Using Texel Inlet as a sediment transport belt

Feasibility study

Master Thesis
J.W.A. Lakeman

June 2009
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Faculty of Civil Engineering
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PREFACE

This report contains the feasibility study of using the Texel Inlet as a sediment transport belt. The study is my Master Thesis for the section Coastal Engineering of Delft University of Technology (TUD) at the faculty of Civil Engineering.

The study has been carried out at Delft University and Technology and at consultancy and engineering company DHV. DHV is gratefully acknowledged for giving me the possibility of conducting this study with the necessary supervision.

I would like to thank my supervisors: Prof. dr. ir. M.J.F. Stive (TUD), ir. M. Sokolewicz (DHV), ir. J.G. de Ronde (TUD and Deltares), ir. R.J. Labeur (TUD) dr. ir. Z.B. Wang (TUD) for sharing their knowledge and for their support during this study. I would also like to thank my temporary colleagues at DHV and my roommates at the TUD Hydraulic Engineering department for supporting me and making my stay a pleasant one. Further a thankful word is assessed to Deltares for Delft3D-model support, especially for Carola van der Hout and Robert McCall. Finally I would like to thank my family and my friends for their support during the years I spent in Delft.

Jeroen Lakeman
Delft, June 2009
ABSTRACT

The Afsluitdijk does not comply with the strength safety regulations of the Netherlands. Therefore the Dutch government decided to reinforce the Afsluitdijk. A consortium of DHV, Imares and Alle Hospers proposed the reclamation of tidal marshes in front of the Afsluitdijk. During severe storms the tidal marshes reduce the wave attack and therefore improve the safety assessment of the Afsluitdijk. The construction of the tidal marshes implies the transportation of approximately 50 Mm$^3$ sediment. This study deals with the feasibility of transporting a considerable part of this volume by using the sediment transport processes at the Texel Inlet. The morphological development of the dump of a significant volume of sediment in the deeper parts of the Texel Inlet has been examined. The amount of the dumped volume that sedimentates at the end of the Texel Inlet close to the Afsluitdijk determines the efficiency of the method.

The Texel Inlet is a tidal inlet in the western part of the Dutch Wadden Sea. The main hydrodynamic forcing of the Texel Inlet is the tide. The tidal wave in the North Sea propagates along the Dutch Coast from south to north. The tidal wave in the Texel Inlet has a standing nor propagating character. Bottom friction in the basin significantly reduces the tidal wave amplitude over the Texel Inlet. Therefore the reflected tidal wave amplitude is considerably smaller than the incoming tidal wave. The basin itself is characterized by meandering channels and shoals, for which friction, storage capacity and flow properties have all significant contributions in the hydrodynamic assessment.

The residual sediment transport of the Texel Inlet is directed towards the Afsluitdijk. This is mainly caused by the tidal asymmetry of the Texel Inlet. To determine the morphological development of the Texel Inlet and surrounding shoals use has been made of a process-based model of Delft3D (2H-D). This model was developed by [Van der Waal (2006)]. The only hydrodynamic forcing of the model is the tide, which is expected to represent about 70 percent of the sediment transport processes. A comparison of a morphological simulation with this model of the present bathymetry with [Elias, 2006] indicated an overestimation of the sediment transport with an average factor of 1.9. The process-based model has been used to simulate the morphological development of the Texel Inlet and surrounding shoals after the dump of a considerable amount of sediment.

Two locations have been defined for the dump of a significant amount of sediment (16 Mm$^3$). The purpose of the dump was to obtain a migration of sediment towards the channel-section Doove Balg. The first location is situated at the channel-section Texelstroom West, where the residual sediment transport is relatively strong, but the distance to the Doove Balg large. The second location is situated at the channel-section Texelstroom Bend, where the residual sediment transport is relatively weak, but the distance to the Doove Balg smaller. Besides the use of a dumping location to transport sediment one can also make use of a sand pit. Sand can be dredged from a location nearby the new tidal marshes. By sediment transport processes the sediment from both the dumping location and the surrounding shoals was expected to sedimentate the sand pit.

Morphological simulations of 10 year of the two dump locations and of the combination of a dump location and a sand pit location indicated two main processes:
1. Diffusion of sediment with a time-scale of months to years
2. Migration of sediment towards the Afsluitdijk with a time-scale of years to decennia

After 10 year the sedimentation at the and of the Texel Inlet is insignificant for all configurations. Therefore it is concluded that it is not feasible to use the Texel Inlet as a sediment transport belt for the construction of tidal marshes at the Afsluitdijk. The impact on the surrounding shoals is considerable with locally severe sedimentation and erosion. The total shoal volume remains almost the same.
SAMENVATTING

De Afsluitdijk voldoet niet aan de sterkte veiligheidseisen van Nederland. Daarom heeft de Nederlandse overheid besloten de Afsluitdijk te versterken. Een consortium van DHV, Imares en Alle Hosper heeft voorgesteld om kwelders aan te leggen aan de Waddenzee zijde van de Afsluitdijk. Tijdens zware stormen reduceren de kwelders de golflasting en verbeteren daardoor de veiligheidstoets van de Afsluitdijk. De constructie van de kwelders impliceert het transport van ongeveer 50 Mm$^3$ sediment. Deze studie behandelt de haalbaarheid van het transporteren van een aanzienlijk deel van deze hoeveelheid door gebruik te maken van sediment transport processen in het Zeegat van Texel. De morfologische ontwikkeling van een dump van een significante hoeveelheid sediment in de diepere delen van het Zeegat van Texel is beschouwd. De hoeveelheid van het de gedumpt volume dat sedimenteert aan het einde van het Zeegat van Texel nabij de Afsluitdijk bepaalt de efficiëntie van de methode.

Het Zeegat van Texel is een getijdennaal in het westelijk deel van de Nederlandse Waddenzee. De voornaamste hydrodynamische excitatie van het Zeegat van Texel is het getij. De getijde golf in de Noordzee plant zich langs de Hollandse Kust voort van zuid naar noord. De getijde golf in het Zeegat van Texel heeft een staand noch lopend karakter. Bodem frictie in het bassin reduceert de getijde golf amplitude significant over de Texel Inlaat. Daardoor is de gereflecteerde golfamplitude aanzienlijk kleiner dan de inkomende golf. Het getijde bassin zelf wordt gekenmerkt door meanderende geulen en platen, waarvoor weerstand, berging en stroomvoering allen significante bijdragen leveren in de hydrodynamische beoordeling.

Het residu ële sedimenttransport van het Zeegat van Texel naar de Afsluitdijk gericht. Dit wordt met name veroorzaakt door de getij asymmetrie van het Zeegat van Texel. Om de morfologische ontwikkeling van het Zeegat van Texel en de omliggende platen te bepalen is er gebruik gemaakt van een process-based model van Delft-3D (2D-H). Dit model is ontwikkeld door [Van der Waal (2006)].

Er zijn twee locaties gedefinieerd voor de dump van een significante hoeveelheid sediment (16 Mm$^3$). Het doel van de dump is het bewerkstelligen van een migratie van sediment naar de geulsectie Doove Balg. De eerste locatie is op de plaats van de geulsectie Texelstroom West, waar het residu ële sedimenttransport relatief sterk is, maar de afstand tot de Doove Balg groot. De tweede locatie is op de plaats van de geulsectie Texelstroom Bocht, waar het residu ële sedimenttransport relatief zwak is, maar de afstand tot de Doove Balg kleiner. Naast het gebruik van een dump locatie voor het transport van sediment kan er ook gebruik worden gemaakt van een zand put. Zand kan worden gewonnen uit een locatie dichtbij de aan te leggen kwelders.

Het sediment van de dump locaties zou naar verwachting migreren en sedimenteren bij de zand put. Morfologische simulaties van 10 jaar voor de twee dump locaties en voor de combinatie van een dump locatie en een zand put laten de volgende twee algemene processen zien:

1. Diffusie van sediment met een tijdsschaal van maanden tot jaren
2. Migratie van sediment in de richting van de Afsluitdijk met een tijdsschaal van jaren tot decennia

Na 10 jaar is de sedimentatie aan het einde van het Zeegat van Texel insignificant voor alle configuraties. Derhalve kan geconcludeerd worden dat het niet haalbaar is om het Zeegat van Texel te gebruiken als transportband van sediment voor de aanleg van de kwelders bij de Afsluitdijk.
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>bottom layer thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$A$</td>
<td>proportionality constant of Groen model</td>
<td>[-]</td>
</tr>
<tr>
<td>$A_0$</td>
<td>mean value of a time series of the water elevation</td>
<td>[m]</td>
</tr>
<tr>
<td>$A_i$</td>
<td>amplitude of the $i^{th}$ constituent of the tidal wave</td>
<td>[m]</td>
</tr>
<tr>
<td>$A_y$</td>
<td>current carrying cross-section</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$B$</td>
<td>storage width</td>
<td>[m]</td>
</tr>
<tr>
<td>$B_s$</td>
<td>current carrying width</td>
<td>[m]</td>
</tr>
<tr>
<td>$c$</td>
<td>propagation speed</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$c$</td>
<td>concentration of sediment</td>
<td>[kg/m$^3$] or [-]</td>
</tr>
<tr>
<td>$c_a$</td>
<td>sediment concentration at interface bed and suspended load transport</td>
<td>[kg/m$^3$] or [-]</td>
</tr>
<tr>
<td>$c_0$</td>
<td>propagation speed in absence of resistance</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$c_f$</td>
<td>dimensionless friction coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$C$</td>
<td>Chézy friction coefficient</td>
<td>[m$^{1/2}$/s]</td>
</tr>
<tr>
<td>$D$</td>
<td>sediment particle diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>mean sediment particle diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>$f_i$</td>
<td>frequency of the $i^{th}$ constituent of the tidal wave</td>
<td>[Hz]</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
<td>[m/s$^2$]</td>
</tr>
<tr>
<td>$h$</td>
<td>water depth</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_0$</td>
<td>undisturbed water depth</td>
<td>[m]</td>
</tr>
<tr>
<td>$H_s$</td>
<td>significant wave height</td>
<td>[m]</td>
</tr>
<tr>
<td>$k$</td>
<td>wave number</td>
<td>[rad/m]</td>
</tr>
<tr>
<td>$k_0$</td>
<td>wave number in the absence of resistance</td>
<td>[rad/m]</td>
</tr>
<tr>
<td>$L$</td>
<td>length of channel section</td>
<td>[m]</td>
</tr>
<tr>
<td>$m$</td>
<td>multiplication coefficient of Engelund and Hansen</td>
<td>[s$^4$•kg/m$^5$]</td>
</tr>
<tr>
<td>$n$</td>
<td>direction normal to the flow velocity</td>
<td>[-]</td>
</tr>
<tr>
<td>$p$</td>
<td>power coefficient of Engelund and Hansen</td>
<td>[-]</td>
</tr>
<tr>
<td>$p$</td>
<td>hydrodynamic pressure</td>
<td>[N/m$^2$]</td>
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<tr>
<td>$q$</td>
<td>specific discharge</td>
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<tr>
<td>$Q$</td>
<td>discharge</td>
<td>[m$^3$/s]</td>
</tr>
<tr>
<td>$R$</td>
<td>hydraulic radius</td>
<td>[m]</td>
</tr>
<tr>
<td>$s$</td>
<td>direction parallel to the flow velocity</td>
<td>[-]</td>
</tr>
<tr>
<td>$S$</td>
<td>sediment transport</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>$S_b$</td>
<td>volume of bed load transport per unit width</td>
<td>[m$^3$/m'/s]</td>
</tr>
<tr>
<td>$S_s$</td>
<td>volume of suspended load transport per unit width</td>
<td>[m$^3$/m'/s]</td>
</tr>
<tr>
<td>$S_{t}$</td>
<td>volume of total load transport per unit width</td>
<td>[m$^3$/m'/s]</td>
</tr>
<tr>
<td>$T$</td>
<td>period of tidal wave</td>
<td>[s]</td>
</tr>
<tr>
<td>$t$</td>
<td>duration of a water elevation record</td>
<td>[s]</td>
</tr>
<tr>
<td>$t'$</td>
<td>integration period</td>
<td>[s]</td>
</tr>
<tr>
<td>$u$</td>
<td>instantaneous horizontal flow velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$\bar{u}$</td>
<td>depth-averaged horizontal flow velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$\hat{u}$</td>
<td>depth-averaged and time-averaged horizontal flow velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$\tilde{u}$</td>
<td>amplitude of the horizontal flow velocity</td>
<td>[m/s]</td>
</tr>
</tbody>
</table>
\( u \): horizontal shear stress flow velocity \([\text{m/s}]\)

\( v \): instantaneous vertical flow velocity \([\text{m/s}]\)

\( \bar{v} \): depth-averaged vertical flow velocity \([\text{m/s}]\)

\( \bar{v} \): depth-averaged and time-averaged vertical flow velocity \([\text{m/s}]\)

\( w \): fall velocity of the particle \([\text{m/s}]\)

\( \alpha \): coriolis acceleration \([\text{m/s}^2]\)

\( \beta \): settling lag time factor \([-]\)

\( \delta \): angle of resistance \([-]\)

\( \Delta \): relative sediment density \([-]\)

\( \varepsilon \): sediment diffusion coefficient \([\text{m}^2/\text{s}]\)

\( \zeta \): water surface elevation relative to mean sea level \([\text{m}]\)

\( \zeta^+ \): amplitude of the incoming tidal wave \([\text{m}]\)

\( \zeta^- \): amplitude of the reflected tidal wave \([\text{m}]\)

\( \theta \): phase angle of the \( i \)th constituent of the tidal wave \([\text{deg}]\)

\( \mu \): damping coefficient along the channel \([1/\text{m}]\)

\( \nu \): kinematic viscosity \([\text{m}^2/\text{s}]\)

\( \rho_s \): specific sediment density \([\text{kg/m}^3]\)

\( \rho_w \): water density \([\text{kg/m}^3]\)

\( \sigma \): order of magnitude of ratio of resistance and inertia \([-]\)

\( \tau_b \): bed shear stress \([\text{N/m}^2]\)

\( \varphi \): Earth’s latitude \([\text{deg}]\)

\( \Phi \): dimensionless transport parameter \([-]\)

\( \Psi \): dimensionless flow parameter \([-]\)

\( \omega \): angular frequency of the tidal wave \([\text{rad/s}]\)

\( \omega_e \): angular frequency of the Earth \([\text{rad/s}]\)

\( z_r \): Rouse number \([-]\)
1 INTRODUCTION OF THE STUDY

1.1 Introduction

This chapter deals with the inducement of this study. The necessity of a reinforcement of the Afsluitdijk is elaborated, supplemented by a description of the construction of tidal marshes on the Wadden Sea side of the Afsluitdijk. The objectives of this study are subsequently discussed. The chapter finishes with a formulation of the reader of this report.

The set-up of this chapter is:
1.2 Introduction to the Afsluitdijk
1.3 Explanation of the objectives of this study
1.4 Formulation of a reader of this report

1.2 The Afsluitdijk

The Afsluitdijk is a major dam in the Netherlands, constructed between 1927 and 1933. The dam runs from Den Oever on Wieringen in North-Holland province, to the village of Zurich in Friesland province and has a length of 32 km, a width of 90 m and an initial height of 7.25 m above sea level, see Figure 1.

![Figure 1: The Afsluitdijk](www.energieportal.nl)

The Afsluitdijk forms a fundamental structure of the Zuiderzee Works. The goal of the Zuiderzee Works was the closure of the tidal connection of the former Zuiderzee and the North Sea. By the completion of the Afsluitdijk the former Zuiderzee was turned into a fresh water lake and renamed as the IJsselmeer, see Figure 2.

The Afsluitdijk is a primary flood defense structure covering the IJsselmeer off the direct influence of extreme circumstances at the Wadden Sea. The motor highway over the Afsluitdijk forms a part of the national and international road network. The road is indicated as A7 respectively E22.
Construction of the Afsluitdijk
The material used to construct the Afsluitdijk was mainly till (bounder clay). Till was used because previous experiences had demonstrated that it was the best primary material for a structure like the Afsluitdijk and it could be retrieved in large quantities by simply dredging it from the bottom of the Zuiderzee. Initially the work was executed at both sides of the mainland and on two special-made construction islands (Kornwerderzand and Breezand) in the alignment of the future dam. From these points the dam was constructed by the deposition by dredging ships of till into the open sea in two parallel lines. In between these two dikes sand was deposited and as it emerged above the surface it was covered by another layer of till. The dike was covered from land by basalt rocks and mats of willow switch at its base. The dike was finished off by raising it further with sand and finally clay for the surface of the dike, planting the dike with grass. The total amount of material used is estimated at 23 million m³ of sand and 13.5 million m³ of till.

The Afsluitdijk consists also of two complexes of shipping locks and discharge sluices at both ends of the dike. The complex at Den Oever consists of the Stevin lock and three series of five sluices for discharging water from the IJsselmeer into the Wadden Sea. The other complex is located at Kornwerderzand and composes the Lorentz locks and two series of five sluices, making a total of 25 discharge sluices. Periodically discharging water from the lake is necessary since it is continuously fed by rivers and streams (most notable the IJssel river) and polders draining their water into the IJsselmeer.

Safety verification of the Afsluitdijk
In 2005 the results of a safety verification of the Afsluitdijk by Rijkswaterstaat indicated that the dam, the two locks and two complexes of discharge sluices cannot sufficiently resist a normative storm at the Wadden Sea. The defence barrier needs to be improved to fulfil to the safety standard.

Under the recent test conditions the crest height of the current uniform cross-section is approximately 2.5 m too low. By significant overtopping the risk of erosion or a slide of the cover of grass on the crest of the dam and the inner slope becomes too high.
Conceptual designs for the reinforcement of the Afsluitdijk

The current safety level of the Afsluitdijk is 1 : 1430 per year. The Afsluitdijk has to be reinforced to a safety level of 1 : 10000. Rijkswaterstaat asked competitive consultants and contractors in the Netherlands to send in a conceptual design of the reinforcement of the Afsluitdijk. After the first selection in July 2008 four basic concepts can be distinguished:

• Construction of tidal marshes at the Wadden Sea side of the Afsluitdijk to reduce the wave run-up² [DHV; Wageningen Imares; Alle Hosper, 2008]
• Construction of an intermediate lake at the IJsselmeer side of the dam to intercept the overtopping salt water. The intermediate lake has also to increase the flexibility of water management of the IJsselmeer and is to be developed as brackish nature area. [Arcadis, Dredging International, Nuon, HNS; Alkyon, 2008]
• Construction of a curved concrete wall on top of the Afsluitdijk. The wall has to decrease the wave run-up. [NoordPeil; GD Architecten; CE Delft; Oranjewoud, 2008]
• Raise of the current Afsluitdijk and the construction of a sand dam at the IJsselmeer side of the Afsluitdijk. The area between the current Afsluitdijk and the sand dam has to function as a nature development area and might be used for the generation of energy. [Wubbo Ockels B.V.; Royal Haskoning; Van Oord; Lievense; BAM; Rabobank; Eneco, 2008]

This report focuses on the alternative of the construction of tidal marshes at the Wadden Sea side of the Afsluitdijk.

Construction of tidal marshes at the Afsluitdijk

Traditional methods for reinforcing a dam imply a raise of the Afsluitdijk of several meters coupled with a new revetment. By the construction of tidal marshes the dam will not be raised, but widened, which creates a robust barrier that will grow with the sea. The design includes 1500 ha of new tidal marshes in the western Wadden Sea. By raising local shoals the new tidal marshes will be more sheltered from wind and water. High water rescue shoals for birds, seals and other animals are implemented in the design. By smart use of the discharge sluices in combination with the sheltered shoals the effect of fresh water discharge in the salt Wadden Sea will be reduced, which will improve the quality of shallow habitats near the discharge sluices. Part of the design is also the construction of a fresh-salt transition at the section with maximum width of the tidal marshes. The tidal marshes and the Afsluitdijk are connected by a tidal marsh ridge. In between a valley will be constructed, by which the Afsluitdijk stays recognizable and a visual separation between past and present can be observed. In Figure 3 an artist impression of the construction of tidal marshes is given.

Figure 3: Artist impression of the construction of tidal marshes

² Maximum vertical extent of wave up-rush on a structure above the still water level
The cross-section of the construction of the tidal marshes at the Wadden Sea side of the Afsluitdijk is given in Figure 4. The tidal marshes will grow naturally to a height a bit higher than average high water. During flood and design conditions the tidal marshes are too low to give sufficient wave reduction. Therefore the tidal marsh crest has to be constructed for the final wave reduction, necessary to avoid overtopping of the dam. The tidal marsh crest has a width of approximately 80 m and in between the original dam and the tidal marsh crest a valley is situated.

![Figure 4: Pencil sketch of the design of the tidal marsh ridge](image)

1.3 Problem description of the Msc Thesis

For the construction of the tidal marshes an amount of approximately $50 \text{ Mm}^3$ of sediment has to be dumped at the Wadden Sea side of the Afsluitdijk. This amount of sediment is more than $1/5$ times the total amount of sediment used for the construction of Maasvlakte II ($240 \text{ Mm}^3$).

There are several options to transport the sediment towards the Wadden Sea side of the Afsluitdijk. During a morphological workshop\(^4\) d.d. 22-10-2008 about the construction of the tidal marshes three basic concepts were evaluated:

1. Dredging from IJsselmeer and transportation by pumping

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\(^3\) Maasvlakte II is reclamation project at the sea side of the port of Rotterdam. Directly to the west of the current port and industrial area, a new location for port activities and industry is to be created in the North Sea. Maasvlakte 2 will shortly cover 1000 hectares net of industrial sites, located directly on deep water. [www.maasvlakte2.com]

\(^4\) Morphological workshop was initiated by ir. De Ronde and attended by Kees Dijkema (IMARES), Bert van der Valk (Deltares), Menno Eelkema (TUD), John de Ronde (Deltares) and Jeroen Lakeman (TUD).
Small dredging ships can be used to extract sediment of the IJsselmeer bed. The extracted sediment of the IJsselmeer can be transported to the Wadden Sea by pumping through pressure pipes. This results in a reclamation area on the Wadden Sea side of the Afsluitdijk. Small dredge ships on the water side and excavators on the land side can be used to apply the final tidal marsh alignment.

2. Dredging from the North Sea and transportation by pumping from Den Oever with small dredgers;

Large dredge ships can be used to extract sediment of the deeper parts of the North Sea. Subsequently small dredge ships can be used to transport the extracted sediment to the Wadden Sea. By means of a pumping installation with floating pipelines the sediment can be transported and distributed over the length of the Afsluitdijk. Again small dredging ships on the water side and excavators on the land side can be used to apply the final tidal marsh alignment.

3. Dredging from the North Sea and transportation by use of the tidal inlets and tidal trenches.

Large amounts of sediments can be dredged from the North Sea and dumped at the Texel Inlet. The tidal currents in the tidal inlets and trenches may be able to transport the sediments to the Afsluitdijk or a sedimentation area nearby the Afsluitdijk. The sediment can be moved subsequently from the sedimentation area to the Afsluitdijk by small dredgers or by floating pipelines.

Moreover it is possible to create a sand pit close to the Afsluitdijk. The extracted sediment of the sand can be used for the construction of the tidal marshes. It is expected that the sand pit sedimentates with the sediment that has been dumped in the lagoon system.

The morphological development of the combination of a dredge location close to the Afsluitdijk and a dump location at the Texel Inlet is to be studied. In the current project description the possibilities and efficiency of this method are unknown. Furthermore the morphological effects of the surrounding tidal flats and tidal trenches need to be determined.

Building with nature
A new fundamental concept of using of natural processes for a sustainable maintenance and development of coastal, river and delta areas is called **building with nature**. The technologies are based on ecosystems and make use of natural processes. Different specializations as ecology, biology and technique are involved in all the project phases of design, evaluation, decision making, construction and maintenance. The Dutch government is stimulating the development of this new field of study by various programs. [http://www.verkeerenwaterstaat.nl/onderwerpen/water/050_water_en_ruimte/building_with_nature/]
Study Objectives
This report deals with the technical feasibility of using the currents in the tidal trenches of the Wadden Sea to transport sediments towards the Afsluittdijk for the construction of the tidal marshes.

The main objective of this study is:
**Determination of the technical feasibility of using the Texel Inlet as a sediment transport belt for the construction of tidal marshes at the Afsluittdijk.**

The feasibility of using the Texel Inlet for the transportation of sediment is primarily related to the direction of the sediment transport processes. For an extensive explanation about the physical processes of sediment transport in tidal inlets the reader is referred to chapter 2. For now only the morphological character of sediment transport in relation to the tidal lagoon, the Wadden Sea, is of importance to understand the study objectives. A tidal lagoon is referred to as **morphologically importing** if the net sediment transport is in the direction of the tidal lagoon, this means that sediment is imported by the tidal lagoon. A tidal lagoon is referred to as **morphologically exporting** if the net sediment transport is in the direction of surrounding sea, this means that sediment is exported by the tidal lagoon.

If the Texel Inlet should function as a sediment transport belt towards the Afsluittdijk it is of primary importance that the morphological character of the inlet is importing.

The first research question is:
**Does the Texel Inlet have a morphologically importing character?**

Assuming a net importing character of the Texel Inlet the sediment transport patterns along the channel axis may be varying. The location of the place to dump the sediment is therefore an important parameter.

The second research question is:
**Which location at the Texel Inlet is most suitable as dumping location for sediment?**

Knowing the most suitable dumping location a numerical model\(^5\) can be used to simulate the morphological change in time. Again the morphological behaviour of tidal systems will be explained in chapter 2. However, the results of such simulations provide insight in the transport quantities of sediment.

The third research question is:
**What is the efficiency of the sediment transport in relation to the desired sedimentation location?**

Besides the use of a dumping location to transport sediment one can also make use of a sand pit. Sand can be dredged from a certain location nearby the new tidal marshes prior to dumping. By natural sediment transport processes the sediment from both the dumping location and the surrounding flats may be transported towards the sand pit. This variant of using the natural processes to transport sediment may result in a greater efficiency of the sediment transport in relation to the desired sedimentation location.

The fourth research question is:
**What is the influence of the use of a sand pit on the efficiency of the sediment transport in relation to the desired sedimentation location?**

---

\(^5\) A numerical model is a computer program, or network of computers, that attempts to simulate an abstract model of a particular system. Computer simulations have become a useful part of mathematical modeling of many natural systems in the process of engineering new technology, to gain insight into the operation of those systems, or to observe their behavior. [STROGATZ (2007)]
Finally the influence on the surrounding shoals of the Texel Inlet is to be determined for a judgement by ecologists and biologists for the disturbance of the natural habitat of intertidal flora and fauna.

The fifth research question is:
**What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?**

1.4 **Reader**

**Research methodology**
In the previous paragraph the main study objective was explained and subdivided into five partial study objectives. In this study use will be made of three models to formulate answers to the study questions:
- Instantaneous transport model (model A) used for the determination of the direction of the residual sediment transport;
- Process-based model (model B) used for the determination of the distribution of the residual sediment transport and the impact of human interventions to the systems morphology;
- Schematized transport model (model C) used for the validation of distribution of the residual sediment transport of the process-based model.

The research strategy and the characteristics and application of the models is further elaborated in paragraph 3.2.

**Reader**
A summary of the literature about the hydrodynamics and morphodynamics of the Western Wadden Sea is given in chapter 2. The research strategy and the model set-up are explained in chapter 3. The hydrodynamics of the Texel Inlet is being treated in chapter 4. The hydrodynamics are obtained from a process-based model (model B). In chapter 4 also the direction of the residual sediment transport is determined by using an instantaneous transport model (model A). Chapter 5 deals with the morphodynamic analysis of the Texel Inlet. The results of a process-based model are validated with a well-calibrated model of [Elias (2006)]. Furthermore the distribution of the residual sediment transport is validated by using a schematized transport model (model C). In chapter 6 the influence of human interventions at the Texel Inlet on the morphology will be treated. Sedimentation/erosion patterns are obtained from a process-based model (model B). Finally chapter 7 gives an overview of the conclusions and recommendations.
HYDRAULIC AND MORPHOLOGICAL CHARACTERISTICS OF THE WADDEN SEA

2.1 Introduction

A distinction is made between the shear stress that relates to the grain structure of the bed and the shear stress that relates to the ripple structure of the bathymetry.

2.1.1 Characteristics of the Waddensea

The Waddensea is a coastal system of tidal inlets allowing water to flow into a tidal basin consisting of meandering channels and shoals. The Waddensea is located from Den Helder in The Netherlands to Denmark and can be identified as a tidal lagoon. A tidal lagoon is a volume of water entrapped behind a coastal barrier like a series of islands. The Dutch Waddensea is entrapped between the coast of North-Holland, Friesland and Groningen en de Wadden Islands Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog. The Waddensea basin can be characterized by its tidal inlets, meandering trenches and shallow shoals. Typically tidal basins are sandy systems. They develop at sandy plains, after a breach in the barrier by a storm or the flooding of a coastal plain by sea level rise. Most of the sediment in the basin is imported from the surrounding coast.

2.1.2 Tidal basin morphology

Coastal and river morphology is the field of science dealing with changes of river and coastal plan form and cross-section shape due to sedimentation and erosion processes. Morphology is a branch of geomorphology that deals with the forms of natural water bodies such as rivers, lakes, estuaries, lagoons, coastal zones and seas, as well as with the processes that create and modify these forms. These processes are the erosion, transport and deposition of sediment (cobbles, gravel, sand, silt, clay). In its operational meaning, morphology includes not only plan form and bed topography but also bed sediment composition. Morphological behaviour is the manifestation of the changes in plan form, bed topography and bed sediment composition. Practically all rivers and coasts are subject to morphological processes.

The basin of the Dutch Waddensea can be characterized as a system of channels and shoals. The morphological origination of the system of meandering channels lies in the generation of instability when a tidal flow enters a wide and flat area. This instability occurs at different spatial scales and results in bed forms like ripples, mega ripples, dunes, sills and sandy ridges. The alternating instability between the higher located shoals and deeper channels has grown into a meandering system of channels.

Tidal currents through meandering channels stimulate the development of distinct flood and ebb dominated channels, separated by coastal shoals and elongated sills. Flow divergence and sediment settlement at the end of these channels contribute to the formation of flood and ebb tidal deltas.

The outer bend channel margins are steeper than the inner bend channel margins. Channel branches are located at the outer bends of the channels, while the tidal flats are situated at the inner bends. The channel width and to a less extend the channel depth decrease landwards.

The meander length decreases with decreasing depth. In Figure 5 the system of meandering tidal channels, separated by shoals can be seen clearly.
2.1.3 Tidal flats

Strong tidal flow prevents accumulation of fine sediments on the channel bed. Fine sediment settles at the tidal flats, in the wave sheltered areas at the border of the Waddensea and at the watersheds in the Waddensea. In the areas of the Waddensea closer to the tidal inlets more sandy sediment can be found. The fine sediment that settles during mild summer conditions will be brought into suspension by strong currents and wave action during winter and will be transported to other parts of the Waddensea.

At the landward side of Friesland and Groningen there are many tidal marshes. Tidal marshes are muddy shoals, vegetated by halophytes (plants able to live at strong salty grounds). This vegetation process enlarges the capacity to entrap fine sediments and stimulates lateral growth [FISLIER (2007)]. The dynamics of tidal marshes is strongly depended of the interaction of biological, geological and chemical processes, but also of tides and waves. The main morphological characteristics appear primarily related to the tidal range [DYER (2000)]. Sediment supply to the mudflat is stimulated by the flood dominance of tidal currents [POSTMA (1954)]. The tide also determines the maximum height to which the tidal marshes can grow and determines the duration to which the tidal marsh is subjected to waves.

Several studies point out that the depth profile of a tidal shoal is dependent on the bottom shear stress. Tide and wave action form the depth profile in a way that a uniform bottom shear stress occurs. The gradients in the residual sediment transport are minimized [ZIMMERMAN (1973)]. In case of a small tidal range and strong wave activity the depth profile is characterized as concave, by which the gradient of the wave induced shear stress is minimized. That type of profiles is also found at the coastline of an open coast. The sediment grain size is decreasing with decreasing depth [FRIEDRICH (1996)]. In the opposite situation with a strong tidal range and a small wave activity, the depth profile is characterized as convex, by which the gradients of the maximum tidal flow induced shear stress are minimized. The sediment grain size is increasing with decreasing depth [FRIEDRICH (1996)]. At the Waddensea both phenomena occur, depending on the exposure of the waves [ZIMMERMAN (1973)]. Also other factors influence the tidal shoal profiles, like the coastline curvature. The strong sensibility for wave action causes strong seasonal variations in the sedimentation and erosion of these shoals. The evolution of tidal flats is also subjected to bio-morphological processes: the mutual influence of morphology and biology. The morphology determines where what type of organisms can live and the organisms affect their living environment by reshaping the morphology.
2.2 Tidal Marshes

Tidal Marshes can be found on the interface between land and sea. These are areas under influence of ebb and flood. Some parts of the tidal marshes are almost always dry, while other parts are flooded every high water. If the tidal marsh has been flooded, an amount of sand will remain on it. This way the tidal marshes raise and eventually form new land.

Tidal marshes originate at a shoal in sea. When the sand level is above the water level during ebb, special types of salt tolerant vegetation, like sea grass, will start to grow. In between the vegetation sand will be caught, which creates even more space for vegetation. In the Waddensea the circumstances are good for the origin of tidal marshes, see Figure 6. The basin is under the influence of ebb and flood and the relatively sheltered places are ideal for the development of vegetation. Within five years a vegetated area at such a favorable area can be originated. During high tide the area will be flooded. When the water is flowing away during low tide it forms trenches. These trenches facilitate height differences, by which a varied landscape is created.

Figure 6: Tidal marshes at the Wadden Sea [KENIN (2008)]

Tidal marshes can ultimately contribute to new land. In the past many times this process has been enhanced by human action. Former tidal marshes have delivered vulnerable ground. That is the reason why from the Middle Ages until a century ago huge areas of tidal marshes have been taken away from the sea. Mostly only a dike was enough to secure the land of the former tidal marshes from the sea. Especially in Groningen a lot of agriculture land has been created this way.

Nowadays tidal marshes are mostly valuable because of their natural value. Special types of vegetation only appear in the special circumstances of tidal marshes. Furthermore waders and other birds find their food at the shallow parts of the tidal marsh. The vegetation at the low parts of the tidal marshes attracts ducks and geese. At the higher parts cows and sheep can graze and flowers will attract many insects.
2.2.1 Wadden Works Components

The construction of tidal marshes contains five components [DHV WaddenWerken, 2008]:

Tidal marsh works
Tidal marshes can play an important role in the safety calculations of water barriers. Therefore tidal marshes contribute significantly to the safety of the coast of Friesland and Groningen. The tidal marshes along the Frisian coast are provided with brushwood barrages. In Denmark the primary water barrier consist partly of tidal marshes. A tidal marsh near a dike, functions as a first wave reduction barrier and forms a foreland of the dike. In the current design of the tidal marshes a width of approximately 400 to 600 m is taken into account, including brushwood barrages.

The primary goal for the use of tidal marshes is to increase safety of the hinterland by a reduction of wave action. In a later stadium the tidal marshes can be widened in the direction of the Waddensea. Characteristic of tidal marshes is that they ‘grow’ with sea level rise.

Tidal marsh ridge
The height of the tidal marsh is not sufficient for the necessary wave reduction. Therefore a ridge is implemented in the design of the marshes. The tidal marsh ridge is a local elevation in the cross-section of the tidal marsh. The tidal marsh ridge has a width of approximately 80 m and a height of approximately NAP + 4.5 m. The total design of the tidal marsh (with ridge) has the necessary safety level of 1:10000 per year.

Fresh – salt transition
At the shoals located in the north-east of Den Oever wider tidal marsh area can be developed. This area will function as a fresh – salt transition. The main discharge will be delivered by the most eastern discharge sluice gate. The area will fulfill ecological functions, such as a draw back area for migrating fish and the development of brackish habitats and the possible nursery for sea grass. Brackish water lagoons will be established at the area between the western lee dam and the tidal marshes.

Fresh water discharging strategy
The IJsselmeer discharges water to the Wadden Sea. The water from the IJsselmeer is fresh and the water of the Wadden Sea is salt. Therefore the water in the area close to the discharge sluices is a mix of fresh and salt water, causing severe damage to the local sea fauna. The idea is to discharge as much as possible during ebb. During ebb the discharged fresh water flows more easily out of the basin. The fresh water stays more in the deeper parts of the channel. To facilitate this discharge strategy the construction of new discharging sluices is necessary.

Lee banks and high water safety places
At two locations a shoal is to be developed in a lee bank and high water safety place, see Figure 7. The function of the banks is to bring shelter for wind and water for tidal marsh development, for the canalizing of fresh water discharge and to keep the Doove Balg at distance. The banks are higher than high water level and their width is approximately 100 m.
2.3 Hydrodynamics of the Texel Inlet and its ebb-tidal delta

The tidal forcing is the dominant mechanism of the hydrodynamics of the Texel Inlet. The tidal discharge has therefore been measured in the Texel Inlet for almost 70 years. Most of the measurements have been conducted during a 13-hour observation over a single tidal cycle. The observations were converted to the mean conditions by multiplying with the ratio of measured and mean tidal range. The fluctuations in the magnitude of the residual discharge are large, because of the following reasons:

- The residual discharge is small compared to the total discharge through the channel
- Crude up-scaling of the single-tide observations to mean tidal conditions
- Possible influence of meteorological forcing by wind-driven flow or set-up effects
- Unknown accuracy of the observations
- Large variability in position of channels and shoals on the ebb-tidal delta up to 1975

The over-all estimation of the residual tidal discharge in Texel Inlet is an export between 0 and 200 m$^3$/tide in Marsdiep.

A reliable quantitative indication of the residual flow through the Marsdiep is obtained by NIOZ-ferry measurements. The results are shown in Figure 8.

The main tidal flow constituents have been determined by harmonic analysis [Elias (2006)], [Ridderinkhof (2002)]. The residual flow through the inlet is about $115\times10^5$ m$^3$/tide seawards. The reasons are:

- Internal dominance along the North-Holland coastline
- Larger ebb flow along the Texel coastline

The Texel basin does not form a closed system, but connect to Vlie basin. An exchange of water is the hydrodynamic consequence of this connection. The vertical tide in Vlie has higher amplitudes, which causes a residual flow from Vlie to Texel Inlet.
The flow in the main ebb-tidal channels has been obtained by measurement campaigns of Rijkswaterstaat between 2001 and 2004. The data-sets do not provide long-term time-series, but give an estimation of the discharge and velocity distributions in the individual channels. Figure 9 shows an overview by Elias of the discharge measurements during flood (a), during ebb (b) and the residual discharge (c).

Figure 8: Tide-averaged velocity distribution in Marsdiep for 1999 [ELIAS (2006)] and [RIDDERINKHOF (2002)]

Figure 9: overview of discharge measurement in $10^6$ m$^3$ [ELIAS (2006)] and [RIDDERINKHOF (2002)]
One of the conducted campaigns was at Marsdiep, Breewijd en Molengat. The results of the discharges and residual velocities are shown in Figure 9. The upper panel shows the transact-averaged discharge in the various channels. It can be concluded that the tidal wave in the Marsdiep has a nearly propagating character, with a time lag of approximately 2 hours.

The panels below denote the along-channel tide-averaged velocities for the various channels. Positive values indicate flood-dominant velocities and negative values indicate ebb-dominant velocities. From the cross-section of Marsdiep it can be concluded that the upper water body has an ebb-dominant residual velocity, whereas the velocity near the bed has a zero or slightly flood-dominant residual velocity.

Figure 10: Velocity profiles Texel Inlet [ELIAS (2006)] and [RIDDERINKHOF (2002)]
2.4 Tides in the Dutch Wadden Sea system

2.4.1 Introduction

Tides are the rising of Earth's ocean surface caused by the tidal forces of the Moon and the Sun acting on the oceans. Tides cause changes in the depth of the marine and estuarine water bodies and produce oscillating currents known as tidal streams. The strip of seashore that is submerged at high tide and exposed at low tide is referred to as the intertidal zone.

The changing tide produced at a given location is the result of the changing positions of the Moon and Sun relative to the Earth coupled with the effects of Earth rotation and the bathymetry of oceans, seas and estuaries. Sea level measured by coastal tide gauges may also be strongly affected by wind. More generally, tidal phenomena can occur in other systems besides the ocean, whenever a gravitational field that varies in time and space is present.

2.4.2 Characteristics of tides

Tidal configurations

A tide is a repeated cycle of sea level changes in the following stages:

- Over several hours the water rises or advances up a beach in the flood
- The water reaches its highest level and stops at high water. Because tidal currents cease this is also called slack water or slack tide. The tide reverses direction and is said to be turning.
- The sea level lowers or falls over several hours during the ebb tide.
- The level stops falling at low water. This point is also described as slack or turning.

Tides may be semidiurnal (two high waters and two low waters each day), or diurnal (one tidal cycle per day). In most locations, tides are semidiurnal. Because of the diurnal contribution, there is a difference in height (the daily inequality) between the two high waters on a given day; these are differentiated as the higher high water and the lower high water in tide tables. Similarly, the two low waters each day are referred to as the higher low water and the lower low water. The daily inequality changes with time and is generally small when the Moon is over the equator.

The various frequencies of orbital forcing which contribute to tidal variations are called tidal constituents. In most locations, the largest is the “principal lunar semidiurnal” constituent, also known as the $M_2$ (or $M_{2}$) tidal constituent. Its period is about 12 hours and 25.2 minutes, exactly half a tidal lunar day, the average time separating one lunar zenith from the next, and thus the time required for the Earth to rotate once relative to the Moon.

Tides vary on timescales ranging from hours to years, so to make accurate records tide gauges measure the water level over time at fixed stations which are screened from variations caused by waves shorter than minutes in period. These data are compared to the reference (or datum) level usually called mean sea level. For the Dutch Wadden Sea system the tide is monitored at the following stations:

- Texel North Sea
- Vlieland Harbour
- Den Helder
- Harlingen

Constituents other than $M_2$ arise from factors such as the gravitational influence of the Sun, the tilt of the Earth's rotation axis, the inclination of the lunar orbit and the ellipticity of the orbits of the Moon about the Earth and the Earth about the Sun. Variations with periods of less than half a day are called harmonic constituents. Long period constituents have periods of days, months, or years.
Neap tide and spring tide
The semidiurnal tidal range (the difference in height between high and low waters over about a half day) varies in a two-week or fortnightly cycle. Around new and full moon when the Sun, Moon and Earth form a line, the tidal forces due to the Sun reinforce those of the Moon. The tide's range is then maximum: this is called the spring tide. When the Moon is at first quarter or third quarter, the Sun and Moon are separated by 90° when viewed from the Earth, and the forces induced by the Sun partially cancel those of the Moon. At these points in the lunar cycle, the tide's range is minimum: this is called the neap tide, or neaps. Spring tides result in high waters that are higher than average, low waters that are lower than average, slack water time that is shorter than average and stronger tidal currents than average. Neaps result in less extreme tidal conditions. There is about a seven day interval between springs and neaps. The changing distance of the Moon from the Earth also affects tide heights. When the Moon is at perigee the range is increased, and when it is at apogee the range is reduced. Every 7½ lunations, perigee coincides with either a new or full moon causing perigean tides with the largest tidal range.

2.4.3 Tidal propagation in the North Sea

Amphidromic points
At two locations in the North Sea an amphidromic point can be found. Around an amphidromic point the tide rotates in cyclonic direction as a Kelvin wave. The tidal amplitude at an amphidromic point is exactly zero. Figure 11 shows the location of the amphidromic points and the phase contours of the semidiurnal tidal wave in the North Sea. The tidal wave in the central North Sea is mainly driven by the Atlantic Ocean tide at the northern boundary; the amphidromic point is shifted cyclonically to the eastern part of the basin. The tidal wave in the Southern Bight is mainly driven by the tidal wave in the central North Sea. However, is also influenced by the tidal wave in the English Channel, which causes a westward displacement of the amphidromic point.

---

6 The perigee refers to the point of the Earth of closest approach by the sun or the moon. The apogee refers to the point of the Earth of farthest excursion by the sun or moon. [http://www.perseus.gr/Astro-Lunar-Scenes-Apo-Perigee.htm]
2.4.4 Tidal distortion in the North Sea

Tidal distortion along the Dutch coast
Figure 12 shows the distortion of the tidal wave during its northward propagation along the Dutch coast. The strongest tidal asymmetry in the southern North Sea occurs along the coast of central and northern Holland. This is also the shallowest part of the Southern Bight, with relatively strong influence of friction on tidal propagation. The tidal amplitude is rather small along the coast of Holland; this suggests that the tidal depth variation in the friction term contributes more to tidal distortion than the other nonlinear terms.

Figure 13: Tidal amplitude and tidal asymmetry at various coastal and inland locations. The tidal curves are averaged over a decade [Dronkers, 1998]
Influence of offshore tides

Estuarine morphology is to a large extent determined by the residual sediment transport pattern. However, the inverse statement is also true. Residual sediment transport depends on differences in magnitude and duration between ebb and flood tidal currents. Such differences (tidal asymmetry) are produced by the distortion of the tidal wave propagating on the coastal shelf and entering bays and estuaries. In this study the relationship between tidal asymmetry and estuarine morphology is investigated.

The offshore tide influences the tidal asymmetry. In case of a faster development of the tidal rise of the sea level than the tidal fall of the sea level the flood flow velocities will be higher than the ebb velocities in the adjacent tidal basins. In case of slower tidal rise the opposite effect will occur.

Tidal asymmetry in a tidal basin is influenced by offshore tidal asymmetry. A faster rise than fall at sea causes higher flood flow velocities than ebb flow velocities in the adjacent tidal basins; slower tidal rise has the opposite effect.

In long tidal basins offshore tidal asymmetry can be offset by the influence of basin geometry: in short tidal basins the influence of offshore tidal asymmetry dominates over internally generated asymmetry. A long period of HW at sea causes a long period of slack water, whereas a short period of HW at sea causes a short period of slack water, and the same goes for LW. Tidal wave distortion along a coast influences ebb-flood asymmetry in adjacent basins and therefore the net sediment import or export and morphological development of these basins. Figure 12 show curves for the Dutch coast and its tidal basins; it appears that the shape of the offshore tide often persists within the adjacent basins.

2.4.5 Tidal asymmetry in the Wadden Sea

Groen model

In a study of Bonekamp the sediment transport in the Texel Inlet is based on the model of Groen for the concentration of sediments. This model is based on an equilibrium depth-averaged sediment concentration \( C_{\text{equilibrium}} \). The absolute difference of the instantaneous depth-averaged sediment concentration \( C \) and \( C_{\text{equilibrium}} \) determines the increase or decrease of \( C \). The equilibrium concentration is proportional to the squared current velocity.

\[
\beta \frac{\partial C}{\partial t} = \alpha \left( C_{\text{equilibrium}} - C \right), \quad \beta \geq 0
\]

\[
C_{\text{equilibrium}} = A \left( u^2 + v^2 \right)
\]

in which:

- \((u,v)\) : is the depth-averaged flow
- \(\alpha\) : proportionality factor
- \(\beta\) : settling lag time factor
- \(A\) : proportionality constant depending on the bottom roughness and sediment

To avoid a specification of \(A\), \(C\) is artificially expressed in terms of a squared velocity (\(m^2 s^{-2}\))

By the use of this model the instantaneous depth-averaged sand transport vector is given by:

\[
\vec{s} = \begin{bmatrix} Cu \\ Cv \end{bmatrix}
\]
If the settling lag factor is zero, the concentration adjusts instantaneously to the flow, and $\vec{s}$ is proportional to $u^3$. According to Pingree and Griffiths this is a valid model for bed load transport processes.

A fair reference value for the Dutch Wadden Sea is $\beta=1$, which corresponds to a time lag of just over one hour. Groen further shows that in the special case of the Wadden Sea basin the proportionality factor $\alpha$ becomes almost equal to the angular frequency of the $M_2$-component.

**Tidal constituents interaction**

By the application of straightforward goniometric formula manipulations, $\vec{s}$ can be expressed in terms of the mean flow and the amplitude and phases of the flow tidal constituents. For the Texel Inlet the tidally averaged transport is dominated by the M0-M2 and M2-M4 interactions, according to Kreeke and Robacewska).

The figures below indicate the interaction in the tidal constituents M2 and M4 and the corresponding value of $u^3$.

![Figure 14: interaction of the M2 and M4 tidal constituents with the corresponding value of $u^3$](image1.png)

![Figure 15: interaction of the M2 and M0 tidal constituents with the corresponding value of $u^3$](image2.png)
2.4.6 Tide of the Wadden Sea

The significant tidal constituents of the four reference stations with tide observation of the last 25 years have been indicated in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Texel North Sea</th>
<th>Terschelling North Sea</th>
<th>Den Helder Wadden Sea</th>
<th>Harlingen Wadden Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>0.78</td>
<td>189</td>
<td>0.89</td>
<td>234</td>
</tr>
<tr>
<td>$O_1$</td>
<td>0.10</td>
<td>197</td>
<td>0.09</td>
<td>205</td>
</tr>
<tr>
<td>$K_1$</td>
<td>0.08</td>
<td>358</td>
<td>0.07</td>
<td>2</td>
</tr>
<tr>
<td>$M_4$</td>
<td>0.08</td>
<td>270</td>
<td>0.07</td>
<td>319</td>
</tr>
<tr>
<td>$N_2$</td>
<td>0.12</td>
<td>172</td>
<td>0.15</td>
<td>210</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.07</td>
<td>16</td>
<td>0.07</td>
<td>67</td>
</tr>
<tr>
<td>$S_2$</td>
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<td>0.25</td>
<td>296</td>
</tr>
<tr>
<td>$M_4$</td>
<td>0.10</td>
<td>239</td>
<td>0.09</td>
<td>331</td>
</tr>
<tr>
<td>$M_6$</td>
<td>0.06</td>
<td>307</td>
<td>0.06</td>
<td>43</td>
</tr>
<tr>
<td>$M_6$</td>
<td>0.09</td>
<td>346</td>
<td>0.05</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 1: Results harmonic analysis of the amplitudes ($A$) and phases ($\phi$) of the water levels at the tidal observation points

2.4.7 The concept of secondary flow

In fluid dynamics, a secondary flow is a relatively minor flow superimposed on the primary flow. The primary flow usually matches very closely the flow pattern predicted using simple analytical techniques and assuming the fluid having a zero viscosity.

The primary flow of a fluid, particularly in the majority of the flow field remote from solid surfaces immersed in the fluid, is usually very similar to what would be predicted using the basic principles of physics, and assuming the fluid having a zero viscosity. However, in real flow situations, there are regions in the flow field where the flow is significantly different in both speed and direction to what is predicted for a zero-viscosity fluid using simple analytical techniques. The flow in these regions is the secondary flow. These regions are usually in the vicinity of the boundary of the fluid adjacent to solid surfaces where viscous forces are at work, such as in the boundary layer. The boundary layer is that layer of fluid in the immediate vicinity of a bounding surface, in this case the bottom of the coastal area. The boundary layer effect occurs at the region in which all changes occur in the flow pattern. The boundary layer distorts surrounding non-viscous flow. It is a phenomenon of viscous forces. This effect is related to the Reynolds number.

Secondary flow in bends

Water flowing through a bend in a trench must follow curved streamlines to remain within the banks of the trench or river. The water surface is slightly higher near the concave bank than near the convex bank. (The concave bank has the greater radius, and the convex bank has the smaller radius.) As a result, at any elevation within the trench or river the water pressure is slightly higher near the concave bank than near the convex bank. There is a pressure gradient from the concave bank toward the convex bank. Centripetal forces are necessary for the curved path of each parcel of water, and this centripetal force is provided by the pressure gradient. The primary flow around the bend is vortex flow – fastest speed where the radius of curvature is smallest and slowest speed where the radius is largest. The higher pressure near the concave bank is accompanied by slower water speed, and the lower pressure near the convex bank is accompanied by faster water speed, and all this is consistent with Bernoulli's principle.
There is also a secondary flow in the boundary layer along the floor of the river bed. The boundary layer is not moving fast enough to balance the pressure gradient and so its path is partly downstream and partly across the stream from the concave bank toward the convex bank, driven by the pressure gradient. The secondary flow is then upward toward the surface where it mixes with the primary flow or moves slowly across the surface, back toward the concave bank. This motion is called helicoidally flow.

On the floor of the river bed the secondary flow sweeps sand, silt and gravel across the river and deposits the solids near the convex bank, in similar fashion to sugar or tea leaves being swept toward the centre of a bowl or cup as described above. River bends often have a convex bank which is shallow and comprised of sand, silt and gravel; and a concave bank which is steep and heavily eroded. This process can lead to formation of a meander or a point bar or, eventually, an oxbow lake.

### 2.4.8 Coriolis effect

In all considerations about air or water around the globe, it should be kept in mind that Newton’s equations of motion (displacements, velocities and accelerations) refer to a fixed grid, whereas observations of velocity and acceleration refer to a grid system attached to the moving and rotating earth. According to Newton this system is not at rest for the motion equation. The deviations arising because of relative movements instead of absolute movements are known as the Coriolis effect. In brief, the Coriolis effect causes a free current in the Northern Hemisphere to turn slightly to the right, and in the Southern Hemisphere to the left. The deviation from the straight path can be quantified by the introduction of the Coriolis acceleration:

\[
\alpha = 2 \omega \sin \varphi \ V \sin \theta \approx \omega \ V \sin \varphi \approx 1.16 \times 10^{-5} \ m/s^2
\]

Where:
- \( \alpha \) = Coriolis acceleration [m/s²]
- \( \omega \) = angular velocity of the earth \( \approx 72.9 \times 10^{-5} \) [rad/s]
- \( V \) = current velocity [m/s]
- \( \varphi \) = latitude \( \approx 53 \) [deg]

The influence of latitude is due to the fact that all forces have to be split into a component parallel to the local earth surface and a normal component that works the same vector as gravity. The flow in the Texel Inlet takes place in a channel that to some limits prevents a deviation of the course (steady current). The Coriolis acceleration causes a pressure gradient across the channel:

\[
\frac{1}{\rho} \frac{\partial p}{\partial n} = 1.16 \times 10^{-4} \ V
\]

Where:
- \( \rho \) = water density [kg/m³]
- \( p \) = water pressure [Pa]
- \( n \) = normal to the current

The pressure comes partly visible as a gradient of the water surface. This can be illustrated by computing the sea level difference across the Texel Inlet in case of a complete steady current, which is an oversimplification due to the existence of the surrounding tidal shoals. The Texel Inlet has a current velocity of about 1.0 m/s (close to the Marsdiep) and a width of about 2.0 km.

\[
\frac{1}{\rho} \frac{\partial p}{\partial n} = 1.16 \times 10^{-4} \times 1.0 = 1.16 \times 10^{-4} \ m/s^2
\]
The elevation difference over 2.0 km can be determined as:

\[ \Delta z = \frac{1.16 \times 10^{-4} \times 2.0 \times 10^3}{9.81} = 0.024m \]

2.5 Morpho-dynamics of the Texel Inlet and its ebb-tidal delta

2.5.1 General description of tidal inlets and ebb-tidal deltas

The definition of a tidal inlet can be described as an opening in the shoreline through which water (and sediments, nutrients, etc) is exchanged between the open sea and the back-barrier basin. The tidal inlet has a greater water depth than the surrounding areas, caused by the strong tidal currents. These strong tidal currents erode sediments until a morphological equilibrium has been reached. The flow through the inlet segregates and flow velocities decrease after passing through the narrow inlet throat. The sediments eroded from the inlet, and supplied by alongshore sediments transport accumulate in tidal deltas at the seaward and landward side. These deltas are called the ebb- and flood-tidal delta respectively.

In the analysis of the inlet behaviour the dynamic coupling between the ebb-tidal delta, inlet throat and back-barrier basin is of major importance. The coupled system tends to remain in a dynamic equilibrium to the large-scale hydraulic forcing. A distortion of the equilibrium state in one of the components results in sand exchange between the components. Other parts of the system will deliver or store sand to compensate for the distortion. Large scale permanent distortions due to natural causes or human intervention can cause the entire inlet system to shift towards a new equilibrium state.

The morphology of the ebb-tidal delta is essentially determined by the relative importance of wave- versus tidal energy. Wave dominated ebb-tidal deltas are pushed close to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore. The sediment by-pass is the sand exchange over the ebb-tidal delta from the up-drift to the down-drift beaches. This by-pass is of major importance for the channel-shoals distribution on the ebb-tidal delta. The character of this sediment by-pass can be related to the ratio of longshore sediment transport to tidal inlet currents:

- High ratio: wave-induced sand transport prevails along the margin of the ebb delta
- Low ratio: sediment transport through channels and migration of tidal channels and bars are the major sediment transport phenomena

Conceptual models have been elaborated to explain sediment by-passing under mixed energy condition. These models are based on the relationship between stability of the inlet throat and the movement of the main ebb channels. Basically three models of sediment by-passing can be recognized (FITZGERALD ET AL (2000)), see Figure 16:

1. Cyclic ebb-tidal delta breaching
2. Outer channel shifting
3. Stable inlet process
The ebb-tidal delta dynamics on smaller, decadal, time scales cannot be described in sufficient detail by a general classification based on wave- versus tidal energy. The following secondary external controls influence the inlet behaviour [FitzGerald, 1996]:

- Sediment supply
- Basin geometry
- Sedimentation history
- Regional stratigraphy
- Fresh water discharge by rivers of flush gates

### 2.5.2 Texel Inlet and its ebb-tidal delta

The Texel inlet is the largest inlet of the Dutch Waddensea. The inlet is located in the northwestern part of The Netherlands between Den Helder and the barrier island of Texel, see Figure 17. The Texel Inlet is probably the longest regularly monitored inlet worldwide with bathymetry data and the ebb-tidal delta of the last 4 centuries.

Tides and wind-generated waves are the dominant natural processes governing the morphological developments. The following list indicates some characteristics of the Texel Inlet:

- Mean tidal range is nearly 1.4 m in Marsdiep (2.0 during spring tide and 1.0 during neap tide)
- The average tidal prism through the inlet is about 1000 Mm³
- The maximum ebb and flood tidal velocities range between 1.0 and 2.0 m/s
- The Texel inlet does not form a closed system but the basin connects to the neighboring Vlie basin. An exchange of water is allowed by this connection. A seaward directed residual flow of about 115 Mm³ is present because of the higher amplitude of the vertical tide in the Vlie basin.
- The mean significant wave height is 1.3 m from the west-south-west direction, with a corresponding period of 5 s
- During storm the wind-generated waves reach height of more than 6 m. The additional water level surge can be more than 2 m
- Wave breaking in the surf-zone and on the shallow swash platforms on the ebb-tidal delta can result in wave-driven current of nearly 2 m/s
According to the classification of Hayes the inlet can be qualified as mixed-energy wave-dominated. The large ebb-tidal delta indicates a tide-dominance of the system. The large delta is caused by the large tidal prism and the relatively low wave energy. VAN DER WAAL (2007) investigated the influence of the distinct forcing agents. He concluded that for the Western Wadden Sea the direct influence of waves is most pronounced at the ebb-tidal delta area, where most of the wave energy is dissipated. Moreover he concluded that waves have little influence on the sediment transport inside the basins. In this study the area of interest is the sediment transport in the basin. A model based on tide-dominance of the system is used in this study to investigate the influence of human intervention on the sediment transport in the basin.

2.5.3 Historic evolution of the Texel Inlet

After a number of severe storms around the 12th century the Texel Inlet was evolved from a small drainage channel. Before the breaching of the Texel Inlet, the Vliestroom was the only connection between Zuiderzee and North Sea.

In the following centuries the size of the inlet increased by the subsidence of the surface level. The subsidence of the surface level was mainly caused by excavations and drainage of low-lying peat areas bordering the inlet’s initial basin for agricultural use. The rate of subsidence was approximately 1 m per century. During storm surges, large areas were flooded and even more peat was eroded, resulting in a further expansion of the basin. The increase in volume of the basin resulted in a greater tidal prism. This caused the scouring of the inlet channels and an increase in depth and width.
This phenomenon is called the natural feedback mechanism of erosion and increased tidal prisms. The development of the basin was governed by this mechanism until circa 1600. After 1600 the expansion of the basin was controlled by human activities, such as coastal protection works, dykes and embankments. In the literature the hypothesis that the tidal prism and inlet dimensions have followed the increase and stabilization of the tidal basin is widely accepted [ELIAS (2006)].

By various scientist relations between the tidal prism and the maximum depth of the inlet throat, based on the tidal prism evolution since the breaching of the inlet, have been developed. VAN DER SPEK developed the following expression for estimated tidal prism for a known maximum depth:

$$P_{estimated} = \frac{h_{max} - 13}{37 * 10^{-3}}$$

By the relative sea level rise the accommodation in the tidal basins is expanded. The morphological reaction of the Wadden Sea is the continuous sedimentation in the tidal basin to this phenomenon. The theory is that the bed topography follows the relative sea level rise by the interaction of the tide and the bed topography. The water depth is increased by the relative sea level rise. This causes a reduction in the velocities in the channels and on the tidal marshes. The reduction of the sediment transport capacity is much stronger, because sediment transport and velocity are related to a power (commonly 3 to 5). This reduction in the sediment transport is stronger during ebb than during flood. The transport into the basin is therefore larger than the transport out of the basin. By the continuously sedimentation in the basin areas more sediment must be supplied from the adjacent coastlines and ebb-deltas.

Another important morpho-dynamic characteristic of the Wadden Sea is the presence of erosion-resistant layers. In figure 7 the development of Texel Inlet through time has been presented. The comparison of (B), (C) and (D) indicated that the southwest-northeast outflow from Texelstroom to Marsdiep remained remarkably stable. Only a slightly rotation of the channel to align with the Texel coast occurred after the closure of the Zuiderzee. Recent core data indicates that the seaward part of Texelstroom channel is bounded by or incised into glacial till. The stability in dimensions and position is governed by this stiff deposit. Also the construction of coastal defence structures has contributed to the stability of the channel.

The inflow of sediment of the Marsdiep has two main sources. Approximately 4 Mm$^3$/y of sediment is eroded from the outer delta

Wave induced alongshore sediment transport brings sea sediment into the tidal inlet. This import of sediment is feeding the basin, but also can lead to the gradual constriction of the inlet and in some cases even to the sludge of the basin [7]. The actual inlet width as a dynamic balance between alongshore sediment transport and tidal flow through the inlet [8]. If the alongshore sediment transport is strong, the tidal inlet is narrow; otherwise the inlet is broad.

The section area $A_s$ is primarily related to the tidal prism $P$; to a lesser extent it is influenced by wave induced sand import. Tidal inlet dynamics in the presence of strong tide and wave action is complex. At the inlet an outer delta of shoals is being formed, also known as ebb tidal deltas. The outer delta shoals function as wave run-up shoals for breaking waves. The presence of the wave run-up ridges is an important condition for the origination of a bypass around the inlet of wave induced alongshore sediment transport. Mostly this is not a continuous process, but includes cyclic migration of channels and shoals at the inlet. These inlet cycles have duration of one decade up to a century. The geometry of the tidal inlets can differ strongly, mainly dependent on tidal range and the strength and direction of the wave induced sediment transport. Nevertheless a rough characterization of the outer delta is pointed out to be directly related to the tidal prism.
2.5.4 Present state of morphology of the Texel Inlet and its ebb-tidal delta

The flow patterns and morphological development and estimated transport paths are summarised in Figure 19. By the NIOZ ferry observation it was observed that the residual flow through the inlet is about 115 Mm$^3$/tide.
For the period 1986 – 2003 large morphological changes have been observed. However the shape and form of the main channel and shoals areas is relatively stable. The present morphological development consists of the local interaction between channels and shoals and sediments redistribution.

The morphological development over the period 1986 – 2003 can be treated in a subdivision of the system in 4 areas.

**Morphological developments area 1 (northern part):**
- Landward migration of the Noordelijke Uitlopers of Noorderhaaks
- Displacement of the Molengat towards the Texel coastline, inducing severe erosion

**Morphological developments area 2 (central part):**
- Landward displacement of sediments
- Erosion of the western margin of Noorderhaaks
- Deposition north and south of the supra-tidal parts of Noorderhaaks
- Enlargement in depth of the channels Schulpengat and Nieuwe Schulpengat

The southern area is distinguished in two areas separated by Schulpengat, because they areas show different morphological behaviour.

**Morphological developments of area 3 (Zuiderhaaks):**
- Zuiderhaaks acts as the spill-over lope of Nieuwe Lands Diep and Schulpengat
- Zuiderhaaks shows a trend of sedimentation and southwards growth.

**Morphological developments of area 4 (Nieuwe Schulpengat):**
- Local interaction of the channel with the adjacent shoals
- Migration southwards of the Bollen of Kijkduin
- Small southwards displacement and clockwise rotation of Nieuwe Schulpengat
- Landwards migration of the Franse Bankje shoal
The total sedimentation of the ebb-tidal delta is small compared to the erosion volume. There must be a net sediment transport towards the basin as also the adjacent coastlines loose sediments. The sand influx over the period 1986-2003 is estimated to range between 5 to 6 Mm$^3$/year. In the basin corresponding rates of sedimentation are observed.

2.5.5 Predictability and cascade of scales of the Wadden Sea system

The morphology of tidal inlets and basins is the physical and ecological result of the interaction between the water and sediment motion and the bed topography. The interaction is stochastically forced and nonlinear. The understanding and predicting of this interaction is considered as highly complex. The implications of morphological research can be listed as follows:

1. Dealing with a wide range of space and time scales, with complex multi-scale interactions of the constituent processes.
2. Dealing with strong, partly stochastic variations of the forcing.
3. Dealing with the concept of limited predictability. Coastal systems like the Wadden Sea seem to satisfy all conditions for inherently unpredictable behaviour (cf. De Vriend, 1998). This would imply that large-scale behaviour cannot be derived in a deterministic way from small-scale processes.\(^7\)

In summary it has been concluded by the Delft Cluster [33] that our capability to predict the morphological behaviour of tidal inlets and tidal basins is still unsatisfactory for practical use.

In order to deal with the problem of limited predictability Delft Cluster [33] introduced the concept of the cascade of scales:

- **micro-scale**
  - the level inherent to the underlying processes and the smallest-scale morphological phenomena (ripple and dune formation)
  - the principal forcings are the diurnal tide and the weather

- **meso-scale**
  - the level of the principal morphological features, such as channels or shoals
  - the principal forcings are seasonal and inter-annual variations in the tide and the weather conditions, and human activities such as sand mining
  - a special category of phenomena at this level is the response to extreme events

- **macro-scale**
  - the level at which these features interact (e.g. the ebb-tidal delta functioning)
  - the principal forcing-elements are the longer-term cycles in the tide, decadal-scale variations in the wave climate, consistently repeated human interference activities, etc.,

- **mega-scale**
  - the level at which the principal elements of the entire coast-basin system (barrier islands / adjacent coast, outer deltas, inlets, back-barrier basins / estuary) interact, so generally many kilometres in space and centuries in time;
  - the principal forcing-elements are mean sea-level rise, climatic change, long-term tidal variation, subsidence, etc.

The Cluster pointed out that the highly dynamic nature of the non-linear, stochastically forced systems makes it not very likely that one model will be able to cover all these scale levels at one time. At various points, one must expect to run into intrinsic or practical limits of predictability (cf.\(^7\)

\(^7\) At the moment, the hypothesis of the existence of inherent predictability limits in tidal basin and inlet systems has neither been verified, nor falsified. Practical limits, associated with computer time, for instance, have been encountered.
De Vriend, 1998), see figure 9. In other words: brute-force computing is probably not a viable approach to predicting the macro- and mega-scale behaviour of these systems.

![Figure 20: Cascade of scales [De Vriend, 1993]](image)

In general, predictability limits can be overcome by aggregation. Based on what is known of the system’s behaviour at scales below and above this limit, another model is formulated at the higher scale level, without attempting to describe every detail of what happens at the lower scale level. Hence, one should aim at a cascade of models at different levels of aggregation.

### Time scale of morpho-dynamics in the Texel Inlet

Based on the model results of Kragtwijk, different time-scales in the morphological response of the inlet to the closure of the Zuiderzee are derived. It was shown by Kragtwijk that in the morphological system unequal timescales interact. These time-scales differ in order of magnitude (years, decades, and centuries) due to the interaction between morphological units. Based on the research of Kragtwijk the cascade of scales has been applied to the system of the Texel Inlet:

- **Meso-scale**: the interaction of a single channel and shoal acts on a short timescale of $O(\text{years})$
- **Macro-scale**: interaction of the total basin acts on a medium timescale of $O(\text{decades})$
- **Mega-scale**: the adaptation of the entire morphological system of basin (channels and shoals), ebb-tidal delta (channels and shoals) and adjacent coastlines acts on a long-term timescale, $O(\text{centuries})$

These observed time-scales can function as a valuable indication of the expected time-scales of the response of the system to future changes.

**Specification of the model for the Texel Inlet ebb-tidal delta development (summary of Elias, 2001)**

In order to understand the present morphological processes at the ebb-tidal delta of the Texel Inlet it is necessary to review the morphological developments after the closure of the Zuiderzee. In line with the cascade of scales it has been observed that the rate of adjustments is often proportional to the magnitude of the disruption. The morphological response of tidal basins consists of a complex combination of interactions on several time-scales that may differ by an order-of-magnitude. The conceptual model, developed by Elias, described the morphological response of the Texel Inlet in four stages of development, see Figure 21.
Stage 1: the dynamic equilibrium stage of the ebb-tidal delta preceding the closure
Before the closure of the Zuiderzee, the Texel Inlet was in a dynamic equilibrium state. This state was established based on the conditions of:
- a long-lasting balance between a moderate and approximately constant rate of sea level rise
- a sufficient supply of sediment that enabled the basin to develop towards an equilibrium

The migration of channels and shoals was the dominant morphological feature.

Stage 2: adaption of the basin and ebb-tidal delta to the effects of the closure
The closure of the Zuiderzee resulted in large changes in the morphology of the basin and the ebb-tidal delta. Morphological data of the Texel Inlet indicate that after 1970 a great variability in the erosion and sedimentation patterns develops. The development of this variability suggests a state of dynamic near-equilibrium behaviour after 1970.

The initial morphological response of the closure of the Zuiderzee consists of two main elements:
- Up-drift development of the main-ebb channels, induced by channel-shoals interactions
- Considerable increase of the supra-tidal part of the main shoal

Stage 3: dynamic near-equilibrium state
The increase in supra-tidal shoal area has resulted in a segregation of the tidal flow through the northern and southern part of the ebb-tidal delta. The diversion of the main ebb channel is mainly through the southern part of the system. The shoal acts as a barrier that prevents direct interaction between the northern and southern part. The behaviour of the northern and southern part of the ebb-tidal delta is therefore separated on decadal time-scale.

The dominant morphological development for the northern sub-system is the increase of the shoals, induced by wave action. The tidal currents through the Molengat channel form only a small contribution. The sand volume of Noorderhaaks is redistributed by wind and wave driven currents and transports. The development is described by spit development and breaching.

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8 The supra-tidal part of the main shoal is the part of the shoal that remains dry during high water
9 A spit is a deposition landform found off coasts. At one end, a spit connect to land, while at the far end they exist in open water. A spit is a type of bar or beach that develops where a re-entrant occurs by the process of longshore drift. Longshore drifting is complemented by longshore currents, which transport sediment through the water alongside the beach.
The southern sub-system is dominated by the interaction of the tidal channels and the associated shoals. The tidal channels transport over 90% of the inlets tidal prism. As a result, the southern sub-system forms the active part of the ebb-tidal delta. This conceptual sub-system model describes the behaviour of the last three decades and is expected to do so for the coming decades.

Stage 4: Cyclic morphological evolution
In the longer time scale (centuries) the interaction between the sub-systems cannot be neglected. The ongoing northward extension of Noorderhaaks is expected to continue. For each cycle of spit development and breaching the sand volume reduces. This reduces the southward deflection and the segregation of the tidal flow. It is expected that the reduced segregation and deflection returns the main-ebb channel to the original westward oriented position. Eventually an ebb-tidal delta situation is formed, with a morphology that satisfies the equilibrium conditions.

2.5.7 Current – topography interaction
At first sight one would consider that sedimentary bottom structures erode and flatten out under the permanent energy transmitted by currents. However, sedimentary structures, such as ripples and dunes develop on the sediment bed even under conditions of almost perfect initial uniformity. The development of these ripples and dunes can be explained by the nonlinearity of flow-topography interaction. The nonlinear flow-topography interaction relates to seabed instability. The dynamics of the current-topography interaction is highly complicated. Only mathematical description of the dynamics induce great simplifications. The results of mathematical and numerical models should be interpreted with care, since it is hard to ensure that all essential physical processes are sufficiently involved. The numerical model of Delft3D, used in this study, to simulate the morphological development of the Wadden Sea should therefore not be considered as a substitute for physical reality, but as a tool for improving the ability to interpret phenomena that are observed so far and as a indication of morphological development after human intervention. Sediment grains will suspend in the water from the position in the bed matrix if the shear stress over the sediment bed is high enough. The currents and sediment bed interact by sediment transport. Turbulent fluid motion is of significant importance in sediment transport processes. The turbulence does on its turn depend on the properties of the sediment grains and the interaction of the grains in the sediment bed.

Small scale bedform patterns: dune family
The sediment transport processes are related to the small-scale structures of the seabed. The so-called ripples on the seabed are both a cause and a result of the sediment transport. The formation process is strongly related to the vertical component of flow field. The small scale bedform patterns are known as the dune family. Besides the ripples also mega-ripples and sand-waves can be observed. Figure 22 is a schematic representation of a sand-dune with superimposed smaller mega-ripples, on which smaller current ripples are superimposed. The arrows indicate the average flow patterns. The flow patterns are induced by the bedforms.
Figure 22: Schematic representation of a sand dune [Dronkers, 2005]

**Large scale bedform patterns: sandbank family**
At larger scales rhythmic bedform patterns can also be observed, known as the sandbank family. The bedform are called bars and ridges and are mostly related to the horizontal structure of the flow field. Often both the formation of bedforms of the dune family and the sandbank family occurs at the same location. The bed topography is a superposition of both bedforms. The structures impose different kinds of modification on the flow field, with complex dynamic interaction.
3 RESEARCH STRATEGY AND MODEL DEVELOPMENT

3.1 Introduction

The study has been introduced in chapter 1, containing an inducement of the objectives and the study background. The research strategy of the study will be explained in this chapter, containing a consideration of the hydrodynamics and the sediment transport processes. Subsequently an overview of the hydrodynamic loads is given, including a consideration of the significance of the distinct hydrodynamic excitations. Furthermore the numerical model that will be used for simulation is explained and validated.

The set-up of this chapter is:

3.2 Formulation of the research strategy
3.3 Consideration of the hydrodynamic loads
3.4 Explanation of the numerical model
3.5 Validation of the numerical model

3.2 Research strategy

This paragraph deals with the formulation of the research strategy, including the elaboration of the study objectives.

The determination of the technical feasibility of using the Texel Inlet as a sediment transport belt is the main objective this study. A human intervention in the form of a dump or distraction of a significant amount of sediment at the Texel Inlet is in morphological point of view a disturbance of the natural system. The Wadden Sea is in a non-equilibrium state, which involves an ongoing development of the bathymetry and hydrodynamics.

The hydrodynamics form a fundamental characteristic of the morphological development of a coastal system. The dynamics of water particles induce shear stress on the bed of the system, stirring up sediment, and transport sediment over the bed or in suspension. To examine the morphodynamics of the Texel Inlet and the Wadden Sea system it is necessary to understand and map the hydrodynamic characteristics. The hydrodynamics and morphodynamics are closely related. Based on the hydrodynamics a rough image of the direction and the order of magnitude of the sediment transport processes can be determined. With this analysis it is possible to formulate an answer to the first partial study objective, the determination of the direction of the sediment transport processes. The model referred to of this analysis is model A:

Model A: Engelund and Hansen – instantaneous transport model

In a Delft3D model advective and diffusive transport terms are implemented in the sediment transport (see chapter 5). The process-based model is referred to as model B:

Model B: Delft3D – process-based model

In order to obtain a good understanding of the results of the Delft3D process-based model it is of vital importance to verify the results with a schematized transport model. A notion of the sensitivity of relevant parameters as the water depth, sediment concentration and flow velocity can be obtained. The model referred to of this analysis is model C:

Model C: Bijker – schematized transport model

Previous studies and measurements are used to verify the results. The characteristics of the models have been summarized in Table 2.
### Model Name | Purpose | Characteristics
--- | --- | ---
A Engelund and Hansen | • Preliminary insight in the sediment transport process  
• Determination of the direction of the residual sediment transport  
• Formulation of the hypothesis of morphological response to a dump in the Texel Inlet | • Hydrodynamics conducted from a hydrodynamic simulation with Delft3D  
• Sediment transport determined by using the sediment transport formula of Engelund and Hansen |
B Delft3D | • Full simulation of the sediment transport processes, including advection and diffusion  
• Morphological forecast of the development of a sediment dump at the Texel Inlet at two locations  
• Morphological forecast of the development of a sediment dump and a sand pit at the Texel Inlet  
• Determination of the efficiency of using Texel Inlet as a sediment transport belt  
• Determination of the morphological effects on the surrounding shoals in the Wadden Sea system | • Hydrodynamics conducted from a hydrodynamic simulation with Delft3D  
• Morfodynamics conducted from a morphological simulation with Delft3D |
C Bijker | • Assessment of the morphological results of the Delft3D simulations | • Consideration of sediment transport during maximum ebb tidal flow and flood tidal flow  
• Determination of bed load and suspended load transport by using Bijker sediment transport formulae |

**Table 2: Overview of the three models used in this study**

Based on the distribution of sediment transport over the Texel Inlet the dump locations can be defined (second partial study objective).

After the definition of two dump location at the Texel Inlet, the morphological development can be determined. Again, the change in hydrodynamics is considered in the first place, followed by the sediment transport processes. An overview of all sediment transport processes of the tidal system, obtained by a numerical model, for the original bathymetry Wadden Sea and the Wadden Sea after the human intervention, offers the possibility to identify the resultant sediment transport processes, induced by the changed bathymetry. The output is presented in an overview of the sedimentation-erosion patterns. The efficiency of these resultant sediment transport processes in relation to the desired sedimentation location can be determined (third partial study objective).

Besides the dump of sediment it is also possible to make use of a so-called sand pit, to subtract sediment from the system. The hydraulic conditions at such a sand pit might very well enhance the sedimentation processes. In the same way the efficiency for this alternative can be determined (fourth partial study objective).

The influence of the sand transport processes on the surrounding shoals of the Texel Inlet (fifth partial study objective) can be obtained by the interpretation of the sedimentation-erosion patterns of the shoals.
3.3 Hydrodynamic loads

This paragraph deals with the description of the hydrodynamic load of the water body of the Wadden Sea system. The tide, waves and wind will be briefly discussed, followed by a consideration of the loads to be account for in the further analysis.

Tide excitation
The influence of the tidal components that are considered to be the main driving mechanisms behind the sediment transport is taken into account. The reader is referred to chapter 2.4.6 for the description of the tide of the Wadden Sea.

Wave excitation
The wave field of the North Sea is primarily created by wind action. Figure 5 shows the wave height distribution for the various directions of a wave buoy at Eierlandse Gat.

Figure 23: Wave height distribution for the various direction of a wave buoy at Eierlanse Gat

The strongest wave action is originated from the western direction. The generation of waves is maximum for this direction due to the long fetch. The waves are generated by wind-induced stresses at the sea surface. In general, the total wind stress can be divided into
1. wind induced surface friction (shear stresses)
2. wind induced surface pressure (normal stresses)

The effect of surface friction compared to surface pressure on wave generation is so small that it can be ignored. It is wind induced surface pressure that generates the waves. For the initial phase of wave generation the turbulent pressure field resonates with the free surface waves. When the waves are large enough, they modify the airflow over the surface so that the waves enhance their own growth. The observation data show that the majority of the waves of approximately 80 % does not exceed a wave height of $H_s = 2$ m, while from western direction the wave height can be $H_s = 6$ m. Therefore only the western storms may have a significant contribution to the morphology of the Texel Inlet.

Wind excitation
When the wind is blowing over a water surface, a shear stress is being exerted on the underlying water mass. The consequence is a migration of water in the direction of the wind, which creates a set-up in the water level. If the duration of the wind set-up is long enough, an equilibrium situation will be developed. In the upper part of the vertical the water is flowing in the direction of the wind, while in the lower part the water is flowing backwards. The wind set-up is dependent on wind speed, fetch and water depth. The wind set-up rises with decreasing water depth.
Figure 24 shows the wind speed distribution over the various directions at Eierlandse Gat at Eierlandse Gat.

Figure 24: wind speed distributed over the various directions at Eierlandse Gat

**Significance of the hydrodynamic loads**

The hydrodynamic loads subjected to the water body of the coastal system have been divided into tidal excitations, wave excitation and wind excitations. An analysis of [Van der Waal, 2007] identified the influence of the distinct hydrodynamic loading on the sediment transport processes of the Wadden Sea. One of his conclusions was that 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, the area of interest of this study. Therefore the waves will not be implemented in the analysis of this study. [Van der Waal (2007)] further concluded a ‘limited’ transport of sediments between the basins. According to [Van der Waal (2007)] a spatially varying water level set-up, as a result of the large-scale wind forcing, creates residual flow between the basins that is in the same order of magnitude as the tidal residual flow. In this study the main objective is the determination of the residual sediment transport of the Texel Inlet. Since the transport of sediment between the basins is limited (interpreted as not significant) the wind will not be taken into consideration as well. Therefore the analysis of this study will be focussed on the tidal excitation only. [Elias (2006)] performed extensive research about the Texel Inlet and it’s ebb tidal delta, using and well-calibrated model. The sediment transports patterns with tide only compared to the patterns with all hydrodynamic forcings were almost identical. However the magnitude of the sediment transport for his model is underestimated in the order of about 30 percent [Van der Waal (2007)].

It should be notified that the final purpose of this study is to formulate a feasibility consideration of the use of the Texel Inlet as a sediment transport belt. The resultant sediment transport patterns of the situation with a human intervention compared to the situation is of research importance. Both models have deviations in the sediment transport processes in the order of 30% at the ebb-tidal area or in between the basins of the Wadden Sea. It can be said that the resultant sediment transport processes by a human intervention is locally quite well examined by considering only a tidal forcing. It is however of major importance that results will be verified constantly with [Elias, 2006] and with observation data.
3.4 Model set-up

3.4.1 Delft3D

The morphological modelling is being performed with the software Delft3D. The program is used for the simulation of hydrodynamic and morphodynamic behaviour of coastal, river and estuarine environments.

The basic application that will be used in this Msc Thesis is the Sediment Online Module. During a computation with this module the water flow and sediment transport are calculated and the bed topography is adapted simultaneously.

The modelling in Delft3D consists of different modules, see Figure 25. The most important is the FLOW-module, which solves the unsteady shallow water equations to calculate the flow velocity and water levels as a result of tidal and meteorological excitation. The FLOW-module can be coupled with other modules to implement special excitations or observations.

![Figure 25: Delft3D Module Overview](image)

The model is driven by hydrostatic pressure gradients, but also by other forces, such as wind stresses, bottom friction, the Coriolis force (acceleration), atmospheric-pressure gradients and gradients of wave-induced radiation stresses. However in the simulation the wind and the wind waves have not been taken into account.

The water motion is well described by the shallow water equations which are a set of hyperbolic partial differential equations that describe the flow below a pressure surface in a fluid.

The equations are derived from depth-integrating the Navier-Stokes equations, in the case where the horizontal length scale is much greater than the vertical length scale, which is valid for a tidal wave in the Wadden Sea system. Under this condition, conservation of mass implies that the vertical velocity of the fluid is small. It can be shown from the momentum equation that vertical pressure gradients are nearly hydrostatic, and that horizontal pressure gradients are due to the displacement of the pressure surface, implying that the velocity field is nearly constant throughout the depth of the fluid.

Taking the vertical velocity and variations throughout the depth of the fluid to be exactly zero in the Navier-Stokes equations, the shallow water equations are derived.
Situations in fluid dynamics where the horizontal length scale is much greater than the vertical length scale are common, so the shallow water equations are applicable for the system.

### 3.4.2 Process-based simulation models of coastal systems

The mathematical modeling of the Wadden Sea system in Delft3D is based on the strategy of up-scaling [Terwindt and Battjes, 1990]. The modeling description starts from the observation that tidal inlet and tidal basin large-scale behavior, is the effect of water and sediment motion. Hence it must be possible to simulate this behavior with a model based on description of the elementary hydrodynamic and sediment transport processes. The constituting equations of such a model are derived from conservation laws for wave energy, wave number, water mass, mean flow momentum and sediment mass. This process-oriented approach is the key element in this kind of models.

The state-of-art computer capacities of computers and the development of software packages like Delft3D for the mathematical modeling of waves, currents and sediment transport make it possible to use process-based mathematical simulation models for research of coastal systems like the Wadden Sea. It has to be noted that the literature on applications to model such coastal systems is far from complete.

This can be explained by the extremely complexity of these dynamic systems with a variety of processes and mechanisms. These processes and mechanisms are insufficiently understood to be sure that the elementary physics are sufficient incorporated in the simulation model to reproduce the phenomena of interest exactly. Therefore all morphological simulation models, at each separate scale, has to imply simplifications and approximations. Therefore the long-term effects on the morphodynamic behavior can hardly be overseen. It is therefore impossible to model all processes and mechanisms involved in a coastal system and simulate the large-scale behavior.

**Morphodynamic models**

Process-based simulation models consist of a number of modules which can describe waves, current and sediment transport. Depending on whether the dynamic interaction of these processes with the bed-topography changes is taken into account, these modules are used in series or in a time-loop. Models of this type essentially work at the hydrodynamic time scale (typically one tidal period). Larger time scales are reached by continuing the computations over a longer time-span.

Models which take the interaction with the topographic changes into account are called Medium-Term Morphodynamic (MTM) models. In principle, they are able to describe the meso-scale dynamic behavior of a morphological system, such as the formation and migration of morphological features (channel shoaling or deepening, bar transformation and migrations, sandwaves, etc.).

**Specific aspects of MTM-modeling**

MTM-models of tidal systems are often used to predict the effects of accelerated mean sea level rise, enhanced subsidence due to oil and gas mining, land reclamation, sand mining, coastal nourishments, engineering structures, etc. Many of these disturbances boil down to source or sink terms in the sediment balance equation. An MTM-model is applicable for the elaboration of the objectives of this study.
3.4.3 Grid

Figure 26: Grid of the Delft3D model

Figure 26 shows the grid of the Delft3D model. The grid contains 21,000 cells. The model area is sufficiently large to avoid significant effects of the boundaries. The southern boundary is located at the breakwaters of IJmuiden and is an open boundary. The eastern boundary is located on the watershed at Schiermonnikoog and is a closed boundary, which induces boundary effects in the hydrodynamics. The sea boundary has a distance of approximately 60 km offshore.

3.4.4 Bathymetry

Every six years the National Institute for Coastal and Marine Management (RIKZ) is carrying out bed topography surveys of the Dutch Waddensea. The bathymetry implemented in the Delft3D model dates from 1998. In Figure 27 the bathymetry is shown, relative to MSL.

Figure 27: Bathymetry 1998 of the Dutch Wadden Sea
3.4.5 Initial and boundary conditions

Boundary conditions: tidal excitation
The open boundary of the model is subjected to an excitation, defined as the boundary condition of the model. The boundary conditions that can be implemented in a Delft3D model are water level boundaries, velocity boundaries or flux boundaries. Mathematically a distinction can be made between Neumann and Riemann boundaries.

Neumann boundaries involve a description of water level gradients. Neumann boundaries are generally ascribed to cross-shore boundaries in combination with a water level boundary on the alongshore boundaries.

Riemann boundaries are weakly reflective boundaries, involving both the water levels and currents description. The Riemann boundaries are to a certain level transparent to waves. 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.

For an overview of the applied tidal excitation, the reader is referred to paragraph 2.4.6.

3.5 Model validation

Model validation
A validation of the [VAN DER WAAL (2007)] model for both horizontal and vertical tide has been performed for this study. For the vertical tide observation data is available for four stations: Den Helder, Texel North Sea, Vlieland Harbour and Harlingen.

Vertical Tide
The comparison of the vertical tide of the numerical Delft3D model and the observed data of www.waterbase.nl, see Figure 28 and Figure 29, is quite good. The asymmetry of the tide is substantially visible in the model results. The results of the comparison of the four station have been summarized in Table 3. It can be concluded that the deviations between the observed and modelled vertical tide are within acceptable limits of a few centimetres.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean deviation [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Den Helder</td>
<td>-0.0235</td>
</tr>
<tr>
<td>Texel North Sea</td>
<td>0.0015</td>
</tr>
<tr>
<td>Vlieland Harbour</td>
<td>-0.0114</td>
</tr>
<tr>
<td>Harlingen</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

Table 3: Mean deviation of the vertical tide between observation and model at four observation stations
Figure 28: Harlingen Station, comparison of the model results with the waterbase data of 1998 for 10 days.

Figure 29: Harlingen Station, comparison of the model results with the waterbase data of 1998 for 1 day.
Horizontal tide
For the horizontal tide measurements have been carried out for the Texel Inlet by both NIOZ and Rijkswaterstaat. The NIOZ measurements have been conducted by attaching an Acoustic Doppler Current Profiler (ADCP) to the TESO ferry, sailing between Den Helder and Texel. The model discharge results of the Marsdiep are of the same order as the Rijkswaterstaat measurement, see Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Residual Ebb-Tidal Discharge [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIOZ ferry measurements</td>
<td>2570</td>
</tr>
<tr>
<td>Rijkswaterstaat</td>
<td>2230</td>
</tr>
<tr>
<td>Delft3D Model</td>
<td>2170</td>
</tr>
</tbody>
</table>

Table 4: Residual Ebb-Tidal Discharges

3.6 Model limitations
In engineering practice a model is a representation of the real world. The Delft3D model is representing the Wadden Sea in a way that numerical calculations of hydrodynamics and morphodynamics can be executed. However, only a limited number of physical processes are taken into account in these calculations. Moreover the schematization of grid is rather rough and physical units are subjected to uncertainty errors.

The most obvious limitations 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
  The density gradients have not been taken into account. In reality the density gradient due to the fresh water discharges (from the sluices at Den Oever and Kornwerderzand) has a considerable effect on the sediment transports [ELIAS, 2006].
- Fresh water discharges through the Afsluitdijk
  At two locations in the Afsluitdijk (at Den Oever and Kornwerderzand) fresh water from IJsselmeer flows into the Wadden Sea. On average this fresh water flow has a magnitude of 550 m$^3$/s. [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 in the water column. The discharges are not taken into account.
- 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. The errors near the boundaries have an insignificant role near the area of interest.
4 HYDRODYNAMIC ANALYSIS OF THE TEXEL INLET

4.1 Introduction

This report deals with the technical feasibility of using tidal currents in the Texel Inlet of the Wadden Sea to transport sediments towards the Afsluitdijk. A volume of water will flow into the tidal basin during flood and out of the basin during ebb. This volume of water is referred to as the tidal prism. The tidal flow through the Texel Inlet will expose shear stress on the bed of the tidal trench and the banks of the surrounding shoals. Above a certain threshold value the shear stress will dislodge sediment grains from the bed matrix. A distinction is made between bed load and suspended load. Bed load refers to the particles that are transported along the bed by rolling, sliding or traction. Suspended load refers to the more fine particles that are light enough to be carried in the stream without touching the bed. The size and weight of the particles in the suspended load is directly related to the discharge (velocity) of the stream. To understand and predict the sediment transport processes it is necessary to have a full image of the hydrodynamics. Moreover a consideration of the hydrodynamics enables the draw of a first image of the morphodynamics.

Hydrodynamics of the Texel Inlet

The first part of this chapter deals with the evaluation of the hydrodynamic characteristics of the Wadden Sea system. The hypothesis of the characteristics of the flow field of the Texel Inlet is based on drafts by hand of a highly schematized geometry of the system, supplemented and validated by observations and scientific publications. Subsequently the hypothesis is to be tested by the results of a numerical simulation with a process-based model (model B).

Direction of the residual sediment transport

The second part of this chapter deals with the evaluation of the direction of the residual sediment transport along the Texel Inlet based on the hydrodynamic characteristics. The hypothesis of the direction of the residual sediment transport is based on scientific publications. This model of obtaining information of the sediment transport of the Texel Inlet is assigned as model A:

Model A: Engelund and Hansen – instantaneous transport model

Chapter 5 deals with an evaluation of the sediment transport modes, with according models. The results of the simplified hydrodynamic-based model of this chapter is to be compared with the results of the models defined in chapter 5.

The set-up of this chapter is:

4.2 Explanation of the research objective and the basic assumptions of the hydrodynamic analysis
4.3 Formulation of the hypothesis of the hydrodynamics of the Texel Inlet, based on drafts by hand
4.4 Explanation of the application of the numerical model
4.5 Numerical results of the hydrodynamic simulation, including physical understanding, feedback to the hypothesis and conclusions
4.6 Formulation of the hypothesis of the residual sediment transport along the Texel Inlet
4.7 Numerical results of the residual sediment transport based on the hydrodynamics, including physical understanding, feedback to the hypothesis and conclusions
4.2 Research objective and basic assumptions

The research objectives and the basic assumptions for the hydrodynamic analysis will be explained in this paragraph.

The Wadden Sea is a tidal lagoon system, characterised by a highly non-uniform bathymetry. The system consists of tidal trenches and shoals. Each tidal cycle the tidal prism is flowing into the tidal lagoon through the tidal trenches during flood. The water level increases, storing a significant part of the tidal prism at the tidal shoals. The tidal prism is flowing back to the North Sea during ebb, reducing the water depth in the Wadden Sea again. During low water of the tidal cycle significant parts of the tidal shoals rise above the water level and become visible, see Figure 30.

The Texel Inlet is the largest tidal trench in the system of the Western Wadden Sea. A hydrodynamic analysis of the tidal trench is the starting point of a morphodynamic analysis. Moreover without studying the hydrodynamics of the Texel Inlet it is impossible to understand and interpret the physical processes related to sediment transport.

Hydrodynamic analysis of the Texel Inlet

The main tidal flow constituent is the semi-diurnal tide ($M_2$) with a period of 12 h 25 m. Drafts by hand of a highly schematized geometry of the inlet system are used to sketch up a picture of the hydrodynamic characteristics. This first indication of the tidal flow field is corrected and supplemented with observations and scientific publications. The amount of data and previous scientific interest for a tidal lagoon is unique in the world. A full image of the tidal flow field is obtained by a numerical simulation of the hydrodynamics. The determination of the significant tidal constituents in the tidal trench has been executed by [Van der Waal, 2007]. Moreover the actual bathymetry and phenomena as tidal asymmetry, non-uniformity of the tidal flow,
secondary flow and Coriolis effect are taken into account in such a numerical simulation. The evaluation of the numerical results is focused around 7 cross-sections along the Texel Inlet.

**Morphodynamic characteristics**

The application of the theory of Engelund and Hansen (1967) offers the possibility to identify some characteristics of the morphodynamics of the Texel Inlet. This theory is based on a power proportionality between the depth-averaged horizontal flow velocity and the sediment transport. The application of this theory offers a preliminary insight in the morphodynamics. The preliminary morphodynamic model is in this study referred to as model A:

**Model A:** *Simplified hydrodynamic-based model*

The assumptions and limitations of this theory will be further elaborated in paragraph 4.6.

**Research question 1: Morphological character of the Texel Inlet**

The tidal trench Texel Inlet of the Wadden Sea can only be used as a sediment transport belt if the residual sediment transport is directed towards the Afsluitdijk. The instantaneous direction of sediment transport is directly related to the instantaneous direction of the tidal flow. Phenomena as tidal asymmetry, non-uniformity of the tidal flow and the Coriolis effect induce residual sediment transports. Analysis of the tidal flow in the Wadden Sea can to some extent indicate the direction of the residual sediment transport. Based on this analysis an expectation can be drawn up about the direction of the residual sediment transport for the cross-sections along the Texel Inlet. The relative magnitude of the residual sediment transport can be observed by comparison between the cross-sections. Finally the direction of the residual sediment transports points out the morphological character of the Texel Inlet, being morphologically importing or morphologically exporting.

### 4.3 Hypothesis of the hydrodynamics of the Texel Inlet

The formulation of the hypothesis of the hydrodynamics of the Texel Inlet, based on drafts by hand will be explained in this paragraph.

**Summary of observations, [Elias, 2006] and Ridderinkhof [2004]**

The tide in the Texel Inlet is to a large extend determined by the interaction of the alongshore propagating open-sea tide and the cross-shore inflow and outflow of water of the Wadden Sea. The open-sea tide is generated by a tidal wave flowing into the North Sea from the Atlantic Ocean between Scotland and Norway, and the tidal wave from the south, propagating through the Strait of Dover. The interaction of these two tidal waves, disruption by Coriolis and the bottom friction of the shallow North Sea cause the characteristic tidal pattern in the Southern North Sea. A counter clockwise flow around two amphidromic points. Along the Dutch coast this results in a propagating wave from south to north, while along the Wadden coast a second tidal wave from west to east propagates.

The semidiurnal tide is the major forcing of the water flow through the Texel Inlet, with maximum ebb and flood flow velocities vary between 1 and 2 m/s (dependent of the phase in spring-neap tide cyclus). The tide is asymmetric due to disruption of the $M_2$ component by the $M_4$ component. The vertical tide varies between 1.0 and 2.0 meter, with an average tidal elevation of 1.38 m. In the basin thetidal propagation is further disrupted by bottom friction and reflection against the Afsluitdijk.

Besides the astronomical tide also meteorological affects (like air pressure and set-up) play a significant role in the vertical tide. Especially the wind-induced set-up can cause drastically disrupt the tidal flow, caused by the funnel-shaped geometrie of the North Sea. During storm surges a vertical tide of 2 m is no exception. The elevation of the water level generates complex patterns and flows, caused by the variable bathymetry, can generate circulation between the distinct basins and enhances the inflow and outflow through the inlets.
Harmonic analysis
The hydrodynamic behaviour can be roughly imaged by considering the major tidal component, the $M_2$-tide, and a highly schematized Texel Inlet, see Figure 31. The Texel Inlet has been schematized as a prismatic channel with a storage width.

![Figure 31: Sketch of the highly schematized Texel Inlet](image)

A harmonic analysis is executed to develop insight in the hydrodynamics and the characteristics of the propagation of the tidal wave. The harmonic analysis is based on low, periodic and long waves like the tide. The physical properties of storage, inertia and resistance are implemented in a harmonic analysis. All periodic oscillations are considered to be sinusoidal.

The analysis show that the amplitude of the reflected wave in the mouth is significantly smaller than the amplitude of the incoming wave. However, the incoming wave does not fully dominate the reflected wave. Therefore the tidal wave pattern has a mixed character (propagating nor reflecting).

4.4 Application of the model
The explanation of the application of the process-based model will be explained in this paragraph.

4.4.1 Definition of cross-sections
Seven cross-sections of the Texel Inlet have been defined. Analysis of the hydrodynamics of these sections provides more insight into the local suitability as a dump place for sediments. By the definition of observation point at the various sections the hydrodynamic data is stored during a simulation with Delft3D.

The various cross-sections plotted in an aerial picture of Google Earth can be found is Figure 32. The cross-sections are indicated by the first and the last observation point.
Figure 32: Aerial picture of the location of the various cross-sections, indicated by the first and last observation point of each section

In Figure 33 the observation points in Delft3D are presented.

Figure 33: Delft3D model. Top view of the Texel Inlet. The crosses in the model indicate the observation points. A ray of observation point is defined as a cross-section

The reader is referred to APPENDIX A for the depth profiles of the various cross-sections.
Simulation
The simulation time equals 1 month, in which the calculation interval measures 2 minutes. Each 10 minutes the current magnitude and the current direction are registered for all observation points. The data is exported using the GPP-function of Delft3D and is subsequently transformed into Matlab vectors of the individual observation points.

The transformation of the output of Delft3D into relevant parameters for the purpose of the hydrodynamic analysis has been summarized in APPENDIX B.

4.5 Hydrodynamics of the Texel Inlet

The process-based model results of the hydrodynamic simulation will be explained in this paragraph.

Phase lag
The tidal wave in the Wadden Sea system does not behave as a propagating wave nor as a standing wave. In Figure 34 both the horizontal and vertical tide are plotted for the interval of 1000 time-points, which equals $\Delta t = 1000 * 10 \times \frac{1}{60 \times 24} = 6.94$ days (1 time-point equals 10 minutes).

![Figure 34: Wave data of the Wadden Sea Basin, plot of the vertical tide and the horizontal tide for observation point 8 of cross-section 0.](image)

The vertical tide has a phase lag relative to the horizontal tide of slightly more than a quarter of an oscillating $M_2$ period. For each cross-section the phase lag ($\Delta \vartheta$) is calculated by multiplying the ratio of the time lag of the vertical tide relative to the horizontal tide and the tidal period with a full period:
\[ \Delta \vartheta = \frac{\text{time lag}}{\text{tidal period}} \times 360^\circ \]

The time lag is calculated by subtracting the time-point of high water (horizontal tide) from the time-point of maximum velocity (vertical tide):

\[ \text{time lag} = t\left(\frac{U}{U_{\text{max}}}\right) - t\left(\eta_{\text{max}}\right) \]

Note that the unit of the time-point is 10 minutes. The phase lag of the vertical tide relative to the horizontal tide for the various cross-sections is given in Table 5. The observation points considered for the various cross-section are the closest to the channel axis. The average phase lag equals slightly more than a quarter of a period.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Observation Point</th>
<th>Relative phase lag of vertical tide relative to horizontal tide</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>[ \Delta \vartheta = \frac{18}{77} \times 360^\circ = 84^\circ ]</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>[ \Delta \vartheta = \frac{22}{77} \times 360^\circ = 103^\circ ]</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>[ \Delta \vartheta = \frac{18}{77} \times 360^\circ = 84^\circ ]</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>[ \Delta \vartheta = \frac{21}{77} \times 360^\circ = 98^\circ ]</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>[ \Delta \vartheta = \frac{22}{77} \times 360^\circ = 103^\circ ]</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>[ \Delta \vartheta = \frac{24}{77} \times 360^\circ = 112^\circ ]</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>[ \Delta \vartheta = \frac{23}{77} \times 360^\circ = 108^\circ ]</td>
</tr>
<tr>
<td>Average phase lag</td>
<td></td>
<td>[ \overline{\Delta \vartheta} = \frac{84^\circ + 103^\circ + 84^\circ + 98^\circ + 103^\circ + 112^\circ + 108^\circ}{7} = 99^\circ ]</td>
</tr>
</tbody>
</table>

Table 5: Phase lag of the vertical tide relative to the horizontal tide for the various cross-sections.

Flow velocities at the cross-sections
During the numerical simulation with Delft3D the velocity of the flow is recorded. For every cross-section the flow velocity at ebb peak and flood peak is obtained. By averaging over a tidal cycle the residual flow velocity is determined.

For cross-section 3 the graphs of the ebb flow velocity, the flood flow velocity and the residual flow velocity have been indicated in Figure 35. For the other cross-sections the reader is referred to Appendix C.
From Figure 35 it can be concluded that the maximum ebb flow velocity is approximately 1.20 m/s and the maximum flood flow velocity approximately 1.17 m/s. The graph of the residual flow indicates a net export of water during a full tidal cycle. This means that the volume of water flowing into the basin during flood is smaller than the volume of water flowing out of the basin during ebb.

For a more accurate indication of the residual flow it is of major interest to investigate the discharges. The specific discharge is a quantity defined as the discharge per unit width. Moreover the specific discharge is calculated by multiplying the flow velocity with the channel depth (see Appendix A). For cross-section 3 the graphs of the ebb specific discharge, the flood specific discharge and the residual specific discharge have been indicated in Figure 36. For the other cross-section the reader is referred to Appendix C.
From Figure 36 it can be concluded that the maximum ebb specific discharge is approximately 30 m$^3$/s and the maximum flood specific discharge is approximately 27 m$^3$/s. The graph of the residual specific discharge indicates also a net export of water during a full tidal cycle. The total discharge over cross-section 3 can be calculated by integrating over the cross-section length. The results for all cross-sections have been summarized in Table 6.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Length</th>
<th>$Q_{ebb}$ [m$^3$/s]</th>
<th>$Q_{flood}$ [m$^3$/s]</th>
<th>$Q_{residual}$ [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5467</td>
<td>-1493</td>
<td>1889</td>
<td>-54,7</td>
</tr>
<tr>
<td>2</td>
<td>2773</td>
<td>-2627</td>
<td>2918</td>
<td>-61,6</td>
</tr>
<tr>
<td>3</td>
<td>3502</td>
<td>-2953</td>
<td>3182</td>
<td>-141,5</td>
</tr>
<tr>
<td>4</td>
<td>5315</td>
<td>-3322</td>
<td>3770</td>
<td>-71,8</td>
</tr>
<tr>
<td>5</td>
<td>3912</td>
<td>-1583</td>
<td>1807</td>
<td>-29,3</td>
</tr>
<tr>
<td>6</td>
<td>6937</td>
<td>-2338</td>
<td>2099</td>
<td>-31,9</td>
</tr>
</tbody>
</table>

Table 6: Discharges of the cross-sections

Note that the flood discharge and ebb discharge refer to the peak value. The residual discharge is therefore not a simple summation of the ebb peak discharge and the flood peak discharge, but is averaged over the full tidal period.

**Explanation residual outwards discharge**
The discharge at the flood peak is larger than the discharge of the ebb peak. Therefore on first sight it is expected that the residual flow velocity has a direction inwards the basin. Nevertheless the residual velocity is directed outwards the basin. This is caused by an asymmetric duration and shape of the horizontal tide. An unequal ebb and flood duration is implemented in the tide-averaged flow velocity, resulting in a correction of the direction out of the basin.

### 4.6 Hypothesis of the residual sediment transport of the Texel Inlet

The formulation of the hypothesis of the residual sediment transport along the Texel Inlet will be explained in this paragraph.

**Transport mechanism**
A tidal flow above a loose granular bed induces forces on the grains. The grains will start moving, in case the forces on the grain exert a certain threshold value. With increasing flow velocity more grains start to move, defined as sediment transport.

The sediment transport can be quantified by using sediment transport formulae. All sediment transport formulae state that the sediment transport is a function of the gravity field ($g$), fluid characteristics ($\rho$, $\nu$), sediment characteristics ($\rho_s$, $D$) and one or more parameters for the influence of the flow ($\tau_b$):

$$s = f \left( g, \rho, \nu, \rho_s, D, \tau_b \right)$$

Where:
- $g$ : gravitational acceleration [m/s$^2$]
- $\rho$ : density of the water [kg/m$^3$]
- $\nu$ : kinematic viscosity [m$^2$/s]
- $\rho_s$ : specific sediment density [kg/m$^3$]
- $D$ : diameter of the grain [m]
- $\tau_b$ : bed shear stress [N/m$^2$]
Using a dimension analysis these parameters can be combined into dimensionless variables. In most of the existing only the following dimensionless variables are present:

- **Transport parameter:** \[ \Phi = \frac{s}{\sqrt{g \Delta D^3}} \]
- **Flow parameter:** \[ \Psi = \frac{\mu \tau_b}{\rho g \Delta D} \]

Where:
- \( \mu \): ripple height factor for implementing the bed shape \([\text{m}]\)

**The formula of Engelund and Hansen**

The formula of Engelund and Hansen (1967) is a total transport formula. The calculated transport contains both bed load transport and suspended load transport.

An important restriction of the Engelund and Hansen theory is the ignorance of advection\(^{10} \) and diffusion of sediment. Advecive transport is sediment transport carried by the fluid. This implies a translation of sediment by the fluid flow. The magnitude of the translation of sediment depends on the sediment concentration. Diffusive transport is sediment transport initiated by a gradient in sediment concentrations. This implies a translation of sediment from locations with high a concentration to locations with a low concentration. The Engelund and Hansen sediment transport formula calculates the instantaneous local sediment transport and does not take relaxation effects into account.

The formula can be described as:
\[ \Phi = 0.05 \Psi^{5/2} \text{ with } \mu = \left( \frac{C^2}{g} \right)^{2/5} \]

Where:
- \( C \): Chézy friction coefficient \([\text{m}^{1.2}/\text{s}]\)

The formula can also be described as:
\[ \frac{s}{\sqrt{g \Delta D^3}} = 0.05 \left( \frac{u_*}{\sqrt{g \Delta D}} \right)^3 \left( \frac{u}{\sqrt{g \Delta D}} \right)^2 \]

Originally the formula is derived for bed load transport, but proved to be well applicable to total load transport for relatively fine material, with the major contribution of suspended load transport:
\[ \frac{w}{u_*} < 1 \]

Where:
- \( w \): fall velocity of the particle \([\text{m/s}]\)
- \( u_* \): shear stress velocity \( u_* = \frac{u \sqrt{g}}{C} \) \([\text{m/s}]\)

\(^{10}\) Occasionally, the term *advection* is used as synonymous with *convection*. However, many engineers prefer to use the term convection to describe transport by combined molecular and eddy diffusion, and reserve the usage of the term advection to describe transport with a general (net) flow of the fluid.
For natural sediment the fall velocity be approximated by (Van Rijn, 1993):

\[ w_* = \frac{10v}{D} \left( \sqrt{1 + \frac{0.01 \Delta g D^3}{v^2}} - 1 \right) \text{ for } 100 < D_{50} \leq 1000 \mu m \]

By assuming the following values for the parameters:

\[ \begin{align*}
  v &= 10^{-6} \text{ [m}^2/\text{s]} \\
  D_{50} &= 200 \times 10^{-6} \text{ [m]} \\
  \Delta &= 1.65 \text{ [-]} \\
  g &= 9.81 \text{ [m/s}^2] \\
  C &= 60 \text{ [m}^{1/2}/\text{s]} \\
\end{align*} \]

The fall velocity and the shear stress velocity becomes:

\[ w_* = \frac{10 \times 10^{-6}}{200 \times 10^{-6}} \left( \sqrt{1 + \frac{0.01 \times 1.65 \times 9.81 \times (200 \times 10^{-6})^3}{(10^{-6})^2}} - 1 \right) = 0.0262 \]

\[ u_* = \frac{1 \times 9.81}{60} = 0.0527 \]

\[ \frac{w_*}{u_*} = \frac{0.0262}{0.0527} = 0.497 < 1 \]

**Residual sediment transport**

So far the hydrodynamic analysis indicated a residual export of water over a tidal cycle. The export of water is caused by a tidal asymmetry and an according unequal ebb and flood duration. The residual sediment transport is caused by the hydrodynamic forcing of the tide.

In preliminary morphological analysis often use is made of simplified formulae to gain a quick insight in the morphological behaviour. The sediment transport is assumed to be proportional to a power of the flow velocity. This can be explained by the formula often used in river engineering:

\[ s = mu^n = m \left( \frac{q}{h} \right)^n \]

Where:

- \( s \) : sediment transport [kg/s]
- \( m \) : multiplication coefficient \([s^{n-1} \cdot \text{kg/m}^n]\)
- \( u \) : flow velocity [m/s]
- \( n \) : power coefficient [-]
- \( q \) : specific discharge \([\text{m}^2/\text{s}]\)
- \( h \) : water depth [m]

For the specific discharge \( q \) applies:

\[ q = Ch^{3/2} i^{1/2} \]

Where:

- \( C \) : Chézy friction coefficient \([m^{1/2}/\text{s}]\)
- \( i \) : bottom slope [-]
The combination of the equation for $s$ and $q$ can (assuming $C$ and $m$ to be constant) be transformed to:

$$s \sim q^{n/3} h^{n/3} \text{ and } s \sim q^n h^{-n}$$

For the formula of Engelund and Hansen applies $n = 5$ and for the Meyer-Peter-Muller formula applies:

$$n = \frac{3}{1 - \frac{0.047}{\Psi}}$$

Where:

$$\Psi : \text{ flow parameter } \Psi = \frac{\mu hi}{\Delta D}$$

For applications of non-stationarity flow it is recommended to drop the inclination $i$. Therefore for Meyer-Peter-Muller formula applies $n = 3$.

The $m$ value of Engelund and Hansen can be derived from the general formula:

$$m = \frac{0.05}{\sqrt{g C^3 \Delta^2 D_{so}}} = \frac{0.05}{\sqrt{9.81 * 60^3 * 1.65^2 * 200 * 10^{-6}}} = 1.675 * 10^{-4}$$

In this chapter the residual sediment transport is approximated by this simple power law. To gain an insight in the direction and the relative magnitude of the sediment transport. By averaging over an equal number of full tidal period the accordant residual sediment transport can be obtained.

**Hypothesis of the residual sediment transport**

For the hypothesis of the residual sediment transport of the Texel Inlet reference is made to paragraph 2.4.6 of the analysis of Bonekamp.

The residual water flow was exporting, while the flood peak discharge was higher than the ebb peak discharge. Considering the interaction of the $M_2$ and $M_4$ component. The higher flood flow velocities and the shorter flood duration will result in a higher peak for the sediment transport, see Figure 37, with the interaction of the $M_2$ and $M_4$ component and the corresponding value $u^3$.

Moreover [Elias, 2006] and [Van der Waal, 2007] indicated that the $M_2$ and $M_4$ interaction of the tide is the main driving force of the residual sediment transport.
The hypothesis of the analysis of the residual sediment transport based on the simple power law is that the residual sediment transport is directed inwards the tidal basin. Based on the tidal asymmetry induced by the interaction of the $M_2$ and $M_4$ component, which can be identified as a major driving force of the residual sediment transport [Van der Waal, 2007], the shorter flood duration and according higher flood velocities are expected to result in a higher import of sediment during flood than the export of sediment during ebb.

4.7 Residual sediment transport of the Texel Inlet

The numerical results of the residual sediment transport based on the hydrodynamics, including physical understanding, feedback to the hypothesis and conclusions will be explained in this paragraph.

Results sediment transport processes

The mathematical procedure of computing the residual sediment transport using the simple power law of the flow velocity has been summarized in APPENDIX B.

The resultant parameters of the analysis are the flow velocity $u$, the power of the flow velocity according to Meyer-Peter-Muller $u^3$, and the power of the flow velocity according to Engelund and Hansen $u^5$. The results for the seven cross-section have been summarized in Figure 38.

![Figure 38: Net import/export of the various cross-section. Positive values indicate a net import into the tidal basin, whereas negative values indicate a net export out of the tidal basin.](image)

From Figure 38 it can be concluded that the residual sediment transport has an importing direction. This morphological importing character is at this stage only verified for the highly simplified analysis of a simple power relation between sediment transport and flow velocity.
The precise values of the integrals of the velocities and the powered over the cross-section is not a highly-informative number. However the sign of the integrals of the velocity indicate the direction of the water motion and the sign of the integrals of the powered velocities indicate the direction of the sediment transport.

**Relativity of the residual sediment transport**

Knowing the residual velocities and residual powered velocities it is of major importance to relate these values to the maximum and minimum value during a tidal period. In Table 7 the integrals for the various cross-section are given for:

1. Cross-sectional integral of the flow velocity parallel to the channel axis for maximum **outward** flow of the basin: \[ \pm \int_{L_{\text{section}}} U_{\parallel \text{max,outwards}}(l) \, dl \]
2. Cross-sectional integral of the flow velocity parallel to the channel axis for maximum **inward** flow of the basin: \[ \pm \int_{L_{\text{section}}} U_{\parallel \text{max,inwards}}(l) \, dl \]
3. Cross-sectional integral of the flow velocity parallel to the channel axis **residual** flow of the basin: \[ \int_{L_{\text{section}}} U_{\parallel}(l) \, dl \]

Where:

- \( U_{\parallel \text{max,outwards}}(l) \): the maximum depth-averaged flow velocity during the ebb peak [m/s]
- \( U_{\parallel \text{max,inwards}}(l) \): the maximum depth-averaged flow velocity during the flood peak [m/s]
- \( U_{\parallel}(l) \): the residual depth-averaged flow velocity over one month [m/s]
- \( L_{\text{section}} \): the length of the cross-section [m]

Subsequently the ratio of the integral of the residual flow and the integral of the maximum outwards velocity and the ratio of the integral of the residual flow and the integral of the maximum inwards velocity have been calculated, see Table 7. The average ratio is in the order of 3 percent.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>(1) Integral Maximum Velocity Outwards [m²/s]</th>
<th>(2) Integral Maximum Velocity Inwards [m²/s]</th>
<th>(3) Integral Residual Velocity [m²/s]</th>
<th>(4) Ratio ( \frac{\text{column (1)}}{\text{column (3)}} )</th>
<th>(5) Ratio ( \frac{\text{column (2)}}{\text{column (3)}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1404,3</td>
<td>1554,3</td>
<td>-63,5</td>
<td>0.045</td>
<td>0.041</td>
</tr>
<tr>
<td>1</td>
<td>-1463,5</td>
<td>1735,4</td>
<td>-89,5</td>
<td>0.061</td>
<td>0.055</td>
</tr>
<tr>
<td>2</td>
<td>-2677,4</td>
<td>2970,3</td>
<td>-58,6</td>
<td>0.022</td>
<td>0.020</td>
</tr>
<tr>
<td>3</td>
<td>-3105,5</td>
<td>3303,7</td>
<td>-145,2</td>
<td>0.047</td>
<td>0.044</td>
</tr>
<tr>
<td>4</td>
<td>-3373,7</td>
<td>3775,2</td>
<td>-81,7</td>
<td>0.024</td>
<td>0.022</td>
</tr>
<tr>
<td>5</td>
<td>-1726,4</td>
<td>2022,5</td>
<td>-40,8</td>
<td>0.024</td>
<td>0.020</td>
</tr>
<tr>
<td>6</td>
<td>-2413,5</td>
<td>2961,1</td>
<td>-3,9</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.032</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table 7: Values of cross-sectional integral of the flow velocities parallel to the channel axis for maximum outward flow of the basin (1), maximum inward flow towards to basin (2) and residual flow (3) and ratios of absolute value of the integrals (4) and (5)
The relatively analysis of the residual velocities is also executed for the powered velocities, see Table 8 and Table 9.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>(1) Integral Maximum Velocity(^3) Outwards ([\text{m}^3/\text{s}^3])</th>
<th>(2) Integral Maximum Velocity(^3) Inwards ([\text{m}^3/\text{s}^3])</th>
<th>(3) Integral Residual Velocity ([\text{m}^3/\text{s}^3])</th>
<th>(4) Ratio column (1) column (3)</th>
<th>(5) Ratio column (2) column (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2112.7</td>
<td>2967.4</td>
<td>150.14</td>
<td>0.071</td>
<td>0.051</td>
</tr>
<tr>
<td>1</td>
<td>-1763.5</td>
<td>2170.2</td>
<td>9.75</td>
<td>0.006</td>
<td>0.005</td>
</tr>
<tr>
<td>2</td>
<td>-3412.4</td>
<td>3840.7</td>
<td>59.31</td>
<td>0.017</td>
<td>0.015</td>
</tr>
<tr>
<td>3</td>
<td>-3304.5</td>
<td>3682.6</td>
<td>45.06</td>
<td>0.014</td>
<td>0.012</td>
</tr>
<tr>
<td>4</td>
<td>3140.3</td>
<td>3852.0</td>
<td>128.98</td>
<td>0.041</td>
<td>0.034</td>
</tr>
<tr>
<td>5</td>
<td>1417.1</td>
<td>2061.8</td>
<td>48.95</td>
<td>0.035</td>
<td>0.024</td>
</tr>
<tr>
<td>6</td>
<td>688.0</td>
<td>1477.6</td>
<td>100.34</td>
<td>0.146</td>
<td>0.068</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.047</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Table 8: Values of cross-sectional integral of the flow velocities\(^3\) parallel to the channel axis for maximum outward flow of the basin (1), maximum inward flow towards to basin (2) and residual (3) and ratios of absolute value of the integrals (4) and (5).

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>(1) Integral Maximum Velocity(^5) Outwards ([\text{m}^5/\text{s}^5])</th>
<th>(2) Integral Maximum Velocity(^5) Inwards ([\text{m}^5/\text{s}^5])</th>
<th>(3) Integral Residual Velocity ([\text{m}^5/\text{s}^5])</th>
<th>(4) Ratio column (1) column (3)</th>
<th>(5) Ratio column (2) column (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-3582.7</td>
<td>5995.5</td>
<td>552.97</td>
<td>0.154</td>
<td>0.092</td>
</tr>
<tr>
<td>1</td>
<td>-2579.0</td>
<td>3063.9</td>
<td>100.92</td>
<td>0.039</td>
<td>0.033</td>
</tr>
<tr>
<td>2</td>
<td>-4698.5</td>
<td>5099.7</td>
<td>190.39</td>
<td>0.041</td>
<td>0.037</td>
</tr>
<tr>
<td>3</td>
<td>-3947.5</td>
<td>4376.8</td>
<td>189.80</td>
<td>0.048</td>
<td>0.043</td>
</tr>
<tr>
<td>4</td>
<td>-3329.3</td>
<td>4096.8</td>
<td>242.84</td>
<td>0.073</td>
<td>0.059</td>
</tr>
<tr>
<td>5</td>
<td>-1223.9</td>
<td>2142.7</td>
<td>106.59</td>
<td>0.087</td>
<td>0.050</td>
</tr>
<tr>
<td>6</td>
<td>-233.3</td>
<td>875.7</td>
<td>83.01</td>
<td>0.356</td>
<td>0.095</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.114</td>
<td>0.059</td>
</tr>
</tbody>
</table>

Table 9: Values of cross-sectional integral of the flow velocities\(^5\) parallel to the channel axis for maximum outward flow of the basin (1), maximum inward flow towards to basin (2) and residual (3) and ratios of absolute value of the integrals (4) and (5).

The comparison of the values of the integrals of the velocities and the powered velocities of the residual flow with the same integrals of maximum flow both in positive and negative channel direction indicate ratios in the order of 5 percent.

**Feedback to the hypothesis**

The hypothesis of the analysis of the residual sediment transport based on the simple power law was that the residual sediment transport is directed inwards the tidal basin. From the direction of the computed residual sediment transport it can be concluded that the hypothesis has been proofed. The contrary direction of the residual water volume flow and the residual sediment transport is explained by the tidal asymmetry, identified for the Texel Inlet by Bonekamp [2204]. The latter statement however is at this stage not fully verified, since effects of advection and diffusion have not been taken into account. The sediment transport processes will be further elaborated in chapter 5.
Feedback to the research objective 1
The morphological consequences of the human intervention of dumping a significant amount of sediment at the Texel Inlet can further be elaborated. Model A (simplified hydrodynamic-based model) indicates that the Texel Inlet is morphologically importing. This first condition for using the Texel Inlet as a sediment transport belt towards the Afsluitdijk has been satisfied.

Hypothesis morphological forecast
The magnitude of both the residual and the instantaneous sediment transport have been determined. The magnitude of the residual sediment transport of the Texel Inlet turns out to be in the order of 5 percent of the maximum instantaneous sediment transport. Therefore the following hypotheses for the morphological forecast can be formulated:

*Although the residual sediment transport has a positive direction, initially the dumped sediment will diffuse in both positive and negative direction when dumped at the Texel Inlet. On the long term it is expected that the sediment migrates in positive direction.*

The diffusion of sediment in both directions on the short term is caused by the relative strength of the instantaneous ebb and flood sediment transports compared to residual sediment transport. The positive migration of sediment on the long term is caused by the positive direction of the residual sediment transport.

This hypothesis is elaborated in chapter 5, considering the sediment transport processes in a more detailed manner.
5 SEDIMENT TRANSPORT PROCESSES OF THE TEXEL INLET

5.1 Introduction

Bed load and suspended load transport
Tidal currents induce bed shear stress at the lagoon bottom. For a fluid to begin transporting sediment that is at rest on the bed, the boundary (or bed) shear stress exerted by the fluid must exceed the critical shear stress for the initiation of motion of grains at the bed. Sediment transport takes place both at the bed and in the water column. Not only tidal currents, but also waves, exert shear stress on the bed. According to [Van der waal, 2007] waves have little influence on the sediment transport inside the basin, the area of interest of this study. Therefore the waves will not be implemented in the analysis of this study (see chapter 3.3).

The term bed load describes particles in a flowing fluid that are transported along the bed. Bed load moves by a variety of methods, including rolling, sliding, traction, and saltation. Suspended load is the term for the fine particles that are light enough to be carried in a stream without touching the stream bed. These particles are generally of the fine sand, silt and clay size, although they can be larger, especially in cases of high discharge, such as during floods. This is in contrast to bed load which is carried along the bottom of the stream. The size and weight of the particles in the suspended load is directly related to the discharge of the stream. In case of a higher discharge, the particles transported are larger and heavier.

In this chapter the sediment transport is further elaborated, considering the distinct bed load transport and suspended load transport.

A full image of the sediment transport processes is obtained by a numerical simulation of the Wadden Sea. The results of the process-based model of Delft3D of the Texel Inlet are assigned to as model B:

Model B: Delft3D – process-based model

The results of the process-based model are verified with a schematized transport model. The schematized transport model is based on the Bijkers formulation for bed load and suspended load transport. A notion of the sensitivity of relevant parameters can be obtained. The results of the schematized transport model of Bijkers of the Texel Inlet are assigned to as model C:

Model C: Bijkers – schematized transport model

This chapter deals with the evaluation of sediment transport processes of the Texel Inlet in the Wadden Sea system. The results of a process-based model (Model B) will be compared with the results of an instantaneous transport model (Model A) and a schematized transport model (Model C). Furthermore the sensitivity of the process-based model (Model B) is elaborated by using a schematized model (Model C)

The set-up of this chapter is:
5.2 Explanation of the research objective and the basic assumptions of the sediment transport processes
5.3 Explanation of the sediment transport modes
5.4 Process-based model results of sediment transport processes
5.5 Sensitivity verification of relevant parameters
5.6 Comparison of the model results
5.7 Summary and conclusions
5.2 Research objective and the basic assumptions

The research objectives and the basic assumptions for the sediment transport analysis will be explained in this paragraph.

One of the conclusions of the hydrodynamic analysis (Model A) is that residual flow in the Texel Inlet is directed outwards of the tidal system. Based on the proportionality between sediment transport and the flow velocity to a power 3 or 5, the analysis indicated a residual sediment transport that is directed inwards the tidal lagoon. This type of analysis, however, only indicates the sediment transport based on the flow velocity. Sediment transport processes are in reality far more complicated. The physical processes involved can be summarised as:

- Tidal asymmetry
- Tidal dispersion
- Estuarine circulation
- Secondary flow
- Suspension and erosion time lags
- Flood and ebb dominated channels
- Non-uniform tidal flow

These concept have been treated in the literature study extensively and will be used in this chapter to interpret the simulation results.

Research objective

The first partial study objective is to determine the morphological character of the Texel, being importing or exporting. The instantaneous transport model (Model A) points out an importing behaviour of the Texel Inlet. The hypothesis is therefore that the sediment transport has a positive residual direction. This hypothesis is elaborated by the results of the process-based model (Model B).

The second partial study objective is the determination of the most suitable location for the dump and extraction of sediment. Based on the process-based analysis (Model B) of sediment transport through several cross-section along the Texel Inlet it is possible to identify the channel-sections of erosion and sedimentation. The determination of these morphological developments along the Texel Inlet enables the designation of locations for the dump and extraction of sediment.

5.3 Sediment transport modes

The sediment transport modes, bed load transport and suspended load transport, will be explained in this paragraph.

5.3.1 Definition of sediment transport modes

In coastal engineering sediment transport is often integrated over time (such as a tidal period or a year) and over a certain ray (like the cross-section defined for the Texel Inlet). Therefore the sediment transport in this chapter is per meter width and per second, with a unit of \( \text{m}^3/\text{m}^2/\text{s} \). The sediment transport at one particular location follows from the integration of the vertical sediment transport distribution over the entire water column. To compute the sediment transport distribution it is first necessary to determine the velocity distribution \( u(z) \) and the sediment concentration distribution \( c(z) \).
The sediment transport in a thin layer close to the bed is referred to as bed load transport. The transport in the upper layer is called suspended load transport. The concentration over the water column depends on the shape of the vertical distribution curve and on the so-called reference concentration. The reference concentration is the concentration near the bed \(c_a\).

Many shape functions can be found in literature. The reference concentration is deducted from a separate calculation of the bed load transport, for which aim sediment transport formulae are applied which are also used in river engineering.

### 5.3.2 Basic formulation of sediment transport

Basically, sediment transport can be defined as a quantity of sediment that is moving with a specific velocity through a well-defined (part of a) plane. Expressed in terms of a very simple equation:

\[
S = cu
\]

Where:
- \(S\): Sediment transport through a well defined (part of a) plane \([\text{kg/s}]\)
- \(c\): Concentration of sediment \([\text{kg/m}^3]\)
- \(u\): Flow velocity \([\text{m/s}]\)

In this analysis it is assumed that particles in suspension move essentially with the same speed as the water surrounding the particle; so with the local velocity of the water. The mass of particles in suspension is usually so small, that they are able to follow water velocity fluctuations without a significant time delay.

Sediment concentration can be defined in two ways:
- Volumetric concentration \((\text{m}^3\text{ sediment per m}^3\text{ water; or simply in %})\)
- mass concentration \((\text{kg/m}^3)\)

Volumetric concentration thus gives the percentage of the total volume (for instance \(1\text{ m}^3\)) which is occupied by grains. This may be with or without voids in between the particles; voids which would be present if the particles would be settled at the bottom. In sediment transport formulae, volumetric concentrations are often directly multiplied by \(\frac{1}{1-p}\) \((p: \text{porosity})\) as that results in direct information on accretion or erosion quantities if the sediment transport rate changes.

In this analysis sediment concentrations will be expressed in \([\text{kg/m}^3]\). Because the mass concentration is used as the unit for the sediment concentration \(c\) in sediment transport formulae, the results have to be multiplied by \(\frac{1}{\rho_s}\) to get \([\text{m}^3/\text{s/m}^2]\) as unit for \(S\). Where \(\rho_s\): mass density of particles \((\text{kg/m3})\).
The sediment transport equation can be used to calculate the sediment transport rate in a specific point. In the analysis of the Texel Inlet the interests lies in a more integrated measure. The total amount of transport between the bed and the water surface is one of parameters of interest. Therefore the sediment transport rate can be described as the same product of sediment concentration \( c \) and water velocity \( u \), though integrated over the local water depth \( h \):

\[
S = \int_{z=0}^{h} c(z)u(z) \, dz
\]

Both the concentration \( c \) and the velocity \( u \) are allowed to vary as a function of the elevation \( z \) above the bed. This type of equation can be applied for the assessment of the sediment transport rate in the Texel Inlet if we can assume that both concentration and velocity vary only slowly with time. However both the velocity and the concentration exhibit large variations in time on the time scale of a tidal wave period. Consequently the equations will have to be extended yielding:

\[
S = \int_{t'=0}^{t'=0} \int_{\eta=0}^{\eta} c(z,t)u(z,t) \, dz \, dt
\]

Where:
- \( t' \) integration period
- \( \eta \) instantaneous water surface elevation
- \( h \) average water depth
- \( u(z,t) \) instantaneous velocity at height \( z \) (in channel direction)
- \( c(z,t) \) instantaneous concentration at height \( z \)

For the time interval over which the integration in the equation is carried out, denoted as \( t' \), a sufficient number of tidal wave periods is taken into account. For the upper boundary of the integration vertical, the instantaneous level of the water surface is used.

The local variation in the velocity and consequently the local variation in the sediment concentration are in general related to the oscillating movement of the tidal waves. That means that a sediment transport formula fully based on this equation can in fact not yet be used. By applying some simplifications it is possible to derive formulae for special (restricted) cases.

The approach in the analysis of the sediment transports through the Texel Inlet is to make distinction in the sediment transport that is occurring in two horizontal transport layers. If one refers to the material that is transported in a layer very near to the bottom, it is the so-called bed load transport. The material transport in the region above this 'bottom layer' is referred to as suspended load transport. Although the actual boundary between the two layers is not always clear, the distinction is considered very practical.

### 5.4 Numerical simulation of the sediment transport

This paragraph deals with the process-based results of the suspended load transport, bed load transport and total load transport (Model B). In contrast to the instantaneous transport model (Model A), the process-based model (Model B) accounts for inter-local sediment transport processes. For the instantaneous transport model the sediment transport results from the instantaneous local flow velocity. For the process-based model also advection and diffusion terms are taken into account. The results of the process-based model will be compared with the results of [Elias (2006)].
5.4.1 Suspended load transport

The data of the suspended load transport is obtained from a 62.08 h registration (exactly five tidal periods) of the numerical model. The values have an interval of 2 minutes. Figure 40 indicates the registration of the suspended load transport at the centre line of cross section 1.

![Figure 40: Registration suspended load transport at the centre line of cross-section 1](image)

During the slack water\(^{11}\) period the current velocity is beneath the threshold value for sediment motion. The suspended load transport has therefore a zero-value in between the flood and ebb peaks. This can be clearly seen in Figure 41. Both the suspended load transport and the flow velocity are normalized\(^{12}\) and plotted. The threshold value of the flow velocity for the initiation of suspended load transport is 0.38 \* 1.75 = 0.67 m/s. Moreover, the figure shows an ebb durations greater than flood duration.

\(^{11}\) Slack water is the period during which no significant tidal current flows in a body of water. Slack water usually happens near high tide and low tide, and occurs when the direction of the tidal current reverses.

\(^{12}\) Normalization refers to the mathematical operation where all data is divided to the maximum value of the data set.
Figure 41: Interaction between suspended load transport and flow velocity

For further analysis for each point on the cross-section the following physical quantities will be elaborated:

- suspended load transport during the ebb peak
- suspended load transport during the flood peak
- residual suspended load transport

The suspended load transport during both the ebb and flood peak is determined by averaging over the five peaks. The residual suspended load transport is determined by averaging over the entire period of five tidal cycles, for Figure 40 from t=414m to t=3974m.

The suspended load transports for cross-section 1 have been indicated in Figure 42. It can clearly be notified that the residual suspended sediment transport is directed inwards the basin. Moreover, the suspended load transport during the flood peak (magnitude of maximum $1.482 \times 10^{-3}$ m$^3$/s/m') is significantly greater than the during the ebb peak (magnitude of maximum $0.919 \times 10^{-3}$ m$^3$/s/m').
Figure 42: Suspended load transport along cross-section 1

The suspended load transport along cross-section 1 can be compared with the model of Elias, 2006. The well-calibrated model with high-resolution of the grid can be considered as ‘close to reality’. The model results of [Elias, 2006] have been indicated in Figure 43.

Figure 43: Snapshot of the model results of [Elias, 2006] for a morphological tide with all significant tidal constituents for the year 1999 (page 101 dissertation)
The following observations can be obtained from comparison between the model results of this thesis and the dissertation of [Elias, 2006]:

- The flood-averaged suspended load transport profile along the cross-section is identical;
- The flood-averaged suspended load transport values of the model of this thesis have a peak of circa $1.5 \times 10^{-3} \text{m}^3/\text{s/m}$ for the model of [Elias, 2006] a peak of circa $0.8 \times 10^{-3} \text{m}^3/\text{s/m}$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged suspended load transport approximately by a factor of 1.9;
- The ebb-averaged suspended load transport of profile along the section is considerably different. In the model of [Elias, 2006] the largest ebb sediment transports can be found in the North of the Marsdiep, whereas in the model used in this thesis the largest ebb sediment transport is found in the South of the Marsdiep;
- The ebb-averaged suspended load transport values of the model of this thesis have a peak of circa $0.9 \times 10^{-3} \text{m}^3/\text{s/m}$ for the model of [Elias, 2006] a peak of circa $0.7 \times 10^{-3} \text{m}^3/\text{s/m}$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged suspended load transport approximately by a factor of 1.3. However, locally the overestimation factor can rise to 6.
- The profile of the residual suspended load transport along the cross-section is for the South side of the Marsdiep almost identical. For the North side of the Marsdiep the model used for this thesis indicates a continuously decreasing value of the flood-directed residual load sediment towards North, whereas [Elias, 2006] indicated an ebb-directed residual load transport for the northernmost 800 m;
- The residual suspended load transport values of the model of this thesis have a peak of circa $1.5 \times 10^{-3} \text{m}^3/\text{s/m}$; for the model of [Elias, 2006] a peak of circa $0.8 \times 10^{-3} \text{m}^3/\text{s/m}$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged suspended load transport approximately by a factor of 1.9;
- The residual suspended load transport values of the model of this thesis have a peak of circa $11 \times 10^{-4} \text{m}^3/\text{s/m}$; for the model of [Elias, 2006] a peak of circa $5 \times 10^{-4} \text{m}^3/\text{s/m}$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged suspended load transport approximately by a factor of 2.2. The average overestimation factor equals approximately 3.1.

It is noted that the comparison is not completely realistic since the results of the model used in this thesis for both ebb and flood are averaged over the peak values and of [Elias, 2006] the results are averaged over the complete ebb and flood duration.

The residual suspended load transport for all cross-sections is indicated in Figure 44. The plot shows a radical decrease in residual suspended load transport along the Texel Inlet.
Figure 44: Residual suspended load transports along the cross-section for all cross-sections
The residual suspended load transport integrated over the cross-section length gives the suspended load transport through the cross-section. In Table 10 the total residual suspended load transport is indicated for all cross sections.

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Suspended Load Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3086 m³/s = 9.732 Mm³/yr</td>
</tr>
<tr>
<td>2</td>
<td>0.0448 m³/s = 1.413 Mm³/yr</td>
</tr>
<tr>
<td>3</td>
<td>0.0350 m³/s = 1.104 Mm³/yr</td>
</tr>
<tr>
<td>4</td>
<td>0.0137 m³/s = 0.432 Mm³/yr</td>
</tr>
<tr>
<td>5</td>
<td>0.0056 m³/s = 0.177 Mm³/yr</td>
</tr>
<tr>
<td>6</td>
<td>0.0017 m³/s = 0.054 Mm³/yr</td>
</tr>
</tbody>
</table>

Table 10: Total residual suspended load transport

5.4.2 Bed load transport

The data of the bed load transport is obtained analogous to the suspended load transport. Figure 45 indicates the registration of the bed load transport at the centre line of cross section 1.

![Figure 45: Registration bed load transport in the centre line of cross-section 1](image)

Analogous to the suspended load transport, the graphs for the bed load transport have been indicated in Figure 46. The patterns and direction of the bed load transport is directed inwards the basin. The bed load transport during the flood peak (magnitude of maximum $4.115 \times 10^{-5}$ m³/s/m²) is greater than during the ebb peak (magnitude of maximum $3.578 \times 10^{-5}$ m³/s/m²).
Figure 46: Bed load transport along cross-section 1

Also the bed load transport along cross-section 1 can be compared with the model of Elias, 2006. The results of [Elias, 2006] have been indicated in Figure 43 (see paragraph 5.5.1).

The following observations can be obtained from comparison between the model results of this thesis and of the dissertation of [Elias, 2006]:

- The flood-averaged bed load transport profile along the cross-section is identical;
- The flood-averaged bed load transport values of the model of this thesis have a peak of circa $4.1 \times 10^{-3}$ m$^3$/s/m$'$; for the model of [Elias, 2006] a peak of circa $2.6 \times 10^{-5}$ m$^3$/s/m$'$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged bed load transport approximately by a factor of 1.6;
- The ebb-averaged bed load transport of profile along the section is considerably different. In the model of [Elias, 2006] the largest ebb sediment transports can be found in the North of the Marsdiep, whereas in the model used in this thesis the largest ebb sediment transport is found in the South of the Marsdiep;
- The ebb-averaged bed load transport values of the model of this thesis have a peak of circa $3.6 \times 10^{-3}$ m$^3$/s/m$'$; for the model of [Elias, 2006] a peak of circa $3.1 \times 10^{-5}$ m$^3$/s/m$'$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged bed load transport approximately by a factor of 1.17;
- The profile of the residual bed load transport along the cross-section is considerably different. For the North side of the Marsdiep the model used for this thesis indicates a continuously decreasing value of the flood-directed residual load sediment towards to North, whereas [Elias, 2006] indicated a ebb-directed residual load transport for the northernmost 800 m. In contradiction to [Elias, 2006] for the South of the Marsdiep the residual bed load transport of the model used in this thesis indicated an ebb-directed residual load transport for circa 600 m;
- The residual bed load transport values of the model of this thesis have a peak of circa $2.8 \times 10^{-5}$ m$^3$/s/m$'$; for the model of [Elias, 2006] a peak of circa $2 \times 10^{-5}$ m$^3$/s/m$'$ can be retrieved from the diagram. The model used in this thesis overestimated the flood-averaged bed load transport approximately by a factor of 1.4.
The residual bed load transport for all cross-sections is indicated in Figure 47.

![Figure 47: Residual bed load transports along the cross-section for all cross-sections](image)

The residual suspended load transport integrated over the cross-section length gives the suspended load transport through the cross-section. In Table 11 the total residual suspended load transport is indicated for all cross-sections.
### 5.4.3 Residual sediment transport

Research question 2 raised the question which location at the Texel Inlet is most suitable as a dumping location for sediment. The aim of the dumped sediment is a migration towards the Afsluitdijk. The residual sediment transport has been indicated in Figure 48 (Model C).

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Suspended Load Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$6.155 \times 10^{-3}$ m$^3$/s = 0.1941 Mm$^3$/yr</td>
</tr>
<tr>
<td>2</td>
<td>$7.087 \times 10^{-3}$ m$^3$/s = 0.2235 Mm$^3$/yr</td>
</tr>
<tr>
<td>3</td>
<td>$1.145 \times 10^{-3}$ m$^3$/s = 0.0361 Mm$^3$/yr</td>
</tr>
<tr>
<td>4</td>
<td>$3.813 \times 10^{-3}$ m$^3$/s = 0.1202 Mm$^3$/yr</td>
</tr>
<tr>
<td>5</td>
<td>$2.051 \times 10^{-3}$ m$^3$/s = 0.0647 Mm$^3$/yr</td>
</tr>
<tr>
<td>6</td>
<td>$1.329 \times 10^{-3}$ m$^3$/s = 0.0419 Mm$^3$/yr</td>
</tr>
</tbody>
</table>

Table 11: Total residual suspended load transport

With respect to the elaboration of a dump location it can be concluded from Figure 48:
- The first part of the Texel Inlet has a strong residual sediment transport, but a long distance to the Afsluitdijk
- The last part of the Texel Inlet has a weak residual sediment transport, but a shorter distance to the Afsluitdijk

The evaluation of the morphological response to the dump of a significant amount of sediment is therefore be performed for:
- Dump Location 1: between cross-section 2 and cross-section 4
- Dump Location 2: between cross-section 4 and cross-section 6

![Figure 48: Residual sediment transport of the Texel Inlet (Model B)](image-url)
5.5 Sensitivity verification of relevant parameters

This paragraph deals with a sensitivity verification of the results of the process-based model (Model B) by using a schematized transport model (Model C). The schematized transport model is based on the Bijker formulation for bed load and suspended load transport. A notion of the sensitivity of relevant parameters can be obtained. The results of the schematized transport model of Bijker of the Texel Inlet are assigned to as model C:

Model C: \textit{Bijker – schematized transport model}

5.5.1 Bed Load transport

Bed load transport occurs when the bed shear stress or the bed shear stress velocity exceeds a critical value (initiation of motion). Sediment particles start rolling or sliding over the bed. If the bed shear stress increases further, then the sediment particles move across the bed by making small jumps, which are called saltations. Only if the jump lengths of the saltations are limited to a few times the particle diameter, this type of motion is still considered as a part of the bed load transport. Otherwise, if the jumps become larger, it looks more like suspended load transport. This illustrates that the distinction between bed load and suspended load transport is artificial to some extent. However the distinction between bed load transport and suspended load transport is still valuable for simplifying the mathematical description of sediment transport.

Bed load transport is concentrated in a layer close to the seabed, the so-called bottom layer with a thickness $\delta_b$. The mixing due to (vertical) turbulence is often assumed to be still small in this layer, so that it only slightly influences the motion of sediment particles. The movement of the sediment particles is mainly limited by the effect of gravity.

The analysis of the bed load transport through the Texel Inlet focuses on the transport induced by tidal currents. The transport of sediment particles by a uniform current is possible in the form of bed load only or in the combination of bed load and suspended load. This mainly depends on the flow conditions and the size of the bed material. Various formulae are available in literature, many of them originating from river engineering. In the bed load transport analysis the Bijker formulae (1971) will be followed. With this set and various assumptions, it is ultimately possible to calculate the sediment transport by currents.

Kalinske (1947) as well as Einstein (1950) introduced statistical methods for the representation of the turbulent behaviour of the flow. Einstein developed complex formulations for the movement of the particles, whereas Kalinske assumed a normal distribution for the instantaneous fluid velocity at grain level. Frijlink (1952) used a more practical approach and made a fit of various transport formulae. The Kalinske-Frijlink formula for bed load transport (in uniform flow) is:

$$S_b = 5 \cdot D_{so} \sqrt{\mu} \cdot u_s \cdot \exp \left[ -0.27 \frac{\Delta C^2 D_{so}}{\mu u} \right]$$  \hspace{1cm} [m^3/m/s]

The parameters used in the Kalinske-Frijlink formula are:

- $S_b$ bed load transport  \hspace{1cm} [m^3/m/s]
- 5 experimentally derived coefficient (fit parameter)  \hspace{1cm} [-]
- $D_{so}$ mean sediment particle diameter  \hspace{1cm} [m]
- $u_s$ shear stress velocity: $u_s = \frac{u \sqrt{g}}{C}$  \hspace{1cm} [m/s]
- $v$ depth-averaged flow velocity  \hspace{1cm} [m/s]
- $C$ Chézy friction coefficient  \hspace{1cm} [m^{1/2}/s]
μ  ripple factor  [m]
g  gravitational acceleration  [m/s²]
-0.27  experimentally derived coefficient (fit parameter)  [-]
Δ  relative sediment density: \( \Delta = \frac{\rho_s - \rho}{\rho} \)  [-]
\( \rho_s \)  mass density of sediment  [kg/m³]
\( \rho \)  mass density of water  [kg/m³]

For the shear stress under a uniform flow the formula of Chézy can be used:

\[ \tau_c = \rho g \frac{u^2}{C^2} \]  [N/m²]

The Chézy friction factor is defined as:

\[ C = 18 \log \left( \frac{12h}{r} \right) \]  [m¹/²/s]

With the use of the Chézy formula for the shear stress under current the Kalinske-Frijlink formula for bed load transport (in uniform flow) can be transformed into:

\[ S_h = 5 * D_{so} * \sqrt{\mu * u * \exp \left[ \frac{-0.27 * \rho g \Delta D_{so}}{\mu} \right]} \]

The last part of term between brackets is the inverse of the Shields parameter. The second underlined term is a measure for the stirring up of sediment particles, which thus mainly depends on the Shields parameter. The first underlined term is the actual (dimensionless) transport term. Apart from the two fit coefficients and the already known parameters, one typical parameter occurs in both the transport and the stirring parts of the transport equation which needs some explanation: the ripple factor.

Bottom friction is caused by flow resistance at the bottom. Both the bed forms, like ripples, and the grains contribute to this flow resistance (but on different scales). The actual transport of particles occurs due to the forces (shear stresses) acting on the grains itself (not due to the forces acting on the bottom ripples). With the ripple factor it is meant to specify the actual forces at the grains. The factor \( \mu \tau_c \) represents the actual shear stress on the grains within the bed, which is a measure for the forces acting on the grains. Since \( \tau_c \) is the bed shear stress (under currents), the ripple factor can be regarded as that part of the available shear stress that can be used to initiate the movement of sediment particles. The remaining part of the shear stress then is a measure for the flow resistance caused by bed forms like ripples. Mathematically this can be expressed as:

\[ \mu \sim \frac{\tau_{skin\ grains}}{\tau_c} \]

The shear stress at the skin surface of the grains, \( \tau_{skin\ grains} \), is related to a Chézy coefficient of the grain skin \( C_{skin} \):

\[ \tau_{skin\ grains} = \frac{\rho g v^2}{C_{skin}^2} \]  [N/m²]

\[ C_{skin} = 18 \log \left( \frac{12h}{r} \right) \]  [m¹/²/s]
In some transport formulations, $D_{90}$ is used for $D_{skin}$, yielding $D_{90} = D_{skin}$. However, other formulations can be found in literature as well. The ripple factor, according to the above definition, is proportional to $\left( \frac{C}{C_{90}} \right)^2$. In practice however, it appears that the following expression is used for the ripple factor:

$$\mu = \left( \frac{C}{C_{90}} \right)^{1.5}$$

By using the power 1.5 instead of 2, the factor $\mu \tau_c$ actually is a combination of the shear stress on the grains (which was the original definition) and the total shear stress:

$$\mu \tau_c = \tau_{skin,grains} * \tau_c^{0.25}$$

In the Kalinske-Frijlink transport formula for bed load transport under a uniform flow, it follows that skin friction is assumed to be more important for the transport than the total friction (power 0.75 versus power 0.25). The physical meaning of the ripple factor is that it indicates, for a certain amount of available shear stress, how 'easily' sediment particles can be stirred up. It is therefore not logical that $\mu$ (in fact $m$) also appears in the 'transport part' of the Kalinske-Frijlink formula. Bijker (1971) modified the Kalinske-Frijlink formula by indeed leaving out the ripple factor in the 'transport part' of the formula:

$$S_b = 5D_{50}\sqrt{\mu \delta \exp \left[ \frac{\lambda}{\mu} \frac{\rho g \Delta D_{50}}{\tau_c} \right]}$$

The maximum of the bed load transport along the Texel Inlet can be determined based on this equation. The varying parameters along the Texel Inlet are the water depth ($h$) and the maximum of flow velocity ($u$). The reader is referred to appendix D for the spreadsheets with all the involved parameter for the seven cross-sections.

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Mean Water depth [m]</th>
<th>Flow velocity Ebb peak [m/s]</th>
<th>Flow velocity Flood peak [m/s]</th>
<th>Bed load transport Ebb peak [$m^3/m'/s$]</th>
<th>Bed load transport Flood peak [$m^3/m'/s$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>41.3</td>
<td>-1.29</td>
<td>1.45</td>
<td>-3.36*10^5</td>
<td>4.23*10^5</td>
</tr>
<tr>
<td>1</td>
<td>23.5</td>
<td>-1.23</td>
<td>1.31</td>
<td>-3.42*10^5</td>
<td>3.88*10^5</td>
</tr>
<tr>
<td>2</td>
<td>26.8</td>
<td>-1.09</td>
<td>1.23</td>
<td>-2.54*10^5</td>
<td>3.33*10^5</td>
</tr>
<tr>
<td>3</td>
<td>25.4</td>
<td>-1.09</td>
<td>1.17</td>
<td>-2.57*10^5</td>
<td>3.02*10^5</td>
</tr>
<tr>
<td>4</td>
<td>15.1</td>
<td>-0.97</td>
<td>1.04</td>
<td>-2.19*10^5</td>
<td>2.66*10^5</td>
</tr>
<tr>
<td>5</td>
<td>17.1</td>
<td>-0.76</td>
<td>1.01</td>
<td>-1.00*10^5</td>
<td>2.35*10^5</td>
</tr>
<tr>
<td>6</td>
<td>15.5</td>
<td>-0.55</td>
<td>0.65</td>
<td>-0.23*10^5</td>
<td>0.55*10^5</td>
</tr>
</tbody>
</table>

Table 12: Bed load transport along the Texel Inlet at the centre line for Model B
5.5.2 Suspended load transport

When the actual bed shear stress is (much) larger than the critical bed shear stress, the particles will be lifted from the bed. If this lift is beyond a certain level, then the turbulent upward forces may be larger than the submerged weight of the particles. In that case, the particles get into suspension, which means that they lose contact with the bottom for some time. Besides gravity, friction forces between the grains in suspension and the grain-water interaction affect the behavior of the suspended particles. The suspended transport rate $S_z$ is found by:

$$
S_z = \frac{1}{t'} \int_{z=\delta}^{h+z} c(z,t)u(z,t)dz
$$

This equation is quite general and realize that the analysis focuses on the sediment transport through a well-defined plane. The velocity parameter $u(z,t)$ refers consequently always to the component of the total velocity perpendicular to the plane as considered. (The component of the total velocity parallel to the plane of the sediment transport, does not contribute to the transport through the plane; the particles shear along the plane.)

For the further elaboration of suspended load transport equation two parameters must be considered into more detail: $c(z,t)$ and $u(z,t)$. In the coastal area both parameters are in general functions of height above the bed and time.

For a tidal current the time effect of the velocity profile might be neglected when considering the suspended load transport during flood motion or during ebb motion. The aim of this hypothesis is to obtain insight in the sediment transports modes and quantify the sediment transport at the flood and ebb peak of the fluid motion. By regarding a constant velocity profile at a certain time the physical analysis is more straightforward.

In the further analysis it is assumed that for the description of the sediment transport rate where the time effect of the velocity component is not important. Use will be made of the logarithmic velocity distribution as described by:

$$
u(z) = \frac{u_z}{K} \ln \left( \frac{z}{z_0} \right)
$$

In this equation $z_0$ refers to the zero-velocity level ($u_z=0$ at $z=z_0$)

The logarithmic velocity distribution 'predicts' negative velocities for $z<z_0$, which is unrealistic. However this problem does not affect the analysis of suspended load transport, which is by definition above the bottom layer. The thickness of the bottom layer $\delta_0$ has not much in common with $z_0$. However, both are small relative to the water depth and located just above the bottom.

Concentration distribution over the water column

The second important parameter in the elaboration of the suspended load equation is the vertical distribution of the sediment concentration. This depends on various parameters, such as, the overall tidal flow velocity of the Texel Inlet, the water depth along the channel, characteristics of the water and the bed material (assuming that the sediment in suspension originates from the local bottom) and the bottom slope. Because all these parameters and sub-parameters influence each other at various time- and space-scales, it is yet impossible to give a formulation for $c(z,t)$ for an arbitrary combination of conditions. However, in cases where a $u(z)$ description is assumed for the current velocity, it is also allowed to assume a $c(z)$ description for the sediment concentration.
The grains that cause a sediment concentration $c(z)$ at height $z$, will have a tendency to fall down with a fall velocity $w$. The downward transport through a horizontal plane in the water column at level $z$ above the bed thus is $wc(z)$. Local turbulence in the water column leads to upward and downward exchange of water. Averaged over time there is no net exchange of water. However, since the sediment concentration changes over the water column, more grains will be transported in upward direction than in downward direction. This leads to a turbulent transport of sediment, which depends on the gradient in concentration over the vertical axis. Hence the transport is referred to as a gradient-type transport. On average turbulence transports sediment from levels of high concentrations to levels of lower concentrations. An equilibrium situation occurs once the downward transport caused by gravity is compensated by the upward movement of grains by turbulence:

$$wc(z) + \varepsilon_s(z) \frac{dc(z)}{dz} = 0$$

Where:
- $c(z)$: average concentration at level $z$ above the bed [-]
- $\varepsilon_s(z)$: diffusion coefficient for sediment at level $z$ $[m^2/s]$

The assumption of a gradient type transport is only valid in situations with small-scale fluid movements. For the Texel Inlet with highly varying flow velocities this prerequisite is not met. The diffusion is not the primary process. The parameter $\varepsilon_s$ is regarded as a measure for the mixing process.

The general solution of the differential equation of the sediment concentration is:

$$c(z) = c_a \exp \left[ - \int_{z=a}^{z} \frac{w}{\varepsilon_s(z)} dz \right]$$

Where:
- $c_a$: concentration at level $z = a$ (integration constant) [-]
- $w$: fall velocity $[m/s]$
- $z$: height above bed $[m]$

Various researchers have suggested distributions for $\varepsilon_s(z)$. In the analysis of the Texel Inlet a parabolic shape of the diffusion coefficient over the water depth is assumed (Rouse/Einstein):

$$\varepsilon_s(z) = 4\varepsilon_{s,\text{max}} \frac{z}{h} \left[ \frac{h - z}{h} \right]$$

Where:
- $\varepsilon_{s,\text{max}}$: maximum mixing coefficient occurring at half the water depth $[m^2/s]$

This results in a concentration distribution denoted as:

$$c(z) = c_a \left[ \frac{h - z}{z} \frac{a}{h - a} \right]$$

Where:
- $a$: thickness of the bottom layer $[m]$
- $c_a$: concentration at reference level $z = a$ [-]
- $z_s$: Rouse number defined as $z_s = \frac{w}{\kappa \varepsilon_s}$ [-]

This concentration distribution leads to infinite values at $z = 0$ and to zero concentration close to the surface $z = h$, see Figure 49.
Suspended load transport

With a logarithmic velocity distribution and a diffusion equation for the sediment concentration distribution, the suspended load transport can be described as:

\[ S_s = \int_a^h \frac{u_k}{\kappa} \ln \left( \frac{z}{z_0} \right) * c_a \left[ \frac{h - z}{z} \frac{a}{h - a} \right]^\nu \, dz \]

Bogaard and Bakker (1977) developed tables to solve this integral. The suspended load transport is determined from two parameters:

- \[ A = \frac{r}{h} \]
- \[ z_* = \frac{w}{\kappa v_*} \]

The maximum of the suspended load transport along the Texel Inlet can be determined based on these tables. The varying parameters along the Texel Inlet are the water depth (h) and the maximum of flow velocity (v).

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Mean Water depth [m]</th>
<th>A *10^3</th>
<th>( z_* )</th>
<th>( S_s/S_b )</th>
<th>Suspended load transport Ebb peak [m^3/m'/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>41.33</td>
<td>1.45</td>
<td>1.09</td>
<td>12.10</td>
<td>-40.7*10^4</td>
</tr>
<tr>
<td>1</td>
<td>23.52</td>
<td>2.55</td>
<td>1.07</td>
<td>10.96</td>
<td>-37.5*10^4</td>
</tr>
<tr>
<td>2</td>
<td>26.78</td>
<td>2.24</td>
<td>1.23</td>
<td>8.32</td>
<td>-21.1*10^4</td>
</tr>
<tr>
<td>3</td>
<td>25.44</td>
<td>2.36</td>
<td>1.22</td>
<td>8.38</td>
<td>-21.5*10^4</td>
</tr>
<tr>
<td>4</td>
<td>15.07</td>
<td>3.98</td>
<td>1.29</td>
<td>5.47</td>
<td>-12.0*10^4</td>
</tr>
<tr>
<td>5</td>
<td>17.05</td>
<td>3.52</td>
<td>1.67</td>
<td>3.20</td>
<td>-3.19*10^4</td>
</tr>
<tr>
<td>6</td>
<td>15.48</td>
<td>3.88</td>
<td>2.28</td>
<td>1.43</td>
<td>-0.33*10^4</td>
</tr>
</tbody>
</table>

Table 13: Bed load transport along the Texel Inlet at the centre line for the ebb peak for Model C
### Cross-section

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Water depth ([m])</th>
<th>(A \times 10^3) [-]</th>
<th>(z_\ast) [-]</th>
<th>(S_\ast/S_b) [-]</th>
<th>Suspended load transport Flood peak ([m^3/m'/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>41.33</td>
<td>1.45</td>
<td>0.97</td>
<td>16.73</td>
<td>+70.7(\times 10^{-5})</td>
</tr>
<tr>
<td>1</td>
<td>23.52</td>
<td>2.55</td>
<td>1.01</td>
<td>12.07</td>
<td>+46.8(\times 10^{-5})</td>
</tr>
<tr>
<td>2</td>
<td>26.78</td>
<td>2.24</td>
<td>1.09</td>
<td>10.90</td>
<td>+36.3(\times 10^{-5})</td>
</tr>
<tr>
<td>3</td>
<td>25.44</td>
<td>2.36</td>
<td>1.14</td>
<td>9.86</td>
<td>+29.8(\times 10^{-5})</td>
</tr>
<tr>
<td>4</td>
<td>15.07</td>
<td>3.98</td>
<td>1.19</td>
<td>7.32</td>
<td>+19.5(\times 10^{-5})</td>
</tr>
<tr>
<td>5</td>
<td>17.05</td>
<td>3.52</td>
<td>1.26</td>
<td>6.49</td>
<td>+15.3(\times 10^{-5})</td>
</tr>
<tr>
<td>6</td>
<td>15.48</td>
<td>3.88</td>
<td>1.93</td>
<td>1.92</td>
<td>+1.05(\times 10^{-5})</td>
</tr>
</tbody>
</table>

**Table 14: Suspended load transport along the Texel Inlet at the centre line for the flood peak for Model C**

#### 5.5.3 Total load transport

The sum of the bed load transport rate \(S_b\) and suspended transport rate \(S_s\) equals the total transport rate \(S_t\): \(S_t = S_b + S_s\).

The simple summation of the two transport modes is allowed because they are driven by different transport processes. They are, however, closely related, for instance via the bottom concentration.

Table 15 indicates an overview of the sediment transports. The instantaneous total sediment transport rates for both the ebb and flood peak have been indicated in Figure 50 as well.

The summation of \(S_{t\ ebb\ peak}\) and \(S_{t\ flood\ peak}\) is not implemented because it will induce a false image of the residual sediment transport\(^{13}\).

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>(h) ([m])</th>
<th>(u) ebb peak ([m/s])</th>
<th>(u) flood peak ([m/s])</th>
<th>(S_b) ebb peak ([m^3/m'/s])</th>
<th>(S_s) Flood peak ([m^3/m'/s])</th>
<th>(c) ebb peak ([kg/m^3])</th>
<th>(c) flood peak ([kg/m^3])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>41.33</td>
<td>-1.29</td>
<td>1.45</td>
<td>-44.06(\times 10^{-6})</td>
<td>74.93(\times 10^{-5})</td>
<td>0.0219</td>
<td>0.0331</td>
</tr>
<tr>
<td>1</td>
<td>23.52</td>
<td>-1.23</td>
<td>1.31</td>
<td>-40.92(\times 10^{-6})</td>
<td>50.68(\times 10^{-5})</td>
<td>0.0375</td>
<td>0.0436</td>
</tr>
<tr>
<td>2</td>
<td>26.78</td>
<td>-1.09</td>
<td>1.23</td>
<td>-23.64(\times 10^{-6})</td>
<td>39.63(\times 10^{-5})</td>
<td>0.0215</td>
<td>0.0319</td>
</tr>
<tr>
<td>3</td>
<td>25.44</td>
<td>-1.09</td>
<td>1.17</td>
<td>-24.07(\times 10^{-6})</td>
<td>32.82(\times 10^{-5})</td>
<td>0.0230</td>
<td>0.0292</td>
</tr>
<tr>
<td>4</td>
<td>15.07</td>
<td>-0.97</td>
<td>1.04</td>
<td>-14.19(\times 10^{-6})</td>
<td>22.16(\times 10^{-5})</td>
<td>0.0257</td>
<td>0.0375</td>
</tr>
<tr>
<td>5</td>
<td>17.05</td>
<td>-0.76</td>
<td>1.01</td>
<td>-4.19(\times 10^{-6})</td>
<td>17.65(\times 10^{-5})</td>
<td>0.0086</td>
<td>0.0272</td>
</tr>
<tr>
<td>6</td>
<td>15.48</td>
<td>-0.55</td>
<td>0.65</td>
<td>-0.56(\times 10^{-6})</td>
<td>1.6(\times 10^{-5})</td>
<td>0.0017</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

**Table 15: Suspended load transport along the Texel Inlet at the centre line for the flood peak for Model C**

\(^{13}\) A significant parameter in the determination of the residual sediment transport is the tidal asymmetry. By approximating the residual sediment transport as the sum of the sediment transport during maximum ebb flow velocities and the sediment transport during maximum flood flow velocities, the tidal asymmetry of unequal ebb - flood durations and unequal neap tides is not taken into account. Since the tidal asymmetry in the tidal lagoon of the Wadden Sea is of major importance for the residual sediment transports the summation may induce a false image.
5.5.4 Residual sediment transport

Figure 50 shows a constant decrease in total sediment transport along the Texel Inlet. The residual sediment transport can be calculated by the following approach:

1. Assuming the instantaneous flow velocity as a sinusoidal function
2. Calculating the critical velocity using the Shields curve
3. Computing the instantaneous sediment transport for one tidal period, considering the critical velocity and the instantaneous sinusoidal flow velocity

In Figure 51 the results for the residual sediment transport has been plotted over the length of the Texel Inlet. The figure indicates a considerably higher residual sediment transport for cross-section 0, a quite uniform residual sediment transport for cross-section 1 to 5, and a considerable lower residual sediment transport for cross-section 6.

---

14 The sinusoidal function for the description of the sediment transport is split up into a sinusoidal function for the sediment transport during ebb and a sinusoidal function during flood.
5.5.5 Explanation asymmetry of the residual sediment transport

Overall, considering both Figure 50 of the total sediment transport and Figure 51 of the residual sediment transport the conclusion can be drawn up:

The total load transport continuously decreases along the Texel Inlet. The residual sediment transport indicates a quite uniform value for cross-section 1 to 5, with a higher value for cross-section 0 and a lower value for cross-section 6.

To explain the distribution of the total load transport and the residual sediment transport along the Texel Inlet a close look to the parameters involved might reveal the cause. Therefore we consider the basic equation for the sediment transport again:

\[
S_z = \frac{1}{t'} \int_{z=0}^{h_{avg}} \int c(z,t) u(z,t) dt dz
\]

The parameters involved in the equation of sediment transport are:

1. The flow velocity \( u \) is major importance, since the sediment transport \( S \) is the multiplication of the velocity \( u \) itself and the sediment concentration \( c \), which is also related to the velocity \( u \).
2. The distribution of the sediment concentration \( c \) along the Texel Inlet is to be examined. An asymmetry in sediment concentration along the Texel Inlet will be followed by an according asymmetry in the sediment transport \( S \), corrected by the distribution of the flow velocity \( u \) along the channel.
3. The water depth \( h \) of the channel for the cross-sections is at least linearly incorporated in the formula of the sediment transport. Moreover the water depth \( h \) also influences the concentration distribution over the water column \( c(z) \).

These parameters will be one by one examined to sharpen the insight in the cause of the asymmetry of the total load transport and the residual sediment transport

Ad. 1 Distribution of the flow velocity \( u \) along the Texel Inlet

A possible explanation for the asymmetry in residual sediment transport along the Texel inlet would be the existence of unequal flow velocity \( u \). In the analysis of the total load transport only the situation at the point in time where the flow velocity is maximum (flood) and minimum (ebb) is considered. By assuming a sinusoidal profile of the flow velocity in time (which is in fact not the case) the residual sediment transport is determined. The flow velocity \( u \), as already mentioned in chapter 4, is related to a third power to the sediment transport, since sediment transport is the flow velocity \( u \) times the sediment transport \( c \) (related to \( u^3 \)).

The flow velocity \( u \) along the Texel Inlet has been indicated in Figure 52. From Figure 52 it can be concluded that the maximum flood flow velocity is greater than the maximum ebb flow velocity for all cross-sections. Furthermore both the maximum flood flow velocity and maximum ebb flow velocity continuously decrease along the channel length.
Flow velocity along the Texel Inlet for ebb peak and flood peak

Since this analysis is based on the flow velocity at the ebb peak and the flood peak it is interesting to compare $u^3$ with the total load transport $S_t$. Figure 53 indicates the powered velocities for the cross-section, including the summation of the ebb and flood powered velocity:

$$u_{\text{comparison}}^3 = \sum \left\{u_{\text{ebb peak}}^3; u_{\text{flood peak}}^3\right\}$$

Where:

- $u_{\text{comparison}}$: analysis-meant flow velocity for comparison with the total load transport

Figure 52: Flow velocity $u$ along the Texel Inlet for the flood peak and ebb peak

Figure 53: Flow velocities to the third power for both the ebb and the flood peak
To gain insight in the relation between the flow velocity to a power 3, \( u^3 \), and the total load transport \( S \), a picture has been drawn up to compare these units. Both the velocities and the sediment transports have been normalized:

\[
\begin{align*}
\bar{u}_i^{\text{normalized}, i} &= \frac{1}{7} \sum_{j=0}^{6} u_j^3, \\
\bar{S}_i^{\text{normalized}, i} &= \frac{1}{7} \sum_{j=0}^{6} S_j 
\end{align*}
\]

Where:

\( \bar{u}_i^{\text{normalized}, i} \): normalized third power flow velocity for cross-section \( i \) [-]

\( \bar{S}_i^{\text{normalized}, i} \): normalized total load transport for cross-section \( i \) [-]

Figure 54: Comparison of flow velocities to a third power with the total load transport

Figure 54 indicates the comparison for both the ebb and flood peak between the normalized power velocities and total load transport. From the figure it can be concluded that the powered velocity distribution along the Texel Inlet is quite well followed by the total load transport distribution along the channel.

Figure 55 indicates the same type comparison for the residual load transport. Again the distribution of the residual values of the powered velocity along the Texel Inlet is followed quite well by the residual total load transport.
Comparison of residual flow velocities to a third power with the residual sediment transport

Figure 55: Comparison of residual flow velocities to a third power with the residual load transport

**Ad. 2 Distribution of the sediment concentration along the Texel Inlet**

A possible explanation for the asymmetry in residual sediment transport along the Texel inlet would be the existence of an asymmetric distribution of the depth-averaged sediment concentration over the channel length. This means that the sediment concentration at the sea-side (sections 0 and 1) of the channel is significantly higher than the sediment concentration at the lagoon-side (sections 4 and 5) of the channel.

Bearing in mind the general equation of depth-averaged sediment transport:

\[
\overline{S}(t) \left[ \frac{kg}{s} \right] = \overline{c}(t) \left[ \frac{kg}{m^3} \right] \times \overline{u}(t) \left[ \frac{m}{s} \right] \times A_{section} \left[ m^2 \right]
\]

Where:

- \( \overline{S}(t) \): Depth-averaged sediment transport \( [kg/s] \)
- \( \overline{c}(t) \): Depth-averaged sediment concentration \( [kg/m^3] \)
- \( \overline{u}(t) \): Depth-averaged flow velocity \( [m/s] \)
- \( A_{section} \): Cross-sectional area of the cross-section \( [m^2] \)

In the analysis of Model B only 1 meter of width at the centre line of the channel axis is considered. The cross-sectional area is therefore equal to the water depth times 1 m of channel width:

\[
A_{section} \left[ m^2 \right] = h_{channel\ axis} \left[ m \right] \times 1 \left[ m \right]
\]

The total sediment transport calculated has a dimension of \([m^3/m^3/s]\). This indicates the volume of the sediment transport for 1 meter channel width. To obtain the depth average (mass) sediment transport this value has to be multiplied with the density of the sediment and the meter channel width:

\[
\overline{S}(t) \left[ \frac{kg}{s} \right] = \overline{S}(t) \left[ \frac{m^3}{s \cdot m^3} \right] \times \rho_{sediment} \left[ \frac{kg}{m^3} \right] \times 1 \left[ m \right]
\]
Using the general equation for depth-averaged sediment transport the depth-averaged sediment concentration can be determined. The values have been implemented in Table 15 and have been plotted in Figure 56. For cross-section 0 to cross-section 5 the distribution of the concentration along the Texel Inlet is highly variable and does not show a decrease along the Texel Inlet. It can be concluded that the distribution of the sediment concentration along the Texel Inlet is not asymmetric in a sense that sediment concentration decreases along the Texel Inlet. For cross-section 6 a considerable reduction in sediment concentration is obtained.

![Concentration along the Texel Inlet](image)

**Figure 56: Distribution of the sediment concentration along the Texel Inlet**

**Ad 3. The water depth** $h$

The water depth $h$ of the channel for the cross-sections is at least linearly incorporated in the formula of the sediment transport. Moreover the water depth $h$ also influences the concentration distribution over the water column $c(z)$.

The distribution of the water depth of the Texel Inlet has been indicated in Figure 57. The water depth for cross-section 0 is significantly larger than for the other cross-sections. The imbalance between the powered velocity and the sediment transport of Figure 55 for cross-section 0 can be explained by the larger water depth.

![Waterdepth of the Texel Inlet](image)

**Figure 57: Water depth of the cross-sections**
Conclusion asymmetry residual sediment transport:
The asymmetry of the residual sediment transport over the Texel Inlet is explained by an asymmetric flow field of the Texel Inlet. The comparison between a simple power law of the flow velocity and the residual sediment transport is highly similar for cross-section 1 to cross-section 5. For cross-section 0 the residual sediment transport is amplified by a considerable higher water depth. For cross-section 6 the residual sediment transport is reduced by a drop in sediment concentration.

5.6 Comparison of model results

The sediment transport through the Texel Inlet has been calculated with three models:
Model A: Engelund and Hansen – instantaneous transport model
Model B: Delft3D – process-based model
Model C: Bijker – schematized transport model

For channel-section Marsdiep of the Texel Inlet the results of all three models have been indicated in Table 16:
- The sediment transport through the Marsdiep for Model A is based on the Engelund and Hansen sediment transport formula, considering the sediment transport proportional to a power 5 of the flow velocity.
- The sediment transport through the Marsdiep for Model B is obtained from a process-based model of Delft3D.
- The sediment transport through the Marsdiep for Model C is based on a distinction between bed load and suspended load transport. The theory of Bijker has been used to determine the transport processes, based on the current-induced shear stress on the bed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model A Engelund and Hansen</th>
<th>Model B Delft3D Process-based model</th>
<th>Model C Bijker Schematized transport model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{bed ebb peak}$</td>
<td>-</td>
<td>-0.336 * 10^{-6} m^3/m's</td>
<td>-0.167 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{bed flood peak}$</td>
<td>-</td>
<td>0.423 * 10^{-6} m^3/m's</td>
<td>0.292 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{bed residual peak}$</td>
<td>-</td>
<td>0.087 * 10^{-6} m^3/m's</td>
<td>0.011 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{suspended ebb peak}$</td>
<td>-</td>
<td>-3.75 * 10^{-6} m^3/m's</td>
<td>-3.079 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{suspended flood peak}$</td>
<td>-</td>
<td>4.68 * 10^{-6} m^3/m's</td>
<td>7.410 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{suspended residual peak}$</td>
<td>-</td>
<td>0.93 * 10^{-6} m^3/m's</td>
<td>0.518 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{total ebb peak}$</td>
<td>-0.718 * 10^{-6} m^3/m's</td>
<td>-4.092 * 10^{-6} m^3/m's</td>
<td>-3.246 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{total flood peak}$</td>
<td>2.903 * 10^{-6} m^3/m's</td>
<td>5.068 * 10^{-6} m^3/m's</td>
<td>7.702 * 10^{-6} m^3/m's</td>
</tr>
<tr>
<td>$S_{total residual peak}$</td>
<td>0.286 * 10^{-6} m^3/m's</td>
<td>0.894 * 10^{-6} m^3/m's</td>
<td>0.529 * 10^{-6} m^3/m's</td>
</tr>
</tbody>
</table>

Table 16: Comparison of the results of the theoretical model and the numerical of the residual sediment transports

The differences between the three models can be explained by the following considerations:
- The instantaneous transport model (Model A) and the schematized transport model (Model C) are only based on local stirring up of sediment and corresponding concentrations. The process-based model (Model B) also takes into account the irregularities in sediment concentration and corresponding sediment transports. A significant process is the inflow of sediment by the alongshore sediment transport of the Dutch Coast;
Both the instantaneous transport model (Model A) and the process-based model (Model B) are based on a hydrodynamic simulation of the full tidal period. The schematized transport model is based on the maximum ebb and flood velocities during a tidal cycle;

- Critical (threshold) value of the flow velocity is in the instantaneous transport model (Model A) and the process-based model (Model B) on the local instantaneous ripple height $r$. The schematized transport model (Model C) only accounts for one value of the ripple height;

- The process-based model (Model B) accounts for advection and diffusion terms. In the instantaneous transport model (Model A) and the schematized transport model (Model C) the sediment transport processes are only based on the local hydrodynamics and sediment properties.

### 5.7 Conclusion and summary

In this chapter a process-based model (model B) has been used to determine the residual sediment transport processes and the according sedimentation/erosion patterns of the Texel Inlet of the Wadden Sea system. In chapter 4 an estimate was made of the residual sediment transport by using an instantaneous transport model (model A), based on the transport formula of Engelund and Hansen. In contrast to the instantaneous transport model (model A), the process-based model (model B) also takes advection and diffusion terms into account. The results of the process-based model (model B) indicate an asymmetry in the residual sediment transport of the Texel Inlet. To explain the asymmetry in residual sediment transport a schematized transport model (model C) has been used. The results of the schematized transport model (model C) indicate a great similarity between the residual sediment transport and the tidal flow velocity to a power 3 or 5. The sediment concentration of the Texel Inlet has an almost symmetric profile, however sharply decreasing at the end of the Texel Inlet at the Doove Balg.

**Validation of the numerical model**

For the process-based model (model B) a profile of the residual sediment transport along a cross-section of the Marsdiep has been drawn up. This profile was compared to a well-calibrated and widely accepted model of [Elias (2006)]. In the south of the Marsdiep the profiles of the residual sediment transport are quite identical, with an average overestimation factor of model B of 1.9. In the north of the Marsdiep the residual sediment transport has a positive sign (inward directed) for the process-based model (model B) and a negative sign (outward directed) for [Elias (2006)]. The total residual sediment transport through the Marsdiep for the process-based model (model B) equals 9.926 Mm$^3$/yr. The model of [Elias (2006)] with a tidal forcing only indicated an amount of approximately 2-3 Mm$^3$/yr (including wind and waves the sediment transport has an order of 4-4.5 Mm$^3$/yr). Another analysis by [Elias (2006)] based on the erosion of the ebb-tidal delta and adjacent coasts points out a sediment transport of 5-6 Mm$^3$/yr. It can be concluded that the process-based model (model B) is expected to considerably overestimate the sediment transport rates.

**Process-based forecasts**

The sedimentation/erosion patterns, initiated by a dump of a significant amount of sediment at the Texel Inlet, is to be determined. The erosion/sedimentation pattern of the model including a human intervention is corrected for the erosion/sedimentation pattern for the development of the Texel Inlet. The significant overestimation in the sediment transport processes is simulated for both simulations. Only the erosion/sedimentation patterns caused by the human intervention is of major importance for the research objectives. It is expected that the overestimation of the residual sediment has a small effect on the erosion/sedimentation patterns, initiated by a human intervention only. Therefore the process-based model (model B) can be used to forecast the morphological development of the Texel Inlet, initiated by human interventions.

**Research question 2**

Research question 2 raised the question which location at the Texel Inlet is most suitable as a dumping location for sediment. The aim of the dumped sediment is a migration towards the Afsluitdijk. Dump Location 1 is defined between cross-section 2 and cross-section 4, where the
residual sediment transport is relatively strong, but the distance to the Afsluitdijk large. Dump Location 2 is defined between cross-section 4 and cross-section 6, where the residual sediment transport is relatively weak, but the distance to the Afsluitdijk small.
6 MORPHODYNAMIC ANALYSIS OF TEXEL INLET

6.1 Introduction

The aim of this thesis is to investigate the possibility of using the Texel Inlet as a sediment transport belt for the transportation of a significant amount of sediment towards the Afsluitdijk for the construction of tidal marshes. The feasibility of using natural processes for transportation can be investigated by elaborating the morphological response to different human interventions.

1. **Sediment can be dredged from the North Sea and dumped at the Texel Inlet**
   Medium size dredging ships (5000 m$^3$) can dump sediment at the bottom of the Texel Inlet. Sediment transport processes displace the dumped sediment to other areas of the coastal system. The fraction of the sediment volume that deposits at a favorable location near the Afsluitdijk needs to be determined. The hydrodynamic analysis provided insight in the direction and patterns of the sediment transport. Based on this analysis two locations have been defined that are most likely to present importing behavior.

2. **Sediment can be dredged from a sand mining pit at the Texel Inlet**
   A sand mining pit is a location from which sand is extracted. The location of a sand mining pit has to be close to the Afsluitdijk. Small dredging ships (1500 m$^3$) that can navigate at shallow depth can dredge sand from the sand mining pit location and accurately dump it for the construction of the tidal marshes.

3. **Combination of sand pit and dumping area**
   The combination of the distinct human interventions of removing sand from a sand mining pit close to the Afsluitdijk and dumping sand at the tidal trench Texel Inlet might induce a surplus value. The availability of sediment is significantly increased by the dump of sediment at the bottom of the tidal trench. The rate at which the sand mining pits will silt up for the combination of a sand pit and dumping area is to be determined.

This chapter deals with the evaluation of the morphological development of the Wadden Sea system after the mentioned human interventions. The hypotheses for these morphological developments are based on analysis of physical processes, and verified with numerical simulations.

The set-up of this chapter is:

6.2 **Explanation of the research objective and the basic assumptions of the morphodynamic analysis**

6.3 **Explanation of the geometrics of the human interventions that will be subjected to the morphodynamic analysis**

6.4 **Formulation of the hypothesis of the morphological responses to the human interventions in the coastal system**

6.5 **Discussion about the physical parameters of the numerical simulation**

6.5 to 6.7 **Numerical results of the morphodynamic simulations for the human interventions, including physical understanding, feedback to the hypothesis and conclusions**

---

15 In coastal engineering a human intervention refers to all distortions of the natural system, like dredging of sand, reclaiming of land, constructing breakwaters, etc.
6.2 Research objectives and assumptions

The research objectives and the basic assumptions for the morphodynamic analysis will be explained in this paragraph.

The dump of a significant amount of sediment in the Texel Inlet is a human intervention in the lagoon system of the Wadden Sea. It can be concluded from the morphological concepts of the Wadden Sea system discussed in the literature study that the system morphology is in a non-equilibrium state. This means that without any human intervention the bathymetry of the Wadden Sea system will develop in time. The tidal asymmetry and other physical processes are responsible for sediment transport in the coastal system, inducing changes in the bathymetry of the tidal lagoon in time.

A human intervention like the dump of a significant amount of sediment in a tidal trench or the distraction of sediment from a sand mining pit in the coastal system will influence the morphological development of the whole tidal lagoon. Initially the bathymetry is altered significantly, influencing flow velocities, flow patterns and sediment concentration in the water column. Subsequently the sediment transport will be different and the therefore also the development of the bathymetry. Hence the morphological development of the system is different after a human intervention, see Figure 58. On the left hand side the interdependency of bathymetry, flow and sediment transport has been indicated. On the right hand side it is indicated that the initial distortion of the bathymetry by human intervention will also change the flow patterns and the sediment transport rates by the interdependency of these variables.

Figure 58: Morphological development with (right) and without (left) human intervention

During a simulation the bathymetry is updated every time step. One of the output files of a numerical calculation is the bathymetry as a function of time:

\[ z(z(0), t) \]

Where:
- \( z \) bathymetry of the Wadden Sea for all \( x \) and \( y \)
- \( z(0) \) initial bathymetry of the Wadden Sea for all \( x \) and \( y \)
- \( t \) time expired after start simulation

---

16 This statement neglects the use of a morphological scale factor in a numerical simulation. The update of the bathymetry is multiplied by this scale factor.
17 During a numerical simulation with the software Delft3D the bathymetry is updated relative to a reference date.
The morphological implications of a human intervention can be exposed by the bathymetry. Therefore both a simulation with the natural bathymetry $z(0) = z_{Wadden\ Sea}$ and a simulation with a bathymetry corrected for a human intervention $z(0) = z_{human\ intervention}$ are to be executed.

By subtracting the original bathymetry of the Wadden Sea from the disturbed bathymetry by human intervention, the morphological implications of the human intervention can be determined:

$$\Delta z_{human\ intervention}(t) = z_{human\ intervention}(t) - z_{Wadden\ Sea}(t)$$

Where:

- $\Delta z_{human\ intervention}$: difference in bathymetry by human intervention
- $z_{Wadden\ Sea}$: original bathymetry of the Wadden Sea ($t=0$)
- $z_{human\ intervention}$: bathymetry distorted by human intervention ($t=0$)

**Research question 3: efficiency of sediment dump in Texel Inlet**

The main objective of this thesis is the determination of the feasibility of using the Texel Inlet as a sediment transport belt for the construction of tidal marshes at the Afsluitdijk. Above it is explained that the morphological implications of a human intervention can be exposed by the calculated bathymetry from distinct numerical simulations. From the quantified bathymetric changes\(^\text{18}\) the part of sediment volume that deposits at a favorable location near the Afsluitdijk can be determined. From this sediment volume analysis, the efficiency of the human intervention can be quantified.

**Research question 4: efficiency determination sand mining pit**

Besides the use of a dump location as a way of human intervention to transport sediment one can also make use of a sand mining pit. The use of a sand mining pit, close to the Afsluitdijk, is to be elaborated. The rate at which the sand mining pit will silt up can be determined by the bathymetric changes of the numerical simulations.

**Research question 5: influence on the surrounding shoals**

Besides the use of a dump location as a way of human intervention to transport sediment one can also make use of a sand mining pit. The use of a sand mining pit, close to the Afsluitdijk, is to be elaborated. The rate at which the sand mining pit will silt up can be determined by the bathymetric changes of the numerical simulations.

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\(^{18}\) Coastal engineers prefer to use the term sedimentation/erosion pattern. A plot of the bathymetry changes indicates the areas of sedimentation and erosion
Topography

Figure 59: Division of the Texel Inlet into 11 channel-segments. Use is made of these segments for mass balance analysis.

<table>
<thead>
<tr>
<th>Channel-segment number</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Helsdeur</td>
</tr>
<tr>
<td>2</td>
<td>Mardiep</td>
</tr>
<tr>
<td>3</td>
<td>Malzwin</td>
</tr>
<tr>
<td>4</td>
<td>Texelstroom West</td>
</tr>
<tr>
<td>5</td>
<td>Texelstroom Bend</td>
</tr>
<tr>
<td>6</td>
<td>Texelstroom East</td>
</tr>
<tr>
<td>7</td>
<td>Doove Balg</td>
</tr>
<tr>
<td>8</td>
<td>Scheurrak</td>
</tr>
<tr>
<td>9</td>
<td>Nieuwe Schulpengat</td>
</tr>
<tr>
<td>10</td>
<td>Schulpengat</td>
</tr>
<tr>
<td>11</td>
<td>Molengat</td>
</tr>
</tbody>
</table>

Table 17: Definition of channel-segments
6.3 Application of the model

The geometry and location of the human interventions that will be subjected to a morphodynamic analysis will be discussed in this paragraph.

Based on the sediment transport processes analysis of the Texel Inlet two main dump locations can be considered. Moreover also a sand pit location for the distraction of sediment prior to dumping is regarded in this chapter.

6.3.1 Dump Location 1

The first dumping location is located at cross-section 2 to cross-section 4, see Figure 60.

![Figure 60: Dump Location 1, areal picture [Google Earth]](image)

The total amount of sediment that is to be dumped at this location amounts 16.284 Mm$^3$. The configuration of the dumped sediment is indicated in Figure 61. The local water depth is reduced to a maximum value of 20 m. Figure 62 indicates a cross-section of the dump location, showing the reduction of the water depth by the dump of sediment.

![Figure 61: Configuration of the dumped sediment [mm]](image)
6.3.2 Dump Location 2

The second dumping location is located at cross-section 4 to cross-section 6, see Figure 63.

The total amount of sediment that is to be dumped at this location amounts 16.409 Mm$^3$. The configuration of the dumped sediment is indicated in Figure 64. The local water depth is reduced to a maximum value of 16 m.
6.3.3 Sand Pit

The sand pit location is located at the Doove Balg, see Figure 65.

Figure 65: Sand Pit Location, areal picture [Google Earth]

The total amount of sediment that is to be extracted at this location amounts 16.409 Mm$^3$. The configuration of the dredged sediment is indicated in Figure 66. The local water depth is extended to a maximum value of 12 m.

Figure 66: Configuration of the dredged sediment [cm]
6.4 Hypothesis of the morphological responses to the human interventions

The formulation of the hypothesis of the morphological response to Dump location 1, Dump location 2 and Sand Pit Location 1 of the Texel Inlet will be discussed in this paragraph.

6.4.1 Hypothesis morphological response to Dump Location 1

Diffusion of sediment
During flood water is flowing in the tidal basin. The fluid motion exerts bottom friction on the dumped sediment. The bottom friction exceeds the threshold value of the initial of motion. Therefore the sediment is brought into suspension. The suspended sediment in the water column is transported by the fluid motion. As a result the dumped sediment migrates in positive\textsuperscript{19} direction, see Figure 67, upper panel.

During ebb water is flowing out of the tidal basin. The direction of the sediment transport is therefore also reversed. Therefore the sediment migrates in negative direction, see Figure 67, middle panel.

The residual effect of the positive migration of sediment during flood and the negative migration during ebb can be obtained by the superposition of these two processes. Figure 67, lower panel indicates that the superposition of the two processes results in a diffusion of sediment.

\textbf{Figure 67: Explanation of sediment diffusion. Blue line indicates the original geometry of the dumped sediment in the channel; green line indicates the final geometry. Upper panel: positive migration of sediment during flood; middle panel: negative migration of sediment during ebb; lower panel: diffusion of sediment during a tidal cycle.}

The time scale of the process of diffusion of sediment is in order of months to years. This is the time scale for which significant diffusion of sediment occurs on the spatial scale of the tidal channel.

\textbf{Positive migration of sediment}

The residual sediment transport has a positive direction, see Figure 68. Therefore the transport in positive direction is expected to be slightly higher than the transport in negative direction.

\textsuperscript{19} The general axis referred to follows the centre line of the Texel Inlet and has a positive direction inwards the basin
The migration rate depends on tidal flow asymmetry and on the strength of the dominating flow direction. The tidal flow of the Texel Inlet can be characterised as highly asymmetric and relatively strong. The direction of the migration is positive, since the residual sediment transport is positive. The time scale of the migration process is considered to be in the order of years to decades.

The observed sediment transport processes is a superposition of the diffusion of sediment and the positive migration, see Figure 69.

Figure 69: Explanation of the total sediment transport. Blue line indicates the original geometry of the dumped sediment in the channel; green line indicates the final geometry. Upper panel: diffusion of sediment; middle panel: migration of sediment; lower panel: diffusion + migration of sediment.
The hypothesis of the development of the morphology of the dumped sediment at Dump Location 1 can be summarized as:
1. Diffusion of sediment in both directions
2. Sediment migration in the positive direction

6.4.2 Hypothesis morphological response to Dump Location 2

Weak development of Dump Location 2
The instantaneous tidal flow at Dump Location 2 is considerably weaker than at Dump Location 1. In Figure 70 the instantaneous flow velocity for both flood (upper) and ebb (lower) has been indicated.

![Figure 70: Upper panel: instantaneous flow velocity during flood. Lower panel: instantaneous flow velocity during ebb](image)

The considerable reduction in the instantaneous flow velocity along the Texel Inlet, results in a greater reduction of the sediment transport along the Texel Inlet. This is caused by the proportionality between sediment transport and the flow velocity to a power 3 or 5. In Figure 71 the instantaneous sediment transport for both flood (upper) and ebb (lower) has been indicated. The morphological reaction to Dump Location 2 is expected to be significantly weaker than to Dump Location 1.
Diffusion of sediment
For Dump Location 2 the hydrodynamic-based model (Model A) also indicated a residual sediment transport in the order of magnitude of 0.04 – 0.05 the maximum sediment transport through the channel. Therefore it is expected that also for Dump Location 2 the dumped sediment will diffuse in both directions on the short term.

Migration of sediment
The local bathymetry of Dump Location 2 has been indicated in Figure 72. The Texelstroom is split up into the Scheurrak and the Doove Balg. Figure 73 indicates the residual sediment transport for Dump Location 2. Based on the direction and magnitude of the residual sediment transport it is expected that on the long term the sediment migrates partly to the Scheurrak and partly to the Doove Balg.
The hypothesis of the development of the morphology of the dumped sediment at Dump Location 2 can be summarized as:

1. Diffusion of sediment in both directions
2. Migration of sediment partly to the Scheurrak and partly to the Doove Balg

6.4.3 Hypothesis morphological response to Dump Location 2 and Sand Pit 1

The distraction of sediment at the Doove Balg forms an additional distortion of the natural system. The morphological gradient between Dump Location 2 and the Sand Pit is extended. Therefore it is expected that the migration of sediment towards the Doove Balg is greater.

The hypothesis of the development of the morphology of the dumped sediment at Dump Location 2 and Sand Pit can be summarized as:

1. Diffusion of sediment in both directions
2. Migration of sediment to the Doove Balg, filling the sand pit

6.5 Morphological forecast for dump location 1

The numerical results of the morphodynamic simulation for dump location 1, including physical understanding and conclusions will be discussed in this paragraph.

6.5.1 Numerical processing for dump location 1

For the analysis of the morphological consequences in time of the dump of sediment at Dump Location 1, two simulations have been executed with Delft3D:

1. Simulation with the original bathymetry of the Wadden Sea (WAD)
2. Simulation with the bathymetry of the Wadden Sea, superimposed by the sediment dump at Dump Location 1 (DUM1)

The Delft3D simulations have a duration of 1 year. For the simulations a morphological scale factor of 10 has been used. The resultant sedimentation-erosion patterns of the simulations are therefore a 10-year forecast of the bathymetric change under influence of the tide.

The morphological forecast of the dumped sediment is determined by the difference of simulation DUM1 and simulation WAD.
The data extracted from the Delft3D model can be summarized as:

- Initial bathymetry of the original Wadden Sea:
  \[ WAD(t = 0) \]

- Initial bathymetry of the Wadden Sea, including the sediment dump at Dump Location 1:
  \[ DUM1(t = 0) \]

- Sedimentation-erosion pattern of the Wadden Sea for a period of 10 year:
  \[ \Delta WAD(t) \]

- Sedimentation-erosion pattern of the Wadden Sea, including the sediment dump at Dump Location 1, for a period of 10 year:
  \[ \Delta DUM1(t) \]

In the analysis of Dump Location 1 the following figures have been produced, using Matlab:

- Initial disturbance of the bathymetry (see appendix D.1):
  \[ DUM1(t = 0)_{auto} = DUM1(t = 0) - WAD(t = 0) \]

- The development of the bathymetry of Dump Location 1 (see appendix D.2):
  \[ DUM1(t) = DUM1(t = 0) + \Delta DUM1(t) \]

- The development of Dump Location 1 (see appendix D.3):
  \[ \Delta DUM1(t)_{auto} = \Delta DUM1(t) - \Delta WAD(t) \]

- The development of Dump Location 1, including the initial disturbance of the bathymetry (see appendix D.4):
  \[ DUM1(t)_{auto} = DUM1(t = 0)_{auto} + \Delta DUM1(t)_{auto} \]

- The change in sedimentation erosion patterns in a certain time interval (see appendix D.5)
  \[ \Delta DUM1(\Delta t)_{auto} = \Delta DUM1(t_2)_{auto} - \Delta DUM1(t_1)_{auto} \]

The figures have been plotted for t=0, 2.5, 5.0, 7.5, 10 year.

### 6.5.2 Morphological forecast for t=0 to t=10.0 year for dump location 1

Figure 74 indicates the development of the dumped sediment for t=0 year and t=10.0 year. The left hand panel of Figure 75 indicates the morphological change in the interval 0 – 10.0 year.
The morphological forecast for 10 years after the dump at location 1 can be explained by identifying the following processes:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of the dune in positive direction (migration)

The significance of the four processes is variable in time. Table 18 indicates the relative importance of the various processes in time.

<table>
<thead>
<tr>
<th>Process</th>
<th>0-2.5 year</th>
<th>2.5-5.0 year</th>
<th>5.0-7.5 year</th>
<th>7.5-10.0 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Migration</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>+++</td>
</tr>
</tbody>
</table>

Table 18: Relative importance of the sediment processes in time.

Residual sediment transport
Figure 76 indicates the local sedimentation/erosion patterns near dump location 1. The residual sediment transport vectors have been indicated in the figure by the blue arrows. Moreover the channel-sections of the Texel Inlet as defined in paragraph 6.2 have been added to the figure.

Figure 76 shows the diffusion of sediment in both directions of the dump location. Most of the sediment migrates from the dump location (channel-section Texelstroom West) in negative direction towards Marsdiep and Helsdeur and to a lesser extend to Schulpengat en Nieuwe Schulpengat, and in positive direction towards Texelstroom Bend. Moreover the figure shows local interaction with the shoal southwards of the channel-section Texelstroom West. By a local surplus of sediment the shoal volume is increased.
Figure 76: Residual sediment transport of dump location 1. The background-color indicates the sedimentation/erosion pattern as defined in the colormap. The arrows indicate the residual sediment transport for the 10-year forecast. The red boxes indicate the channel-sections as defined in paragraph 6.2.

Mass Balance channel
Figure 77 indicates the mass balance of the channels in the Wadden Sea as a result of the morphological response to the dump at location 1.

Figure 77: Mass Balance of the channel Texel Inlet of the effect of the dump at location 1. Units expressed in Mm$^3$. Positive values indicate sedimentation, whereas negative values indicate erosion.
Figure 77 indicates a considerable diffusion of sediment in both channel directions. The sedimentation at the *Marsdiep* equals 2.3 Mm$^3$, whereas the sedimentation at *Texelstroom Bend* amounts 3.0 Mm$^3$. Figure 75 shows however a positive migration within the polygon of the dump location, *Texelstroom West*.

**Research question 3: What is the efficiency of the sediment transport in relation to the desired sedimentation location?**

Figure 75 indicates the morphological development for the period 0-10 year. The figure shows the superposition of the sedimentation/erosion patterns that result from diffusion, dune formation, dune migration and dune reduction. The results of the morphological forecast show a positive migration of the dump sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk.

The residual morphological response at the Doove Balg ten years after dump can be considered insignificant (Figure 77).

**Mass Balance shoals and surrounding system**

Figure 78 indicates the mass balance of the shoals in the Wadden Sea as a result of the morphological response to the dump at location 1. The figure indicates a significant interaction with the local shoal. The left-hand side of Figure 75 indicates a local relocation of the channel from the shoals in northern direction. This means that the shoal volume increases with approximately 4.7 Mm$^3$.

![Figure 78: Mass Balance of the shoals of the Wadden Sea of the effect of the dump at location 1. Units expressed in Mm$^3$. Positive values indicate sedimentation, whereas negative values indicate erosion.](image)

**Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?**

Figure 78 indicates a local shoal increase near dump location 1 of 4.7 Mm$^3$. The ebb-tidal delta increases with an amount of approximately 0.6 Mm$^3$. On the east side of the Texel Inlet a decrease of sediment is observed with a total amount of approximately 0.1 Mm$^3$. Overall it can be concluded that the shoal area increases, which can be regarded as a positive influence for flora and fauna.

Figure 79 indicates the mass balance of the surrounding system of the Wadden Sea and the North Sea as a result of the morphological response to the dump at location 1. The figure indicates sedimentation of the surrounding North Sea of 1.2 Mm$^3$ and erosion of the surrounding Wadden Sea of 1.1 Mm$^3$. 
6.6 Morphological forecast for dump location 2

The numerical results of the morphodynamic simulation for dump location 2, including physical understanding and conclusions will be discussed in this paragraph.

6.6.1 Morphological forecast for t=0 to t=10.0 year for dump location 2

Figure 80 indicates the development of the dumped sediment for t=0 year and t=10.0 year. Figure 81 indicates the morphological change in the interval 0 – 10.0 year.
The morphological forecast of 10 years of the dumped sediment can be explained by identifying the following processes:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of sediment partly to the Scheurrak and partly to the Doove Balg (migration)

The significance of the two processes is variable in time. Table 19 indicates the relative importance of the various processes in time.

<table>
<thead>
<tr>
<th>Process</th>
<th>0-2.5 year</th>
<th>2.5-5.0 year</th>
<th>5.0-7.5 year</th>
<th>7.5-10.0 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>++</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Migration</td>
<td>+</td>
<td>+++</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 19: Relative importance of the sediment processes in time.

Residual sediment transport

Figure 82 indicates the local sedimentation/erosion patterns near dump location 2. The residual sediment transport vectors have been indicated in the figure by the blue arrows. Moreover the channel-sections of the Texel Inlet as defined in paragraph 6.2 have been added to the figure.
Figure 82: Residual sediment transport of dump location 2. The background-color indicates the sedimentation/erosion pattern as defined in the colormap. The arrows indicate the residual sediment transport for the 10-year forecast. The red boxes indicate the channel-sections as defined in paragraph 6.2.

Figure 82 shows the diffusion of sediment in both directions of the dump location. Most of the sediment migrates from the dump location (channel-section Textelstroom Bend) in negative direction towards Texelstroom West, Marsdiep and Helsdeur and to a lesser extend towards Schulpengat en Nieuwe Schulpengat, and in positive direction towards Texelstroom East. Moreover the figure shows local interaction with the shoal southwards of the channel-section Texelstroom Bend. By a relocation of the channel in southern direction the shoal volume is decreased.

**Mass Balance channel**

Figure 83 indicates the mass balance of the channels in the Wadden Sea as a result of the morphological response to the dump at location 2.

Figure 83 indicates a considerable diffusion and migration of sediment. The erosion at the channel-section Texelstroom Bend amounts approximately 5.7 Mm$^3$. The positive migration of sediment towards the Scheurrak (+1.2 Mm$^3$) and Texelstroom East (+3.2 Mm$^3$) exceeds the negative migration of sediment towards the Texelstroom West (+1.6 Mm$^3$) and the channel-section further westwards (+1.3 Mm$^3$).
Research question 3: What is the efficiency of the sediment transport in relation to the desired sedimentation location?
Figure 81 indicates the morphological development for the period 0-10 year. The figure shows the superposition of the sedimentation/erosion patterns that result from diffusion and migration. The results of the morphological forecast show a positive migration of the dumped sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk. Again the morphological response at the Doove Balg after 10 years can be considered insignificant.

Mass Balance shoals and surrounding system
Figure 84 indicates the mass balance of the shoals in the Wadden Sea as a result of the morphological response to the dump at location 2. The figure indicates a significant interaction with the local shoal. The left-hand side of Figure 75 indicates a local relocation of the channel from the shoals in southern direction. This means that the shoal volume decreases with approximately 2.6 Mm³.

Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?
Figure 84 indicates a local shoal decrease near dump location 2 of 2.6 Mm³. The ebb-tidal delta increases with an amount of approximately 0.5 Mm³. On the west side of the Texel Inlet an increase of sediment is observed with a total amount of approximately 0.5 Mm³. The total shoal volume remains the same, while locally shoal erosion and sedimentation occurs.
Figure 84: Mass Balance of the shoals of the Wadden Sea of the effect of the dump at location 2. Units expressed in Mm$^3$. Positive values indicate sedimentation, whereas negative values indicate erosion.

Figure 85 indicates the mass balance of the surrounding system of the Wadden Sea and the North Sea as a result of the morphological response to the dump at location 2. The figure indicates sedimentation of the surrounding North Sea of 0.3 Mm$^3$ and erosion of the surrounding Wadden Sea of 0.9 Mm$^3$.

Figure 85: Mass Balance of the surrounding system of the Wadden Sea and the North Sea
6.7 Morphological forecast for dump location 2 and sand pit 1

The numerical results of the morphodynamic simulation for dump location 2, including physical understanding and conclusions will be discussed in this paragraph.

6.7.1 Morphological forecast for t=0 to t=10.0 year for dump location 2 and sand pit 1

Figure 86 indicates the development of the dumped sediment for t=0 year and t=10.0 year. The lower panels zoom in at the Doove Balg, the location of the Sand Pit. The left hand panel of Figure 87 indicates the morphological change in the interval 0 – 10.0 year. The right-hand panel of Figure 87 indicates the same change for the Doove Balg only.

![Figure 86: Development of the dumped sediment [mm]. Upper-left panel t=0; Upper-right panel t=10.0 year; Lower-left panel t=0 for Doove Balg; Lower-right panel t=10.0 for Doove Balg](image)

![Figure 87: Left panel: Development of the dumped sediment for the period 0 – 10.0 year [mm]; Right panel: development of the dumped sediment of the Doove Balg for the period 0 – 10.0 year [mm]](image)
The morphological forecast of 10 years of the dumped sediment can be explained by identifying the following processes:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of sediment to the Doove Balg (migration)
3. Erosion of sediment at the end of centre of the Doove Balg channel and deposition of sediment at banks of the end of the Doove Balg channel (channel-reshaping)

The significance of the three processes is variable in time. Table 20 indicates the relative importance of the various processes in time.

<table>
<thead>
<tr>
<th>Process</th>
<th>0-2.5 year</th>
<th>2.5-5.0 year</th>
<th>5.0-7.5 year</th>
<th>7.5-10.0 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Migration</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Channel-reshaping</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 20: Relative importance of the sediment processes in time.

Residual sediment transport
Figure 88 indicates the local sedimentation/erosion patterns near dump location 2 and extraction location 1. The residual sediment transport vectors have been indicated in the figure by the blue arrows. Moreover the channel-sections of the Texel Inlet as defined in paragraph 6.2 have been added to the figure.

![Residual sediment transport](image)

Figure 88: Residual sediment transport of dump location 2 and extraction location 1. The background-color indicates the sedimentation/erosion pattern as defined in the colormap. The arrows indicate the residual sediment transport for the 10-year forecast. The red boxes indicate the channel-sections as defined in paragraph 6.2.

Figure 88 shows the positive migration of sediment towards texelstroom East and Doove Balg. Sediment transport also occurs from the Doove balg to the western shoals. It seems that the local surplus in sediment concentration at the Doove Balg is absorbed by the western shoal.

Mass Balance channel
Figure 89 indicates the mass balance of the channels in the Wadden Sea as a result of the morphological response to the dump at location 2 and extraction location 1.
Figure 89 indicates a considerable migration of sediment in positive direction. The sedimentation at the Texelstroom East equals 4.8 Mm$^3$, whereas the sedimentation at Doove Balg amounts 0.7 Mm$^3$.

**Research question 4: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?**

The left panel of Figure 87 indicates the morphological development for the period 0-10 year. The figure shows the superposition of the sedimentation/erosion patterns that result from diffusion, migration and channel-reshaping. The results of the morphological forecast show a positive migration of the dump sediment towards the Doove Balg. The sedimentation at the Texelstroom East amounts 4.8 Mm$^3$ and at the Doove Balg 0.7 Mm$^3$. Suspended sediment transport towards the Doove Balg is however to a large extend absorbed by the western shoal. The residual sediment migration magnitude is too weak for a realistic use of significant transport towards the Afsluitdijk.

**Mass Balance shoals and surrounding system**

Figure 90 indicates the mass balance of the shoals in the Wadden Sea as a result of the morphological response to the dump at location 2 and extraction location 1. The figure indicates a significant interaction with the local shoals. Suspended sediment transport towards the Doove Balg increases the local sediment concentration. It seems that the suspended sediment is absorbed by the western shoal. Moreover the eastern shoals also significantly increase in volume due to the local surplus of sediment. The shoal to the south of the channel-section Texelstroom Bend considerably decreases in volume due to channel relocation.
Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?

Figure 90 indicates a significant volume increase of the shoals surrounding the end of the Texel Inlet (+3.5 Mm$^3$). The shoals near the channel-section Texelstroom Bend considerably decrease in volume (-3.6 Mm$^3$). Overall it can be concluded that the total shoal volume slightly increases, while locally considerable erosion and sedimentation occurs.

Figure 91 indicates the mass balance of the surrounding system of the Wadden Sea and the North Sea as a result of the morphological response to the dump at location 1. The figure indicates erosion of the surrounding North Sea of 0.2 Mm$^3$ and sedimentation of the surrounding Wadden Sea of 0.2 Mm$^3$. 

Figure 91: Mass Balance of the surrounding system of the Wadden Sea and the North Sea
6.8 Summary and conclusion

The morphological forecast of the dump of a significant amount of sediment in the Texel Inlet has been examined in this chapter. The dump and extraction of sediment has been modelled in the numerical model of Delft3D. The morphological responses to the human interventions in the tidal lagoon have been forecasted by the interpretation of numerical simulations. A summary of the hypotheses and morphological forecasts for the distinct human interventions is elaborated in this paragraph.

6.8.1 Dump Location 1

Morphological forecast
The interpretation of the morphological simulation resulted in an identification of the following processes after the dump:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of sediment in positive direction (migration)

The time scale of the diffusion process is in the order of months to years, while the time scale of the migration process is in the order of years to decennia. For each tidal cycle the sediment transport is directed outwards during ebb and inwards during flood. The alternating direction of the sediment transport causes the diffusion of the dumped sediment. The residual sediment transport has a positive sign, e.g. has a direction inwards the basin. This causes the sediment to migrate in positive direction on a longer time scale.

Research question 3: efficiency of sediment dump in Texel Inlet for Dump Location 1
The results of the morphological forecast show a positive migration of the dump sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk. The residual morphological response at the Doove Balg ten years after dump can be considered insignificant.

Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?
Figure 78 indicates a local shoal increase near dump location 1 of 4.7 Mm3. The ebb-tidal delta increases with an amount of approximately 0.6 Mm3. On the east side of the Texel Inlet a decrease of sediment is observed with a total amount of approximately 0.5 Mm3. Overall it can be concluded that the shoal area increases, which can be regarded as a positive influence for flora and fauna.

6.8.2 Dump Location 2

Morphological forecast
The interpretation of the morphological simulation resulted in an identification of the following processes after the dump:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of sediment partly to the Scheurrak and partly to the Doove Balg (migration)

The instantaneous tidal flow at Dump Location 2 is considerable weaker than at Dump Location 1. Therefore the magnitude of the sediment transport is also reduced. Locally the Texel Inlet bifurcates into the Scheurrak and the Doove Balg. It is therefore expected that sediment migrates to both channels.
Research question 3: What is the efficiency of the sediment transport in relation to the desired sedimentation location?
The results of the morphological forecast show a positive migration of the dumped sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk. Again the morphological response at the Doove Balg after 10 years can be considered insignificant.

Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?
Figure 84 indicates a local shoal decrease near dump location 2 of 2.6 Mm$^3$. The ebb-tidal delta increases with an amount of approximately 0.5 Mm$^3$. On the east side of the Texel Inlet an increase of sediment is observed with a total amount of approximately 2.0 Mm$^3$. Hence the total shoal volume remains the same, while locally shoal erosion and sedimentation occurs.

6.8.3 Dump Location 2 and Sand Pit

Hypothesis
The distraction of sediment at the Doove Balg forms an additional distortion of the natural system. The extraction of sediment at the sand pit results in a bathymetric gradient along the Texel Inlet. Therefore an increase in the migration of sediment towards the Doove Balg is expected.

Morphological forecast
The interpretation of the morphological simulation resulted in an identification of the following processes after the dump and distraction:
1. Diffusion of sediment in both directions (diffusion)
2. Migration of sediment to the Doove Balg (migration)
3. Erosion of sediment at the end of centre of the Doove Balg channel and deposition of sediment at banks of the end of the Doove Balg channel (channel-reshaping)

Research question 4: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?
The results of the morphological forecast show a positive migration of the dump sediment towards the Doove Balg. The sedimentation at the Texelstroom East amounts 4.8 Mm$^3$ and at the Doove Balg 0.7 Mm$^3$. Suspended sediment transport towards the Doove Balg is however to a large extend absorbed by the western shoal. The residual sediment migration magnitude is too weak for a realistic use of significant transport towards the Afsluitdijk.

Research question 5: What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?
Figure 90 indicates a significant volume increase of the shoals surrounding the end of the Texel Inlet (+3.5 Mm$^3$). The shoals near the channel-section Texelstroom Bend considerably decrease in volume (-4.6 Mm$^3$). Overall it can be concluded that the total shoal volume slightly decreases, while locally considerable erosion and sedimentation occurs.
7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Research conclusions

The main objective of this study is the determination of the technical feasibility of using the Texel Inlet as a sediment transport belt for the construction of tidal marshes at the Afsluitdijk. The study curriculum contains five partial study objectives.

Three models have been used to elaborate the research questions.

Model A: Instantaneous transport model
Model A is based on the transport formula of Engelland and Hansen, which assumes proportionality between the instantaneous sediment transport and a power of the instantaneous flow velocity. The application of this transport formula to several cross-sections along the Texel Inlet resulted in a first image of sediment transport along the Texel Inlet. First of all the residual sediment transport proved to have a positive direction for all cross-sections. Secondly the magnitude of the residual sediment transport is about 5% of the maximum sediment transport. A diffusion of dumped sediment with a timescale is in the order of months to years is expected. On a time scale in the order of years to decennia a migration of sediment in positive direction is expected, caused by the positive direction of the residual sediment transport.

Model B: Process-based model
A process-based Delft3D model has been used to identify the morphological forecasts of three human intervention:

The dump of 14 Mm$^3$ at the channel-section Texelstroom West (Dump Location 1);
The results of the morphological forecast show a positive migration of the dump sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk. The residual morphological response at the Doove Balg 10 years after dump can be considered as insignificant.
The local shoals volume increases with 4.7 Mm$^3$. The ebb-tidal delta increases with an amount of approximately 0.6 Mm$^3$. On the east side of the Texel Inlet a decrease of sediment is observed with a total amount of approximately 0.5 Mm$^3$. Overall it can be concluded that the shoal area increases, which can be regarded as a positive influence for flora and fauna.

The dump of 14 Mm$^3$ at the channel-section Texelstroom Bend (Dump Location 2);
The results of the morphological forecast show a positive migration of the dumped sediment. Again the morphological response at the Doove Balg after 10 years can be considered as insignificant.
The local shoals volume decreases with 2.6 Mm$^3$. The ebb-tidal delta increases with an amount of approximately 0.5 Mm$^3$. On the west side of the Texel Inlet an increase of sediment is observed with a total amount of approximately 2.0 Mm$^3$. Hence the total shoal volume remains the same, while locally shoal erosion and sedimentation occurs.

The dump of 14 Mm$^3$ at the channel-section Texelstroom Bend (Dump Location 2) and the extraction of 16 Mm$^3$ at the channel-section Doove Balg (Sand Pit Location 1);
The results of the morphological forecast show a positive migration of the dump sediment towards the Doove Balg. The sedimentation at the Texelstroom East amounts 5.1 Mm$^3$ and at the Doove Balg 0.8 Mm$^3$. Suspended sediment transport towards the Doove Balg is however to a large extent absorbed by the western shoal. The residual sediment migration magnitude is too weak for a realistic use of significant transport towards the Afsluitdijk.
The local shoals volume increases with +3.5 Mm$^3$. The shoals near the channel-section Texelstroom Bend considerably decrease in volume (-4.6 Mm$^3$). Overall it can be concluded that the total shoal volume slightly increases, while locally considerable erosion and sedimentation occurs.
Model C: Schematized transport model
Model C is based on the Bijker approach to use distinct transport formulae for bed load and suspended load transport. Along the Texel Inlet a continuous decrease in both instantaneous and residual sediment transport has been observed. The locations for the dump of sediment have therefore been defined at the channel-sections Texelstroom West and Texelstroom Bend. The asymmetry in sediment transport along the Texel Inlet is caused by the asymmetry in flow velocity. The asymmetry in sediment transport concentration along the Texel Inlet is quite weak. However the sediment transport sharply decreases at the Doove Balg. Further the ratio bed load transport – suspended load transport slightly increases along the Texel Inlet, due to decreasing water depths and instantaneous flow velocities.

The research questions can be answered based on the results of these three models.

Is it technically feasible to use the Texel Inlet as a sediment transport belt for the construction of tidal marshes at the Afsluitdijk?
Using Texel Inlet as a sediment transport belt for sediment, by means of a positive migration of dumped sediment is not feasible within a timeframe of decennia. A morphological forecast of 10 years indicates an initial diffusion of sediment in both directions, caused by a weak residual sediment transport compared to the instantaneous sediment transport. After about 5 years a positive migration of sediment is observed. For the dump of a significant amount of sediment at the channel-section Texelstroom West, respectively Texelstroom Bend, the morphological response after 10 years at the Doove Balg is insignificant. For the combination of the dump of a significant amount of sediment at channel-section Texelstroom Bend and the extraction of a significant amount of sediment at channel-section Doove Balg the morphological response after 10 years at the Doove Balg is less than one-tenth of the initial dumped sediment. The tidal lagoon system can be characterised by the great interaction between shoals and channels. Considerable amounts of sediment erodes and sedimentates at local shoals.

1. Does the Texel Inlet have a morphologically importing character?
The Texel Inlet has a morphologically importing character. The import of sediment is caused by the tidal asymmetry. The instantaneous flood flow velocity exceeds the instantaneous ebb flow velocity. The instantaneous flood sediment transport exceeds the instantaneous ebb sediment transport to a larger extend, caused by a power proportionality between flow velocity and sediment transport. Averaging the instantaneous sediment transport over a large equal number of tidal periods results in a positive directed residual sediment transport. The relaxation and diffusion effects of the sediment transport also significantly effect the residual transport field. Waves and storms also play a significant role in the determination of the residual sediment transport.

2. Which location at the Texel Inlet is most suitable as dumping location for sediment?
The significant parameters for the assessment of a location definition of the dumped sediments are the strength of the local residual sediment transport and the distance to the channel-section Doove Balg. Dump Location 1 has been defined at the channel-section Texelstroom West, where the residual sediment is relatively strong, but the distance to the Doove Balg large. Dump Location 2 has been defined at the channel-section Texelstroom Bend, where the residual sediment is relatively weak, but the distance to the Doove Balg small.

3. What is the efficiency of the sediment transport in relation to the desired sedimentation location?
The results of the morphological forecast of Dump Location 1 of Dump Location 2 show a positive migration of the dump sediment. The sediment migration magnitude however is too weak for a realistic use of significant transport towards the Afsluitdijk. For both locations the residual morphological response at the Doove Balg 10 years after dump can be considered as insignificant.

4. What is the influence of the use of a sand pit on the efficiency of the sediment transport in relation to the desired sedimentation location?
The results of the morphological forecast of the combination of Dump Location 2 and Sand Pit 1 show a positive migration of the dumped sediment towards the Doove Balg. The sedimentation at the Texelstroom East amounts 5.1 Mm³ and at the Doove Balg 0.8 Mm³. Suspended sediment transport towards the Doove Balg is however to a large extend absorbed by the western shoal. The residual sediment migration magnitude is too weak for a realistic use of significant transport towards the Afsluitdijk.

5. What is the influence of the sand transport processes on the surrounding shoals of the Texel Inlet?

Dump Location 1: The local shoals volume increases with 4.5 Mm³. The ebb-tidal delta increases with an amount of approximately 0.6 Mm³. On the east side of the Texel Inlet a decrease of sediment is observed with a total amount of approximately 0.7 Mm³. Overall it can be concluded that the shoal area increases, which can be regarded as a positive influence for flora and fauna.

Dump Location 2: The local shoals volume decreases with 2.1 Mm³. The ebb-tidal delta increases with an amount of approximately 0.5 Mm³. On the west side of the Texel Inlet an increase of sediment is observed with a total amount of approximately 1.7 Mm³. Hence the total shoal volume remains the same, while locally shoal erosion and sedimentation occurs.

Dump Location 2 and Sand Pit 1: The local shoals volume increases with +4.5 Mm³. The shoals near the channel-section Texelstroom Bend considerably decrease in volume (-3.2 Mm³). Overall it can be concluded that the total shoal volume slightly increases, while locally considerable erosion and sedimentation occurs.

7.2 Recommendations

Model application
The objectives of this thesis have been elaborated by the application of three models. The first model was a hydrodynamic-based model, using the transport formula of Engelund and Hansen. The second model was a sediment transport-based model, using the Bijker approach to theoretically calculate the distinct instantaneous bed load transport and suspended load transport. The third model was a numerical Delft3D model. For senior coastal morphologists the first two models might seem needless for elaborating the objectives. However the first two models offered me the opportunity to become familiar with the physics and to access the influence of individual processes. It is therefore recommended that inexperienced users of Delft3D use a separate theoretical model to elaborate hypotheses and considerations.

Hydrodynamic loads
This study deals with a feasibility determination of a method to use the tidal forcing of the Wadden Sea to transport sediment within the tidal inlet. Previous studies concerning the influence of distinct hydrodynamic loads on the Texel Inlet indicate a convincing dominance of the tide over waves and wind, most specifically described by [Van der Waal, 2007]. Moreover [Elias, 2006] concluded only a significant importance of waves at the ebb-tidal delta of the Texel Inlet. For the preliminary objectives of this study only the tide has been modelled as a forcing of the model boundaries. It is expected that the dominant sediment transport processes within the Texel Inlet are sufficiently well implemented in the model. This hypothesis can be further elaborated by examining the influence of wind and waves in the area of interest. In this study it was shown that the instantaneous tidal flow velocity and therefore also the instantaneous sediment transport were considerably reduced along the Texel Inlet, especially at the Doove Balg.

Sediment properties
The bed sediment of the Texel Inlet and surrounding shoals in the numerical model of this study is assumed to be homogeneous in both the vertical and the horizontal plane. Also the sediment used for human intervention was assumed to have the same properties. [Elias, 2006] has performed calculations with variable sediment properties, indicating small differences in sediment transport processes.
It is recommended to perform a distinct calculation with variable sediment properties in three dimensions to access the influence of the asymmetry of sediment properties on the sediment transport processes. Further it is recommended to perform a couple of distinct calculations with different sediment transport properties for the human interventions (dumped sediment). A considerable amplification in morphological response to the human interventions is expected if the sediment has a reduced grain size, i.e. is of a finer type like clay or silt.

**Three-dimensional computations**
The simulations in this study have been carried out with a depth-averaged model (2D-H). Therefore some three-dimensional effects like density-stratification were neglected, while others were simulated in an artificial manner like secondary flow. A comparison with a three-dimensional computation provides an estimate of the influence of three dimensional effects. It is expected that the horizontal and vertical density gradients, induced by fresh water discharge at the Afsluitdijk will have a small but significant effect on the sediment transport processes.

**Grid size**
The grid size in the model used in this study can be considered as rough. An improvement of bathymetry implementation in the model would be attained if a finer grid is used. A simulation with a more finer grid would provide insight in the band width of the simulation results in this study.

**Stability tidal marches**
The morphological forecasts show a considerable reaction of the Wadden Sea system after the dump of an amount of 16 Mm$^3$ at the Texel Inlet. The reclamation of the tidal marshes involves the dump of about 50 Mm$^3$ at the tidal lagoon system. Although pioneer vegetation is expected to stabilize the alignment of the tidal marshes, the initial phase of the tidal marshes remains critical. It is expected that the reclamation of the tidal marshes will have a considerable impact on the morphology of the Wadden Sea system. Therefore it is recommended to perform further research about the effects of the tidal marshes on the morphology of the Wadden Sea.
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