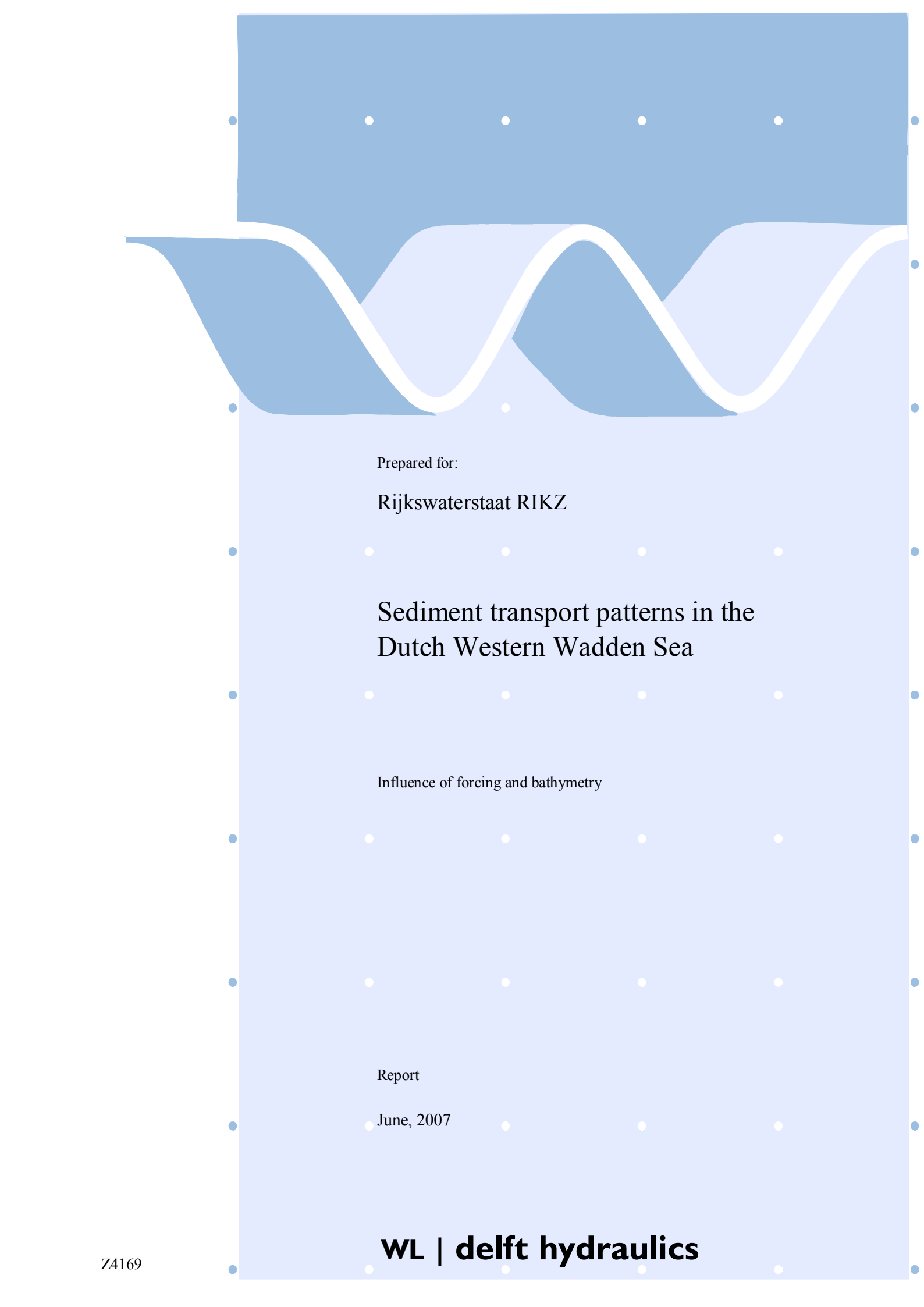




Prepared for:

Rijkswaterstaat RIKZ

Sediment transport patterns in the Dutch Western Wadden Sea

Influence of forcing and bathymetry

Report

June, 2007

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Rijkswaterstaat RIKZ

Sediment transport patterns in the Dutch Western Wadden Sea

MSc thesis

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Report

June, 2007

Preface

In this report the results of my master thesis are presented. The topic of the thesis is the sediment transport patterns in the Dutch Western Wadden Sea, and how it responds to different forcing agents and bathymetric adjustments. It is carried out as a part of the larger project “Interactie tussen de lange termijn ontwikkelingen van de Nederlandse kust en de getijdebekkens Marsdiep en Westerschelde”, in which the sand demand of the inlet systems of the Netherlands is investigated. This thesis is the conclusion of my study at the Delft University of Technology, at the faculty of Civil Engineering. The research is carried out at WL| Delft Hydraulics, which is gratefully acknowledged for allowing me to perform my thesis there.

The people I would like to thank the most are my supervisors: Prof.dr.ir. H.J. de Vriend, Dr.ir. Z.B. Wang, Dr. H.M. Schuttelaars, Ir. J. de Ronde and Dr.ir. E.P.L. Elias. Their guidance, knowledge and critics were very valuable during my research. Furthermore I would like to thank numerous people from WL| Delft Hydraulics, who were always willing to help me with my questions.

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Last but not least, many thanks to my parents, brother and friends, for all the good times I had as a student in Delft.

Delft, June 2006

Robert-Jan van de Waal

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Summary

The coastline of Holland, which consists of beaches and dune formations, suffers erosion of sand. This sand is lost to the Wadden Sea, which is located north of the Holland coast. The Wadden Sea consists of tidal basins that are connected to the North Sea via tidal inlets. It has a shortage of sediments, and as a consequence sediments are subtracted from the beaches of the barrier islands and Holland coast. As a counteraction to the erosion, the Dutch government has set a basal coastline. Every year measurements are carried out, and when the coastline has retreated beyond this basal coastline, beach nourishment is applied.

To get insight in the needed amount of beach nourishment, a better understanding of the morphodynamic processes that drive the sediment imports to the basins is required. The objective of the “Interactie tussen de lange termijn ontwikkelingen van de Nederlandse kust en de getijdebekkens Marsdiep en Westerschelde” project is to determine the total sand demand of the different coastal inlet systems in the Netherlands. The focus is on the most southern inlet, the Western Scheldt, and the Western Wadden Sea, comprising the inlets of Texel, Eierlandse Gat and Vlie. This thesis deals with an aspect of the project, viz. the analysis of the reaction of the sediment transport patterns in the Western Wadden Sea to different forcing agents and to bathymetric adjustments. The sediment transports are simulated with the process based modelling program DELFT3D, which is developed by WL| Delft Hydraulics.

The influence of three forcing agents is investigated: tidal, wave and wind forcing. In case of the tidal forcing, the interaction of the moon and the earth has the largest influence on the sediment transports. When a spatially constant median grain size $D_{50}=250\mu\text{m}$ is applied, through the Texel inlet sediment is imported, approximately $2500 \cdot 10^3 \text{m}^3/\text{yr}$. Through the inlets of the Eierlandse Gat and Vlie a residual export of sediment takes place, respectively $600 \cdot 10^3 \text{m}^3/\text{yr}$ and $2000 \cdot 10^3 \text{m}^3/\text{yr}$. The exports through these inlets predominantly take place in the ebb-channels.

The height and angle of incidence of the waves are important parameters considering the sediment transports. The response of these transports to the wave forcing is most distinct on the ebb-tidal delta region. There most of the wave energy is dissipated. The effect of wave forcing is limited in the basins. Due to the orientation of the inlets, the angle of incidence affects the rate of sediment import. Southwestern waves are most effective, considering the import through the Texel inlet. The waves from this angle increase the transport from the Holland coast towards the inlet. The Vlie inlet is most exposed to waves coming from the north and northwest. Subsequently the response of the sediment transports through this inlet is largest to waves coming from these directions. Waves induce extra import around the tips of the barrier islands. The magnitude of the sediment transports induced by wave forcing is of the same order of magnitude as the transports induced by tidal forcing. A wave with $H_s=1\text{m}$ from the northwest already counteracts the export of sediments through the Vlie inlet induced by tidal forcing. When the wave height (from the northwest) is increased, the imports through this inlet increases considerably, to as much as $\pm 6000 \cdot 10^3 \text{m}^3/\text{yr}$ in case of waves with $H_s=4\text{m}$ (storm waves).

The wind forcing is made up of two parts: large-scale wind forcing and local wind forcing. The large-scale wind forcing implies a water level set-up in the whole Western Wadden Sea. This water level set-up is caused by the shape of the North Sea. Depending on the angle of the wind, water is pushed towards (thus generating a set-up) or pushed away from the

Wadden Sea (thus generating a set-down). As a result of the orientation of the North Sea, southwestern to northern wind generally induces a water level set-up. Wind from other directions generally induces a set-down of the water level. The tidal prism that flows through the inlets is affected by the change in water level. A water level set-up increases the storage area of the basins, and subsequently the prisms are enlarged. In case of a set-down of the water level the storage area is decreased, as well as the tidal prisms. The magnitude of the deflection of the water level depends on the intensity of the wind forcing.

The water level set-up induced by the large-scale wind forcing is not spatially constant. It varies in the Wadden Sea, and this variance causes a residual flow between the basins. The magnitude of this residual flow is of the same order of magnitude as the residual flow induced by the tidal forcing.

The local wind forcing creates both a set-up and currents. The combination of the local wind forcing induced flow together with the flow generated by the large-scale water set-up creates a residual flow that is of the same magnitude as that generated by tidal forcing. The sediment transports through the inlets show a distinct reaction to the addition of wind forcing. For instance, in case of a storm winds originating from the northwest the magnitude of the residual ebb-discharges through the Texel inlet is approximately tripled ($6041\text{m}^3/\text{s}$ compared to $1957\text{m}^3/\text{s}$ induced by tidal forcing). As a consequence, the transport through the Texel inlet has changed from an import of $2417 \cdot 10^3\text{m}^3/\text{yr}$ to an export of $2382 \cdot 10^3\text{m}^3/\text{yr}$. With the same forcing, the large sediment import takes place through the inlets of the Eierlandse Gat and Vlie ($6500 \cdot 10^3\text{m}^3/\text{yr}$ and $14747 \cdot 10^3\text{m}^3/\text{yr}$).

For the determination of the bathymetric influence, a meteorological climate is constructed that represents the average annual forcing. As tidal forcing, the M_2 , M_4 & M_6 are prescribed at the boundaries of the model.

The bathymetry of the year 1998 is taken as a reference. The tidal and meteorological forcing induce an import in the Western Wadden Sea of $6306 \cdot 10^3\text{m}^3/\text{yr}$. For the Texel inlet the import is $3810 \cdot 10^3\text{m}^3/\text{yr}$, for the Eierlandse Gat inlet $664 \cdot 10^3\text{m}^3/\text{yr}$ and for the Vlie inlet $1908 \cdot 10^3\text{m}^3/\text{yr}$.

To investigate the influence of the ebb-tidal deltas, they are removed. As a consequence the inlets are more exposed to the incoming waves. In the Texel inlet, this results in an increase of the tip of the island of Texel. In the Vlie inlets, the export through the ebb-channel is increased to counteract the loss of sediment on the ebb-tidal delta. The effect of the removal of the ebb-tidal deltas is local. Inside the basins the sediment transport show little changes.

With the use of equilibrium relations, for each basin the volume of sediments still needed to be in equilibrium is determined. In total a volume of $13.74 \cdot 10^8\text{m}^3$ is deposited in the three basins. 89% of this volume is placed in the Texel basins, which suffers the most shortage of sediments. For each basin, the added volume of sediments is distributed in such a way that its scaled hypsometry shows the least change. Due to the adjustment of the bathymetry to the equilibrium value, the import ($3810 \cdot 10^3\text{m}^3/\text{yr}$) through the Texel inlet changes to an export of $265 \cdot 10^3\text{m}^3/\text{yr}$. The magnitude of this import is small compared to the import that is the result of the 1998 bathymetry. It is an indication that the equilibrium bathymetry of the Texel basin is indeed close to the actual equilibrium. The Eierlandse Gat and Vlie inlet react in a different way. The imports through these inlets change into considerable exports ($1375 \cdot 10^3\text{m}^3/\text{yr}$ and $3817 \cdot 10^3\text{m}^3/\text{yr}$ respectively). Two reasons can be given for these changes. The first is that the volume of sediments added to these basins predominantly are placed in the ebb-channels. The cross sectional flow area is constricted, and this is most

noticeable during ebb. As a consequence, the ebb-velocities in the ebb-channel are increased. The transport of sediment is related to the velocity to a higher power (3 to 5), and therefore the export during ebb is considerably increased. The large exports through the Eierlandse Gat and Vlie inlet are an indication that the chosen equilibrium bathymetry is incorrect; yet it does not mean that the equilibrium volume is incorrect. More sediment will have to be placed on the flats, and less in the channels.

The second reason is the change in the basin sizes. The transition between one basin to another is denoted with a tidal divide. When a tidal divide is defined as the line on which the deviation of the velocity is minimal, it shows that due to the added volume of sediments the tidal divides have shifted towards the Texel inlet. Most sediments were placed in the Texel basin, and as a consequence the tidal wave in this basin is hindered in its propagation. The Texel basin has reduced in size, whereas the other two basins have increased. The areas the Eierlandse Gat and Vlie inlet have won consist mostly of tidal flats. This distorts the flat/channel ratio in the basins. To restore the original value for this ratio the export through the inlets is increased.

The opposite occurs in the Texel basin. This basin has reduced in size, and the lost areas are tidal flats. To counteract these losses the import through the Texel inlet are increased. In short, the shift of the tidal divide amplifies the export through the inlets of the Eierlandse Gat and Vlie (a destabilising effect) and it reduces the reduction of import through the Texel inlet (a stabilizing effect).

The model applied in the research was not able to reproduce the measured sediment transports over the tidal divides satisfactorily. The largest cause for this is the applied bed schematization. In the model the bed consists of a spatially constant median grain size of $D_{50}=250\mu\text{m}$. In reality, the sediment is much finer at the fringes of the basins. The velocities are low at those locations, and a smaller median grain size probably results in larger sediment fluxes.

The model carries out the simulation depth-averaged. This does not allow density gradient induced flow to be taken into account. As a consequence, the discharges through the Afsluitdijk are not implemented in the model. When the simulations are carried out in 3D, these discharges can be taken into account, and subsequently the influence of density gradient driven flow on the sediment transport can be investigated.

The combination between the determination of volumes with the semi-empirical relations, and the testing of these volumes with a process based modeling program shows promising result. Maintaining the shape of the scaled hypsometric curve is the link between volumes and bathymetries. Although this approach gives promising results, more simulations should be carried out to verify its applicability.

I Introduction

I.1 Background

The Netherlands is a densely populated country, with the majority of the population living in the west, near the North Sea. Over 60% of the Netherlands is situated below sea level. To protect this area of great economical value, the beaches and dune formations of the Dutch¹ coast play an import role. They form the first line of defence against the sea.

Adjacent to the Holland coast the Wadden Sea is situated (see Figure 1.1). This figure shows the three coastal systems that are present in the Netherlands. In the south the Rhine delta is situated. In the middle the beaches and dune formations separate Holland from the sea and the north consists of tidal inlet systems called the Wadden Sea. The Wadden Sea consists of multiple tidal inlet systems that start at Den Helder with the Texel inlet and extend all the way to Denmark.



Figure 1.1 The three coastal systems in the Netherlands, 1) the Rhine delta, 2) beach and dune formations of the Holland coast and 3) the tidal inlet systems of the Wadden Sea

The tidal inlets systems are basins, which are connected to the North Sea via their inlets. Through these inlets, water is transported between the North Sea and Wadden Sea. An important mechanism is the tide. With rising tide (i.e. flood) water is transported from the North Sea to the Wadden Sea, and during falling tide (i.e. ebb) the water flows in opposite direction. As a result of the flow, there is also an exchange of sediments. In the situation that a basin is in equilibrium, there is no net exchange between this basin and its surrounding. However, due to various reasons, the tidal inlet systems of the coast of the Netherlands are out of equilibrium, and they are importing sediment. The relative sea level rise contributes to this importing behavior, as well as the closure of the Zuiderzee, which was completed in 1932.

The volume of sediments that is imported through the inlets originates from the ebb-tidal deltas and the beaches of North Holland and the barrier islands. Consequently, these deltas

¹ The coastal zone between Hoek van Holland and Den Helder, denoted with “2” in Figure 1.1.

and beaches are eroding. The eroded beaches from the Holland coast are weakened in their defense against the sea. Mitigation measures are needed to make sure that the North Holland coast stays strong enough to withstand the sea.

Preservation of the 1990 coastline

As a response to this potential threat to the Holland coastal defences the Dutch government introduced an innovative way of coastal preservation (in the year 1990). From that year on erosion of the Holland coast has been compensated by beach nourishment. To define erosion, the coastline of the year 1990 is taken as a reference; the so called BKL². Each year beach measurements are made and compared to the BKL. When a retreat of the coastline, with respect to the BKL, is detected beach nourishment is carried out. Over the years this approach has proven to be a successful way of maintenance. However, the drawback of this approach is that the beach nourishment cannot be stopped. As long as erosion of the beach occurs it has to be counteracted.

1.2 Objectives of the overall project

The infilling nature of the Western Wadden Sea is an important factor in the amount of sand that is needed to apply sufficient beach nourishment. To get insight in the needed amount of sediments the aim of the “Interactie tussen de lange termijn ontwikkelingen van de Nederlandse kust en de getijdebekkens Marsdiep en Westerschelde”³ project is to determine the total sand demand of the different coastal systems that make up the coast of the Netherlands (see Figure 1.1). Sand demand is defined as the volume of sediments that is needed by the inlet system in order to reach its equilibrium state. The focus of the overall project is on the most southern inlet, the Western Scheldt, and the Western Wadden Sea, comprising the inlets of Texel, Eierlandse Gat and Vlie.

1.3 Objectives of this thesis

This thesis aims to improve the insight in the sediment transports in the Western Wadden Sea, and how these transports react to various influences. The focus is the short-term reaction, but this thesis is linked to other studies in the project, which focus on the long-term morphological behaviour. The objective of this thesis is to provide an answer for the following research questions:

- In what way do different forcing agents influence the sediment transport pattern in the Western Wadden Sea?
- In what way is the sediment transport pattern changed when the bathymetry is adjusted?

The answer to the first research question provides insight in the importance of a forcing agent, and whether it should be considered significant when bathymetric changes are applied.

²BKL: Basis Kust Lijn (in Dutch). Basal Coastal Line (in English)

³In English: Interaction between long term developments of the Dutch coast and the tidal basins Marsdiep and Western Scheldt

Together with the results from the other studies, an estimate of the total amount of sediments still required in the Western Wadden Sea can be made. The second objective also provides insight in the function and effect of the individual sub-systems of a tidal inlet system, considering the sediment transport.

I.4 Reader

The thesis first describes the study area, the Western Wadden Sea, in chapter 2. Chapter 3 discusses a more elaborate approach, and the set-up of the means to answer the research questions. The research itself is divided in two parts. The first part deals with the forcing influence. The results are presented and discussed in chapter 4. The bathymetric influence is presented and discussed in chapter 5. The conclusions and recommendations for further studies are given in chapter 6.

I.5 Acknowledgements

This thesis is the result of a project executed at WL| Delft Hydraulics, which is gratefully acknowledged. The thesis-work was supervised by:

- Prof.dr.ir. H.J. de Vriend, TUDelft
- Dr.ir. Z.B. Wang, TUDelft
- Dr. H.M. Schuttelaars, TUDelft
- Ir. J. de Ronde, Rijkswaterstaat
- Dr.ir. E.P.L. Elias, WL| Delft Hydraulics

The author thanks these people for their input and support.

2 The Western Wadden Sea

2.1 Introduction

This chapter gives a description of the study area. It deals with the location and characteristics of the Western Wadden Sea. An overview of the water motion in the North Sea, and in more detail the Wadden Sea is given. The chapter concludes with a description of the mechanism responsible for residual sediment transport.

2.2 Characteristics of the Western Wadden Sea

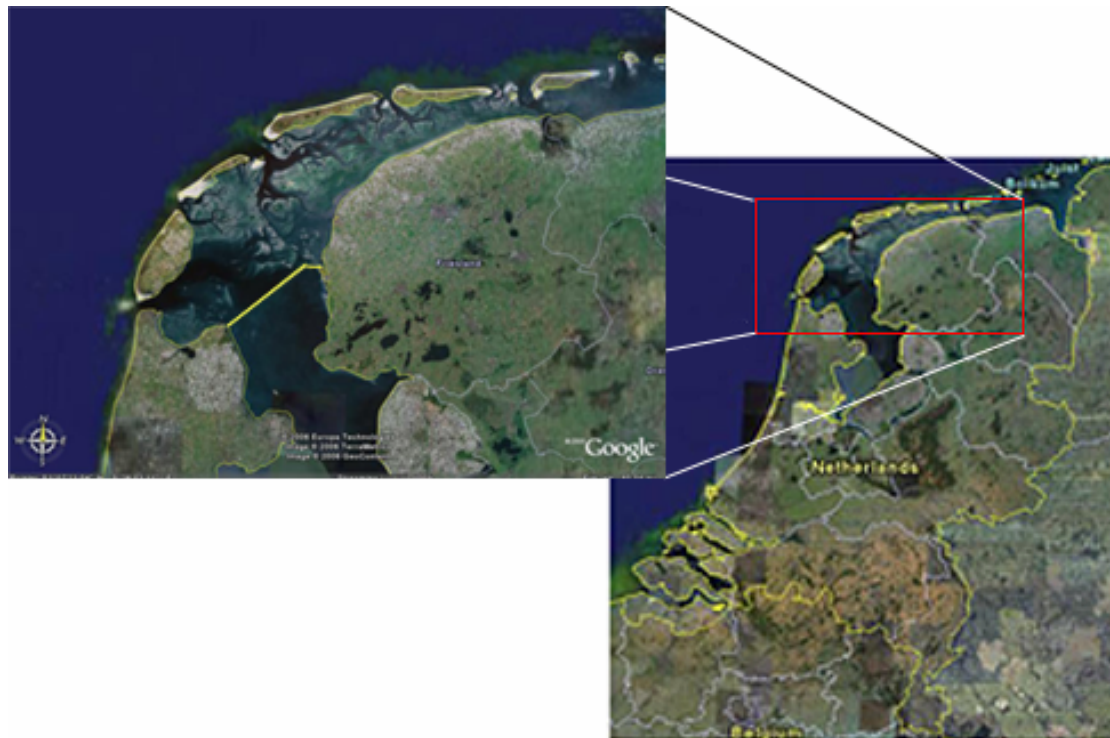


Figure 2.1 Location of the Wadden Sea (adapted from earth.google.com)

The complete Wadden Sea stretches from The Netherlands to Denmark. The Dutch part (for the location see Figure 2.1) consists of five tidal basins. These basins are connected to the North Sea via tidal inlets.

The Western Wadden Sea comprises the three most westerly situated basins. These basins are the Texel basin (or Marsdiep basin), the Eierlandse Gat basin and the Vlie basin. In Table 2.1 the surface area, the tidal range and tidal prism of each of the basins is shown. The Texel and Vlie basin are of comparable size while the Eierlandse Gat basin is smaller.

In the south, the Texel basin is restricted by a large dam called the Afsluitdijk. It separates the Wadden Sea from Lake IJssel. The lake IJssel is connected to the river IJssel, and to discharge excesses of (fresh) water two sluices are placed in the Afsluitdijk. One is placed at Den Oever and the other one at Kornwerderzand.

Table 2.1 Characteristics of the basins in the Western Wadden Sea (Eysink, 1993)

	Surface area [km ²]	Tidal range [m]	Tidal prism [$\cdot 10^6$ m ³]
Texel basin	656	1.65	1015
Eierlandse Gat basin	161	1.65	205
Vlie basin	719	1.9	1190

2.3 Closure of the Zuiderzee

In 1932, 75 years ago, the Afsluitdijk was constructed, cutting of the Zuiderzee from the Wadden Sea. Before the closure, the Zuiderzee was a part of both the Texel and Vlie basin. In total, the basin had a surface area of more than 4000 km². The length of the basins was in the order of 130 km. Due to the closure, the size and length of the basins is reduced considerably. Furthermore, the basins are separated by a tidal divide⁴. Figure 2.2 shows the propagation of the tidal wave before and after the construction of the Afsluitdijk. It shows that prior to the closure, water from both the Texel and Vlie inlet flowed to the Zuiderzee.

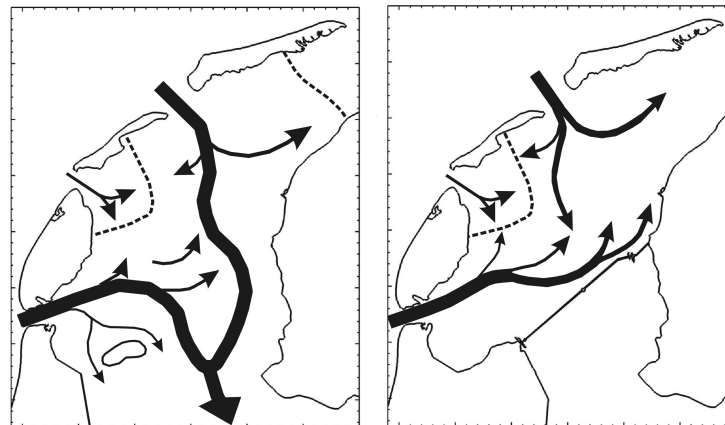


Figure 2.2 Tidal wave propagation of the tidal wave before (on the left) and after (on the right) the closure (Elias, 2006)

Due to the closure of the Zuiderzee, the basins relatively lost a large amount of sediments. The Zuiderzee consisted of large tidal flat areas. Near the inlet gorge, channels take up a large portion of the basin area. The construction of the Afsluitdijk separated the tidal flats in the Zuiderzee from the channels near the gorges, resulting in tidal basins with a shortage of sediments. As a reaction the basins work towards a new equilibrium. To reach this new equilibrium there is a need for sediment. Elias et al (2006) indicate that in the period 1930-1994 an amount of 480 Mm³ has been deposited in the Wadden Sea. The basins borrow this sediment from their ebb-tidal deltas, who in turn extract sediment from the adjacent coasts to counteract their loss of sediment.

In the forty years following the year 1932, when the closure of the Zuiderzee was completed, the first stage adjustment of the Western Wadden Sea to the new situation occurred. Recent research (Elias, 2006) shows that the second stage reaction of the system

⁴ A tidal divide is the border between two basins, over which theoretically there is no transport of water and/or sediments

still induces an annual import of sediments through the Texel inlet in the order of 5 to 6Mm³/yr.

2.4 Water motion

The water motion is the most important parameter for the transport of sediments. The influence of each forcing agent can differ both on the spatial and temporal scale. The magnitude of the individual influences differs as well. This section describes the forcing agents of which the influence is investigated in the research. Three types of forcing are taken into account: tidal, wave and wind forcing.

2.4.1 Tidal propagation

The term tide implies the periodical deflection of the water surface at large water bodies such as the oceans and seas. The tide is caused by the gravitational forces of celestial bodies such as the sun and moon. Due to the earth's rotation the tide (if undisturbed) would have a sinusoidal character. However, the tide is disturbed by friction and land boundaries, so it gets distorted. In this section the behaviour in the North Sea and (in more detail) the Western Wadden Sea is described.

Tidal propagation in the North Sea

The North Sea is a relative shallow sea which is bordered by the United Kingdom in the west, northwest Europe (Belgium, the Netherlands, Germany and Denmark) in the southeast and Norway in the northeast. It is connected to the Atlantic Ocean in the north and through the Channel, a small opening between southern UK and France. The restriction by the land boundaries causes the tide to rotate around three amphidromical points⁵, see also Figure 2.3. One of these points is located on land, in the south of Norway. The arrow in the figure shows that the tide propagates counter clockwise, so high water arrives in the south of the Netherlands first and propagates north.

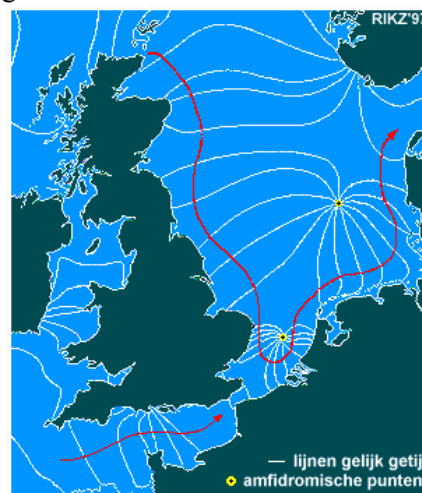


Figure 2.3. The North Sea including amphidromical points (www.getij.nl)

⁵ Amphidromical points are points where the tidal elevation tends to zero

The presence and location of the amphidromical points also influence the amplitude of the tide. Figure 2.4 shows the tides for several points in the Netherlands, and it can be seen that at the mouth of the Western Scheldt the amplitude is around 2m; it reduces to 0.66m at the Texel inlet and amplifies to 1m at the Frysian inlet again.

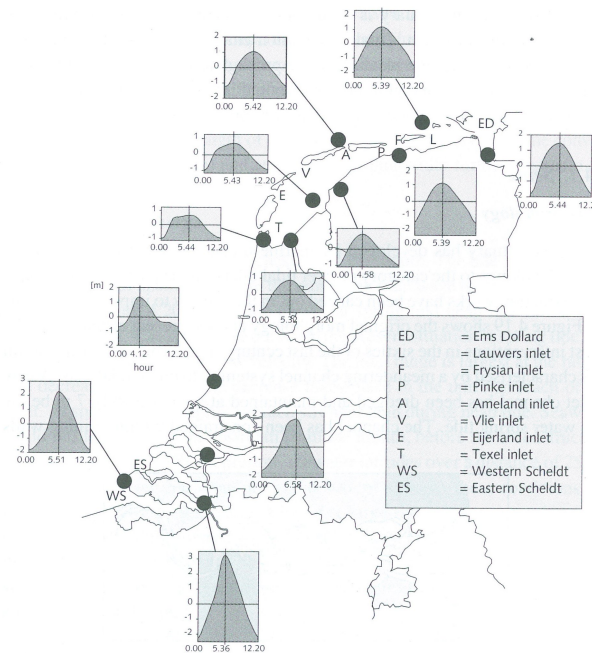


Figure 2.4 Tidal signal in the Netherlands (J. Dronkers, 2005)

Tidal propagation in the Western Wadden Sea

The Western Wadden Sea consists of tidal basins that are connected to the North Sea through inlets such as the Texel inlet and the Vlie inlet. During flood water is imported through the inlets, during ebb water is exported. The amount of water that is imported during flood and exported during ebb is called the tidal prism.

The length of a tidal basin determines the type of propagation. In elongated basins such as the Western Scheldt the tide will have a propagating character, in short basins it will have a standing character. The term propagating implies a maximal (minimal) flow velocity at the maximal (minimal) deflection of the water level. A standing wave means maximal flow velocities at minimal deflection of the water level and vice versa.

The two largest basins in the Western Wadden Sea, Texel basin and Vlie basin, are of such length that the tidal wave is a combination of a standing and a propagation one. As illustration the computed tidal signal for both the water level and the velocity in the Marsdiep are shown together in Figure 2.5. At low water, the flow velocity is in between its minimal value and zero, which is in accordance with the statement above.

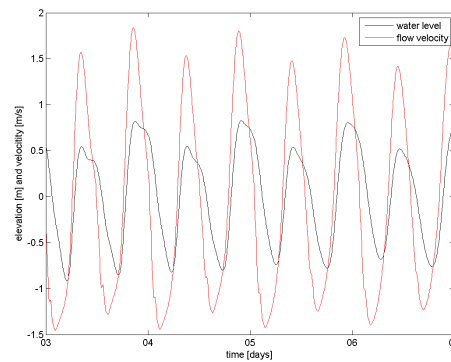


Figure 2.5 Tidal signal and subsequent flow velocities in the Marsdiep

Figure 2.4 showed that the amplitude of the tidal signal varies along the Dutch coast. At the Texel inlet the average tidal range is 1.32m, varying to 2m during spring tide and 1m at neap tide. In the vicinity of the Vlie inlet, the mean tidal range is approximately 1.80m, varying to 2.3m at spring tide and 1.3m at neap tide. This implies a higher range at the Vlie inlet than at the Texel inlet. There is also a difference in tidal range in the basins, and this causes a residual flow over the tidal divide and through the inlets. Ridderinkhof (1998, part II) indicated that the magnitude of the residual flow over the divide is in the order of $900\text{m}^3/\text{s}$, in the direction to the Texel basin. NIOZ ferry measurements (e.g. Elias et al, 2006) indicate a residual ebb-discharge in the Texel inlet of $2570\text{m}^3/\text{s}$, whereas Rijkswaterstaat measurements (e.g. Elias et al, 2006) show a residual ebb-discharge of $2230\text{m}^3/\text{s}$. The magnitude of the residual flow between the basins is in the order of 1% of the tidal prisms that flow through the inlets.

2.4.2 Meteorological conditions

Wind

The wind effects can be divided into two parts, viz. large-scale and local effects. In the manner that the Wadden Sea is a basin of the North Sea, the North Sea itself can be considered as a basin of the Atlantic Ocean. The North Sea is relatively shallow; on average it has a depth of 94m. This enables the wind to have effect on water levels and gradients. The magnitude of the water level set-up, induced by wind stresses, is dependent on the velocity and the fetch of the wind. Figure 2.6 shows the relation between the wind velocity, wind direction and water level set-up for the wave buoy “Eierlandse Gat”. This wave rider is located in front of the Eierlandse Gat (Paris coordinates X: 106.514km, Y:587.985km, see also Figure 2.7). Wind from western and northern direction induces a larger water level set-up than wind with the same velocities from other directions. The fetch is largest for these directions (see Figure 2.3).

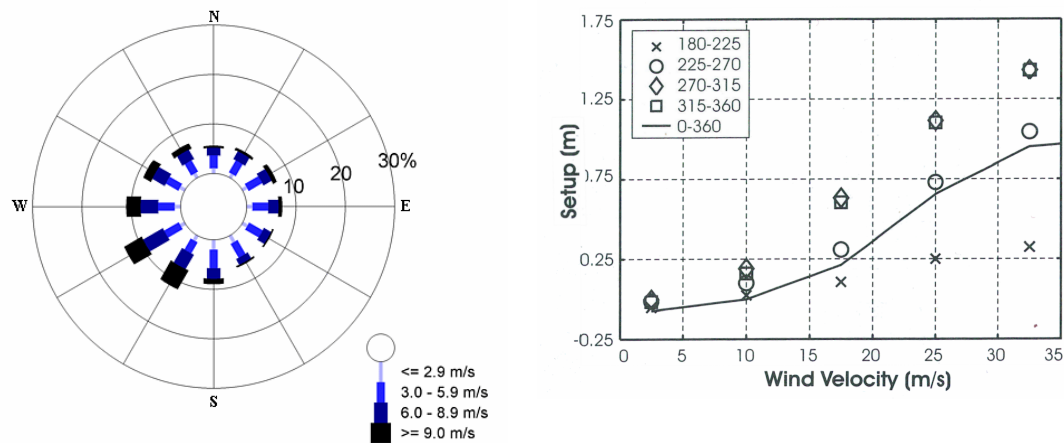


Figure 2.6 Left: Wind rose for station De Kooy near Den Helder (adapted from www.knmi.nl). Right: Relation between wind velocity, wind direction and water level set-up (Elias, 2006)

The left figure in Figure 2.6 shows the long term distribution of the wind angle and velocity, measured at station De Kooy, near Den Helder. Figure 2.6 shows that in the Western Wadden Sea the wind predominantly originates from the south to northwest. The majority of the wind speed measured did not exceed 9m/s. This velocity is a 5 on the Beaufort scale, and is classified as a fresh breeze. Yet values for the wind velocity of over 35m/s have been recorded. Winds of these magnitudes can be considered as gales, or storm winds.

Waves

In the area of the Western Wadden Sea the waves predominantly are generated by wind action on the North Sea. Waves with longer periods (e.g. swell) are less frequent. Figure 2.7 shows the long term wave height distribution for wave rider “Eierlandse Gat”. The majority of the waves (80%) does not exceed a height of $H_s=2\text{m}$. The waves can reach the largest heights when they come from the west to northwest. For these directions the fetch is the largest, and this is favourable to the generation of wave energy by wind action. Waves from these direction can reach heights of up to $H_s=6\text{m}$. The wave period (T_{m02}) that corresponds to the lower wave height is around five seconds, for higher waves the period can be as large as ten seconds.

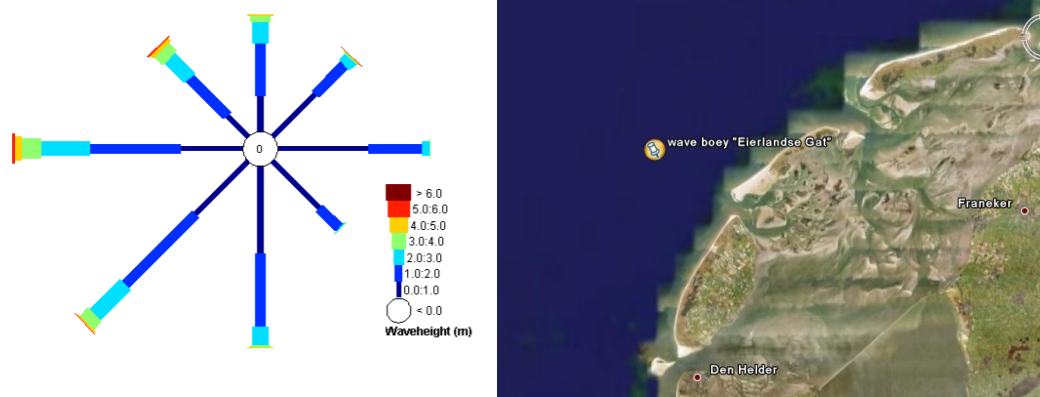


Figure 2.7 Wave height distribution for wave rider Eierlandse Gat (adapted from www.golfklimaat.nl) and its location (earth.google.com)

2.5 Sediment transport

The sediment transport is a consequence of the water motion, which is forced by the agents mentioned in section 2.4. The mechanisms responsible for the residual transport of sediments are described in this section.

2.5.1 Residual flow

Both the tidal and meteorological forcing are able to generate residual currents. The tidal flow generates residual currents via the exchange of water over the tidal divides, which implies that the amount of ebb-discharges through an inlet is not equal to the amount of flood-discharges. If the wave in a tidal basin is not a true standing one, the cross sectional area during ebb differs from that during flood. When the same amount of water is exported as is imported, the velocities must differ. This phenomenon, also referred to as the Stokes drift, causes a residual flow.

Waves also generate a residual flow. If they approach the shoreline obliquely, an alongshore current is generated when they are breaking. The breaking of waves induces a wave setup, which is proportional to the incoming wave height. When the approaching wave height varies spatially, due to the difference in water level set-up a water level gradient parallel to the shore is created, which itself drives a current.

The wind action on the water surface creates wind stresses. These stresses induce a water level set-up and/or a current in the direction of the wind. The latter contributes to the residual flow.

All the mechanisms described above contribute to the residual flow (M_0). The interaction of the residual flow with the amplitude of the tidal velocity (M_2) is a mechanism that generates a residual sediment transport that is called the M_0M_2 residual flow. The mechanism is expressed with equation(2.1).

$$u(t) = \hat{u}_{M_0} + \hat{u}_{M_2} \cos(\omega t - \varphi_{M_2}) \quad (2.1)$$

Where

$\hat{u}_{M_0}$ = amplitude of the M_0 constituent

$\hat{u}_{M_2}$ = amplitude of the M_2 constituent

φ_{M_2} = phase of the M_2 constituent

The interaction between these two constituents is the main contributor to the tidally averaged sediment transport induced by residual flow (Van de Kreeke and Robaczewska, 1993). Figure 2.8 gives an example of this mechanism. In this example the sediment transport is considered to be proportional to the flow velocity to the fifth power. This higher order proportionality causes the relatively small amplitude of the M_0 (in the example only 10% of the amplitude of the M_2) to have a considerable effect in the difference in transport during ebb and flood. If in the figure positive values denote velocities during flood (and negative velocities during ebb), there is a residual import of sediment as a result of the M_0M_2 -interaction.

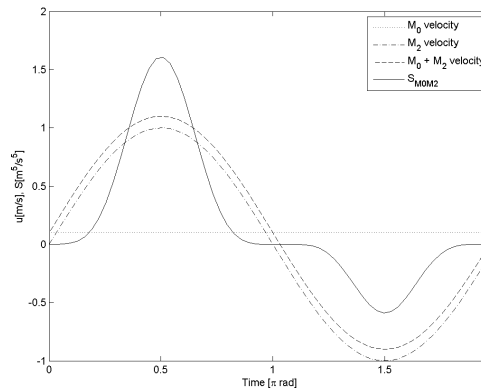


Figure 2.8 Interaction between M_0 - and M_2 -velocities and the subsequent magnitude of sediment transport

2.5.2 Tidal asymmetry

In shallow water, a (tidal) wave gets distorted. The shallowness and the bottom friction alter the propagation speed of the wave during ebb as well as during flood. This influence is called tidal asymmetry, and can be represented with the overtides of the primary constituents (e.g. the M_2 and S_2 constituents). The overtides have a frequency that is a multiplication of the primary constituent. In the Wadden Sea, the M_2 constituent is the largest contributor to the tidal signal. Its first overtide, the M_4 constituent, has the largest contribution to the tidal asymmetry.

An asymmetry in the tidal velocities implies that the ebb-velocity curve differs from that of the flood velocity. If, for tidal asymmetry, only the M_2 constituent and its first overtide M_4 are taken into account, the tidal velocity can be expressed as equation(2.2).

$$u(t) = \hat{u}_{M_2} \cos(\omega t - \varphi_{M_2}) + \hat{u}_{M_4} \cos(2\omega t - \varphi_{M_4}) \quad (2.2)$$

Where $\hat{u}_{M_2}$ = amplitude of the M_2 constituent

φ_{M_2} = phase of the M_2 constituent

$\hat{u}_{M_4}$ = amplitude of the M_4 constituent

φ_{M_4} = phase of the M_4 constituent

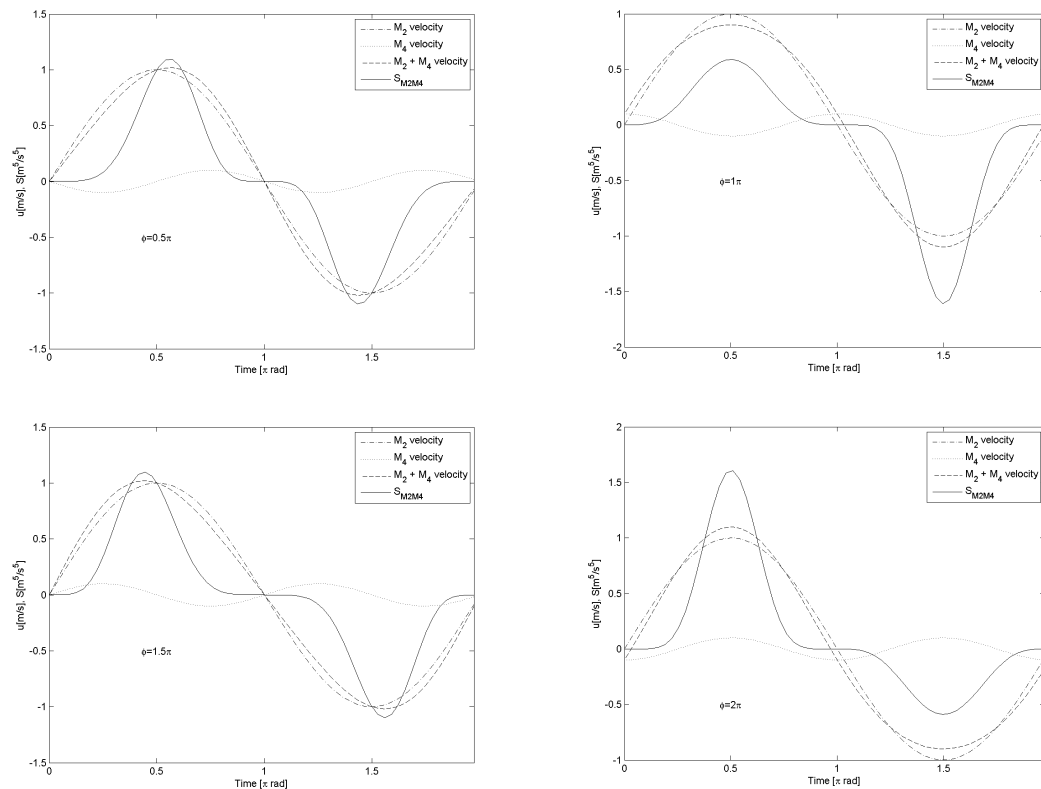


Figure 2.9 tidal velocity for various phase differences, and subsequent sediment transport magnitude

The relative phase difference (ϕ) between the two constituents is expressed with $\phi = 2 * \varphi_{M2} - \varphi_{M4}$. If $0.5\pi < \phi < 1.5\pi$, the ebb-velocities are higher than the flood-velocities, and the duration of ebb is shorter than that of flood. Due to the higher power proportionality between sediment transport and flow velocity, in this situation an residual export of sediment is generated by the tidal asymmetry. If $1.5\pi < \phi < 2.5\pi$, it is vice versa, and the tidal asymmetry generates a residual import of sediments (Van de Kreeke and Robczewska, 1993). This is illustrated by Figure 2.9. Positive values denote flood-velocities, negative ebb-velocities. The figure also shows the order of magnitude of sediment that is induced by the tidal asymmetry, if proportionality to the fifth power is assumed. The sediment transport reacts in two ways to the tidal asymmetry:

- The difference in amplitude of the flood- and ebb-velocity, and subsequently the duration of flood and ebb causes a residual bed-load transport (i.e. coarser grains) (Friedrichs and Aubrey, 1988). This difference is largest when the relative phase difference $\phi = \pi$ and $\phi = 2\pi$.
- Tidal variations in the periods around high-water and low-water slack affects the capability of suspended sediments to settle (Dronkers, 1986).

2.5.3 Wave induced transport mechanisms

Wave action can have considerable effect on the sediment transport. A number of mechanisms play a role. They are listed below:

- The non-sinusoidal character of the wave signal (due to the higher harmonics) causes an asymmetry in the waves. With a transport proportionality of a power higher than 1 (e.g.

5) to the velocity a residual transport of sediments is generated. This transport is in the direction of the wave propagation.

- Even if the wave signal has a perfect sinusoidal shape, a net transport of water is generated, i.e. Stokes drift. The propagation speed is dependent on the water depth ($c \sim d^{1/2}$). The crest of a wave has a propagation speed that is a little larger than the trough. This results in a small net displacement in the direction of the wave propagation.
- When waves approach the coast perpendicular, the Stokes drift has to be counteracted. Otherwise water would pile up against the coast. The counteraction takes place in the form of an undertow at the bottom, which generates a seaward directed sediment transport.
- When the waves approach the coast obliquely, a longshore current is generated when the waves break. This current is the result of the dissipation of the wave energy due to the wave-breaking.
- The orbital motion of the waves increases the bed shear stresses (τ_b). This enhancement allows more sediment to go into suspension. This extra amount of suspended sediment can be transported by tidal and wind-driven flow. This effect is also referred to as the “stirring-up” effect. The interaction between the bed shear stresses induced by currents and waves is non-linear. Figure 2.10 shows a schematic view of the interaction. As a result of the increase of the bed shear stresses (induced by the orbital motion of the waves) the sediment transport direction can differ from the current direction.

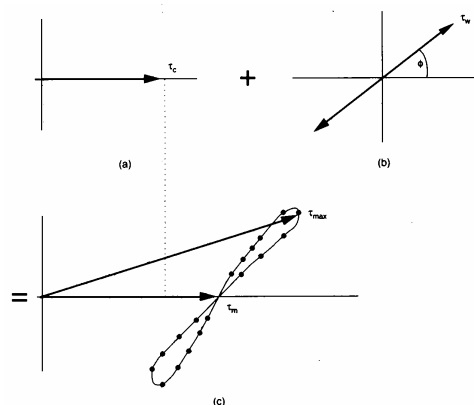


Figure 2.10 Schematic view of non-linear interaction of current and wave bed shear stresses (from Soulsby et al, 1993)

With respect to the sediment transport patterns in tidal inlet systems, the mechanisms mentioned above affect the import and export of sediments through the inlet. The barrier islands and the shallow ebb-tidal delta have a filtering effect. The waves break and therefore lose their height and energy when they enter the basin.

The volume of sediments that goes into suspension as a result of the “stirring-up” effect is related to the wave height. The higher waves at the ebb-tidal delta area induce a larger volume of sediments to go into suspension than the smaller waves in the basin. The extra volume of sediments that is gone into suspension can be transported through the inlet during flood (i.e. a larger amount of imported sediments). The “stirring-up” effect of the waves in the basin have the same effect, only now the amount of sediments exported through the inlet during ebb is increased. However, as the waves are the highest on the ebb-tidal area, the extra volume that is imported during flood generally is larger than the volume that is exported during ebb.

In general, the wave action has a positive effect on the residual import of sediments through an inlet.

3 Research approach and model set-up

This chapter deals with the approach on how to accomplish the objectives. First the objectives are translated into research questions. Secondly the research approach is described, followed by the model used to acquire results. The set-up of the models is described afterwards. The chapter is concluded with some of the model limitations.

3.1 Objectives translated into research questions

The objectives formulated in section 1.3 can be translated into research questions. The aim of the thesis is to find an answer to these questions, and in this way the objectives are accomplished. For each objective the research (sub) questions are stated.

Objective #1: Determination of the forcing influence

- *Question #1:* What is the influence of the tidal forcing on the transport of sediments through the three inlets and over the three divides, and in what way does it influence the sediment transport pattern in the vicinity of the Texel and Vlie inlets?
 - *Sub question #1.1:* In what way does the tidal representation influence the transport rates through the inlets?
 - *Sub question #1.2:* What is the influence of the tidal residual flow between the basins?
- *Question #2:* What is the influence of wave forcing on the transport of sediments through the three inlets and over the three divides, and in what way does it influence the sediment transport pattern in the vicinity of the Texel and Vlie inlets?
 - *Sub question #2.1:* What is the influence of the height of the incoming wave?
 - *Sub question #2.2:* What is the influence of the angle of the incoming wave?
- *Question #3:* What is the influence of wind forcing on the transport of sediments through the three inlets and over the three divides, and in what way does it influence the sediment transport pattern in the vicinity of the Texel and Vlie inlets?
 - *Sub question #3.1:* What is the influence of the angle of the wind forcing?
 - *Sub question #3.2:* What is the influence of the intensity of the wind forcing?

Objective #2: Determination of the bathymetric influence

- *Question #4:* What is the amount of annual sediment import in the Western Dutch Wadden Sea in case of the reference bathymetry?
- *Question #5:* What is the reaction of the sediment transports on the removal of the ebb-tidal deltas?
- *Question #6:* What is the reaction of the sediment transport when equilibrium related bathymetries are applied? Does the rate of transport through an inlet decrease when the basin bathymetry approaches its equilibrium?

Two aspects in the research reoccur with each research question: a) the sediment transport rates through the inlets and over the tidal divides, and b) the sediment transport patterns in the Texel and Vlie inlets. Figure 3.1 shows the cross sections, over which the amount of sediment transports are determined. The black lines denote the cross sections in the inlets.

The cross section located at the tidal divide behind the island of Terschelling is grouped with the inlets. This is because it denotes a boundary of the study area.

The red lines denote the cross sections at the tidal divides between the three basins.

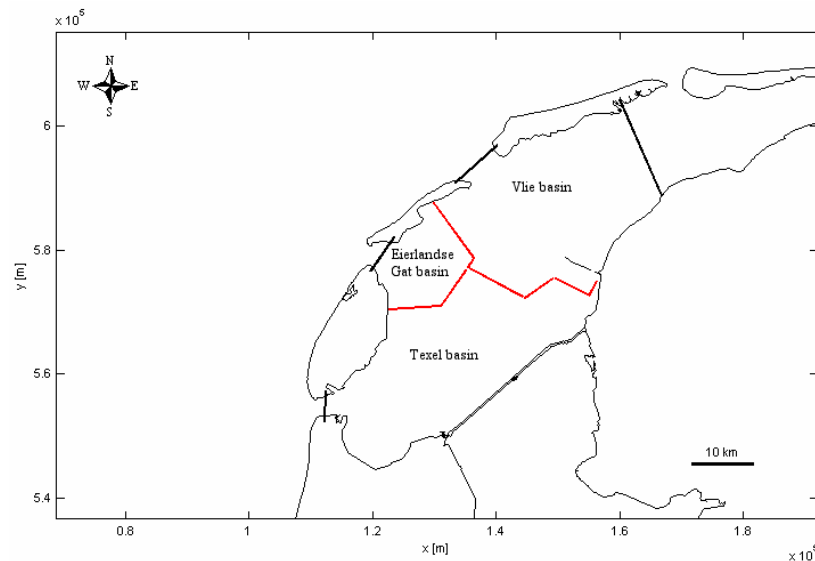


Figure 3.1 Locations of the cross-sections in the Western Wadden Sea

3.2 Research approach

The aim of the thesis is to improve the insight on how sediment transport patterns initially react on:

- *Forcing agents*
- *Bathymetric changes*

The research can be divided into two parts. In the first the influence of the different types of forcing is investigated, in the second phase the reaction of the sediment transports on the bathymetric changes is investigated.

3.2.1 Forcing influence

The influence of two types of forcing is investigated: tidal and meteorological. Meteorological forcing consists of a wave and wind part. Both the wave and wind part are taken into account. Figure 3.2 shows the different experiments that will be performed. Three main sections are distinguished:

- *Tidal forcing.* The tidally driven transport patterns through the inlets and over the tidal divides are investigated. This is done with by representing the tide in two ways. The first is a representation of the complete tidal signal, including all the major constituents. Secondly the influence of the constituents that are considered to be the main driving mechanisms behind the sediment transport is determined. In this case, only the semidiurnal lunar constituent (M_2) in combination with its overtides (M_4 & M_6) generate this mechanism.
- *Tidal and wave forcing.* In this section wave forcing is added to the tidal forcing. Waves differ in height and they can approach the inlets from different directions. In this section the influence of the wave height and angle is investigated. In order to determine the

influence of the wave height, the effect of four different wave heights ($H_s=1\text{m}$, 2m , 3m and 4m) from the northwest is investigated.

To investigate the influence of the wave angle, experiments with a wave of constant height ($H_s=2\text{m}$) but from varying directions are done. Three directions are applied; southwest, northwest and north. Figure 2.7 shows that the majority of the incoming waves originate from the southwest to north.

- *Tidal, wave and wind forcing.* In this section wind forcing is added in three scenarios; I) a wave with $H_s=2\text{m}$ from the northwest, II) a wave with $H_s=4\text{m}$ from the northwest and III) a wave with $H_s=2\text{m}$ from the southwest. The wind direction in each simulation is the same as the direction of the waves that are approaching the Wadden Sea. The wind velocity (U_{10}) has the corresponding (see appendix E) value to the applied wave height. The large-scale wind effects are accounted for by means of a water level set-up prescribed at the boundaries, see appendix D.

The tidal signal in the sections investigating the wave and wind forcing is represented with three constituents, viz. the M_2 , M_4 and M_6 constituents. With this tidal representation the spring-neap effects are excluded. The cyclic pattern of the tide is reduced from ± 28 days (two spring-neap cycles) to one tidal cycle (12 hrs and 25 min). This allows for a large reduction in simulation time and thus in computational costs.

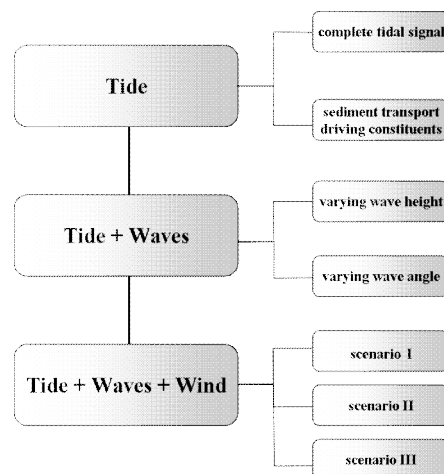


Figure 3.2 Stages in the tidal forcing investigation

3.2.2 Influence of bathymetric changes

In this phase the bathymetry is altered in order to see how the sediment transports react to these alterations. Table 3.1 shows the simulations that are carried out.

- *Simulation #1.* This simulation is done with the 1998 bathymetry and serves as the reference simulation. The results of the other simulations are compared to the results of this one.
- *Simulation #2.* To investigate how the initial sediment transport pattern responds to a sudden removal of the ebb-tidal deltas this simulation is carried out.
- *Simulations #3 and #4.* With the use of empirical relations the equilibrium sediment volumes for the basins are determined. A tidal basin in equilibrium does not have a net exchange of sediments with its surroundings. Both the equilibrium volume and the

volume that is halfway to this equilibrium are converted into bathymetries to investigate if the imports and exports through the inlets reduce.

Table 3.1 Simulations in phase B

Simulation #	Bathymetry
1	1998
2	No ebb-tidal deltas
3	Halfway the equilibrium bathymetry
4	Equilibrium bathymetry

3.3 Research means

The applied means to fulfil the research objectives is the software package DELFT3D. DELFT3D is developed by WL| Delft Hydraulics. Its purpose is to simulate the hydrodynamic and/or morphodynamic behaviour of coastal, river en estuarine environments. The simulation can be carried out two-dimensional (depth-averaged 2DH or width-averaged 2DV) or three-dimensional. The software is able to simulate flow, waves, water quality, ecology, sediment transport and morphological development.

The heart of DELFT3D is the FLOW-module. This module solves the unsteady shallow water equations to calculate the flow velocity and water levels as a result of forcing (e.g. tidal and meteorological). The FLOW-module can be coupled to other modules that are able to simulate specific phenomena. One of these modules, the WAVE-module, is applied in this thesis to simulate the distribution and evolution of short-crested waves. DELFT3D-FLOW has an application that allows for a simultaneous computation of flow and sediment transport, including a simultaneous feed-back from the bed level update. This application is called the Sediment Online Module. Figure 3.3 shows the outline of the processes in DELFT3D.

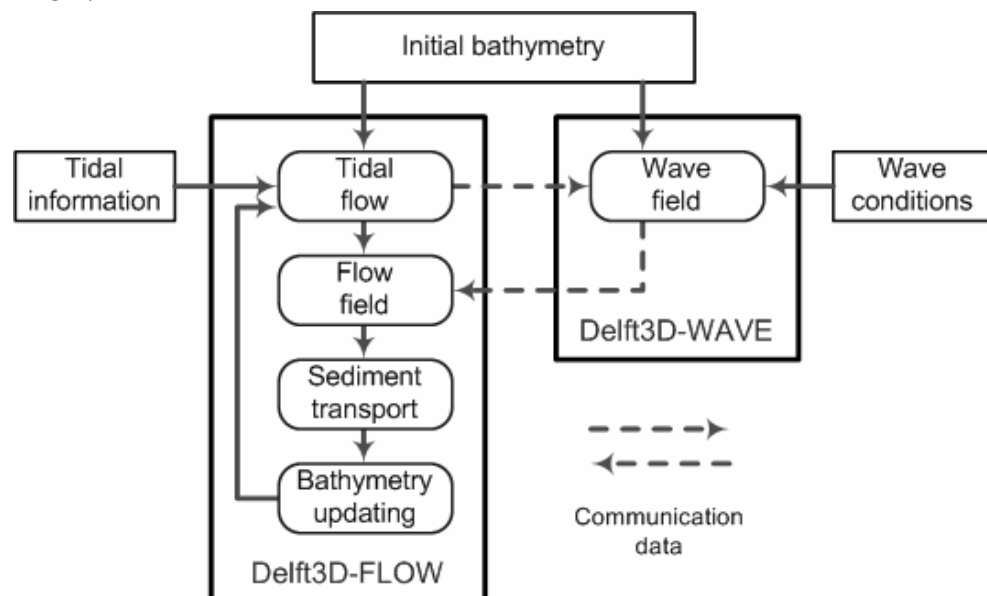


Figure 3.3 DELFT3D morphological computation scheme (adapted from Sun, 2004)

3.4 Model set-up

3.4.1 Grid

Figure 3.4 shows the grid and location of the Wadden Sea model. The grid consists of over 21.000 grid cells. The southern end is located just above the breakwaters of IJmuiden; the northern end is located on the watershed at Schiermonnikoog. In between these ends all of the Wadden Sea is taken into account; the western boundary lies in the North Sea at a distance of approximately 60 km from the shore. There are sixty open boundary points; 11 on the southern, 37 on the western and 12 on the eastern boundary. In between the coast of Friesland and the island of Schiermonnikoog the boundary is closed instead of open. This induces boundary effects in the hydrodynamics. The study area is located sufficiently far away and these boundary effects do not play a role.

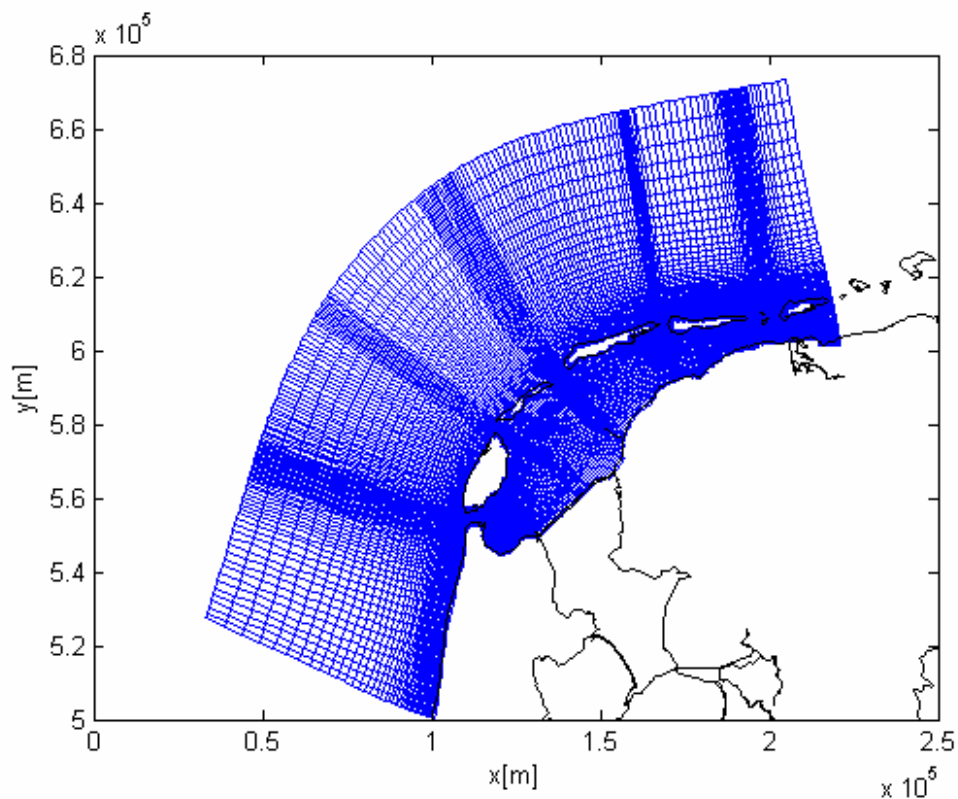


Figure 3.4 Wadden Sea model grid

3.4.2 Bathymetries

In total four different bathymetries are considered. Each is described below.

1998 bathymetry

The National Institute for Coastal and Marine Management (RIKZ) carries out bed level measurements on a regular basis. This way the whole bathymetry of the Wadden Sea is determined every six years. These measurements are carried out with echo sounders on measuring ships.

The bathymetry that is applied for the research on the reaction of sediment transports to the type of forcing, as well as the reference simulation, is determined in the year 1998. Figure 3.5 shows the bathymetry. The bed levels are relative to Mean Sea Level (*MSL*).

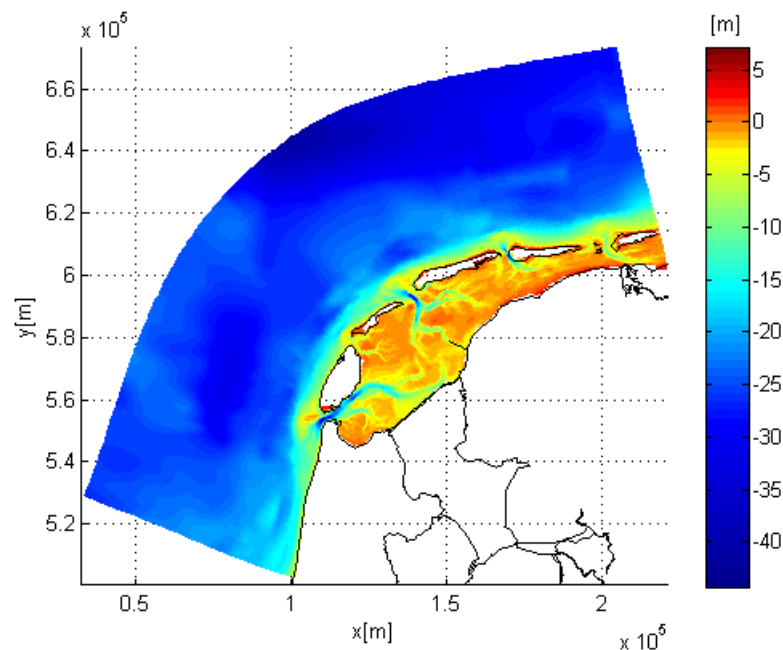


Figure 3.5 Bathymetry of the year 1998

No ebb-tidal deltas bathymetry

Definition of the ebb-tidal delta

An ebb-tidal delta is the additional volume of sediment that is located in the vicinity of a tidal inlet. The term additional denotes the volume of sediments that is present because of the tidal inlet system. It is determined via the difference between the volume that is present and the volume that would be present if the shoreface was undisturbed.

Applied bathymetry

The bathymetry of 1998 is used as starting point. Figure 3.6 gives the applied bathymetry without the ebb-tidal deltas and its difference with the 1998 bathymetry. The slope and bed level of the adjacent beaches is extended to the deltas, in this way removing the surplus of sand. The channels that are present in the delta area are not changed. This is to avoid instability in the simulation. The volume of removed sediments is described in Table 3.2. Note that the volume of removed sediments is around ten times smaller for the Eierlandse Gat, compared to the other inlets. This inlet system is a lot smaller than the other two systems.

Table 3.2 Amount of removed sediments per tidal inlet

Texel inlet delta $\Delta V \text{ [m}^3\text{]}$	Eierlandse Gat delta $\Delta V \text{ [m}^3\text{]}$	Vlie delta $\Delta V \text{ [m}^3\text{]}$
$3.9447 \cdot 10^8$	$4.2941 \cdot 10^7$	$2.3932 \cdot 10^8$

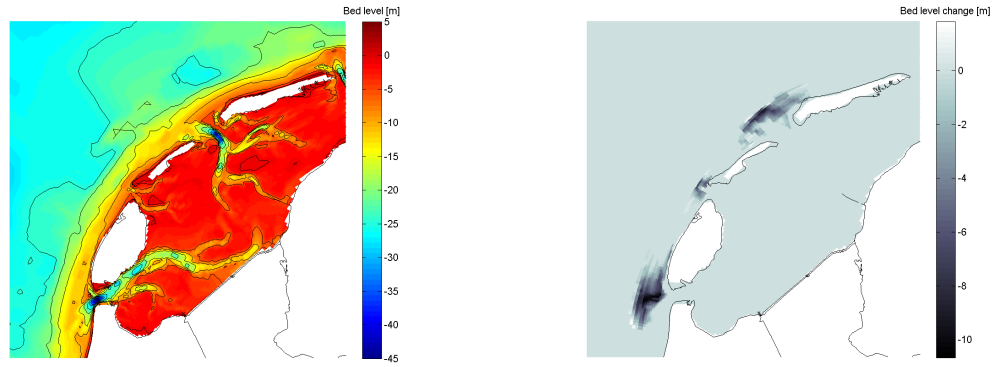


Figure 3.6 Bathymetry and bed level change compared to the 1998 bathymetry

Equilibrium related bathymetries

The volume of sediments that is required for a tidal basin to be in equilibrium is dependent on the tidal range and prism and on the shape of the basin. Equilibrium implies that there is little to no net sediment exchange between a basin and its surroundings. This dependency is expressed in equilibrium relations. In this section these relations are applied to calculate the equilibrium volumes as well as the volumes that are halfway the equilibrium (for each basin). The new basin volumes are then converted into new bathymetries.

Equilibrium volumes

The volume of the basin can be divided into one of the channels and one of the tidal flats. The basin area that has a bed level lower than mean low water (MLW) is channel area. Basin area with bed level between mean high water (MHW) and MLW makes up the tidal flat area.

The equilibrium flat volume (V_{fe}) is expressed in equation(3.1). It depends on the tidal range and the basin area. The basin area is assumed to be constant in time (i.e. there is no shift of the location of the tidal divides).

$$V_{fe} = h_{fe} * A_{fe} \quad (3.1)$$

Where $h_{fe} = \alpha_{fe} * H$

$$A_{fe} = A_b - 2.5 * 10^{-5} * A_b^{3/2}$$

$$\alpha_{fe} = \alpha_f - 0.24 * 10^{-9} * A_b$$

H = tidal range [m]

A_b = basin area [m²]

α_f = coefficient (Eysink, 1992 phase 2) = 0.41

For the equilibrium channel volume (V_{ce}) equation(3.2) applies. The channel volume depends on the tidal prism and on the shape of the basin.

$$V_{ce} = \alpha_c * P^{1.55} \quad (3.2)$$

Where $P = H * A_b - V_{fe}$

α_c = coefficient, depending on the shape of the basin [$m^{-0.55}$]
P = tidal prism [m^3]

Table 3.3 shows the applied characteristics for each basin. For the values of coefficient α_c reference is made to Van Goor, 2001 in case of the Eierlandse Gat basin; Kragtwijk, 2001 in case of the Vlie basin and Van Geer, 2007 in case of the Texel basin. For the determination of the α_c for the Eierlandse Gat, Van Goor, 2001 included the effect of sea level rise (SLR). Van Goor indicated that the volumes of the basins elements are do not vary much in time. This is an indication that the basin is in equilibrium, and the coefficient α_c will not vary much. For the determination of the α_c for the Vlie basin, SLR was not taken into account (Kragtwijk, 2001). This induces an uncertainty in the magnitude of the equilibrium volumes of the basin elements. This indicates that the value of α_c is not certain, but ranges between $8*10^{-6}m^{-0.55}$ and $11*10^{-6}m^{-0.55}$.

The value of α_c for the Texel basin is deduced with the help of the α_c of the Vlie basin. This factor is converted to a value for the Texel basin, with the use of the relation to the basin shape (Van Geer, 2007). This implies that the uncertainty in the value of α_c for the Vlie basin is also present in that of the Texel basin. For instance, Kragtwijk, 2001 applied a value of $\alpha_c = 21*10^{-6}m^{-0.55}$ for the Texel basin.

The resulting additional volumes needed for the basins to be in equilibrium are shown in Table 3.4. The basin volumes for the situation in which the basins are halfway in their development into equilibrium are shown too. The majority of the additional sediments are needed in the Texel basin.

Table 3.3 Applied basin characteristics

	A_b [$10^8 m^2$]	H [m]	α_c [$10^{-6} m^{-0.55}$]
Texel basin	6.89	1.52	13.2
Eierlandse Gat basin	1.49	1.41	14.2
Vlie basin	6.57	1.89	9

Table 3.4 Additional volumes for the equilibrium related bathymetries

	ΔV Equilibrium [m^3]	ΔV halfway equilibrium [m^3]
Texel basin	$12.2*10^8$	$6.1*10^8$
Eierlandse Gat basin	$7.15*10^7$	$3.58*10^7$
Vlie basin	$8.25*10^7$	$4.13*10^7$
$\Sigma \Delta V$	$13.74*10^8$	$6.87*10^8$

Bathymetries

Data analysis shows that the scaled hypsometric curve of a basin is fairly constant in time. The additional volumes are applied so that the new hypsometric curve resembles the one of 1998. Appendix A shows the hypsometric curves, as well as the method used to convert the volumes into bathymetries. Figure 3.7 and Figure 3.8 shows the bathymetry and bed level

change compared to the 1998 bathymetry for the equilibrium scenario and halfway scenario respectively.

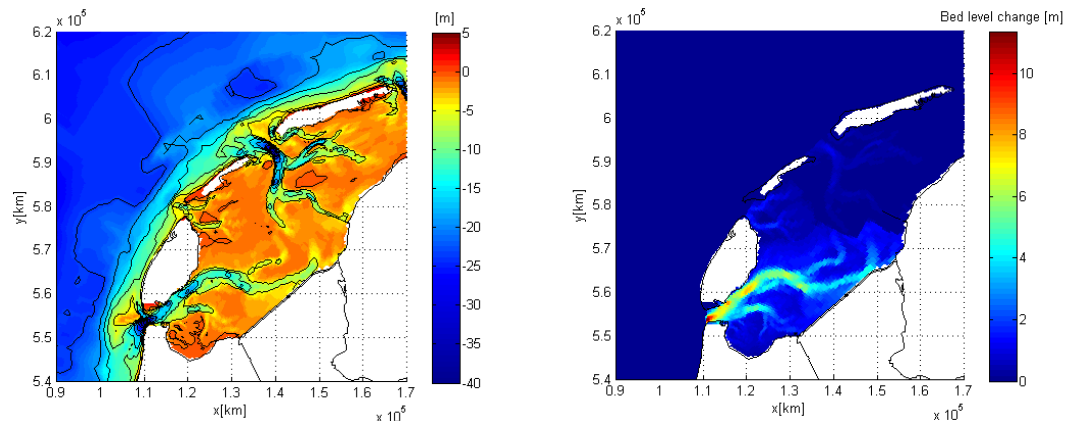


Figure 3.7 Equilibrium bathymetry and bed level change compared to the 1998 bathymetry

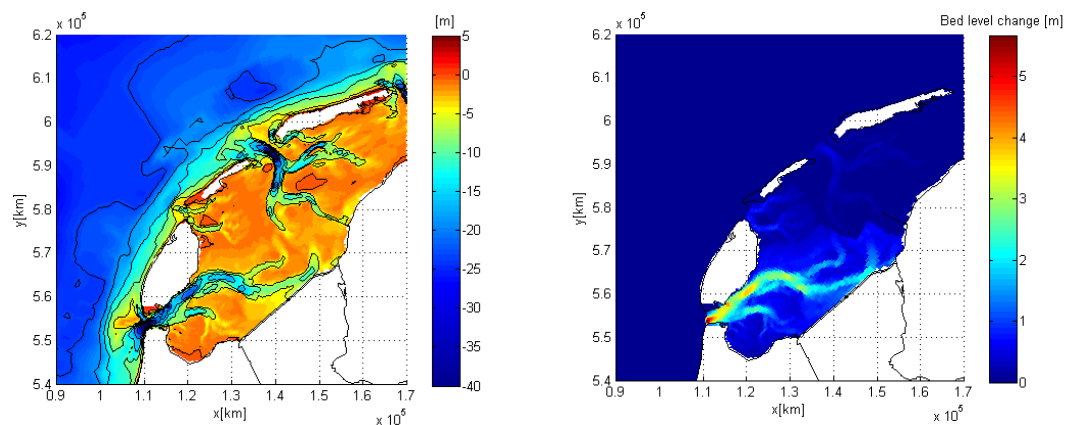


Figure 3.8 Halfway equilibrium bathymetry and bed level change compared to the 1998 bathymetry

3.4.3 Initial and boundary conditions

Boundary conditions for flow

There are five types of open boundaries that can be applied to a model. Each is suitable for different types of situations and simulations:

- Water level boundaries
- Velocity boundaries
- Flux boundaries
- Neumann boundaries
- Riemann boundaries

Neumann boundaries are boundaries where water level gradients are described. They can be ascribed to cross-shore boundaries. They must be in combination with a water level boundary on along-shore boundaries.

Riemann boundaries are weakly reflective boundaries. For this type of boundaries both the water levels and currents have to be known. Main characteristic is that the boundaries are

transparent to waves (to a certain level). Outgoing waves passing the boundaries are not reflected and hence do not propagate into the computational domain as would happen with the other types of boundaries.

The choice of which type of boundary to apply depends on the phenomena that is to be studied. When flow in large tidal basins is modelled, generally forcing by water levels only is preferred. If this forcing only is not satisfactory, a combination of both water levels and currents can be subscribed on the boundary.

The flow model in this research is subscribed with water level boundaries only. The water levels are represented with astronomical constituents as expressed in equation(3.3).

$$\zeta(t) = A_0 + \sum_{i=1}^n A_i \cos(2\pi f_i t - \varphi_i) \quad (3.3)$$

Where

$\zeta(t)$ = water elevation

A_0 = mean value of a time series of the water elevation

A_i = amplitude of the i^{th} constituent

f_i = frequency of the i^{th} constituent

φ_i = phase of the i^{th} constituent

The astronomical constituents are harmonically analyzed from a water level time series. This is done for each boundary point. The harmonic analysis is more elaborately described in appendix B. The water level time series originates from a larger model of the North Sea, the ZUNO-Grof model. The Wadden Sea model is nested in this model. For explanation on the ZUNO-Grof model and the nesting procedure, see appendix C. In the simulations in which wind forcing is applied, the large-scale wind set-up is deduced from the ZUNO-Grof model as well. The method to derive the large-scale wind set-up is explained in appendix D. The initial water level in the model is set on zero. To dissipate errors due to the discrepancy between initial state and boundary conditions the model has a spin-up time of two days.

Boundary conditions for waves

The wave forces are calculated in the WAVE module of DELFT3D. The wave boundary conditions are subscribed to each open water boundary. They are constant in both time and space. The wave is represented with a wave height (H_s), peak wave period (T_p) and wave angle (α).

3.4.4 Numerical and Physical parameters

Transport mode

For the calculation of the sediment transports the method of Van Rijn (1993) is applied. This method makes a distinction between the bed-load and suspended sediment transport. The bed-load transport is the transport of sediments that occurs close to the bed (beneath a reference height (δ)). It is assumed to react instantaneous to the flow.

The sediment transport that takes place above the reference height is the suspended sediment transport. In depth-averaged computations the three-dimensional advection-

diffusion equation (expressed with equation(3.4)) is approximated by the depth-integrated advection-diffusion equation(3.5).

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial z} - \frac{\partial}{\partial x} \left(\varepsilon_{s,x} \frac{\partial c}{\partial x} \right) - \frac{\partial}{\partial y} \left(\varepsilon_{s,y} \frac{\partial c}{\partial y} \right) - \frac{\partial}{\partial z} \left(\varepsilon_{s,z} \frac{\partial c}{\partial z} \right) = 0 \quad (3.4)$$

Where

c = mass concentration of sediment [kg/m^3]
 u, v and w = flow velocity components [m/s]
 $\varepsilon_{s,x}$, $\varepsilon_{s,y}$ and $\varepsilon_{s,z}$ = eddy diffusivities [m^2/s]

$$\frac{\partial h\bar{c}}{\partial t} + \bar{u} \frac{\partial h\bar{c}}{\partial x} + \bar{v} \frac{\partial h\bar{c}}{\partial y} - D_H \frac{\partial^2 h\bar{c}}{\partial x^2} - D_H \frac{\partial^2 h\bar{c}}{\partial y^2} = h \frac{\bar{c}_{eq} - \bar{c}}{T_s} \quad (3.5)$$

Where

h = water depth [m]
 $\bar{u}$, $\bar{v}$ = depth averaged velocity components in x- and y-directions [m/s]
 D_H = horizontal dispersion coefficient [-]
 $\bar{c}$ = depth-averaged sediment concentration [-]
 $\bar{c}_{eq}$ = depth=averaged equilibrium sediment concentration [-]
 T_s = adaptation time-scale [s]

Numerical stability

The Courant number (C) gives an indication of the numerical stability and accuracy. In models that have large differences in the geometry or coastline, the Courant number should not exceed a value of 10. The Courant number for two-dimensional models is defined as equation(3.6) (Stelling, 1984):

$$C = 2\Delta t \sqrt{gh \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right)} \quad (3.6)$$

Where

C = Courant number [-]
 Δt = time step [s]
 g = gravitational acceleration [m/s^2]
 h = local water depth [m]
 Δx = grid mesh size in x-direction [m]
 Δy = grid mesh size in y-direction [m]

By means of adjusting the time step the Courant number can be set. The Courant number reduces as the time step is decreased. However, the required computational time is increased when the time step is decreased. A time step of $\Delta t = 60\text{s}$ is sufficiently small not to violate the criterion $C \leq 10$, and it keeps the computational time to an allowable value.

Physical parameters

There is no variation in the temperature and salinity of the water (i.e. density differences are not taken into account). The sluices in the Afsluitdijk at Den Oever and Kornwerderzand discharge fresh water and in reality cause large density gradients in the Wadden Sea (Elias,

2006). In the model these discharges are not taken into account. For horizontal eddy viscosity (K) and diffusivity (N) values of $1 \text{ m}^2/\text{s}$ are taken. The bed consists of a spatially constant $D_{50} = 250 \mu\text{m}$. Table 3.5 shows the main physical and numerical parameter settings.

In 2D depth averaged flow (2DH) the bed shear stresses (τ_b) are expressed by a quadratic friction law (equation(3.7)):

$$\vec{\tau}_b = \frac{\rho_0 g \vec{U} |\vec{U}|}{C_{2D}^2} \quad (3.7)$$

Where

$$\begin{aligned} \vec{U} &= \text{depth averaged velocity magnitude [m/s]} \\ C_{2D} &= \text{two-dimensional Chézy coefficient [m}^{0.5}/\text{s]} \end{aligned}$$

From the two dimensional Chézy coefficient Manning's coefficient (n) can be determined with equation(3.8). For depth averaged modelling of sediment transports Chézy generally is preferred. This is because with Manning the channels suffer too much scouring. In this model a constant Chézy coefficient $C_{2D} = 63 \text{ m}^{0.5}/\text{s}$ is applied.

$$n = \frac{\sqrt[6]{H}}{C_{2D}} \quad (3.8)$$

Where

$$H = \text{water depth [m]}$$

Wind stresses

The interaction of the wind (U_{10}) with the water surface generates stresses (τ_s) on the water surface. In the model the wind stresses are expressed with equation(3.9):

$$|\tau_s| = \rho_a C_d U_{10}^2 \quad (3.9)$$

Where

$$\begin{aligned} \rho_a &= \text{air density [kg/m}^3\text{]} \\ U_{10} &= \text{wind speed 10m above the surface [m/s]} \end{aligned}$$

The drag coefficient (C_d) is defined with equation(3.10) (WL | Delft Hydraulics, 2006):

$$C_d(U_{10}) = C_d^A + (C_d^B - C_d^A) \frac{U_{10} - U_{10}^A}{U_{10}^B - U_{10}^A} \quad (3.10)$$

Where

$$\begin{aligned} U_{10}^A &= 0 \text{ [m/s]} \\ U_{10}^B &= 100 \text{ [m/s]} \\ C_d^A &= 0.00063 \text{ [-]} \\ C_d^B &= 0.00723 \text{ [-]} \end{aligned}$$

Table 3.5 Main numerical and physical parameters

Module	Parameter	Value	Description
<i>Flow</i>	Δt	60	flow time step [s]
	φ	1000	water density [kg/m ³]
	K	1	horizontal eddy viscosity [m ² /s]
	N	1	horizontal eddy diffusivity [m ² /s]
	C	63	Chézy coefficient [m ^{0.5} /s]
	Dryflc	0.1	threshold depth [m]
	ROUwav	FR84	stress formulation due to wave forces [-]
	CSTbnd	TRUE	boundary condition [-]
<i>Wave</i>	spectrum	JONSWAP	shape of spectrum [-]
	gamma1	3.3	peak enhancement factor JONSWAP spectrum [-]
	Set-up	FALSE	wave-related set-up [-]
	forcing	radiation stresses	computation of wave forces [-]
	generation mode	3 rd	generation mode for physics [-]
	breaking	B&J model	depth-induced breaking model [-]
	alfa1	1	coefficient for wave energy dissipation in the B&J model [-]
	gamma2	0.73	breaker parameter in the B&J model [-]
	triads (LTA)	FALSE	non-linear triad wave-wave interactions [-]
	bottom friction	JONSWAP	bottom friction formulation [-]
	coefficient	0.067	coefficient for bottom friction
	diffraction	FALSE	
	wind growth	TRUE	formulation for exponential wave growth [-]
	white capping	TRUE	formulation for white capping
	quadruplets	TRUE	quadruplet wave-wave interactions [-]
	ref	TRUE	refraction is activated for waves propagation in spectral space [-]
	freq	TRUE	frequency shift is activated for wave propagation in spectral space [-]
<i>Transport</i>	MORFAC	1	morphological scale factor [-]
	THRESH	0.05	threshold sediment thickness [m]
	EQMBC	TRUE	equilibrium sediment concentration profile at open boundary [-]
	DENSIN	FALSE	include effect of sediment on water density [-]
	AKSFAC	1	Van Rijn's reference height factor [-]
	RWAVE	2	estimated ripple height factor [-]
	ALFABS	1	longitudinal bed gradient factor for bed load transport [-]
	ALFABN	1.5	transverse bed gradient factor for bed load transport [-]
	SUS	1	current-related reference concentration factor [-]
	BED	1	current-related transport vector magnitude factor [-]
	SUSW	1	wave-related suspended sediment transport factor [-]
	BEDW	1	wave-related bed load sediment transport factor [-]
	SEDTHR	0.1	threshold depth for sediment computations [m]
	FWFAC	1	tuning parameter for wave streaming [-]
	Cref	1000000	reference density for hindered settling calculations [kg/m ³]
	RHOSOL	2650	density sediment [kg/m ³]
	CDryB	1600	dry bed density [kg/m ³]
	D ₅₀	250	median grain diameter [μm]

3.5 Model calibration

The tidal motion in the model is calibrated on the vertical and horizontal tide. For the vertical tide observation data is available for a number of stations in the Wadden Sea. For the horizontal tide, model results are compared to observations in the Texel inlet.

Vertical tide

The amplitudes and phases of the main tidal constituents as a result of the model and the observation data (RIKZ, personal communication) are compared. This is done for four stations (see Figure 3.9): Texel Noordzee, Terschelling Noordzee, Den Helder and Harlingen. Two gauges (Texel Noordzee and Terschelling Noordzee) are located in the North Sea, the Den Helder gauge is located in the Texel inlet and the Harlingen gauge is located in the back of the Wadden Sea.

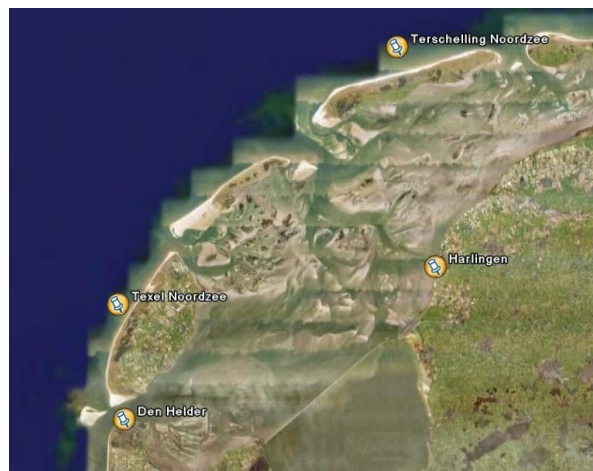


Figure 3.9 Locations of the tidal gauges

In Table 3.6 and Table 3.7 the amplitudes and phases are presented, for both observations and model results. In the Texel inlet the model underestimates the amplitude of the M_2 -constituent with 0.05m, yet in the back of the basin the dissimilarity is reduced to 0.01m.

Table 3.6 Observed amplitudes (A) and phases (ϕ) of the water levels at the tidal gauges

	station							
	<i>Texel Noordzee</i>		<i>Terschelling Noordzee</i>		<i>Den Helder</i>		<i>Harlingen</i>	
	A [m]	ϕ [°]	A [m]	ϕ [°]	A [m]	ϕ [°]	A [m]	ϕ [°]
M_2	0.78	189	0.89	234	0.66	190	0.83	278
O_1	0.10	197	0.09	205	0.10	203	0.10	235
K_1	0.08	358	0.07	2	0.07	6	0.08	38
Mu_2	0.08	270	0.07	319	0.08	273	0.11	356
N_2	0.12	172	0.15	210	0.10	172	0.13	260
L_2	0.07	16	0.07	67	0.07	15	0.08	109
S_2	0.23	256	0.25	296	0.18	258	0.21	353
M_4	0.10	239	0.09	331	0.11	221	0.11	98
MS_4	0.06	307	0.06	43	0.06	286	0.06	175
M_6	0.09	346	0.05	65	0.06	345	0.04	225

Table 3.7 Computed amplitudes (A) and phases (φ) of the water levels at the tidal gauges

	station							
	<i>Texel Noordzee</i>		<i>Terschelling Noordzee</i>		<i>Den Helder</i>		<i>Harlingen</i>	
	$A [m]$	$\varphi [^\circ]$	$A [m]$	$\varphi [^\circ]$	$A [m]$	$\varphi [^\circ]$	$A [m]$	$\varphi [^\circ]$
M ₂	0.74	189	0.90	230	0.61	188	0.82	274
O ₁	0.11	197	0.10	203	0.11	205	0.10	237
K ₁	0.09	9	0.08	15	0.09	18	0.08	57
Mu ₂	0.07	255	0.07	310	0.08	256	0.12	353
N ₂	0.11	172	0.12	202	0.09	180	0.10	266
L ₂	0.07	18	0.07	70	0.06	16	0.04	160
S ₂	0.21	257	0.24	292	0.16	262	0.20	355
M ₄	0.10	256	0.09	321	0.09	240	0.14	94
MS ₄	0.06	318	0.06	31	0.06	299	0.07	174
M ₆	0.06	346	0.06	38	0.04	340	0.03	226

Horizontal tide

In the Texel inlet, NIOZ ferry measurements have been carried out in the period between 1998 and 2003. An ADCP (Acoustic Doppler Current Profiler) was attached to the TESO ferry that sails between Den Helder and Texel, enabling the measurement of e.g. surface temperature, salinity and discharges. Table 3.8 shows the amplitudes and phases of the discharges in the Texel inlet, both the observation data and the model results. The NIOZ ferry measurements indicate a residual ebb-discharge through the Texel inlet of 2570m³/s, Rijkswaterstaat measurements indicate a residual ebb-discharge of 2230m³/s. In the model the tidal forcing induces a residual ebb-discharge of 2170m³/s. This is of the same order of magnitude as the Rijkswaterstaat measurements, but compared to the NIOZ ferry measurements the model underestimates the ebb-discharge with 18%.

Table 3.8 Observed and computed amplitude (A) and phases (φ) of the discharges through the Texel inlet

	Discharges through the Texel inlet			
	$A [m^3/s]$		$\varphi [^\circ]$	
	<i>NIOZ-ferry data</i>	<i>modelled</i>	<i>NIOZ-ferry data</i>	<i>modelled</i>
M ₂	67812	68096	155	146
O ₁	6350	5033	134	135
K ₁	6520	4949	353	314
Mu ₂	9054	8837	219	226
N ₂	10751	8081	122	135
L ₂	6941	4390	166	359
S ₂	18152	16211	253	225
M ₄	6682	7566	240	266
MS ₄	3404	3778	324	318
M ₆	6238	4524	371	343

3.6 Model limitations

The model has a number of limitations. They are listed below:

- *Depth averaged computations.* The size of the model does not allow fully three dimensional computations, as this would take too much computational time. For the scale of the study area the large-scale horizontal circulation patterns are assumed to be the most important. Three dimensional effects are of minor importance.
- *Density gradients.* As a result of the decision to calculate the flow patterns depth averaged, the density gradients cannot be taken into account. In reality the density gradient due to the fresh water discharges (from the sluices at Den Oever and Kornwerderzand) have a considerable effect on the sediment transports (Elias, 2006).
- *Fresh water discharges through the Afsluitdijk.* A two locations in the Afsluitdijk (at Den Oever and Kornwerderzand) fresh water from Lake IJssel flows into the Wadden Sea. On average this fresh water flow has a magnitude of $550\text{m}^3/\text{s}$. Research (Elias, 2006) shows that this inflow induces a vertical density gradient in the Texel inlet. This gradient increases the import of sediments through this inlet. The model applied in this research is depth-averaged, and is not able to reproduce vertical gradients. It cannot simulate the effects of the fresh water discharges, and therefore these discharges are not taken into account.
- *Time scale of the computations.* The time scale of the computations is in the order of a tidal cycle. The results of the sediment transports are initial responses of the system to the forcing. Long term adaptation of the system to the forcing is not possible with the model, as this would take too much computational time.
- *Schematization of the bathymetry.* The bathymetry is schematized with a spatially constant median grain diameter of $D_{50} = 250\mu\text{m}$. In reality the median grain diameter varies spatially. At locations with large flow velocities the grain generally is larger (e.g. in the channels). In shallower areas such as on tidal flats, where the tidal velocities are low, the grain can have a smaller diameter. At the fringes of tidal basins the flow velocities can be sufficiently small for very fine sediments ($D_{50} \leq 60\mu\text{m}$) such as silt and clay to settle. Figure 3.10 shows the distribution of the median grain size in the Western Wadden Sea.

In the same manner that the bed schematization overestimates the median grain diameter on the tidal flats, the grain size in the inlets in general is underestimated. Figure 3.10 shows that in the inlet the median grain diameter exceeds $300\mu\text{m}$. In the model, the transport rates through the inlets as a result of the advection mechanism are overestimated.

- *Grid size.* The study area comprises a considerable surface area. To prevent that the computational time is too large, the mesh grid size is rather coarse. This limits the schematization of the geometry.
- *Accuracy of the results.* The boundary effects in the model causes inaccuracies near the model boundaries. There the results are not trustworthy, and cannot be taken into account. However, the study area is located sufficiently far away from the boundaries, and the boundary conditions do not play a role.

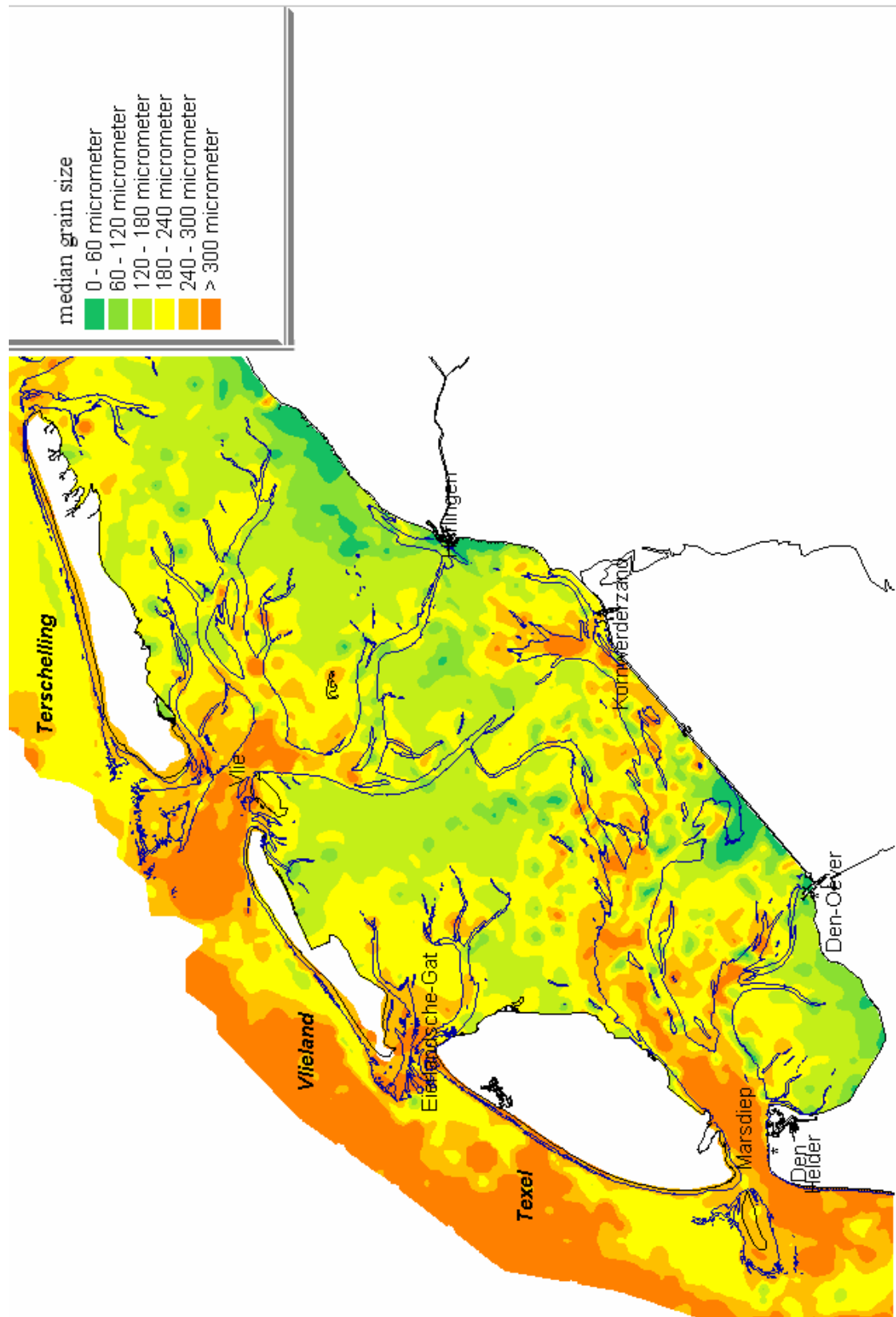


Figure 3.10 Distribution of the median grain size in the Western Wadden Sea (adapted from www.waddenzee.nl)

4 Forcing influence

In this chapter the influence of the different forcing agents on the sediment transport pattern is investigated. Three forcing agents are investigated, viz. tidal, wave and wind forcing. To dissipate discrepancies between the boundary conditions and the initial state conditions, the FLOW-module of DELFT3D has a spin-up time of two days. In case of simulations that include wave action (computed with the WAVE-module of DELFT3D) the spin-up time is increased with one tidal cycle (745min.). This is done to make sure that the wave effects on the flow are fully present in the model.

Section 4.1 investigates the influence of the tidal forcing on the sediment transport patterns. With respect to generating residual sediment transport, the most important tidal constituent is the M_2 in combination with its overtides M_4 and M_6 . The sediment transports as a result of forcing with these 3 constituents is compared to the sediment transports that are the result of the forcing of 55 constituents. These 55 constituents represent the complete tidal signal. The simulation with 3 tidal constituents has a length of one tidal cycle only, as this signal is constant. In the simulation with 55 constituents, however, the spring-neap effect due to the interaction between the M_2 and S_2 constituents is included. Therefore this simulation has a length of two spring-neap cycles, to include this effect.

The three basins are not completely singular. They are connected to each other in the sense that there is a residual flow from the Vlie inlet and the tidal divide behind Terschelling towards the Texel inlet. Rijkswaterstaat measurements indicate this residual flow has a magnitude of $2230\text{m}^3/\text{s}$, or 1% of the tidal prism. With the use of artificial tidal divides between the three basins this residual flow is excluded. In this way the influence of the connections between the basins is investigated. The location of the artificial tidal divides is shifted to see how the sediment transports react to the change in basin sizes. The simulations in this section are carried out with a forcing with the 3 constituents, implying a simulation time of one tidal cycle.

In section 4.2 wave forcing is added to the tidal forcing with 3 constituents. To investigate the influence of the wave height, the sediment transports as a result of four different wave heights ($H_s=1\text{m}$, $H_s=2\text{m}$, $H_s=3\text{m}$ and $H_s=4\text{m}$) from the northwest are determined. Figuur 2.7 shows that of the higher waves ($H_s \geq 3\text{m}$), a major part originates from this direction.

To investigate the influence of the angle of origin, an additional two simulation are applied. In one a wave with $H_s=2\text{m}$ from the southwest is implemented, in the other a wave with the same height from the north. In between these two directions the majority of the waves originates.

In all the simulations wavegrowth induced by wind action is allowed. Therefore the corresponding⁶ wind speed is applied in the WAVE-module. The wind is not applied to the FLOW-module, so the wind only influences the wave height, and not the flow.

The third forcing agent to investigate is wind. This is done in section 4.3. To investigate the influence of wind on the flow, and subsequently the sediment transport pattern, three simulation from section 4.2 are extended with wind forcing in the FLOW-module. Both the

⁶ Corresponding value: The value of the concerning parameter (e.g. wind velocity (U_{10})) that is most probable to occur simultaneously with another parameter (in this case wave height (H_s)).

large-scale and the local wind effects are taken into account. The model is well able to simulate the local wind effects, but it is too small to simulate the large-scale wind effects. To implement these effects a large-scale wind set-up (A_0) is prescribed to the boundaries. This wind set-up varies in space and its magnitude depends on the applied local wind speed and wave height. The values of the wind set-up are derived from the large ZUNO-Grof model (see appendix C). This model has simulated the water motion in the the southern North Sea as a result of tidal and wind forcing, for the year 1998. In this year, for each simulations a period of time is selected in which the wind conditions correspond to the ones implemented in the simulations itself. The tidal signal is subtracted from the total signal at the boundaries of the model, resulting in the large-scale wind set-up (A_0).

Three simulations are carried out in this section. In the first wind is implemented in the simulation with $H_s=2\text{m}$ from the southwest, in the second wind is implemented in the simulation with $H_s=2\text{m}$ from the northwest and in the last wind is implemented in the simulation with $H_s=4\text{m}$ from the northwest.

4.1 Tidal forcing influence

This section investigates the tidal influence on the sediment transports. Section 4.1.1 deals with the influence of the tidal motion representation. The tide is represented in two ways, a) only the semidiurnal lunar constituent (M_2) and its overtides (M_4 & M_6) are prescribed to the boundaries, and b) all the major constituents are prescribed to the boundaries.

In section 4.1.2 the connection between the three basins is excluded. This causes the basins to behave like autonomous basins. The difference in the resulting sediment transports of simulations with and without interaction of the basins gives an indication of the influence of this interaction. To investigate the influence of the location of the applied separations (and subsequently the size of the autonomous basins), three different simulations are carried out. In each of these three simulations, the separation between the basins has a different location. For the tidal representation only the M_2 , M_4 & M_6 constituents are prescribed at the boundaries.

4.1.1 Tidal representation

Results

In Table 4.1 the residual flow and imports and exports through the inlets are shown. The tidal divide “Terschelling” is grouped with the inlets because it is set as one of the boundaries of the study area. Table 4.2 shows the same information for the fluxes over the tidal divides.

For both tidal representations there is a residual discharge directed from the Vlie inlet and tidal divide “Terschelling” towards the Texel inlet (and in a lesser degree towards the Eierlandse Gat). The residual discharges are in both cases of the same order of magnitude.

Due to tidal forcing the Texel inlet is importing sediment, approximately a volume $2.6 \cdot 10^6 \text{ m}^3/\text{yr}$. The inlets of the Eierlandse Gat and Vlie are exporting due to the tidal flow. The representation of the tide has got little influence on the volume of annual tide-averaged export through the Eierlandse Gat. In both cases the annual tide-averaged export is around $0.6 \cdot 10^6$ to $0.8 \cdot 10^6 \text{ m}^3$. The export through the Vlie inlet increases with $\pm 0.8 \cdot 10^6 \text{ m}^3$ per year.

Table 4.1 Tidally averaged flow $\langle Q \rangle$ and annual tide-averaged sediment transports $\langle S \rangle$ through the inlets due to tidal forcing

Number of tidal constituents	Texel inlet		Eierlandse Gat inlet		Vlie inlet		Tidal divide "Terschelling"	
	$\langle Q \rangle$	$\langle S \rangle$	$\langle Q \rangle$	$\langle S \rangle$	$\langle Q \rangle$	$\langle S \rangle$	$\langle Q \rangle$	$\langle S \rangle$
	[m ³ /s]	[10 ³ m ³ /yr]	[m ³ /s]	[10 ³ m ³ /yr]	[m ³ /s]	[10 ³ m ³ /yr]	[m ³ /s]	[10 ³ m ³ /yr]
55	-2170	2584	-96	-804	1348	-2793	702	128
3	-1957	2417	-106	-595	1478	-2017	622	73

The annual tide-averaged transports over the tidal divides are small, regardless of the tidal representation. The magnitude is in the order of a few percent compared to the imports and exports that are transported yearly through the inlets.

Table 4.2 Tidally averaged flow $\langle Q \rangle$ and annual tide-averaged sediment transports $\langle S \rangle$ over the tidal divides due to tidal forcing

Number of tidal constituents	Texel basin → Eierlandse Gat basin		Texel basin → Vlie basin		Eierlandse Gat basin → Vlie basin	
	$\langle Q \rangle$ [m ³ /s]	$\langle S \rangle$ [10 ³ m ³ /yr]	$\langle Q \rangle$ [m ³ /s]	$\langle S \rangle$ [10 ³ m ³ /yr]	$\langle Q \rangle$ [m ³ /s]	$\langle S \rangle$ [10 ³ m ³ /yr]
55	-531	-65	-1597	8	-623	-85
3	-451	-34	-1498	-17	-631	-55

Residual flow

The tide induces a pattern of residual currents in the Wadden Sea. In general, water flows from the Vlie inlet towards that of Texel (see Table 4.1), but in more detail complex flow patterns are generated. This is illustrated by Figure 4.1, which shows the residual flow pattern as a result of the M₂M₄M₆ tidal representation. In the inlet of the Vlie there is a residual flood-discharge of 1478m³/s. This predominantly occurs around the tip of the barrier island of Vlieland. Through the ebb-channel in the inlet there is a residual ebb-flow. Note the circular pattern of the residual flow at the ebb-tidal delta region.

Through the ebb-channel of the Texel inlet there is a residual ebb-flow. Through this channel the residual ebb-discharge of 1957m³/s (originating from the Vlie inlet and the tidal divide "Terschelling") is conveyed.

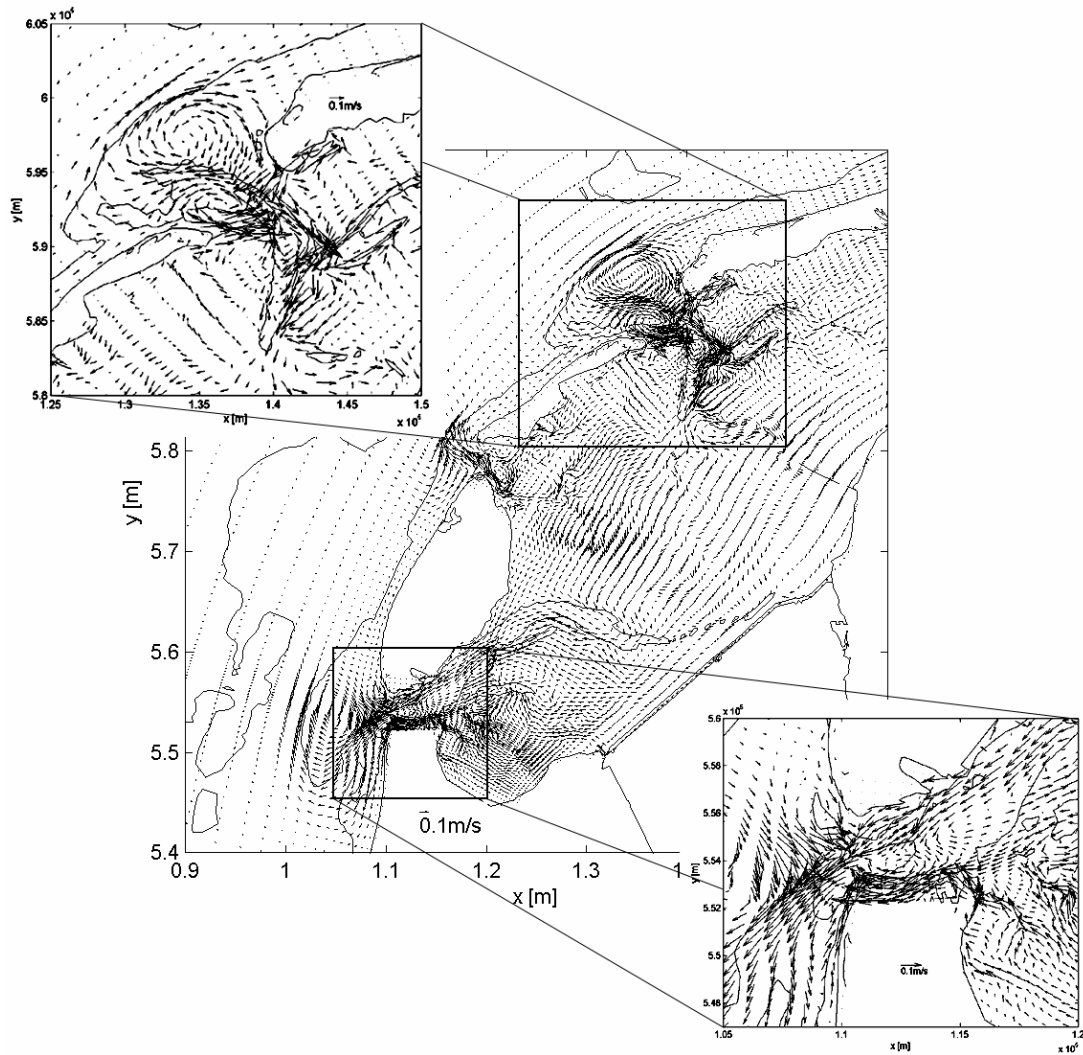


Figure 4.1 Residual flow pattern in the Western Wadden Sea

Transport mechanisms

The M_0M_2 residual flow driven sediment transport is shown in Figure 4.2, as well as the M_2M_4 tidal asymmetry driven sediment transports (see section 2.5 for elaboration on the mechanisms). A relation between sediment transport and flow velocity of $S \sim U^5$ is assumed. For both mechanisms the magnitude of the residual (over a tidal period) sediment transport is determined. The result gives no information on the amount of sediments that are transported, but it allows a comparison of the importance of the two mechanisms.

In the inlets of the Vlie and Eierlandse Gat the residual flow is dominant over the tidal asymmetry. In these inlets the maximum of the residual flow driven sediment transport is in the order of $0.4\text{m}^5/\text{s}^5$. The maximum of the tidal asymmetry driven transports is in the order of $0.1\text{m}^5/\text{s}^5$.

A dominance index (I_D) gives an indication which of the two mechanisms is dominant for the transport of sediments. The dominance index is expressed with equation(4.1) (Van der Molen and de Swart, 2001). It ranges between -1 and 1. When $I_D < 0$ tidal asymmetry is dominant, when $I_D > 0$ the residual flow is the dominating mechanism.

$$I_D = \frac{|S_{res}| - |S_{asym}|}{|S_{res}| + |S_{asym}|} \quad (4.1)$$

In the Texel inlet both mechanisms are of the same order of magnitude ($0.5 \text{ m}^5/\text{s}^5$). The dominance index (see Figure 4.2c) shows that on the fringes of the basins (i.e. near the tidal divides) the tidal asymmetry is dominant. In the channels and on the ebb-tidal delta the residual flow is the most important mechanism.

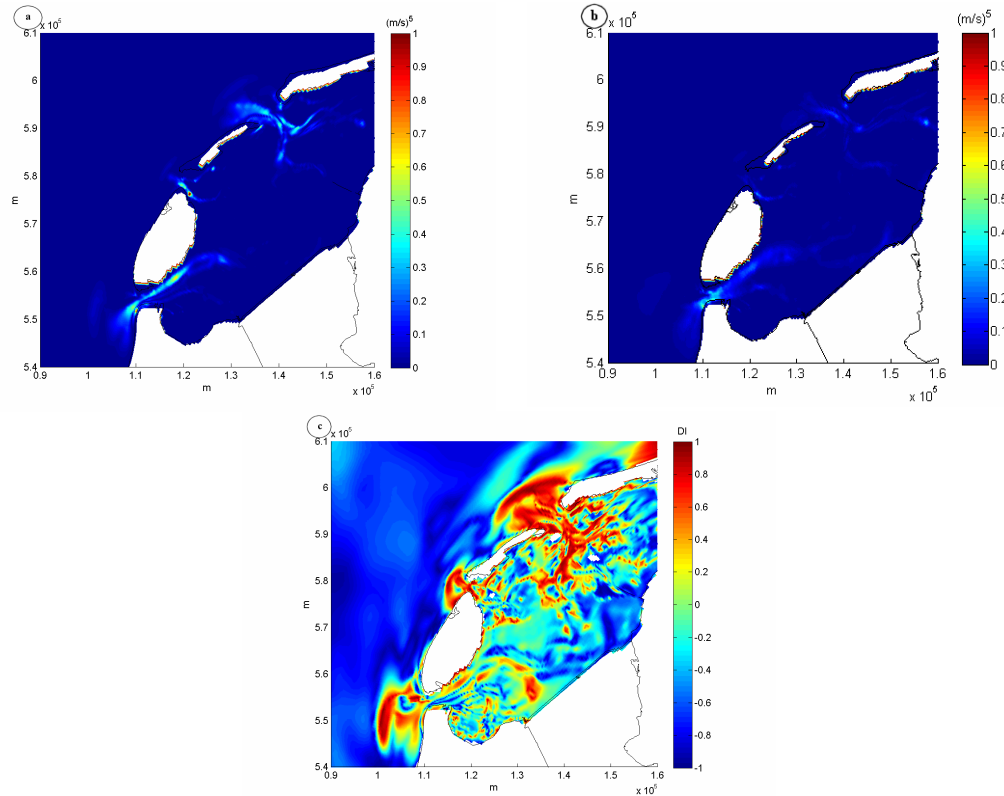


Figure 4.2 a) Magnitude of the M_0M_2 driven transport, b) Magnitude of the M_2M_4 driven transport and c) dominance index for the $M_2M_4M_6$ tidal representation

Texel inlet

Figure 4.3 shows the residual sediment transport pattern in the Texel inlet, together with the two transport mechanisms. This is done for both tidal representations. The patterns are the same for both representations. The transport due to the M_0M_2 residual flow is directed outward in the main ebb-channel, small import is induced south of this channel. The transport that is the result of the M_2M_4 asymmetry is directed inward at all locations in the Texel inlet.

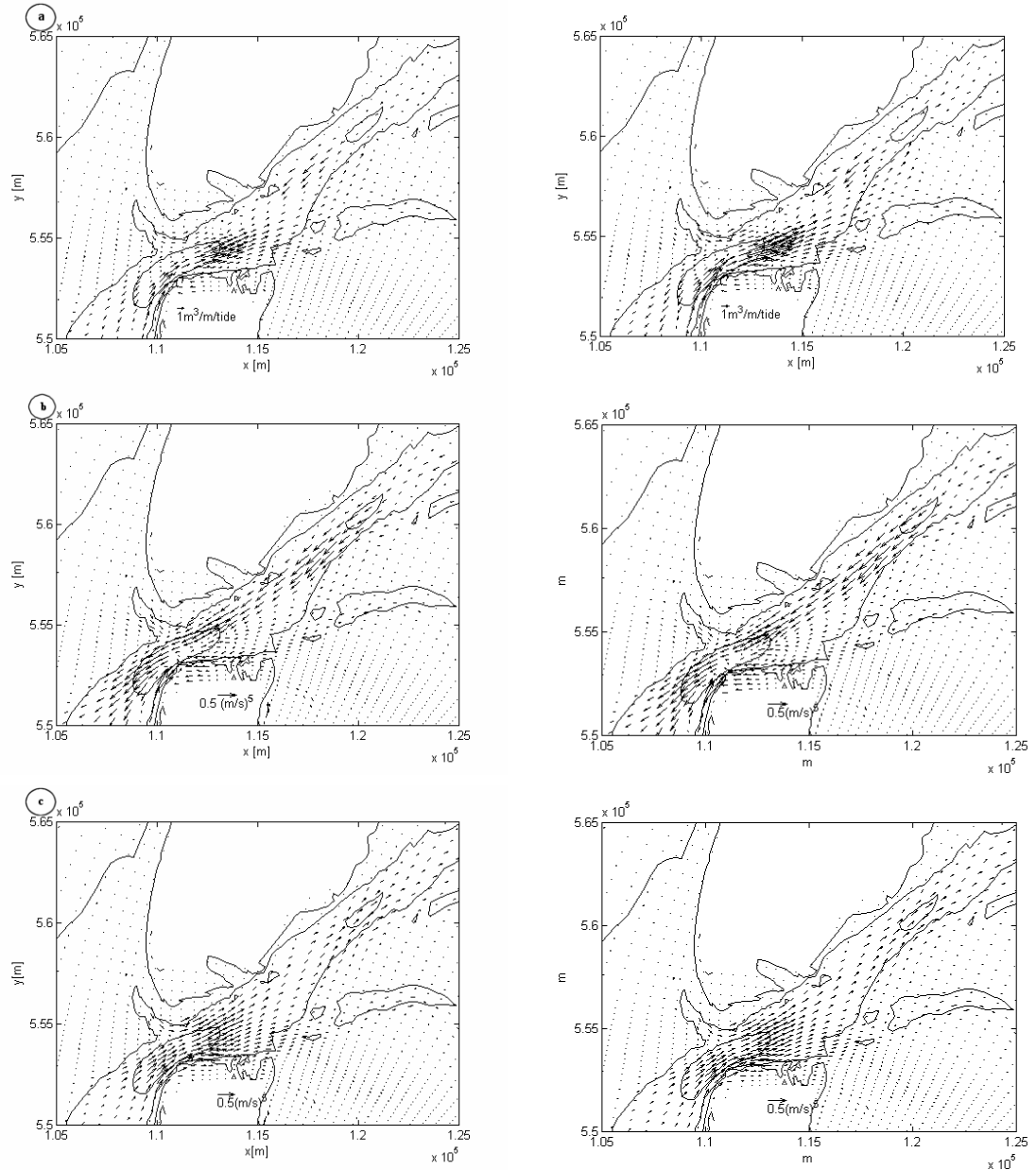


Figure 4.3 a) Residual sediment transport pattern, b) M_0M_2 driven transport pattern and c) M_2M_4 driven transport pattern. The figures on the left are the result of the $M_2M_4M_6$ tidal representation, on the right the result of the 55 constituents tidal representation

Vlie inlet

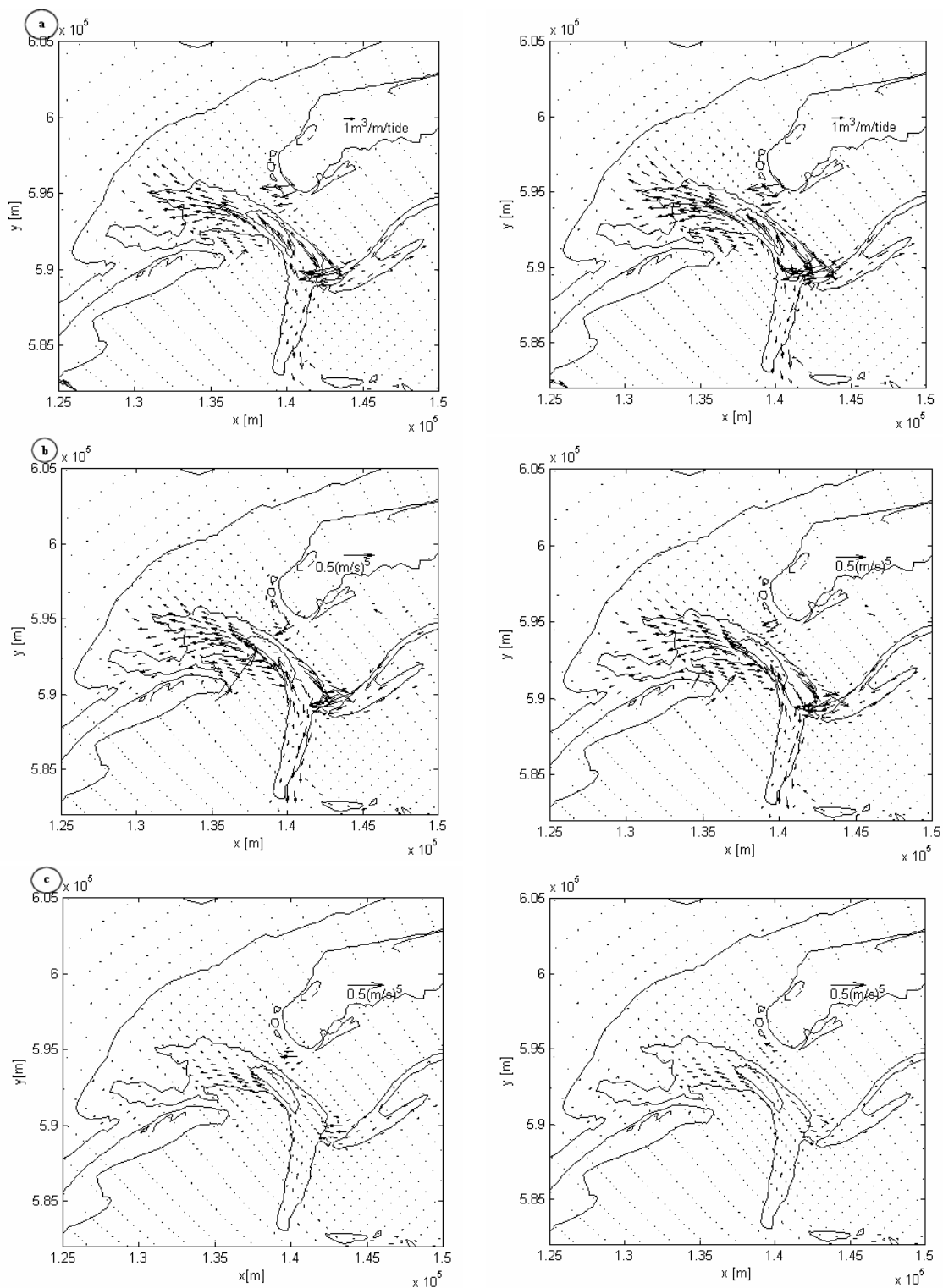


Figure 4.4 a) Residual sediment transport pattern, b) M_0M_2 driven transport pattern and c) M_2M_4 driven transport pattern. The figures on the left are the result of the $M_2M_4M_6$ tidal representation, on the right the result of the 55 constituents tidal representation

Figure 4.4 shows the residual sediment transport pattern for both tidal representations in the Vlie inlet. The figure shows the patterns of the transport mechanisms as well. All the export

of sediments takes place in the ebb-channel “Vliestroom”. Around the tips of the barrier islands, and especially around the tip of Vlieland, sediment is imported. Both the residual flow and the tidal asymmetry induce an export of sediments.

The difference in yearly export that is the result of the different tidal representation ($0.8 \cdot 10^6 \text{ m}^3$) is caused by the difference in outward directed M_0M_2 driven transport through the Vliestroom. This transport is larger when the tidal signal is represented with 55 than with 3 constituents.

4.1.2 Disconnection of the tidal basins

Location of the tidal divides

Figure 4.5 shows the location of the implemented tidal divides. The divide between the Vlie and the Ameland basin is placed at the same location for each simulation. In each simulation, the divide that separates the Texel and Eierlandse Gat basin is placed at the same location. Between the basins of Texel and Vlie, the tidal divide is placed at the same locations for the simulations #1 and #3. In simulation #2, this divide is moved more towards the Texel inlet.

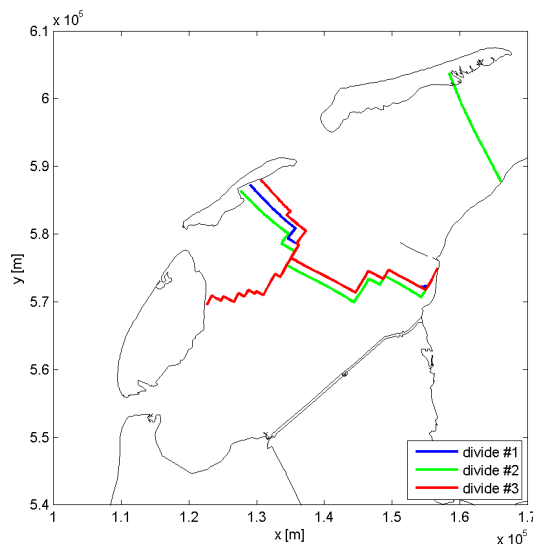


Figure 4.5 Locations of the applied tidal divides

Results

Table 4.3 shows the sediment transports through the inlet as a result of the implementation of the tidal divides. Positive values denote imports, negative export. In case of the two largest inlets, those of Texel and Vlie, the rate of transport is amplified by the disconnection of the basins. If there is no divide between the basins, the residual transport through the Texel inlet is an import of $2417 \cdot 10^3 \text{ m}^3/\text{yr}$. The implementation of the tidal divides increases the import to maximally $6421 \cdot 10^3 \text{ m}^3/\text{yr}$ (in case of the implementation of divide #2). Without tidal divides the Vlie inlet exports sediments at a rate of $2017 \cdot 10^3 \text{ m}^3/\text{yr}$. With tidal divides, the export through this inlet is enlarged to a maximum of $5773 \cdot 10^3 \text{ m}^3/\text{yr}$ (also in case of the implementation of divide #2).

The reaction of the sediment transport through the Eierlandse Gat inlet is less pronounced. Due to the implementation of divides #1 and #3, the initial export of $595 \cdot 10^3 \text{ m}^3/\text{yr}$ is

increased to $647 \cdot 10^3 \text{ m}^3/\text{yr}$ and $693 \cdot 10^3 \text{ m}^3/\text{yr}$ respectively. The implementation of a divide at the location of divide #2 reduces the export to $490 \cdot 10^3 \text{ m}^3/\text{yr}$.

Table 4.3 Annual tide-averaged sediment imports through the inlets

	Texel inlet Sediment import S [$10^3 \text{ m}^3/\text{yr}$]	Eierlandse Gat inlet Sediment import S [$10^3 \text{ m}^3/\text{yr}$]	Vlie inlet Sediment import S [$10^3 \text{ m}^3/\text{yr}$]
No divide	2417	-595	-2017
Divide #1	5641	-647	-4544
Divide #2	6421	-490	-5773
Divide #3	5663	-693	-3879

Sediment transport patterns in the inlets

Figure 4.6 shows the sediment transport patterns in the Texel inlet as a result of the simulations with and without the implemented tidal divides. In the inlet, the import rate shows a considerable increase as a reaction to the tidal divides. In the channel inside the basin (called the Texelstroom), sediment is transported towards the back of the basin when tidal divides are implemented.

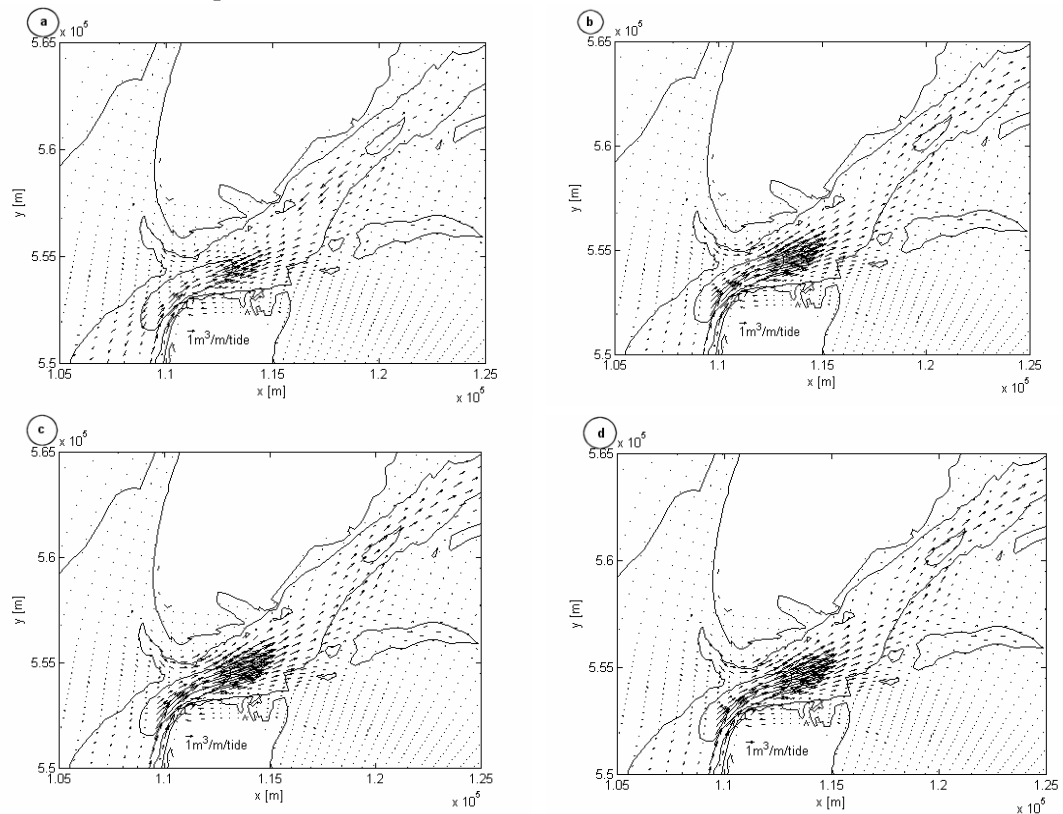


Figure 4.6 Sediment transport pattern in the Texel inlet as a result of a) no divide, b) divide #1, c) divide #2, d) divide #3.

Figure 4.7 shows the sediment transport patterns in the Vlie inlet as a result of the simulations with and without the implementation of the tidal divides. Due to the implementation of the divides, irrespective their exact location, the export rate through the ebb-channel increases. When there are no tidal divides, the southern channel in the basin transports sediment towards the back. However, when divides are implemented, this

transport changes direction. Sediment is transported, in this channel, from the basin towards the inlet.

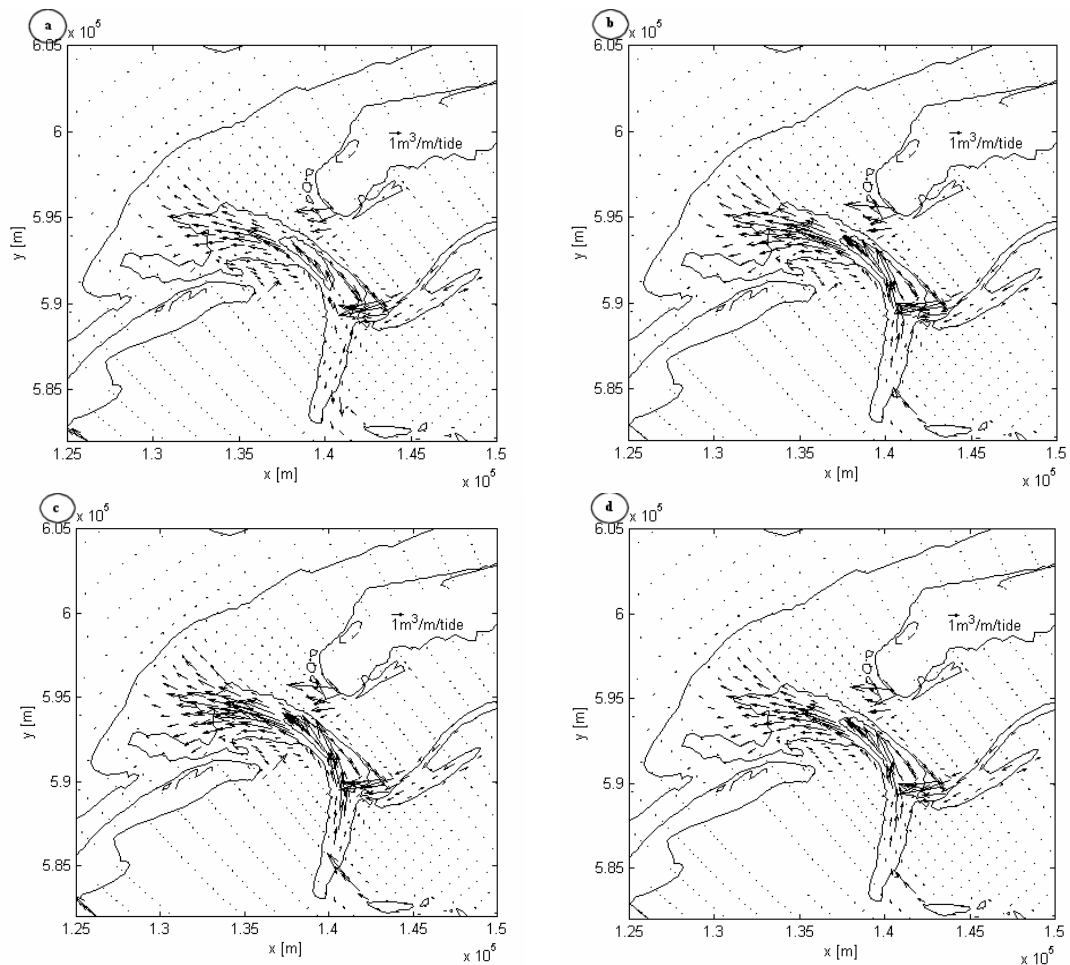


Figure 4.7 Sediment transport pattern in the Vlie inlet as a result of a) no divide, b) divide #1, c) divide #2, d) divide #3.

Discussion

Hydrodynamics

The implementation of the tidal divides eliminates the flow between the basins. This affects the magnitude of the residual flow through the inlets. The residual discharges are now zero, and the residual flow is generated by Stokes drift only (see section 2.5.1). Figure 4.8 shows the residual flow in the inlets as a result of the simulation without tidal divides, and as a result of the simulation with tidal divide #1. In the Texel inlet, the outward directed residual flow in the ebb-channel is reduced. This is caused by the elimination of the residual ebb-discharges of $1957\text{m}^3/\text{s}$, which in the simulation without tidal divides originate from the Vlie inlet and tidal divide “Terschelling”. Due to the implementation of the tidal divide, the Vlie inlet has to transport more ebb-discharges. Without tidal divides, the Vlie has a residual flood-discharge of $1478\text{m}^3/\text{s}$, which flows to the Texel inlet. The tidal divides disconnect the basins, and this discharge can only leave the Vlie basin through its own inlet. Therefore there no longer is a residual flood-discharge. The extra ebb-discharges take place in the ebb-channel of the Vlie inlet, and as a result the residual flow there is enlarged (see Figure 4.8).

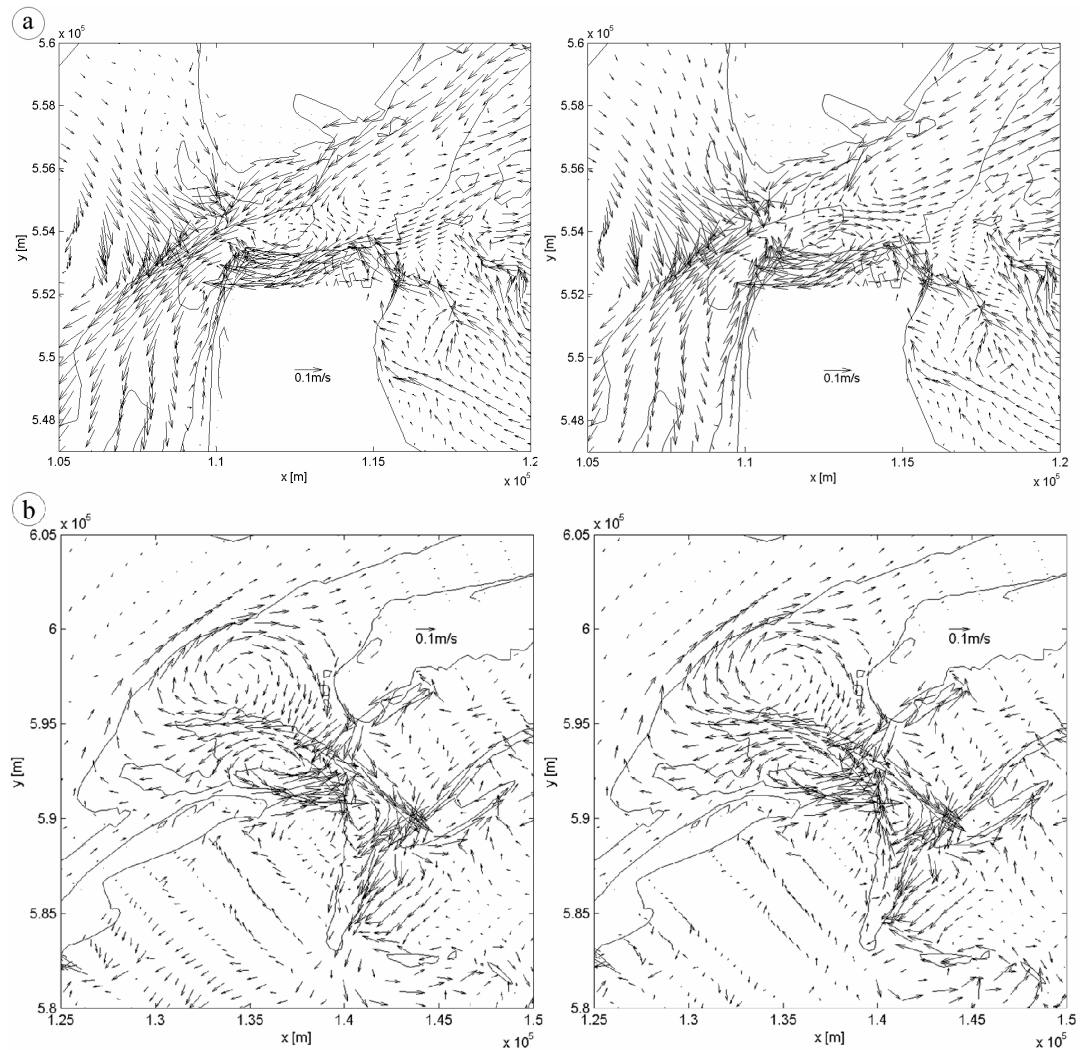


Figure 4.8 Residual flow as a result of the simulation without tidal divide (left) and with tidal divide #1 (right), a) in the Texel inlet and b) in the Vlie inlet

The change in the residual flow affects the magnitude of the transport induced by residual flow (see Figure 4.9) and tidal asymmetry (see Figure 4.10). In the Texel inlet, the outward directed transport of sediments generated by the M_0M_2 residual flow is reduced. The cause for this is the reduced residual flow (M_0). The inward directed sediment transport of sediments generated by the M_2M_4 tidal asymmetry is increased. The increase is largest in case of the implementation of tidal divide #2. Compared to the locations of the other divides; the location of this divide results in the smallest basin area. The area the Texel basin has lost mostly is flat area (see Figure 4.5). Now the Texel basin relatively has a larger channel area. This is counteracted by an increase of residual import of sediment (see Table 4.3). The extra import through the Texel inlet as a result of the implementation of tidal divide #2 ($6421 \cdot 10^3 \text{ m}^3/\text{yr}$ versus $\pm 5650 \cdot 10^3 \text{ m}^3/\text{yr}$ as a result of the other divides) is generated by the tidal asymmetry.

In the Vlie inlet, the magnitude of the M_0M_2 residual flow, in the ebb-channel is increased when the basins are disconnected. This mechanism is directed outward, and subsequently the more sediment is exported through the ebb-channel. In the same way as the location of tidal divide #2 results in the smallest area for the Texel basin, the Vlie basin is the largest when this divide is implemented. The extra area that the Vlie basin has gotten consists of

tidal flats. A larger part of the Vlie basin now consists of flats, and as a response the export through the inlet increases (see Table 4.3).

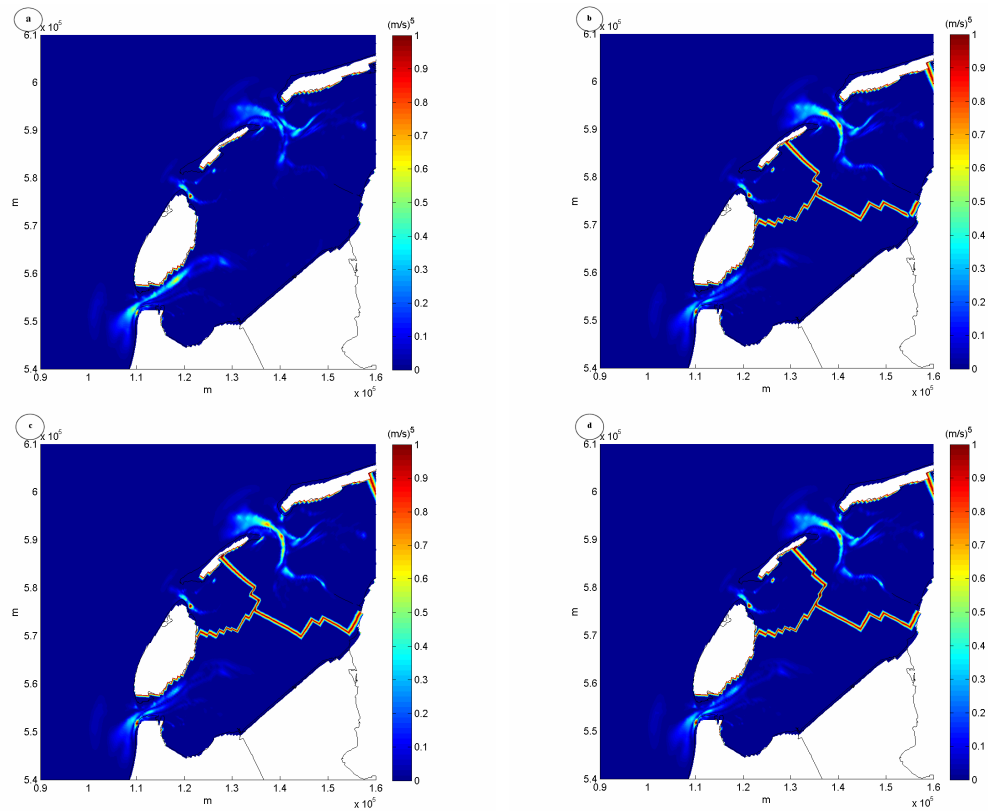


Figure 4.9 Amplitude of the M_0M_2 residual flow mechanism for a) no tidal divide, b) tidal divide #1, c) tidal divide #2 and d) tidal divide #3.

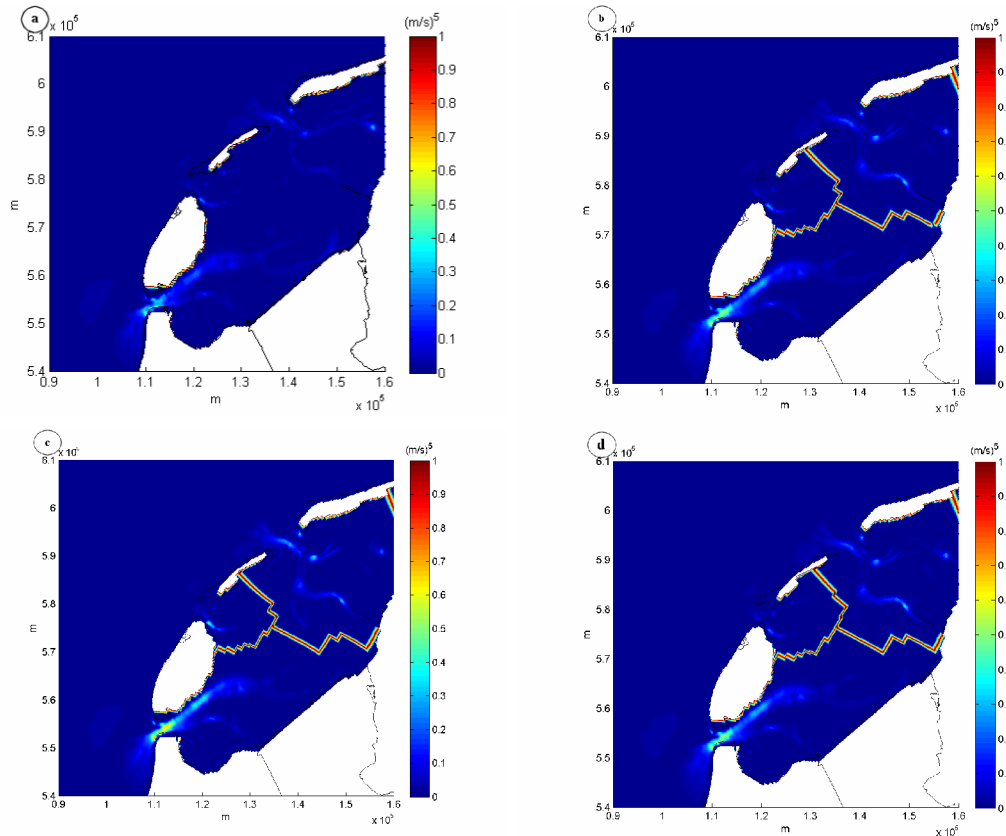


Figure 4.10 Amplitude of the M_2M_4 tidal asymmetry mechanism for a) no tidal divide, b) tidal divide #1, c) tidal divide #2 and d) tidal divide #3.

4.2 Wave forcing influence

4.2.1 Introduction

This section deals with the different types of influence waves can have on the sediment transport patterns. Wave height and wave direction are important parameters concerning the influence of the waves on the sediment transports. In this section the influence of both parameters is investigated. Waves of different heights and from different directions are prescribed at the boundaries, in combination with tidal forcing. This tidal forcing is represented with the M_2 , M_4 and M_6 constituents. The results of the influence of the wave height and angle are presented and discussed separately. The simulation with tidal forcing only is the reference simulation to which all the simulations in which wave forcing is implemented are compared.

In the WAVE-module of DELFT3D wind growth is allowed. The corresponding wind velocity (U_{10}) to the applied wave height is determined from the long-term statistics of the probability of occurrence of waves and wind (www.golflimaat.nl).

For the investigation of the wave height influence on the sediment transports, four different wave heights are applied. They all originate from the northwest. For the wave angle influence, the sediment transport as a result of waves coming from three different angles is investigated. Table 4.4 lists the prescribed boundary conditions for each simulation. The wave angle is related to the north, and the rotation clockwise. Simulations 1 to 4 are used to investigate the influence of the wave height investigation on the sediment transport, simulations 1, 2, 6 & 7 the wave angle influence.

Table 4.4 Prescribed forcing on the boundaries for the applied simulations

Simulation #	Tidal representation	H_s [m]	Angle [°]	Period T_p [s]	Wind velocity U_{10} [m/s]
1	$M_2M_4M_6$	-	-	-	-
2	$M_2M_4M_6$	1	315	6.05	5.05
3	$M_2M_4M_6$	2	315	7.12	7.77
4	$M_2M_4M_6$	3	315	8.09	10.63
5	$M_2M_4M_6$	4	315	9.06	13.05
6	$M_2M_4M_6$	2	225	7.12	7.77
7	$M_2M_4M_6$	2	0	7.12	7.77

4.2.2 Wave height influence

Results

Wave height distribution

The waves are prescribed at the boundaries, which are located at a distance of approximately 60 km from the study area. This implies that waves have a distance to cover before they influence the sediment transport patterns in the Western Wadden Sea. Figure 4.11 shows the wave height distributions (at an arbitrary point in time) in (the vicinity of) the Western Wadden Sea. For each boundary wave height the wave height in the study area has decreased, compared to the prescribed values at the boundaries.

The waves break on the shallow ebb-tidal deltas of the inlets and they are not more than 0.6m high inside the basins.

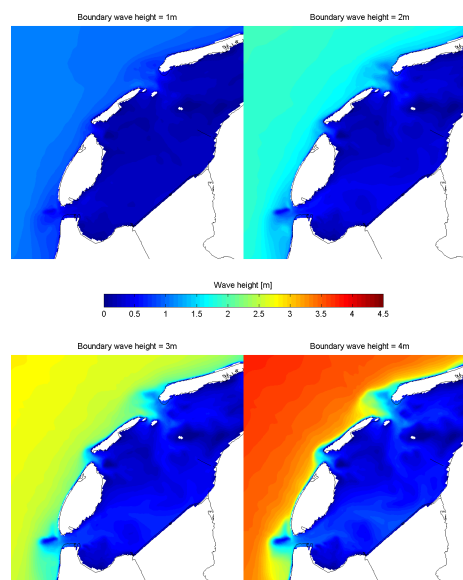


Figure 4.11 Wave height propagation in the study area for the different wave heights

Sediment transports

The annual tide-averaged sediment imports through the inlets and transports over the tidal divides are shown in Figure 4.12. These annual tide-averaged values are the tidally averaged fluxes over the cross sections, converted to yearly values. The reference result for the transports induced by tidal forcing is shown in red. The reaction of the import/export to the implemented wave height differs for each inlet. The changes of the fluxes through the inlets due to the wave implementation is shown in Figure 4.12a.

- *Texel inlet.* The addition of wave forcing to tidal forcing has a varying result on the yearly imports through the Texel inlet. For prescribed wave heights of up to $H_s=2\text{m}$, the import increases. The rate of import with an implemented wave height of $H_s=2\text{m}$ is $2817 \cdot 10^3 \text{ m}^3/\text{yr}$, compared to an import of $2334 \cdot 10^3 \text{ m}^3/\text{yr}$ as a result of tidal forcing only. When the prescribed wave height becomes larger than $H_s=2\text{m}$, the rate of import decreases again. Compared to the imports generated by tidal forcing alone, the implementation of the wave height with $H_s=4\text{m}$ causes a smaller annual tide-averaged import ($2155 \cdot 10^3 \text{ m}^3/\text{yr}$) through the Texel inlet.
- *Eierlandse Gat inlet.* In general, the addition of wave forcing to the tidal forcing decreases the net export generated by tidal forcing alone. Yet this effect is small, and there is no trend to it. The implementation of the smallest wave height ($H_s=1\text{m}$) reduces the net export (that is generated by tidal forcing) with $0.2 \cdot 10^6 \text{ m}^3/\text{yr}$. Yet, when the implemented wave height increases to $H_s=2\text{m}$ and $H_s=3\text{m}$, this reduction decreases (i.e. the net export increases again). This trend is broken with the implementation of a wave height with $H_s=4\text{m}$. This wave height causes a larger decrease of the export generated by tidal forcing.
The difference in the amount of yearly export of the separate simulations is small. The largest generated export through the Eierlandse Gat (induced by tidal forcing alone) is $0.6 \cdot 10^6 \text{ m}^3/\text{yr}$. The smallest export (induced by tidal forcing combined with waves with $H_s=1\text{m}$) amounts to $0.4 \cdot 10^6 \text{ m}^3/\text{yr}$.
- *Vlie inlet.* In case of tidal forcing alone there is a yearly export of about $2 \cdot 10^6 \text{ m}^3$. The addition of wave forcing to the tidal forcing has a distinct influence on the transport through the Vlie inlet. The addition of the smallest wave height of $H_s=1\text{m}$ already causes the net export to be converted into a small import of $0.3 \cdot 10^6 \text{ m}^3/\text{yr}$. This trend continues. When the added wave increases in height, the net import through the Vlie inlet increases as well. The implementation of waves with $H_s=2\text{m}$, $H_s=3\text{m}$ and $H_s=4\text{m}$ generates a net annual tide-averaged import of $2.4 \cdot 10^6 \text{ m}^3$, $4.4 \cdot 10^6 \text{ m}^3$ and $5.9 \cdot 10^6 \text{ m}^3$ respectively.
- *Tidal divide Terschelling.* The sediment imports induced by tidal forcing are small, especially compared to the millions of cubic meters yearly imported or exported through the inlets. The addition of waves has little to no effect; the annual tide-averaged sediment export over this divide does not exceed $73 \cdot 10^3 \text{ m}^3$. This is in the order of one percent of the imports through the inlets.

Figure 4.12b shows the influence of the implementation of the different wave heights on the sediment transports over the tidal divides. In case of forcing by tide only (shown in red), the transport over each of the three divides is small. The addition of the forcing by relatively low wave heights ($H_s=1\text{m}$ and $H_s=2\text{m}$) to the tidal forcing has little influence. The resulting transport over each divide remains small. The largest effect of these lower wave heights is on the transports over the tidal divide between the Texel basin and Eierlandse Gat basin. The addition of a wave with $H_s=2\text{m}$ causes a transport from the Eierlandse Gat to the Texel basin of $200 \cdot 10^3 \text{ m}^3/\text{yr}$, compared to a transport of $37 \cdot 10^3 \text{ m}^3/\text{yr}$ in the other direction generated by tidal forcing alone.

The addition of the higher waves to the tidal forcing has more influence on the sediment transports. The combination of tidal forcing and a wave height of $H_s=3\text{m}$ still has little effect

on the transport between the Texel and Vlie basin as well as that over the divide between the Eierlandse Gat and Vlie basin. Yet this combination generates an annual tide-averaged transport of $800 \cdot 10^3 \text{ m}^3$ directed from the Eierlandse Gat to the Texel basin. When a wave height of $H_s=4\text{m}$ is considered the transports over this divide increases to $1400 \cdot 10^3 \text{ m}^3/\text{yr}$. This value is of the same order of magnitude as the imports/exports through the inlets. This wave height increases the transports over the other divides as well. An amount of $170 \cdot 10^3 \text{ m}^3/\text{yr}$ is transported from the Vlie towards the Texel basin. $148 \cdot 10^3 \text{ m}^3$ of sediments per year is exchanged between Eierlandse Gat and Vlie basin.

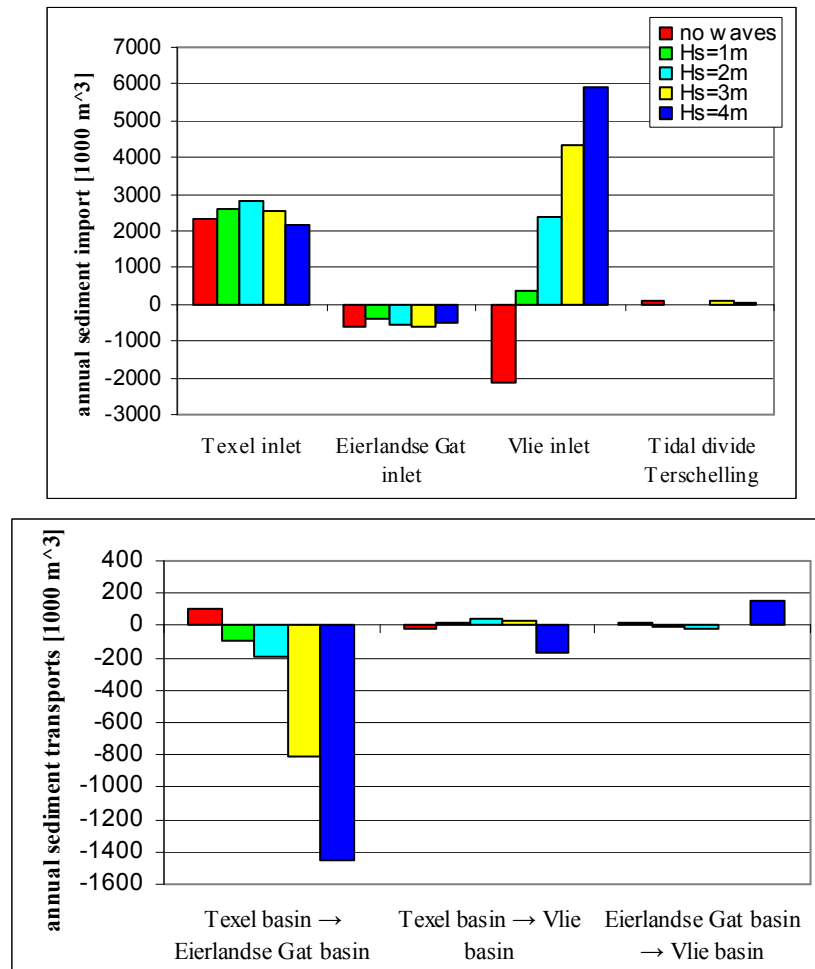


Figure 4.12 a) Annual tide-averaged sediment imports through the inlets and over the tidal divide “Terschelling”,
b) Annual tide-averaged sediment transports over the tidal divides

Transport pattern in the Texel and Vlie inlets

Figure 4.13a) to Figure 4.13e) show the sediment transport patterns in the inlets, generated by tidal forcing alone and by the addition of waves of the different heights. The reaction of the transport patterns to the different forcing in the two inlets are mentioned separately.

- *Transport patterns in the Texel inlet.* The addition of a wave with $H_s=1\text{m}$ (Figure 4.13b) increases the transport of sediment on the shallow ebb-tidal delta. This transport increases with the increase of the implemented wave height (see Figure 4.13c to Figure 4.13e). All the large changes in transport due to the implementation of waves occur on the northern part of the ebb-delta. This is due to the angle from which the waves

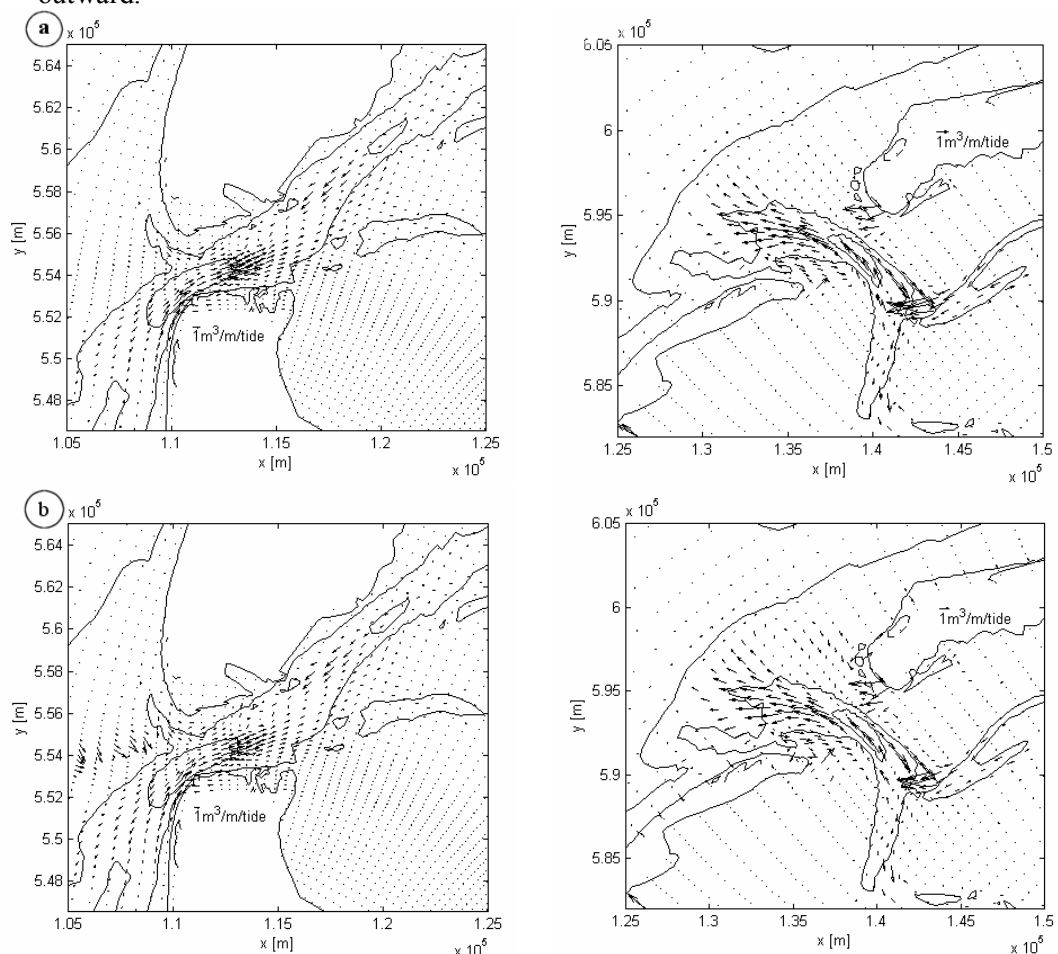
originate (northwest). The shallow ebb-delta has a sheltering effect. The waves break and have little influence on the southern part of the ebb-delta.

From the point that the added waves have a height of $H_s=2\text{m}$ or more, a parallel transport along the Texel beach can be distinguished. This is caused by the oblique angle of incidence the waves have, compared to the orientation of the Texel beach. When the waves break on the shallow beaches, a longshore current is generated. This current transports sediments, and in case of northwestern waves this transport is towards the Texel inlet.

Compared to the outward side of the inlet, the waves have little influence on the sediment transports inside of the Texel inlet.

- *Transport patterns in the Vlie inlet.* The added wave forcing has most effect on the shallow areas (i.e. the ebb-tidal delta and the beaches of the barrier islands). The effect of the wave forcing on the northeastern part of the ebb-delta already is visible when the waves have a height of $H_s=1\text{m}$ (Figure 4.13b). Due to the increase of the height of the implemented wave the sediment transports from the deeper areas towards the shallow ebb-delta and beaches increases considerably.

The oblique angle of incidence (described above) of the waves generates a current towards the Vlie inlet, from both sides. Due to this current, sediment from the beaches of both the island of Vlieland and Terschelling is transported through the inlet. The increase of sediment import through the Vlie inlet, that is shown in Figure 4.12a, occurs predominantly around the tips of the barrier islands. Through the ebb-channel “Vlietroom”, in the center of the inlet, the direction of the sediment transport remains outward.



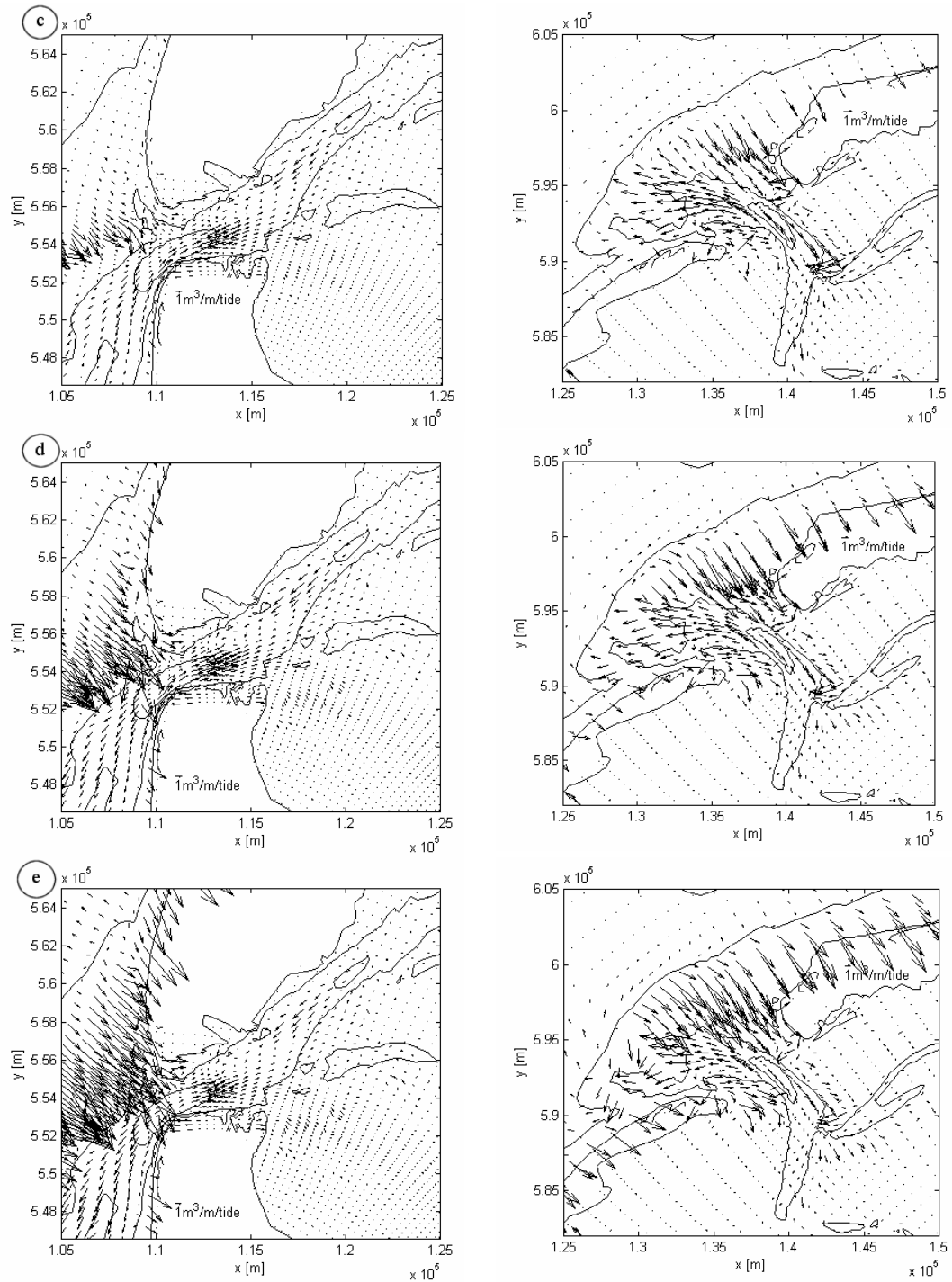


Figure 4.13 Sediment transport pattern in the Texel (on the left) and Vlie (on the right), a) Tidal forcing only, b) Forcing by tide and wave ($H_s=1\text{m}$), c) Forcing by tide and wave ($H_s=2\text{m}$), d) Forcing by tide and wave ($H_s=3\text{m}$) and e) Forcing by tide and wave ($H_s=4\text{m}$),

Discussion

Averaged bed shear stresses development

Due to the orbital motion of the waves, the bed shear stresses (τ_b) have increased. This effect is the largest in areas that are shallow, and it depends on the wave height.

Figure 4.14 shows the development of the tidally averaged bed shear stresses in the Western Wadden Sea that is the result of the addition of the wave forcing. The figure illustrates that the wave have little influence on the bed shear stresses inside the basins. It does not matter whether there is wave forcing and if there is, how high the wave is, the magnitude of the averaged bed shear stresses are comparable to the results of tidal forcing only. This implies that inside the basins the stirring-up effect of the waves is limited. The sediment concentration in the water column during ebb does not increase due to this effect. The stirring-up effect of the waves does not increase the export of sediments during ebb. The averaged bed shear stresses are most influenced by the addition of wave forcing on the ebb-tidal deltas. On the deltas of the Texel and Vlie inlet they are increased in the same areas as the sediment transports in Figure 4.13. Due to the orbital motion of the waves more sediment goes into suspension and is transported in the direction of the waves.

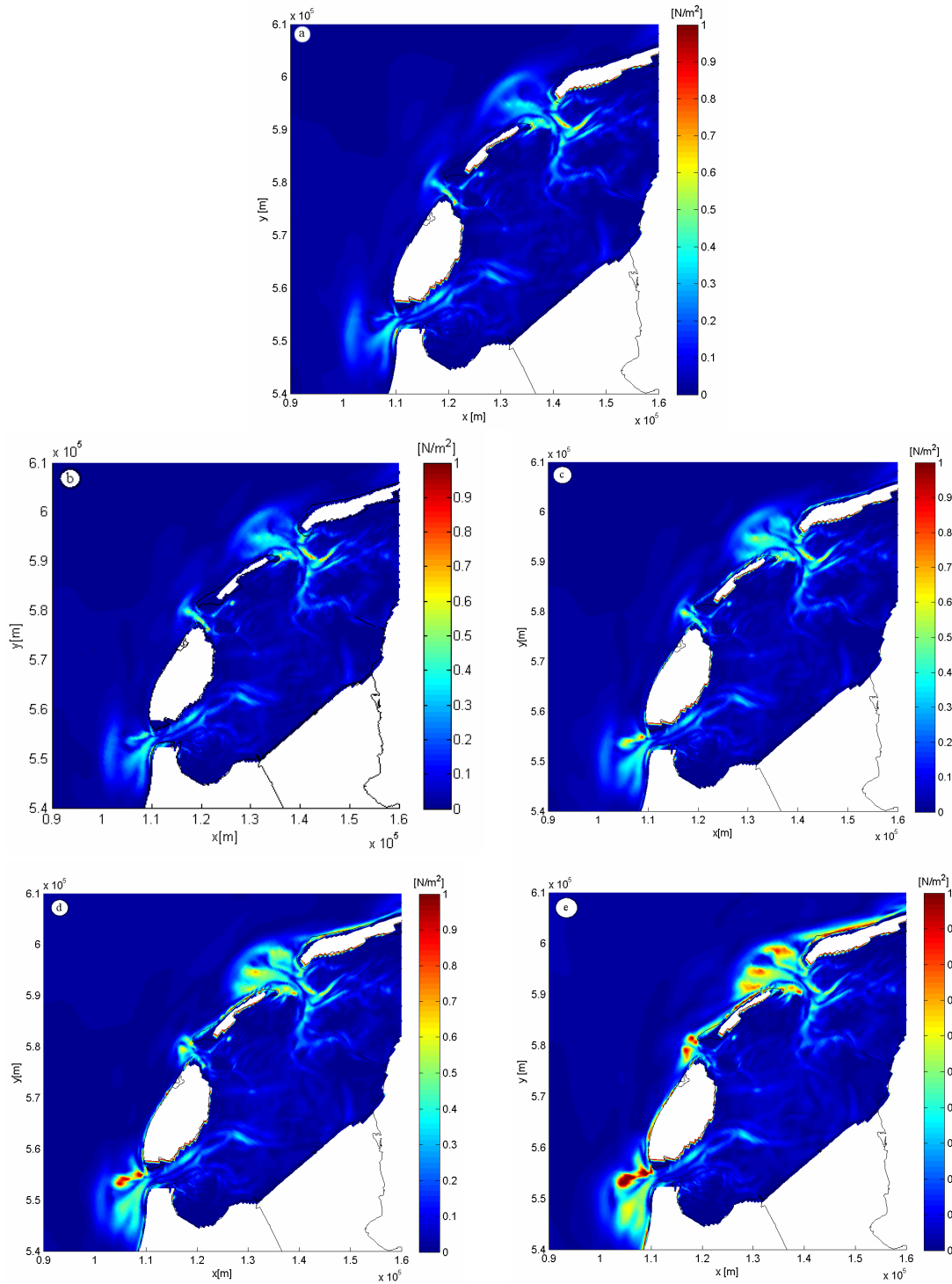


Figure 4.14 Average bed shear stresses as a result of a) tidal forcing only, b) tidal and wave ($H_s=1\text{m}$) forcing, c) tidal and wave ($H_s=2\text{m}$) forcing, d) tidal and wave ($H_s=3\text{m}$) forcing and e) tidal and wave ($H_s=4\text{m}$) forcing

Hydrodynamics

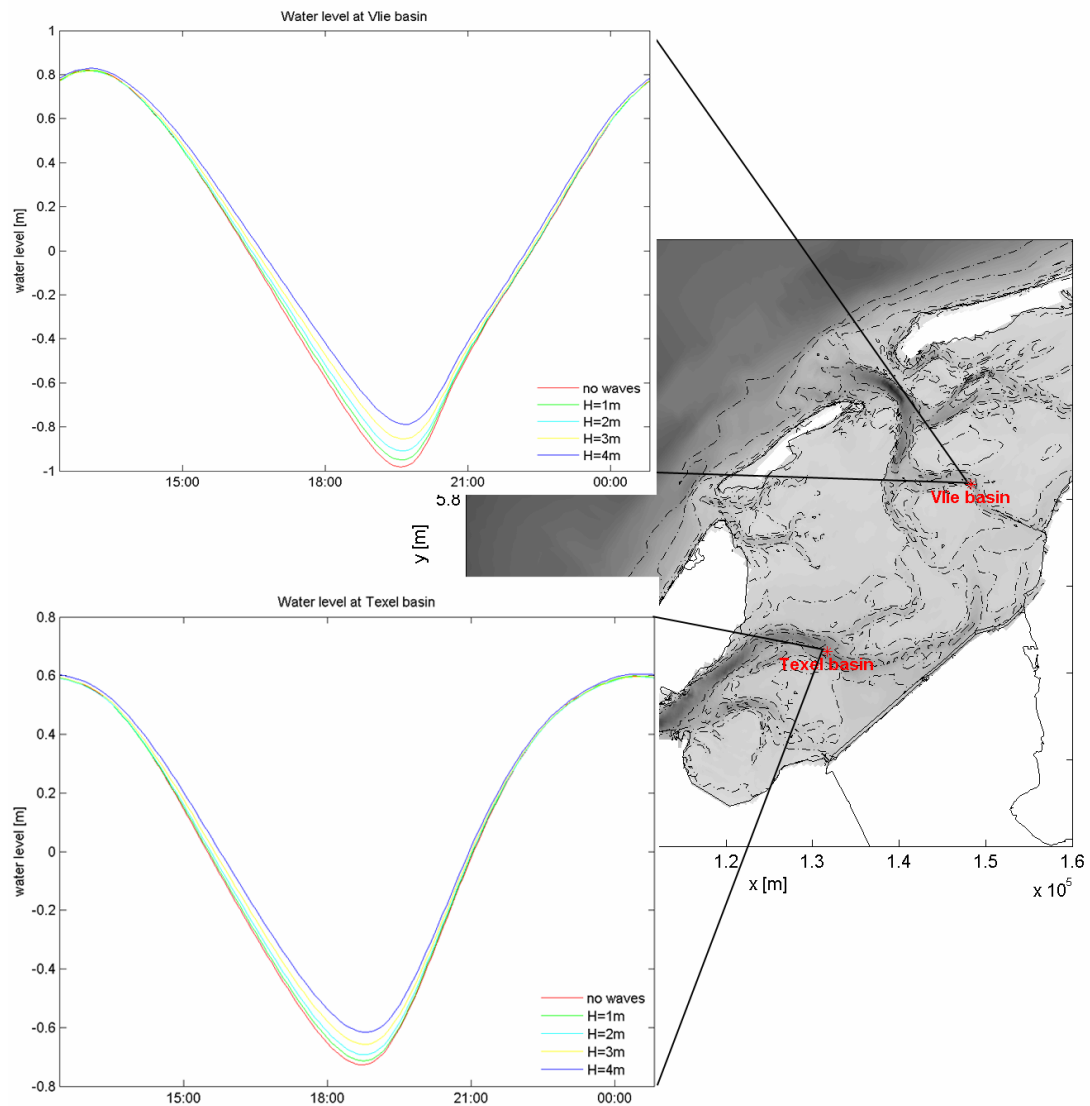


Figure 4.15 Tidal signal at locations Texel basin and Vlie basin

Figure 4.15 shows the tidal signal in the Texel and Vlie basin as a result of the five different prescribed types of forcing. The addition of waves causes a reduction of the tidal signal. This reduction of the tidal signal implies that the tidal prism reduces as well. Less water has to be imported during flood and exported during ebb through the inlets. The magnitude of the velocities in the inlets decreases. This is illustrated by Figure 4.16, where the velocities in the inlets are shown. The red graph denotes the velocities due to tidal forcing only. Due to the addition of wave forcing the velocities reduce, and the reduction becomes larger as the implemented wave height increases.

The decrease of the tidal range takes place in the form of a set-up of the water level at low water. The magnitude of this set-up depends on the size and angle of the incoming wave. A larger wave induces a larger water level set-up (see Figure 4.15). When an inlet is more exposed to the incoming waves the set-up is larger. This is illustrated by Figure 4.15, where the incoming wave originates from the northwest. The Vlie inlet is fully exposed to waves from this direction. However, the Texel inlet, for a large part, is sheltered from waves from

the northwest. This has its effect on the wave induced set-up in the basins. Comparing the situation with tidal forcing only (in red) with the combination of tidal forcing and a wave height $H_s=4\text{m}$ (in blue), the water levels in the basins react differently. The maximal set-up in the Texel inlet is 0.12m. In the Vlie inlet the maximal set-up is 0.19m.

This difference in water level set-up creates a gradient in the water level inside the basins. The set-up is most significant at low water, and this causes an increase in the residual flow directed from the Vlie inlet towards the Texel inlet. This is illustrated by Figure 4.17, which shows the residual discharges through the inlets. When northwestern waves are implemented, the residual discharges through the Texel inlet increase. This increase is larger when the incoming wave is higher, and the origin of the discharge is from the other two inlets and tidal divide “Terschelling”.

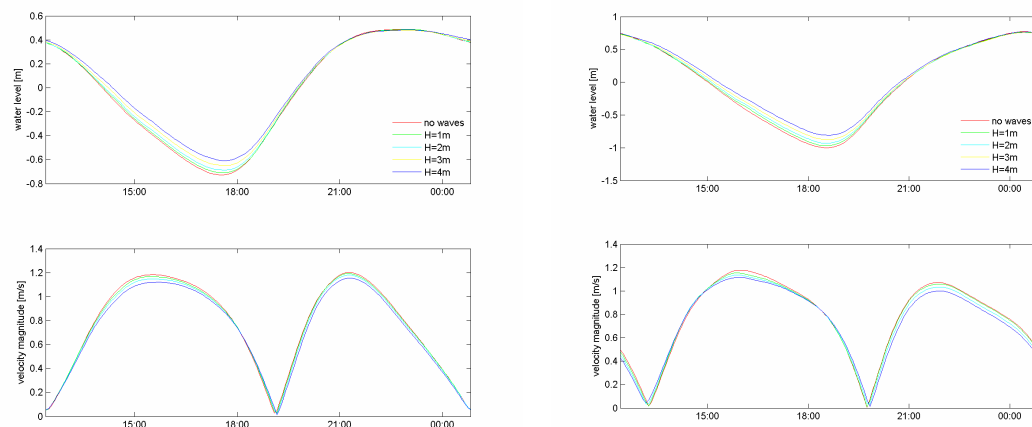


Figure 4.16 Water levels and velocities in the Texel inlet (left) and the Vlie inlet (right)

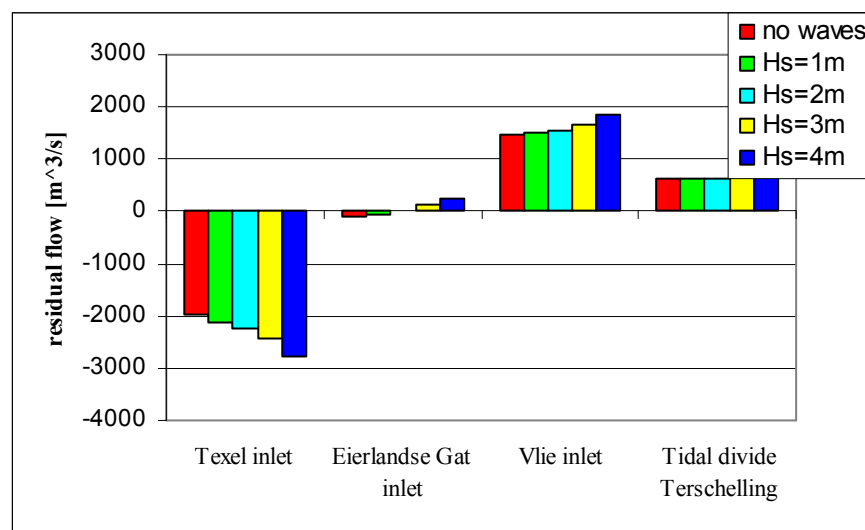


Figure 4.17 Residual discharge through the inlets.

The effect of the waves on the velocities in the basins also shows in the M_0M_2 residual flow and M_2M_4 tidal asymmetry mechanisms. The development of the magnitude of the M_0M_2 residual flow mechanism as a result of the implementation of the wave forcing is shown in Figure 4.18. The magnitude of this mechanism, in the Texel inlet, does not change a lot due to the implementation of wave forcing. The decrease of the M_2 -velocity (due to the decrease

of the tidal prism) is counteracted by the increase of the M_0 -velocity (due to the increase of the water level gradient in the basins). The implementation of the higher waves ($H_s=3\text{m}$ and $H_s=4\text{m}$) increases the M_0M_2 residual flow through the northern channel, located between the ebb-delta and the island of Texel. This channel is called the Molengat. The increase of the residual flow mechanism is caused by the oblique angle of incidence of the waves. They break when they approach the Texel beach. A longshore current is generated, and this is directed towards the Texel inlet.

The amplitude of the M_0M_2 residual flow in the ebb-channel of the Vlie inlet increases due to the implementation of the forcing of waves from the northwest. The flow is ebb-dominant in this channel, and the reduction of the velocities because of the reduced tidal prism is more significant during flood than during ebb (see Figure 4.16b). The ebb-dominance is more pronounced, implying a larger outward directed M_0M_2 residual flow mechanism.

The magnitude of the M_2M_4 tidal asymmetry shows more reaction to the implementation of the waves from the northwest. In the Vlie inlet, it reduces as the implemented wave height increases. In the Texel inlet, the tidal asymmetry mechanism is relatively constant for the lower wave heights ($H_s=1\text{m}$ and $H_s=2\text{m}$). When the implemented waves become larger ($H_s=3\text{m}$ and $H_s=4\text{m}$), the M_2M_4 tidal asymmetry amplitude decreases. The reduction of the M_2 -velocities in the inlet due to the decrease of the tidal prism is a non-linear effect. The reduction of the magnitude of the velocity due to the set-up induced by a wave with $H_s=4\text{m}$ is more than twice the reduction induced by a wave with $H_s=2\text{m}$ (see Figure 4.16b). The M_2M_4 tidal asymmetry is the importing mechanism in this inlet, and its decrease as a result of the forcing from the higher wave causes the rate of import to decrease as well (Figure 4.12a).

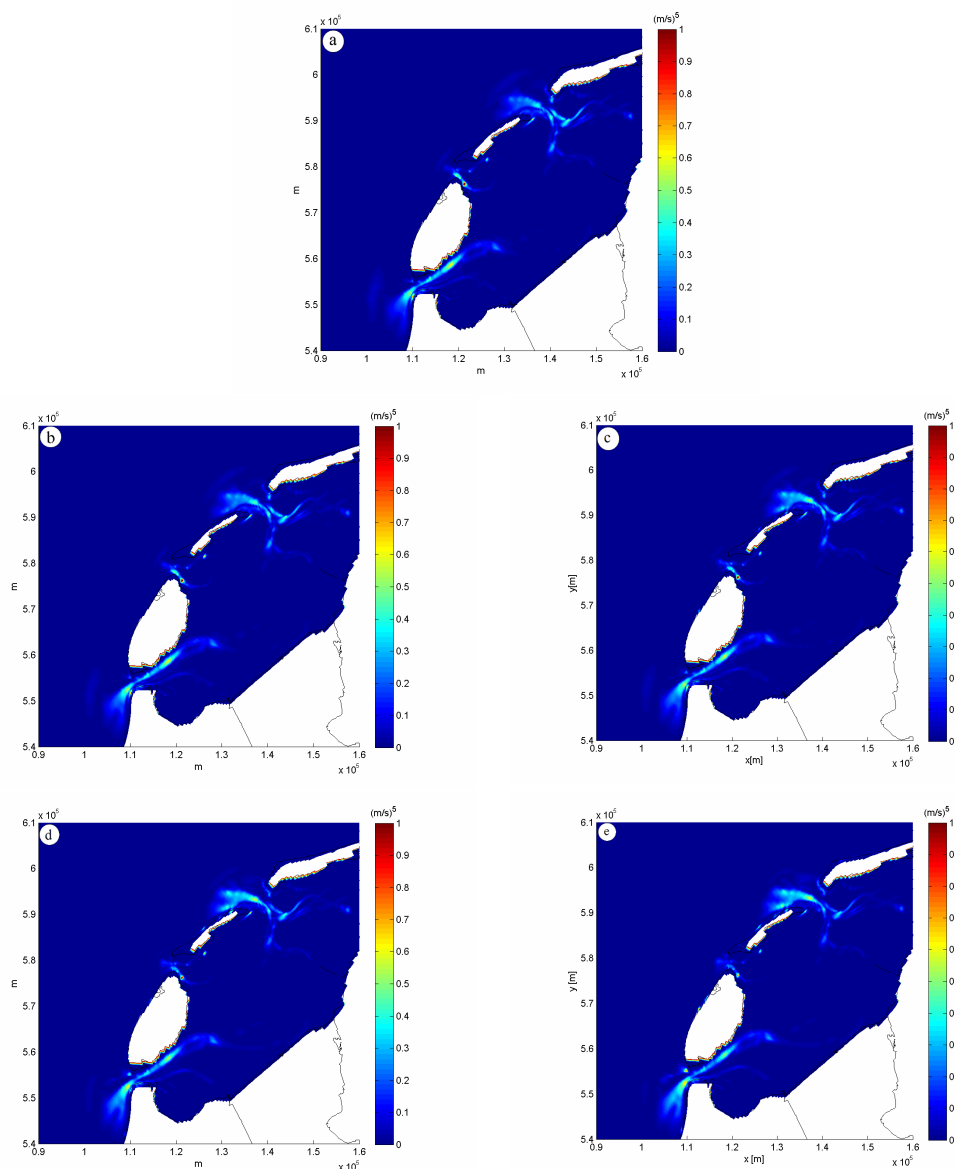


Figure 4.18 Amplitude of the M_0M_2 residual flow as a result of a) tidal forcing only, b) tidal and wave ($H_s=1m$) forcing, c) tidal and wave ($H_s=2m$) forcing, d) tidal and wave ($H_s=3m$) forcing and e) tidal and wave ($H_s=4m$) forcing

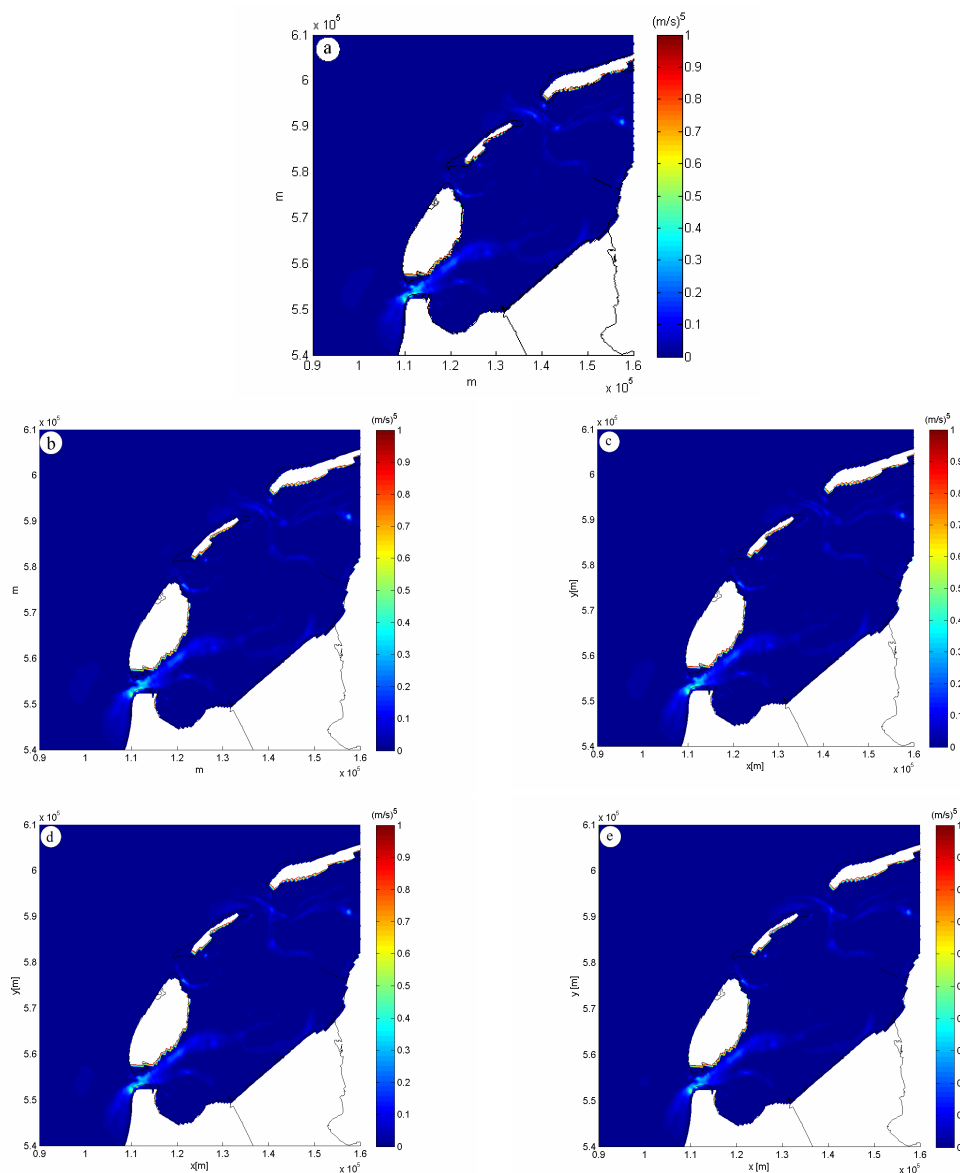


Figure 4.19 Amplitude of the M_2M_4 tidal asymmetry as a result of a) tidal forcing only, b) tidal and wave ($H_s=1m$) forcing, c) tidal and wave ($H_s=2m$) forcing, d) tidal and wave ($H_s=3m$) forcing and e) tidal and wave ($H_s=4m$) forcing

4.2.3 Wave angle influence

Results

Wave height distribution

In Figure 4.20 the wave height distributions in the Western Wadden Sea and its surroundings are shown, for each of the three applied wave angles, at an arbitrary point in time. The wave height inside the basins is not influenced by the angle of the wave. The height is equal for all three angles and it is not larger than $H_s=0.6\text{m}$. The wave height at the North Sea, near the barrier islands, varies with changing angles. Depending on the angle, the barrier islands and shallow ebb-tidal deltas have sheltering effects. In case of the southwestern waves ($\alpha=225^\circ$), the Vlie inlet and the adjacent beaches are sheltered by the islands of Texel and Vlieland. In the inlet and in front of the beaches the waves do not exceed a height of $H_s=1\text{m}$. However, due to this angle the waves are less hindered near the Texel inlet. The waves do not break as much, and the wave height in the inlet is higher, compared to the situation where the wave approach the inlet from another direction.

When the waves approach from the northwest ($\alpha=315^\circ$), and to a lesser degree from the north ($\alpha=0^\circ$), the inlet of the Eierlandse Gat and the Vlie are not sheltered by the barrier islands. Only their ebb-tidal deltas have some sheltering effect. Therefore, the wave height in these inlets is higher when the waves approach from these angles than when they come from the southwest.

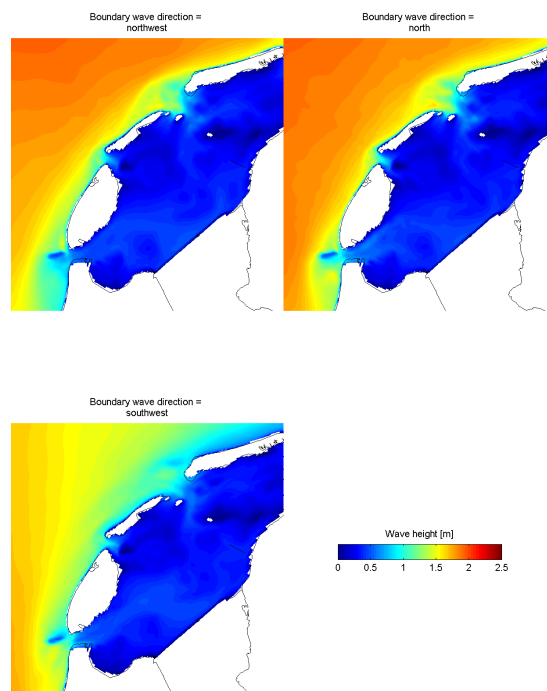


Figure 4.20 Wave height distribution as a result of waves with $H_s=2\text{m}$ coming from different angles

Sediment transports through the inlets and over the tidal divides

The combination of the tidal forcing with a wave with $H_s=2\text{m}$ generates a residual sediment transport through the inlet. Figure 4.21 shows the magnitude of these transports, as a result of tidal forcing only (red) and as a result of tidal forcing combined with the waves from the different directions. Positive values denote import, negative export through the inlet. The residual transports in each inlet show different responses to the different types of forcing.

- *Texel inlet.* The import of sediments through the Texel inlet increases the most when the added wave forcing has an angle of $\alpha=225^\circ$ (southwest). With waves coming from this direction, the import amounts $3355 \cdot 10^3 \text{m}^3/\text{yr}$. This is an increase of $1021 \cdot 10^3 \text{m}^3/\text{yr}$ compared to the import that is induced by tidal forcing only ($2334 \cdot 10^3 \text{m}^3/\text{yr}$). The rate of import is less when the waves approach from the northwest ($\alpha=315^\circ$), namely $2817 \cdot 10^3 \text{m}^3/\text{yr}$. This is still an increase of $483 \cdot 10^3 \text{m}^3/\text{yr}$ compared to the import generated by tidal forcing only. When the waves originate in the north, the tidal and wave forcing generate an import of $2130 \cdot 10^3 \text{m}^3/\text{yr}$. This is a decrease of $204 \cdot 10^3 \text{m}^3/\text{yr}$ compared to the imports generated by tidal forcing only.
- *Eierlandse Gat inlet.* Irrespective whether waves are present, and if they are, from which direction they originate, the Eierlandse Gat inlet is exporting sediments. Due to tidal forcing only, the export has a magnitude of $595 \cdot 10^3 \text{m}^3/\text{yr}$. If wave forcing is added, and the waves originate in the southwest, the export decreases to $356 \cdot 10^3 \text{m}^3/\text{yr}$. This is a decrease of $239 \cdot 10^3 \text{m}^3/\text{yr}$. The addition of waves coming from the northwest and north has less effect. Due to the addition of wave coming from the northwest the export reduces with $54 \cdot 10^3 \text{m}^3/\text{yr}$ to $541 \cdot 10^3 \text{m}^3/\text{yr}$. The effect of the northern wave is comparable; the export through the Eierlandse Gat inlet reduces with $46 \cdot 10^3 \text{m}^3/\text{yr}$ to an amount of $549 \cdot 10^3 \text{m}^3/\text{yr}$.
- *Vlie inlet.* The transports through the Vlie inlet react strongly to the implementation of wave forcing. As a result of tidal forcing only the Vlie inlet is exporting sediment with $2124 \cdot 10^3 \text{m}^3/\text{yr}$. The implementation of wave forcing, irrespective of the wave angle, counteracts this export and even generates a residual import through the Vlie inlet. The implementation of a wave with $H_s=2\text{m}$ from the southwest has the least effect, but the combination of this wave and tidal forcing results in an import of $124 \cdot 10^3 \text{m}^3/\text{yr}$. This is an increase of import of $2248 \cdot 10^3 \text{m}^3/\text{yr}$. The effect of the implementation of northwestern and northern waves is larger. Due to the implementation of the waves, in both cases the import increases with $4501 \cdot 10^3 \text{m}^3/\text{yr}$ to a residual import of $2377 \cdot 10^3 \text{m}^3/\text{yr}$.
- *Tidal divide Terschelling.* The implementation of forcing of a wave with $H_s=2\text{m}$ has little effect on the transports over this divide. The rate of transport remains small and marginal compared to the total volumes that pass the inlets.

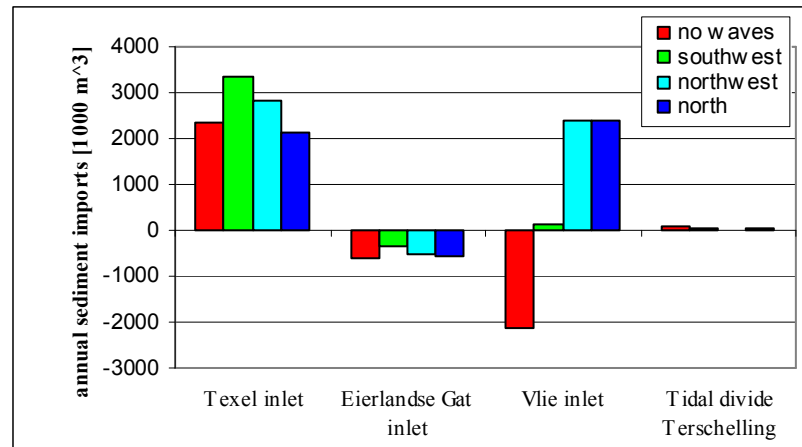


Figure 4.21 Imports through the inlets as a result of waves from different angles

Figure 4.22 shows the residual transports over the tidal divides as a result of the different types of forcing. Due to the implementation of wave forcing, there is a transport of sediments from the Eierlandse Gat to the Texel basin. Tidal forcing alone already induces a transport in the same direction ($34 \cdot 10^3 \text{ m}^3/\text{yr}$), but the implementation of wave forcing increases this magnitude to $\pm 200 \cdot 10^3 \text{ m}^3/\text{yr}$. In case of tidal forcing only, the Vlie basin transports sediment to the Texel basin. If wave forcing is added, this residual transport changes direction. If the added waves come from the southwest, the sediment transport from the Texel to the Vlie basin is $211 \cdot 10^3 \text{ m}^3/\text{yr}$. Due to the implementation of northern and northwestern waves the sediment transport is $59 \cdot 10^3 \text{ m}^3/\text{yr}$ and $37 \cdot 10^3 \text{ m}^3/\text{yr}$ respectively. The implementation of the northern and northwestern wave with $H_s=2\text{m}$ has little effect on the transport between the basins of the Eierlandse Gat and the Vlie. However, the transports over the divide that separates these basins react strongly when the implemented wave approaches from the southwest. Due to the waves the residual transport increases from $55 \cdot 10^3 \text{ m}^3/\text{yr}$ (tidal forcing only) to $506 \cdot 10^3 \text{ m}^3/\text{yr}$.

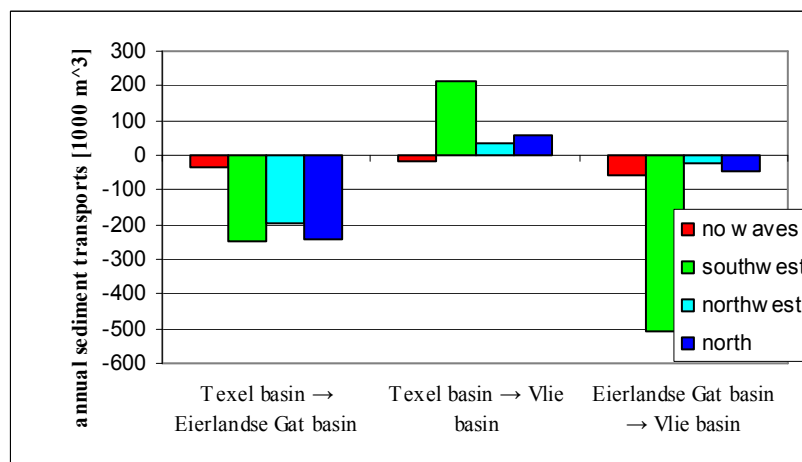


Figure 4.22 Annual tide-averaged transports over the divides as a result of different wave angles

Transport patterns in the Texel inlet

Figure 4.23 shows the sediment transport patterns in the Texel inlet as a result of the combination of tidal and wave forcing. Figure 4.23d shows the transport pattern in the Texel inlet due to tidal forcing only, which serves as reference. The waves, irrespective of their origin, have most influence on the transport in the outer delta region. The implementation of waves with $H_s=2\text{m}$ from the northwest (Figure 4.23a) and north (Figure 4.23b) induces an increase of transport from the northern part of the delta in southward direction. The increase of this flux is larger when the waves come from the northwest. This is the result of the fact that the area is better sheltered from the northern waves by the island of Texel.

When the waves approach from the southwest (Figure 4.23c), there is an increase of transport towards the shallow ebb-delta from the deeper areas located southwest of this delta. The import of sediments that takes place parallel to the Holland coast as a result of the tidal forcing is increased by the waves from the southwest. This increase of transport continues as far as into the Texel inlet itself. This is in correspondence with the results of the import over the transection in the inlet (Figure 4.21).

The implementations of the wave forcing from the three directions have in common that their influence is limited to the delta and inlet areas. Inside the Texel basin the pattern of the transport and its magnitude are not increased by the waves, irrespective the origin.

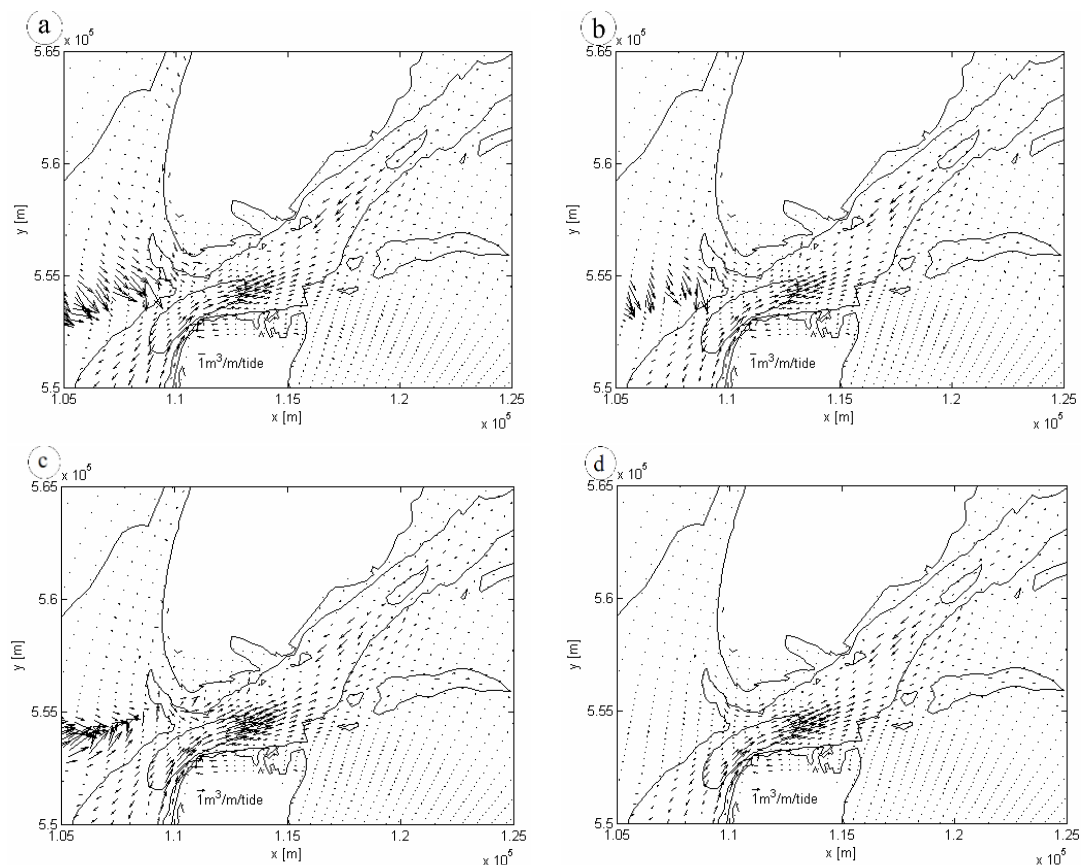


Figure 4.23 Transport pattern in the Texel inlet as a result of tidal forcing in combination with waves from a) northwest, b) north, c) southwest, d) no waves

Transport patterns in the Vlie inlet

Figure 4.24 shows the transport patterns that are the result of the tidal forcing with and without the wave forcing, in the Vlie inlet. The waves from the northwest (see Figure 4.24a) and north (see Figure 4.24b) have the most effect on the sediment transport pattern. The transports on the shallow ebb-tidal deltas are increased considerably. The same effect is visible at the beach of the island of Vlieland, where the waves transport sediments from the deeper areas towards the shore. The residual transport through the ebb-channel in the inlet remains exporting. The import around the tips of the barrier islands is increased by the northern and northwestern waves. This increase is the largest around the island of Terschelling.

Compared to waves from the other two directions, southwestern waves have less influence (see Figure 4.24c). The large sediment transport on the ebb-tidal delta, that is the result of the northern and northwest waves, is absent when the waves come from the southwest. The southwestern waves increase the import of sediment around the tip of the island of Vlieland. Because of this increase the export through the ebb-channel is counteracted. The residual transport through the Vlie inlet is an import of $124 \times 10^3 \text{ m}^3/\text{yr}$ (see Figure 4.21).

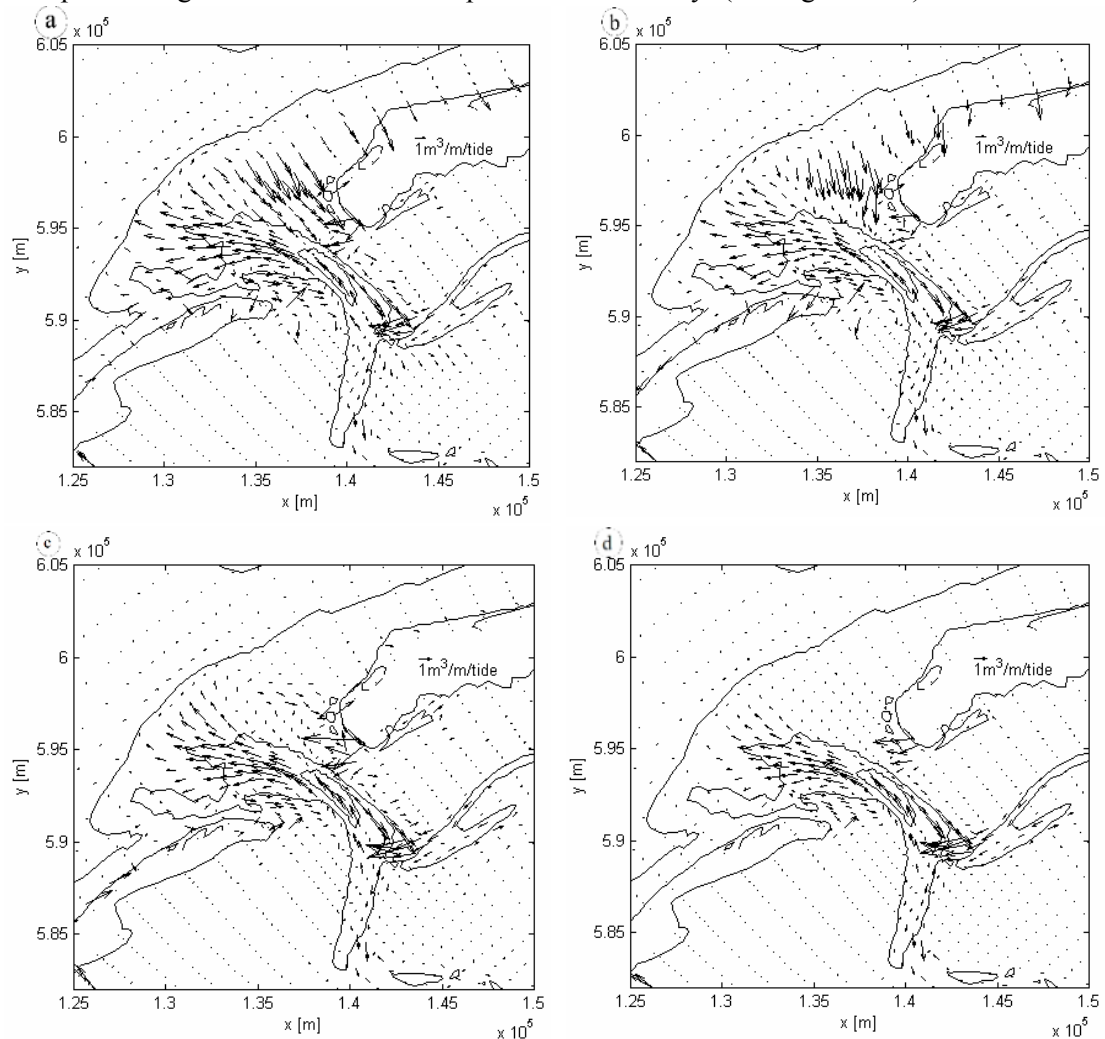


Figure 4.24 Transport pattern in the Vlie inlet as a result of tidal forcing in combination with waves from a) northwest, b) north, c) southwest, d) no waves

Discussion

Averaged bed shear stresses development

Figure 4.25 shows the bed shear stresses, averaged over a tidal period. This is done for the simulations including wave forcing (each wave angle) and the simulation with tidal forcing only. Compared to the bed shear stresses as a result of tidal forcing only, the northern and northwestern waves cause an increase in the average bed shear stresses at the ebb-delta of the Vlie inlet. In this shallow area the waves have large influence, generating a sediment transport from deeper towards the shallower areas. This explains the increase in sediment transport induced by the northern and northwestern waves shown in Figure 4.24a and b. The large increase in bed shear stresses on the ebb-delta also causes more sediments to go into suspension (the stirring-up effect of the waves), which can be imported into the basins during flood. This effect is most distinct around the tips of the barrier islands, where the flow is flood dominant. Figure 4.24a and b show the increase in transport at these locations. When the waves originate in the southwest the increase in averaged bed shear stresses at this location is absent (see Figure 4.25c). The ebb-delta is sheltered from these waves by the barrier islands of Texel and Vlieland. The waves are not as high as the waves coming from other directions, and the increase of bed shear stresses due to the orbital motion of the waves is not as distinct. As a result the change in sediment transports at that location is not changed due to southwestern waves.

The averaged bed shear stresses at the ebb-tidal delta of the Texel inlet are increased due to the implementation of the wave forcing. This applies to each of the three wave angles. The exact location of the increase of the bed shear stresses is dependent on the wave angle. The waves coming from the north and northwest increase the bed shear stresses at the northern side of the ebb-delta, whereas the southwestern waves have more influence on the bed shear stresses located south to west of the ebb-delta. The wave transport sediments parallel to their direction, as illustrated in Figure 4.23.

The increase of the averaged bed shear stresses due to waves inside the basins is small for each of the wave angles. This implies that there is little stirring-up effect in the basins, and subsequently little extra sediment goes into suspension to be exported during ebb.

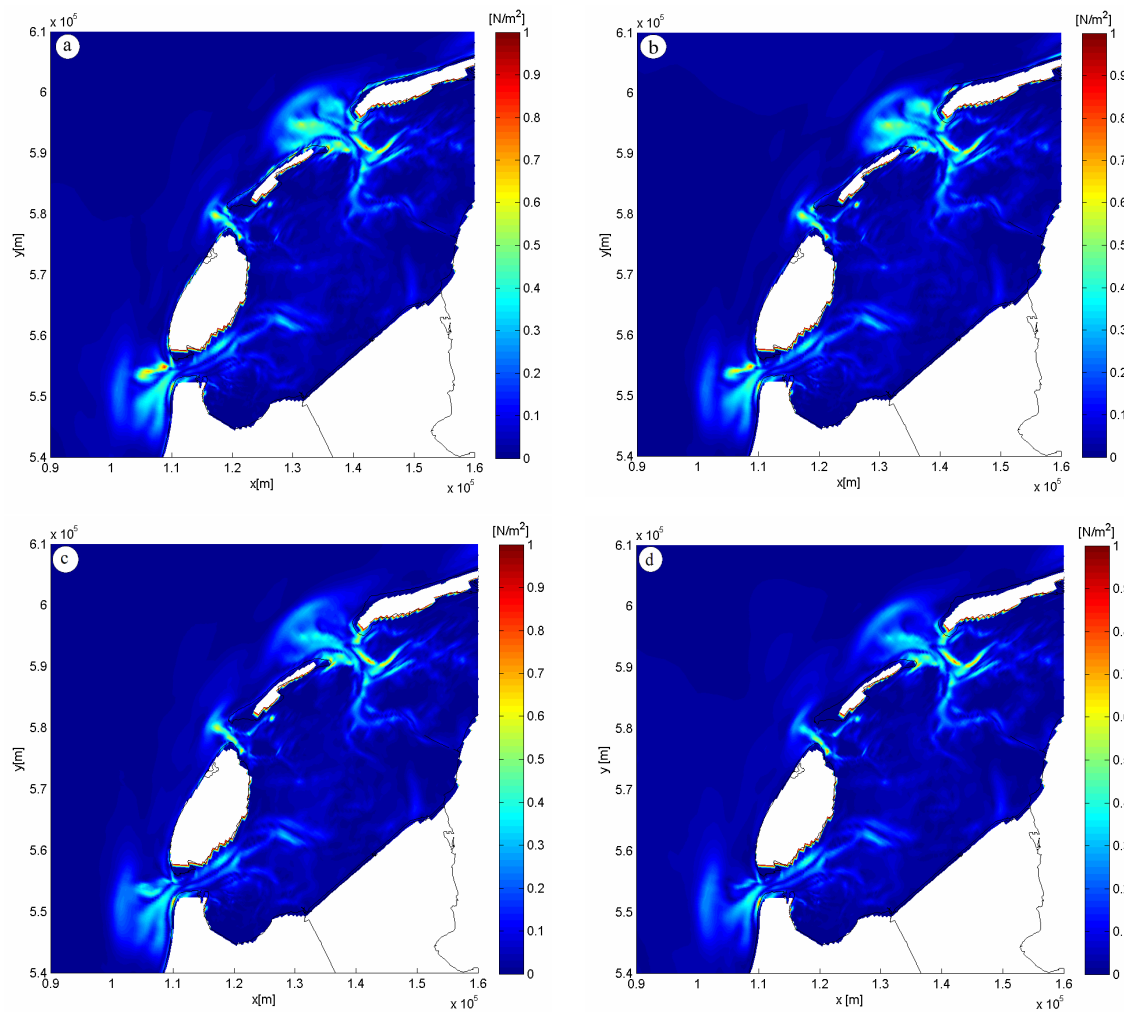


Figure 4.25 Averaged bed shear stresses as a result of tidal forcing in combination with waves from a) northwest, b) north, c) southwest, d) no waves

Hydrodynamics

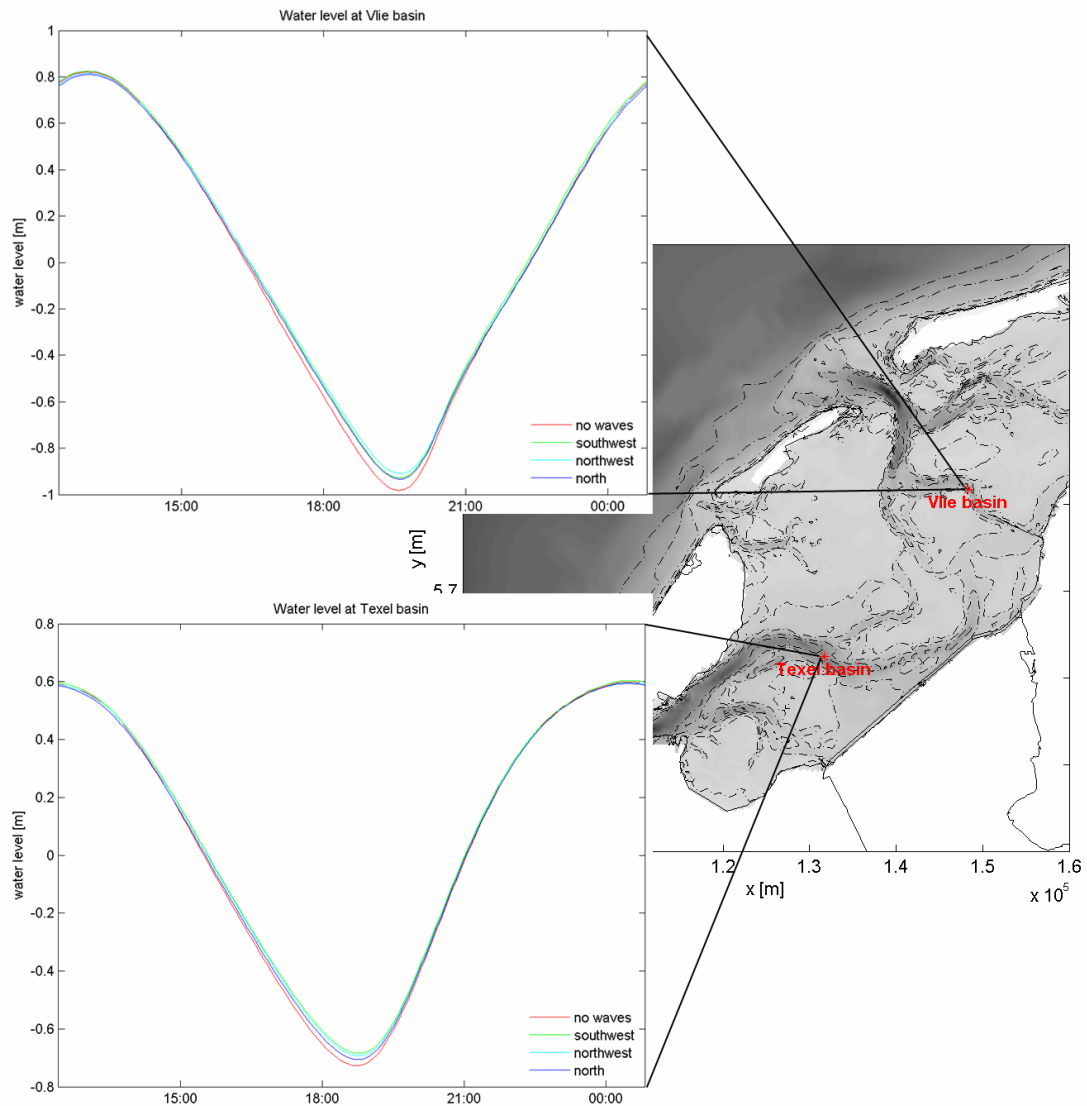


Figure 4.26 Water level inside the basins as a result of tidal forcing with and without wave forcing from different angles

The implementation of wave forcing induces a decrease of the tidal range in the basins, illustrated in Figure 4.26. The decrease is the result of a set-up of the water level at low water. The magnitude of this set-up depends on the wave angle. If an inlet is more exposed to an incoming wave, the set-up during low water in its basin is larger. This implies that due to northern and northwestern waves the set-up in the Vlie basin is larger than that in the Texel basin. With waves coming from these directions the water level gradient between the basins is increased during ebb. More water is transported from the Vlie towards the Texel basin.

When the waves come from the southwest the opposite occurs. In this case the Texel inlet is more exposed than the Vlie inlet. Subsequently the set-up during low water is higher in the Texel inlet. This reduces the water level gradient and less water is transported from the Vlie towards the Texel basin.

This is illustrated with Figure 4.27, in which the residual discharges through the inlets are shown. Due to tidal forcing only there is residual ebb-discharge through the Texel inlet of $1957\text{m}^3/\text{s}$, which originates from the Vlie inlet and the tidal divide Terschelling. The implementation of wave with $H_s=2\text{m}$ from the north and northwest increases the residual ebb-flow through the Texel inlet to $2250\text{m}^3/\text{s}$, whereas the implementation of the southwestern waves decreases this ebb-flow to $1535\text{m}^3/\text{s}$.

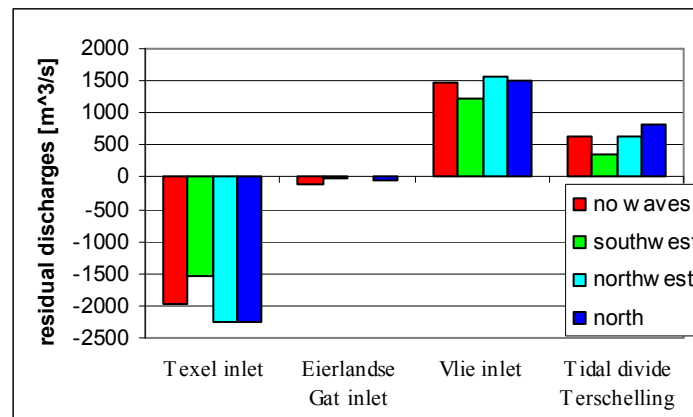


Figure 4.27 Residual discharges through the inlets

The reduction of the tidal range (and subsequently the tidal prism) causes a decrease of the M_2 -velocities in the inlets, because less water is imported in and exported out each tidal period. The influence of the waves on the water level gradients in the basins has effect on the residual discharges and therefore on the residual flow (M_0) velocities.

The effect of the implementation of waves with $H_s=2\text{m}$ coming from varying angles on the sediment transport mechanisms is shown in Figure 4.28 and Figure 4.29. Figure 4.28 shows the magnitude of the M_0M_2 residual flow mechanism; Figure 4.29 the magnitude of the M_2M_4 tidal asymmetry. The M_0M_2 residual flow mechanism increases in the Vlie inlet when forcing of northwestern (Figure 4.28a) and northern (Figure 4.28b) waves is implemented. With waves from these two directions the magnitude of the M_0M_2 residual flow in the Texel inlet approximately is equal as the magnitude as a result of tidal forcing only. The reduction of the M_2 -velocity (due to the decrease of the tidal prism) is counteracted by the increase of the M_0 -velocity (due to the increase of the water level gradient in the basins).

When the waves approach from the southwest the magnitude of the M_0M_2 residual flow increases in the ebb-channel of the Vlie inlet. The reduction of the water level gradients inside the basins during low water causes the ebb-discharges in the Vlie inlet to increase. The ebb-discharges, for a large part, are conveyed through the ebb-channel, inducing the increase in the M_0M_2 residual flow mechanism. The amplitude of the M_0M_2 residual flow mechanism in the Texel inlet reduces, because both the M_0 -velocity (due to the decrease of the water level gradient at low water) and the M_2 -velocity (due to the decrease of the tidal prism) decrease.

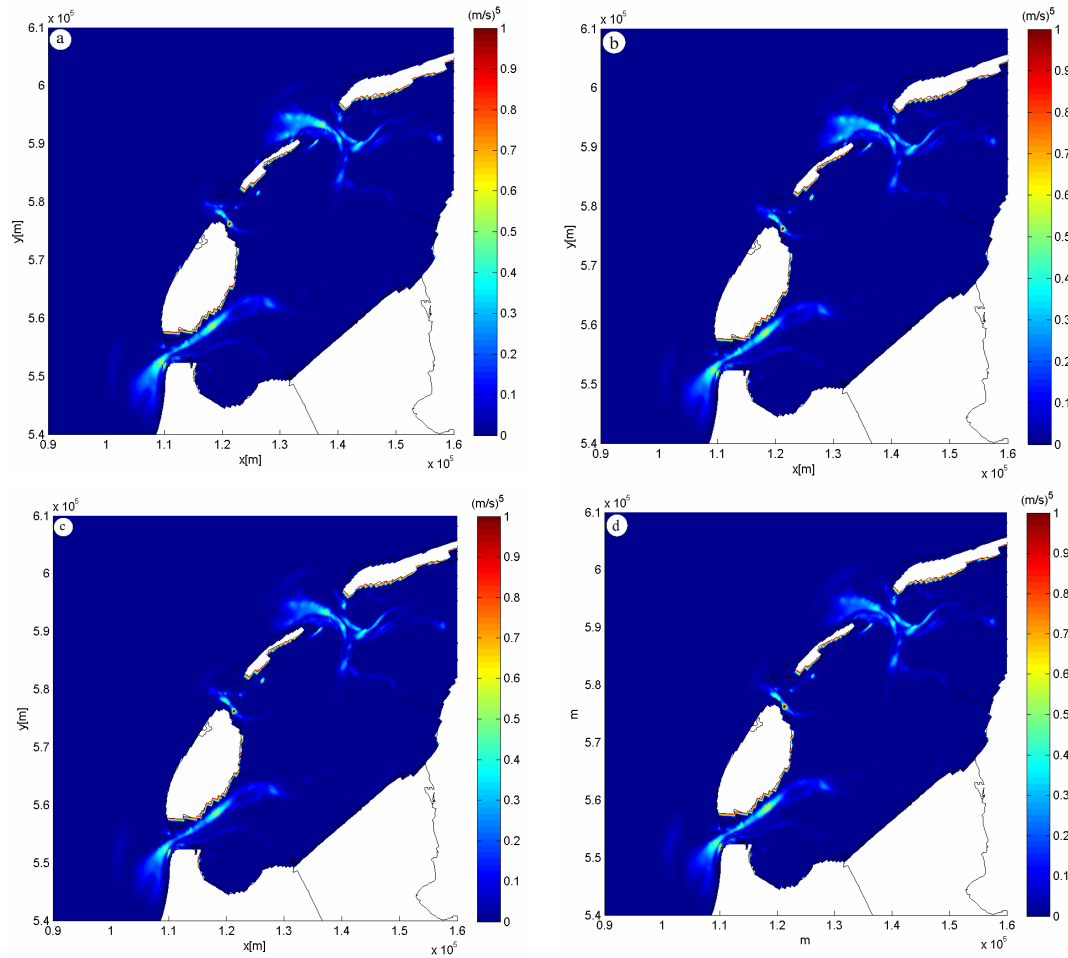


Figure 4.28 M_0M_2 residual flow magnitude as a result of tidal forcing in combination with waves from a) northwest, b) north, c) southwest, d) no waves

The M_2M_4 tidal asymmetry magnitude, in the Vlie inlet, decreases as a result of the implementation of wave forcing, irrespective of the angle the waves have. In the Texel inlet, the implementation of the wave forcing has little effect on the tidal asymmetry mechanism.

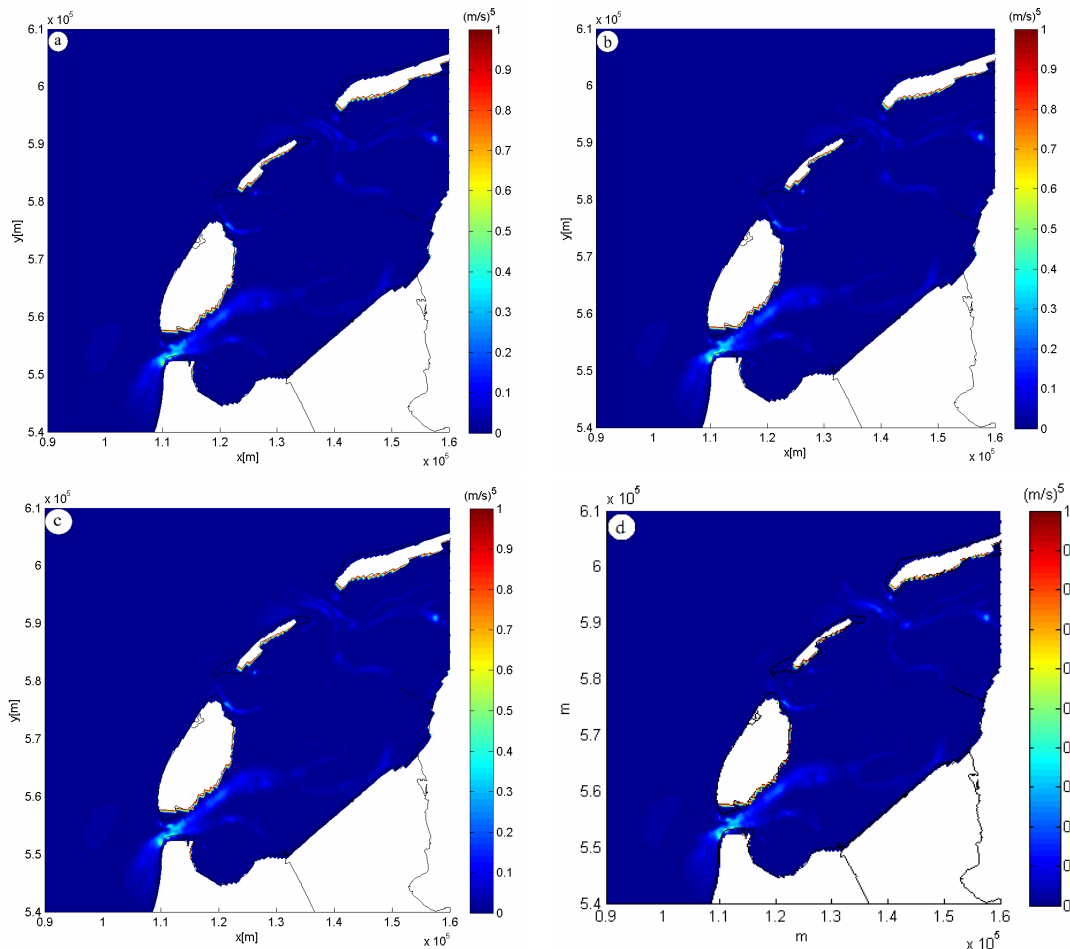


Figure 4.29 M_2M_4 tidal asymmetry magnitude as a result of tidal forcing in combination with waves from a) northwest, b) north, c) southwest, d) no waves

4.2.4 Conclusions

Wave forcing affects both the hydrodynamics and the sediment transport patterns in the Western Wadden Sea. The effects on both mechanisms are listed below.

Wave forcing effects on the hydrodynamics

- Waves cause a reduction of the tidal range inside the basins. This reduction is visible in a water level set-up that is larger during low water than during high water. The magnitude of the set-up is dependent on the height and angle of the incoming wave. When the incoming wave is higher, the set-up during low water inside the basin is higher as well. A better exposure of a tidal inlet also increases the set-up of low water.
- The reduction of the water level set-up during low water (as an effect of the wave forcing) in the basins induces a decrease of the tidal prism. The magnitudes of the flood- and ebb-velocities in the inlets reduce.
- The inlets in the Western Wadden Sea each have a different orientation. This causes the set-up during low water as a result of an incoming wave to differ per basin. The Eierlandse Gat and Vlie inlet are more exposed to northwestern waves than the Texel

inlet. The set-up in these basins as a result of waves from these two angles subsequently is higher. The difference of set-up during low water increases the water level gradient between the basins, which itself increases the residual flow between the basins. Due to the implementation of waves with $H_s=2\text{m}$ from the northwest and north the residual ebb-discharge through the Texel inlet increases from $1957\text{m}^3/\text{s}$ (tidal forcing only) to $2250\text{m}^3/\text{s}$.

When the waves approach from the southwest the Texel inlet is more exposed than the other inlets. Subsequently the water level set-up during low water in the basins is higher in the Texel basin compared to the set-up in the other basins. The water level gradient is reduced and the residual flow between the basins as well.

- The reduction of the tidal range and prism causes a decrease of the magnitude of the M_2 -velocity in the inlets and in the basins. Depending on the wave angle, the residual flow velocities in the inlet (M_0) are either increased or decreased. As a result of waves from the northwest and north the residual flow is increased in the Texel inlet. However, the magnitude of the M_0M_2 residual flow transport mechanism does not change in the Texel inlet. This is because the reduction of the M_2 -velocity is counteracted by the increase of the M_0 -velocity.

Wave forcing effects on the sediment transport

- The wave forcing induces most reaction on the transport patterns at the ebb-tidal delta areas. Inside the basins the sediment transport is only marginally influenced.
- The sediment transport through the Vlie inlet reacts strongly to forcing of waves from the northwest. As a result of tidal forcing only this is an export of $2017 \cdot 10^3\text{m}^3/\text{yr}$, but the addition of wave forcing changes this into an import of maximal $5900 \cdot 10^3\text{m}^3/\text{yr}$ (the result of a wave with $H_s=4\text{m}$). This is predominantly caused by the increased bed shear stresses on the ebb-tidal delta, which force more sediment to go into suspension. This sediment is then imported into the basin during flood.
- The implementation of the forcing from waves of various heights from the northwest induces a changing import pattern in the Texel inlet. As a result of tidal forcing only there already is an import of $2334 \cdot 10^3\text{m}^3/\text{yr}$. With the implementation of waves from the northwest this import increases with increasing wave height, but only until the waves reach a height of $H_s=2\text{m}$. The import through the Texel inlet is in this case $2817 \cdot 10^3\text{m}^3/\text{yr}$. If the wave become larger that $H_s=2\text{m}$ the rate of import decreases again. If the northwestern waves have a height of $H_s=4\text{m}$ the import is $2155 \cdot 10^3\text{m}^3/\text{yr}$. The reduction of import is a result of a decrease of the magnitude of the M_2M_4 tidal asymmetry mechanism, which occurs as a result of the higher waves. The tidal asymmetry is an importing mechanism in the Texel inlet. Therefore the amount of sediments imported by this mechanism decreases. As a result the rate of import has decreased.
- Southwestern waves are most favorable for the import rate in the Texel inlet. Due to this wave angle a longshore current, parallel to the Holland coast is generated when the waves break. This current increases the transport of sediments from the beaches of Holland towards the inlet.
- Northern and northwestern wave are more favorable in the Vlie inlet compared to southwestern waves. The Vlie inlet is sheltered from the southwestern waves by the barrier islands Texel and Vlieland. Still, the combination of tidal forcing and southwestern waves generates a sediment import of $124 \cdot 10^3\text{m}^3/\text{yr}$ through the Vlie inlet.

4.3 Wind forcing influence

4.3.1 Introduction

In this section the influence of wind forcing on the sediment transport pattern is investigated. Three simulations carried out in paragraph 0 are extended with wind forcing. Both the large-scale and the local wind effects are taken into account. Table 4.5 gives the values of the applied local meteorological conditions that are prescribed at the boundaries. The angle α applies to the wind as well as to the waves. Simulation #1 and simulation #2 are normal weather conditions. Simulation #3 has represents storm conditions.

Table 4.5 characteristics of the simulations in which wind forcing is implemented

Simulation #	Wind velocity U_{10} [m/s]	Angle α [°]	Wave height H_s [m]	Wave period T_p [s]
1	7.77	225	2	7.12
2	7.77	315	2	7.12
3	13.05	315	4	9.06

The model is large enough to simulate the local wind effects, but it is too small to simulate the large-scale effects. These effects are represented by a water level set-up (A_0), prescribed to the boundaries. Each of the following sections starts with a description of the applied water level set-up along the boundary.

4.3.2 Simulation #1, $U_{10}=7.77\text{m/s}$ from the southwest

Large-scale wind set-up (A_0)

Figure 4.30 shows the prescribed large-scale wind set-up along the western boundary (for a model description see section 3.4). The blue dots represent the real value of the water level set-up; the red line denotes the smoothed line of the actual applied water level set-up. The southwestern wind induces a large-scale water level set-down, which is the largest in the south (0.16m) and the smallest in the north (0.08m).

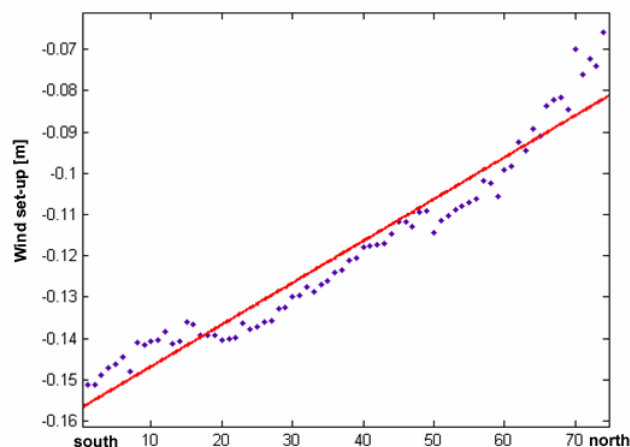


Figure 4.30 prescribed large-scale wind set-up along the western boundary

Results

Table 4.6 shows the annual tide-averaged imports through the inlets as a result of simulations with and without wind forcing. Positive values denote import, negative export. The results of the simulation without wind forcing are discussed in section 4.2.3. Due to the implementation of a southwestern wind ($\alpha=225^\circ$) with a velocity $U_{10}=7.77\text{m/s}$, the import through the Texel inlet increases with $636 \cdot 10^3 \text{ m}^3/\text{yr}$ to $3991 \cdot 10^3 \text{ m}^3/\text{yr}$. The export through the Eierlandse Gat decreases from $356 \cdot 10^3 \text{ m}^3/\text{yr}$ (no wind forcing) to $321 \cdot 10^3 \text{ m}^3/\text{yr}$. If forcing from a southwestern wind is absent, there is an import through the Vlie inlet of $124 \cdot 10^3 \text{ m}^3/\text{yr}$. The wind forcing changes this into an export of $1456 \cdot 10^3 \text{ m}^3/\text{yr}$. The small import that takes place over the tidal divide Terschelling ($52 \cdot 10^3 \text{ m}^3/\text{yr}$) is changed into an export of $82 \cdot 10^3 \text{ m}^3/\text{yr}$ when the wind forcing is implemented.

Table 4.6 Annual tide-averaged sediment transports through the inlets

	Wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]
Texel inlet	3991	3355
Eierlandse Gat inlet	-321	-356
Vlie inlet	-1456	124
Tidal divide Terschelling	-82	52

Table 4.7 shows the sediment transports over the tidal divide as a result of simulations with and without the wind forcing. Due to the implementation of the southwestern wind, an increase in the sediment transport in northeastern direction is generated. The residual transport from the Eierlandse Gat to the Texel basin is reduced with $167 \cdot 10^3 \text{ m}^3/\text{yr}$ to $79 \cdot 10^3 \text{ m}^3/\text{yr}$. The sediment transport from the Texel to the Vlie basin is increased with $59 \cdot 10^3 \text{ m}^3/\text{yr}$ to $270 \cdot 10^3 \text{ m}^3/\text{yr}$. The sediment transport of $506 \cdot 10^3 \text{ m}^3/\text{yr}$ from the Vlie to the Eierlandse Gat basin, when wind forcing is excluded, is changed into a transport in the other direction of $117 \cdot 10^3 \text{ m}^3/\text{yr}$, when wind forcing is applied.

Table 4.7 Annual tide-averaged sediment transports over the tidal divides

	Wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]
Texel basin $\rightarrow$ Eierlandse Gat basin	-79	-246
Texel basin $\rightarrow$ Vlie basin	270	211
Eierlandse Gat basin $\rightarrow$ Vlie basin	117	-506

Sediment transport pattern in the Texel inlet

Figure 4.31 shows the sediment transport patterns in the Texel inlet as a result of simulations with and without wind forcing. The implementation of the southwestern wind does not affect the pattern, but it increases the magnitude of the fluxes. The volume of imported sediments predominantly comes from the beaches of Holland, south of the inlet.

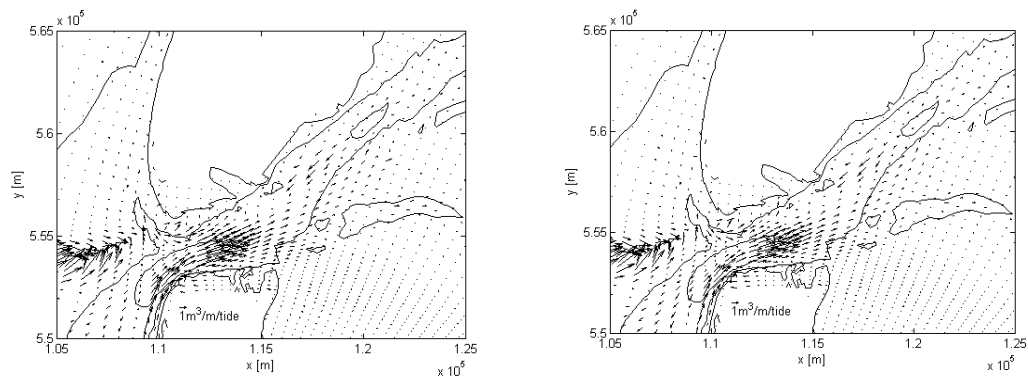


Figure 4.31 Sediment transport pattern in the Texel inlet with wind forcing (left) and without wind forcing (right)

Sediment transport pattern in the Vlie inlet

Figure 4.32 shows the sediment transport pattern in the Vlie inlet, as a result of the simulations with and without wind forcing. The wind forcing does not affect the pattern. The magnitude of the transports does not change much as well, save for the transports in the ebb-channel. There the export is increased, which is in correspondence with the change in transport over the cross section shown in Table 4.6.

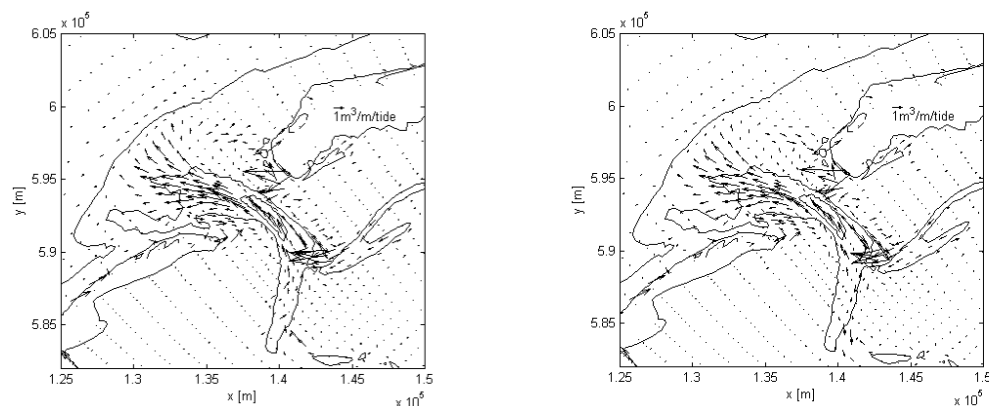


Figure 4.32 Sediment transport pattern in the Vlie inlet with wind forcing (left) and without wind forcing (right)

Discussion

Averaged bed shear stresses development

In Figure 4.33 the tidally averaged bed shear stresses are shown. The left figure shows the results of the simulation with wind forcing, the right the results of the simulation without wind forcing. In the ebb-channel of the Texel inlet the average bed shear stresses decrease. This is explained in the discussion of the hydrodynamics. Near the Holland coast they increase. At the shallow shoreface the wind has more influence, generating a current towards the inlet. This current increases the bed shear stresses and transports more sediment, as was indicated in Figure 4.31.

In the ebb-channel of the Vlie inlet the averaged bed shear stresses are increased due to the forcing of the southwestern wind. This is explained in the discussion of the hydrodynamics.

In the North Sea, there is an increase in the bed shear stresses. The varying water level set-up induces a gradient, which itself generates a current.

At the ebb-tidal deltas of both inlets, the bed shear stresses at the seaside fringe are increased. The transition from deeper to shallower water is located at those locations, and in the shallow water the wind can generate a larger current. This shows in the increase of the bed shear stresses.

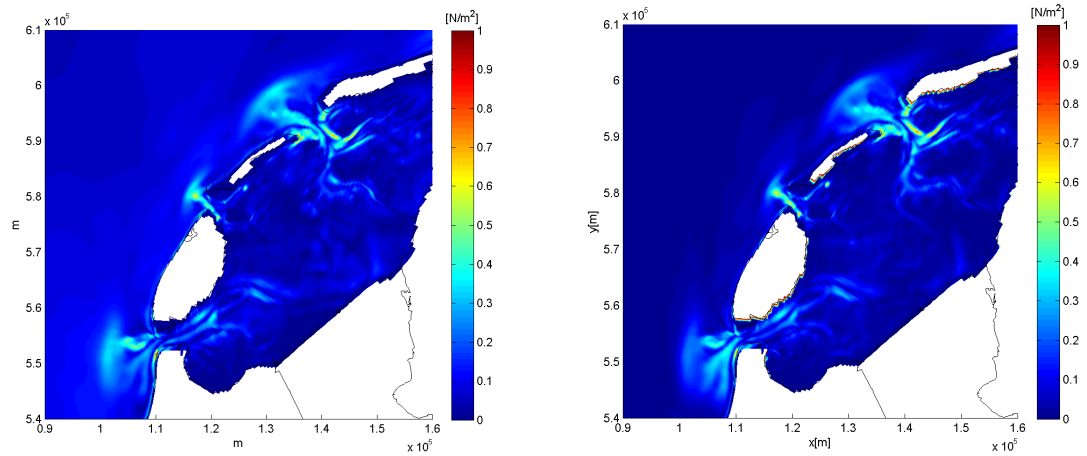


Figure 4.33 Averaged bed shear stresses as a result of the simulation with (left) and without (right) wind forcing

Hydrodynamics

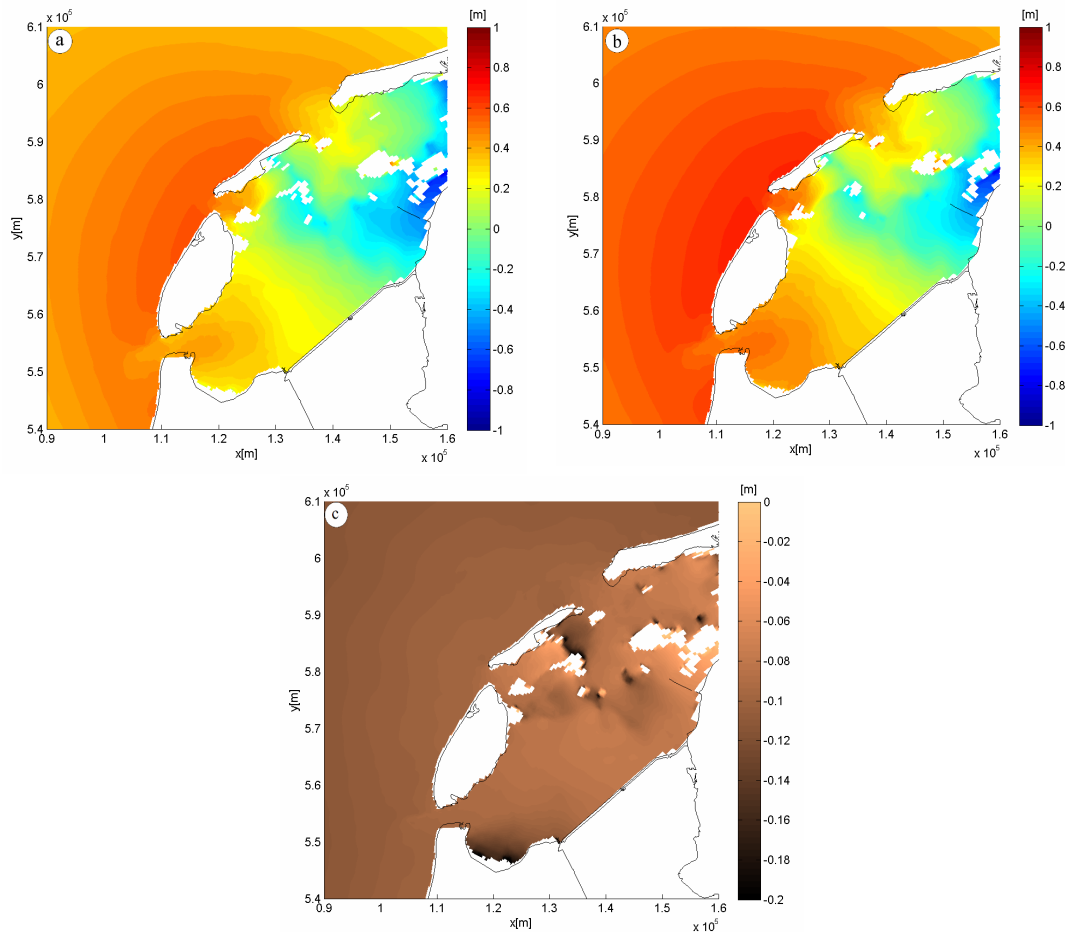


Figure 4.34 a) Water level with wind forcing, b) Water level without wind forcing and c) Wind forcing induced water level set-up

The combination of the large-scale and local wind effects generates a wind set-up in the basins which varies spatially. The wind induced set-up is shown in Figure 4.34. The wind set-up is actually a set-down, maximally 0.2m in the south and zero near Harlingen.

The local wind forcing also generates wind stresses on the water surface. These stresses generate an extra current in the direction of the wind. The combination of the water level gradient induced by the wind forcing and the wind stresses generated current affects the residual flow pattern. This is illustrated by Table 4.8, which shows the residual discharges through the inlets, as a result of the simulation with and without wind forcing. Positive values denote import, negative export. Due to the implementation of the wind forcing the residual ebb-discharge through the Texel inlet decreases considerably, from 1535m³/s to 132 m³/s. The residual discharge in the Eierlandse Gat inlet changes from ebb-dominant (26m³/s) to flood-dominant (169m³/s). The residual flood-discharge through the Vlie inlet reduces from 1237m³/s to 620m³/s. Over the tidal divide Terschelling, the implementation of the wind forcing causes the residual discharge to change from 366m³/s, flood-dominant, to 664m³/s, ebb-dominant.

The flow generated by the wind forcing counteracts the residual flow directed from the Vlie inlet and tidal divide Terschelling towards the Texel inlet. Instead there is now a net flow

directed from the Eierlandse Gat towards the Texel inlet, and another one directed from the Vlie inlet towards the tidal divide Terschelling.

Table 4.8 Residual flow through the inlets

	Wind forcing Residual discharge [m^3/s]	No wind forcing Residual discharge [m^3/s]
Texel inlet	-132	-1535
Eierlandse Gat inlet	169	-26
Vlie inlet	620	1237
Tidal divide Terschelling	-664	366

The change in residual flow affects the magnitude of the M_0M_2 residual flow mechanism, shown in Figure 4.35. In the Texel inlet, the magnitude decreases, because the magnitude of the residual flow (M_0) has decreased. The M_0M_2 residual flow mechanism induces export in the Texel inlet, and due to its reduction the exports decrease as well. At the tip of the Holland coast, the magnitude of the M_0M_2 residual flow mechanism increases. At that location this mechanism (due to tidal and wave forcing) is directed towards the inlet. The wind forcing induces a current northward (i.e. in the direction of the M_0M_2 residual flow mechanism). This additional current increases the residual flow, and subsequently the M_0M_2 residual flow mechanism. This increase creates a larger rate of sediment transport to the inlet (as shown in Figure 4.31).

In the ebb-channel located in the Vlie inlet, the M_0M_2 residual flow mechanism increases. This is caused by the increased ebb-discharges that have to be transported. This induces an increase in the outward directed residual flow velocity (M_0), and an increase in the M_0M_2 residual flow mechanism. In the ebb-channel of the Vlie this mechanism is exporting, and subsequently more sediment export takes place. This explains the export of $1456 \cdot 10^3 \text{ m}^3/\text{yr}$ through the Vlie inlet shown in Table 4.6.

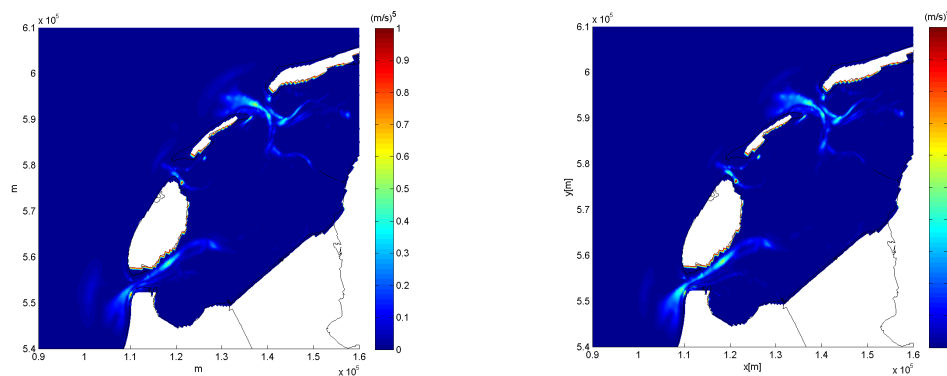


Figure 4.35 Magnitude of the M_0M_2 residual flow as a result of wind forcing (left) and no wind forcing (right)

In Figure 4.36 the development of the magnitude of the M_2M_4 tidal asymmetry mechanism as a result of the implementation is shown. The set-down of the water level in the basins decreases the storage area in the basins, and subsequently the tidal prism. The reduction of the tidal prism causes the M_2 velocities in the inlets to decrease. Figure 4.34 shows that the set-down of the water level is larger in the Texel basin than in the Vlie basin. Subsequently the decrease of the amplitude of the M_2M_4 tidal asymmetry mechanism is larger in the Texel inlet. In the Texel inlet this mechanism generates an import of sediment.

Although the amplitude of the M_2M_4 tidal asymmetry decreases, its decrease is less significant than the decrease of the amplitude of the M_0M_2 residual flow mechanism, which generates exports. As a result the net import through the Texel inlet increases, see Table 4.6.

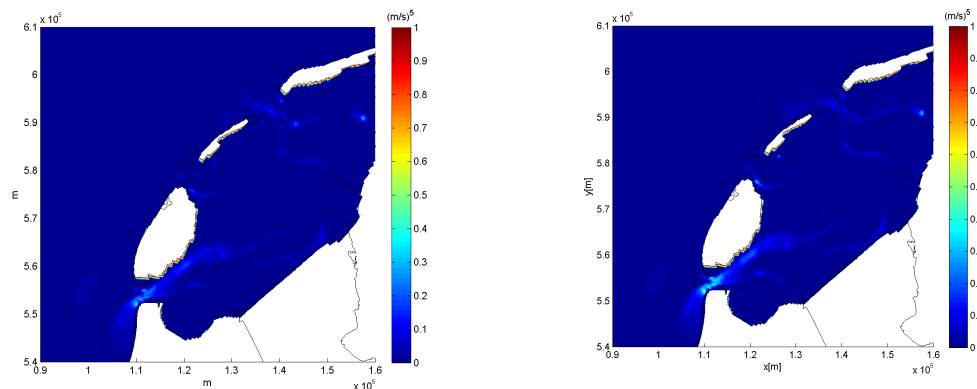


Figure 4.36 Magnitude of the M_2M_4 tidal asymmetry as a result of wind forcing (left) and no wind forcing (right)

4.3.3 Simulation #2, $U_{10}=7.77\text{m/s}$ from the northwest

Large-scale wind set-up (A_0)

Figure 4.37 shows the prescribed set-up along the boundary that represents the large-scale wind effect. The blue dots denote the real values of the water level set-up at the boundary points and the red line shows the smoothed line of the applied A_0 on the boundary. At the southern end of the model the set-up is 0.32m, it decreases to 0.26m in the middle and increase to 0.35m at northern end.

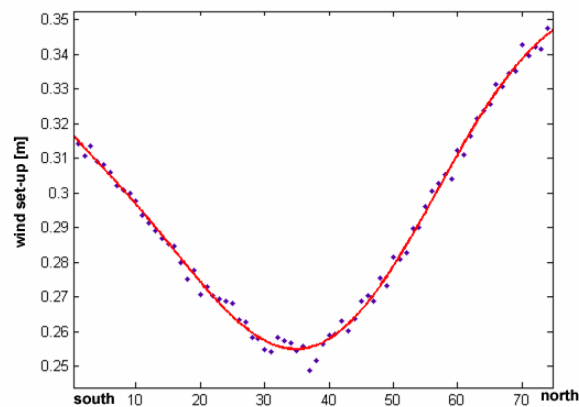


Figure 4.37 prescribed set-up along the boundary

Results

Table 4.9 shows the results for the transports over the cross sections in the inlets, for the simulations with and without the tidal forcing. Positive values denote import, negative export. The results of the simulation without wind forcing are discussed in section 4.2. Due to the implementation of wind forcing, the rate import through the Texel inlet increases from $2817 \cdot 10^3 \text{m}^3/\text{yr}$ to $3548 \cdot 10^3 \text{m}^3/\text{yr}$. The export of sediment ($541 \cdot 10^3 \text{m}^3/\text{yr}$) through the

Eierlandse Gat inlet changes into an import of $715 \cdot 10^3 \text{ m}^3/\text{yr}$. When the wind forcing is applied, the import through the Vlie inlet decreases from $2378 \cdot 10^3 \text{ m}^3/\text{yr}$ to $1590 \cdot 10^3 \text{ m}^3/\text{yr}$. The transports over the tidal divide Terschelling remain small when the wind forcing is implemented, yet the export of $9 \cdot 10^3 \text{ m}^3/\text{yr}$ is changed into an import of $13 \cdot 10^3 \text{ m}^3/\text{yr}$.

Table 4.9 Annual tide-averaged sediment imports through the inlets

	Wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]
Texel inlet	3548	2817
Eierlandse Gat inlet	715	-541
Vlie inlet	1590	2378
Tidal divide Terschelling	-9	13

The sediment transports over the tidal divides that separate the basins are presented in Table 4.10. Both the results of the simulations with and without wind forcing are shown. The rate of transports over the divides remains small compared to the sediment transports through the inlet. The northwestern wind reduces the residual transport from the Eierlandse Gat to the Texel basin with $173 \cdot 10^3 \text{ m}^3/\text{yr}$ to an amount of $21 \cdot 10^3 \text{ m}^3/\text{yr}$. The transport of sediments from the Texel to the Vlie basin is increased. Without wind forcing this transport is $37 \cdot 10^3 \text{ m}^3/\text{yr}$, but with the wind forcing this is increased with $131 \cdot 10^3 \text{ m}^3/\text{yr}$ to an amount of $168 \cdot 10^3 \text{ m}^3/\text{yr}$. Without wind forcing sediment is transported from the Vlie toward the Eierlandse Gat basin ($22 \cdot 10^3 \text{ m}^3/\text{yr}$). When the wind forcing is applied, the direction of the residual transport over this divide changes direction. Now there is a residual sediment transport of $44 \cdot 10^3 \text{ m}^3/\text{yr}$ from the Eierlandse Gat towards the Vlie basin.

Table 4.10 Annual tide-averaged sediment transports over the tidal divides

	Wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]
Texel basin → Eierlandse Gat basin	-21	-194
Texel basin → Vlie basin	168	37
Eierlandse Gat basin → Vlie basin	44	-22

Sediment transport pattern in the Texel inlet

Figure 4.38 shows the sediment transport pattern in the Texel inlet as a result of the simulation with and without wind forcing. Due to the implementation of the northwestern wind the sediment transport (directed inward) around the tip of the barrier island of Texel increases. The import that takes place around the tip of North Holland is increased by the implementation of the wind forcing. The transport rates at the ebb-delta are increased because of the wind forcing as well.

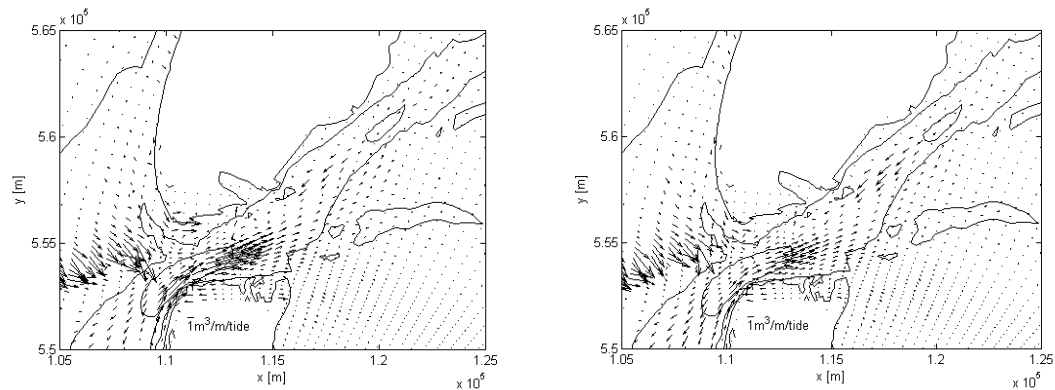


Figure 4.38 Sediment transport pattern in the Texel inlet with wind forcing (left) and without wind forcing (right)

Sediment transport pattern in the Vlie inlet

Figure 4.39 shows the sediment transport pattern in the Vlie inlet as a result of the simulations with and without wind forcing. The pattern does not change when the wind forcing is implemented, only the magnitudes of the fluxes. The increase of the transport is the largest in the ebb-channel. The transport is directed outward at this location, so the export through the ebb-channel is increased. This is in correspondence with the sediment transport over the cross section. Due to the implementation of the wind forcing the import reduced (see Table 4.9). This reduction of the import is caused by the increase of the export through the ebb-channel.

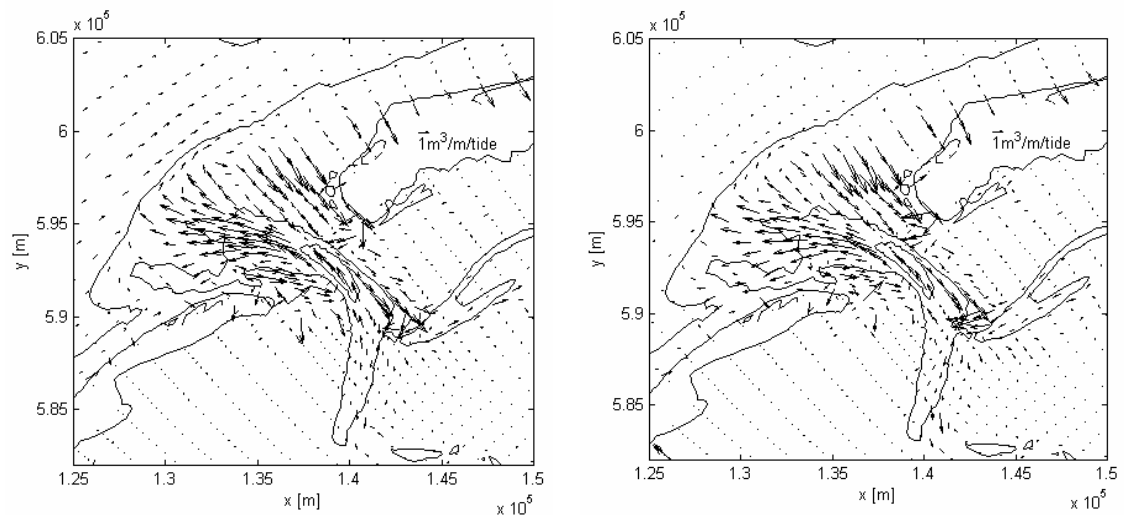


Figure 4.39 Sediment transport pattern in the Vlie inlet with wind forcing (left) and without wind forcing (right)

Discussion

Bed shear stresses development

Figure 4.40 shows the development of the averaged bed shear stresses. Most noticeable is the large increase on the North Sea. In the Texel inlet the average bed shear stresses around the tips of the island of Texel and of the Holland coast increase. This increase is caused by

an increase in flow velocities, which subsequently also increases the import of sediment (see Figure 4.38). In the ebb-channel of the Texel inlet the averaged bed shear stresses have decreased because of the implementation of the wind forcing. This is caused by a reduction of the residual ebb-flow, which is discussed in the hydrodynamics section.

On the ebb-tidal delta of the Vlie, the averaged bed shear stresses have decreased due to the implementation of wind forcing. The waves now have less influence because of the increased water depth (see Figure 4.41).

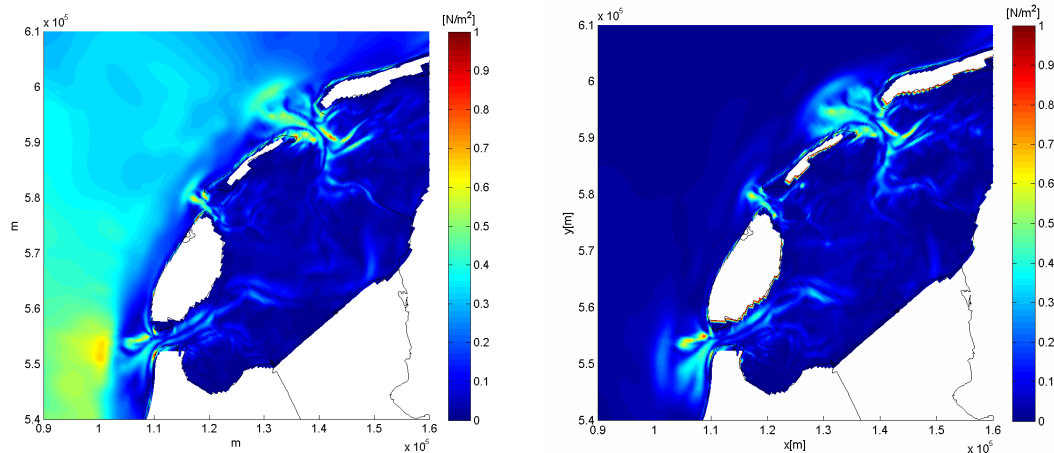


Figure 4.40 Averaged bed shear stresses as a result of the simulation with (left) and without (right) wind forcing

Hydrodynamics

Figure 4.41c shows the water level set-up in the basins induced by the wind forcing. The set-up is the largest in the Texel basin, approximately 0.5m. In the Vlie inlet this set-up is around 0.4m. Due to this difference the water level gradient between the Vlie and Texel inlet decreases, and subsequently the residual discharges decrease too. This is illustrated by Table 4.11, that describes the residual flow through the inlets as a result of the simulations with and without wind forcing. Positive values denote residual flood-flow, negative residual ebb-flow. Due to the implementation of wind forcing, the residual ebb-flow through the Texel inlet decreases with 43% to $1293\text{m}^3/\text{s}$. In the Vlie inlet, the residual flood-flow decreases with 33% to $1052\text{m}^3/\text{s}$. For both inlets the magnitude of the residual flow (M_0) has decreased.

Without wind forcing, the residual flow through the Eierlandse Gat is approximately zero ($16\text{m}^3/\text{s}$). When wind is implemented this increases to a residual flood-flow of $382\text{m}^3/\text{s}$. The wind forcing changes the residual flow over the tidal divide Terschelling from $635\text{m}^3/\text{s}$ in flood direction to $112\text{m}^3/\text{s}$ in ebb direction.

The set-up in the basins has an increasing effect on the storage area. With the same tidal range (wind forcing has no effect on it), more water has to be imported and exported through the inlets. This implies that the tidal velocities (M_2) are increased.

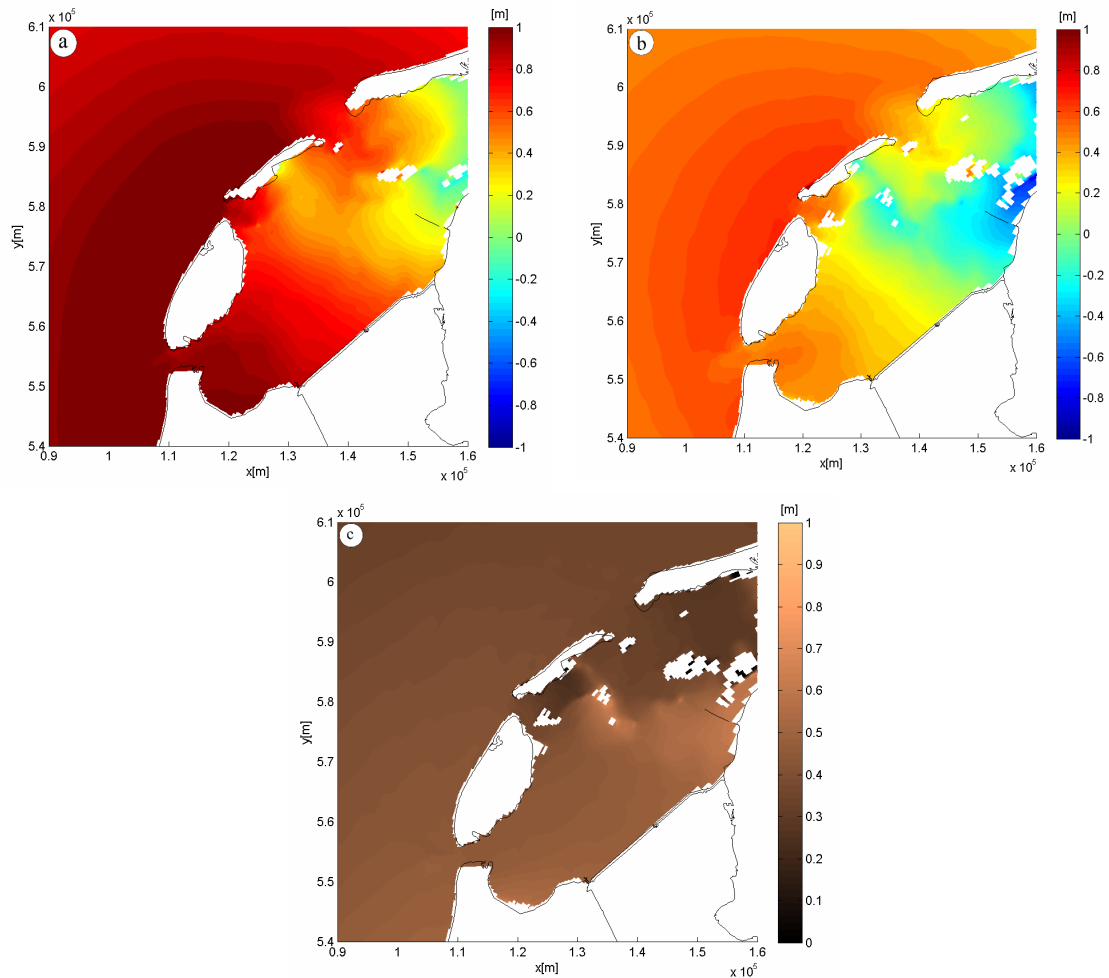


Figure 4.41 a) Water level with wind forcing, b) Water level without wind forcing and c) Wind forcing induced water level set-up

Table 4.11 Residual discharges through the inlets, with and without wind forcing

	Wind forcing Residual discharges [m³/s]	No wind forcing Residual discharges [m³/s]
Texel inlet	-1293	-2258
Eierlandse Gat inlet	382	16
Vlie inlet	1052	1559
Tidal divide Terschelling	-112	635

Due to the changes in the hydrodynamics described above the transport mechanism have changed as well. Figure 4.42 shows that the M_0M_2 residual flow mechanism has increased considerably in the ebb-channel of Vlie inlet. The residual flow there already was exporting. Due to the decreased exchange of water between the Vlie and Texel basin, more water has to be exported during ebb. The majority of this added volume is transported through the ebb-channel. The decrease in sediment import through the Vlie inlet (see Table 4.9 is mainly caused by the increased export in the ebb-channel due to the increased M_0M_2 residual flow mechanism.

The magnitude of the M_0M_2 residual flow mechanism in the Texel inlet does not change due to the implementation of the wind forcing. The reduction of the M_0 velocity is counteracted by the increase of the M_2 velocity.

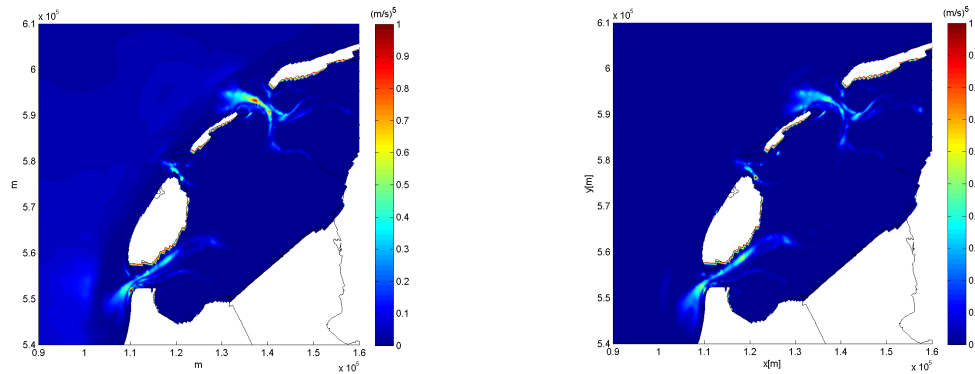


Figure 4.42 Magnitude of the M_0M_2 residual flow as a result of wind forcing (left) and no wind forcing (right)

In the Texel inlet, the M_2M_4 tidal asymmetry mechanism is not affected by the wind forcing. Figure 4.43 shows the influence of the wind forcing on the M_2M_4 tidal asymmetry mechanism. In the Vlie inlet, however, the magnitude of this mechanism is increased, but to a lesser extent than the increase of the M_0M_2 residual flow mechanism.

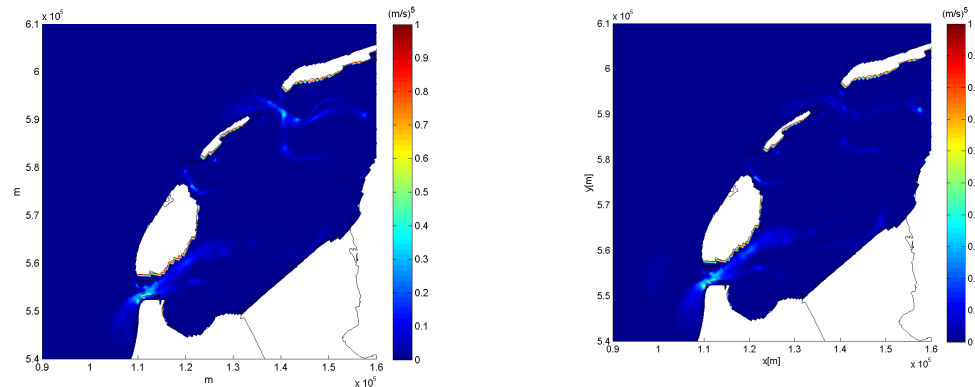


Figure 4.43 Magnitude of the M_2M_4 tidal asymmetry as a result of wind forcing (left) and no wind forcing (right)

4.3.4 Simulation #3, $U_{10}=13.05\text{m/s}$ from the northwest

Large-scale wind set-up (A_0)

Figure 4.44 shows the prescribed water level set-up along the boundary. The curve of the set-up is roughly the same of that applied in simulation #2, see section 4.3.3. However, this set-up, that corresponds to a higher wind velocity ($U_{10}=13.05\text{m/s}$ versus $U_{10}=7.77\text{m/s}$) from the northwest, has a larger magnitude. It is at the maximum 0.52m (in the south), it first decreases to 0.46m (in between the northern and southern end) to increase to 0.50m at the northern end.

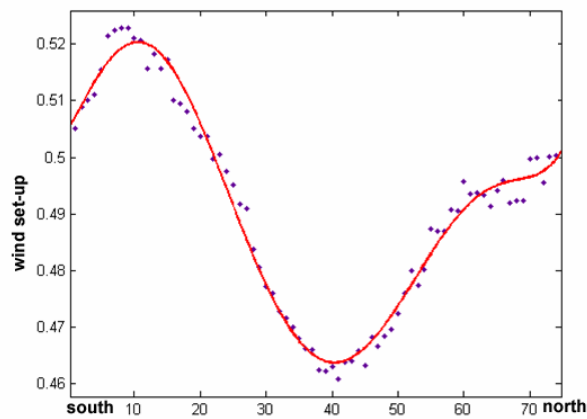


Figure 4.44 prescribed large-scale wind set-up along the western boundary

Results

In Table 4.12 the sediment transports through the inlets are shown, as a result of the simulations with and without wind forcing. Positive values denote import, negative export. The results of the sediment transports as a result of the simulation without wind forcing are discussed in section 4.2. The transport rates are greatly affected by the implementation of wind forcing. Without wind forcing, the Texel inlet imports sediments with $2155 \cdot 10^3 \text{ m}^3/\text{yr}$. When wind forcing is applied this import changes into an export of $2383 \cdot 10^3 \text{ m}^3/\text{yr}$. For the Eierlandse Gat, the export of $526 \cdot 10^3 \text{ m}^3/\text{yr}$ is changed to an import of $6500 \cdot 10^3 \text{ m}^3/\text{yr}$. The import through the Vlie inlet is increased from $5923 \cdot 10^3 \text{ m}^3/\text{yr}$ to $14747 \cdot 10^3 \text{ m}^3/\text{yr}$. Compared to the wind forcing inflicted changes in transport through the inlets, the transport over the tidal divide Terschelling is not affected much. Still, the wind forcing changes the import of $39 \cdot 10^3 \text{ m}^3/\text{yr}$ to an export of $142 \cdot 10^3 \text{ m}^3/\text{yr}$.

Table 4.12 Annual tide-averaged sediment imports through the inlets

	Wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment import S [$\cdot 10^3 \text{ m}^3$]
Texel inlet	-2382	2155
Eierlandse Gat inlet	6500	-526
Vlie inlet	14747	5923
Tidal divide Terschelling	-142	39

In Table 4.13 the transports over the tidal divides are shown, as a result of the simulations with and without wind forcing. Due to the implementation of wind forcing the transport from the Eierlandse Gat to the Texel basin decreases, from $1447 \cdot 10^3 \text{ m}^3/\text{yr}$ to $1029 \cdot 10^3 \text{ m}^3/\text{yr}$. With wind forcing there is a transport of $44 \cdot 10^3 \text{ m}^3/\text{yr}$ from the Texel to Vlie basin. Without wind forcing there is a transport in the other direction of $169 \cdot 10^3 \text{ m}^3/\text{yr}$. The transport between the Eierlandse Gat and Vlie basin does not change direction. The magnitude does decrease due to the wind forcing, from $148 \cdot 10^3 \text{ m}^3/\text{yr}$ to $109 \cdot 10^3 \text{ m}^3/\text{yr}$.

Table 4.13 Annual tide-averaged sediment transports over the tidal divides

	Wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]	No wind forcing Sediment transport S [$\cdot 10^3 \text{ m}^3$]
Texel basin $\rightarrow$ Eierlandse Gat basin	-1029	-1447
Texel basin $\rightarrow$ Vlie basin	44	-169
Eierlandse Gat basin $\rightarrow$ Vlie basin	109	148

Transport pattern in the Texel inlet

The influence of the wind forcing on the sediment transport pattern is shown in Figure 4.45. On the left the results of the simulation with the wind forcing is plotted, on the right the result of the simulation without wind forcing. The northwestern wind with $U_{10}=13.05\text{m/s}$ has a large influence. Without wind forcing, there is an import through the inlet. When the wind forcing is applied, this import is gone. Now the inlet is exporting sediment. The import of sediment around the tip of North Holland has decreased.

The magnitude of the transports on the ebb-tidal delta has increased due the implementation of wind forcing. The import that takes place around the tip of Texel has increased as well. The channel inside the basin has an increase in the rate of sediment export.

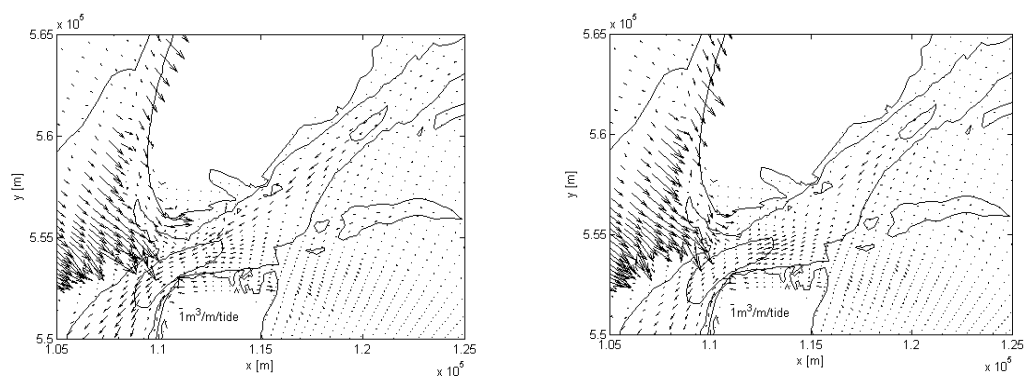


Figure 4.45 Sediment transport pattern in the Texel inlet with wind forcing (left) and without wind forcing (right)

Transport pattern in the Vlie inlet

Figure 4.46 shows the influence of the wind forcing on the sediment transport pattern in the Vlie inlet. On the left the results of the simulation with implementation of wind forcing is shown, on the right the result of the simulation without wind forcing. The magnitude of the transport is increased considerably. More sediment is pushed towards the beaches of the islands of Vlieland and Terschelling. The imports that occur around the tips of these islands show a large increase, especially the import around Terschelling. The export of sediments in the ebb-channel decreases. As a result the total import through the inlets is greatly increased, which is also shown in Table 4.12.

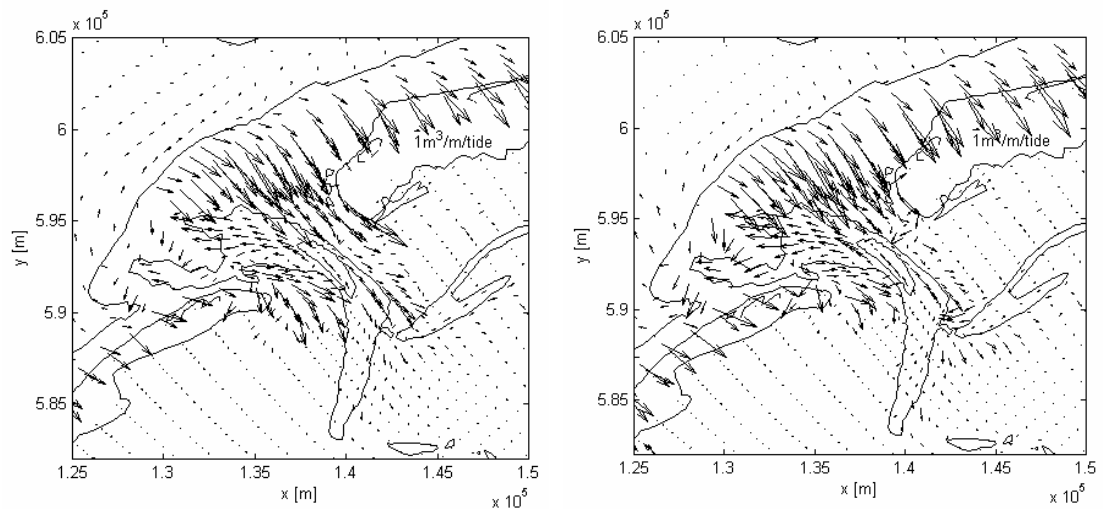


Figure 4.46 Sediment transport pattern in the Vlie inlet with wind forcing (left) and without wind forcing (right)

Discussion

Average bed shear stresses

Figure 4.47 shows the development of the average bed shear stresses as a result of the implemented wind forcing. In the ebb-channel of the Texel inlet and delta, the stresses are increased considerably. The cause of this increase is discussed in the hydrodynamics section. On the shallow parts of the ebb-tidal delta of the Vlie inlet there is an increase in the averaged bed shear stresses. On this shallow area the wind forcing has more influence, pushing sediments towards the inlet (see Figure 4.45).

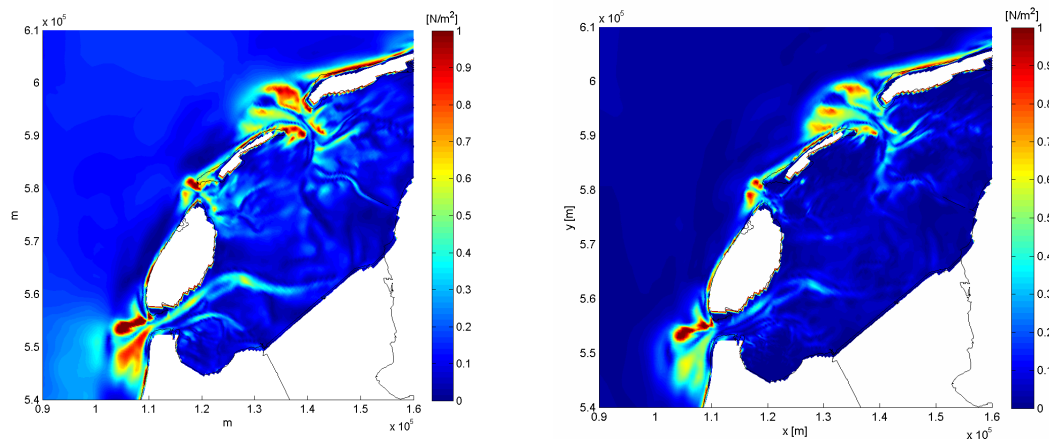


Figure 4.47 Averaged bed shear stresses as a result of the simulation with (left) and without (right) wind forcing

Hydrodynamics

Figure 4.48c shows the set-up of the water level inside the basins as a result of the wind forcing. The set-up is the largest at Harlingen (1m), in the rear of the basins. The set-up of the water level is higher in the Texel basin than it is in the Vlie basin. This difference causes a decrease in the water level gradient between the two basins. This decrease occurred with the implementation of a northwestern wind of $U_{10}=7.77\text{m/s}$ as well, and here it reduced the

residual flow between the basins. With a stronger wind from the northwest this is not the case. The residual flow from the Vlie towards the Texel inlet increases considerably. This is illustrated with Table 4.14, where the residual discharges through the inlets are described. Positive values denote residual flood-discharges, negative residual ebb-discharges. The residual ebb-discharge through the Texel inlet more than doubles due to the implementation of the wind forcing ($6041\text{m}^3/\text{s}$ with wind forcing versus $2793\text{m}^3/\text{s}$ without). The residual flood-discharge through the Eierlandse Gat increases with $1891\text{ m}^3/\text{s}$ to $2150\text{m}^3/\text{s}$. In the Vlie inlet the simulation including wind forcing induces a residual flood-flow of $4469\text{m}^3/\text{s}$, compared to a residual flood-flow of $1854\text{m}^3/\text{s}$ induced by the simulation without wind forcing. When the wind forcing is excluded, there is a residual flood-discharge of $738\text{m}^3/\text{s}$ over the tidal divide Terschelling. When wind forcing is included, this residual flood-discharge is converted in a residual ebb-discharge of $542\text{m}^3/\text{s}$. In short, due to the forcing from the northwestern wind with $U_{10}=13.05\text{m/s}$ the flood-discharges through the Eierlandse Gat and Vlie inlet are increased. In the Texel inlet and over the tidal divide Terschelling the ebb-discharges are increased. The strong wind forcing generates stresses on the water surface. These stresses generate the set-up in the basin (in combination with the large-scale set-up, see Figure 4.44), but also currents. The angle of the wind ($\alpha=315^\circ$) is perpendicular to the Eierlandse Gat and Vlie inlet. The wind pushes the water towards the back of the basin. One of the reactions is the set-up of the water level. The other reaction is the generation of currents towards the Texel inlet and the tidal divide Terschelling.

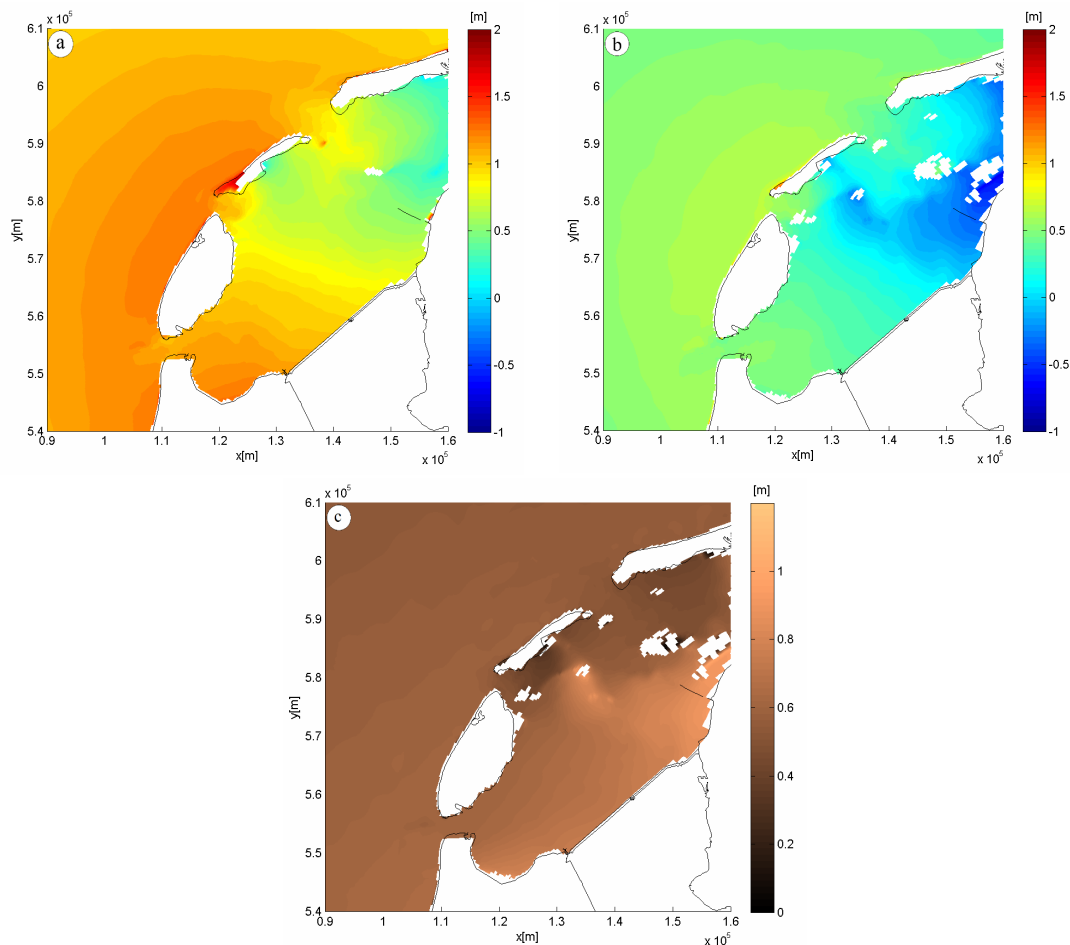


Figure 4.48 a) Water level with wind forcing, b) Water level without wind forcing and c) Wind forcing induced water level set-up

Table 4.14 Residual discharges through the inlets

	Wind forcing Residual discharges [m^3/s]	No wind forcing Residual discharges [m^3/s]
Texel inlet	-6041	-2793
Eierlandse Gat inlet	2150	259
Vlie inlet	4469	1854
Tidal divide Terschelling	-542	738

Due to the wind-driven water level set-up the storage area in the basins is increased. This causes an increase of the tidal prisms of each basin, and subsequently the increase of the magnitude of the tidal M_2 -velocities.

The changes in the hydrodynamics also reflect in the sediment transport mechanisms of residual flow and tidal asymmetry. Figure 4.49 shows the reaction of the M_0M_2 residual flow mechanism. The combination of the increased residual flow and tidal velocities results in a large increase of the mechanism in the Texel inlet. The M_0M_2 residual flow mechanism is exporting in this inlet and this increase is the main cause of the residual export through this inlet (see Table 4.12 and Figure 4.45). In this inlet the M_2M_4 tidal symmetry mechanism increases as well due to the implementation of the wind forcing (shown in Figure 4.50). This mechanism is importing in this inlet, but the increase is much less than that of the M_0M_2 residual flow mechanism.

In the Vlie inlet the M_0M_2 residual flow mechanism increases, both in the ebb-dominant ebb-channel and around the tips of the barrier islands, where the flow is flood-dominant. The increase of the M_0M_2 residual flow mechanism in the ebb-channel is counteracted by the increased of the M_2M_4 tidal symmetry mechanism.

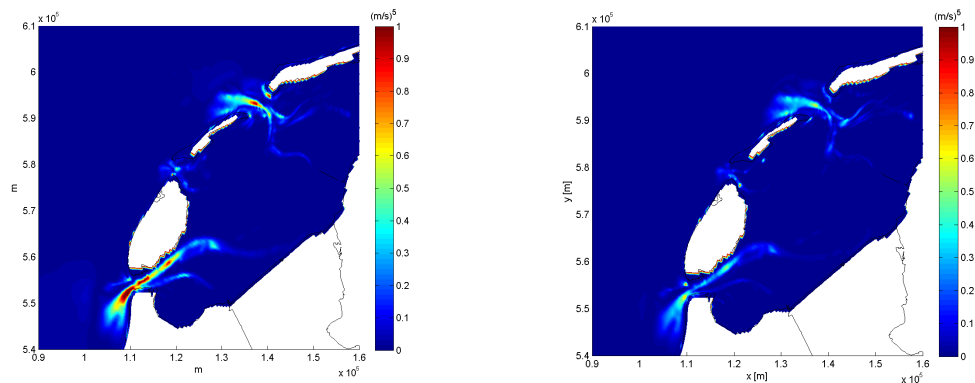


Figure 4.49 Magnitude of the M_0M_2 residual flow as a result of wind forcing (left) and no wind forcing (right)

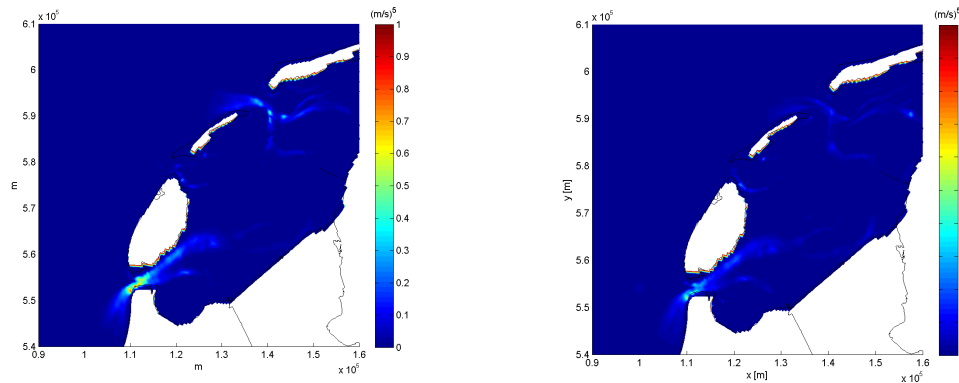


Figure 4.50 Magnitude of the M_2M_4 tidal asymmetry as a result of wind forcing (left) and no wind forcing (right)

4.3.5 Conclusions

The implementation of the different types of wind forcing affects the hydrodynamics, and subsequently the sediment transports. The effects are listed below, divided in effects on the hydrodynamics and on the sediment transports.

Wind forcing effects on the hydrodynamics

- The combination of the large-scale water level set-up with the local wind forcing generates a water level set-up or set-down in the basin. When there is water level set-up the tidal prism increases, and subsequently the amplitude of the tidal velocities in the inlet increases as well. When there is a set-down, the tidal prism decreases. As a consequence the tidal velocities in the inlets decrease as well.
- A spatially varying large-scale water level set-up causes the water level set-up in the basins to vary in space as well. The differences in the water level set-up affect the water level gradient between the inlets. This changes the magnitude of residual flow between the inlets.
- The wind forcing creates an additional longshore current. The direction of this current depends on the angle of the wind forcing. A southwestern wind creates a current that is directed northward. This is favourable for the transport of sediments from the beach of North Holland towards the Texel inlet. When there is a northwestern wind the transports around the tip of Texel, towards the Texel inlet, are increased.

Wind forcing effects on the sediment transport patterns

- The effect of the wind forcing on the residual flow is apparent in the sediment transport patterns. The decrease of the residual ebb-discharges through the Texel inlet decreases the magnitude of the exporting M_0M_2 residual flow mechanism. This increases the importance of the M_2M_4 tidal symmetry mechanism, which is importing. This results in an increase of the residual import of sediments through the Texel inlet. When the residual ebb-discharges through the Texel inlet decrease, the residual flood-discharges through the Vlie inlet decrease as well. This implies that relatively more water is exported. Most of these extra discharges take place in the ebb-channel. The M_0M_2 residual flow mechanism in this channel, which is exporting, is increased. This increases the export of sediments.

- When a storm wind from the northwest is implemented, the locally generated wind stresses are dominant over the wind-driven water level gradient in the basin. As a result the residual flow between the basins increases. The residual ebb-discharges to the Texel inlet increase, and as a result the net import through the inlet is converted to export. In the inlets of the Eierlandse Gat and the Vlie the implementation of the forcing of the storm wind induces a large rate of import. In the Vlie inlet, most of this import occurs around the tips of the barrier islands, but there is also a decrease in the export of sediments in the ebb-channel.
- The implementation of the wind forcing has limited effect on the sediment transports over the tidal divides. Even in case of the implementation of the strongest wind forcing ($U_{10}=13.05\text{m/s}$ from the northwest), the change in transport over the tidal divides does not exceed $418 \cdot 10^3 \text{m}^3/\text{yr}$ (over the tidal divide that separates the Texel and Eierlandse Gat basin).

4.4 Conclusions

The three different forcing agents each have their distinct influence on the sediment transports, especially on the ones through the inlets. For each of the forcing agents the main conclusions are listed below. Referring to section 3.1, the conclusions on the tidal forcing give answer to the research question #1. Research question #2 is answered by the conclusions on the wave forcing, and the conclusions on the wind forcing apply to research question #3. This section is concluded with general conclusions, which can be drawn from the results that are presented in previous sections.

Tidal forcing

- Due to the tidal forcing there is a sediment import through the Texel inlet. This import is mainly generated by the tidal asymmetry mechanism.
- The inlets of the Eierlandse Gat and the Vlie are exporting sediments as a result of tidal forcing only. In the Vlie basin, this export is caused by a large sediment export in the ebb-channel.
- Due to tidal forcing only the sediment transports over the tidal divides are small compared to the fluxes through the inlets.
- The interaction of the flow between the basins is an important factor in the transport rates through the inlets. When the interaction is shut off, the transport through the inlets increases with as much as a factor 2 to 3. In the Texel inlet, the reduction of the residual ebb-flow causes the net import to increase. In the Vlie inlet, due to the reduction of the residual flood-flow, the export through the ebb-channel is increased.
- The location of the tidal divides influences the rate of transport through the inlets. A shift of the divide towards/away from an inlet implies an increase/decrease of the relative flat area in its basin. The rate transport is increased or decreased to restore the initial ratio between flat and channel area. Because at its fringes a basin predominantly consists of tidal flats, a shift of the tidal divides towards an inlet results in an increase (decrease) of the import (export). The other way around, a shift away from the inlet results in a decrease (increase) of the import (export).

Wave forcing

- The wave forcing has most influence on the sediment transport patterns on the ebb-tidal deltas. Inside the basins the direct wave influence is limited.
- The wave forcing affects the hydrodynamics in the basins. It induces a water level set-up that is larger at low water than at high water, thereby reducing the tidal prism. The magnitude of the water level set-up depends on the wave height and wave angle. A higher wave prescribed on the boundaries induces a higher water level set-up. When an inlet is more exposed to the incoming wave the water level set-up is higher as well. The different orientation of the inlets causes a difference in water level set-up in the basins, subsequently altering the water level gradient. This affects the residual flow between the basins.
- The lower wave heights have little influence on the sediment transports over the tidal divides. When the wave height becomes $H_s=3\text{m}$ or higher, the transport over the divides is of the same magnitude as the imports and exports through the inlets.

Wind forcing

- Both the large-scale and local wind forcing have large effects on the sediment transport pattern. The large-scale wind set-up (or set-down) increases (or decreases) the storage area in the basins, subsequently increasing (or decreasing) the amplitude of the velocities in the inlet. The spatially varying large-scale water level set-up affects the water level gradient in the basins. This affects the residual flow between the basins.
- The local wind forcing generates flow in the direction of the wind. This can counteract or amplify the tidal residual flow. When the local wind forcing is significant (during storm conditions), it dominates the large-scale wind effects. It creates currents that are of the same order of magnitude as or larger than the tidal residual flow. Depending on the wind angle, this can multiply the amount of sediment transport through an inlet or convert an export into import (and vice versa).

General conclusions

- The tidal forcing can be represented with the semidiurnal constituent (M_2) and its overtides of the first two orders (M_4 & M_6). The transport rates through the inlets as well as the sediment transport patterns in the same inlets as a result of a more accurate tidal representation and the schematized representation correspond well.
- Waves have an effect on the sediment transports that is of the same order of magnitude as the effect of tidal forcing. However, the impact of the wave forcing strongly depends on the height (H_s) and angle (α) of the incoming waves. For the determination of the annual sediment transports, a schematization of the yearly wave climate with a single wave does not suffice. A climate of multiple waves, coming from different angles and of different heights, is required to give a good representation of the annual sediment transports.
- Wind forcing consists of two parts: a large-scale forcing and a local forcing. The large-scale forcing induces a water-level set-up (or set-down), called A_0 , which influences the magnitude of the tidal prisms that flow through the inlets. The set-up of the water level, induced by the large-scale wind forcing, is space varying. This induces a water level

gradient between the inlets, which can generate a flow that is of the same order of magnitude as the tidal flow.

The local wind forcing creates stresses on the water surface, which generates currents in the direction of the wind. These locally generated currents are of considerable magnitude, especially during storm conditions.

For a good representation of the yearly sediment transports, both the large-scale and local wind forcing have to be taken into account. A spatially varying large-scale water level set-up has a large influence on the transports, and should therefore also be taken into account. Drawback here is that it is difficult to calibrate this variance in the set-up (A_0), as there is only one measuring station in the area that can measure wind set-up.

5 Bathymetric influence

5.1 Introduction

The chapter deals with the changes in sediment transport patterns due to changes in bathymetry. The same forcing is applied to four different bathymetries. In section 5.2 the forcing representation is described. The reference bathymetry is the one of the year 1998, which is applied in chapter 4 as well. The sediment transports that are the result of the other three bathymetries are compared to the results of the simulation with the reference bathymetry. In this way the influence of the applied change in the bathymetry on the sediment transport pattern can be distinguished. To investigate the effect the ebb-tidal deltas have on the sediment transports, they are removed.

The Western Wadden Sea is an infilling system, which implies that sediments accumulate in the basins. With the use of equilibrium relations of the basins volumes with tidal prism and range, the needed sediment volumes for the basins to be in equilibrium are determined (see section 3.4.2). Two new bathymetries, related to the equilibrium volume, are applied. The first bathymetry contains the equilibrium volume of sediments, the second half this volume.

5.2 Forcing representation

To be able to compare the sediment transports induced by the new bathymetries to those induced by the original of 1998 the applied forcing to all bathymetries must be equal. To see how the bathymetry change influences the yearly averaged sediment transports the forcing should represent a year as well.

For the tidal representation the M_2 , M_4 and M_6 constituents are applied. The best way for wind and wave forcing is to subscribe the real time values at the boundaries. This implies that the simulation time is one year, and that takes too much computational time.

To shorten the computational time a wave climate is constructed that is representative for the yearly wave climate in the Western Wadden Sea. With the representation the focus is on the transport of sediments. The constructed wave climate induces a transport of sediments that is comparable to the transport that is caused by the real time waves. The wave climate consists of a number of conditions, each with its own wave (angle and height) and wind forcing (angle and velocity). Each condition simulates one tidal cycle.

Approach

For a number of stations in the North Sea and Wadden Sea long term (of measurements between 1979 and 2002) wave statistics are available. One of these stations is located offshore of the Eierlandse Gat. See Figure 5.1 for its location and the corresponding distribution of the wave height and direction. This wave rider gives the wave height distribution that is the most representative for the Western Wadden Sea.

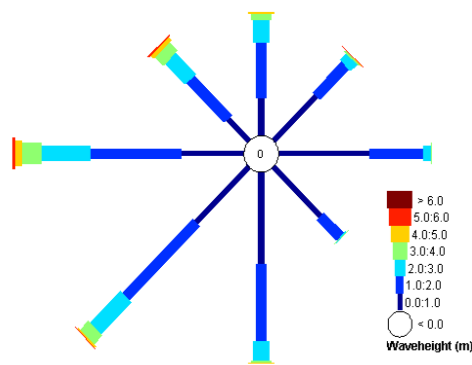


Figure 5.1 Wave height distribution for wave rider Eierlandse Gat (adapted from www.golflimaat.nl) and its location (earth.google.com)

The wave rose shows that the majority (80%) of the waves do not exceed a height of two meter. Most waves are from southern to northern direction. For the wave climate six direction bins that each covers 45° are chosen. They are listed in the table below.

The highest and relatively most influential waves are located in bins 2 to 5. For these bins a representative wave for the lower ($0 < H_s < 2\text{m}$) and higher waves ($H_s > 2\text{m}$) is determined. The waves in the other two bins are lower and their effect will be less. This is because that (at least a part of) the study area is sheltered from waves from these directions. In case of northeastern waves the Marsdiep lies sheltered; the Vlie inlet is sheltered from southern waves. Therefore for the waves in these bins one representative wave height is determined. This means that in total there are 10 wave classes.

Waves from the other directions are not taken into account. For the study area they are directed offshore and of minor importance. In total 81% of all waves is represented and 97% of the high waves.

Table 5.1 Direction bins

Direction bin #	Name	Covered angles α [°]
1	Northeast	$22.5 < \alpha < 67.5$
2	North	$-22.5 < \alpha < 22.5$
3	Northwest	$292.5 < \alpha < 337.5$
4	West	$247.5 < \alpha < 292.5$
5	Southwest	$202.5 < \alpha < 247.5$
6	South	$157.5 < \alpha < 202.5$

Wave characteristics

To determine the representative wave height (H_{mor}), for each class, the probability of occurrence of the wave height is subdivided in bins of 0.10 meters. The following assumptions are made for the determination of H_{mor} :

- The wave height inside each 0.10 meter bin is uniformly distributed.
- The morphological impact of a wave is related to its height with the power 2.5. This power is derived from the *CERC*-formula concerning wave induced sediment transport.
- The wave height distribution inside each class is according to the probability of occurrence.

For each class the morphological wave height is determined with equation(5.1).

$$H_{mor} = \left(\frac{\sum_{i=1}^{i=n} p_i (H_{m0}(i))^k}{\sum_{i=1}^{i=n} p_i} \right)^{1/k} \quad (5.1)$$

Where H_{m0} = significant wave height in bin “i”
 p_i = probability of wave height $H_{m0}(i)$ in the class
 n = number of bins in the class
 k = power relation between wave height and sediment transport, here 2.5

Using the same long term wave statistics the corresponding significant wave period T_{m02} and wind velocities U_{10} are determined. Corresponding means the wave period or wind velocity that is most likely to occur with the relevant wave height. In the simulations with the wave climate use is made of peak period T_p instead of T_{m02} . The conversion of the latter to the first is done applying equation(5.2), which is applicable when dealing with unimodal waves.

$$T_p = T_{m02} / 0.78 \quad (5.2)$$

Wave climate

The last step towards the wave climate that is representative to a yearly climate is the assignment of the yearly occurrence of each wave class. In Table 5.2 below the applied wave climate is described, together with the number of days they represent in a year.

Table 5.2 Applied wave climate

Wave condition	H_{mor} [m]	T_p [s]	U_{10} [m/s]	α [°]	Number of days	
1	1.27	6.37	4.82	0	31	
2	2.92	7.96	7.79	0	9	
3	1.32	6.37	5.12	315	31	
4	3.13	8.01	9.03	315	18	
5	1.27	5.90	5.97	270	54	
6	3.15	7.64	11.14	270	27	
7	1.25	5.64	7.03	225	63	
8	2.75	7.12	11.86	225	23	
9	1.43	5.78	7.66	180	68	
10	1.37	5.71	7.22	45	41	
					365	Σ days

5.3 1998 bathymetry

5.3.1 Results

Table 5.3 shows the annual tide-averaged imports through the inlets. Positive values denote imports and negative exports. All the three inlets import sediments. In total, an amount of $6306 \cdot 10^3 \text{ m}^3/\text{yr}$ is accumulated in the Western Wadden Sea. There is a little volume of residual export of sediments over the tidal divide at Terschelling ($76 \cdot 10^3 \text{ m}^3$). This volume is only 1.2% of the total amount of accumulated sediments. Compared to the simulations

with tidal forcing only (see section 4.1), the results differ considerably. As a result of tidal forcing only the Western Wadden Sea has a net export of $122 \cdot 10^3 \text{ m}^3/\text{yr}$ (see Table 4.1). The difference with the total amount of sediment transport through the inlets that is the result of the applied forcing in this simulation is $6428 \cdot 10^3 \text{ m}^3$. This difference is caused by the meteorological forcing (i.e. waves and wind). The meteorological forcing is most influential on the sediment transport in the Vlie inlet. There the transport induced by tidal forcing alone is an export ($2017 \cdot 10^3 \text{ m}^3$, see Table 5.3). The combination of the tide and the applied wave and wind climate causes an import of $1908 \cdot 10^3 \text{ m}^3$. This is a difference of $3925 \cdot 10^3 \text{ m}^3$, caused by the wind and wave forcing. The meteorological effect on the transport through the Eierlandse Gat is not as large. It converts a tidal forcing induced export of $595 \cdot 10^3 \text{ m}^3$ (Table 4.1) to an import of $664 \cdot 10^3 \text{ m}^3$ (see Table 5.3). Tidal forcing alone already induces an import ($2417 \cdot 10^3 \text{ m}^3$, see Table 4.1) through the Texel inlet, but the meteorological forcing increases the value to $3810 \cdot 10^3 \text{ m}^3$. Table 5.4 shows the sediment transports over the tidal divides that separate the basins. These values denote the average amount of annual tide-averaged transport over the tidal divide. Figure 5.2 shows that the magnitude of transported sediments is dependent on the location. Over the western part of the divide between the Texel and Eierlandse Gat basins on a yearly basis $59 \cdot 10^3 \text{ m}^3$ is transported to the Eierlandse Gat basin. On the eastern part of this divide there is a yearly transport of $52 \cdot 10^3 \text{ m}^3$ in the other direction. As a result there is a net sediment transport of $7 \cdot 10^3 \text{ m}^3/\text{yr}$ from the Texel basin towards the Eierlandse Gat basin.

The same phenomenon occurs over the divide that separates the Texel and Vlie basins. Over the western side sediment is transported from the Vlie to the Texel basin ($49 \cdot 10^3 \text{ m}^3$). Yet over the eastern side there is a net transport of $42 \cdot 10^3 \text{ m}^3$ in the other direction.

The volumes of sediment that are transported over the tidal divides are very small compared to the volumes that are imported through the basin on a yearly basis (in the order of percentages). This implies that the sediments that are transported through a specific basin is deposited in its own basin. Only a small amount is exchanged between the basins.

Table 5.3 Annual tide-averaged Sediment imports through the inlets (1998 bathymetry)

	Sediment import S [10^3 m^3]
Texel inlet	3810
Eierlandse Gat inlet	664
Vlie inlet	1908
Tidal divide Terschelling	-76

Table 5.4 Annual tide-averaged Sediment transports over the tidal divides (1998 bathymetry)

	Sediment transport S [10^3 m^3]
Texel basin → Eierlandse Gat basin	7
Texel basin → Vlie basin	4
Eierlandse Gat basin → Vlie basin	113

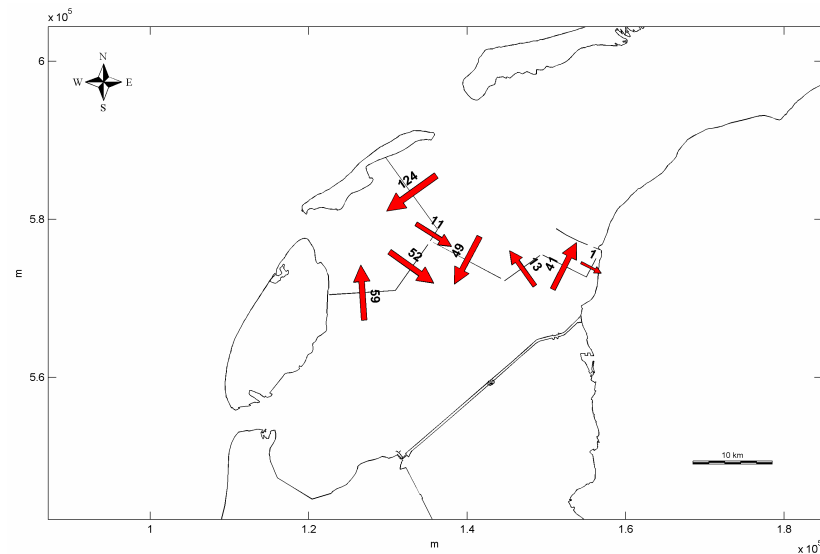


Figure 5.2 Spatial distribution of the sediment transports over the tidal divides

Sediment transport patterns in the inlets

Figure 5.3 shows the sediment transport pattern in both the Texel and Vlie inlet. In the Texel inlet the most sediment is transported from the beach of North Holland, located south of the inlet. A smaller amount of sediments is transported from the beaches of Texel towards the inlet. Due to wave action sediments are transported from adjacent deeper areas towards the shallow ebb-tidal delta. The large ebb-channel “Schulpengat” transports sediments in outward direction. The largest fluxes of sediment occur in the inlet and around the tip of North Holland. More towards the basin the magnitude of the sediment transports decreases quickly. This implies that the majority of the imported sediments are not transported inside the basin, but it is deposited near the inlet.

Over the cross section placed in the Vlie inlet, on a yearly basis, a volume of $1908 \cdot 10^3 \text{ m}^3$ is imported. Figure 5.3 (see also appendix F) shows that this import predominantly takes place around the tips of the barrier islands, and especially around that of Vlieland. The ebb-channel exports sediments.

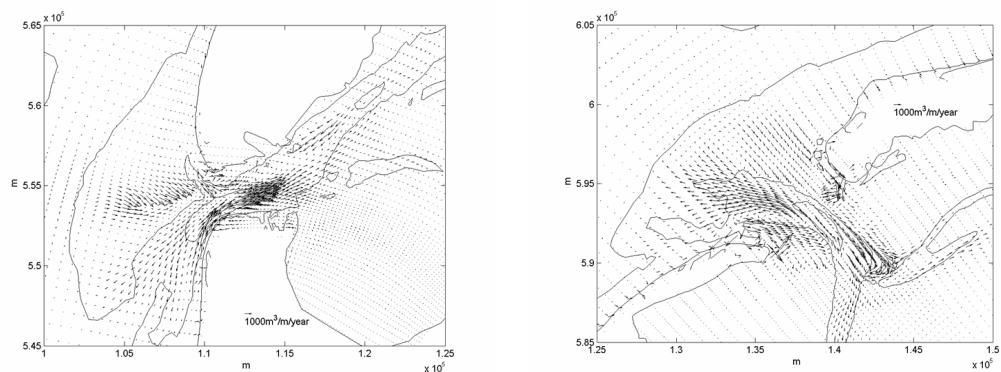


Figure 5.3 Sediment transport patterns in the Texel and Vlie inlets

5.4 Removal of the ebb-tidal deltas

5.4.1 Results

Table 5.5 gives the annual tide-averaged sediment imports belonging to the 1998 bathymetry and the bathymetry without ebb-tidal deltas. The sediment imports over the cross sections in the Texel and Eierlandse Gat inlet decrease a little. The import that takes place through the Vlie inlet ($1908 \cdot 10^3 \text{ m}^3$) becomes an export of $552 \cdot 10^3 \text{ m}^3$ due to the removal of the ebb-delta. The sediment transport over the tidal divide behind Terschelling is not influenced by the removal of the ebb-deltas.

Table 5.6 shows the transports over the tidal divides that belong to the 1998 bathymetry and the bathymetry without the ebb-deltas. The sediment fluxes over the divides are influenced, yet the magnitude remains of the same order.

Table 5.5 Annual tide-averaged sediment import with the 1998 bathymetry and the bathymetry without ebb-tidal deltas

	1998 bathymetry Sediment import S [$\cdot 10^3 \text{ m}^3$]	No ebb-delta bathymetry Sediment import S [$\cdot 10^3 \text{ m}^3$]
Texel inlet	3810	3571
Eierlandse Gat inlet	664	614
Vlie inlet	1908	-552
Tidal divide Terschelling	-76	-76

Table 5.6 Annual tide-averaged sediment transport over the tidal divides with the 1998 bathymetry and the bathymetry without ebb-tidal deltas

	1998 bathymetry Sediment transport S [$\cdot 10^3 \text{ m}^3$]	No ebb-delta bathymetry Sediment transport S [$\cdot 10^3 \text{ m}^3$]
Texel basin → Eierlandse Gat basin	7	-22
Texel basin → Vlie basin	4	6
Eierlandse Gat basin → Vlie basin	113	-128

Sediment transport pattern in the Texel inlet

The sediment transport patterns in the Texel inlet for the simulations with (1998) and without the ebb-tidal delta are shown in Figure 5.4 (see also appendix G). The considerable sediment transports on the shallow parts of the delta that are present in the reference simulation are gone when the ebb-delta is removed. The sediment transports around the tip of the island of Texel, towards the inlet, are increased. The export of sediments through the ebb-channel “Schulpengat” is increased as a result of the removal of the ebb-tidal delta. However, the change in the bathymetry has only effect on the western part of the inlet. The cross section, over which the sediment transport of Table 5.5 is determined, is located too far inside to show the effects of the removal of the ebb-delta.

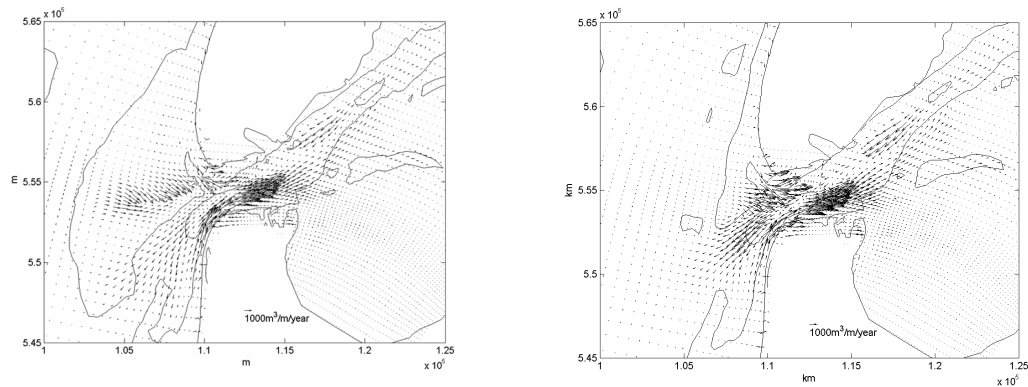


Figure 5.4 Left: sediment transport pattern (1998 bathymetry) and right: sediment transport pattern when the ebb-tidal delta is removed, in the Texel inlet

Sediment transport patterns in the Vlie inlet

As a result of the removal of the ebb-delta of the Vlie inlet the sediment export through the ebb-channel increases. This is shown in Figure 5.5 (see also appendix H). The import of sediment that occurs around the tip of the island of Vlieland is not affected. The deepening of the shallow area located in between the ebb-channel and the island of Terschelling causes the sediment transports there to decrease. Instead these transports are shifted more towards the inlet.

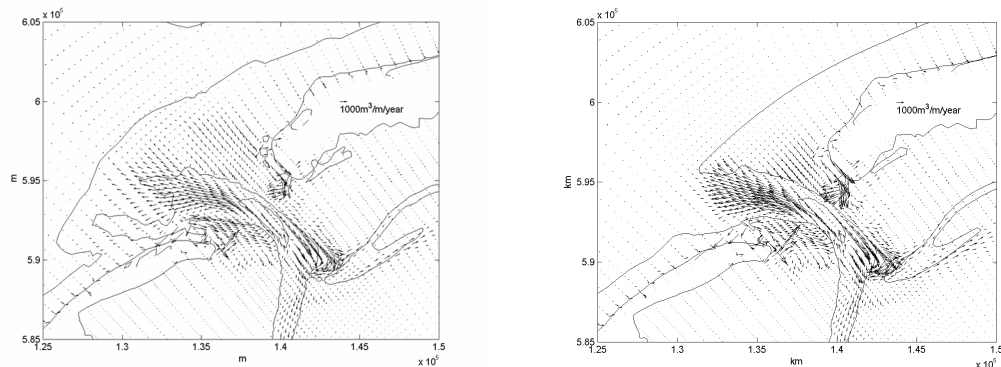


Figure 5.5 Left: sediment transport pattern (1998 bathymetry) and right: sediment transport pattern when the ebb-tidal delta is removed, in the Vlie inlet

5.4.2 Discussion

Averaged bed shear stresses development

Figure 5.6 shows the tidally averaged bed shear stresses in the Western Wadden Sea, as a consequence of a bathymetry with (Figure 5.6a) and without (Figure 5.6b) the ebb-tidal deltas. At the locations where sediment is removed (i.e. the shallow areas of the ebb-tidal deltas) the average bed shear stresses decrease. Due to the deepening the waves have less influence on the bed. In the ebb-channels of both the Texel and Vlie inlet the bed stresses increase. Around the tip of the island of Texel, where Figure 5.4 indicated a large increase of sediment transport, the averaged bed shear stresses increase. This location is more exposed to incoming waves as the ebb-tidal delta is gone.

The magnitude of the bed stresses around the tip of the island of Vlieland does not change. This is in correspondence with the sediment transport pattern shown in Figure 5.5, which shows no change in sediment transport at that location. On the north-eastern side of the ebb-channel in the Vlie inlet, the average bed shear stresses increase. The ebb-tidal delta is removed, and waves have more influence close to the inlet as they do not break on the delta. The averaged bed shear stresses inside the basins do not change, implying that the waves there are not larger as an effect of the bathymetric changes. They do not stir up more sediment that can be exported during ebb.

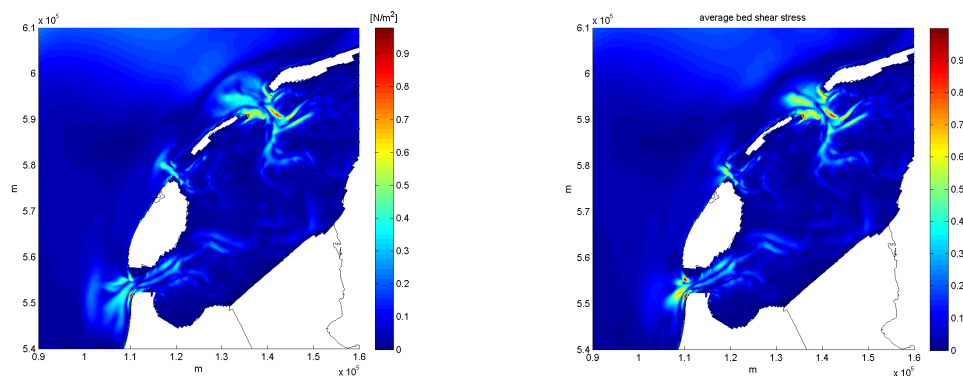


Figure 5.6 Tidally averaged bed shear stresses for the 1998 bathymetry (left) and the bathymetry without ebb-tidal deltas (right)

Sediment transport generating mechanisms

The Figure 5.7 and Figure 5.8 show the development of the M_0M_2 residual flow and M_2M_4 tidal asymmetry mechanisms. The magnitude of the sediment transport generated by tidal asymmetry is not influenced by the removal of the ebb-tidal deltas. The M_0M_2 residual flow is affected by the bathymetric changes. Especially in the ebb-channels of the three inlets the magnitude increases. The increase of the M_0M_2 residual flow in the ebb-channels is most predominant in the two largest inlet systems, viz. the Texel and Vlie inlets. The residual sediment transport due to this mechanism is directed outward. The combination of no change in transport generated by tidal asymmetry (which is an importing mechanism) with the increase of transport generated by residual flow (on locations where this is an exporting mechanism) causes the inlet to increase the export of sediment.

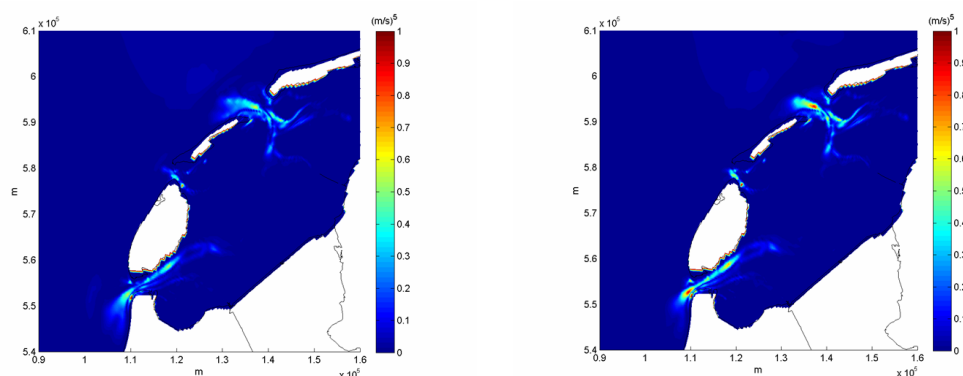


Figure 5.7 Magnitude of the M_0M_2 generated sediment transport for the 1998 bathymetry (left) and the bathymetry without ebb-tidal deltas (right)

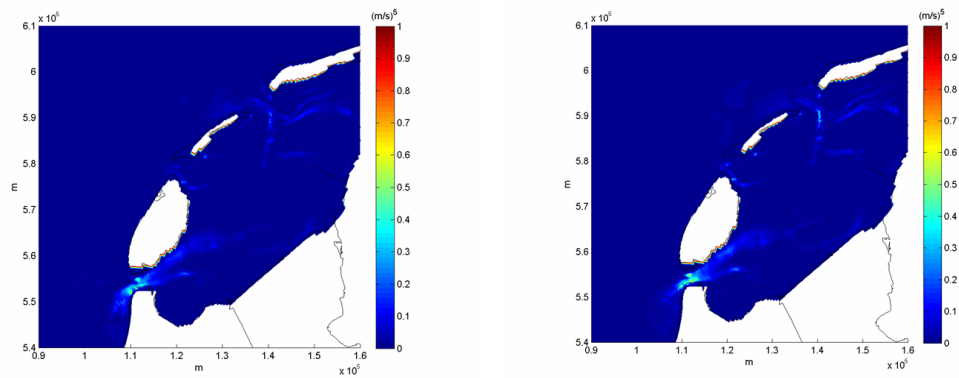


Figure 5.8 Magnitude of the M_2M_4 generated sediment transport for the 1998 bathymetry (left) and the bathymetry without ebb-tidal deltas (right)

5.5 Equilibrium related bathymetries

5.5.1 Results

Table 5.7 shows the sediment transports over the cross sections in the inlets, as a result of the 1998 bathymetry, the bathymetry halfway the equilibrium and the equilibrium bathymetry. The addition of sediments causes the import rate through the Texel inlet to decrease. With the reference bathymetry (that of the year 1998) there is an import of $3810 \cdot 10^3 \text{ m}^3/\text{yr}$. The basin bathymetry that is halfway the equilibrium volume causes this import to decrease to $1046 \cdot 10^3 \text{ m}^3/\text{yr}$. When the equilibrium bathymetry is applied the import through the inlet is changed into an export of $256 \cdot 10^3 \text{ m}^3/\text{yr}$. This export is an order of magnitude smaller than the import that is the result of the reference bathymetry.

The transports through the inlet of the Eierlandse Gat react strongly to the applied bathymetric changes. In case of the reference bathymetry this inlet is importing $664 \cdot 10^3 \text{ m}^3/\text{yr}$, yet with the halfway equilibrium bathymetry this has changed into an export of $868 \cdot 10^3 \text{ m}^3/\text{yr}$. When the basin bathymetry is adjusted more (the equilibrium volume), the export enlarges to an amount of $1375 \cdot 10^3 \text{ m}^3/\text{yr}$.

The sediment transports in the Vlie inlet react to the bathymetric changes in the same manner as the ones in the inlet of the Eierlandse Gat. As a result of the reference bathymetry the inlet is importing ($1908 \cdot 10^3 \text{ m}^3/\text{yr}$), but the changes in basin bathymetry change transports into export. Depending on the magnitude of the alteration, the export through the Vlie inlet becomes $2264 \cdot 10^3 \text{ m}^3/\text{yr}$ (halfway equilibrium bathymetry) and $3817 \cdot 10^3 \text{ m}^3/\text{yr}$ (equilibrium bathymetry).

The export of sediments over the tidal divide Terschelling increases as a result of the changes in basin bathymetry. Before the changes there is an export of $76 \cdot 10^3 \text{ m}^3/\text{yr}$, and this increases to $90 \cdot 10^3 \text{ m}^3/\text{yr}$ and $94 \cdot 10^3 \text{ m}^3/\text{yr}$. The magnitude of the exports over this divide remains small, compared to the volumes that are transported through the inlets.

Table 5.7 Annual tide-averaged sediment imports through the inlets as a result of the 1998 and equilibrium related bathymetries

	1998 bathymetry Sediment import S [*10³ m³]	Halfway equilibrium bathymetry Sediment import S [*10³ m³]	Equilibrium bathymetry Sediment import S [*10³ m³]
Texel inlet	3810	1046	-265
Eierlandse Gat inlet	664	-868	-1375
Vlie inlet	1908	-2264	-3817
Tidal divide			
Terschelling	-76	-90	-94

Table 5.8 shows the transports over the divides in the Western Wadden Sea as a result of the bathymetric changes. For none of the divides, a clear trend can be distinguished in the development of the transports. In case of the reference bathymetry the Texel basin gives sediment to the basin of the Eierlandse Gat. As a result of the changes in bathymetry this transport changes direction and becomes $89 \cdot 10^3 \text{ m}^3/\text{yr}$. This value is constant for the two bathymetry changes.

With the reference bathymetry, there is an exchange of sediments from the Texel to the Vlie basin of $76 \cdot 10^3 \text{ m}^3/\text{yr}$. When the basin bathymetry is adjusted to the equilibrium, this amount initially decreases to $28 \cdot 10^3 \text{ m}^3/\text{yr}$. When the bathymetry is in equilibrium, the transport has increased to $156 \cdot 10^3 \text{ m}^3/\text{yr}$.

In case of the sediment exchange between the basins of the Eierlandse Gat and the Vlie, the basin of the Eierlandse Gat gives sediment to that of the Vlie in case of the reference bathymetry. The bathymetry adjustments change the direction of the sediment transport. However, the magnitude of the transport over the divide as a result of the smaller adjustment is larger ($172 \cdot 10^3 \text{ m}^3/\text{yr}$) than that as a result of the larger adjustment ($154 \cdot 10^3 \text{ m}^3/\text{yr}$).

Table 5.8 Annual tide-averaged sediment transports over the tidal divides as a result of the 1998 and equilibrium related bathymetries

	1998 bathymetry Sediment import S [*10³ m³]	Halfway equilibrium bathymetry Sediment import S [*10³ m³]	Equilibrium bathymetry Sediment import S [*10³ m³]
Texel basin → Eierlandse gat basin	7	-89	-89
Texel basin → Vlie basin	76	28	156
Eierlandse Gat basin → Vlie basin	113	-172	-154

Sediment transport patterns in the Texel and Vlie inlets

Figure 5.9 shows the development of the transport patterns in the Texel and Vlie inlets, as a result of the bathymetric changes. The transport patterns in the inlet as a result of the equilibrium bathymetry are also shown in appendix H. Comparing the patterns of the simulation with the halfway equilibrium bathymetry to the reference simulation, in the Texel inlet the magnitude of the residual fluxes decreases. The pattern does not change. The pattern changes when the bathymetry is altered more (i.e. the equilibrium bathymetry). In the inlet the export of sediment is now dominant. The large flux of sediment that is directed

inwards (in the southern part of the inlet) that is present with the reference bathymetry, is almost completely gone when the equilibrium bathymetry is applied. In the Vlie inlet the transport pattern does not change because of the bathymetric changes. Only the net outward flux of sediments in the ebb-channel becomes larger as the bathymetry is more adjusted.

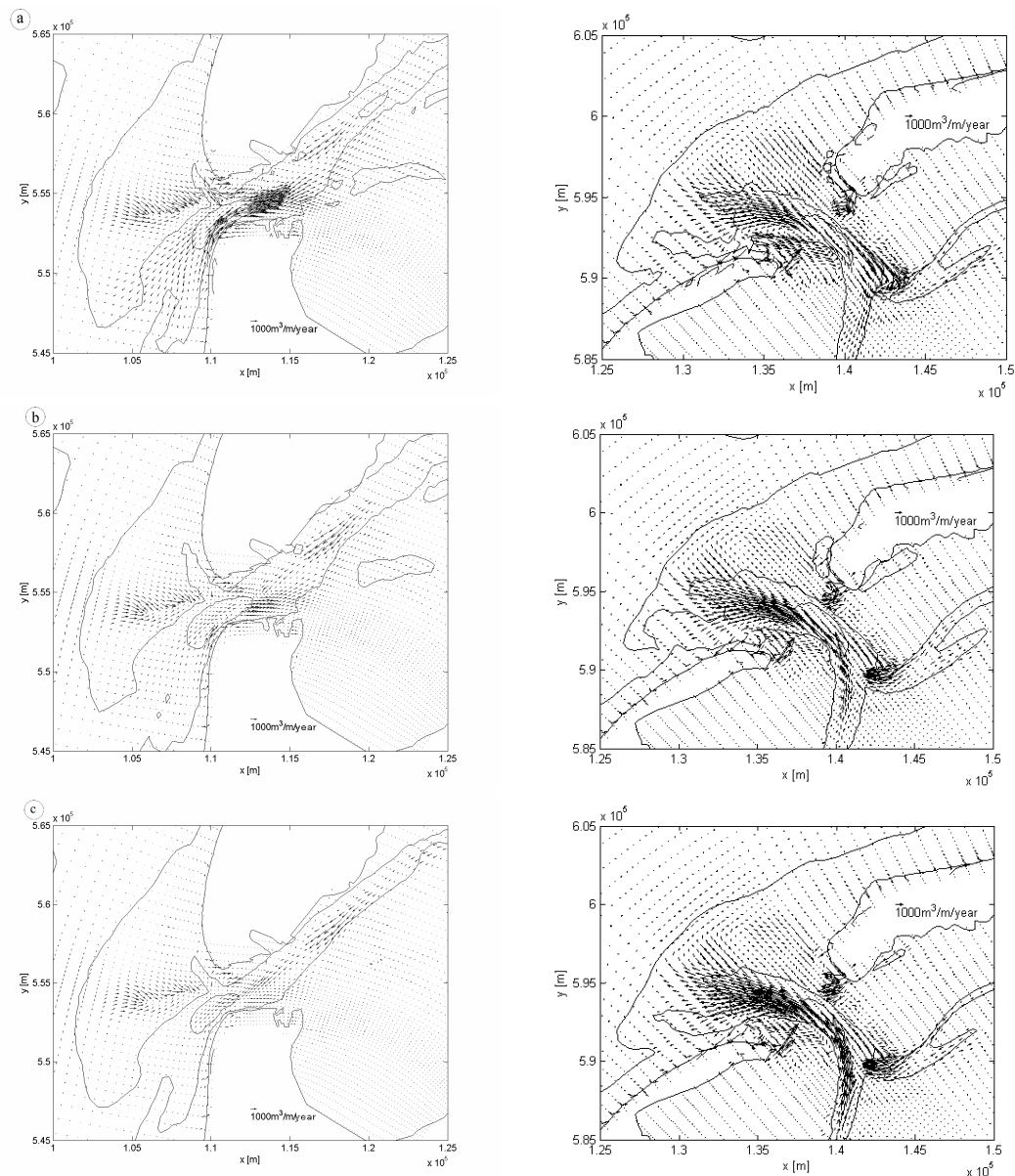


Figure 5.9 Sediment transport patterns in the Texel (left) and Vlie (right) inlets. a) 1998 bathymetry, b) halfway the equilibrium bathymetry and c) equilibrium bathymetry

5.5.2 Discussion

Averaged bed shear stresses development

In Figure 5.10 the averaged bed shear stresses are shown. The increase of the stresses in the ebb-channel of the Vlie inlet is caused by the larger velocities (discussed in the

hydrodynamics section). The large amount of sediment volume placed in the Texel basin induces a large decrease in the tidal prism. Subsequently the amplitude of the tidal velocity in the Texel inlet decreases, which is illustrated by the decrease of the averaged bed shear stresses in the Texel inlet, and in the ebb-channel “Schulpengat”. In the Texel basin, the averaged bed shear stresses in the channel have increased. The flow in the basins is more concentrated to this channel. The average rise of the flat height (in case of the adjustment to the equilibrium bathymetry) is approximately 2m. The relative friction on the flats is increased more than in the channel, and as a result more water is conveyed through the channel.

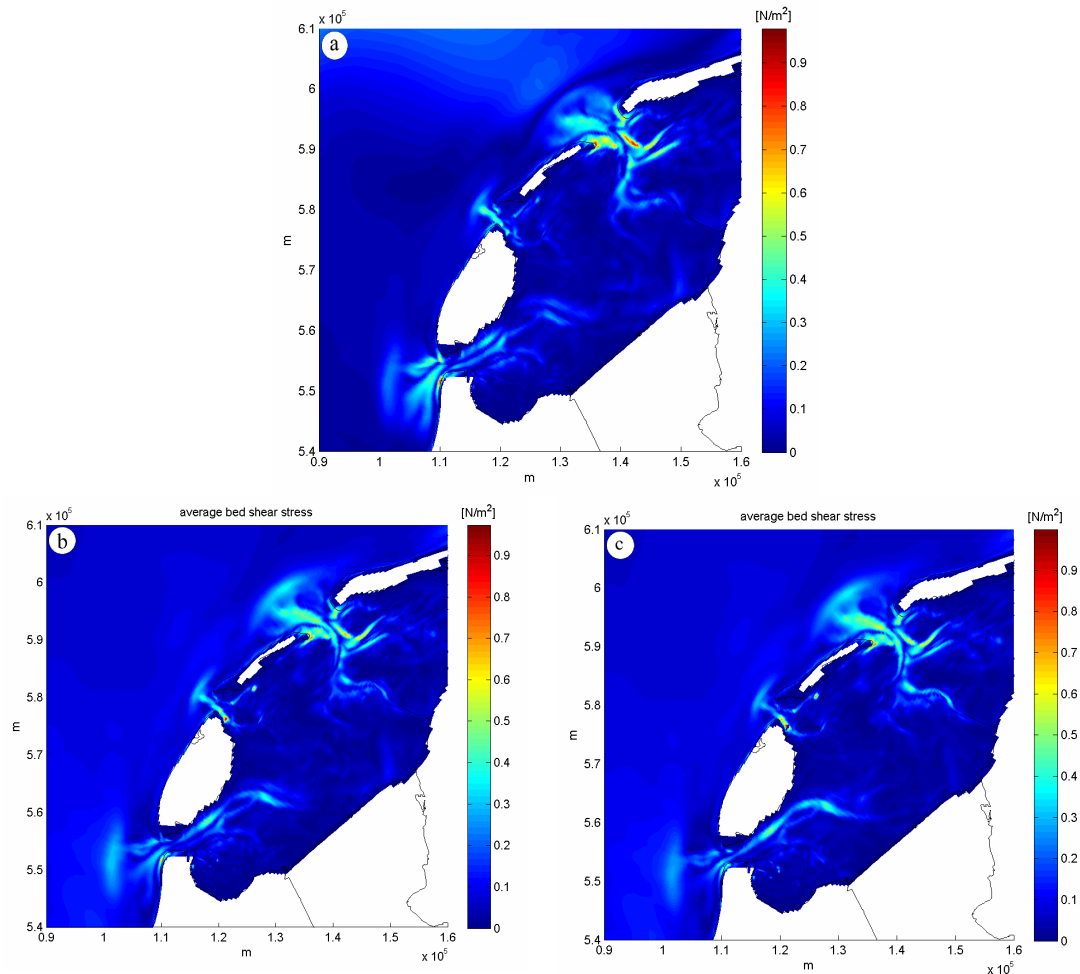


Figure 5.10 Averaged bed shear stresses for a) 1998 bathymetry, b) halfway equilibrium bathymetry and c) equilibrium bathymetry

Shift of the tidal divides

The elevation of the geometry hinders the propagation of the tidal wave in the basins. As a result of the large amount of sediments deposited, the tidal wave propagation is most influenced in the Texel basin. The location where the tidal waves in the basins meet (i.e. the

tidal divides) shifts towards the Texel inlet. Figure 5.11a) to c) show the standard deviation⁷ (σ_{st}) of the flow velocity, for the three bathymetries. Between basins, where the standard deviation of the flow velocity is minimal, the divide is located. Figure 5.11d) shows the contour lines of the location where the standard deviation is minimal, for each bathymetry. It shows that, due to the addition of sediments, the tidal divides shift towards the Texel basin. The Texel basin reduces in size; the Eierlandse Gat and, predominantly, the Vlie basin become larger.

Section 4.1.2 showed that a shift of the tidal divide has a distinct effect on the transport rate through the inlets. When the divide is shifted towards the inlet, the relative flat area reduces. The import through the inlet increases (or the export decreases) in order to counteract the loss of flat area. When the tidal divide is relocated away from the inlet, the opposite occurs. The relative flat area is increased, and as a response the import through the inlet reduces (or the export increases).

Due to the addition of sediments (which predominantly occurred in the Texel basin), the tidal divides have shifted towards the Texel inlet, and away from the inlets of the Eierlandse Gat and Vlie. This shift has an increasing effect on the exports through the inlets of the Eierlandse Gat and Vlie (see Table 5.7). The reaction of the transport rate through the Texel inlet is different. Here the shift of the tidal divide induces an increase of the import of sediments. It therefore counteracts the decrease of import that is shown in Table 5.7. The shift of the tidal divides towards the Texel inlet therefore has a stabilising effect on the transport rate in the Texel inlet, and it amplifies the transport rate in the other two inlets.

$$^7 \sigma_{st} = \sqrt{\frac{\sum_{i=1}^{i=n} (x_i - \mu)^2}{n}} . \text{ The standard deviation is a measurement of the spread of the data about the mean value } \mu.$$

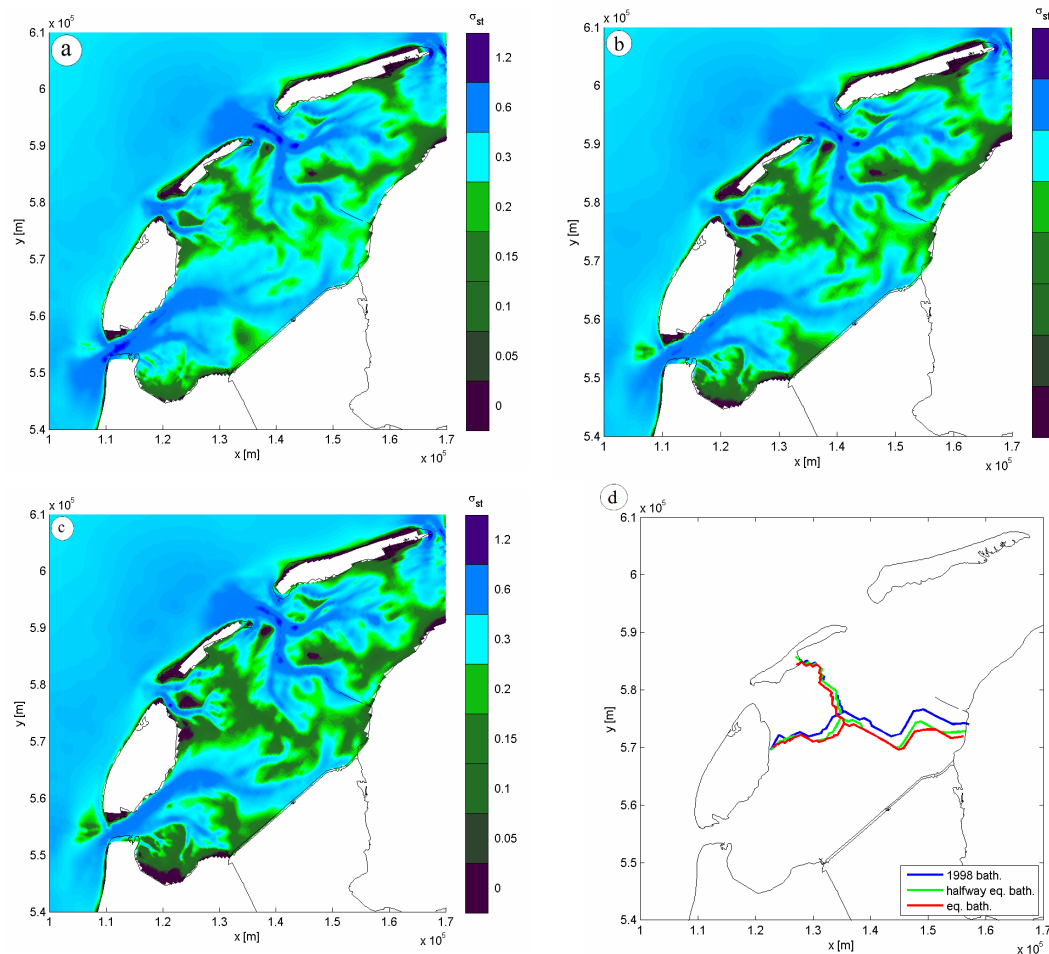


Figure 5.11 Standard deviation of the flow velocities for a) 1998 bathymetry, b) halfway equilibrium bathymetry, c) equilibrium bathymetry and d) locations of the tidal divides.

Hydrodynamics

In Figure 5.12 the reaction of the M_0M_2 residual flow and M_2M_4 tidal asymmetry to the bathymetric changes is shown. The magnitude of the M_0M_2 residual flow decreases in the Texel inlet when the bathymetry adjustment becomes larger. The increase in basin bathymetry adjustment increases the M_0M_2 residual flow in the ebb-channel in the Vlie inlet. The large volumes that are deposited in the Texel basin to acquire the equilibrium related bathymetries ($6.1 \cdot 10^8 \text{ m}^3$ for the halfway equilibrium and $12.2 \cdot 10^8 \text{ m}^3$ for the equilibrium bathymetry, see Table 3.2) decrease the tidal prism that goes through the inlet. The magnitude of the M_2 velocities in the Texel inlet decreases, and as a result the magnitude of the M_0M_2 residual flow as well.

The volumes of sediment that are added to the Vlie basin are an order of magnitude smaller ($4.13 \cdot 10^7 \text{ m}^3$ for the halfway equilibrium and $8.25 \cdot 10^7 \text{ m}^3$ for the equilibrium bathymetry, see Table 3.2) than those in the Texel basin. The tidal prism through the Vlie inlet does not decrease as much due to the bathymetric changes as the one through the Texel inlet does. Furthermore, the added sediments are for the majority placed in the channels; see Figure 3.7 and Figure 3.8. The combination of the low reduction of discharges with the constriction of the channel cross-sectional area induces an increase in the M_0M_2 residual flow in the Vlie

inlet. The residual flow is ebb-dominant, and as a result the export of sediments increases due to this mechanism.

As a result of the bathymetric changes the magnitude of the sediment transport, generated by the M_2M_4 tidal asymmetry, decreases in the Texel inlet. The decrease of the magnitude of the M_2 velocity, described above, causes this decrease. In the Vlie inlet the magnitude of the M_2 velocity is not affected as much, and the magnitude of the M_2M_4 tidal asymmetry does not change.

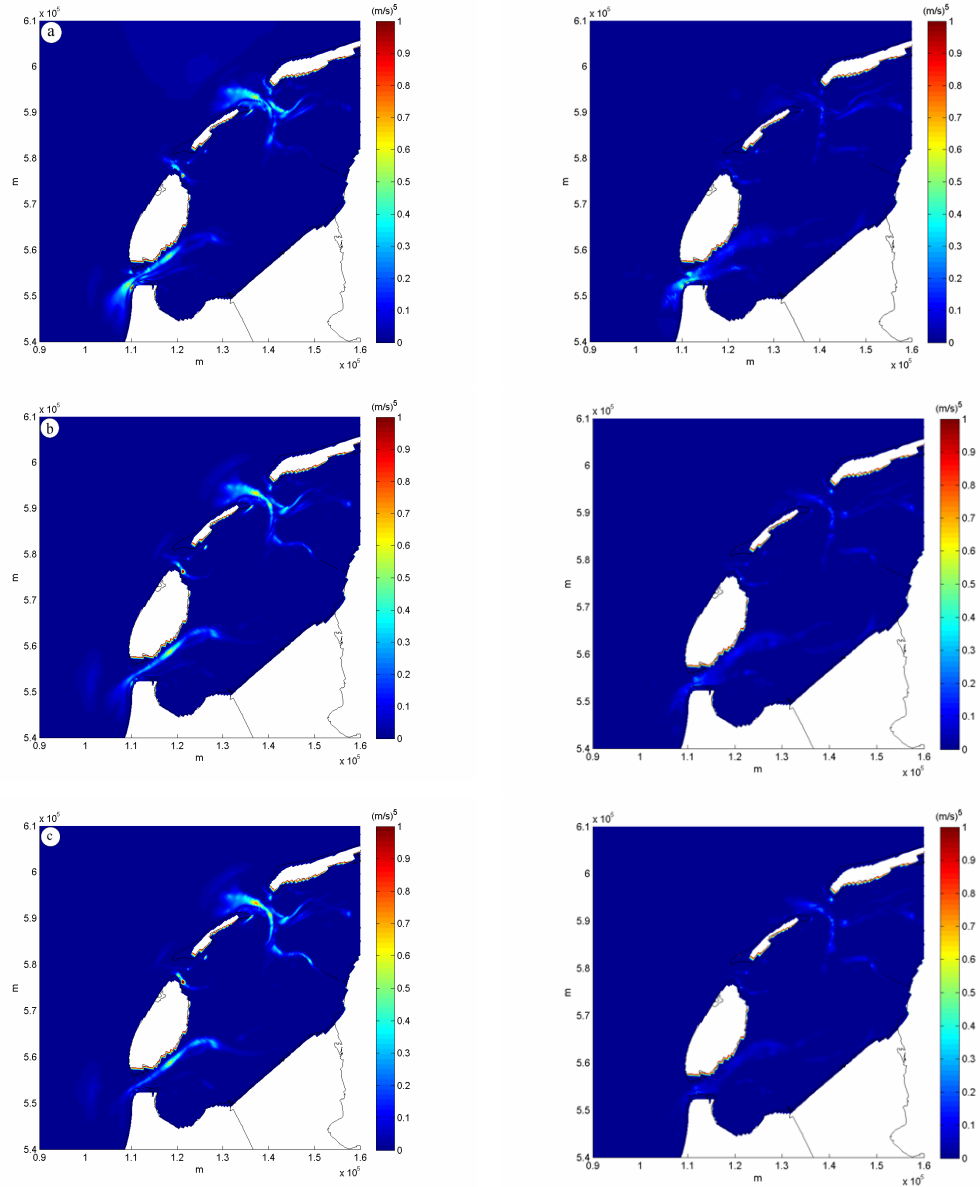


Figure 5.12 M_0M_2 residual flow (left) and M_2M_4 tidal asymmetry (right) magnitudes for a) 1998 bathymetry, b) halfway the equilibrium bathymetry and c) equilibrium bathymetry

5.6 Conclusions

The results of the sediment transports as result of 1998 bathymetry, the bathymetry without ebb-tidal deltas and the equilibrium related bathymetries are discussed separately. They answer the research questions #4 to #6 of section 3.1.

- *1998 bathymetry.* The tidal forcing combined with the wind and wave climate generates a residual import of sediments in the Western Wadden Sea of a magnitude of $6306 \cdot 10^3 \text{ m}^3/\text{yr}$. The meteorological forcing is largely responsible for this amount of import.
- *No ebb-tidal delta bathymetry.* Due to the removal of the ebb-tidal deltas the waves are no longer hindered and they have more effect in the inlet region. In case of the Texel inlet the tip of barrier island of Texel suffers increased scouring because of the increased wave action in the area. The effect of the removal of the ebb-tidal delta is limited to the entrance of the inlet. Further inside the inlet and in the basin the sediment transport patterns hardly change.

The systems try to compensate for the loss of sediments by transporting sediments out of the inlets towards the outer delta region. These sediments are transported via the ebb-channel by an increase of the magnitude of the M_0M_2 residual flow mechanism.

- *Equilibrium related bathymetries.* The large volume addition in the Texel basin initially reduces the rate of import through its inlet from $3810 \cdot 10^3 \text{ m}^3/\text{yr}$ to $1046 \cdot 10^3 \text{ m}^3/\text{yr}$. When the equilibrium bathymetry is applied the import has changed in to a little export of a magnitude of $265 \cdot 10^3 \text{ m}^3/\text{yr}$. This is a small amount compared to the initial import.

The transport rates through the inlets of the Eierlandse Gat and the Vlie react strongly to the bathymetric changes. Initially the inlets are importing sediment, $664 \cdot 10^3 \text{ m}^3/\text{yr}$ and $1908 \cdot 10^3 \text{ m}^3/\text{yr}$ for the Eierlandse Gat and Vlie inlet respectively. This is an indication that the basins have not reached their equilibrium state yet. Yet the addition of the sediment volumes that are needed to reach the equilibrium volumes results in a considerable export of $1375 \cdot 10^3 \text{ m}^3/\text{yr}$ and $3817 \cdot 10^3 \text{ m}^3/\text{yr}$ for the Eierlandse Gat and Vlie respectively. This is caused by the fact that the majority of the additional sediment volumes are placed in the channels. This increases the ebb-velocities and this causes the M_0M_2 residual flow mechanism to export more sediments.

In addition, there is a shift of the location of the tidal divides due to the bathymetry adjustments. The shift is towards the Texel inlet, thus decreasing the Texel basin and increasing the basins of the Eierlandse Gat and Vlie. This effect has a reducing (and thus stabilizing) effect on the export through the Texel inlet. Due to the increase of their basins, the export rate through the inlets of the Eierlandse Gat and Vlie is increased.

There is no clear trend in the reaction of the sediment transport over the tidal divides. They remain of the same order of magnitude, which is small compared to the amount of sediments that are transported through the inlets.

6 Conclusions and recommendations

In this chapter the main findings of the research are stated. This is done in the section research conclusions. The section discussion compares the main findings with the objectives stated in section 1.3, and to what extent the research set-up is satisfactory to accomplish the objectives. The chapter is concluded with recommendations for further studies on the topic.

6.1 Research conclusions

The research consists of two parts. In the first part the influence of the different forcing agents is described. The second part deals with the influence of bathymetric changes on the sediment transports. The main findings of the two parts are mentioned separately.

Forcing agents influence

The influence of three forcing agents on the sediment transports is investigated, viz. tidal, wave and wind forcing.

- Due to tidal forcing, only the Texel inlet is importing sediments. The Eierlandse Gat 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.
- Waves have little influence on the sediment transport inside the basins.
- Indirect effects of waves are the generation of a residual flow between the basins, and the reduction of the tidal range. The importance of the effects is larger when the incoming wave is larger. The direction of the residual flow depends on the angle of incidence of the wave.
- The increase of import generated by waves occurs mainly around the tips of the barrier islands.
- 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. The set-up affects the storage area in the basins, subsequently increasing (in case of a set-up) or decreasing (in case of a set-down) the tidal velocities in the inlets.
- The transport of sediments between the basins is limited, and shows little reaction to a change in the forcing.

Bathymetric influence

- With the bathymetry of the year 1998 the Western Wadden Sea has an import rate of $6306 \cdot 10^3 \text{ m}^3/\text{yr}$. This volume is divided over the three inlets. $3810 \cdot 10^3 \text{ m}^3/\text{yr}$ is imported through the Texel inlet, $664 \cdot 10^3 \text{ m}^3/\text{yr}$ through the Eierlandse Gat inlet and $1908 \cdot 10^3 \text{ m}^3/\text{yr}$ through the Vlie inlet.
- The annual tide-averaged 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.
- 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 is limited. The transport in the basins is not influenced.
- 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 Texel basin suffers the largest shortage of sediment. When a volume of $1220 \cdot 10^6 \text{ m}^3$ is added to the bathymetry of the year 1998, the transport rate through the inlet changes to an export of $265 \cdot 10^3 \text{ m}^3/\text{yr}$. This is a small amount compared to the initial import of $3810 \cdot 10^3 \text{ m}^3/\text{yr}$. 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.
- The added sediments induce little reaction in the transport of sediments over the tidal divide. They remain marginal compared to the transports through the inlets.

6.2 Discussion

Model set-up

In order to keep the computational time acceptable some simplifying assumptions had to be made. The first was that the computations were carried out depth-averaged. That made it impossible to include density driven flow. As a result of the discharges through the sluices in the Afsluitdijk, density gradient driven flow does occur in reality. The discharges through the Afsluitdijk were not taken into account in the model.

The mesh size of the grid is rather coarse in the basins. This induces a coarse representation of the geometry there, and this may influence the flow. However, the vertical tide in the back of the basin, at station Harlingen, shows good correspondence with the observation data. The residual discharges through the Texel inlet are comparable to the NIOZ-ferry data as well.

The bed schematization of a uniform $D_{50}=250\mu\text{m}$ overestimates the grain size in the shallower areas in the basins. As the flow is relatively low in these shallow areas, the sediment transport is underestimated there. This is an important factor in the discrepancy between the observed and modeled transports over the tidal divides. Observations indicate a transport over the tidal divide from the Texel basin towards the Vlie basin with a magnitude of $\pm 4000 \cdot 10^3 \text{ m}^3/\text{yr}$, while the transport in the model is almost zero. With a more precise bed schematization (i.e. finer grains in the back of the basins) the discrepancy probably would be smaller. However, the simplification is considered justified, as the focus was to determine the demand for sand. A more detailed analysis of the transports over the divides implies the implementation of mud-transport (i.e. cohesive sediment). This is a different study, and not the scope of this research.

Model results

One of the objectives of this thesis was to investigate the influence of the individual forcing agents. First the tidal forcing influence was investigated. Then wave forcing was added and finally the wind forcing. Because the meteorological forcing (i.e. wave and wind forcing) can occur in various intensities and from various angles, a number of specific conditions were selected and investigated. The advantage of this approach is that it enables to investigate the influence of both the angle of incidence and the intensity of the meteorological forcing. However, it does not give a reflection on what the sediment transports on a yearly basis are. To be able to give an estimate of the annual import of sediment, a wind and wave climate is constructed. This makes it possible to compare the results of the different bathymetries, and give an indication of what will happen in reality.

The best climate would be a real-time representation of the wind and wave forcing. As this takes too much computational time, the decision was made to construct a simplified climate that represents the real-time values. Ten different cases of meteorological forcing were constructed, each representing a class of different forcing intensity and angle of origin. The impact of each case varies, as the classes they represent differ in probability of occurrence. Therefore a weight factor is applied for each forcing case. This approach is a simplification of the reality, but the results are satisfactory. The residual annual tide-averaged import through the three inlets is $6306 \cdot 10^3 \text{ m}^3/\text{yr}$, where measurements indicate an annual import of $10000 \cdot 10^3 \text{ m}^3/\text{yr}$. There is a difference between the model results and measurements, but there is enough correspondence that conclusions from the model results can be drawn.

For the equilibrium bathymetry in total a volume of $13.74 \cdot 10^8 \text{ m}^3$ was added to the bathymetry of the year 1998. The majority (89%) is placed in the Texel basin. Although the added volumes to the Eierlandse Gat and Vlie basin are more than ten times smaller, the response of the transport patterns is in the same order of magnitude. It shows that the location of the placed sediments is an important factor. In the Eierlandse Gat and Vlie basin, the added volume was relatively small, but it was predominantly placed in the ebb-channels. This constriction of the flow area induced an increase in the velocities in these channels. The ebb-dominance implied a larger amount of annual export. In the Texel basin, the added sediments are more evenly distributed over the channels and tidal flats. As a result the response of the transport rate is more moderate (in relation to the applied basin volume adjustment).

The term “equilibrium bathymetry” appears to be suitable for the determined volume and subsequent bathymetry of the Texel basin, and less to that of the Eierlandse Gat and Vlie basin. However, the large amount of export through these two inlets is probably for a large part caused by the relative large constriction of the ebb-channels. The ratio between the flat volume and channel volume, for these basins, is distorted too much in these basins. This is illustrated by the development of the scaled hypsometric curves (see appendix A). The curve of the Texel basin shows the least variation compared to the hypsometric curve of the year 1998. A better fit of the scaled hypsometric curves of the other two basins probably decreases the rate of export. The determined “equilibrium bathymetries” of these basins is not the correct one, yet it does not imply that the added volume is incorrect.

Although the results for the Texel basin are promising, the same questions can be asked. Although its scaled hypsometric curve shows a better response to the added volume, the grid size does not allow a perfect fit. The ratio between the flat volume and the basin volume is distorted, albeit to a lesser extent as that of the other basins. The determination of the equilibrium volume, with the use of the empirical equilibrium relation, also does not give a result that is unconditionally correct. However, the determined volume is a good indication of the existing demand of sediment. The results of the simulations agree with that. The sediment demand of the Texel basin is in the order of $1200 \cdot 10^6 \text{ m}^3$.

6.3 Recommendations

For future studies on the topic, the following recommendations apply:

- For a better understanding in the transport of sediments between the basins, the bed schematization should be improved. This includes the modelling of fine sediments such as clay and silt.
- If more computational capacity is available, simulations including real-time forcing representations can be carried out. The grid size can be reduced as well, allowing a better schematization of the geometry.
- The simulations in this thesis are carried out depth-averaged (2DH). A comparison with 3-dimensional computations gives an estimate of the influence of horizontal and vertical density gradients, induced by the fresh water discharge through the sluices.
- In this thesis the simulations cover one tidal cycle. This gives only insight into the initial response of the system to the changes in forcing or bathymetry. Simulating longer periods gives more insight in the response of the system on longer timescales.
- The determination of equilibrium states still leaves much room for discussion. The equilibrium relations are still under development. Studies that combine the calibration of the coefficients with the use of process based models can provide valuable tools in the validation of these coefficients.

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A Hypsometric curves of equilibrium related bathymetries

This appendix shows the scaled hypsometric curves of the equilibrium related scenarios. The curves that belong to the 1998 bathymetry are shown in the same figure in order to see the agreement they have.

Approach

The determined volumes that are needed for the new scenarios are distributed over the basin area. The magnitude of the rise (Δh) of the bed level per grid cell is dependent on its depth, expressed in equation(A.1). The values of the coefficients α and β are varied to obtain the best fitting new scaled hypsometric curve.

$$\Delta h = \alpha * z^{\beta} \quad (A.1)$$

Where z = water depth relative to MHW

The curves of the three basins are constructed separately, and the applied MHW values and coefficients vary per basin. The applied values are shown in Table 1.

Table 1 Applied MHW levels and coefficients

	MHW [m]	α halfway equilibrium	α equilibrium	β
Texel basin	0.72	0.261	0.522	0.8
Eierlandse Gat basin	0.63	0.148	0.3	0.8
Vlie basin	0.89	0.02	0.04	0.9

The hypsometric curves for scenario III and IV are plotted in Figure A.1 and Figure A.2 respectively. For both scenarios goes that although the adjustment is the largest in the Texel basin, the new scaled hypsometric curve of this basin agrees best to the one of 1998.

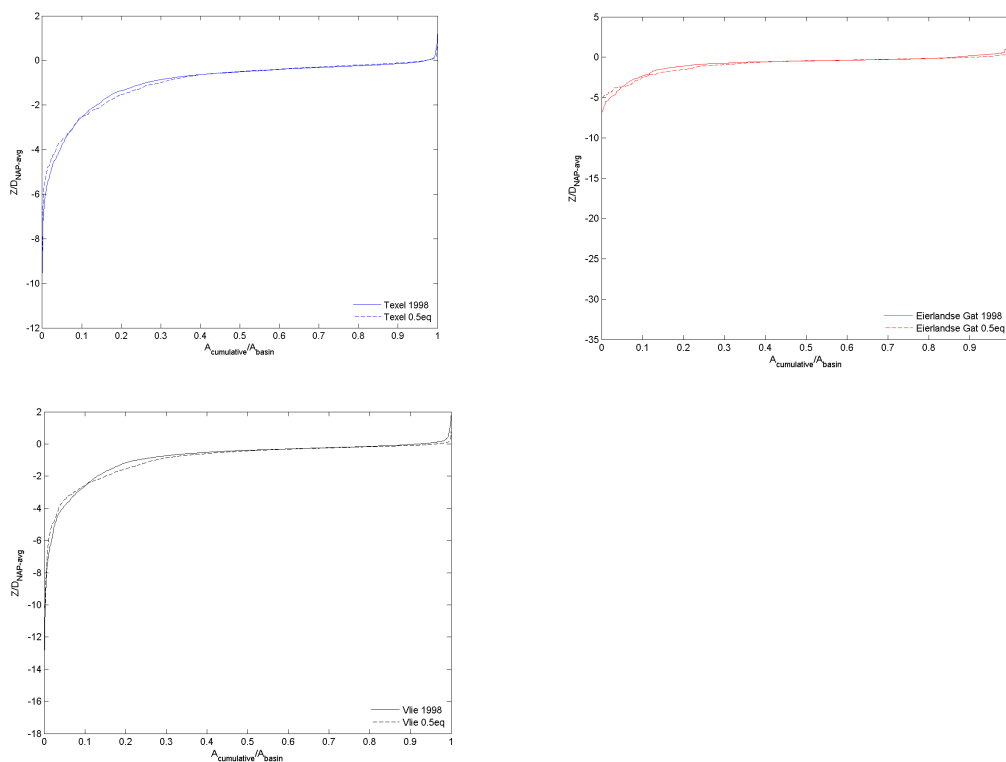


Figure A.1 Scaled hypsometry of the halfway equilibrium scenario (III) for the three basins

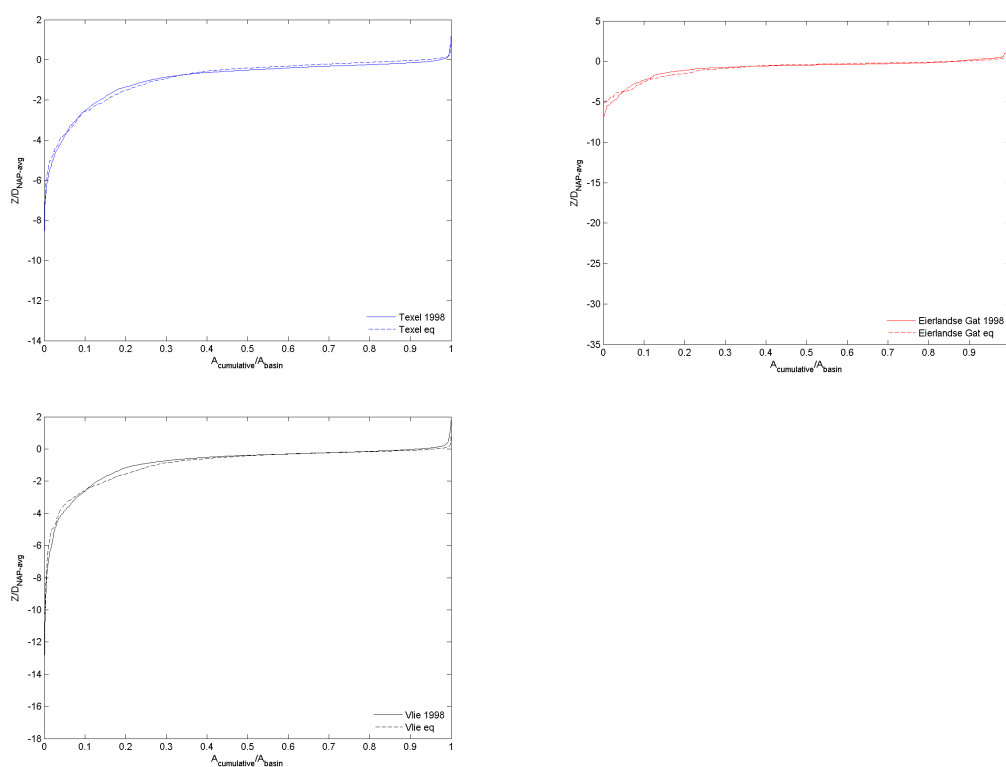


Figure A.2 Scaled hypsometry of the equilibrium scenario (IV) for the three basins

B Harmonic analysis of the tidal signal

The tidal signal is generated by the gravitational forces of both the sun and the moon. These gravitational forces have a sinusoidal behavior, and can be represented by the following formula:

$$\zeta(t) = A_0 + \sum_{i=1}^n A_i \cos(2\pi f_i t - \varphi_i) \quad (\text{B.1})$$

$\zeta(t)$ = water elevation

A_0 = mean value of a time series of the water elevation

A_i = amplitude of the i^{th} constituent

f_i = frequency of the i^{th} constituent

φ_i = phase of the i^{th} constituent

The most important principle tidal constituents are mentioned in Table B.1, together with information whether they appear twice a day (semidiurnal), once a day (diurnal) or over a longer period.

Table B.1 Principle tidal constituents (Stewart, 2002)

Tidal species	Name	Frequency [hr]
<i>Semidiurnal</i>		
Principle lunar	M_2	12.4206
Principle solar	S_2	12.0000
Lunar elliptic	N_2	12.6584
Lunisolar	K_2	11.9673
<i>Diurnal</i>		
Lunisolar	K_1	23.9344
Principle lunar	O_1	25.8194
Principle solar	P_1	24.0659
Elliptic lunar	Q_1	26.8684
<i>Longer Period</i>		
Fortnightly	M_f	327.85
Monthly	M_m	661.31
Semiannual	S_{sa}	4383.05

Harmonic analysis

With the use of a harmonic analysis tidal components can be filtered from the tidal signal. With this analysis method use is made of the least-squares technique, which is based on the minimization of the squared error. This technique originates with Lord Kelvin (1824-1907) around 1867. This technique permits the generation of several hundreds of tidal constituents, 45 of which are astronomical. Each one of these 45 astronomical constituents corresponds to one of the relative motions between the earth, sun and moon. The remaining constituents are amongst others shallow water constituents corresponding to frictional effects and non-linear terms in the equations of motion (viz. the M_4 and M_6 constituents), but also radiational constituents corresponding to atmospheric effects.

Rayleigh criterion

In order to be able to distinguish two different constituents a certain minimal length T of the time series of the tidal signal is required. This length T is determined with the use of the Rayleigh criterion, which is expressed in equation(B.2).

$$|f_1 - f_2| = \frac{1}{T} \quad (\text{B.2})$$

f_1 = frequency of the first constituent
 f_2 = frequency of the second constituent
 T = record length

For example, the minimal record length needed to distinguish M_2 ($f = 0.0805 \text{ hr}^{-1}$) and S_2 ($f = 0.0833 \text{ hr}^{-1}$) is $T = (|0.0805 - 0.0833|)^{-1} = 357 \text{ hr} = 14.9 \text{ days}$.

In Table B.1 for some constituents the needed record length to distinguish them from another is given. Figure B.1 and Figure B.2 show for different record lengths (5 to 230 days) which constituents are distinguished. This is done for the semidiurnal and quarterdiurnal constituents. These figures show that indeed the S_2 constituent can be distinguished from the M_2 after ± 15 days.

Table B.1 Required record length to distinguish the two constituents in days (Luijendijk, 2001)

	O_1	P_1	K_1	MU_2	N_2	NU_2	M_2	λ_2	L_2	S_2	K_2	M_4	MS_4	M_6
O_1		14.8	13.7	1.1	1	1	1	1	1	0.9	0.9	0.3	0.3	0.2
P_1			183	1.1	1.1	1.1	1.1	1	1	1	1	0.3	0.3	0.2
K_1				1.2	1.1	1.1	1.1	1	1	1	1	0.3	0.3	0.2
MU_2					31.8	27.6	14.8	10.1	9.6	7.4	7.1	0.5	0.5	0.3
N_2						206	27.6	14.8	13.8	9.6	9.1	0.5	0.5	0.3
NU_2							31.8	15.9	14.8	10.1	9.6	0.5	0.5	0.3
M_2								31.8	27.6	14.9	13.7	0.5	0.5	0.3
λ_2									206	27.6	23.9	0.5	0.5	0.3
L_2										31.7	27.1	0.5	0.5	0.3
S_2											183	0.5	0.5	0.3
K_2												0.5	0.5	0.3
M_4													14.8	0.5
MS_4														0.5
M_6														

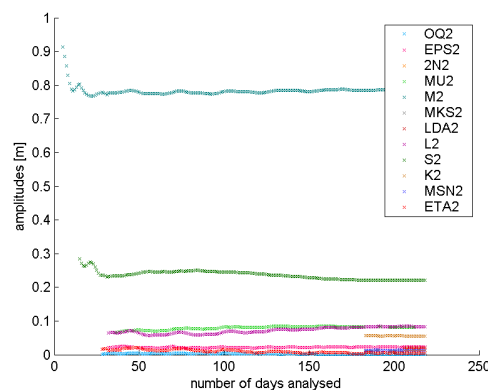


Figure B.1. Development of the semidiurnal constituents

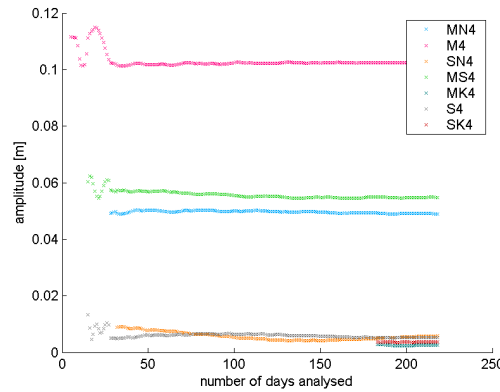


Figure B.2. Development of quarterdiurnal constituents

Accuracy of the harmonic analysis

The harmonic analysis method aims to minimize the squared error, but there will always be some inaccuracy. Figure B.1 shows that for record lengths shorter than 15 days the amplitude of the M_2 constituent is rather variable. For these short periods the analysis is not capable to separate the S_2 and M_2 constituents. The output for M_2 in fact now represents both the M_2 and the S_2 constituents. In records longer than 15 days these two constituents can be distinguished, and the amplitude of M_2 is more constant.

Figure B.1 gives the root-mean-squared error (RMSE)⁸ between the record and the tidal signal formed with the distinguished constituents, plotted against the record length that was used (again 5 to 230 days). This figure shows that the RMSE is rather high in shorter runs, and becomes relatively stable after approximately 32 days. In combination with Figure B.1 and Figure B.2 it can be seen that when the record length is long enough to distinguish more constituents, it is favorable for the RMSE. Yet, after 32 days the RMSE is small enough to say that the amplitude of the distinguished constituents is correct. This record length implies that for instance the K_2 constituents will not be distinguished, but this will be accepted. The alternative is to use a record length of 183 days, but that would take too much computing time.

Figure B.2 gives the dependency of the phase of the M_2 and M_4 constituents; it shows that with shorter record lengths the phase is very dependent on the record length. After 32 days most of the influential constituents can be distinguished and the phases are stable.

⁸ $RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (computed_i - observation_i)^2}$. It gives an indication of the accuracy of the computed values compared to the observations.

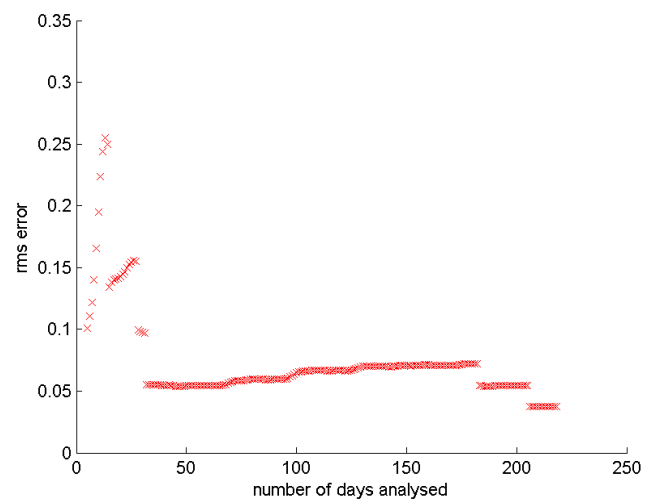


Figure B.1. Root mean squared error development

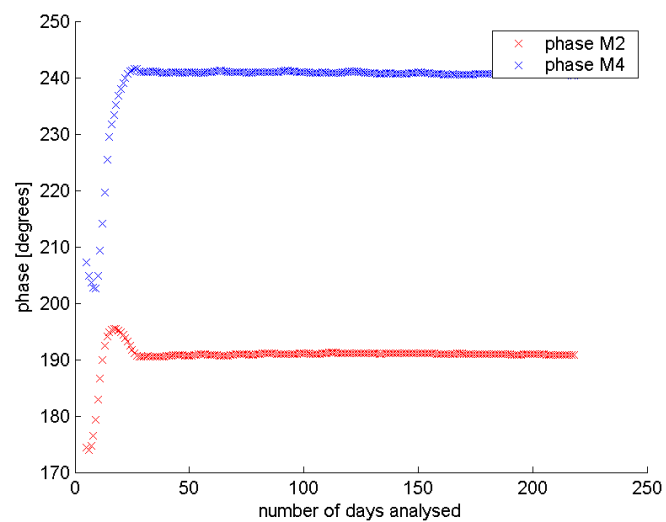


Figure B.2. Development of the phases of the M₂ and M₄ constituents

C ZUNO-Grof model and the nesting procedure

The tidal signal in the North Sea can be simulated with the ZUNO-Grof⁹ model. The tidal signal of the Wadden Sea model is deduced from the ZUNO-Grof model via the nesting procedure. In this appendix the ZUNO-Grof model is described, as well as the nesting procedure. The amplitudes and phases of the most import constituents of the tidal signal are then compared to the observation data (RIKZ, personal communication).

The ZUNO-Grof model

Figure C.1 shows the grid and bathymetry of the model, as well as the location. The grid is curvilinear and has got over 21.000 grid cells. The open water boundaries are located in the north (between Scotland and Denmark) and in the southwest (in the Channel, in between England and France). The model is forced by 50 astronomical constituents; a number of these (M2, S2, O1, K1 and P1) are corrected for both phase (additive) and amplitude (multiplicative). The main discharges such as from the river Rhine are also included in the model. Meteorological forces are represented with the HIRLAM¹⁰ data.

The applied friction coefficient is a Manning coefficient of $n=0.026$. The model computations are carried out three-dimensional; the water depth is divided into 5 layers. The computational time step applied is 5 minutes.

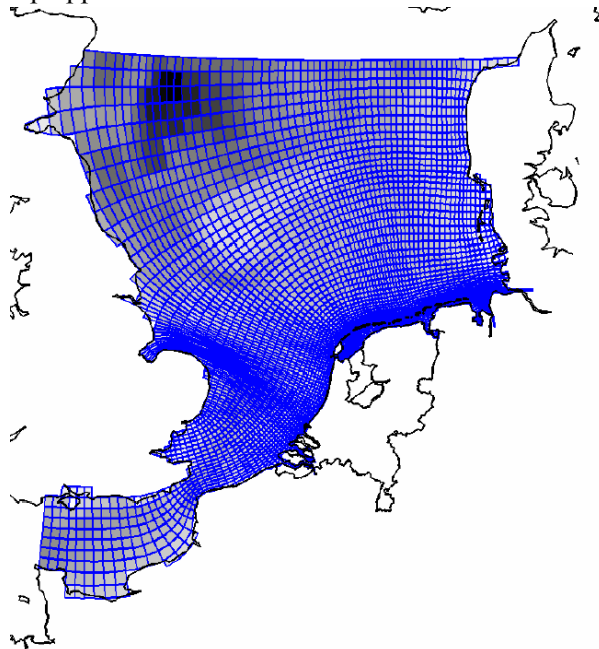


Figure C.1 ZUNO-model grid and bathymetry

⁹ ZUNO-model is an abbreviation of *ZU*iderlijk *NO*ordzee-model (Southern North Sea model).

¹⁰ HIRLAM is short for *H*igh *R*esolution *L*imited *A*rea *M*odel. It is a model developed by the meteorological institutes of Denmark, France, Finland, Ireland, Iceland, Norway, Spain, Sweden and the Netherlands to predict short term weather forecasts.

Nesting procedure of the Wadden Sea model in the ZUNO-Grof model

Some of the boundary points of the Wadden Sea model coincide with water level points in the ZUNO-Grof model. Via the nesting procedure these Wadden Sea model boundary points copy the time series of the water level of ZUNO-Grof model. Figure C.1 shows the positioning of the Wadden Sea model in the ZUNO-Grof model.

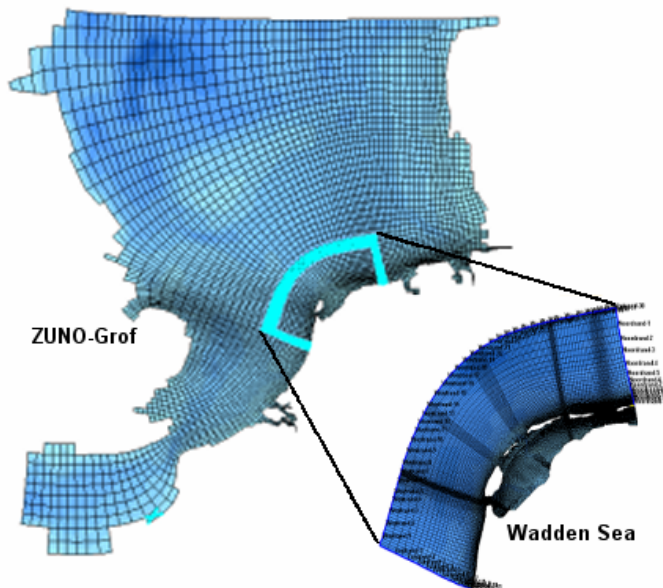


Figure C.1 Location of the Wadden Sea model in the ZUNO-Grof model

D Determination of large-scale wind forcing induced water level set-up

This appendix describes the method to determine the large-scale wind set-up corresponding to the concerned wind conditions. First the method is described, and it is followed by an example.

Approach

Figure 2.6 showed the water level set-up corresponding to wind velocity (U_{10}) and angle (α) at the location of wave rider Eierlandse Gat. Unfortunately this only gives information on the order of magnitude of the water level set-up induced by large scale wind-effects. It does not give information on how the water level gradient in the Western Wadden Sea develops as a result of the large-scale wind effects.

The ZUNO-Grof model described in appendix C includes the wind conditions on the North Sea for the year 1998. Subsequently the times series of the water level at the boundaries of the Wadden Sea model include the wind set-up driven by large-scale wind effects. This wind set-up varies over the boundaries, in time as well as in space. To be able to prescribe the large-scale wind set-up to the boundaries in the simulations, in which wind forcing is applied (i.e. the simulations in section 4.3 and chapter 5), a period in the year 1998 is selected in which the wind conditions correspond to the wind forcing in the concerned simulation. The period length has to be six hours minimally, in order for the water level to adjust to the large-scale wind forcing.

The water level at the boundaries is harmonically analyzed (see appendix B) to exclude the major tidal constituents. The result is a, spatially varying, water level set-up (A_0) on the boundaries.

Example: wind forcing $U_{10}=7.77$ m/s with $\alpha=225^\circ$

In this example the large-scale wind set-up corresponding to a local wind velocity $U_{10}=7.77$ m/s from the southwest ($\alpha=225^\circ$) is determined. This wind forcing is the same as that of the simulation in section 4.3.2. Figure D.1 shows the wind velocity and angle at the location of the wave rider Eierlandse Gat, prior to February 7th 1 a.m. Although the wind velocity is larger than desired, the angle of the wind corresponds well to the desired value. The tidal signal computed with the harmonic analysis is subtracted from the water level at the boundaries. The result, a wind forcing induced water level set-up, for the western boundary is shown in Figure D.2. The blue dots denote the result of the analysis, the red line the smoothed values applied in the simulation.

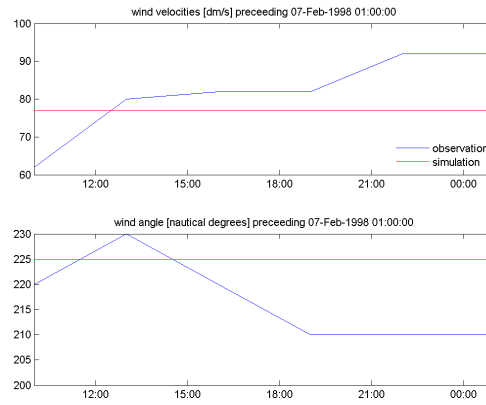


Figure D.1 Wind velocity (U_{10}) and angle (α) preceding February 7th 1 a.m.

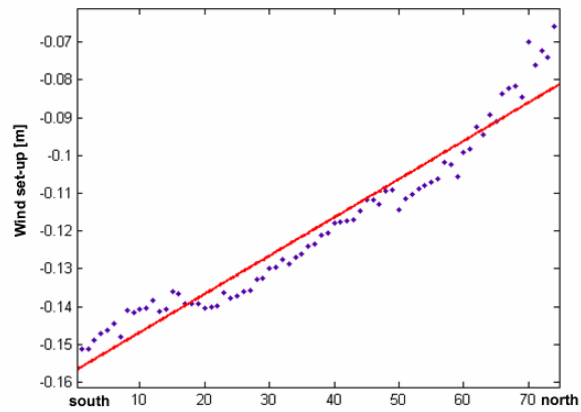


Figure D.2 Water level set-up induced by large-scale wind effects on the western boundary, derived from the ZUNO-Grof model (blue dots) and prescribed in the simulation (red line)

E Determination of corresponding values of the wave period and wind velocity to the wave height

In this appendix the method to determine the values of wind velocity (U_{10}) and wave period (T_{m02}) that correspond to a specific wave height (H_s).

Approach

With the use of the long-term wave statistics (www.golfklimaat.nl), the wind velocity/ wave period is plotted as a function of the wave height. An example is shown in Figure E.1, which shows the relation between wind velocity and the wave height from a southwestern direction. In this example there is a linear relation. A southwestern wave with $H_s=2\text{m}$ has a corresponding wind velocity $U_{10}=9.45\text{m/s}$.

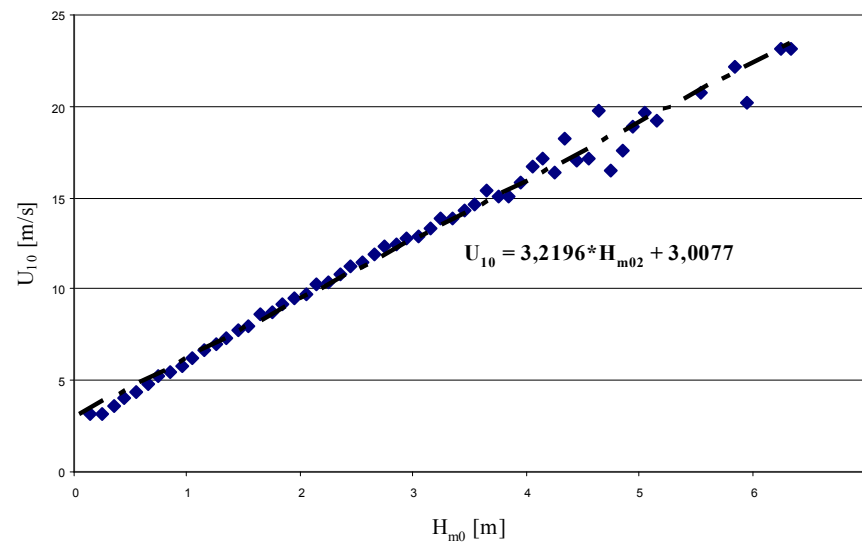


Figure E.1 Relation between southwestern wind velocity (U_{10}) and wave height (H_{m0}).

F Sediment transport patterns in the inlets induced by the 1998 bathymetry

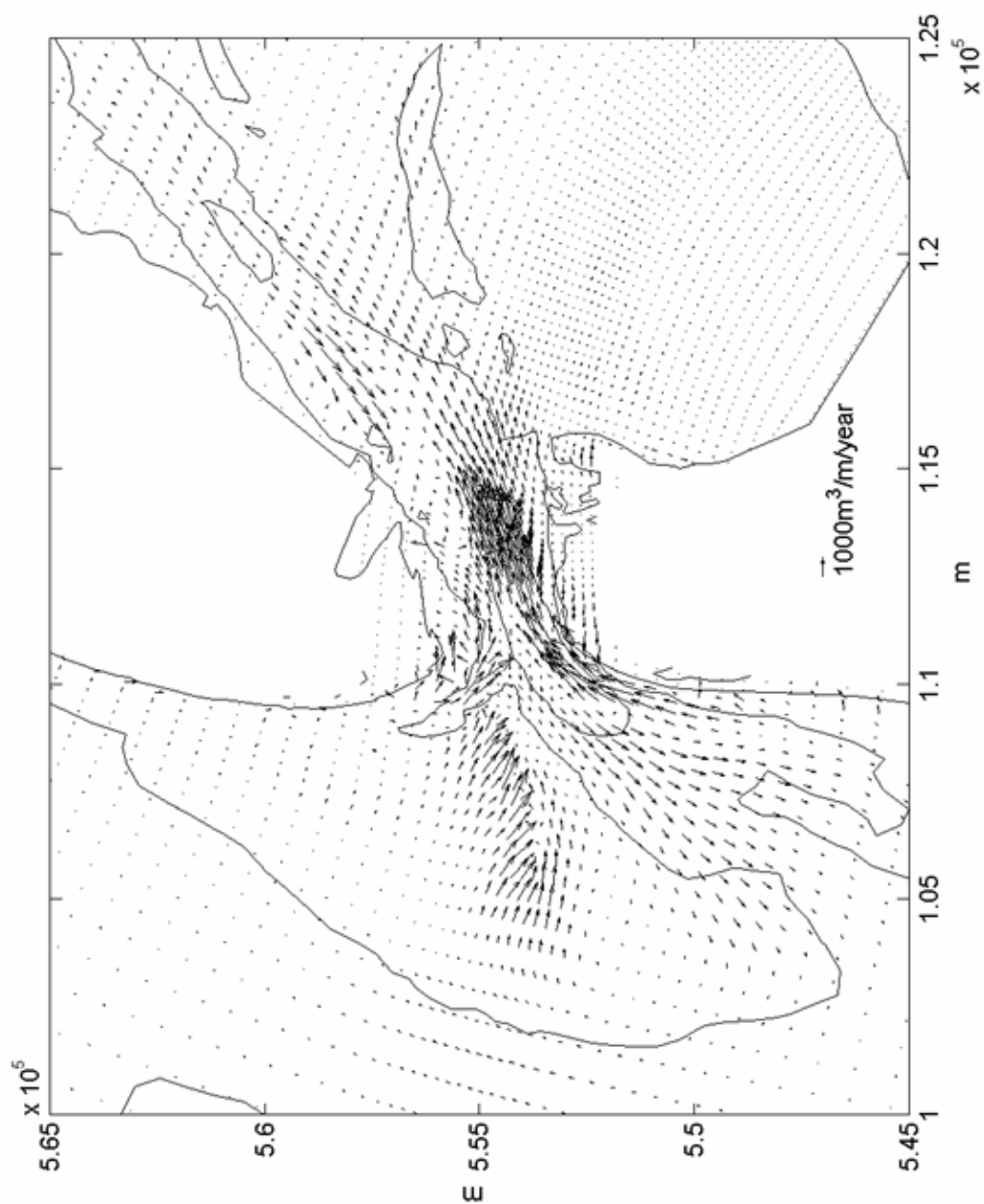


Figure F.1 Sediment transport pattern in the Texel inlet

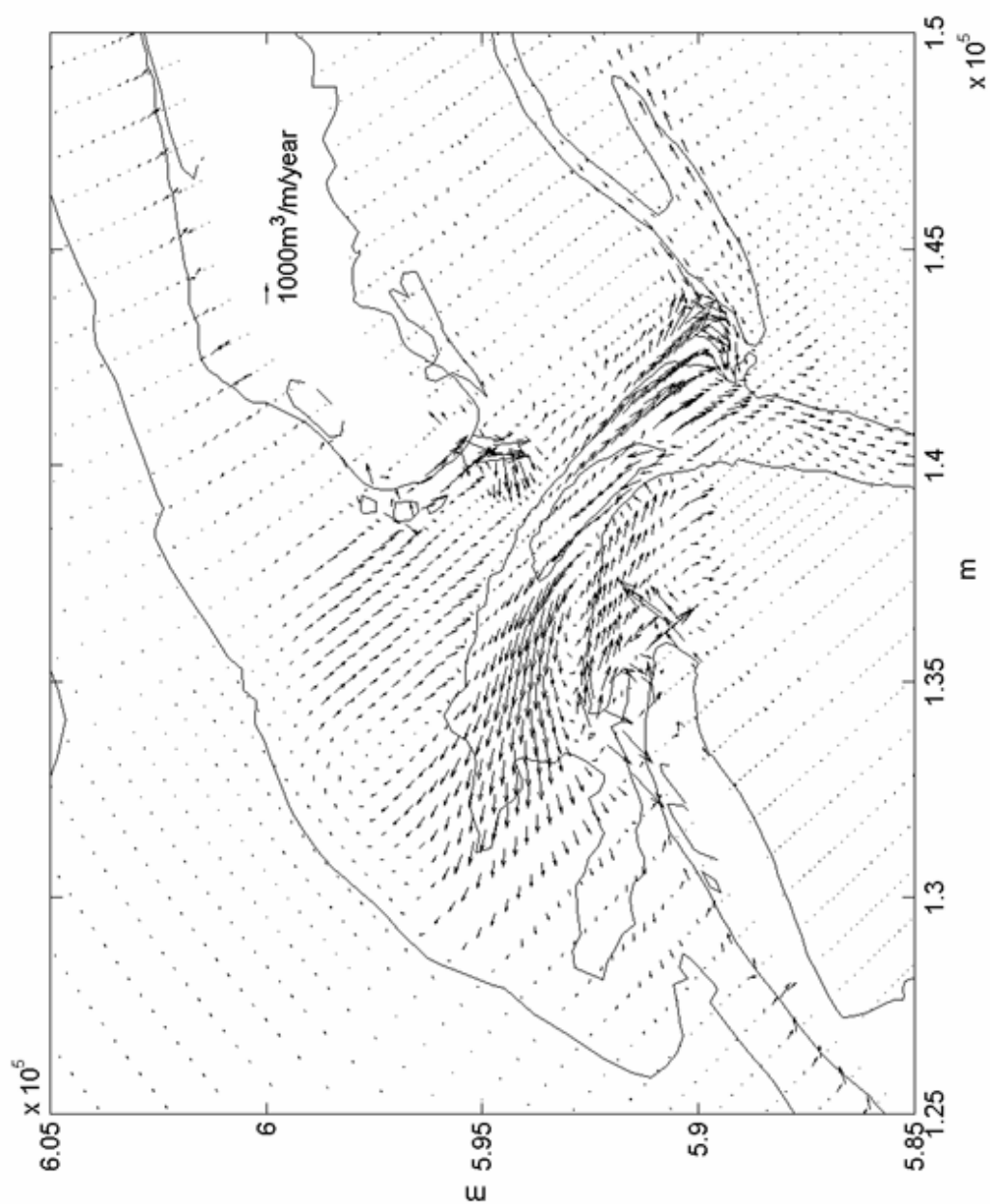


Figure F.2 Sediment transport pattern in the Vlie inlet

G Sediment transport patterns in the inlets induced by the bathymetry without ebb-tidal deltas

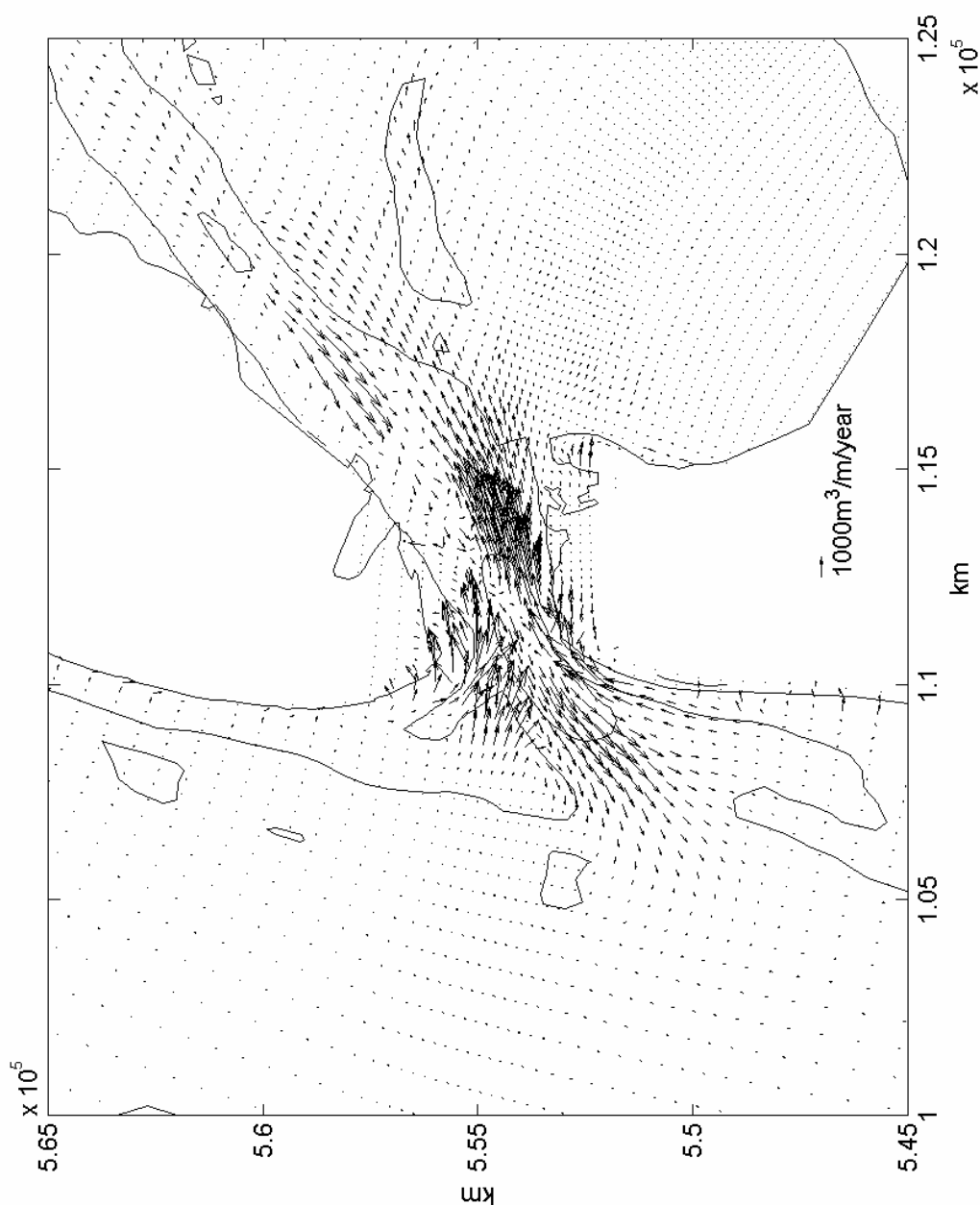


Figure G.1 Sediment transport pattern in the Texel inlet

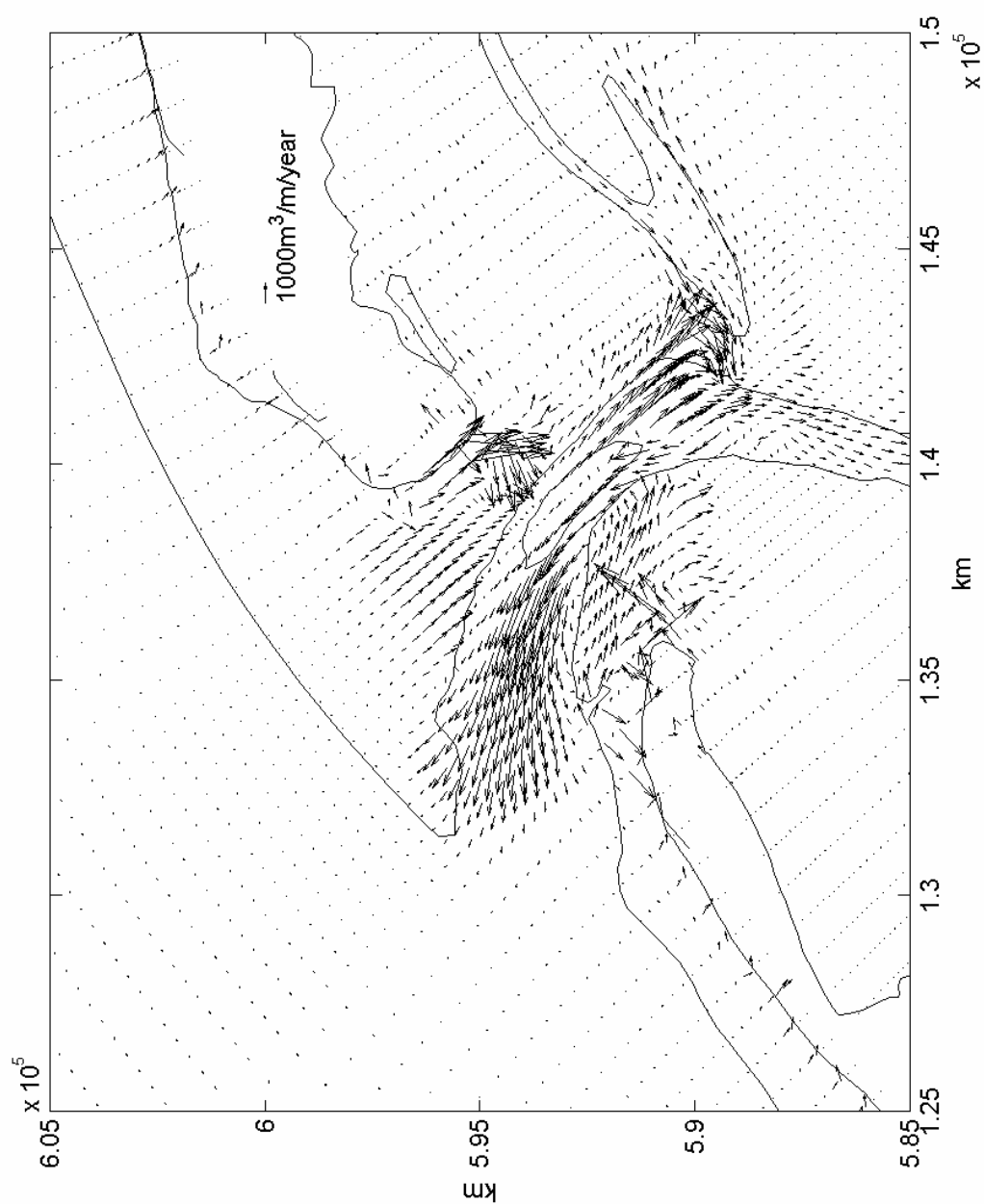


Figure G.2 Sediment transport pattern in the Vlie inlet

H Sediment transport patterns in the inlets induced by the equilibrium bathymetry

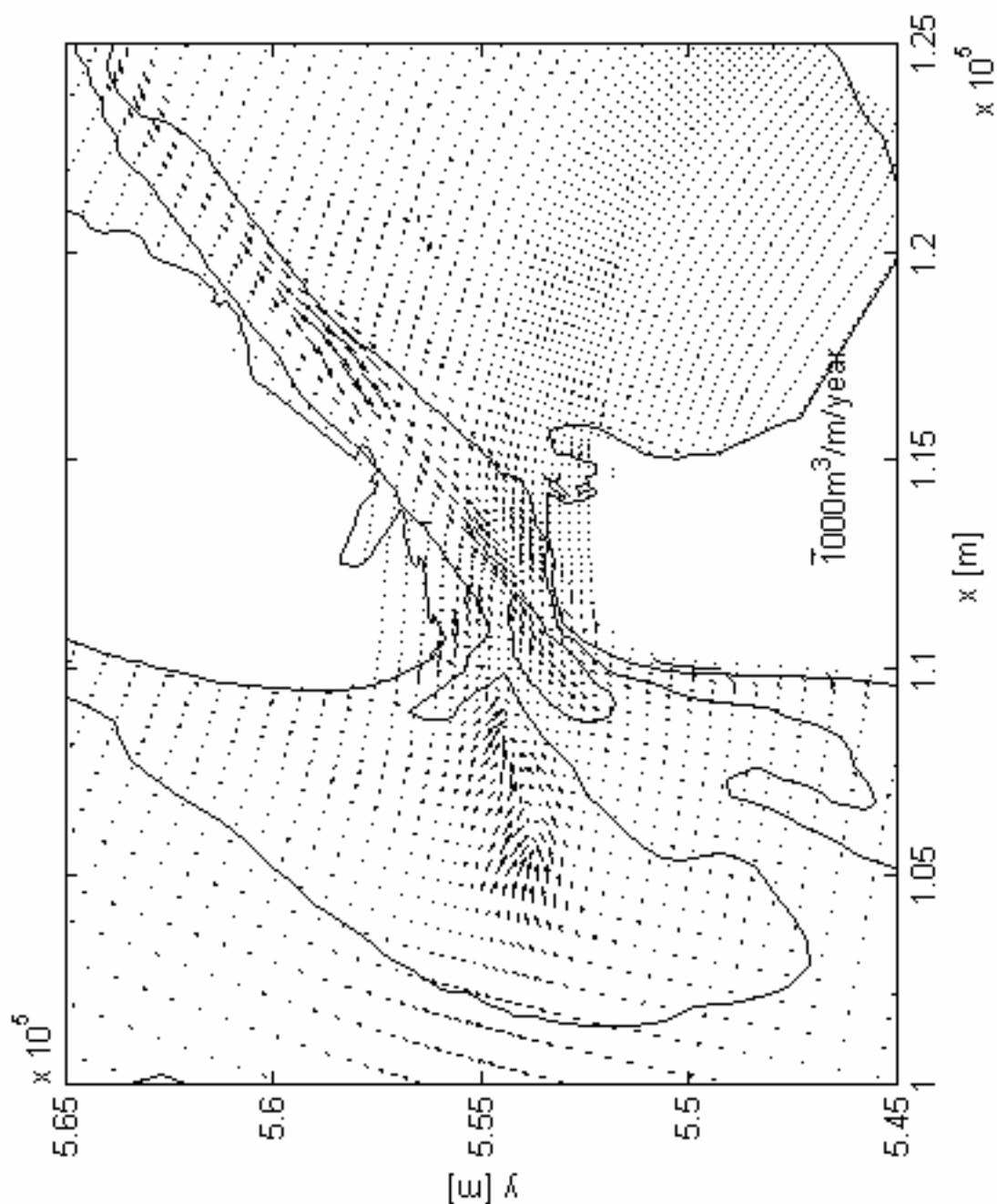


Figure H.1 Sediment transport pattern in the Texel inlet

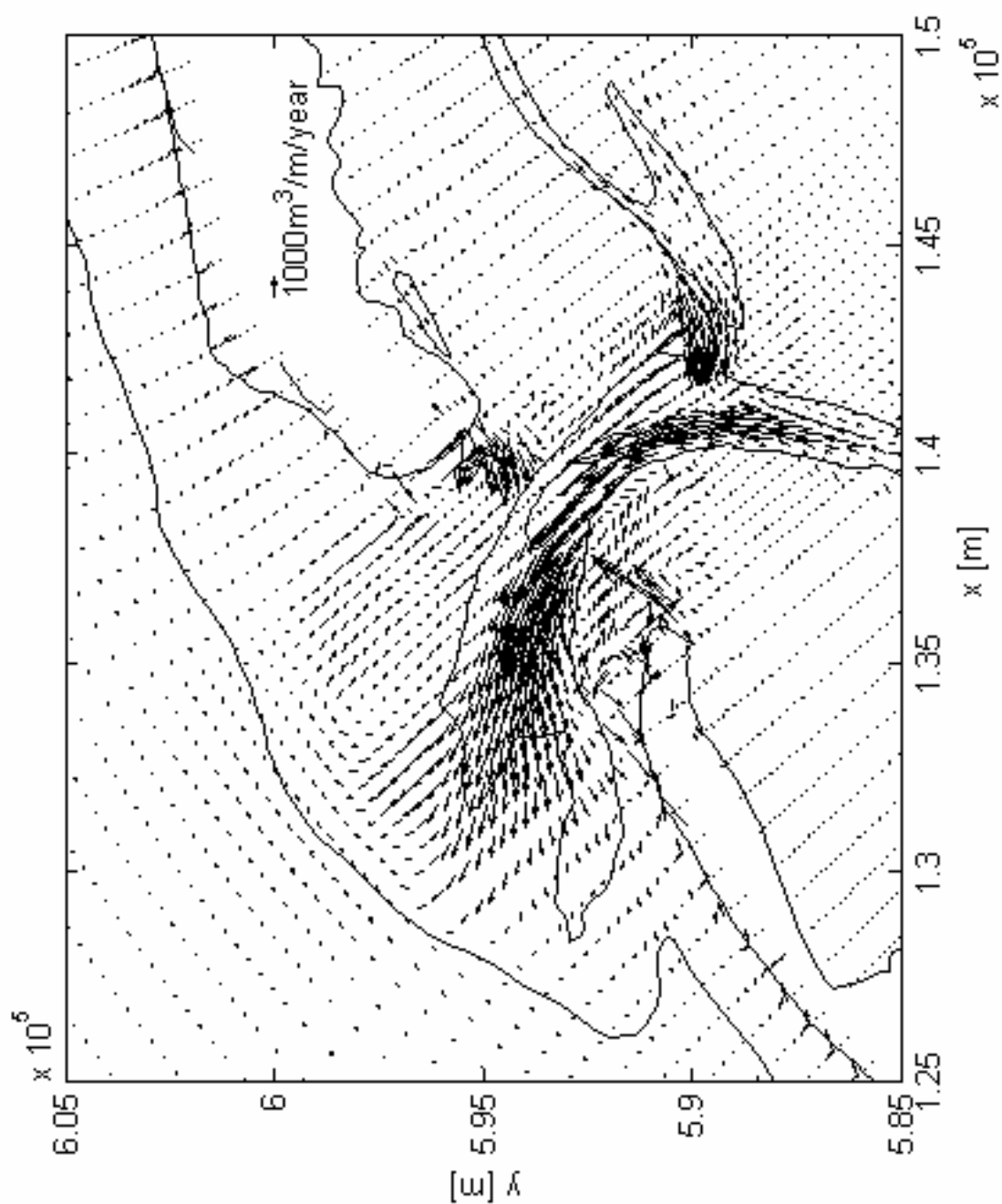


Figure H.2 Sediment transport pattern in the Vlie inlet