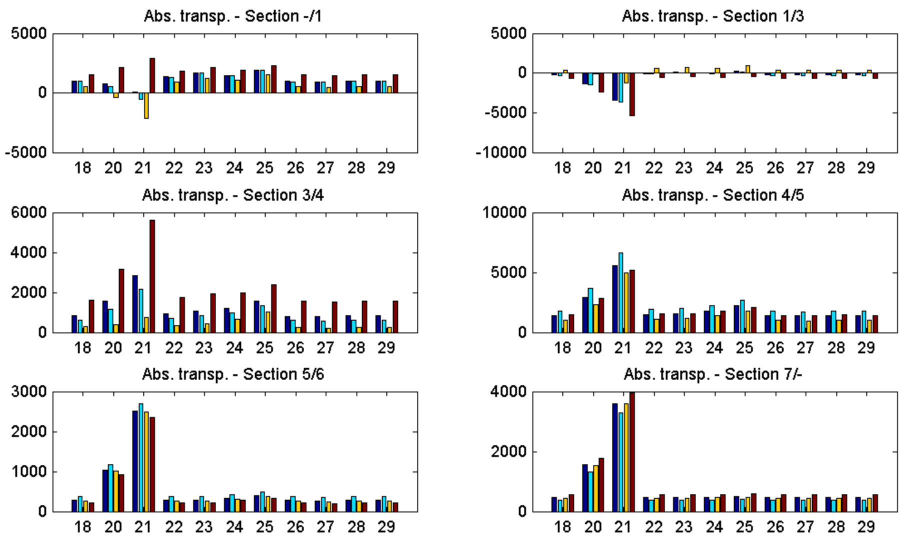

Figure B.7 Transport rates for Test 20 to Test 29 plotted over different cross-sections.

Figure B.8 describes the sedimentation/erosion patterns in the cells dividing the Western Scheldt (Figure B.3). For all Tests 20 to 29, the trends reproduce generally the results obtained with Test 18. Erosion is noticed in cells 3 and 4, whereas sedimentation occurs in cells 1+2 and 5. Cell 6+7 remains stable. Based on the sediment transports description, an import pattern is deduced for Test 22 to 29. Similar trend is obtained for Test 20 and 21, considering results obtained with the delimiting set C of cross-sections. On the other hand, export of sediments is obtained for these 2 Tests, when considering the set B of cross-sections. Only an increase of 50% of the amplitude of the M2 component (Test 21) is associated with an export trend, when considering set A.

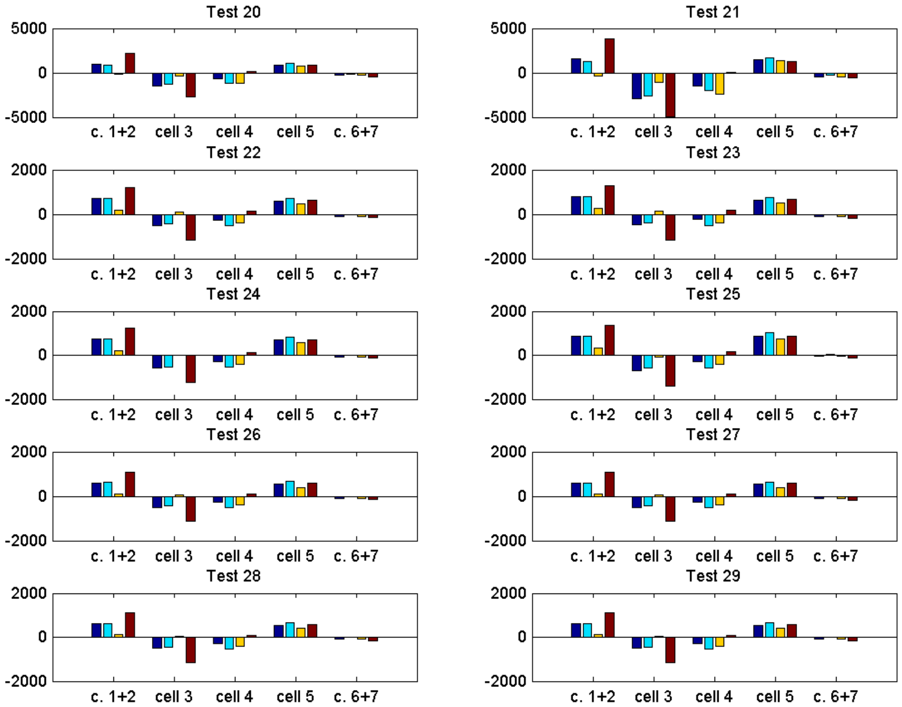

Figure B.8 Evolution of the sedimentation/erosion in the cells for the selected set of cross-sections A (light blue), B (yellow) and C (red). Averaged values are plotted in dark blue). Results are shown for Test 20 to 21.

Bed-load transports

The local residual sediment transport is directly related to the asymmetry of the horizontal tide. Van de Kreeke and Robaczewska (2003) found that the long-term mean bed-load transport is determined by the flow velocities associated with M_0, M_2 and its overtides M_4 and M_6. The tidally-averaged bed load transports express therefore the tendencies induced by the horizontal tidal asymmetry. Considering only the bed-load transports, Figure B.9 and Figure B.10 show that sediment export occurs at the mouth for Test 20 and Test 21. Using another approach than the Van Rijn formulations, by expressing the total transport based on a bed load formulation, an export trend can therefore be expected at the mouth when increasing the amplitude of the M_2 component about 25% and 50%.

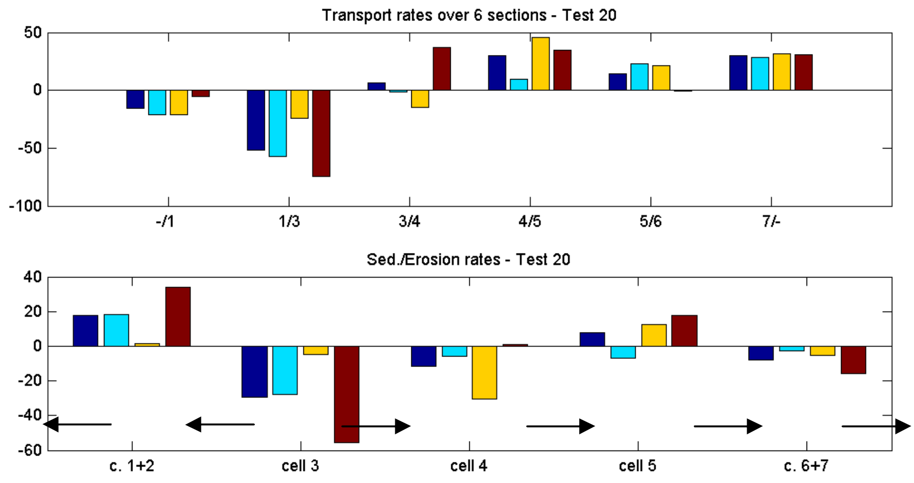

Figure B.9 (a) Bed load transport rates over the cross-sections delimiting the studied cells. A positive value denotes an eastward transport, whereas a negative value denotes a westward transport. For each section, rates are plotted for the set A (light blue), B (yellow) and C (red). The main value is also plotted (dark blue). (b) Sedimentation/erosion rates in the cells of the Western Scheldt for the same selected sets of cross-sections (as shown in Figure B.8).

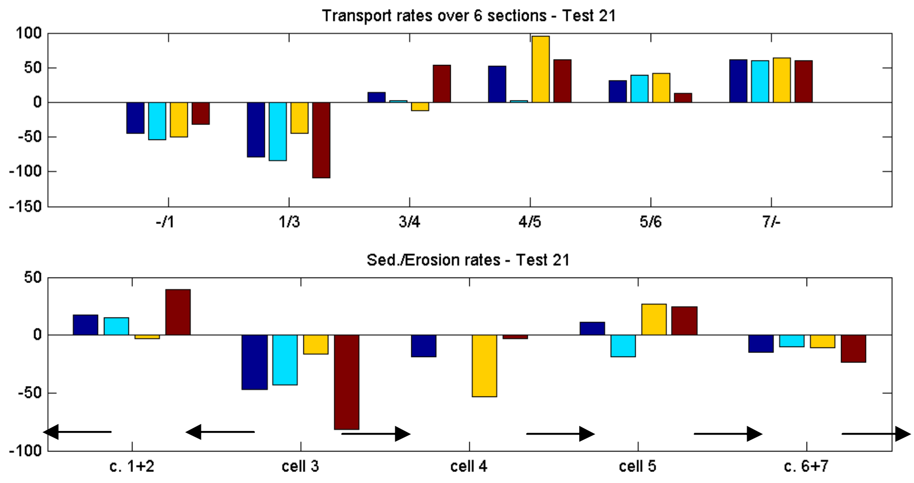

Figure B.10 (a) Bed load transport rates over the cross-sections delimiting the studied cells. A positive value denotes an eastward transport, whereas a negative value denotes a westward transport. (b) Sedimentation/erosion rates in the cells of the Western Scheldt.

B.5 Conclusions

The DELFT3D-model has been used to study the interaction between the bathymetry 2002 and the tide in the Western Scheldt. Using three bathymetries (1970, 1983 and 2002), Bolle (2006) showed that the trends in the different parameters describing the tidal asymmetry were reproduced well enough to give confidence in the model results. However, the change from import to export at the mouth was not reproduced in the 2002 model. The non-ability of the model to reproduce the change from import to export at the mouth can be explained by an insufficient accuracy in the forcing of the model. In particular, Bolle (2006) found irregularities in the water level upstream form Hansweert. Further simulations have been performed, by calibrating the model boundaries (modification of amplitudes and phases of M2, M4 and M6 components).

Analysis of the results showed:

- Modification of the boundary conditions induce significant changes of the sediment transports in the mouth (over sections -/1 and 1/3), whereas no influence is noticed in the upstream part (from section 3/4 to 7/upstream) in comparison to Test 18.
- Significant changes are noticed only in the mouth (over sections -/1 and 1/3) when modifying the amplitude of the M2 component.
- The model is not able to reproduce the export trend when modifying the amplitudes and the phases of the M4 and M6 components in the boundary conditions.
- Export pattern is obtained only for Tests 20 and 21 (increase of 25% and 50%, respectively, of the amplitude of the M2 component), when considering the set B of cross-sections. With the selected set A, an export pattern is obtained only for Test 21.
- Results depend strongly on the selected set of cross-sections.
- Export/import trend are influenced by the choice of the sediment transport formulation.

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WL | Delft Hydraulics

Rotterdamseweg 185
postbus 177
2600 MH Delft
telefoon 015 285 85 85
telefax 015 285 85 82
e-mail info@wldelft.nl
internet www.wldelft.nl

Rotterdamseweg 185
p.o. box 177
2600 MH Delft
The Netherlands
telephone +31 15 285 85 85
telefax +31 15 285 85 82
e-mail info@wldelft.nl
internet www.wldelft.nl