Morphological development of the Bollen van de Ooster

A potential hazard for Goeree-Overflakkee?

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TU Delft Delft University of Technology

Deltares Enabling Delta Life

waterschap Hollandse Delta

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by

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Cover: Bollen van de Ooster seen from the coast of Goeree. Photography by Maurits Groenewegen

Preface

I always like to go to the coast. It is a place where I can relax. It is a place where I love to kitesurf, experiencing the power of nature. It is fascinating that every time you return, something has changed. The shape of the beach, the waves, the flow. I think that is what inspired me to study coastal engineering. I am glad I have been given the opportunity to work on this topic, contributing to the knowledge of the Dutch coastal system.

This thesis concludes my master's degree in Hydraulic Engineering at Delft University of Technology. It was carried out at Waterschap Hollandse Delta, which provided me the opportunity to work on this interesting topic and use their facilities to conduct my research. Furthermore, this research was partly carried out at Deltares, which allowed me to use their facilities and expertise in numerical modelling. I would also like to take this opportunity to highlight a few important people who made my graduation possible.

I would like to thank my graduation committee members from the TU Delft for their guidance and support during the entire project. Stefan Aarninkhof, thank you for bringing me in contact with WSHD and your constructive feedback during the multiple meetings. It gave me new insights in my research, bringing it a step further. Sierd de Vries, thank you for your enthusiasm about my work, taking the time to discuss my findings and helping with structuring my report. Ana Colina Alonso, thank you for your interest in my work, support with working with data and the interesting discussions.

I would like to thank Rachid Abraimi for guiding me on a daily basis and always be open to discuss my work. Moreover, in general I would like to thank the colleagues of WSHD for their interest in my work and the fun times during my project. Discussions about your experiences in the field of hydraulic engineering, helped me with thinking about my career after my graduation.

I would like to thank Pieter Koen Tonnon for the hospitality to conduct part of my research at Deltares and investing time in my project. Your support with Delft3D definitely brought my research a step forward. Moreover, I would like to thank the fellow master thesis students at Deltares for sharing experiences in doing a master thesis, making the fridays very enjoyable and motivated me to keep going.

Lastly, and most importantly, I would like to thank my family and friends for their support during my whole carrier as a student, encourage me to go forward and stay motivated.

Maurits Groenewegen
Delft, November 2019

Summary

The Bollen van de Ooster, in this report referred to as the Ooster, is a sand bar in the outer delta of the Grevelingen. The Ooster is separated from the coast by a relatively deep channel, called the Schaar. Closure of the Grevelingen in 1971, with the construction of the Brouwersdam, initiated vast changes in morphology. Damming of the estuary mainly affected the tide-induced flow patterns and therefore the relative influence of the waves at the outer delta. In this study the main focus is on the morphological development near the coastline of Goeree-Overflakkee. During the past years an erosion trend of locally up to 27 m/year, just south of the Flaauwe Werk, led to concerns with Rijkswaterstaat. This erosion is caused by the migration of the Ooster along the coast. Out of precaution a beach nourishment has been planned in this area due to the potential danger for the Flaauwe Werk. However, uncertainty about the future morphological development and therefore the necessity to take measures remains. The aim of this study is to provide a better understanding in the changes that have occurred, bring more certainty about the future and therefore contribute to informed decision-making.

The coast of Goeree-Overflakkee has had a long history of coastline erosion. Closure of the Grevelingen estuary led to an increase of this erosion trend at the Westhoofd due to a combination of increased tide-induced flow velocities and morphological development of the Ooster. The latter was characterised by an eastward migration which forced the Schaar into the coastline. This process initiated multiple nourishments in the period 1969-1985. The attachment of one of the shoals of the Ooster resolved this problem, resulting in a large accumulation of sediments on the beach. In the years thereafter these sediments have been eroded as the Ooster migrated along the coast and transported further north. The latter resulted in beach widening along the coast of Goeree-Overflakkee. Due to the rapid elongation of the Ooster the erosion problems of the 80's returned.

The Schaar shows a continuous decrease in depth and flow surface since 2003, according to data analysis. Model results show that the channel mainly plays a role during low tide when the Ooster is emerged. Significant tide-induced flow velocities occur in the channel. In general, the decreasing channel dimensions lead to an increase of the magnitude of the flow in the channel. However, this occurs for a limited time duration during the full tidal cycle. A striking observation is the small influence of the wave angle on the wave-induced flow velocities near the channel. Waves coming from the north are refracted considerably due to the extension of the Haringvliet outer delta. The result is a large net longshore sediment transport rate at the seaward side of the Ooster. This could explain the pace of the migration in eastern direction. Moreover these sediments are a source for the channel, contributing to decreasing the channel dimensions. In general the presence of wind decrease the magnitude of the flow in the channel.

Based on these findings it can be concluded that the waves are the dominant forcing mechanism in shaping the morphology and attachment of the Ooster is expected to occur in the near future. Attachment of the Ooster implies the disappearing of the eroding currents. The duration at which this attachment can be expected cannot be deduced from this study. The erosion of the coastline will continue as long as the channel is present. Based on the width of the dune row and the presence of beach groynes the potential treat of the morphological development for the primary flood defences seems minor.

Samenvatting

De Bollen van de Ooster, in dit rapport beschreven als de Ooster, is een zandplaat in de voordelta van het Grevelingen. De Ooster is gescheiden van de kust door een relatief diepe geul, genaamd de Schaar. Afsluiting van het Grevelingen in 1971, met de aanleg van de Brouwersdam, heeft grote morfologische veranderingen in gang gezet. Afdamming van het estuarium heeft voornamelijk de getij gedreven stromingspatronen beïnvloed en daarmee de relatieve dominantie van golven in de voordelta. In deze studie ligt de focus op de morfologische ontwikkelingen nabij de kust van Goeree-Overflakkee. Gedurende de afgelopen jaren heeft een erosie trend van lokaal tot 27 m/jaar, ten zuiden van het Flaauwe Werk, tot zorgen geleidt bij Rijkswaterstaat. De erosie is veroorzaakt door de verplaatsing van de Ooster langs de kust. Uit voorzorg is een strandsuppletie gepland in dit gebied vanwege het potentiële gevaar voor het Flaauwe Werk. Echter, is er onzekerheid over de toekomstige morfologische ontwikkeling en daarmee de noodzakelijkheid tot het nemen van maatregelen. Het doel van deze studie is te zorgen voor een beter inzicht in de veranderingen die hebben plaatsgevonden, meer zekerheid geven over de toekomst en daarmee bijdragen aan weloverwogen besluitvorming.

De kust van Goeree-Overflakkee heeft een lange geschiedenis met erosie van de kustlijn. Afsluiting van het Grevelingen estuarium heeft geleidt tot een toename van deze erosie trend nabij het Westhoofd als gevolg van een combinatie van toegenomen getij gedreven stroomsnelheden en de morfologische ontwikkeling van de Ooster. De laatstgenoemde was gekenmerkt door een oostwaartse verplaatsing die de Schaar in de kustlijn heeft gedrukt. Dit proces heeft geleidt tot verscheidene suppleties in de periode 1969-1985. De aanlanding van één van de zandplaten van de Ooster heeft dit probleem opgelost. Dit leidde tot een grote ophoping van sediment op het strand. In de jaren daarna is dit sediment geërodeerd toen de Ooster verplaatste lang de kust en verder noordwaarts getransporteerd. Dat laatste heeft gezorgd voor een uitbreiding van het strand langs de kust van Goeree-Overflakkee. Vanwege de snelle verlenging van de Ooster zijn de erosie problemen van de jaren 80 teruggekeerd.

De Schaar laat een geleidelijke verkleining van de diepte en doorstromingsoppervlak zien sinds 2003, volgens de data analyse. Model resultaten laten zien dat de geul met name een grote rol speelt gedurende laag water wanneer de Ooster droog valt. Significante getij gedreven stroomsnelheden vinden plaats in de geul. Echter, dit gebeurt gedurende een korte periode binnen de gehele getijde cyclus. Een opvallende constatering is de kleine invloed van de golf richting op de golf gedreven stroomsnelheden nabij de geul. Golven vanuit het noorden ervaren een aanzienlijke refractie vanwege de Haringvliet voordelta. Het resultaat is een groot netto langs sediment transport aan de zeewaartse zijde van de Ooster. Dit kan de snelheid van de oostwaartse verplaatsing verklaren. Bovendien zijn deze sedimenten een bron van sediment voor de geul, en dragen daarmee bij aan het verkleinen van de geul afmetingen. In het algemeen zorgt de aanwezigheid van wind voor een verkleining van de grootte van de stroming in de geul.

Op basis van deze bevindingen kan worden geconcludeerd dat de golven een dominant mechanisme zijn in het vormen van de morfologie en kan een aanlanding van de Ooster worden verwacht in de nabije toekomst. Aanlanding van de Ooster impliceert dat de erosieve stromingen verdwijnen. De tijdduur waarop deze aanlanding kan worden verwacht kan niet uit deze studie worden opgemaakt. De erosie van de kustlijn zal voorduren zo lang de geul aanwezig is. Op basis van de breedte van de duinen rij en de aanwezigheid van strandhoofden lijkt het potentiële gevaar van de morfologische ontwikkeling klein.

Contents

1

Introduction

In this chapter the subject of this thesis is introduced. A concise description of the study area is provided. It addresses the current issues in the study area which expresses the relevance of this research. The objective is defined with the formulation of the research questions. Lastly, the approach and structure of the report are described.

1.1. Study area

The Bollen van de Ooster, hereafter referred to as the Ooster, is a sandbar located in the outer delta of the Grevelingen. The Grevelingen is one of the five (former) estuaries in the southwestern delta of the Netherlands. With a length of approximately eight kilometers, the Ooster covers a large part of the Grevelingen outer delta. It extents from the middle of the outer delta to nearby the coastline of the Westhoofd, the western tip of the island Goeree-Overflakkee. The shoal is separated from the Westhoofd by a channel called the Schaar. Figure 1.1 illustrates the layout of these components within the southwestern delta. The presence of the Ooster is important for the habitat of seals, which use the shoal as a resting area, and all kinds of birds, which use the Ooster for foraging, resting and moulting (Rijkswaterstaat, 2018b). Because of these natural values the Ooster has received a protected status within the Natura 2000-area Voordelta. In this report the word 'outer delta' is used to indicate the Grevelingen outer delta, the area seaward of the Brouwersdam, and not the complete Natura 2000-area if not explicitly stated otherwise.

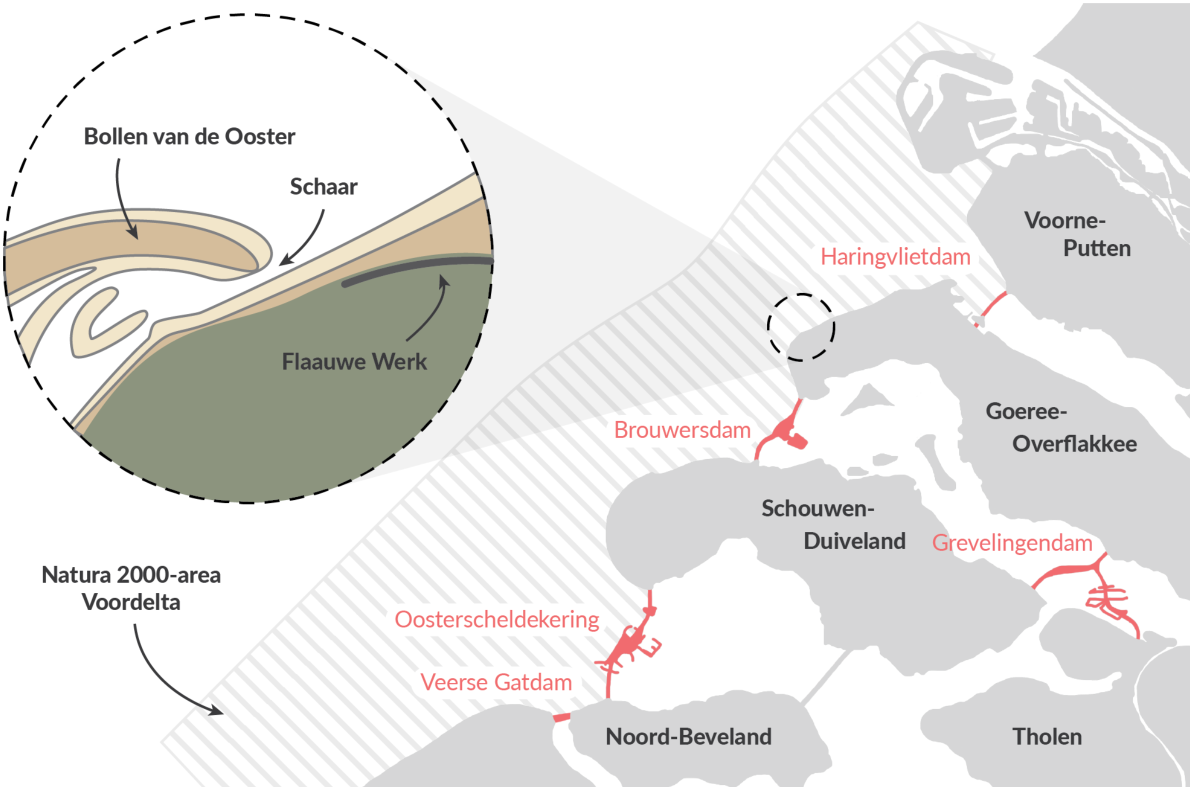


Figure 1.1: Overview of the study area. The southwestern delta in the Netherlands with a closeup of eastern edge of the Ooster near the coastline of Goeree-Overflakkee. The position of the Schaar and Flaauwe Werk are indicated in the closeup. The Delta Works are highlighted in red. Moreover the Natura 2000-area Voordelta is indicated.

1.1.1. Anthropogenic interferences and morphological evolution

The southwestern delta has been under the influence of anthropogenic interferences since the 1950s. In 1950 the construction of the Delta Works began with the closure of the Brielse Gat. This was the result of studies of Rijkswaterstaat since 1937, which indicated that the safety of the Netherlands during large storms and high water levels could not be guaranteed (Stichting Deltawerken Online, nd). The 'Verlandingsplan' and later called the 'Deltaplan' was developed including the plans for closure of the river estuaries Oosterschelde, Haringvliet, Grevelingen and Brielse Gat. The purpose of the Delta Works was to shorten the Dutch coastline in order to reduce the length of dikes that had to be raised. Additionally it created opportunities to establish freshwater basins for agriculture and drinking water facilities. After the flood in 1953, during which 1835 people were killed, the importance of this plan became clear and the execution of the plan was accelerated (Stichting Deltawerken Online, nd).

The Brouwersdam was the seventh structure of the Delta Works constructed after the flood of 1953. The Brouwersdam is a dam which completely blocked of the Grevelingen estuary, allowing no flow between the sea and the water basin landward of the dam. The execution of this structure began in 1962 and was finished in 1971. In the meantime the Grevelingendam was finished in 1965 closing of the eastside of the estuary. The Grevelingendam reduced the tidal volume already with approximately 14% (Haring, 1978). In between these structures a salt lake emerged which is called the Grevelingen Lake (in Dutch: Grevelingenmeer). The construction of the Brouwersdam had and still has enormous implications on either side of the dam. In the Grevelingen Lake mainly in terms of water quality and in the Grevelingen outer delta this is reflected by vast changes in morphology. The latter is illustrated in Figure 1.2.

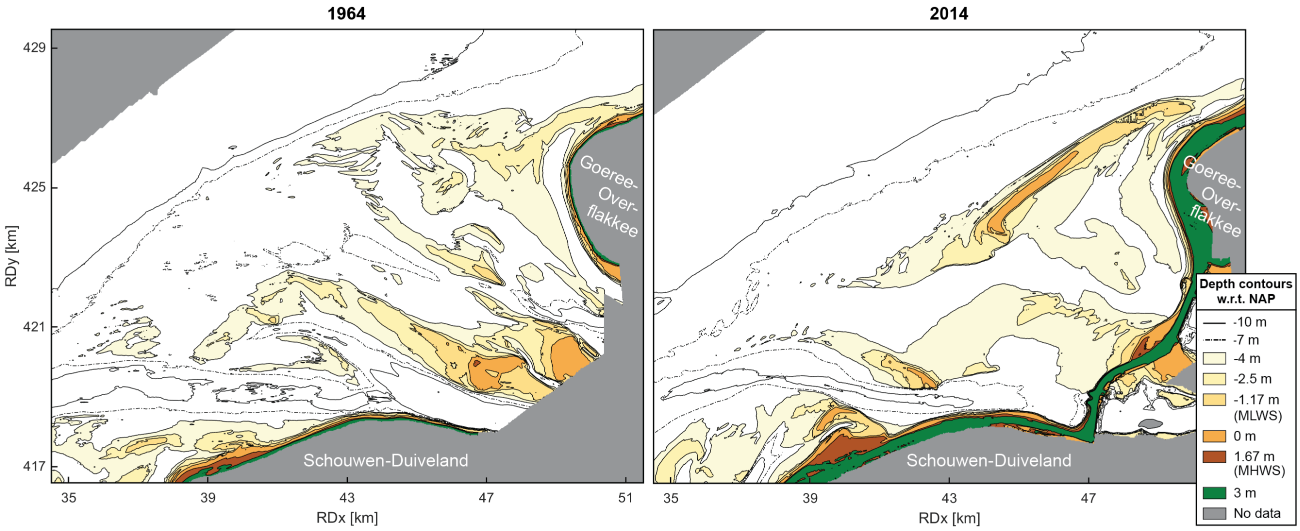


Figure 1.2: Evolution of the Grevelingen outer delta between 1964 and 2014, derived from the Vaklodingen dataset. The left picture, the morphology of 1964, is the initial situation before closure of the estuary. The outer delta edge had a spherical shape, the shoals were generally east-west orientated and the depth gradients were relatively large. The right picture, the morphology of 2014, is the last available measurement in the Grevelingen outer delta. The outer delta edge has been eroded, the Ooster was developed into a intertidal shoal at the outer delta edge and depth gradients reduced.

The emergence of a shore parallel sandbar, known as the Ooster, was one of these morphological changes. Apart from the outer delta, also the downdrift coast of Goeree-Overflakkee experienced significant changes in morphology. This coast has known periods of erosion and accretion over the years which led to large variations in the coastline position. Figure 1.3 shows aerial pictures, taken in northeastern direction along the coast of Goeree-Overflakkee, which reveals the deformation of the beach. Furthermore it shows the position of the Flaauwe Werk, a sea dike part of the flood defences of Goeree-Overflakkee, and the groyne field in front.

In recent years a local erosion trend just south of the Flaauwe Werk led to concerns with Rijkswaterstaat (RWS). The coastline shows a landward directed trend locally up to 27 m/year according to Rijkswaterstaat (2018a). In general, RWS is responsible for monitoring and maintaining the position of the coastline. Since 1990 a reference coastline has been defined which in principle may not be exceeded by the instantaneous

(a) Situation in 1987
(Rijkswaterstaat, ndb)

(b) Situation in 2005
(Hollandse Delta, 2016)

(c) Situation in 2018
(Google, nd)

Figure 1.3: Morphological evolution at the coast of Goeree-Overflakkee in front of the Flaauwe Werk

coastline. The first is known as the 'Basiskustlijn' (BKL) and has the purpose to indicate coastal erosion (Rijkswaterstaat, 2018a). The latter is known as the 'Momentane Kustlijn' (MKL) and is derived on a yearly basis (Rijkswaterstaat, 2018a). Based on the 10 year trend of the MKL, RWS determines the necessity to intervene usually by the application of a nourishment (Rijkswaterstaat, 2018a). However the decision to apply a nourishment in case of a BKL exceedance depends on the local circumstances. It depends on whether the erosion is considered as structural or temporal. Structural erosion entails the situation when there is long-term erosion of a stretch of coast. Moreover it depends on the impact on the functions of the coastal zone. These functions are related to recreation, nature, drinking water areas and water safety.

The observed erosion trend at Goeree-Overflakkee is considered to be temporal according to RWS (R. Hoogland, personal communication, 14 February 2019), however the effect on the local primary flood defences, and therefore the water safety, is considered to be potentially negative. Nonetheless questions remain about the future morphological evolution, and therefore the necessity to take measures in this area. Out of precaution RWS has included a beach nourishment in their nourishment program 2020-2023 for this particular location (Rijkswaterstaat, 2019) and is planned to be executed in the period 2020-2021.

1.1.2. Prospective changes of the hydraulic boundary conditions

Recently the deteriorated water quality in the Grevelingen Lake, as a result of the Brouwersdam, has led to a plan to realize a passage in the Brouwersdam. The lack of flow and refreshment in the lake resulted in absence of oxygen in the deeper channel, particularly in the summer period, and therefore dying of bottom life (Houtekamer & Van Kleef, 2016). The construction of a passage in the Brouwersdam is suggested to set the water into motion by allowing a reduced tide into the Grevelingen Lake and therefore improve the water quality. Additionally the passage is an opportunity to generate sustainable energy by an tidal power station.

The consequences of such a passage will also be of influence on the other side of the Brouwersdam, the outer delta. It will introduce changes in flow patterns and therefore affect the morphological development to a certain extent. Moreover it might be of influence on the erosion trend at the coast of Goeree-Overflakkee which RWS is currently facing.

1.2. Relevance of the research

The water managers in the study area, including RWS and the local waterboard, Waterschap Hollandse Delta (WSHD), are currently missing sufficient certainty about the morphological developments impacting the coast of Goeree-Overflakkee and therefore the necessity to take protective measures. In the past several studies have been conducted into the effects of large-scale engineering on the outer deltas in the southwestern part of the Netherlands. Here large-scale engineering is related to the Delta Works and the port expansion of Rotterdam, known as the Maasvlakte. Elias et al. (2016) provides a concise overview of morphological changes and sediment budget in the southwestern delta in the period 1964-2012. Furthermore the situation at the coast of Goeree-Overflakkee has also been considered specifically. Elias (2015) evaluated the effects of a channel slope nourishment (in Dutch: geulwandsuppletie) in the Schaar with a brief study using measured data and model simulations. Concluded was that a natural arrival of the Ooster at the coast of Goeree-Overflakkee could not be deduced from the data. With respect to the changing hydraulic boundary conditions by the construction of a passage in the Brouwersdam, experts expect that a new passage will result in a decrease in tidal flow velocities through the Schaar due to the damping effect of the passage on the water levels (Houtekamer & Van Kleef, 2016). Therefore they suspect that the likelihood of an arrival of the Ooster to the coast of Goeree will increase in case of a new passage, however the uncertainty about this event is high.

1.3. Objective and research questions

This research aims to provide a better understanding in the changes that have occurred and moreover bring more certainty about the future. It is meant to provide a better estimate about the potential threat Goeree-Overflakkee will experience in the near future and therefore contribute to informed decision-making. Hereby the focus lies on the natural dynamics without the implementation of a nourishment, implementation of a passage in the Brouwersdam or other interventions. The effects of a passage are discussed, but no extensive model simulations are performed for this purpose. Due to the rapid morphological development, and implicit erosion trend at the coast of Goeree-Overflakkee, recent data will provide new information.

This objective has resulted in the following main research question that will be answered in this thesis:

Is the future morphological development of the Ooster a potential hazard for Goeree-Overflakkee?

In order to provide an answer to this question knowledge of the morphological developments in the past is required. Not only the morphological developments near the coast of Goeree-Overflakkee but also on the scale of the entire Grevelingen outer delta, to obtain a conceptual understanding how the system is adapting to the anthropogenic interferences. Furthermore knowledge about the prevailing forcing mechanisms is key to elaborate on why these changes occur. These considerations have led to three consecutive sub-questions:

1. What has been the morphological evolution of the Ooster and the Schaar since the construction of the Brouwersdam in the Grevelingen estuary?
2. What are the characteristics of the water motion, which mechanisms are most dominant, and how does this lead to the current morphology of the Ooster?
3. What is the expected morphological development of the Ooster in the case of non-changing hydraulic boundary conditions?

1.4. Approach and thesis structure

A methodological approach has been used consisting out of three steps to conduct this research: a literature study, data analysis and a modelling study. The literature study has the purpose to get acquainted with the study area, developments in the past and the current state of knowledge about the subject. This closely resembles chapter 2, Background. A data analysis has been applied to evaluate the morphological changes and provide a conceptual understanding of the dynamics. This can be found in chapter 3 and provide an answer to sub-question 1. Subsequently the modelling study provides insight into the prevailing hydrodynamics and gives understanding of the origin of the changes in morphology. This can be found in chapter 4 and provides an answer to sub-question 2. Thereafter the results of the these three segments are used to elaborate on the future developments in chapter 5. This chapter answers sub-question 3. The thesis is finalized with a discussion, conclusion and recommendations. Figure 1.4 provides a visual representation of the report structure.

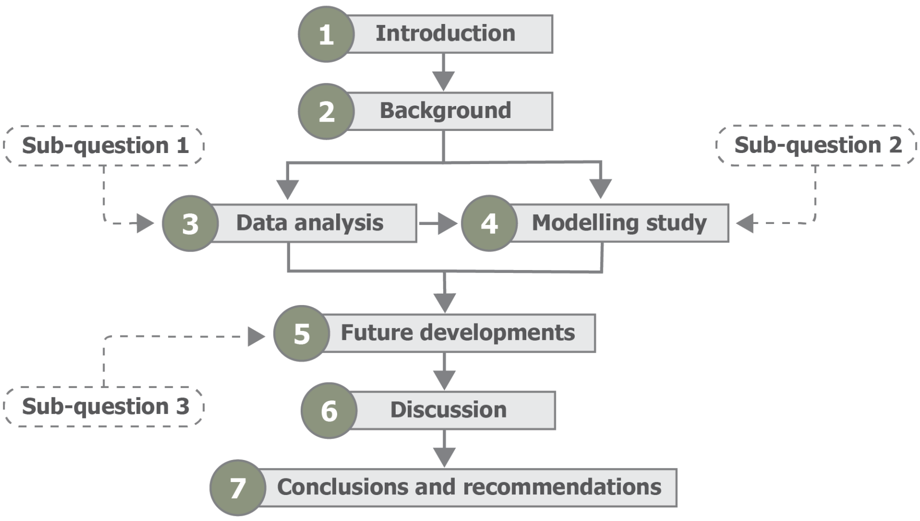


Figure 1.4: Structure of the report

2 Background

In this chapter general background information is given to provide a better understanding of the hydrodynamic changes in the study area. Thereafter, the coastal maintenance in the area is elaborated. Furthermore, a description is given about the present primary flood defences. Lastly, similar morphological development after inlet closures is discussed.

2.1. Coastal inlets and consequences of a closure

In the introduction the vast changes in morphology in the Grevelingen outer delta as a result of anthropogenic interferences have been introduced. Figure 1.2 showed the evolution the Grevelingen outer delta went through in the previous half a century. In order to understand why these changes took place some theoretical background is required, and is therefore provided in this chapter.

2.1.1. Tidal inlet system

The outer delta of the Grevelingen, in literature also referred to as ebb-tidal delta, is part of a larger system which is called a tidal inlet system. Figure 2.1 shows a schematic illustration of such a system indicating the different morphological elements. Different types of tidal inlet systems exist depending on the relative influence of the prevailing hydrodynamic processes, for example fresh-water run-off, waves, tide and wind. Due to changes in water level at sea, as a result of the tidal propagation along the Dutch coast, flow will be induced in and out of the estuary, and therefore shaping the morphology. The result is a complex system of channels and flats. The outer delta is the result of tide-induced flow directed out of the estuary, where the flow velocities decreases as is diverges from the inlet and as a consequence sediments are deposited (Bosboom and Stive, 2015). The volume of the outer delta is related to the water volume that is being discharged through the inlet during a tidal cycle, also known as the tidal prism. The extension of the outer delta is limited by the waves which induce a net onshore directed movement of sediments. Waves act as a bulldozer on the tidal inlet morphology (Hageman, 1969).

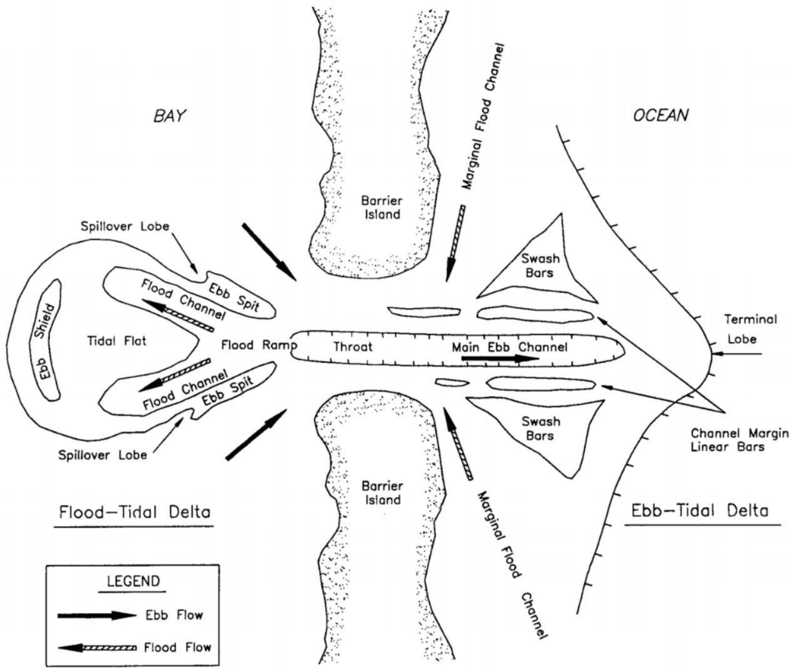


Figure 2.1: Morphological elements of a tidal inlet (Boothroyd, 1985)

2.1.2. Changes in the hydrodynamics after closure

The construction of the Brouwersdam led to an abrupt change in the prevailing hydrodynamic processes. The tidal flow was disturbed due to the separation of the outer delta from its basin. The result was a significant decrease in tidal prism and therefore the relative influence of the tide reduced. The wave forcing was not affected directly by the closure of the estuary and therefore became relatively more dominant. The effect was a net sediment transport in landward direction as a result of the reduced seaward directed sediment transport by the ebb-tidal currents (Elias et al., 2016). In terms of morphology this led to erosion of the outer delta edge and the formation of sand bars on the edge of the outer delta (Elias et al., 2016). In the Grevelingen outer delta this led to the formation of the Ooster. Besides the reduced tidal flow, the orientation of the tidal propagation changed. This is illustrated in Figure 2.2 which shows the isolines for the phase of the M2-tide, before and after the closure of the Grevelingen. It shows that at the outer delta the orientation of the tidal propagation changed from a mainly east-west orientation to a north-south orientation.

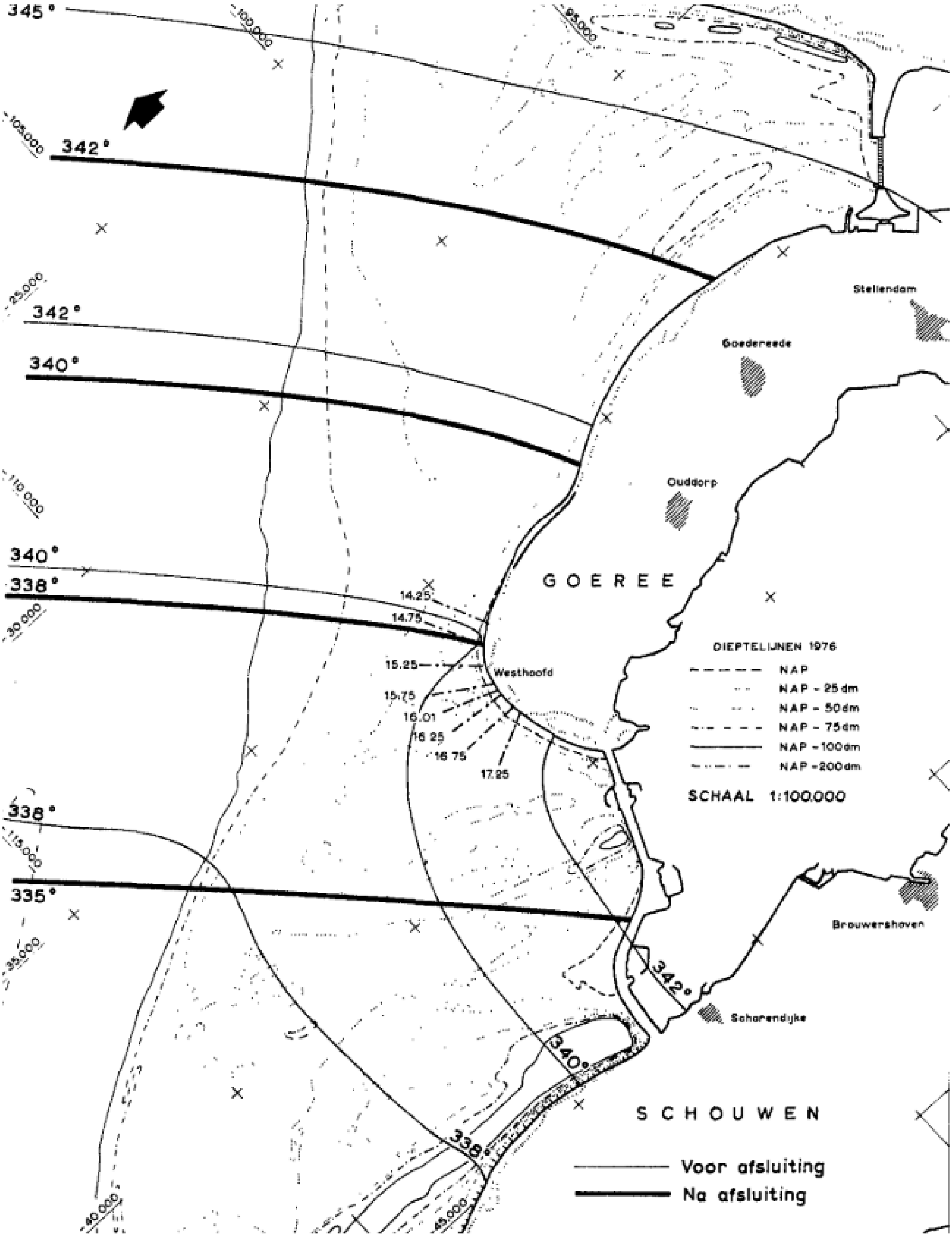


Figure 2.2: Isolines for the phase of the M2-tide before (thin line) and after (thick line) closure of the Grevelingen estuary and Haringvliet (Bakker, 1980). The orientation of the tidal propagation changed at the Grevelingen outer delta from east-west to north-south. In the situation before closure, a distribution point was located at the Westhoofd.

The abrupt change in the system also affected the flow patterns and magnitude of the tide induced flow in the Schaar. Rijkswaterstaat (1973) gives a detailed description of the flow patterns near the Westhoofd during different stages of the tidal cycle. It elaborates on the situation before and after the closure based on field measurements and tide calculation. The findings from this research are elaborated below.

In the situation before the closure the flow in the Schaar was mainly determined by the water level gradient between the Haringvliet and the Grevelingen estuary. This gradient was the result of a phase difference in the tidal propagation between both estuaries, since the flow reversal in the Grevelingen occurred earlier than in the Haringvliet. Figure 2.3 shows a schematization of the tide induced currents during different stages before closure. In general the tidal currents at sea (in deeper water) and in the Schaar were oppositely directed. Furthermore the current reversal, which is known as the horizontal tide, coincided with the vertical tide, high water (HW) and low water (LW).

The first picture illustrates the flow patterns in the period before HW (2h - 0h before HW) when both the Haringlvliet and Grevelingen were being filled. A distribution point was located at the Westhoofd near JarKus transect 1500. Note that this distribution point is also recognizable at the 340° isoline in Figure 2.2. During this stage the tide induced flow was directed over the Ooster. After HW (second picture), the flow in the Grevelingen inlet was reversed (in seaward direction) while the Haringvliet was still being filled. This phase differences resulted in relatively large velocites around the Westhoofd, particularly southward of transect 1500. At transect 1500 the velocities decreased significantly resulting in a sandbar at this location. This situation continued until currents in the Haringvliet also reversed between 2 and 3 hours after HW (3th picture), gradually reducing the currents through the Schaar. Approximately 4 hours after HW (4th picture) a similar situation arose as in picture 1 but with reversed current directions. At transect 1500 the water from the Haringvliet and Grevelingen met. As time proceeded this point migrated southward when the ebb-currents from the Grevelingen inlet reduced and ebb-currents from the Haringvliet were larger (5th picture). This led to the situation where water from the Haringvliet flowed into the Grevelingen (6th picture). This flow gradually reduced over time between 6 and 3 hours before high water (7th picture) until the flood came in and the distribution point was moved towards transect 1500 again (picture 1). Overall it was found that the northward flow through the Schaar was much larger than the southward directed flow. This lead to a net sediment transport in northward direction according to sediment transport calculations.

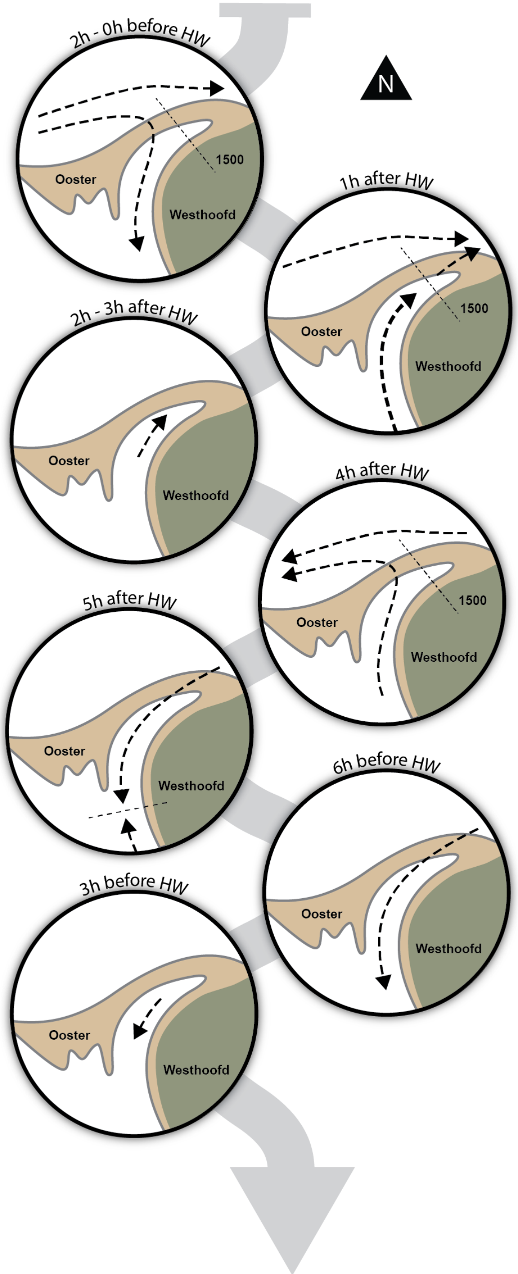


Figure 2.3: Tide induced currents around the Westhoofd before the closure of the estuaries, based on Rijkswaterstaat (1973). The Grevelingen estuary is located south of this location. The Haringvliet estuary is located northeast of this location.

After closure of both estuaries, the tide-induced current in the Schaar became much more depending on the tidal propagation at sea. This situation is schematized in Figure 2.4. The flow in the Schaar was roughly in phase with with the flow at sea. With respect to the magnitude of the tide induced flow, the maximum velocities increased significantly at the Westhoofd, particularly in northward direction during high water.

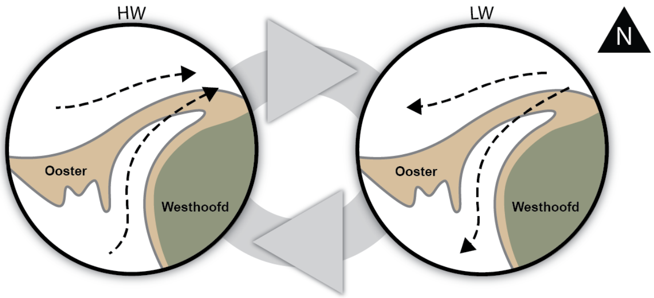


Figure 2.4: Tide induced currents around the Westhoofd after the closure of the estuaries, based on Rijkswaterstaat (1973). The Grevelingen estuary is located south of this location. The Haringvliet estuary is located northeast of this location.

2.2. Coastal maintenance

Since 1990 the Dutch coastal system is maintained according to the Dynamic Preservation policy, which was introduced to stop the structural coastal erosion and preserve the coastline of 1990, the Basiskustlijn (BKL). The method used by RWS to assess this coastline position has been briefly discussed in Section 1.1.1. This section elaborates on the coastal maintenance in the study area to get insight into the non-natural volume changes in the system. Table 2.1 gives an overview of the applied sand nourishments in the Westhoofd area and in front of the Flaauwe Werk (between transects 1145 and 1285).

Table 2.1: Sand nourishment at the Westhoofd in the period 1966-2017 (Mastbergen and Nederhoff, 2018)

Year of implementation	Begin transect	End transect	Length [m]	Volume [m^3]
1969-1970	1300	1500	2000	401,000
1971-1971	1501	1601	1000	610,000
1973-1974	1450	1750	3000	2,300,000
1977-1977	1450	1750	3000	1,267,000
1984-1984	1450	1750	3000	330,000
1985-1985	1450	1750	3000	530,000
1994-1994	1025	1200	1750	505.678
2004-2004	1025	1275	2500	920,424
2005-2005	1550	1875	3250	1,000,552
2016-2016	1525	1725	2000	500,000

In the period 1969 till 1985 multiple nourishments have been executed at the Westhoofd area between transects 1450 and 1750 with a total volume of approximately 5.5 million m^3. After 1985 no new nourishments have been executed in this area until 2005. The former period was characterized by a regression of the coastline which formed the basis of these nourishments (Bakker, 1980, Rijkswaterstaat, 1973). In this period of time multiple reports have been published about the situation, predictions about the future and possible measures to counteract this coastal erosion trend. Figure 2.5 reveals the landward migration of the coastline in history. According to Rijkswaterstaat (1973) the annual coastal erosion since the turn of the century of 1900 was approximately 7 m. In the period after the closure the coastal erosion increased to approximately 20 m per year (Rijkswaterstaat, 1979). This increase was probably the result of the increased flow velocities around the Westhoofd, described in section 2.1.2.

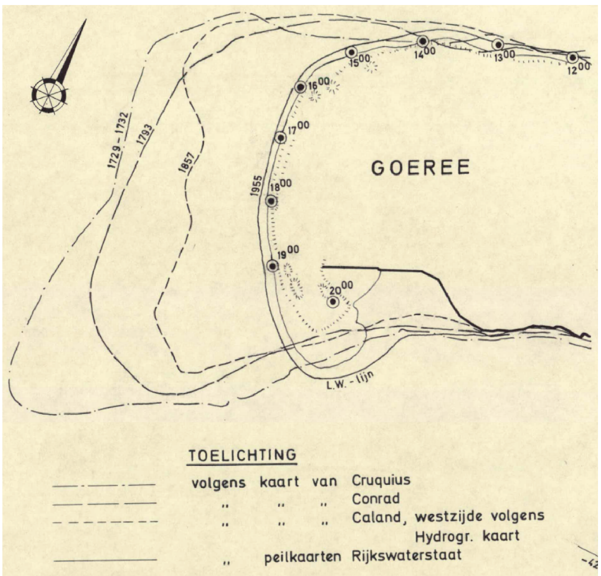


Figure 2.5: History of the coastline of Goeree (Rijkswaterstaat, 1973)

This rapid increase led to several nourishments. A plan was proposed to construct a sand dam which would close off the Schaar in order to protect the Westhoofd from further erosion. This plan has been further elaborated by Bakker (1980). Bakker (1980) studied the changes in sediment transport that would occur in case of an interference in the system among which the construction of a sand dam or a 'normal' nourishment. A sketch of this proposed sand dam on top of the morphological situation around 1980 is shown in Figure 2.6. Note that the Ooster was not yet developed into one shoal at this time. There was a so-called short-circuit channel (in Dutch: Kortsluitgeul) present separating the individual shoals of the Ooster. The position of this channel was described as highly unstable as both inflow and outflow of the estuary and waves at the shallow shoal did affect this channel (Bakker, 1980).

Bakker (1980) concluded that a sand dam would be beneficial in stopping the coastal erosion during its lifetime, which was estimated at 10 to 30 year depending on the layout of the sand dam. However the sand volume necessary for the sand dam would be larger than a regular nourishments. Furthermore the morphological situation after disappearance of the sand dam was considered to be less favourable. Therefore the normal nourishments were applied until 1985. Thereafter the erosion trend disappeared as a result of natural morphological developments. The latter is discussed in chapter 3.

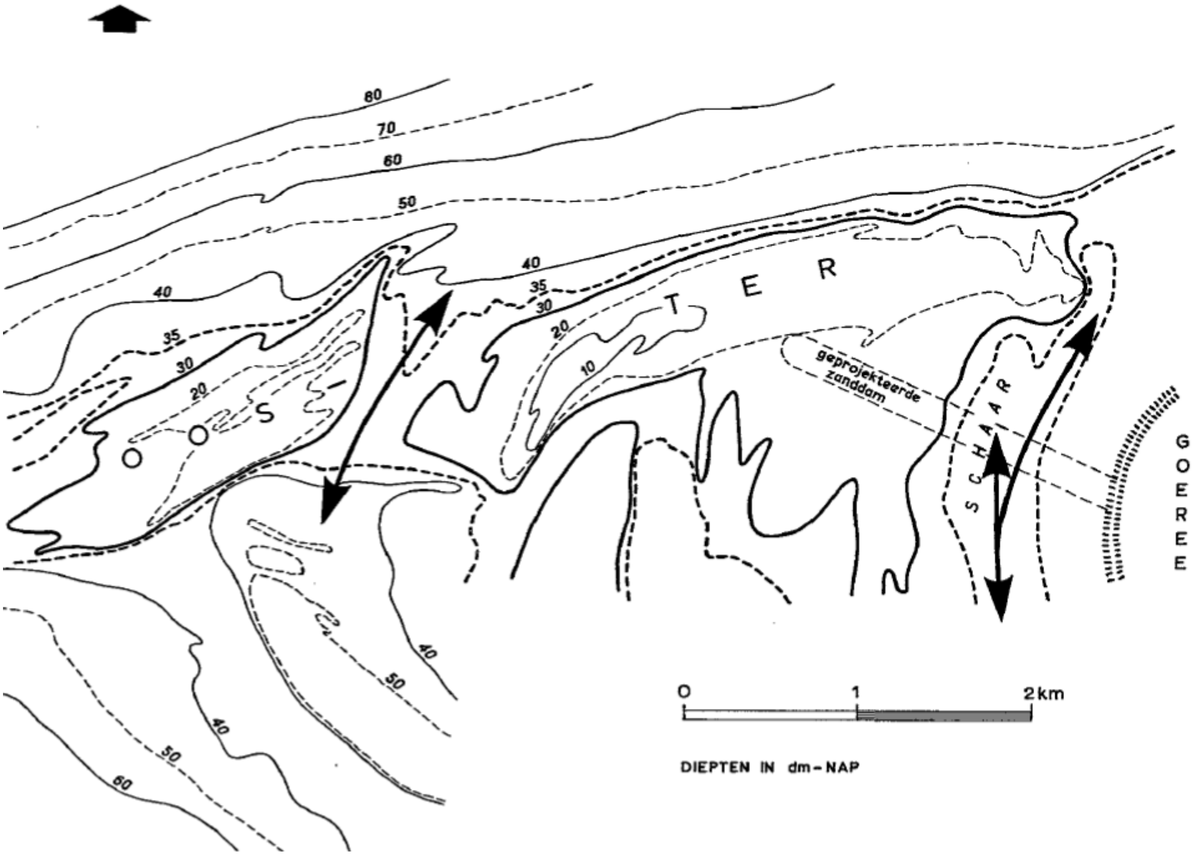


Figure 2.6: Morphological situation around 1980 with the Ooster including the short-circuit channel and the proposed sand dam to close off the Schaar. (Bakker, 1980)

The present-day erosion trend at the coastline of Goeree led to a new proposed nourishment (Rijkswaterstaat, 2019). Commissioned by Rijkswaterstaat, Deltares conducted an investigation into the morphological effects of a channel slope nourishment (in Dutch: geulwandsuppletie) to assess the efficiency to execute this nourishment (Elias, 2015). Elias (2015) performed Delft3D model simulations comparing different nourishment alternatives with the reference situation without human intervention. The morphological changes have been assessed by considering the modelled residual flow as an indicator for sediment transport, and is therefore called an initial study into the morphological effects. Elias (2015) concluded that the occurrence of a natural arrival of the Ooster to the coast of Goeree could not be deduced from measurement data. However, based on a clear landward trend in 2013 which has resulted in a buckling point in the inflow channel, a natural arrival to the coast could be expected. Based on the simulation it was concluded that the nourishment will decrease the process of movement of the Ooster and the evasive channels towards the coast, however it is unknown how the system will behave on the long term. Complete filling of the channel will change the morphological characteristics of the area and the effects are therefore hard to predict based on this initial study. Finally it was appointed that the formation of a new tidal channel through the Ooster could not be excluded as these type of sand banks do not have infinitely long stability. The latter conclusion is based on the developments of the Hinderplaat in the Haringvliet outer delta (see section 2.4).

Because of the uncertainty about the future morphological development and the not decreasing erosion trend, which might compromise the hard flood defence the Flaauwe Werk, RWS made the dicision to include a nourishment at this location as part of their nourishment program 2020-2023. From the point of view of practicability, a beach nourishment is planned because the execution of a channel slope nourishment is difficult to implement in this channel (R. Hoogland, personal communication, 14 February 2019). A beach nourishment means sand will be added on the dry beach. This will compensate for the eroded sediments such that there will be enough sand volume present in front of the hard flood defence.

2.3. Primary flood defences

According to Rijkswaterstaat (2019) the decision to apply a nourishment is related to the functioning of the hard flood defence, the Flaauwe Werk. Rijkswaterstaat (2019) states that the presence of a foreshore is important for the stability of the dike. The Flaauwe Werk is part of dike section 25-1, which extents from the Brouwersdam till Stellendam with a length of 16.7 km. The majority of this dike section consists out of dunes. The Flaauwe Werk is located between transects 1200-1325. Since January 1st, 1997 the responsibility for the head of Goeree was transferred from RWS to the local waterboard, Waterschap Goeree-Overflakkee, currently part of Waterschap Hollandse Delta. At that time a transfer document was composed by Van Dijk (1997) in which the history of this part of the Dutch coast was described. A small summary of this document is elaborated here. The head of Goeree has a large history of continuous beach and dune erosion among others due to the unpredictable currents, which required measures in order to protect the hinterland from flooding. The

Figure 2.7: Aerial photograph of the Flaauwe Werk in 1953 (Rijkswaterstaat, ndb)

original dyke was probably built in the second half of the 18th century, however the precise year in which the dyke was built is no longer traceable. The first dyke was a clay dyke in combination with beach groynes which where constructed to keep the currents away from the beach. After the construction there were periods in which the dyke was completely covered with sand. The dyke was irreversibly damaged during the flood of 1953 which has led to the construction of a new dyke inland. Figure 2.7 shows the situation in 1953 after the flood with the ongoing construction of the current dyke. The new dyke was built from sand covered with an asfalt layer. Later on the dyke has been reinforced multiple times. The Flaauwe Werk was one of the weak links (in Dutch: zwakke schakels) in the Dutch coastal system. The most recent reinforcement was in 2008 including a crest elevation and landward widening of the dyke. Currently the Flaauwe Werk is not directly recognizable as a dyke as it is completely covered with sand, however it is being assessed as a dyke, the sand has no water retaining function (Van Dienst, 2018).

In front of the Flaauwe Werk beach groynes are present which are currently covered with sand for the largest part. Figure 1.3a shows the layout of the groynes. In the current morphological configuration only a small tip of one of these groynes reveal the presence of these structures. During a reinforcement of the dyke around the year 1984 some groynes were extended backwards to the dyke. In the current assessment by RWS these groynes do not play a role anymore and are not being maintained (G. Ramaekers, personal communication, 23 May 2019). However in case the beach erosion in front of the Flaauwe Werk will continue, these groynes will affect the morphological development.

In the current morphological state the most severe erosion rates occur further south where the flood defence is composed out of dunes. The reduced beach width does affect the appearance of these dunes as can be seen in Figure 2.8. Figure 2.8a is a picture of the dune row directly behind the Ooster and Figure 2.8b in further north towards the Flaauwe Werk.

(a) Dunes behind the Ooster

(b) Dunes in eastward of the Ooster

Figure 2.8: Current state of the dunes south of the Flaauwe Werk. The red mark indicates the location where the picture was taken. Figure 2.8b shows the dune erosion as a result of the local coastline erosion.

2.4. Similar morphological evolution after inlet closures

The morphological evolution of the outer delta and the development of a shore parallel sand bar after the closure of the estuary is not an unique event in the Dutch coastal system. Similar evolution can be observed in the Haringvliet outer delta, in the form of the Hinderplaat, shown in Figure 2.9b. This sandbar was formed after the construction of the Haringvlietdam in the period 1965-1970. Further back in history the closure of the Brielse Gat in 1950 resulted in a shore parallel sand bar named the Westplaat. The latter was used for the expansion of the Port of Rotterdam and therefore no longer exists.

(a) Westplaat in 1961 (Terwindt, 1964)

(b) Hinderplaat in 1987 (Rijkswaterstaat, ndb)

Figure 2.9: Comparable cases of morphological development after an estuary closure

The Hinderplaat showed many similarities with the Ooster in terms of location, orientation and evolution within the outer delta. It states 'showed' because the shoal breached in 1995 mainly due to a high discharge event in 1995 (Colina Alonso, 2018). Before this event occurred the shoal migrated landwards, became longer and increased in height until the Hinderplaat lowered in 1992 (Colina Alonso, 2018). Although there are many similarities between the Hinderplaat and the Ooster, there are also some differences in terms of surroundings that are worth mentioning. Firstly the Haringvlietdam is not a completely closed boundary like the Brouwersdam. Fresh water from upstream is discharged in sea through the sluices in the dam, inducing currents on the outer delta and therefore impacting the morphology. Until 2018 only outflow (during ebb) was permitted, however a recent change in policy is the introduction of the 'Kierbesluit' allowing a reduced tide into the Haringvliet estuary by a partly opening of the sluices. Secondly the Haringvliet area has been influenced by the construction of multiple land reclamations. The stepwise extension of the Port of Rotterdam, with the construction of Maasvlakte 1 (1967-1976), the Slufter (1986-1987) and Maasvlakte 2 (2008-2013), resulted in changing flow patterns and sheltering of the outer delta from waves from northern direction.

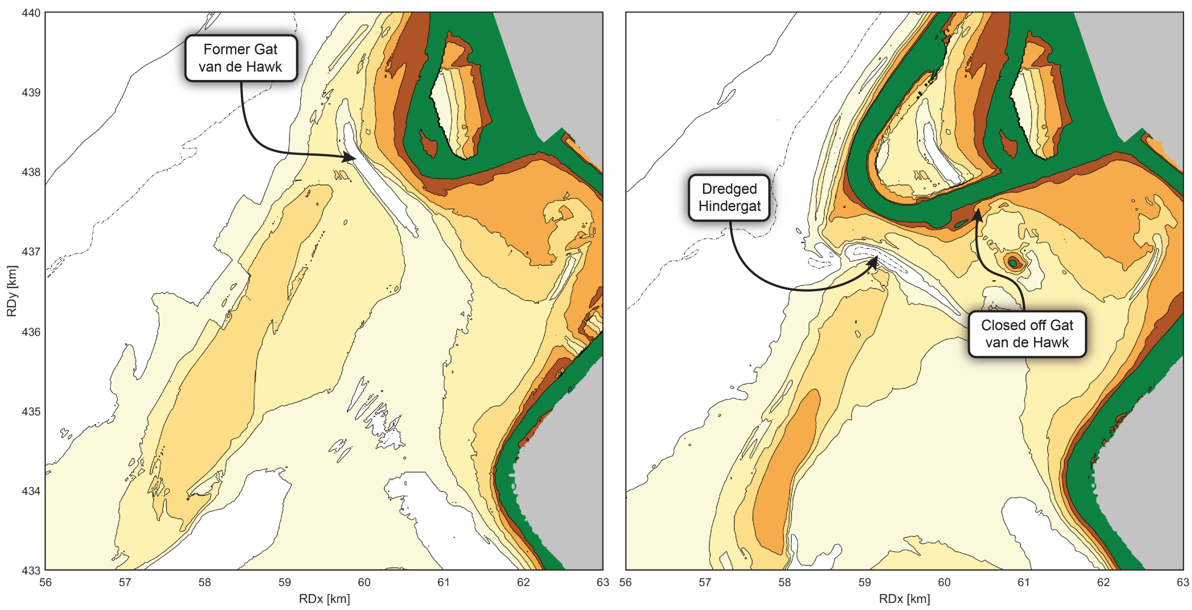


Figure 2.10: Hinderplaat and tidal channel before (1986) and after (1989) construction of the Slufter, derived from the Vaklodingen dataset

Mainly the construction of the Slufter led to severe changes near the Hinderplaat. The construction of the Slufter closed of the channel Gat van de Hawk which separated the Hinderplaat from the beach. A new channel was dredged further south which is called the Hindergat. Figure 2.10 shows the situation before (1986) and after (1989) the construction of the Slufter. The orientation and position of the Hinderplaat with respect to the coastline in 1986 shows many similarities with the Ooster in the mid-nineties. Apart from the discharge event in 1995 this influenced the morphogical developement of the Hinderplaat.

A comparison of cross-sections of the latest measurement of the Ooster and the Hinderplaat just before the breaching event is shown in Figure 2.11. These cross-sections are taken in the middle of both shoals. The seaward side of the Hinderplaat in 1992 was relatively higher compared to the Ooster in 2013. Furthermore the profile of the Ooster near the highest point is narrower and steeper. In Appendix A more cross-section profiles are compared, showing similar trends. Therefore, based on the morphology, the Ooster is expected to be less stable than the Hinderplaat. However, breaching of the Hinderplaat shows that the development of Hinderplaat and the Ooster cannot be related one-to-one.

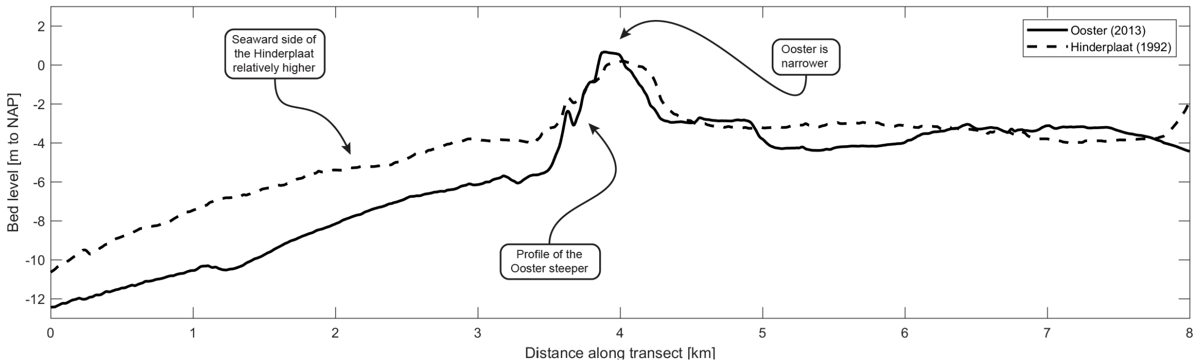


Figure 2.11: Comparison of cross-sections of the Hinderplaat in 1992 and Ooster in 2013, derived from the Vaklodingen dataset

2.5. Summary

In this chapter it was revealed that the construction of the Brouwersdam led to an abrupt change in the prevailing hydrodynamic processes with changes in the morphology as a result, among with the development of the Ooster. The flow patterns in the Schaar changed completely. Before the closure the flow was mainly determined by the water level gradient between the Haringvliet and the Grevelingen, whereas after the closure the flow became much more depending on the tidal propagation at sea. Moreover the maximum tide-induced flow velocity increased. The latter resulted in an increased erosion trend at the Westhoofd which subsequently led to multiple nourishments in the period 1969-1985. The current erosion trend led to a new investigation by Elias (2015). Concluded was that a natural arrival of the Ooster could not be deduced from measurement data, however it could be expected based on the clear landward trend in 2013 which resulted in a buckling point in the inflow channel. A new beach nourishment is planned to be executed in the period 2020-2021 in order to protect the hard sea defence, the Flaauwe Werk, for which the presence of a foreshore is important according to RWS. The evolution of the Ooster shows a lot of similarities with the Hinderplaat in the Haringvliet, however after the construction of the Slufter and the breaching event the development of both shoals differ.

3

Data analysis

In this chapter bathymetric data is analysed to evaluate morphological evolution. First, the complete outer delta is considered. Secondly, the evolution near the coastline of Goeree-Overflakkee is considered in detail. Furthermore, the characteristics of the governing hydraulic boundary conditions are described.

3.1. Morphological evolution

The Grevelingen outer delta experienced significant changes in morphology as a result of the anthropogenic interferences, discussed in section 1.1.1. The change in hydrodynamics, discussed in section 2.1.2, led to the formation of Ooster and an increased erosion trend of the coastline of Goeree-Overflakkee. Collected measurement data of the bed level in the period just before this interference till recently allows to visualize these changes and provide a conceptual understanding of what exactly occurred after the construction of the Brouwersdam.

3.1.1. Data sources

The development of the bed level is measured regularly by RWS. Two types of bed level measurements are used in this research:

- **Vaklodingen**
  Vaklodingen are bed level measurements which are carried out on salt waters and on the large fresh water basins with a frequency of once every 3 or 6 years (Rijkswaterstaat, nda). These measurements extent to approximately the 20m NAP depth contour. The measurements are interpolated and saved into a grid with a resolution of 20 meter.
- **JarKus**
  Jarkus, an abbreviation of JAaRlijkse KUStmetingen, are yearly coastal measurements which in general extent from the first dune row to approximately the -13m NAP depth contour (Rijkswaterstaat, nda). They are saved in profiles along an imaginary line perpendicular to the coast with an intermediate distance of 250 meter. Additionally they are saved in a grid similar to the Vaklodingen, the so called Jarkus-grids.

Jarkus data has the benefit of the higher measurement frequency, allowing to study the changes in morphology in more detail. However due to the limited measured area JarKus data does not allow to study the complete outer delta. In the Grevelingen outer delta Vaklodingen are available from 1964, just before the construction of the Brouwersdam started. The most recent Vaklodingen originate from 2016, however due to unknown reason the data of 2016 were not yet processed by the time this data analysis was performed. Therefore Vaklodingen data until 2013 have been used. The most recent developments have been studied using Jarkus from the period 2014-2018.

The bed level measurements have a certain degree of accuracy that needs to be taken into account when analysing this data. Inaccuracies could be the result of limitation of the measuring equipment, difficult or variable circumstances, errors during the calibration or human errors during processing of the data (Marijs and Parée, 2004). Due to the various recording techniques and processing methods over the years, the accuracy of the measurements have changed. According to Wiegmann et al. (2005) and Perluka et al. (2006), the vertical accuracy of Vaklodingen data is estimated between 0.11m and 0.40m.

3.1.2. Morphological evolution of the Grevelingen outer delta

Figure 3.1 shows four distinct stages in the morphological development of the Grevelingen outer delta. A brief description of these individual stages are described below:

- **1964: First measurement of the Grevelingen outer delta, initial situation**
  The year 1964 was the first year in which the bathymetry was measured in this area. It illustrates the situation just before the construction of the Brouwersdam. The tides could penetrate into the Grevelingen estuary. The east-western orientation of the tidal propagation at the outer delta before the closure, shown in Figure 2.2, shaped the morphology to a cross-shore orientation of the shoals and channels. The relatively large tidal velocities, compared to the situation after the closure, led to large depth gradients within the outer delta. In the middle of the outer delta multiple regions of depths larger than -7m NAP are present. In the inlet of the estuary two intertidal shoals were present, the Kabbelaarsbank and the Middelplaat, which later on became part of the Brouwersdam. The Brouwershavense Gat, near the coast of Schouwen-Duiveland, was the main channel with depths up to 30 meters. The Ooster in the northwestern part of the outer delta was connected with the coast. Its maximum height was below MLWS, so it was flooded during the complete tidal cycle. The connection of the Ooster to the coast formed a sill in the Schaar around transect 1500. This location could be explained by the tidal flow patterns in the Schaar after flow reversal in the Grevelingen. The large flow velocities which occurred as a

result of the water level gradient between the Grevelingen and Haringvliet, were significantly reduced and subsequently sedimentation at this location (see section 2.1.2).

- **1980: The Ooster developed into multiple separated inter-tidal shoals**
The Brouwersdam was constructed which led to an abrupt change in the tide induced flow. Around the year 1980, the Ooster had developed into various separate shoals which emerged during low tide. The shoals were separated by a so-called short-circuit channel, which was located farther away from the coastline. A detail of this situation is shown in Figure 2.6. Bakker (1980) described the location of this shoal as highly unstable due to the influence of flow at sea as well as the in- and outflow in the estuary. The sill in the Schaar was eroded, probably due to the increased tide induced velocities (see section 2.1.2). In general a landward migration of the present shoals in the outer delta can be observed. The deeper areas, below -7m NAP, reduced indicating sedimentation.

- **1996: The Ooster became one shoal**
The landward migration of shoals and sedimentation of the deeper areas continued. Around the year 1996 the Ooster became one distinct shoal as the unstable short-circuit channel had disappeared. The inter-tidal area of the Ooster increased and the Schaar became deeper. At the coast of Goeree-Overflakkee a large accumulation of sediments can be observed. These sediments originated from the most eastern shoal of the Ooster which arrived at the coast of Goeree. In section 3.1.3 this process is described in more detail.

- **2014: Latest measurement of the Grevelingen outer delta, elongation and elevation of the Ooster**
The following years the Ooster became longer and increased in height. The western part of the Ooster researched an elevation above MHWS, meaning this area remains dry during the full tidal cycle. The elongation mainly took place at the eastern edge of the Ooster migrating along the coast of Goeree-Overflakkee. The accumulation of sediments at the Westhoofd has been eroded and transported along the coastline, resulting in a beach widening along the coast. This process was shown in Figure 1.3.

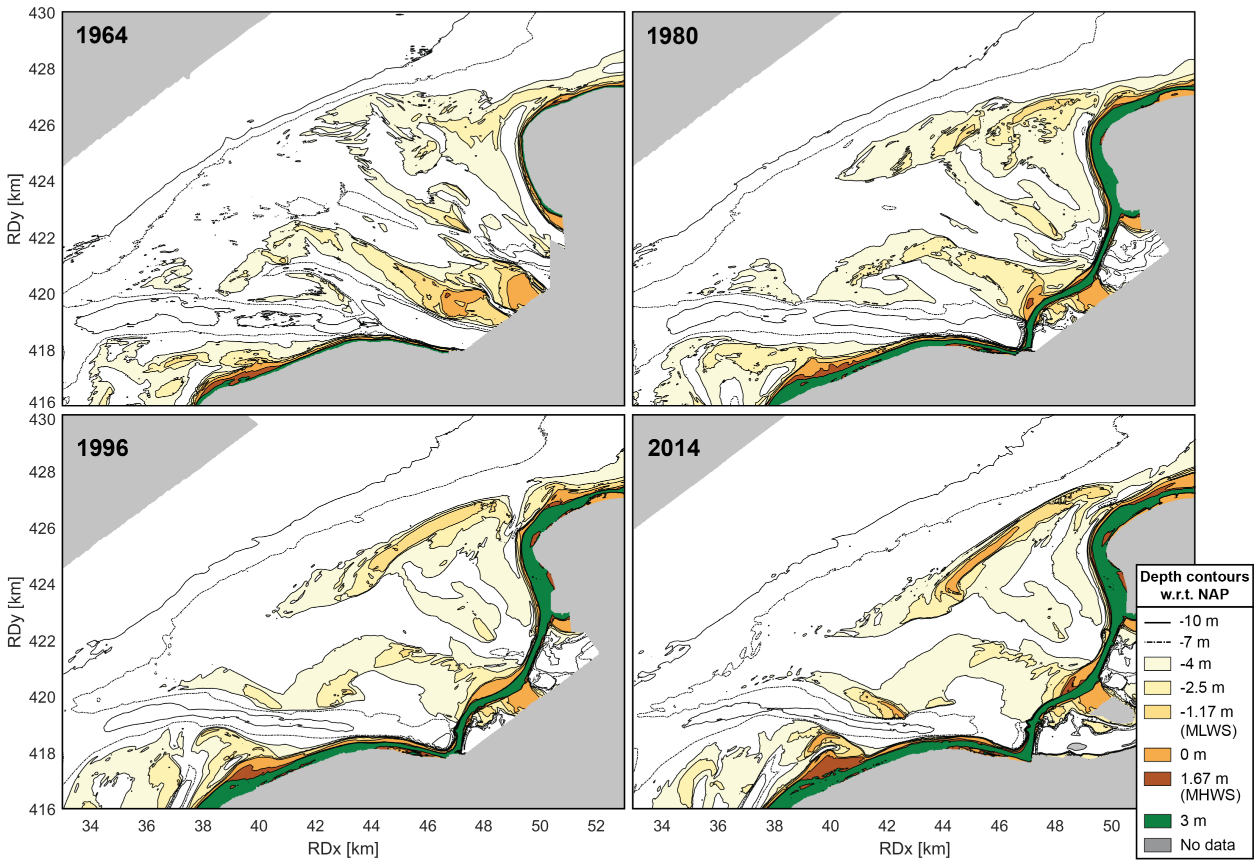


Figure 3.1: Grevelingen ebb-tidal delta evolution in the period 1964-2014, derived from the Vaklodingen dataset

Based on these four distinct morphological states a couple of trend can be deduced in the Grevelingen outer delta after the closure of the estuary. First of all the depth gradients reduced. Sedimentation occurred in the deeper areas and shoals were eroded, resulting in the flatting of the outer delta. An exception is the development of the Ooster at the outer delta edge. Figure 3.2 shows the sedimentation and erosion patterns in the period 2010-2013. It reveals the difference at both sides of the Ooster. Seaward of the Ooster erosion dominates while landward of the Ooster sedimentation prevails. An exception is the coastline at the Westhoofd which shows a decrease in bed level.

The second trend is the elongation of the Ooster at its eastern edge. This trend is highlighted in Figure 3.2 which shows the large sedimentation that occurs in this area. The elongation is accompanied by relatively large erosion near the coastline which expresses the problem RWS is currently facing. The elongation of the Ooster forces the flow in the Schaar in the direction of the coastline, resulting in a locally strong retreating coastline. Meanwhile further north sedimentation dominates, resulting in an advancing coastline.

The third trend is the landward migration of the western tip of the Ooster. The cross-shore development of the Ooster is highlighted in Figure 3.3. It shows the evolution of three cross-sections perpendicular to the orientation of the Ooster in 2014 with a frequency of ten years. In cross-section 1 the steep outer delta edge can be recognized in the undisturbed situation of 1964. The evolution of the bed level in this cross-section shows the magnitude of the erosion that occurred due to the increased dominance of the waves. The outer delta edge became less steep. Note that this erosion only takes place in the areas above the -10m NAP depth contour approximately. In the deeper areas waves are not able to induce sediment transport and therefore the dominance of the waves did not affect the morphology. The eroded sediments where transported in landward direction and accumulated in the Ooster. The height of the Ooster increased over time, indicated by the black arrow, and moved in landward direction. Landward of the Ooster the deeper areas where filled and shoals were eroded resulting in a flatting out of the shoals which was already concluded in the first trend.

Lastly the depth contours have become more alongshore uniform. In the undisturbed situation of 1964 the outer delta edge had a spherical shape around the inlet. In the situation of 2014 these depth contours had become more linear. From this it can be deduced that the outer delta is transforming to a normal alongshore uniform coast, similar to the Dutch coast north of the Port of Rotterdam.

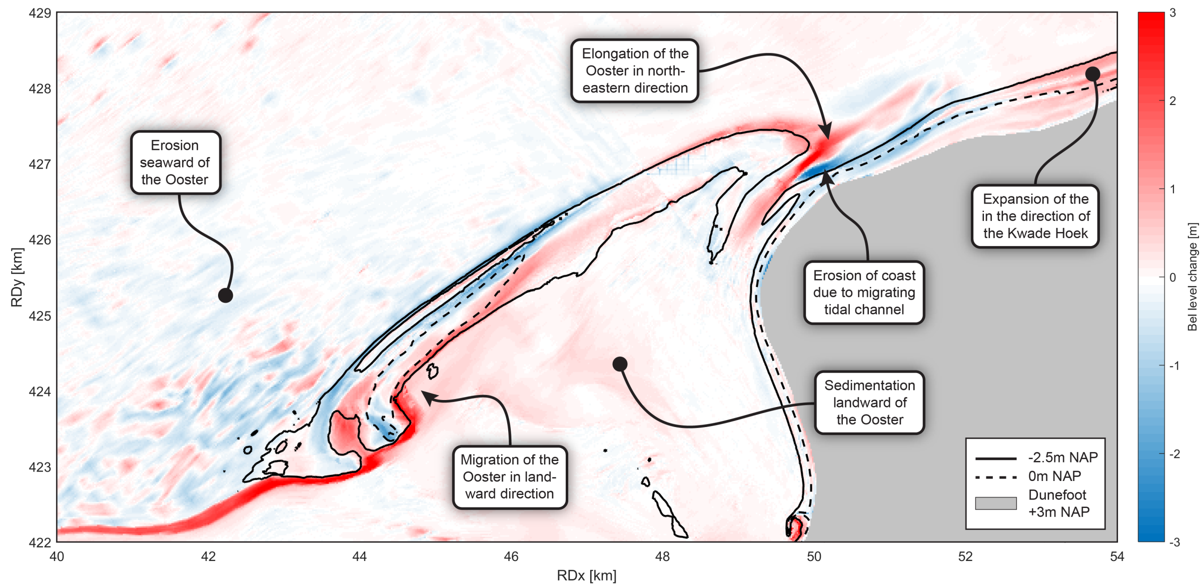


Figure 3.2: Sedimentation and erosion patterns in the period 2010-2013 with contours of the morphological situation of 2010, derived from the Vaklodingen dataset

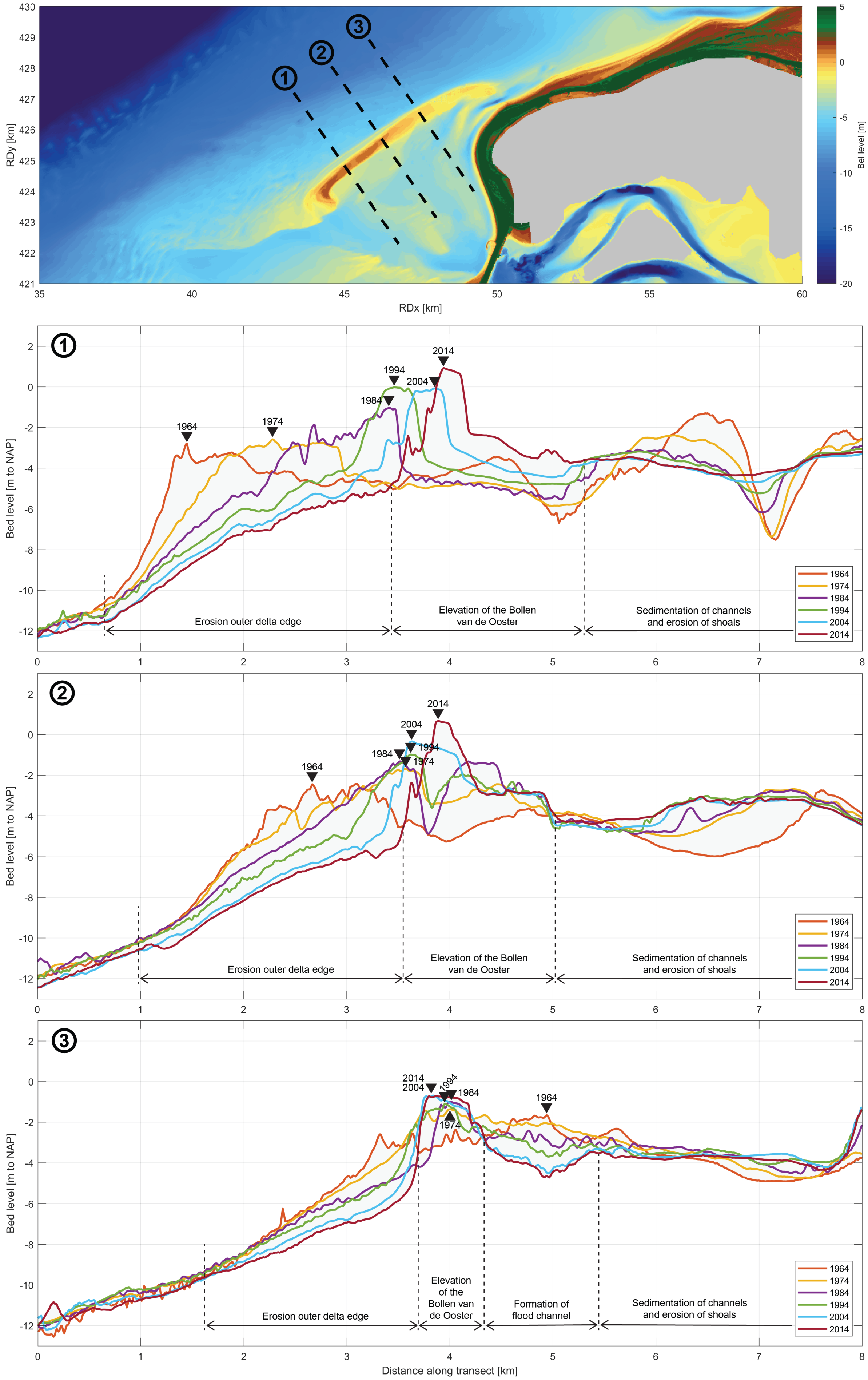


Figure 3.3: Cross-sectional evolution of the Ooster for the period 1964-2014, derived from the Vaklodingen dataset

3.1.3. Morphological evolution near the coastline of Goeree-Overflakkee

Subsequently a closer look is taken at the evolution near the Westhoofd with the knowledge about the outer delta evolution. Figure 3.4 shows the morphological evolution near the Westhoofd in the period 1964-2018 in more detail. These pictures were derived from Vaklodingen data except from 2018 which was derived from the JarKus-grids and therefore has a limited measurements distance from the coastline.

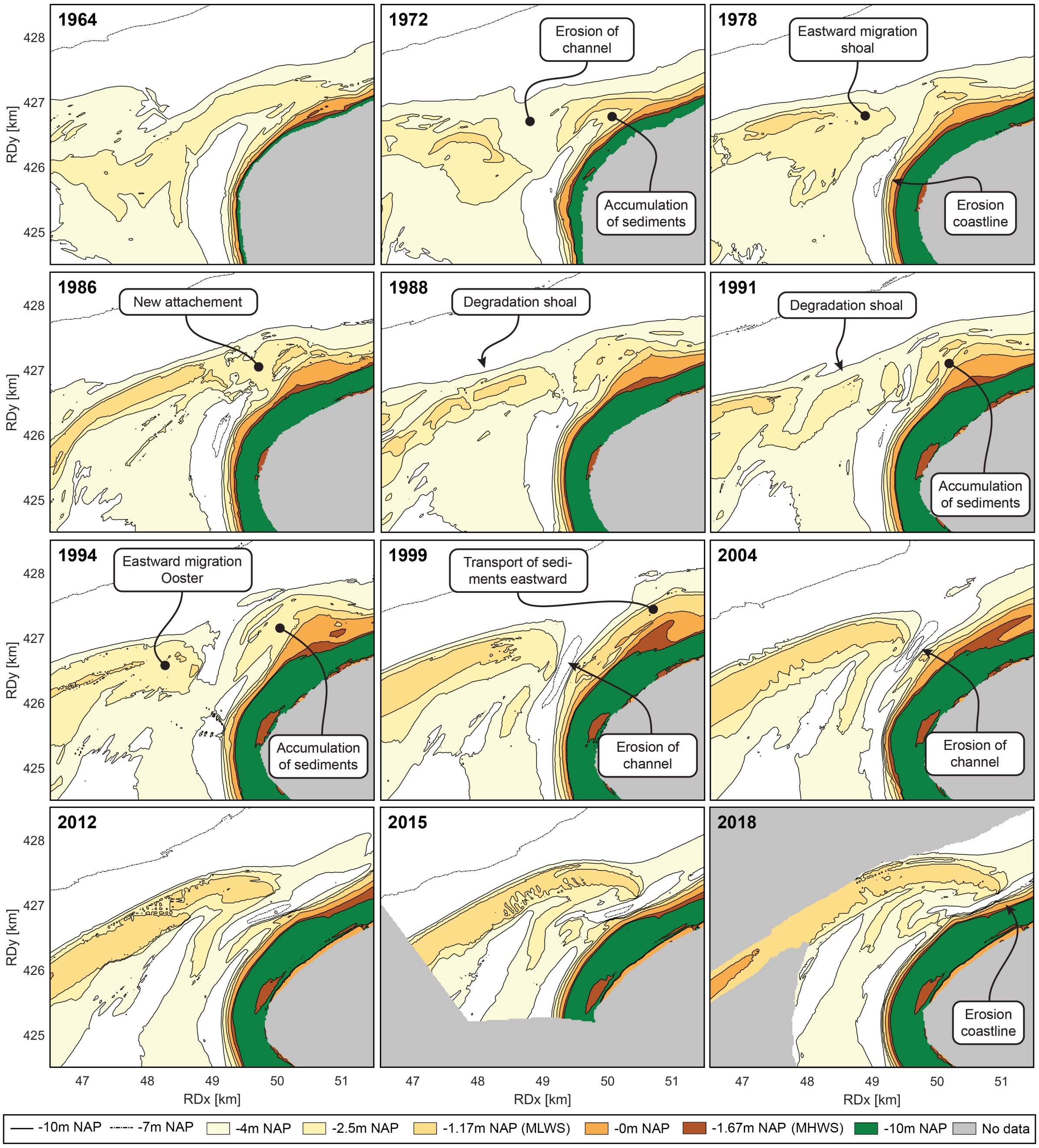


Figure 3.4: Evolution near the Westhoofd in the period 1964-2014, derived from the Vaklodingen dataset

From 1964 until the mid nineties a periodic pattern of breaching and eastward migration of the Ooster can be observed. This led to accumulation of sediments at the Westhoofd which has been growing in volume over time due to the periodic arrival of shoals at the coastline. In Figure 3.4 this process can be seen two times. In the period 1964-1972 the sill eroded, shifting the location of the Schaar seaward and resulting in an accumulation of sediment east of the new channel. Subsequently the shoal west of the Schaar migrated in eastern direction, forcing the Schaar towards the coast. This process led to the multiple nourishments in this period until 1985 in order to maintain the coastline, discussed in section 2.2. Around 1986 a new connection was formed between the shoal and the coast. The following years, this shoal started degrading and led to an even larger accumulation of sediment at the Westhoofd. The Schaar was again shifted seaward which explains the sudden stop in nourishments after 1985 in this region. Accordingly the eastern shoal of the Ooster, migrated in eastern direction resulting in a narrowing and deepening of the Schaar at the Westhoofd around the turn of the millennium. In the picture of 2004 the -10m NAP depth contour is visible in the Schaar. Different than the previous times, this shoal did not degrade and kept moving eastward accompanied by the Schaar which keeps the Ooster from arriving at the Coastline. The pictures from 2004 till 2018 show a rapid movement of the Ooster along the coast and further narrowing of the channel. However, the maximum depth of the Schaar seems to decrease. Furthermore the Ooster shows no sign of degradation according to these pictures.

Taking a closer look at the dimensions of the Schaar, a gradual reduction in depth as well as flow surface area can be observed. The first is shown in Figure 3.5. In a period of 15 years the depth decreased from almost 12 meter till less than 7 meter. Figure 3.6 shows the evolution of the minimum cross-sectional surface of the channel. Due to the migration of the Ooster the location of this cross-section is not static. It has been derived based on visual observations of the bathymetric data. The cross-section of the channel below four different levels are shown. It reveals the continuous reduction decrease below MLWS from over 2100 m^2 in 2003 till approximately 400 m^2. This entails a reduction in flow surface during low tide and therefore a stronger convergence of the flow. Based on these observations it can be concluded that the channel dimensions are decreasing.

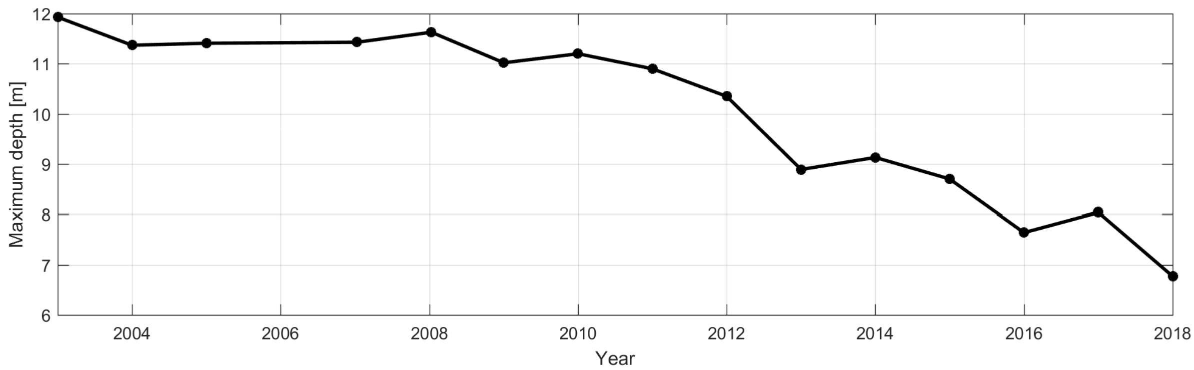


Figure 3.5: Evolution of the maximum depth of the Schaar in the period 2003-2018, derived from the JarKus-grids

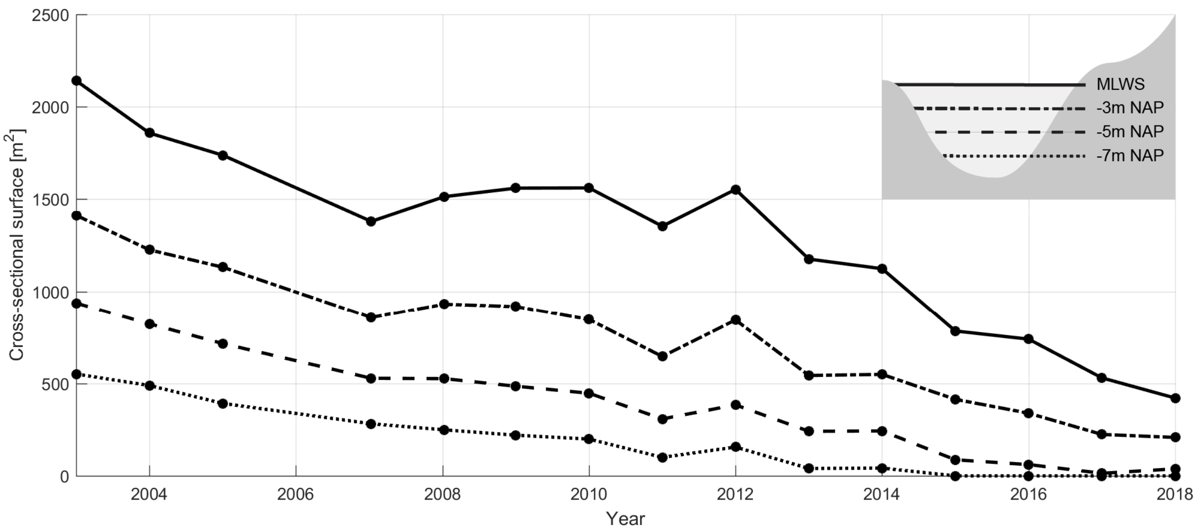


Figure 3.6: Evolution of the minimum cross-sectional surface of the Schaar below different levels in the period 2003-2018, derived from the JarKus-grids

3.2. Hydraulic boundary conditions

There are three distinctive forcing mechanisms which are able to induce flow and subsequently shape the morphology in the Grevelingen outer delta: the tide, waves and wind. River discharge from the Haringvliet is considered to be subordinate to the Grevelingen outer delta. Below a brief description of the characteristics of these hydrodynamic forcing mechanisms is given.

3.2.1. Tide

The propagation of the tide along the Dutch coast induces water level variations and flow patterns in the Grevelingen outer delta. Figure 2.2 already showed the how this propagation looks like in northern direction. To provide insight into the magnitude of the water level variations, Figure 3.7 shows the measured water levels in a period of two months. This signal has been measured in front of the Haringvliet approximately 5 kilometers from the coast of Goeree-Overflakkee. It shows a semi-diurnal tide including significant variations in water level over the spring-neap tidal cycle as well as daily inequality. The MHWS (Mean High Water Springs) and MLWS (Mean Low Water Springs) have been used to indicate the intertidal area in the morphological evolution.

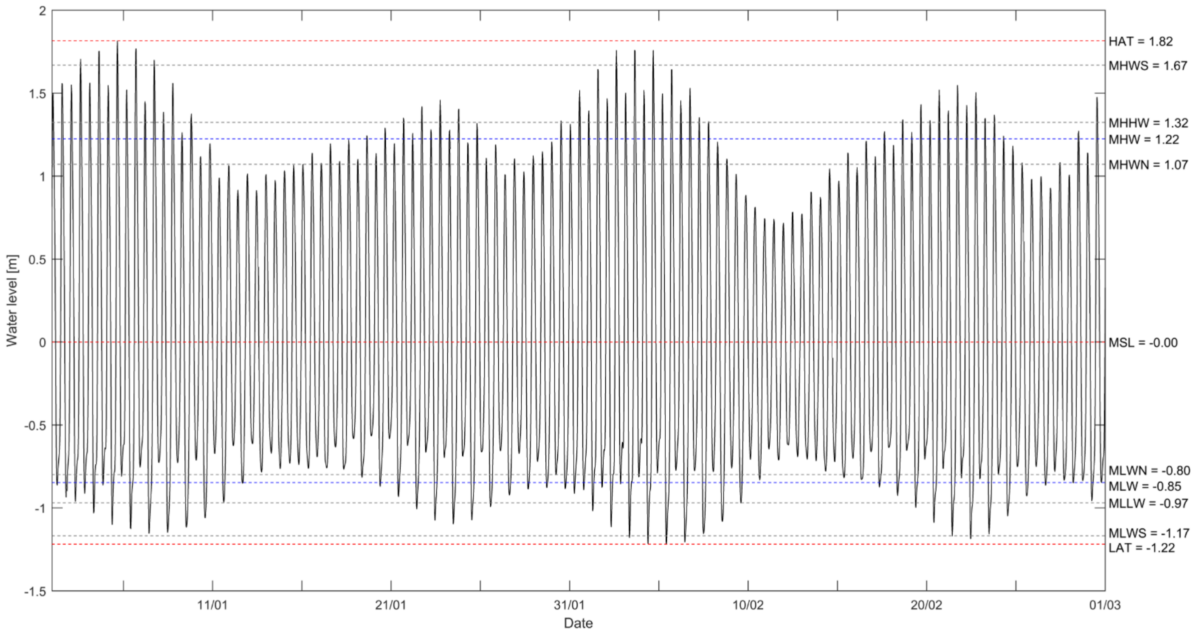


Figure 3.7: Tidal signal measured at Tidal Station Haringvliet 10 during January and February 2018, retrieved from DelftDashboard (Colina Alonso, 2018)

3.2.2. Waves

The wave climate measured at the Europlatform, in the period 1979-2001, is shown in Figure 3.8. This dataset has been used because it contains information about the wind at the same location. This in contrast to another available dataset for the period 2006-2012. Colina Alonso (2018) stated that both datasets are quite similar in terms of mean, maximum and minimum measured wave height. The wave climate shows a directionally bi-modal wave spectrum in which waves from the north and southwest are most frequent. In general waves exert a force on the water and as a result generate water level variations, cross-shore and longshore currents in the near-shore zone (De Vries, 2007). Occasionally wave heights of >6m are reached during storms (Elias et al., 2016).

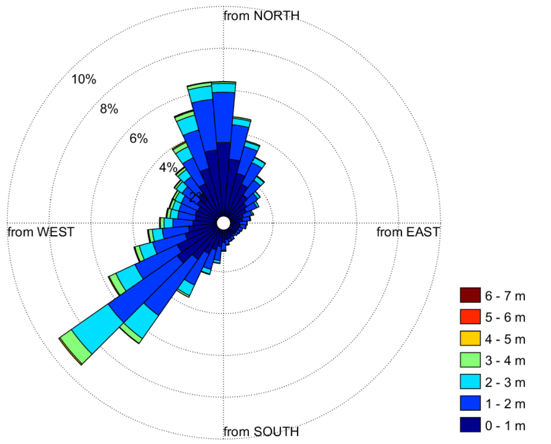


Figure 3.8: Wave climate at the Europlatform in the period 1979-2001.

3.2.3. Wind

The last relevant hydrodynamic forcing mechanism is the wind. Figure 3.9 shows the wind climate measured in the period 1979-2001. The wind is able to induce a shear stress on the water surface which subsequently lead to movement of the upper parts of the water layer in the wind direction (Bosboom and Stive, 2015). Furthermore near the coast the wind is able to induce a water level set-up. Colina Alonso (2018) concluded that in the Haringvliet outer delta regular wind speeds of in the order of 10 m/s are very effective in changing the flow patterns in in front of the Hinderplaat during low water.

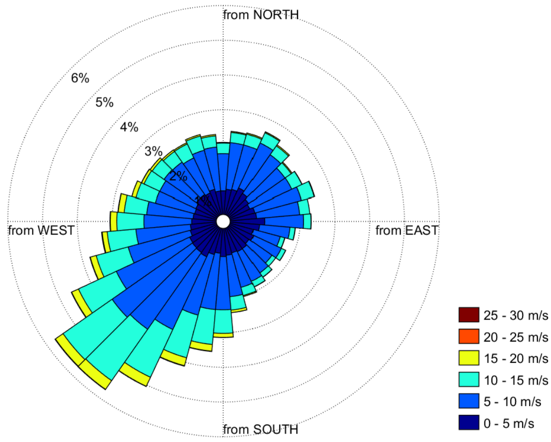


Figure 3.9: Wind climate at the Europlatform in the period 1979-2001.

3.2.4. Storms

In this study the focus is on the morphological development under normal conditions. However, extreme conditions with storm that occur with very low frequency, will result in rapid morphological changes. Such type of conditions could also impact the stability of the Ooster and potentially lead to a breach in the shoal. This scenario is not researched in this study. However, when considering the morphological development on a longer time scale, the occurrence of such an event is relevant.

3.3. Summary

In this chapter a data analysis has been applied to evaluate the morphological changes and provide a conceptual understanding of the dynamics. The morphological development of the Grevelingen outer delta shows a couple of trends. The depth gradients reduced. The outer delta edge eroded as a result of the relative increase of wave forcing dominance. The depth contours became more alongshore uniform. An intertidal sand bar emerged. The latter is known as the Ooster and shows a landward migration at the western tip and elongation at the eastern edge. After closure of the estuary the Ooster has shown a periodic pattern of breaching and eastward migration, forcing the Schaar towards the coast. This process continued until the mid nineties when the Ooster became one distict shoal. Accordingly the eastern shoal of the Ooster, migrated along the coastline resulting in a narrowing and deepening of the Schaar. However, since 2003 a gradual reduction in depth as well as flow surface area can be observed.

4

Modelling study

In this chapter the application of a numerical model is discussed. First, the aim of the modelling study is described. Secondly, the applied methodology is discussed. Thirdly, the model setup is elaborated briefly. Lastly the modelling results are presented.

4.1. Modelling objective

Based on the gained insight into the historic evolution of the Ooster and the outer delta as a whole, a modelling study is applied to achieve a better understanding of the water motion induced by the hydrodynamic processes (elaborated in Section 3.2). The hydrodynamics, the motion of water due to the hydrodynamic processes, are able to transport sediments with a change in morphology as a result. Intrinsically the hydrodynamics are influenced by the morphology. Thus there is a feedback mechanism between the hydrodynamics and morphology which is called morphodynamics. Morphodynamics is defined as the "mutual adjustment of morphology and hydrodynamics processes involving sediment transport" (Bosboom and Stive, 2015). With the Delft3D software suite the hydrodynamic processes can be modelled along with their effect on the sediment transport. Moreover this software is capable of modelling this interaction between hydrodynamics and morphology. This type of simulation is called a morphodynamic simulation which can be used to simulate the morphological development over a certain time duration.

In this modelling study three modelling objectives are defined, shown in Figure 4.1

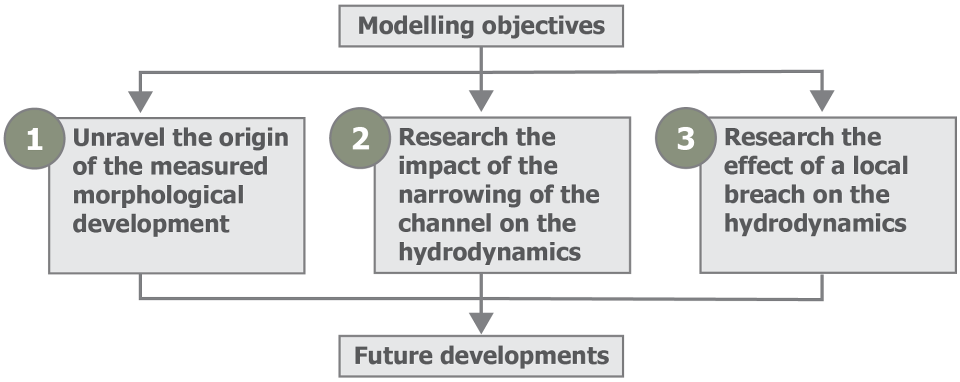


Figure 4.1: Objectives in the modelling study

Together they provide knowledge about the morphodynamics of the system and allow to elaborate on the future evolution. Furthermore it provides insight in the necessity to take protection measures against the eroding trend and therefore the potential threat regarding coastal safety. The modelling study is considered as a tool to obtain insight in the system and has not the aim to optimize the model in order to improve the simulation results. Therefore a detailed calibration and validation of the model lies outside the scope of this study. However, a brief description about prior sensitivity analysis is elaborated in section 4.3.1.

4.2. Modelling methodology

An existing Delft3D model of the study area is used to simulate the water motions under different hydrodynamic forcing. This model provided by Deltares is called the Haringvliet-model which was originally developed to study the morphological effects on the outer delta of the Haringvliet as a result of the changing in lock management of the Haringvlietdam and the construction of Maasvlakte 2 (Van Holland, 1997). Over the years this model has been improved to obtain more reliable predictions by preceding morphological model studies, further elaborated in section 4.3.1. In this study, the revised Haringvliet-model by De Vries (2007) is used.

The methodology consist of multiple morphostatic simulation with varying boundary conditions. Morphostatic means that the model does not execute the feedback loop between the hydrodynamics and morphology. Therefore only the initial sediment transport is calculated. The varying boundary conditions are related to different wave conditions (explained in section 4.3.3) and different bottom profiles.

Five bottom profiles scenarios have been defined, shown in Figure 4.2. It includes two measured profiles of respectively 2014 (I) and 2018 (II). The latter is based on the first and modified with Jarkus grids of 2018. This is a consideration between on the one hand lack of available recent measurement data and on the other hand the ambition to model the prevailing situation. It entails that only the area relatively close to the coastline is different. Nonetheless, this is justifiable as the area with the largest morphological change is within this grid and the time span is not that long. Additionally, three conceptual bottom profiles have been derived

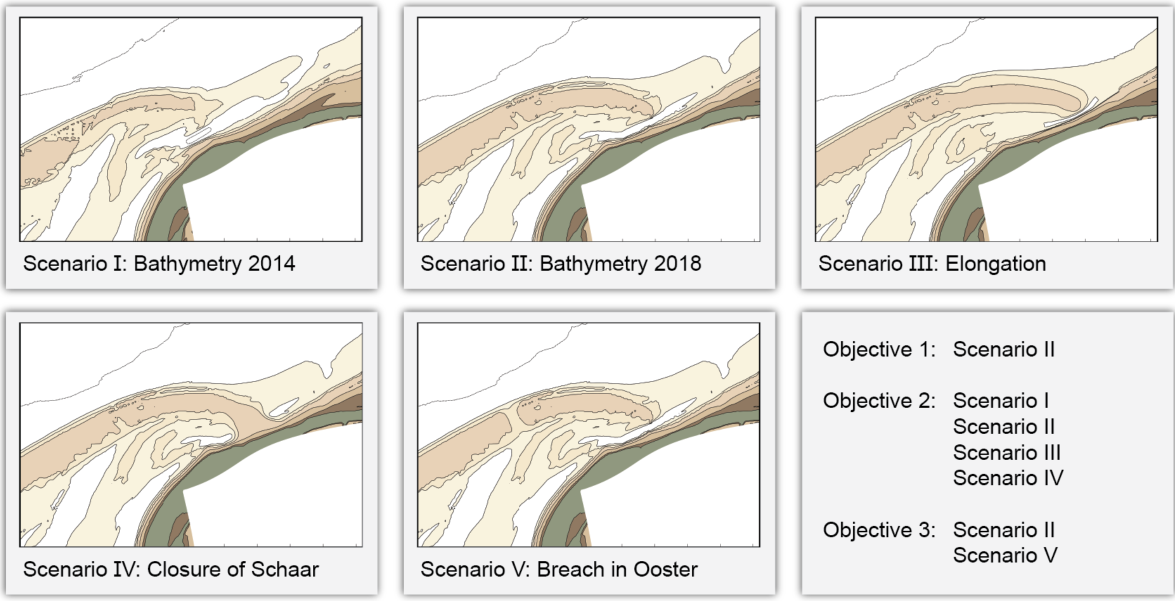


Figure 4.2: Bottom profile scenarios. In the lower right an overview of the discussed scenarios per objective is stated.

based on the conceptual understanding of the system. This first conceptual profile (III) is deduced from the natural morphological evolution observed in the most recent years. The depth contours of the measured bottom profiles have been extrapolated. It involves an elongation of the Ooster in eastward direction, decrease of cross-sectional flow surface of the channel and further erosion of the coastline. Considering the cross-sectional flow surface only this situation is expected to occur mid-2020 based on the trend in Figure 3.6. The second conceptual profile (IV) involves a complete closure of the channel. This could be the result if the trend continues and the channel naturally disappears or due to a nourishment. Lastly the third conceptual profile (V) including a breach. Historical morphological development showed several shifts between channels in the past. The emergence of a breach in the Ooster might lead to relocation of the eroding currents away from the beach. A breach could be the result of natural morphological changes, similar to the Hinderplaat. The breach in the Hinderplaat was the result of a high discharge event, discussed in section 2.4. Because of to the absence of discharge in the Grevelingen, a natural breach must have an other origin. For example the continuous narrowing of the Ooster, indicated in Figure 3.3, in combination with an extreme wave condition could potentially create a breach. The likelihood of this event is not treated in this study. The location of the breach is chosen at the end of a flood channel perpendicular at the Ooster.

4.3. Model description

Delft3D is a computer software suite developed to perform 3D simulations of among others flows, sediment transport, waves and morphological developments (Deltares, 2019a). It consists of multiple modules including Delft3D-flow and Delft3D-wave which interact with each other during a simulation. The FLOW-module calculates flow and transport as a result of tidal forcing while the WAVE-module calculates the wave propagation and generation of waves by wind (Deltares, 2019a,b). In this section a brief description about prior sensitivity analysis is given. Subsequently the model settings that were implemented including the computational grid, boundary conditions and other model settings are elaborated on.

4.3.1. Calibration and validation

The Haringvliet-model was initially developed by Van Holland (1997) and subjected to a qualitative validation and sensitivity analysis showing large deviations between the model results and measurements. The latter was the result of shortcomings in the model. The model was further developed in the study by Roelvink et al. (1998). It was assessed to which extent the model is capable to simulate morphological changes in the Haringvliet outer delta. Moreover the purpose was to indicate the capability to model the effects of the to be constructed Maasvlakte 2. In the study by Steijn et al. (2001) results from the FLOW-module were validated and subsequently the model was calibrated and validated for the morphodynamics. However the model was not able to reproduce the morphological development of the Haringvliet outer delta sufficiently. In the study by the De Vries (2007) the model was revised. In this modelling study this revised model is used. Prior sensitivity studies were focused on the Haringvliet outer delta and not on the area of interest in this study. Elias (2015) indicated that simulated flow velocities do not give a reason to question this assumption. However this should be kept in mind when analysing the model results. Further calibration and validation of the model is not within the scope of this study.

4.3.2. Computational grid

The Haringvliet-model by De Vries (2007) consists of one grid for the FLOW-module extending from Noordwijk until Nieuw Haamstede and two grid for the WAVE-module. Since this model was originally developed for Maasvlakte 2 and Haringvliet outer delta, the resolution is largest near these areas. Yet near the Ooster the resolution is poor. In order to obtain valuable results the resolution of the grid of the FLOW-module was increased in this region in the study by Elias (2015) through the application of domain decomposition. With this technique the model is divided into multiple smaller model domains separated by internal boundaries, so called DD-boundaries (Deltares, 2019a). This resulted in a resolution of approximately 20x20m near the Ooster (Elias, 2015). The WAVE-module has one large grid, comparable with the large FLOW-grid, and a finer grid at the Haringvliet outer delta. Also in this module the resolution near the Ooster is poor. Therefore an additional grid has been added to the WAVE-module in this study. The computational grids for both modules are shown in Figure 4.3

In general the number of grid cells should be limited in order to restrict computational time, however the computational grid should cover sufficient area to avoid disturbances propagating into the area of interest and moreover should have enough resolution near the area of interest. The modification of the FLOW-grid by domain decomposition is therefore not favourable in terms of computational time but it will lead to more valuable results in modelling the water motions near the Ooster. If the ambition is to perform a long time morphodynamic simulation of the Ooster and the channel, the grid should be optimized for this particular area.

4.3.3. Boundary conditions

The open boundaries at the grid, which are not enclosed by land, require boundary conditions. Below the imposed boundary conditions are described briefly.

Flow boundary conditions

The FLOW-module requires boundary conditions containing information about the water level, discharges and sediments transport. The water level is determined by the combination of tidal elevation and water level set-up. The first is depending on the amplitude and phase of the tidal components. The latter is depending on the prevailing wave and wind condition. In the model a morphological tide has been induced at the alongshore boundaries. This harmonic boundary consists out of eight tidal components which were schematized and validated in preceding studies (Roelvink et al., 1998, Steijn et al., 2001). A morphological tide is a single tide which in theory should result in equal net sediment transport to the complete neap-spring tidal cycle. This limits the computational effort of the simulation. At the northern and southern boundary a Neumann type boundary is prescribed. At these model boundaries the alongshore water level gradient are imposed which are equal in cross-shore direction and vary in time when the tidal wave travels along the coast (De Vries, 2007). Regarding the sediment transport, Neumann boundary conditions (zero concentration gradient) are set at all open inflow boundaries. This means the sediment sediment concentration at the boundary and just inside the model domain are equal (De Vries, 2007). A detailed description of the induced flow boundaries has been done by De Vries (2007).

Wave boundary conditions

The WAVE-module requires boundary conditions at all open boundaries of the WAVE grid. In preceding studies different wave schematizations have been carried out. In the study by De Vries (2007) the wave climate was schematized into 127 wave conditions based on measurements at the Europlatform in the period 1986-2000. Accordingly individual wave conditions were eliminated depending on their contribution to the sediment transport near the Hinderplaat. This method is called the "Optimum" wave class selection and briefly elaborated in Appendix B. The result was a wave climate with nine conditions. In the study by Colina Alonso (2018) data from the Europlatform was used of the period 1979-2001. In this latter study the wave climate was schematized into 46 conditions.

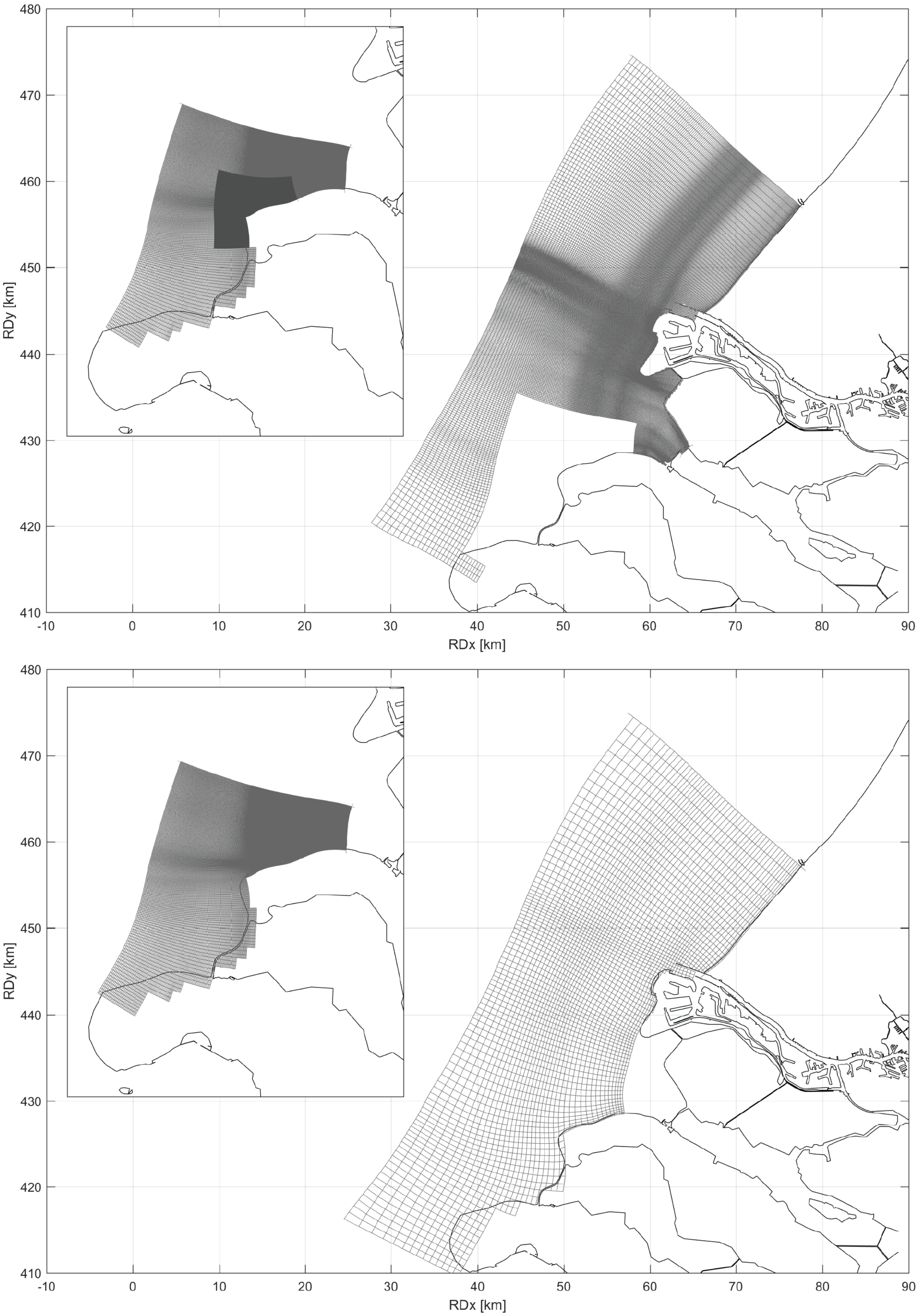


Figure 4.3: Delft3D model grids for FLOW-module (upper image) and WAVE-module (lower image).

In this study a new wave schematization has been made with the focus on the Ooster. The choice for a new wave schematization is based on two reasons: firstly, it is desired to limit the number of wave conditions because of the number of bottom profile scenarios. Secondly, the wave climate by De Vries (2007) was optimized for sediment transports near the Hinderplaat, which is not necessary a good representation of sediment transport near the Ooster.

Data has been retrieved from the Europlatform and simplified to five wave conditions. These conditions include the two most frequent wave directions, waves from the north and from the southwest, described in section 3.2. For each wave direction two wave conditions were derived. A regular condition with a wave height in the order of 1-1.5m and a more energetic conditions with a wave height in the order of 3-3.5m. Furthermore a fifth condition has been derived without waves (WC0). This incorporates the situation in which easterly waves are generated which are not able to affect the morphology. The reduction of wave conditions is called wave input reduction which has the aim to reduce the computational effort of the simulation while still representing the wave climate. A detailed description of the wave input reduction process can be found in Appendix B. The results are shown in Table 4.1. Note that wind is incorporated in the wave conditions. Therefore, when spoken about wave conditions, both wave and wind forcing are meant. The wind parameters were measured along with the wave parameters. For each condition representative values of the wind parameters were determined based on these measurements. The derivation of the wind parameters can also be found in Appendix B. The wave conditions from Table 4.1 have been implemented in the model via a so-called wavecon file.

Table 4.1: Reduced wave climate and corresponding wind conditions

Parameter	**Unit**	**WC 0**	**WC 1**	**WC 2**	**WC 3**	**WC 4**
Significant wave height	[m]	-	1.50	3.39	1.17	3.01
Wave direction	[°N]	-	249.60	249.92	358.46	348.59
Wave period	[m]	-	4.27	5.81	4.52	5.86
Wind velocity	[m/s]	3.92	8.28	15.42	5.79	12.13
Wind direction	[°N]	164.32	231.24	245.63	175.45	243.94
Water level set-up	[cm]	-	5.70	30.10	-3.78	26.12
Probability	[%]	18.10	39.31	4.03	34.99	3.57
Morphological impact	[%]	17.29	29.88	23.29	14.18	15.35

4.3.4. Main model settings

The model is run for a simulation period of 3 tidal cycles for each scenario. The first 2 tidal cycles are spin-up time during which the flow in the model is adapting to the boundary conditions. After the spin-up time the sediment transport computations are initiated. The model is run with the Parallel Online approach. With this modelling approach the different (wave) conditions are run simultaneously and share the same bathymetry (De Vries, 2007). The bed level change of each condition is scaled by their morphological impact, shown in Table 4.1. The result is a weighted average bed level change.

A uniform water level of 1.326m in combination with a sediment concentration of 0 kg/m^3 are applied as initial conditions. The sediment in the model is schematized into one sediment fraction: Sand with a medium grain size of 160 μm. The outer delta consists mainly out of sand, apart from local mud deposits in the areas with lower flow velocities and smaller waves, according to Elias (2015). In the area of interest the flow velocities and wave forcing are relatively large. Therefore the exclusion of mud from the model is assumed to be acceptable.

In the model a MorFac (abbreviation of morphological factor) of 0.05 is used to assess the flow patterns. Thereafter a MorFac of 1 has been used to assess the sediment transport. The computed erosion and deposition fluxes are multiplied by this morphological factor at each computation time-step and can therefore be used to accelerate bed-level changes. A MorFac smaller than 1 means the bed-level changes are reduced and therefore affect the hydrodynamics less. In Appendix C a summary of the main model parameter settings can be found.

4.4. Model results

In this section the most relevant result of the modelling study are presented. The results are discussed by means of the three model objectives specified in section 4.1.

4.4.1. Objective 1: origin of the measured morphological development

First of all, understanding of how the prevailing hydrodynamic forcing mechanisms are able to induce flow in the area is required to elaborate on the future evolution. This corresponds to sub-question 2, defined in section 1.3. The flow is able to transport sediments and subsequently result in a change in morphology. The first objective is therefore to provide insight in the prevailing hydrodynamics. For this objective the model results of bottom profile scenario II are discussed in detail.

Tide-induced currents

Figure 4.4 shows the depth average velocity and flow direction during four distinctive stages of the tidal cycle. This is the result of model simulations without wave forcing (wave condition 0 from Table 4.1). A short description of the four stages is given below:

Stage A Low tide (low water levels): the Ooster is emerged during this stage. Flow is concentrated in the channel which result in significant flow velocities up to 1.67 m/s.

Stage B Rising tide (increasing water levels): flow can be observed in southerly direction as the Ooster gets inundated. This occurs for a limited time duration till the flow direction landward of the Ooster has change from ebb to flood. Flow velocities in the Schaar are minimum.

Stage C High tide (high water levels): flow velocities on top of the Ooster increase in northerly direction until maximum flood velocities are reached around the time maximum water level is reached.

Stage D Falling tide (decreasing water levels): flow velocities on top of the Ooster decrease. For a short duration the flow on top of the Ooster increases till the flow direction landward of the Ooster has changed from flood to ebb. Flow velocities in the Schaar are minimum.

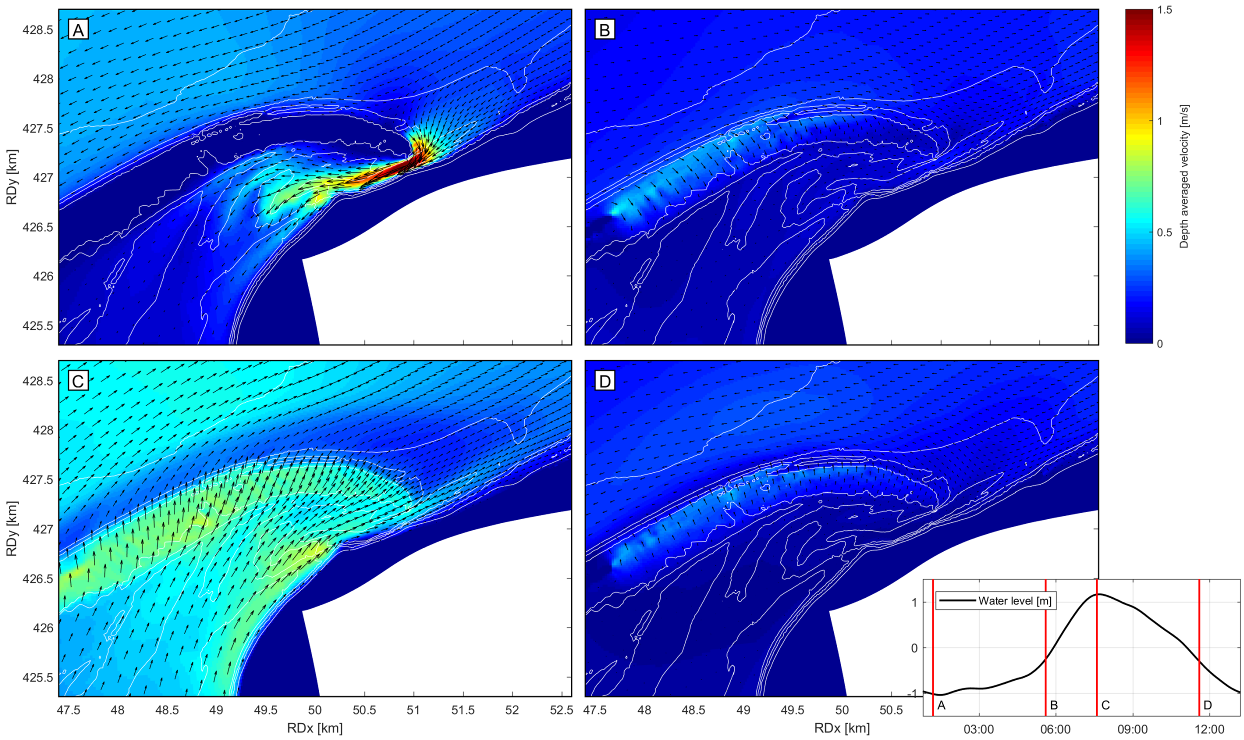


Figure 4.4: Tide-induced currents without wave forcing during four distinctive stages of the tidal cycle. The colors indicate the instantaneous depth averaged flow velocities. The arrows illustrate the flow direction. The black line in the lower right corner shows the water level during one tidal cycle where the red lines indicate the moment in time of the four plotted stages.

In general, the horizontal and vertical tide are approximately in phase, meaning the maximum flow velocities occur during maximum and minimum water levels. The flow on top of the Ooster during stages B and D is the result of a small delay in the tide landward of the Ooster with respect to deeper water.

Integration of the tide-induced currents over a complete tidal cycle results in the tidally-averaged (residual) currents. The residual current shows the mean flow patterns and can be used as an indicator for sediment transport (Elias, 2015). In Delft3D this is achieved through a Fourier analysis on the computed velocity components (for more information see Deltares (2019a)). Figure 4.5 shows the residual currents of the tide-induced currents. The largest residual currents occur in the channel and on top of the Ooster. In the channel the residual current is in southwestern direction with a magnitude up to 0.25 m/s, and is therefore ebb-dominant. On top of the Ooster the flow is directed in north-northeast direction with a magnitude ranging from 0.15 to 0.25 m/s, and is therefore flood dominated. These contrary flow directions result in a circular flow pattern near the edge of the Ooster. At the coastline the residual flow is generally northward directed apart from the area near the channel. These opposite currents meet near JarKus transact 1425, where a bulge of sand can be recognized.

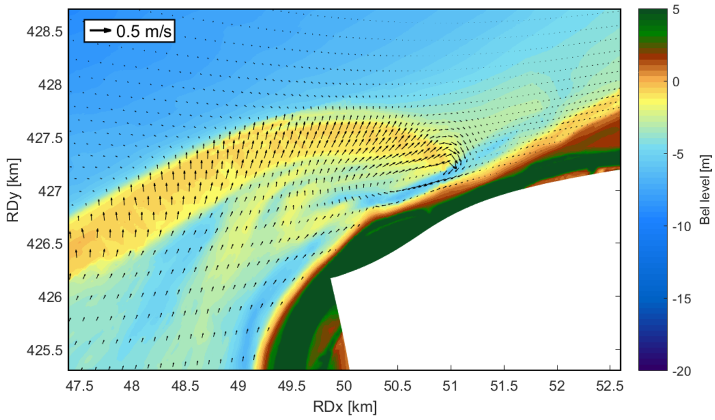


Figure 4.5: Residual current of one tidal cycle.

Wave propagation and currents induced by the wave conditions

In shallow water, waves are an important forcing mechanism that is able to transport sediments. Waves generate longshore currents as a result of energy dissipation during wave breaking. Moreover they stir up sediments into the water column that can be transported by the local currents. A longshore current will occur in the case of obliquely incident waves. Therefore the angle of wave incidence is important when considering longshore sediment transport. Figure 4.6 shows the mean wave propagation direction and the wave-induced force for the four defined wave conditions. The black arrow in the upper left corner illustrates the mean wave direction offshore. Due to spatial differences in water depth, the wave direction can change as waves propagate towards shallower water. This phenomenon is called depth-refraction. Comparing the offshore induced wave direction and the local simulated wave direction, Figure 4.6 shows the large amount of refraction that occurs seaward of the Ooster. Especially in the case of the more energetic wave conditions from the north (WC4). This can be explained by the relatively shallow area of the Haringvliet outer delta which extends into the sea. The consequence is that both energetic conditions, WC2 and WC4, result in alongshore transport in northeastern direction. This can explain why the expansion of the Ooster at the eastern edge occurs at such a high rate.

The current layout of the Ooster ensures a relatively mild wave climate at its landward side. In a sense, the Ooster acts as a wave barrier protecting the coast from large wave heights. This is illustrated in Figure 4.6, which shows the wave induced force. Wave-induced force is the result of a change in wave-induced momentum flux due to wave transformation in the shoaling zone (Bosboom and Stive, 2015). The larger the wave height and/or change in water depth over a certain length, the larger the change in wave energy and therefore the largest wave-induced force. Therefore the more energetic wave conditions WC2 and WC4 shows the largest wave induced forces. The largest wave induced forces occur at the seaward side of the Ooster. In the case of obliquely incident waves, the wave-induced force generates a longshore current. Also the beach further east of the Ooster experiences significant wave forcing. At this particular location the beach profile is relatively steep due to the presence of the channel between the Ooster and the coastline. The effect of wave forcing at this particular location is clearly visible in the appearance of the dunes, see Figure 2.8b.

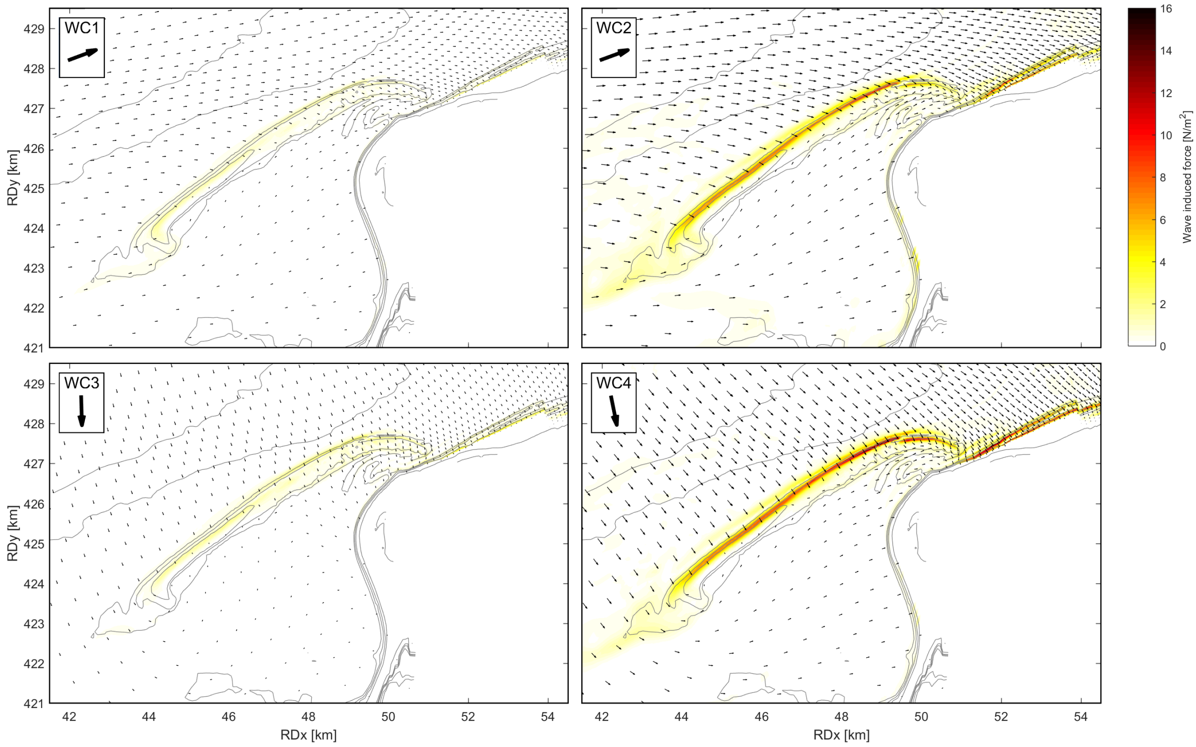


Figure 4.6: Mean wave propagation direction and wave-induced force near the Ooster for the four different wave conditions when the water level approximately NAP 0 m.

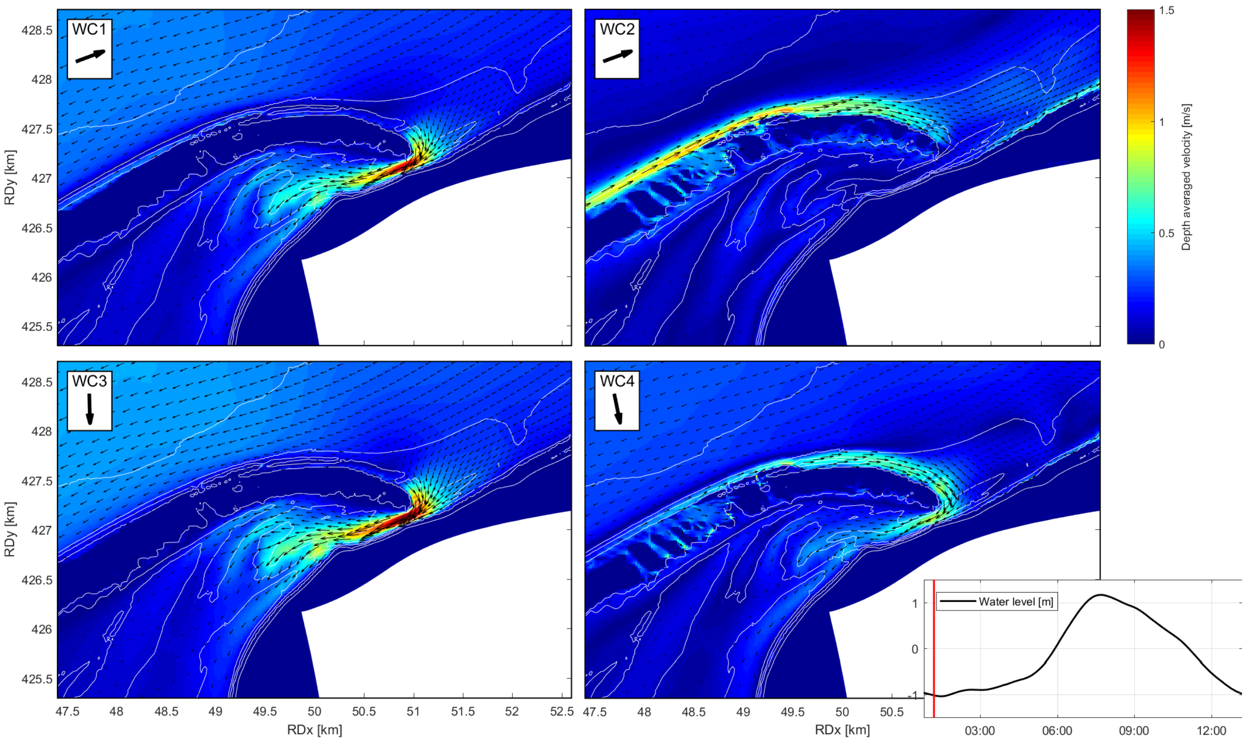


Figure 4.7: Flow patterns during low tide (stage A) for the four different wave conditions including tide induced flow. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. The larger arrow in the upper left corner shows the offshore wave direction.

The effect of the wave and wind forcing on the prevailing tide induced currents is illustrated in Figure 4.7. It shows the flow patterns for the four wave conditions during stage A, the low tide stage. In these conditions waves, wind and tide are simulated, so the effect of wave conditions is the difference with respect to the tide-only simulation in Figure 4.4. Firstly the results show that the large wave forcing at the seaward side results in the generation of wave-driven alongshore flow in the case of WC2 and WC4. Secondly the effect of wave refraction of northern waves becomes visible as both WC2 and WC4 lead to transport in eastern direction. Lastly WC1 to WC4 all show a reduction in maximum flow velocity in the channel compared to the simulation without waves (WC0). This effect is largest for the energetic conditions WC2 and WC4. A sensitivity analysis of the influence of waves versus wind shows that the latter is mainly due to the presence of wind forcing. Thus the magnitude of the flow velocities in the channel during low tide is a balance between tide-induced flow and wind-driven flow. Comparison of simulations with and without the presence of waves can be found in Appendix D.4.

During stages B, C and D, shown in Appendix D.1, the wave-driven longshore current at the seaward side remains dominant. The flow velocities on top of the Ooster, during stage C, show an increase in comparison with WC0, particularly for WC2. This is also the result of the wind forcing. During stages B and D an increase in flow velocity in the channel in northward direction is visible.

Sediment transport

From the results above it can be deduced that waves are an important forcing mechanism in determining the flow patterns and therefore shaping the morphology. Apart from the hydrodynamics, Delft3D calculates the total sediment transport based on the prevailing hydrodynamics. Based on the computed morphological impact of each wave condition, shown in Table 4.1, the sediment transport can be scaled in order to obtain the weighted sediment transport in the study area. Figure 4.8 shows the mean weighted sediment transport rates in the study area, computed over one full tidal cycle. Note that these sediment transport rates are initial transport rates computed with the morphology in the model. Due to morphological changes these rates will change. Moreover these transport rates are calculated with the assumption that the wave climate can be schematized with five conditions.

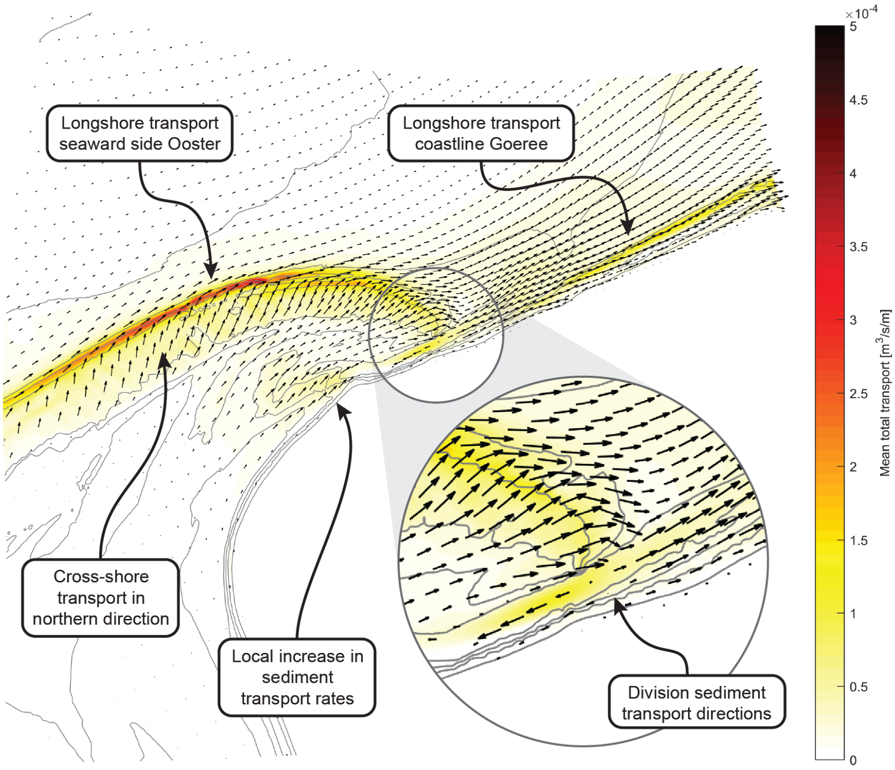


Figure 4.8: Mean weighted sediment transport bottom scenario II after one tidal cycle

The sediment transport rates in Figure 4.8 reveal several of trends. Significant longshore sediment transport rates occur at the seaward side of the Ooster in northeastern direction as a result of the wave-driven longshore currents. This sediment is transported in the direction of the channel. In the narrowest part of the Schaar a division in sediment transport directions can be observed. This indicates that at this location erosion takes place. The cross-shore transport on top of the Ooster is primarily northward directed. This can be explained by the fact that the Ooster is only flooded during high tide. Lastly behind the Ooster near transact 1500 a local increase in sediment transport can be observed.

With the use of Detran (DElft TRansport ANalyzer), sediment transport rates can be calculated through arbitrary chosen transects (Deltares, 2010). It provides insight in the volume rates that occur in the study area. The transport rates are calculated based on the mean total transport of Figure 4.8 and subsequently scaled over a certain time duration. Figure 4.9 shows the calculated annual net sediment transport rates. Again the same remark has to be made regarding the initial transport rates. Therefore the values are not the exact transport rates that would occur in a year. However it provides insight into the net sediment transport directions and volumes on either side of the Ooster (the longshore transport) as well as the sediment transport across the Ooster (the cross-shore transport).

At the seaward side of the Ooster, the longshore transport volumes are larger compared to the down drift coast of Goeree. This indicates that sediments are deposited in this region, which benefits the growth of the Ooster in eastward direction. Behind the Ooster, the net longshore transports are significantly smaller. The volume decreases towards the Brouwersdam. The cross-shore sediment transport on top of the Ooster benefits the alongshore transport at the seaward side and ensures that sedimentation occurs at the seaward side of the Ooster.

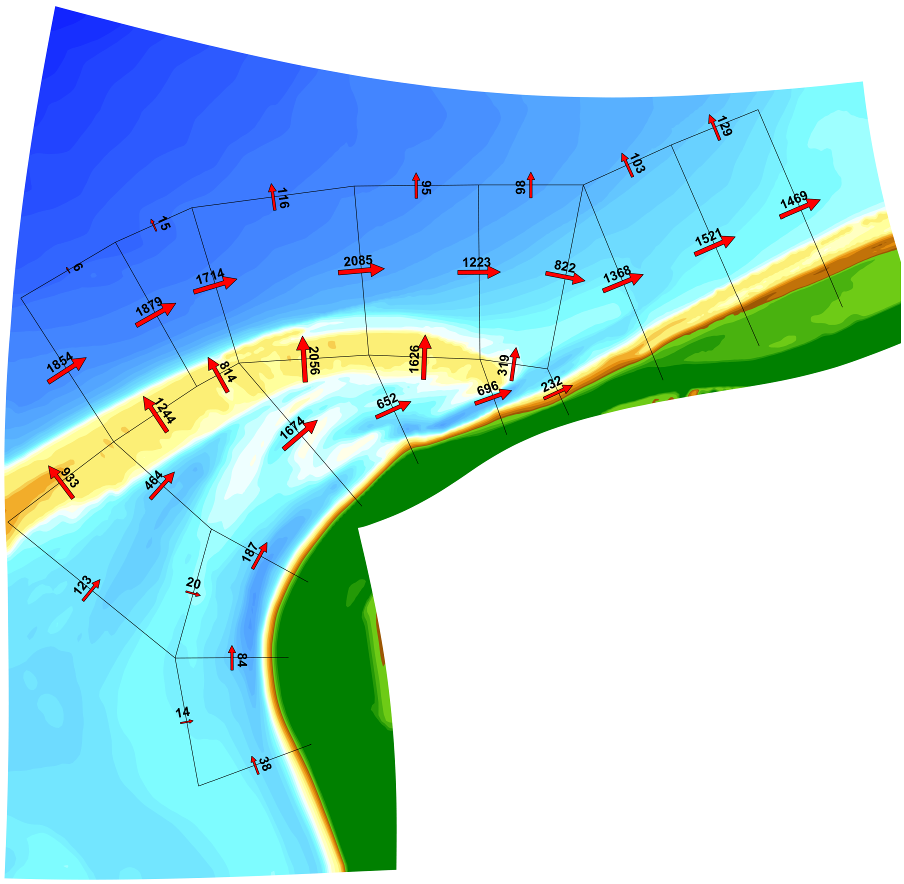
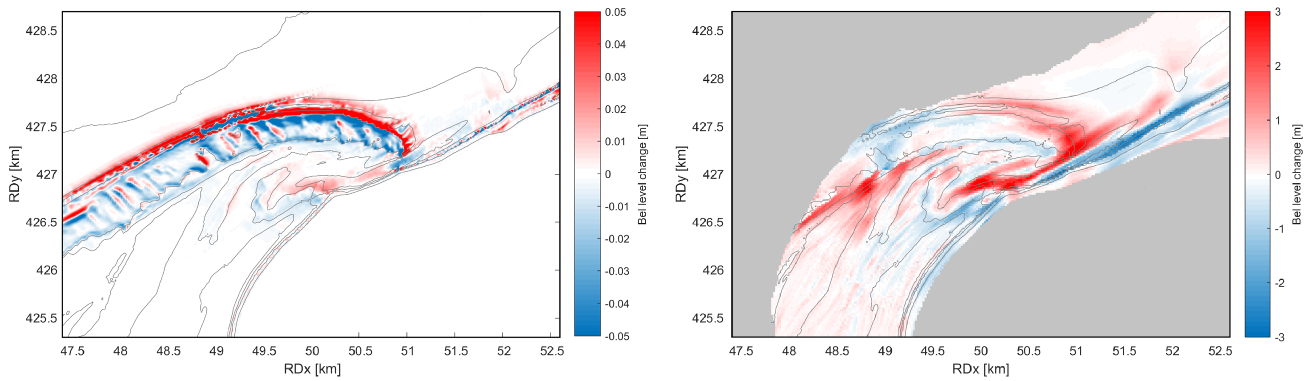


Figure 4.9: Annual net sediment transport rates through transacts in m^3 (x1000)

Figure 4.10a shows the simulated initial bed level changes as a result of the weighted sediment transport rates of all wave conditions. The model results show mainly sedimentation at the seaward side of the Ooster in this area and erosion on top. This is the result of the cross-shore sediment transport in northward direction on top of the Ooster, which was shown in Figure 4.8, as well as the longshore wave-drive transport in eastern direction. Figure 4.10b shows the measured bed level change in the period 2017-2019 to test the capability of the model to represent the sediment transport in reality. Note that the modelled sediment transports are the initial sediment transports after one tidal cycle, whereas the measured bed level change is the result of a two year of morphological development. Therefore no direct comparison can be made with regards the volume change. However, the sedimentation and erosion patterns can be compared. The eastward migration of the Ooster observed in the measured data can be seen in the model results. The same applies for the erosion of the coastline near the smallest part of the channel and the sedimentation southward behind the shoal.



(a) Modelled initial bed level change with bottom profile II after one tidal cycle

(b) Measured bed level change in the period 2017-2019, derived from the JarKus-grids

Figure 4.10: Comparison of the modelled initial bed level change with bottom profile scenario II after one tidal cycle and the measured bed level change in the period 2017-2019

Conclusion based on objective 1

The tidal flow along the coast induces large flow velocities in the Schaar during low tide when the Ooster falls dry. These ebb-tidal currents reach up to 1.67 m/s. In the remaining periods of the tidal cycle the channel does not play a large role in facilitating flow. The high tide stage is characterized by northward directed flow over the Ooster. From the simulated wave propagation in the model, it can be deduced that significant depth refraction occurs, particularly for the northern waves. The result is a large net longshore sediment transport at the seaward side of the Ooster. Moreover the presence of the wind reduce tide induced flow velocities in the channel during low tide.

4.4.2. Objective 2: impact of the narrowing of the channel

Figures 3.5 and 3.6 indicated the continuous decrease in channel dimensions of the Schaar. This has been the result of the hydrodynamic forcing, elaborated in the previous objective. The second objective has the purpose to evaluate the impact on the hydrodynamics and sediment transport as a results of this morphological development. For this objective, the model results of bottom profile scenarios I, II, III and IV are compared.

Tide-induced currents

In section 4.4.1 it was revealed that the channel plays an important role in carrying flow during the low tide stage. Significant flow velocities arise up to 1.67 m/s as a result of the tidal propagation along the coast. A comparison of the tide induced flow during this stage under different morphological configurations is shown in Figure 4.11. The bottom depth scenarios are arranged from the largest channel dimensions in scenario I to full closure in scenario IV.

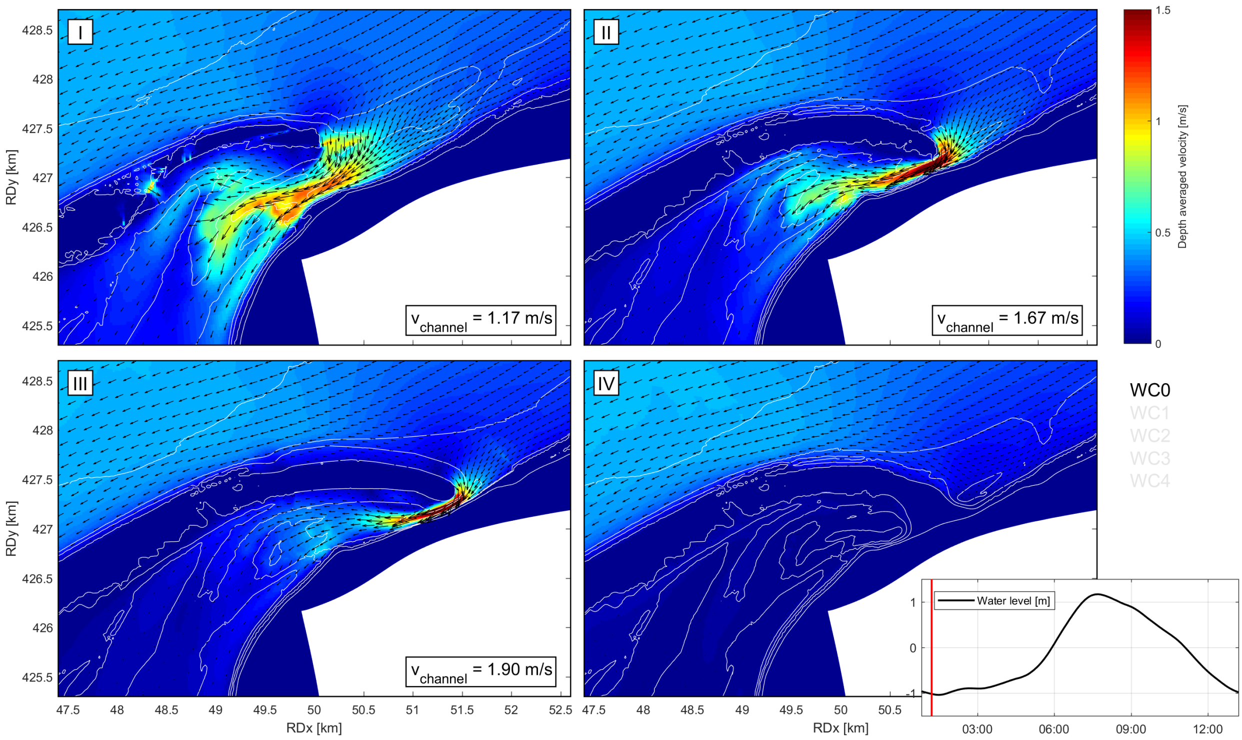


Figure 4.11: Tide-induced currents during low tide (stage A) for bottom scenarios I, II, III and IV. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. In the lower right corner of each plot the maximum velocity in the channel shown.

The results show that in general the reduced channel dimensions lead to an increase in maximum flow velocity in the channel. However, in the case of the absence of a channel in scenario IV, the ebb-tidal flow and therefore the erosive trend, seems to be completely absent during this low tide stage. Although the maximum flow velocity does increase as a result of the decreased channel dimensions, this increase is only the case for a limited time duration within the full tidal cycle. Figure 4.12 shows the fluctuations of this maximum flow velocity in time in the area around the channel. The differences in flow velocities during the remaining tidal cycle are negligible. Despite the limited time duration, the increase of tide induced flow velocity does affect the sediment transport rate in the channel. Figure 4.13 shows an increase in the tide-induced transport rates in southwestern direction.

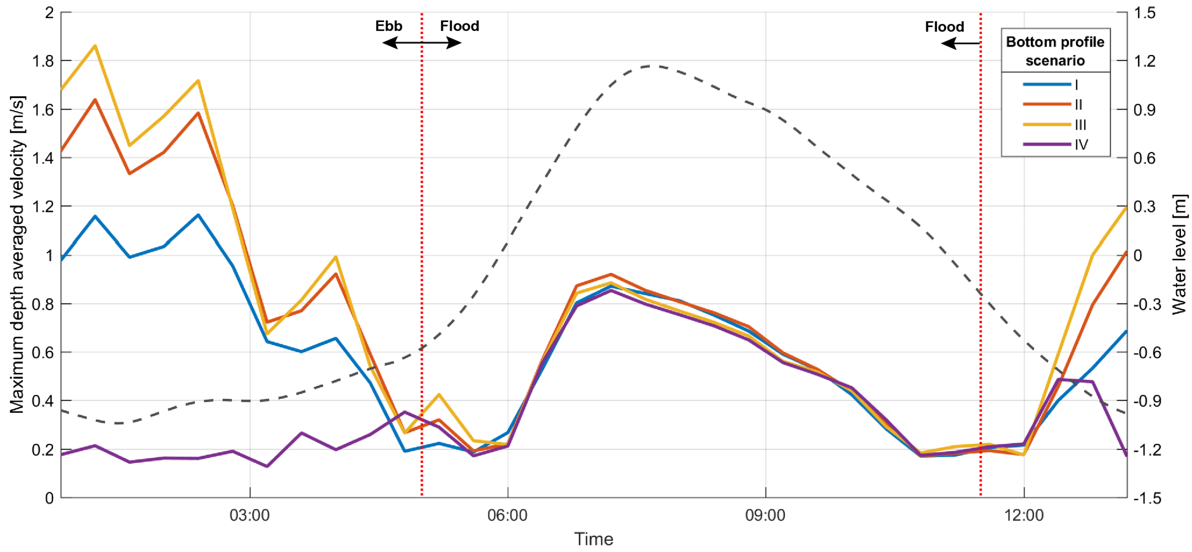


Figure 4.12: Maximum instantaneous depth averaged tide-induced velocity in the area of the channel during one tidal cycle for bottom profile scenarios I, II and III. The instantaneous water level is indicated by the dashed line. The red dashed line indicates approximately the moment of flow reversal in the channel.

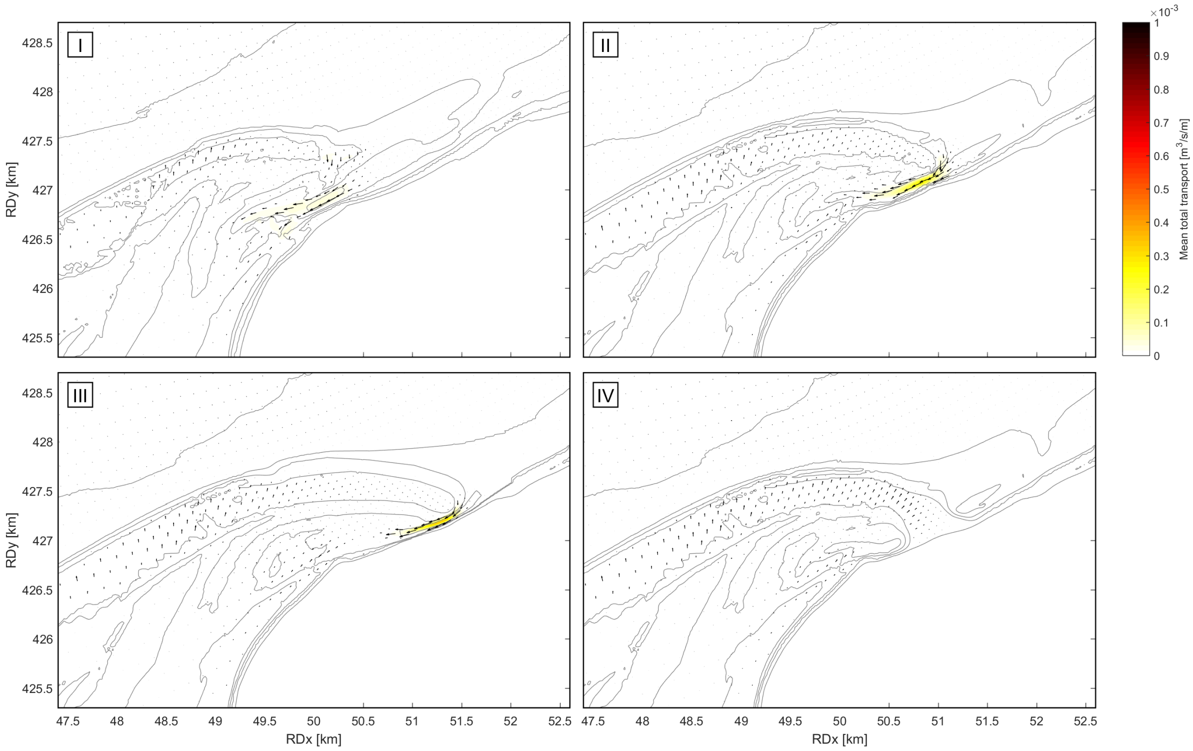


Figure 4.13: Mean sediment transport due to the tide-induced currents without waves for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

Currents induced by the wave conditions and sediment transport

Model results show that the changing channel dimensions mainly affect the magnitude of the tide-induced flow during the low tide stage. Considering the simulations with wave- and wind forcing, the morphological development does have a much smaller effect of the flow patterns. The longshore currents at the seaward side are not significantly affected. Moreover the dominance of wind, in determining the flow patterns in the channel, is also valid for bottom profile scenarios I and III. In Appendix D the flow pattern comparison for the remaining wave conditions can be found.

This observation about the dominance of wind for the different bottom scenarios also appears in the mean weighted sediment transport calculations. Although the tide-induced flow patterns and the induced sediment transport show an increase as the channel dimensions decrease, the mean weighted sediment transport rates over all wave conditions shows no significant increase. Figure 4.14 shows these mean weighted sediment transports. Furthermore the longshore transport by waves at the seaward side of the Ooster are a source of sediments for the channel.

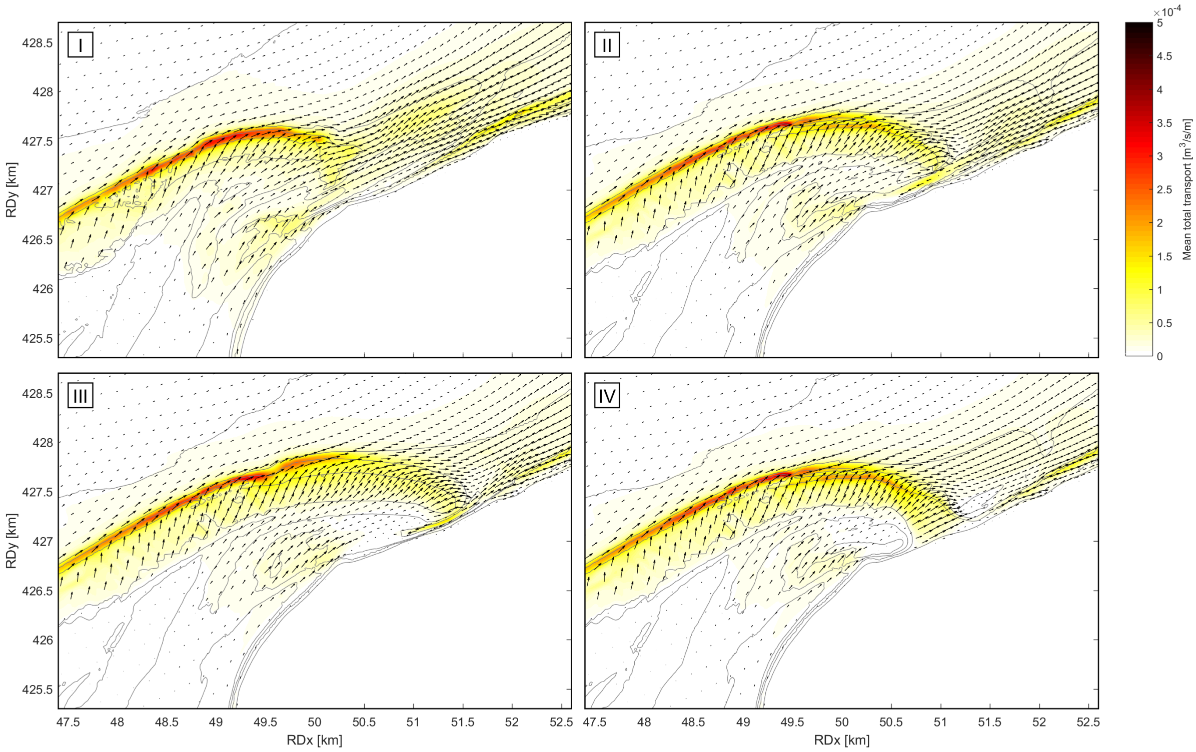
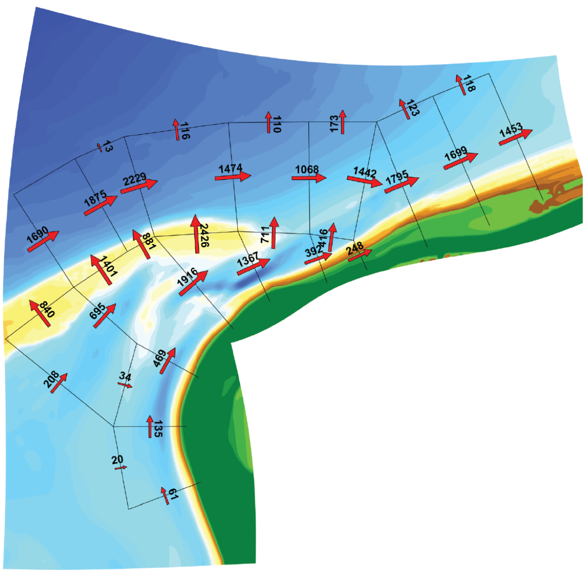
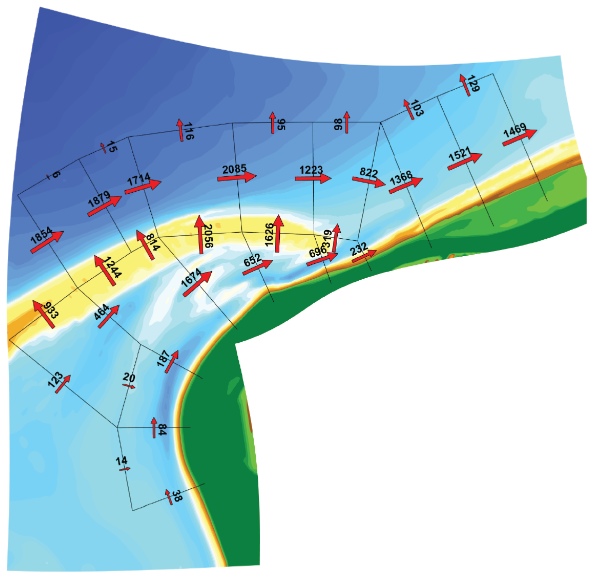


Figure 4.14: Mean weighted sediment transport for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

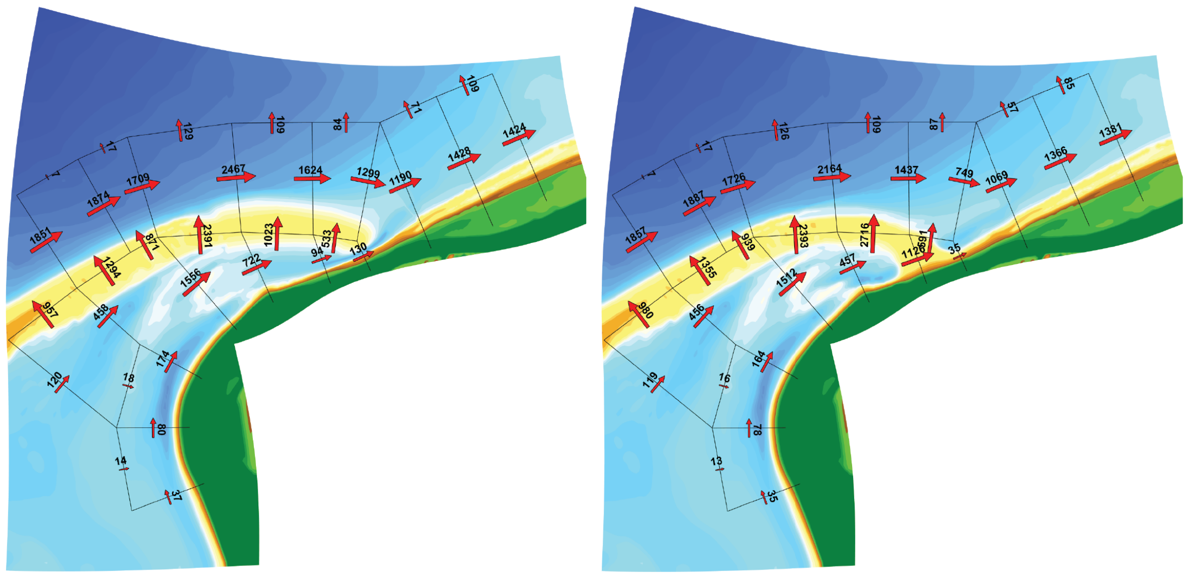
Comparing the annual sediment transport rates based on the modelled initial sediment transport rates, shown in Figure 4.15, reveals a decrease in net longshore transport at the downdrift coast as the channel dimensions decrease. Furthermore the transport rates at the landward side of the Ooster decrease as well.



(a) Scenario I



(b) Scenario II



(c) Scenario III

(d) Scenario IV

Figure 4.15: Comparison of annual net sediment transport rates through transacts in m^3 (x1000)

Figure 4.16 shows the initial bed level changes of scenarios I,III,IV and V after one tidal cycle. In general the sedimentation and erosion patterns do resemble of Figure 4.10a. However, results of scenario IV shows that with the absence of the channel, the erosion trend near the coast disappears.

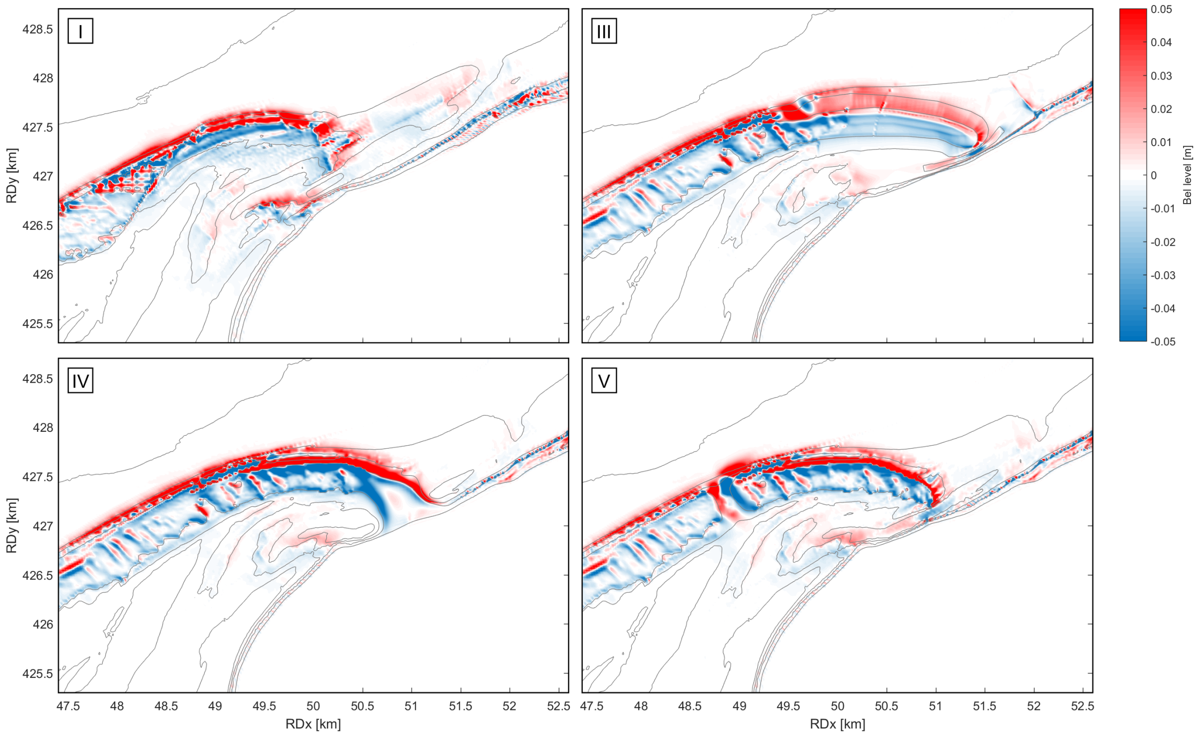


Figure 4.16: Initial bed level changes of scenarios I, III, IV and V.

Conclusion based on objective 2

The reduced channel dimensions mainly affect the tidal flow patterns during the low tide stage resulting in an increase of tide-induced maximum flow velocity. However sediment transport calculations show that presence of wind nullifies this effect on the morphological development. This, in combination with the sediment source provided by the longshore current, could explain the gradual decrease in channel depth and channel dimensions in general.

4.4.3. Objective 3: effect of a local breach

The last objective considers the effect of a breach in the Ooster. For this model results from bottom depth scenarios II and V are compared.

Tide-induced currents

The flow patterns in the breach predominantly resemble the patterns in the present channel. Figure 4.17 shows a comparison of the flow patterns during stages A till D. The resemblance entails relatively large flow

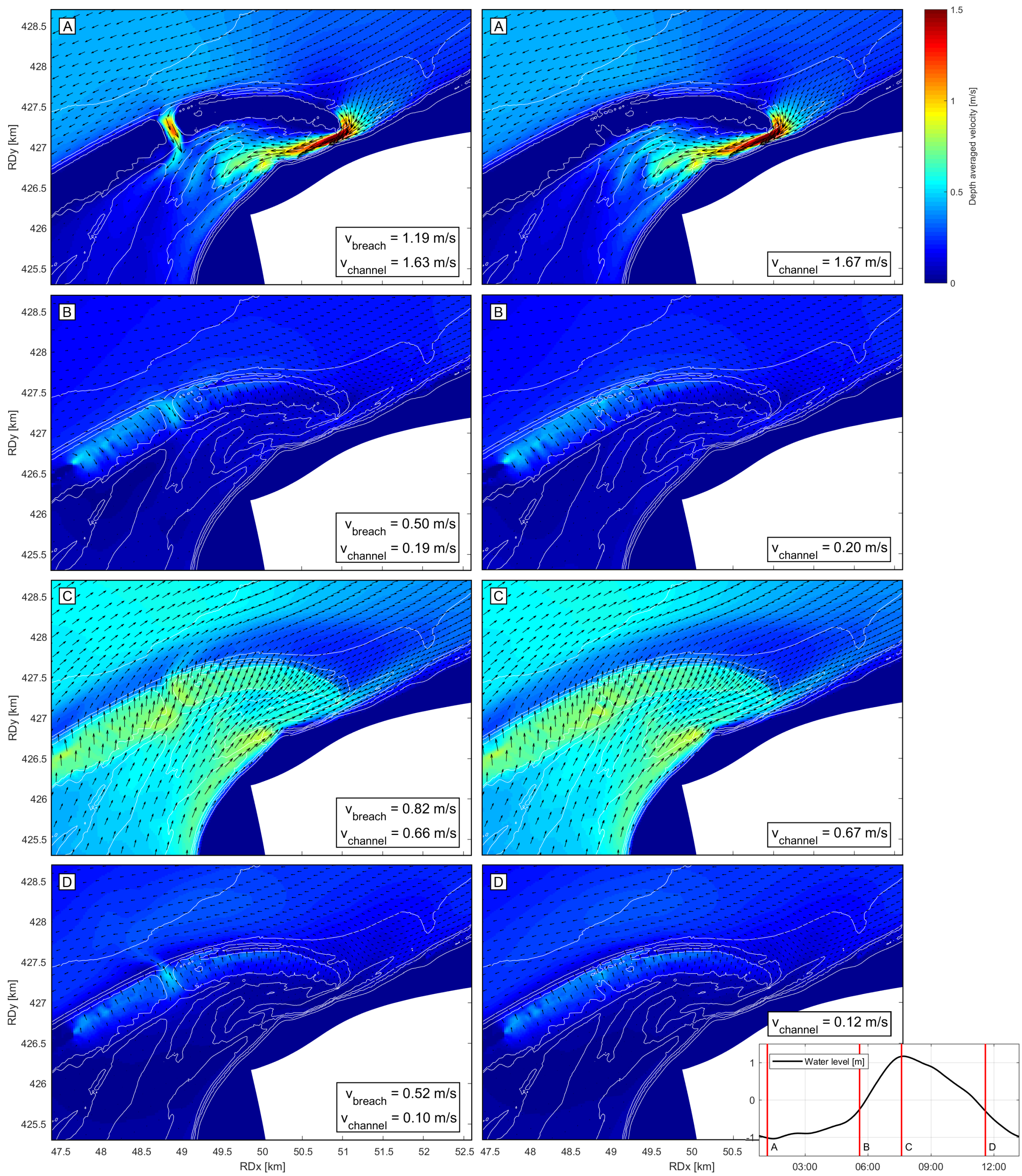


Figure 4.17: Comparison of the tide-induced currents during four stages of the tidal cycle for last measured bottom profile II on the right side and the bottom profile including a breach (V) on the left side. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. In the lower right corner of each plot the maximum velocity in the channel shown.

velocities during the low tide stage. A peak flow velocity of 1.19 m/s can be observed in the breach. During the remaining stages of the tidal cycle the breach does not play a large role in facilitating flow, similar to the main channel. During flow reversal, a slight increase in flow at the location of the breach is observed. This can be explained by the short delay in flow reversal behind the Ooster and at deeper water. During this time the breach functions as a shortcut channel. The presence of a breach results in a limited decrease in the channel velocities in the order of 0.04 - 0.02 m/s. In the case of enlargement of the breach due to eroding currents, the decrease in maximum flow velocities in the channel could become larger.

Wave-induced currents and sediment transport

In general the presence of waves does not lead to larger flow velocities in the breach. Moreover the effect for the main channel does not differ from the model simulation with waves: the channel velocities show a slight decrease overall. The mean weighted sediment transport of bottom scenario V, shown in Figure 4.18, indicate no severe transport through the breach and therefore the conservation of this breach seems unlikely. The sediment supply by the longshore current at the seaward side of the Ooster will lead to sedimentation in the breach and will lead to closure.

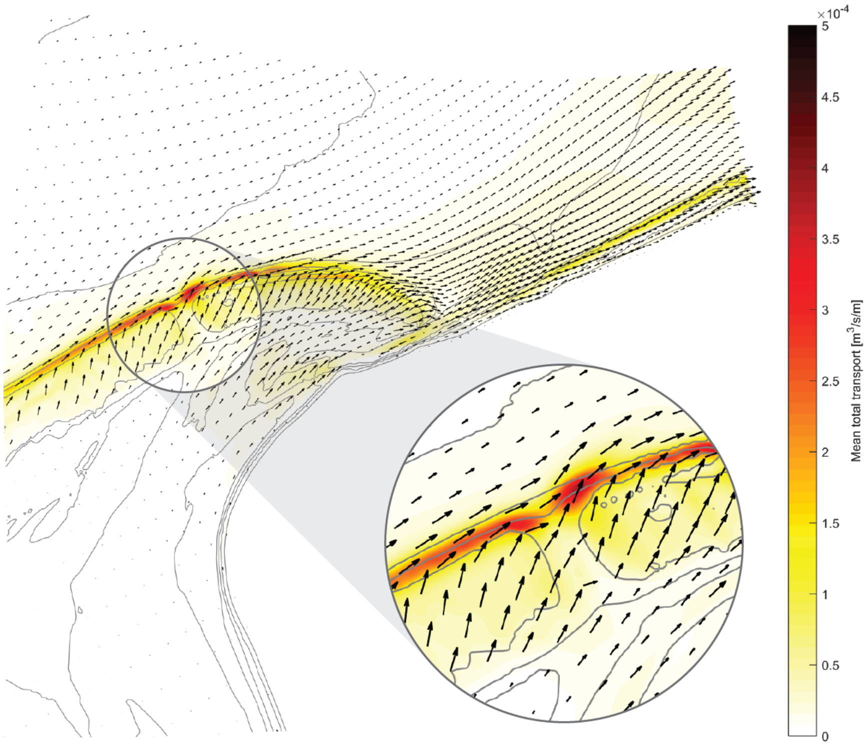


Figure 4.18: Mean weighted sediment transport bottom scenario V

Conclusion based on objective 3

During low tide significant tide-induced currents occur in the breach. A breach does lead to a reduction in flow velocity in the channel, however this effect is almost negligible. Sediment transport patterns with the inclusion of wave patterns indicate that conservation of this breach is unlikely due to the longshore sediment transport at the seaward side of the Ooster.

4.5. Conceptual model of model results

To synthesise the results of the modelling study, a conceptual model is proposed, summarizing the dominant processes and the resulting morphological development. This conceptual model is shown in Figure 4.19.

During regular wave- and wind conditions, the flow in the Schaar is dominated by the ebb-tidal currents in south-western direction. Significant flow velocities arise during low tide resulting in erosion of the coastline at this location. Wind forcing does affect the magnitude of these currents in the Schaar. In the case of more energetic conditions, with wind speeds in the order of 12-15 m/s from west-southwest direction, the wind becomes dominant in determining the flow direction in the Schaar. Landward and on top of the Ooster the flood-tidal currents in northward direction dictate. This flow result in a net sediment transport over the Ooster leading to erosion at the landward side and sedimentation at the seaward side.

Wave-driven flow dominates at the seaward side of the Ooster and the downdrift coast of Goeree-Overflakkee. Waves are able to stir-up sediments and creating a longshore current. As a result of depth refraction of northern waves in particular, a large net longshore sediment transport is generated in eastern direction. This longshore transport is a sediment source for the Schaar. The result is a decrease of the channel dimensions, which was shown in Figure 3.6. Moreover, this longshore sediment transport makes it unlikely that a stable breach will arise at this area with the current morphological configuration.

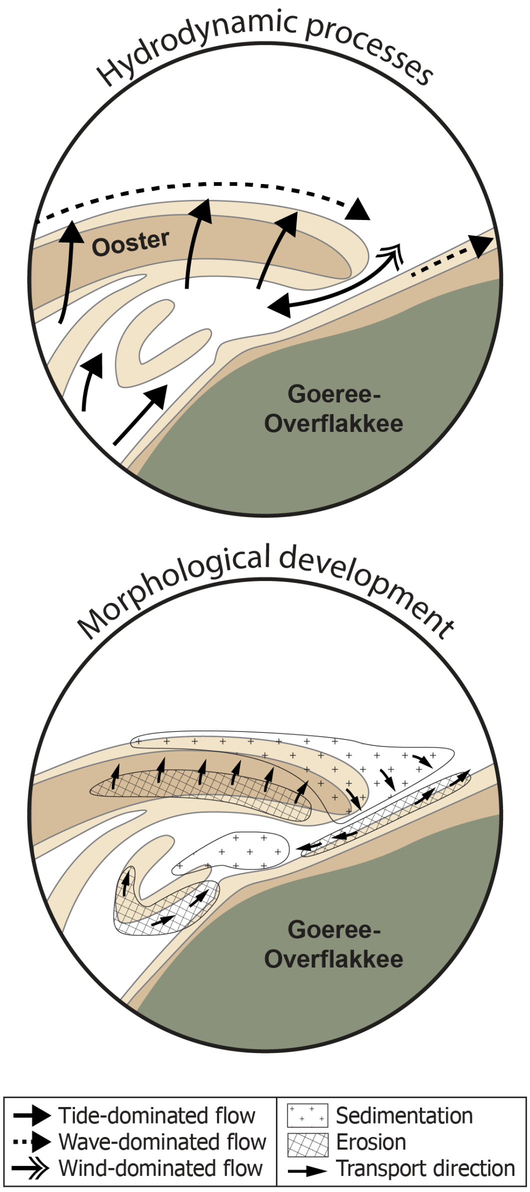


Figure 4.19: Conceptual model of the dominant hydrodynamic processes and morphological development at the eastern edge of the Ooster near the coast of Goeree-Overflakkee.

5

Future Development

In this chapter the results presented in the data analysis and modelling study as well as the gained knowledge about the background are interpreted and used to draw conclusions about the expected morphological development in the future.

5.1. Interpretation of findings

Literature (Bakker, 1980, Rijkswaterstaat, 1973) provides valuable insights into the history of coastal erosion at Goeree-Overflakkee. The erosion trend of the Westhoofd goes back in history for multiple centuries. The closure of the Brouwersdam mainly affected the tidal flows patterns in the outer delta, which resulted in vast changes in morphology. A net landward sediment transport was initiated and resulted among others in the rise of the Ooster. At the Westhoofd the tide-induced flow velocities increased due to the closure and accelerated the erosion of the coastline leading to the application of multiple nourishments. Moreover the eastward migration of the individual shoals of the Ooster, the Bollen van de Ooster, forced the tidal flows in landward direction. Periodic attachment of the individual shoals onto the coast forced the channel away from the coastline. After the mid-nineties this periodic behaviour stopped when only one shoal remained. Thereafter the Ooster developed undisturbed and showed a rapid elongation in eastern direction. Since 2003 the depth and flow surface of the channel, which separates the Ooster from the coastline, shows a continuous decrease. According to model results this could be explained due to the dominance of wave forcing with respect to the tide-induced flow. The wave-induced currents are generally reducing the large tide-induced velocity in the channel. Moreover they induce a net longshore sediment transport at the seaward side of the Ooster which acts as a sediment source for the channel.

Based on these considerations, an attachment of the Ooster onto the coastline is expected in the near future. However, what would such an attachment look like and what does this mean for the morphological development thereafter? Attachment of shoals in the past resulted in a large accumulation of sediments onto the coast. Subsequently the tidal flow was moved away from the coastline and eroded a new channel between the shoals. However, these attachments happened while there were still multiple smaller shoals present. In the current situation the Ooster is one large shoal and the expected location of the attachment is located further down the coast. Model results shows that the emergence of a new stable breach in the Ooster is unlikely to occur in the current morphological configuration, although the narrowing trend of the Ooster indicates that the stability of the Ooster might be an important to consider on the long term.

5.2. Attachment of shoals

Other cases of shoal attachment in outer deltas could provide insight in the development of the Ooster. Therefore two cases in the Waddensea area are considered which both show different types of shoal attachment. Firstly the attachment of the Bornrif at the coast of Ameland and secondly the recent attachment of the Noorderhaaks at the coast of Texel. The description of these cases do not include extensive data analysis of the morphology, other literature can be consulted for this purpose (Elias et al., 2017, Lenstra et al., 2019, Nederhoff et al., 2015). It must be noted that unlike the Grevelingen outer delta, these tidal inlet systems are not closed off by a structure like the Brouwersdam. While the development of the Ooster is described as a one-time event related to the closure of the Grevelingen by Elias (2015), the attachments in the Waddensea area are not initiated by anthropogenic interferences but due to the natural development in the outer delta.

5.2.1. Bornrif

Bornrif was a shoal in the outer delta of the Ameland inlet which attached onto the coast of Ameland around 1970. A detailed description of this morphological process is given by Nederhoff et al. (2015) and briefly elaborated here. Figure 5.1 shows a schematic illustration of this process. The attachment of the Bornrif dates from 1970 when the eastern edge of the shoal attached onto the coast of Ameland and the local channel

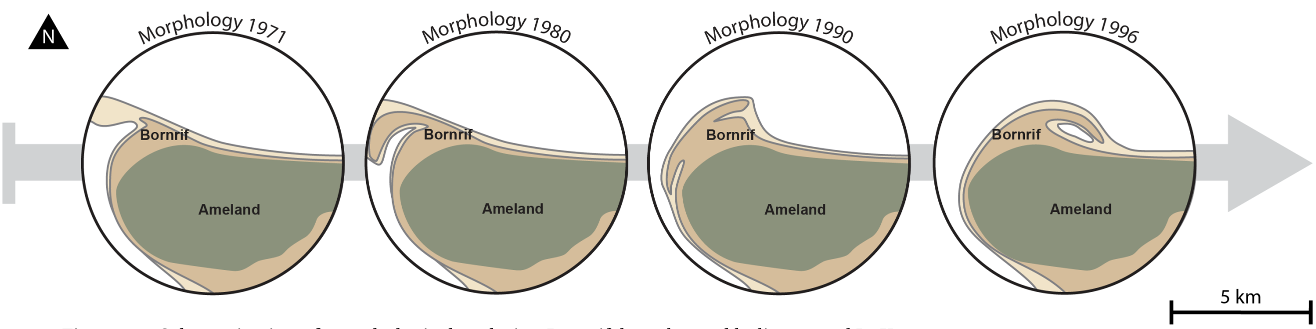


Figure 5.1: Schematization of morphological evolution Bornrif, based on vaklodingen and JarKus.

called Oostgat was closed. In the years thereafter this connection with the beach broadened till around 1990 the complete shoal merged with the island of Ameland. Accordingly the large accumulation of sediments were spread along the downdrift coastline forming a spit which migrated in eastward direction. A lagoon was formed between this spit and the beach. This lagoon was connected to the sea by a channel which showed meandering behaviour along the coast of Ameland as time proceeded. This process continued til around 2000 when the channel could not longer be maintained by the tide-induced flow. A new channel was formed in the spit. In Figure 5.1 the 'new' Bornrif could already be seen which attached onto the coast recently further east compared to the previous attachment.

5.2.2. Noorderhaaks

The Noorderhaaks is a shallow area in the outer delta of the Marsdiep inlet. A short summary of the morphological development of the Marsdiep is given by (Elias et al., 2017). The described development regarding the Noorderhaaks is briefly elaborated here. The Noorderhaaks consists out of an area which is usually above water, the 'Razende Bol', and an elongated spit at the northern side called the 'Noordelijke Uitlopers van de Noorderhaaks' (NUN). A schematization of the morphological evolution of this situation is shown in Figure 5.2. Over the years the NUN extended in northern direction along the coast of Texel. The NUN was separated from the coast by a deep channel called the Molengat. As time proceeded the NUN migrated in northern direction and eventually attached onto the coast of Texel.

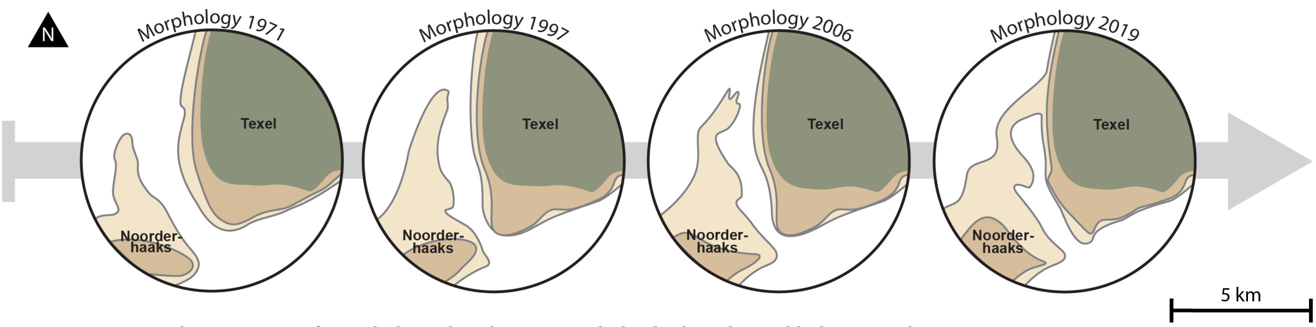


Figure 5.2: Schematization of morphological evolution Noorderhaaks, based on vaklodingen and JarKus.

5.3. Expected future development of the Ooster

The attachment of the Bornrif closely resembles the attachment of the previous shoals of the Ooster which was shown in Figure 3.4. The complete shoal merged with the beach resulting a large accumulation of sediments which over time were spread along the coastline. The orientation as well as the process of elongation of the NUN shows many similarities with the Ooster in the Grevelingen outer delta. It is therefore expected that the attachment of the Ooster will have a similar appearance compared to the Noorderhaaks. Figure 5.3 shows a schematization of the development of the Ooster and the expected morphology after attachment.

After attachment of the Ooster the eroding tide-induced currents will disappear. Furthermore the downdrift coastline will be supplied by the longshore sediment transport at the seaward side of the Ooster which was observed in Figure 4.8. This longshore sediment transport will continue to erode the seaward side of the Ooster. As a result the ongoing process of narrowing of the Ooster, which was observed in Figure 3.3, will continue and potentially make the Ooster more vulnerable for a breaching event.

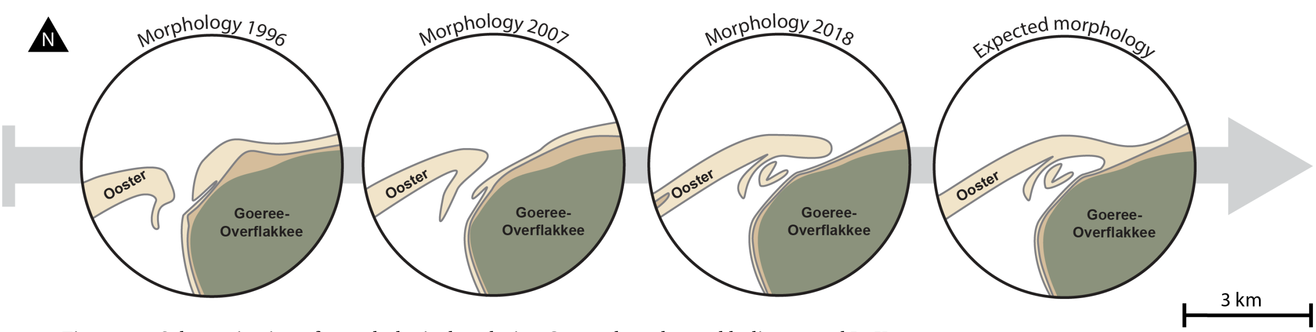


Figure 5.3: Schematization of morphological evolution Ooster, based on vaklodingen and JarKus.

6 Discussion

6.1. Limitations in data analysis

The morphological development of the study area has been analysed using bathymetric measurements. The frequency of these measurements do not allow to investigate the morphological response to short-term events. These events can be related to particular wave and wind forcing and setup. For example, extreme conditions will have a relatively large impact on the morphological development.

6.2. Accuracy of model results

The modelling study has been used to provide insight into the hydrodynamic and sediment transport processes in the study area. In general, use of a model inevitably leads to inaccuracies when representing reality. Assumptions have been made regarding the physical parameters and boundary conditions in the model. Physical parameters are related to - among others - the bottom characteristics such as bed roughness and the sediment characteristics. These parameters were adopted from the Haringvliet-model by De Vries (2007). This model was validated for the Haringvliet outer delta to reproduce morphological development. However, this has not been the case for the study area near the Ooster. Therefore computed sediment transport rates should be considered qualitatively instead of quantitatively.

The flow boundary conditions in the model were adopted from the model by De Vries (2007). According to Elias (2015) the modelled flow velocities do not give a reason to question this assumption. However the application of a morphological tide neglects the natural variability due to the spring-neap tidal cycle. Especially during spring tide the differences in water level are larger and therefore the flow velocities in the channel are larger.

As waves are considered to be the dominant hydrodynamic forcing mechanism, the assumptions regarding the schematization of the wave climate is expected to be the largest source of inaccuracy. The wave climate has been reduced to the two most frequent occurring wave directions. This method implicitly focuses on the longshore sediment transports and therefore might neglect the effect of cross-shore waves. The model results with wave-forcing indicate that offshore induced wave directions are not dominant in changing the flow direction near the channel, however expansion of the wave climate will provide more accuracy in the calculation of the sediment transport rates.

Lastly, wind forcing has been incorporated in the wave conditions. Especially with the conditions with northern wave directions the wind direction shows little correlation with the wave direction. To assess the affect of the wind direction on the wave propagation and flow patterns in the model, additional model simulations with bottom profile scenario II have been performed. Results are shown in Appendices D.5 and D.6. It shows that deviation of the wind and wave direction does not lead to major differences compared to the case when wind direction is equal to the wave direction.

6.3. Stability of the Ooster

Based on the data analysis and model results the attachment of the Ooster seems inevitable in the near future. However the development of the Ooster on a longer timescale mainly depends on the stability of the Ooster. Data analysis showed the continuous narrowing of the shoal which potentially makes the Ooster more unstable. Model results showed no sign of breaching in the current morphological state under the applied hydrodynamic forcing. A breach like the Hinderplaat is unlikely to occur due to absence of land reclamations and discharge from the estuary. However the combination of continuous narrowing and an extreme wave event could potentially result in a stable breach.

The prospective changes in the hydrodynamics due to the construction of a passage in the Brouwersdam will impact the current morphological development. The tide will induce cross-shore flow patterns which are likely to affect the stability of the Ooster as water level gradients will arise at both sides of the shoal. The exact impact will depend on the magnitude of the flow through the passage and can not be extracted from results in this study. Based on previous research into the changed tide-induced flow in the Schaar, the flow is likely to decrease at the Westhoofd and therefore have a positive effect on reducing the current erosion problems. However, the morphology has changed considerably which makes this one-to-one comparison with the past uncertain.

A potential breach of the Ooster could benefit the coast of Goeree-Overflakkee as has been the case in the past. Further research with respect to this anthropogenic interference is required to evaluate the effects in detail. For this the application of a numerical model is recommended.

6.4. Assessment of primary flood defences

In this study the focus was on the morphological development of the foreshore with the purpose to evaluate the potential risk for Goeree-Overflakkee. The risk seems to be minor due to the prospected attachment of the Ooster and the presence of a wide dune row. Moreover, the presence of a groyne field in front of the Flaauwe Werk, will have a positive effect in reducing the erosion trend to proceed until the dike toe. However, to exclude the danger of the coastline erosion for the Flaauwe Werk, the limits of coastline retreat should be assessed.

7 Conclusions and recommendations

7.1. Conclusions

The objective of this research was to investigate if the future morphological development of the Ooster is a potential hazard for Goeree-Overflakkee. Therefore three consecutive sub-questions were defined: 1) What has been the morphological evolution of the Ooster and the Schaar since the construction of the Brouwersdam in the Grevelingen estuary? 2) What are the characteristics of the water motion, which mechanisms are most dominant, and how does this lead to the current morphology of the Ooster? 3) What is the expected morphological development of the Ooster in the case of non-changing hydraulic boundary conditions? In this chapter, these questions will be answered by summarizing the major findings.

The Westhoofd of Goeree-Overflakkee has had a history of coastline erosion in the past, and the anthropogenic interference in the form of the Brouwersdam led to an increase in this erosion trend since. Multiple nourishments followed in order to preserve the coastline position. The increasing erosion trend was the result of a combination of a local increase in tide-induced flow velocities and morphological development of the Ooster in this area. Analysis of bathymetric data shows that the Ooster developed from a permanently submerged shoal into multiple intertidal shoals which over time migrated in eastern direction and periodically arrived at coast. This periodic process was accompanied by the Schaar which was forced in the direction of the coastline due to the migrating Ooster resulting in coastline retreat. Due to the periodic arrival of shoals the erosion trend was temporarily solved, however the arrival of shoals stopped after the Ooster developed into one individual shoal. The development of the latter included an increase in height, elongated mainly in eastern direction and narrowing as time proceeded.

The rapid migration in eastern direction currently has resulted in a new erosion problem further north, potentially threatening the local flood defences. Results from morphostatic model simulations demonstrate that this rapid development near the coastline of Goeree-Overflakkee can explained by the significant wave refraction of the northern waves in the outer delta. The latter leads to substantial net alongshore sediment transport rates at the seaward side of the Ooster in eastern direction. In addition, the tide induces large flow velocities in the Schaar, particularly during ebb currents with the current morphological configuration. This is the result of the tidal propagation along the Dutch coast which is being converged through this relatively deep channel. This convergence of flow is occurring for a limited time period when the Ooster is emerged. In the remaining stages of the tidal cycle the channel does not play a large role in facilitating currents. Model simulation show that the wind in general have a positive effect in reducing the magnitude of the ebb currents in the Schaar. The existence of the channel between the Ooster and the coastline of Goeree-Overflakkee is a balance between wave forcing and tide-induced flow. Data analysis shows that since 2003 the maximum depth in the channel gradually decreased from almost 12 meter to less than 7 meters. Moreover the minimum flow surface area shows a gradual decrease. This indicates that the wave forcing is currently more dominant with respect to the tide-induced flow in determining the morphological evolution.

Based on these considerations it can be concluded that the channel between the Ooster and the coastline is likely to disappear and therefore the Ooster will connect to the coast in the near future. This means the current erosion at the coast of Goeree-Overflakkee is of a temporary nature. The duration at which this event will occur can not be extracted from this study. However based on the trend of the decreasing channel dimensions this event is expected to occur sometime in the next few years. In the meantime the erosion will continue to proceed.

The potential danger of this future development for the primary flood defences is expected to be minor. Currently the effects of the coastline retreat are visible in the dunes. However, due to the width of the dune row the potential danger seems negligible. The limits to which the erosion of the coastline may proceed to endanger the hard flood defence, the Flaauwe Werk, could not be extracted from this study. However, in the case the erosion continues, the present groyne field will most likely prevent the erosion trend to reach the dike toe.

7.2. Recommendations

Monitoring of morphological development
Continuation of the coastline retreat in the near future requires a close monitoring of the morphological development in this area. This does not only include monitoring of the coastline position, but also surveying the channel dimensions. In this way, the decreasing trend of the channel can be monitored and the process of attachment could be followed.

Assessment the Flaauwe Werk
Apart from monitoring, the limits of the coastline retreat with regards to the safety of the Flaauwe Werk should be assessed. In other words, the maximum BKL exceedance should be assessed to formulate clear guidelines when an interference in the form of a nourishment is necessary. With this information informed decisions can be taken based on the observed morphological development.

Application of a nourishment
The prospected breach nourishment will provide extra safety for the coastline. However, the erosion problem will remain as long as the channel is present. The development of the channel dimensions shows that the channel is closing naturally. Therefore it is recommended to reconsider a nourishment which completely fills the channel instead of a beach nourishment. In this way the origin of the erosion problem is tackled, and the coastline retreat will not proceed for an unknown period of time. Moreover, in this way the sediments from the Ooster could contribute to a seaward migration of the coastline.

Stability of the Ooster
Based on model results the emergence of a breach in the current morphological configuration is unlikely to occur under the imposed hydrodynamic conditions in this study. However the process of narrowing of the Ooster potentially makes the shoal more likely to breach in the future. Future research could investigate the stability of the shoal under extreme conditions. Furthermore the effect of a passage in the Brouwersdam could be investigated more precisely by incorporating this passage in a morphological model.

Improving the accuracy of predictions
In the modelling study assumptions have been made which affect the accuracy of predictions. In this study the modelling results have mainly been used to interpret the observed morphological evolution. However, in the case of a morphodynamic simulation over a longer time period, this will probably not lead to precise predictions. In case a more precise estimate about the future morphological development is demanded, future research is recommended to expand the complexity by expanding the wave climate. This would also incorporate the effects of cross-shore wave incidence.

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APPENDICES

A

Supporting results data analysis

In this appendix additional results from the data analysis are presented to support the findings in Chapter 3.

A.1. Detailed comparison cross-sections Hinderplaat and Ooster

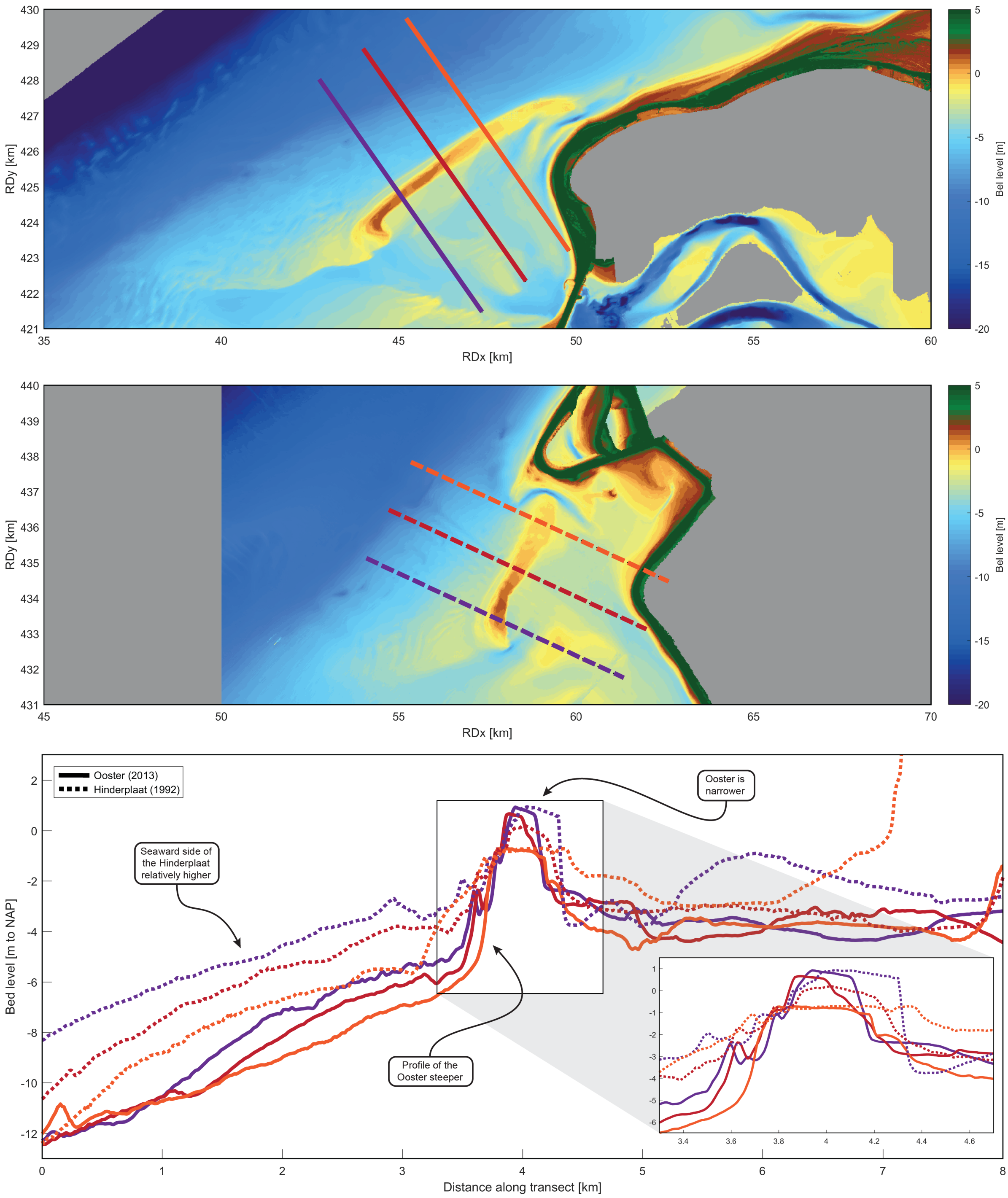

Figure A.1: Comparison of three cross-sections of the Hinderplaat in 1992 and the Ooster in 2013, derived from the Vaklodingen dataset.

B

Wave schematization

In this appendix the wave schematization process is described in detail. The method used to derive the wave and wind conditions as input for the Delft3D model.

In the nearshore region waves do have an important contribution in the sediment transport. However wave characteristic are constantly changing in time in terms of wave height, wave direction and wave period. These characteristics determine the wave induced sediment transport patterns and rates and therefore the morphological development. In order to obtain a realistic morphological development with the Delft3D model, ideally all these different conditions should be incorporated in the model. Yet this would result in a very large computation time. The number of wave conditions should be limited to accelerate the simulation. This is called wave input reduction.

The objective of wave input reduction is to obtain a limited number of wave conditions which combined result in equal sediment transport patterns and rates (Lesser, 2009). Based on offshore measurements at the Europlatform in the period 1979-2001 the wave climate in the study area is determined. Figure B.1 shows the position of the Europlatform relative to the Dutch coast and the directional wave rose which shows the frequency of the wave heights from particular directions. It shows that waves coming from the north and southwest (225°N) are most frequent. It must be noted that the measurements were done offshore, so waves coming from the east had enough fetch to develop to a significant wave height, while this is not the case for the nearshore area. Therefore waves coming from the east (45°N - 210°N) have been excluded from the data for the wave schematization.

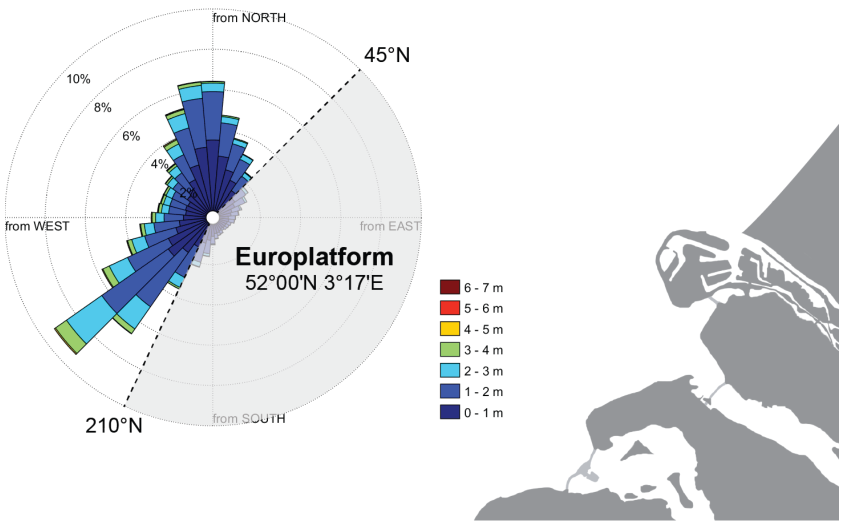

Figure B.1: Position of the Europlatform and the wave rose of the measured wave climate in the period 1979-2001

Figure B.2 shows an other representation of the same data in which the waves are classified in bins with an direction interval of 15° and 0.5m interval in wave height. For each bin a representative value for of the wave height is determined ($H_{s,rep}$).

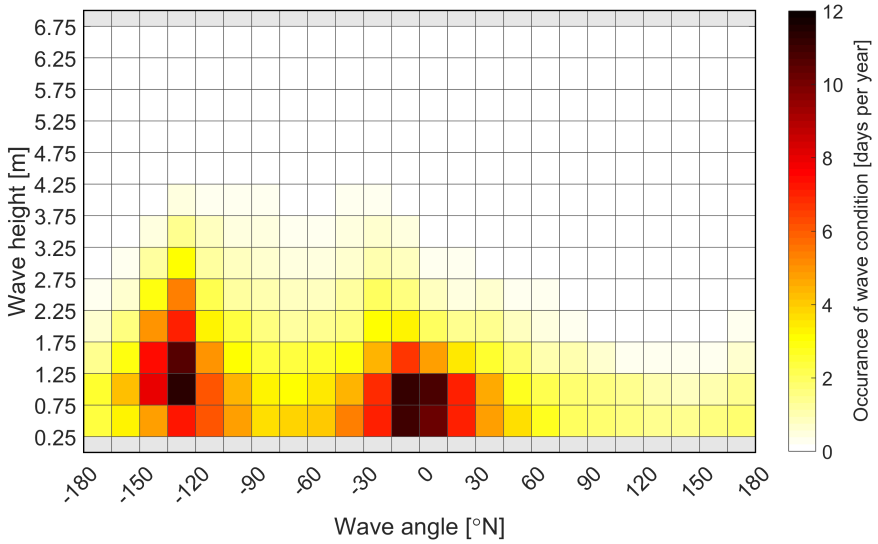

Figure B.2: Wave climate measured at the Europlatform in the period 1979-2001

Extreme conditions with large wave heights will lead to relative large sediment transports, while these conditions may only occur a for a limited time. To incorporate the importance of these conditions to the morphological development, the probability of occurrence of each binned wave condition is scaled by the their impact on the sediment transport. This results in a weighted contribution of each wave condition to the sediment transport. The simplified CERC formula (Equation B.1) is applied for this purpose. The result is shown in Figure B.3.

$$S \sim H_s^{2.5} \tag{B.1}$$

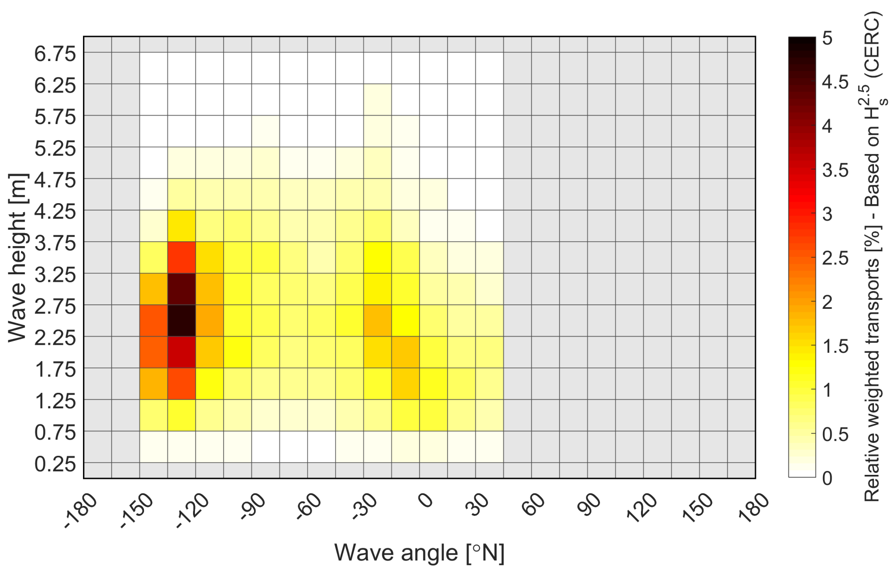

Figure B.3: Relative weighted transports per wave condition

With the exclusion of the eastern wave conditions still 169 wave conditions remain. Every condition has a relative weight and a representative wave height. Accordingly the wave conditions are grouped into different classes. There are different wave input reduction methods available to select representative wave classes (Lesser, 2009). In this study the 'manual wave class selection' method is applied. The number of desired wave conditions is set to 4. The wave conditions are divided based on their wave direction. A division is made at 315°N (-45°N) which is approximately perpendicular on the orientation of the Ooster. This separates the most frequent wave conditions from the north and southwest. Thereafter the two directional wave classes are divided based on their wave height. This result in a wave condition for 'regular' and 'strong' conditions. The division for the latter is based on equal weight, which entails that the relative weighted transports of each condition are approximately equal. Figure B.4 gives an visual representation of the waves classes indicated by the red squares. The representative wave height of each class is derived by equation B.2.

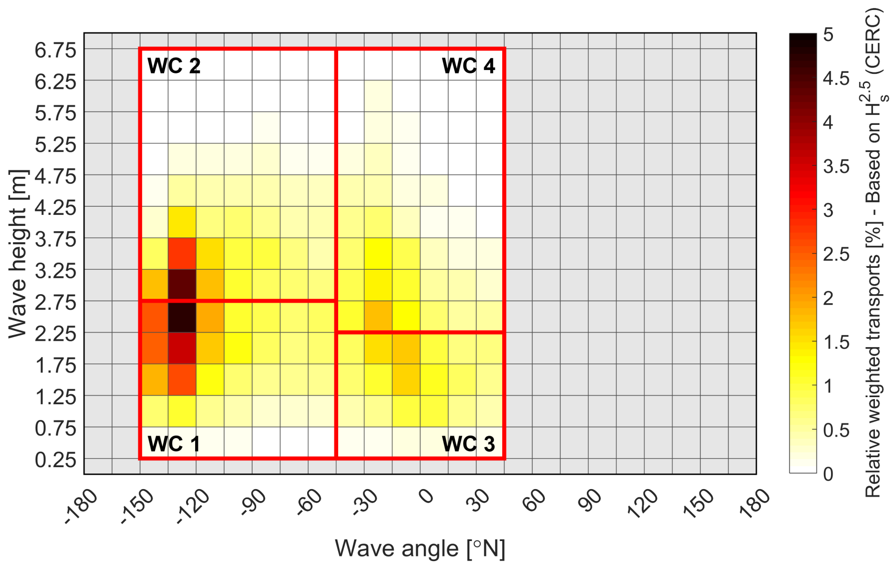

Figure B.4: Wave classes

$$H_{s,rep} = \left(\frac{\sum P(H_{s,bin}, Dir_{bin}) H_{s,bin}^{2.5}}{\sum P(H_{s,bin}, Dir_{bin})} \right)^{0.4} \tag{B.2}$$

Besides the wave direction and significant wave height, the wave period, wind velocity wind direction and water level setup have been measured at the same time. The last step is the derivation of these other wave, wind and water level characteristics of the selected wave classes. For each bin in Figure B.3 the representative value of the remaining parameters is determined. Accordingly the representative value for the wave classes are determined in a similar way compared to the wave height. Because these parameters do not have a one-to-one correlation with the wave height (see B.5) this will method will lead to inaccuracies in the generation of a representative wave climate. In Table 4.1 the results of this wave input reduction are shown. The waves coming from the east were excluded from the wave schematization however these conditions should be incorporated in the model in order to calculated a realistic annual sediment transport. During these conditions only the wind and tide will play a role. This is represented by wave condition 0.

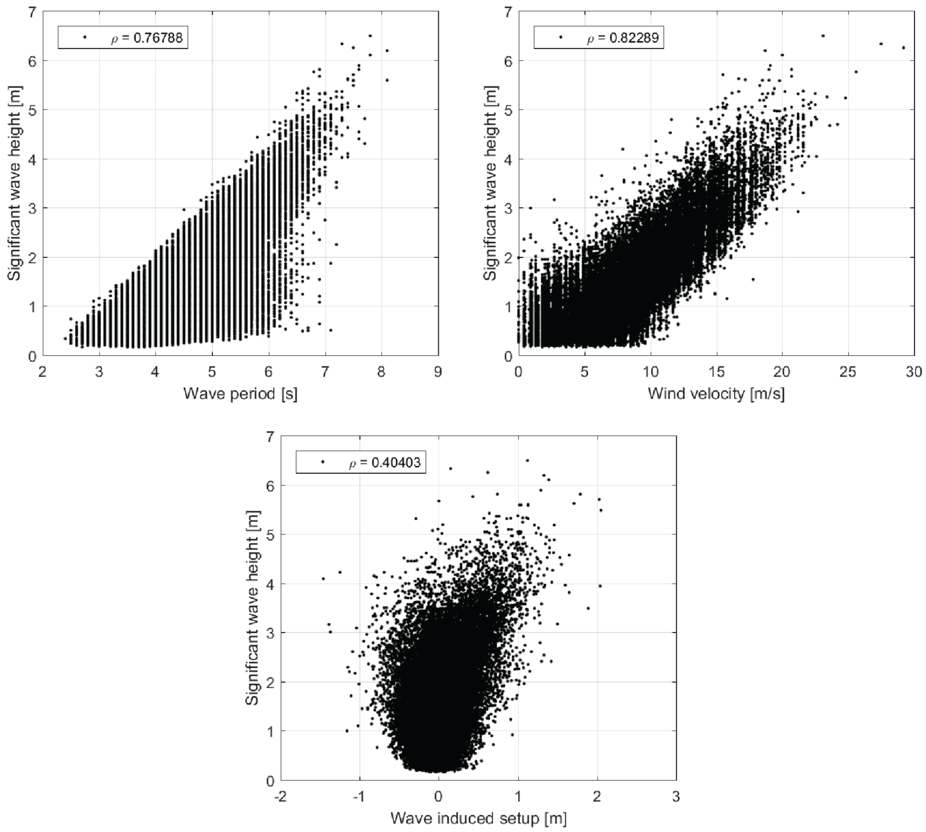

Figure B.5: Correlations of measurement data at the Europlatform

The reduction of the wave climate to four wave conditions may have consequences for the accuracy of the simulations. Especially for the representation of the morphological development of an outer delta, the impact of slightly different wave angles may lead to very different morphological changes. The approach of four wave conditions mainly focuses on the alongshore sediment transports. Because the Ooster has a coast parallel orientation, this approach is though to be reasonable, however cross-shore sediment transports at the Ooster may be underestimated.

Besides the manual wave selection method other methods are available for the wave input reduction. The "Optimum" wave class selection is an input reduction method which is mainly relevant for long time morphological simulations. The principle of this method is that every wave condition is run for a limited time to determine the sediment transport rates. In this way the morphological impact of each condition can be determined more accurately. Thereafter the conditions which contributes least are dropped (see Lesser (2009) for more information).

C

Main model settings Delft3D

Table C.1: Summary of the main model parameter settings, adapted from Colina Alonso (2018)

Model	Parameter	Value	Description
Flow	Δt	0.1	Computational time step [min]
	ρ_w	1025	Density of water [kg/m3]
	ρ_a	1	Air density [kg/m3]
	Roumet	C,Chezy	Type of bottom friction formulation [-]
	Ccofu	60	Uniform bottom roughness in u-dir [m1/2/s]]
	Ccofv	60	Uniform bottom roughness in v-dir [m1/2/s]]
	Vicouv	1	Uniform horizontal eddy viscosity [m2/s]
	Dicouv	0.5	Uniform horizontal eddy diffusivity [m2/s]
	ROUwav	FR84,	Bottom stress formulation due to wave action [-]
	Dryflc	0.1	Threshold depth for drying and flooding [m]
	CSTbnd	yes	Boundary condition [-]
Wave	Spectrum	jonswap	Shape of the wave spectrum [m]
	PeakEnhancFac	3.3	Peak enhancement factor in case of jonswap spectrum [-]
	Setup	false	No wave related setup [-]
	GenModePhys	3	Generation mode of physics [-]
	Breaking	true	Include wave breaking, B&J model [-]
	BreakAlpha	1	Alpha coefficient for wave breaking [-]
	BreakGamma	0.73	Gamma coefficient for wave breaking [-]
	Triads	false	Include triads [-]
	BedFriction	jonswap	Bed friction type [-]
	BedFricCoef	0.067	Bed friction coefficient [-]
	Diffraction	false	Include diffraction [-]
	WindGrowth	true	Include wind growth [-]
	WhiteCapping	Komen	Formulation for white capping [-]
	Quadruplets	true	Include quadruplets [-]
	Refraction	true	Include refraction [-]
	FreqShift	true	Include frequency shifting in frequency space [-]
	WaveForces	dissipation 3d	Method of wave force computation [-]
Transport	MorFac	0.05/1	Morphological scale factor [-]
	MorStt	1488	Spin-up interval for start of morphological changes [min]
	MorUpd	true	Update bathymetry during FLOW simulation [-]
	EqmBc	true	Equilibrium concentration profile at inflow boundaries [-]
	DensIn	false	Include effect of concentration on fluid density [-]
	$D_5 0$	160	Median grain diameter [µ m]
	TraFrn	vanrijn07	Sediment transport formula [-]
	Gammax	0.8	Cut-off criterion, represents the ratio wave height/water [-]

D

Supporting model results

In this appendix additional model results are presented to support the findings in Chapter 4.

D.1. Flow patterns of scenario II during stages B, C and D for WC 1-4

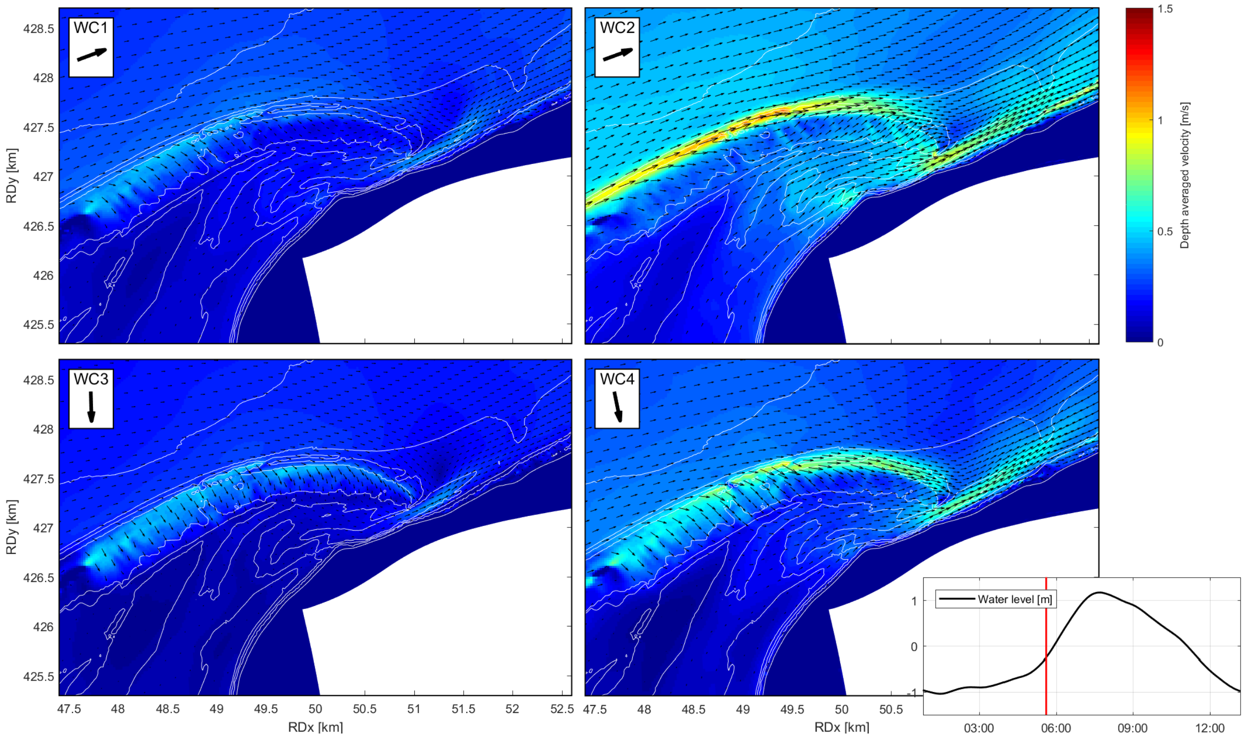

Figure D.1: Flow patterns during rising tide (stage B) for the four different wave conditions. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. The larger arrow in the upper left corner shows the offshore wave direction.

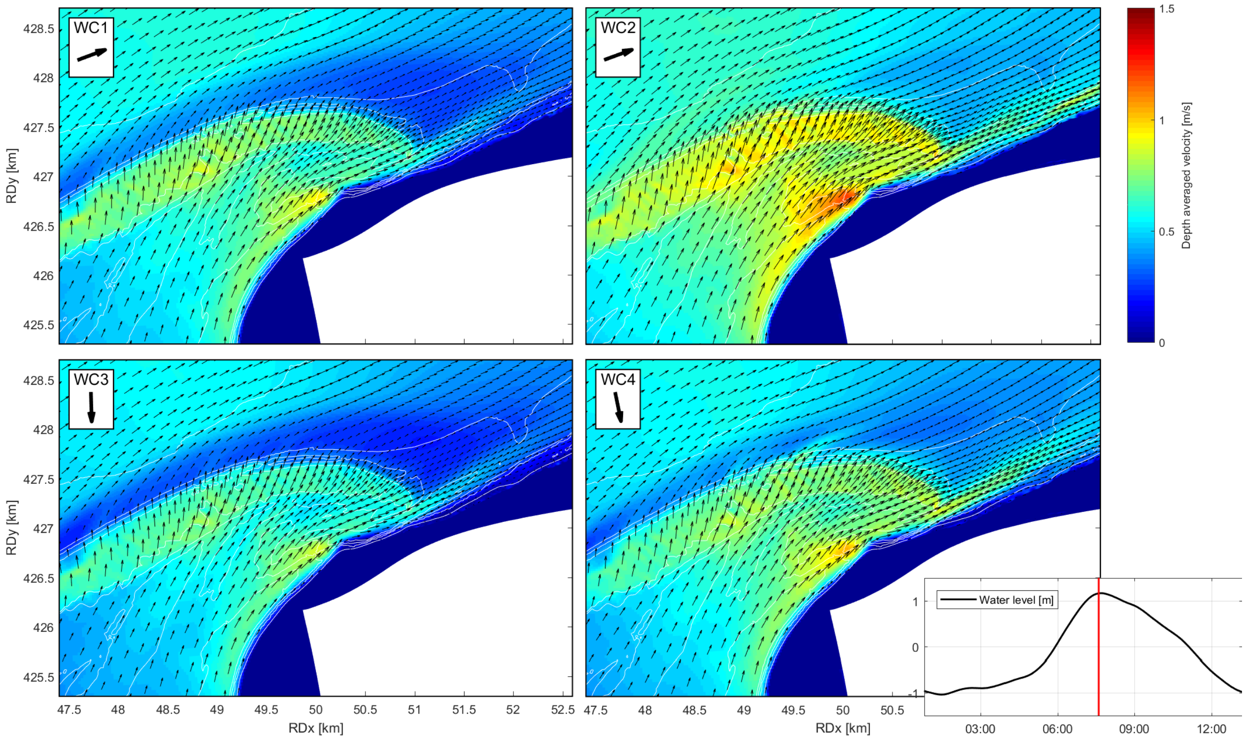

Figure D.2: Flow patterns during high tide (stage C) for the four different wave conditions. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. The larger arrow in the upper left corner shows the offshore wave direction.

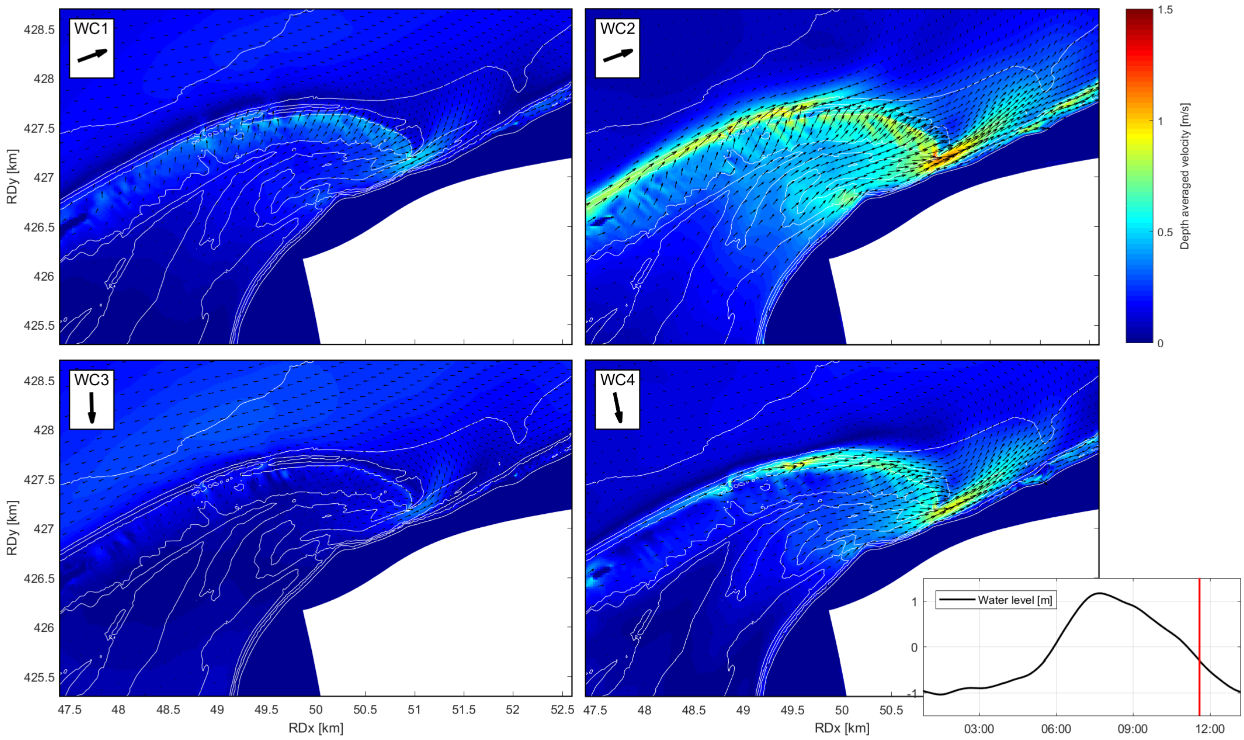

Figure D.3: Flow patterns during falling tide (stage D) for the four different wave conditions. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. The larger arrow in the upper left corner shows the offshore wave direction.

D.2. Flow patterns of scenarios I, III, V, IV during stages B, C, D for WC 0

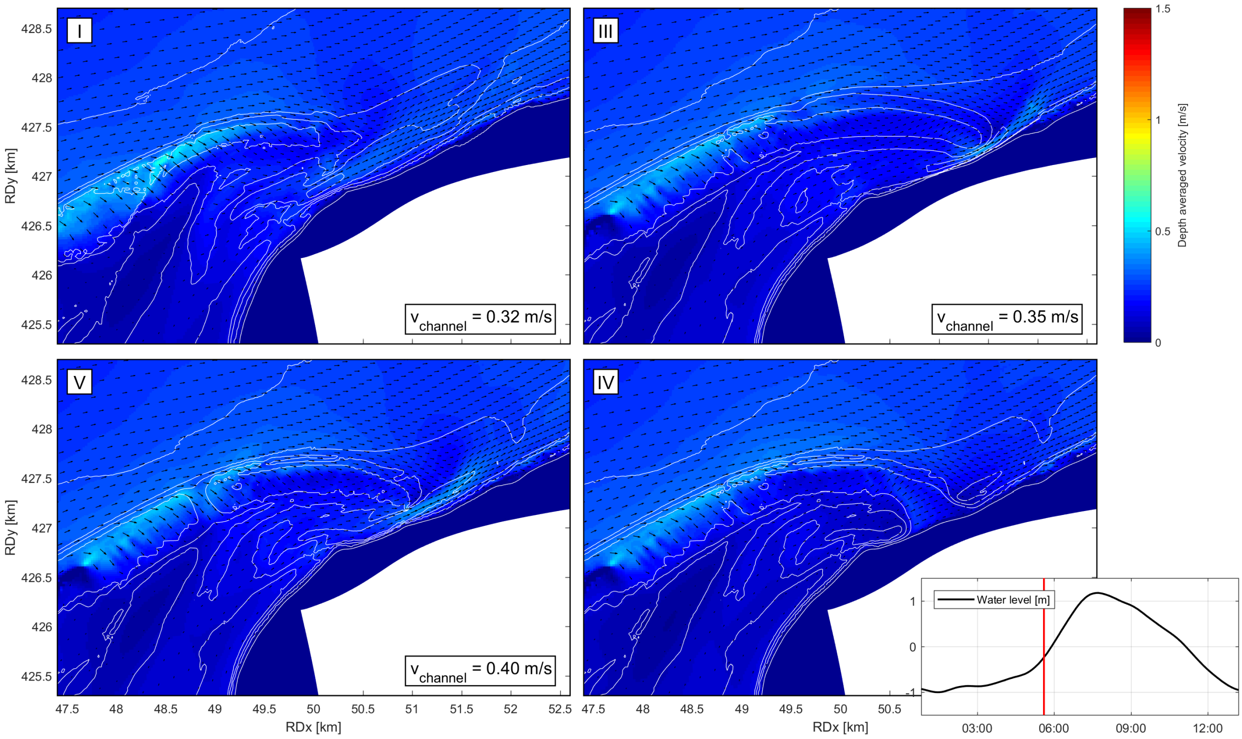

Figure D.4: Tide-induced currents during rising tide (stage B) for bottom scenarios I, III, V and IV. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. In the lower right corner of each plot the maximum velocity in the channel shown.

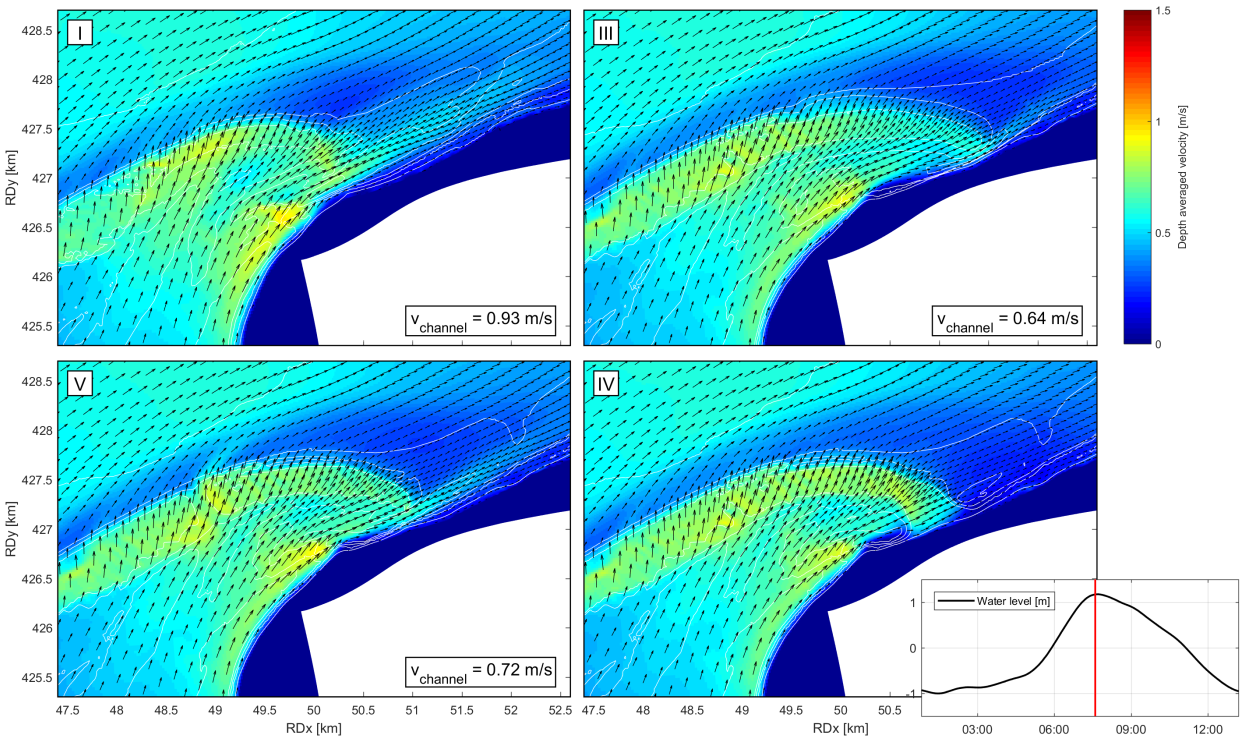

Figure D.5: Tide-induced currents during high tide (stage C) for bottom scenarios I, III, V and IV. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. In the lower right corner of each plot the maximum velocity in the channel shown.

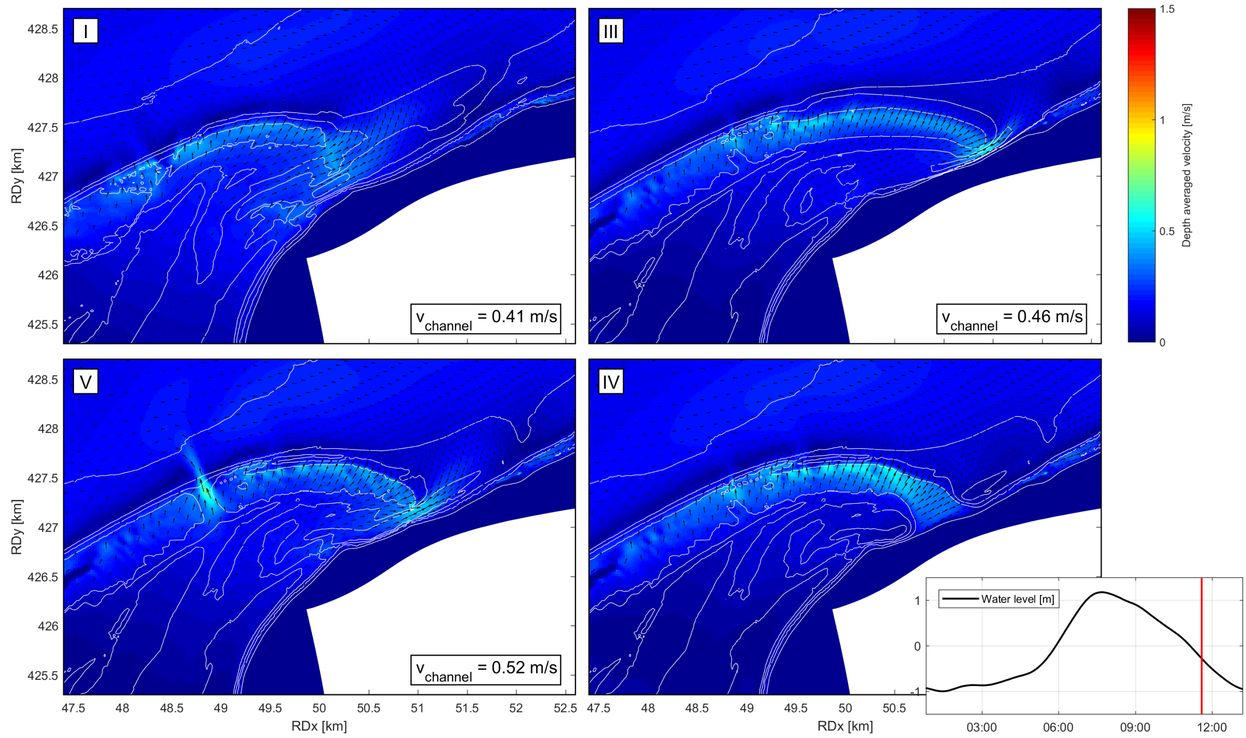

Figure D.6: Tide-induced currents during falling tide (stage D) for bottom scenarios I, III, V and IV. The colors indicate the instantaneous depth averaged flow velocities and the arrows illustrate the flow direction. In the lower right corner of each plot the maximum velocity in the channel shown.

D.3. Mean sediment transport of scenarios I-IV and WC 1-4

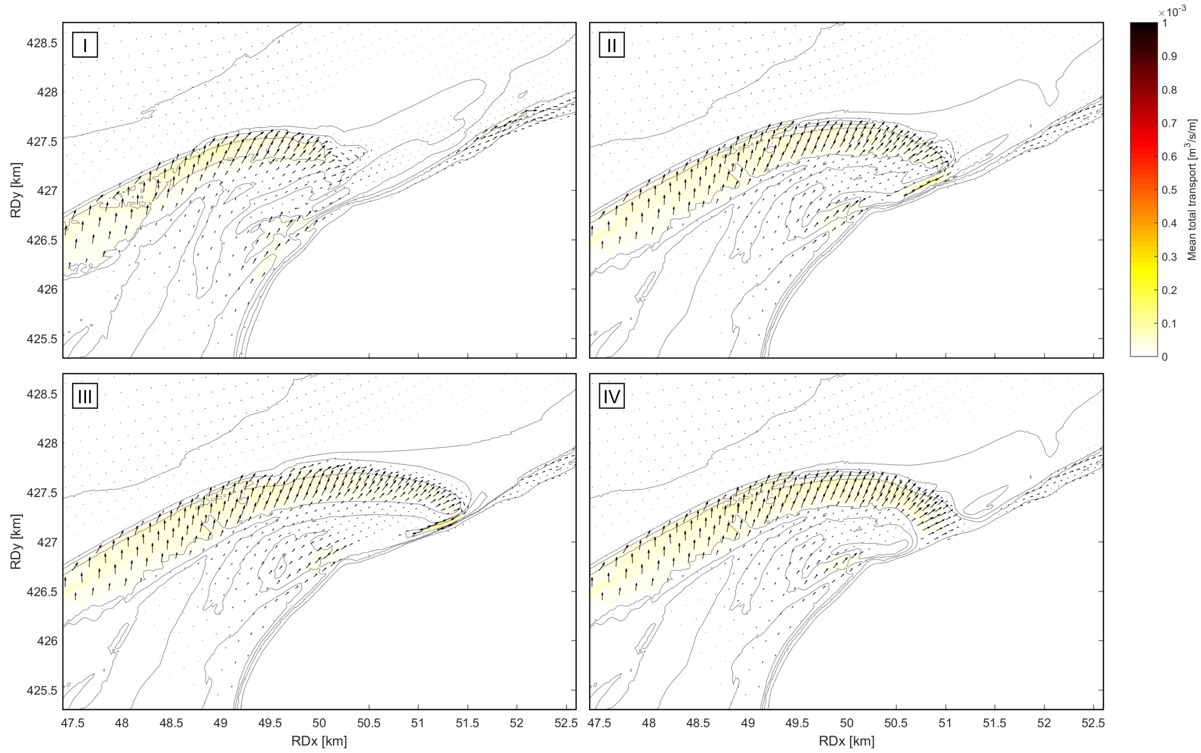

Figure D.7: Mean sediment transport for wave conditions WC1 for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

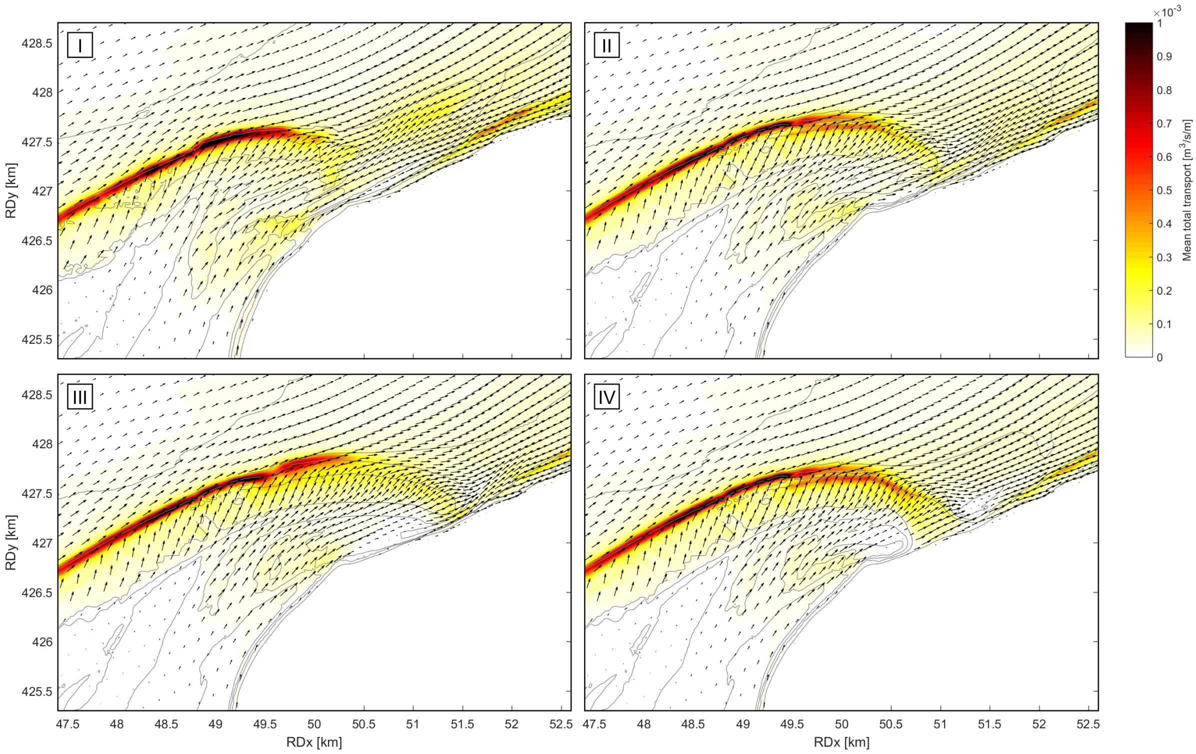

Figure D.8: Mean sediment transport for wave conditions WC2 for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

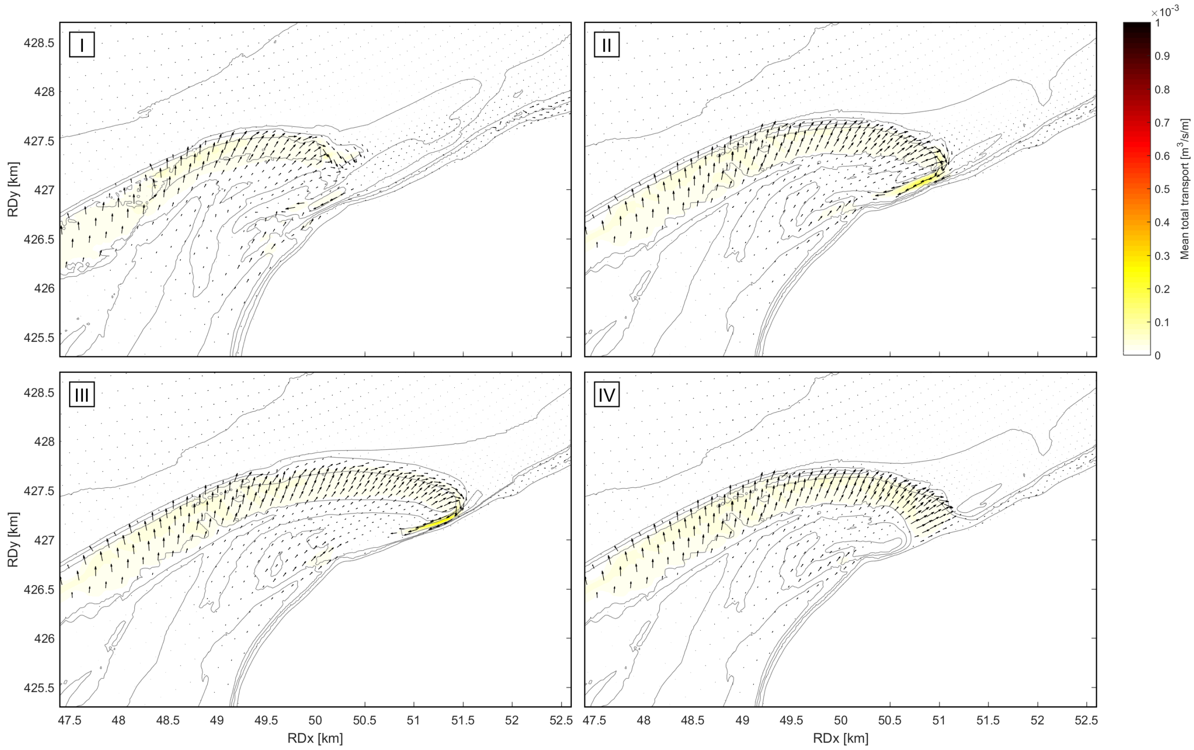

Figure D.9: Mean sediment transport for wave conditions WC3 for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

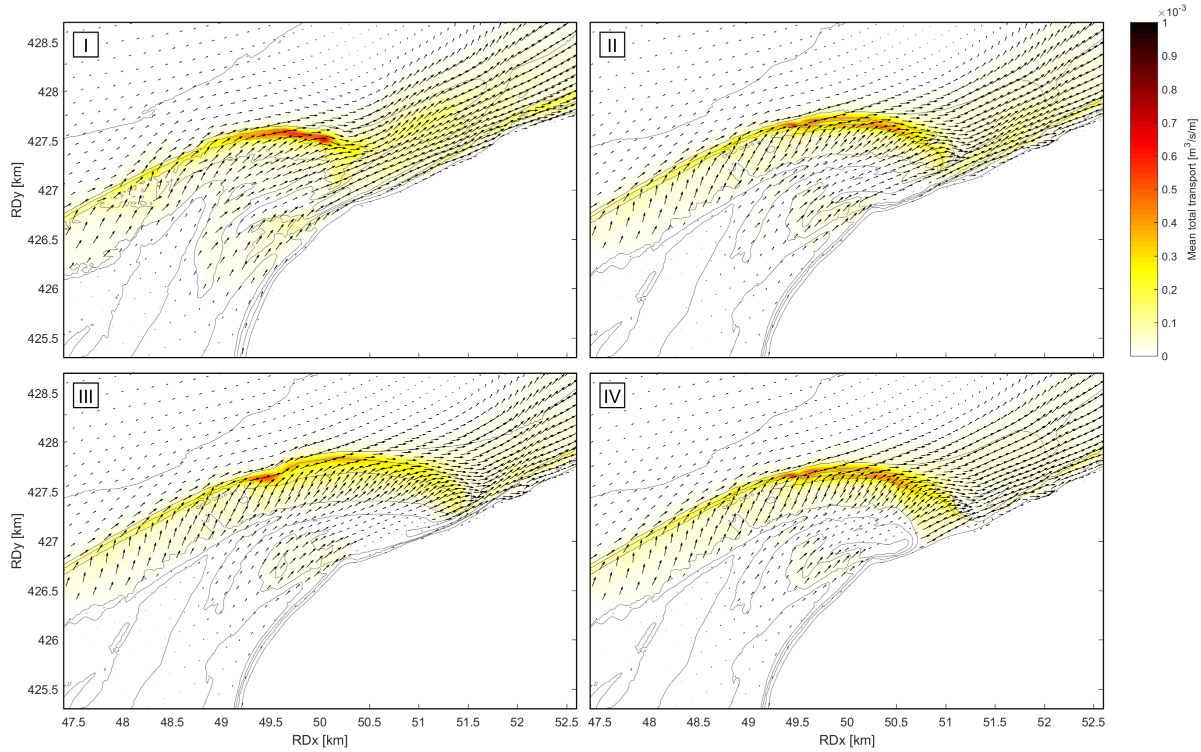

Figure D.10: Mean sediment transport for wave conditions WC4 for bottom scenarios I, II, III and IV. The colors indicate the amount of sediment transport and the arrows illustrate the transport direction.

D.4. Individual impact of wind and waves on the flow patterns

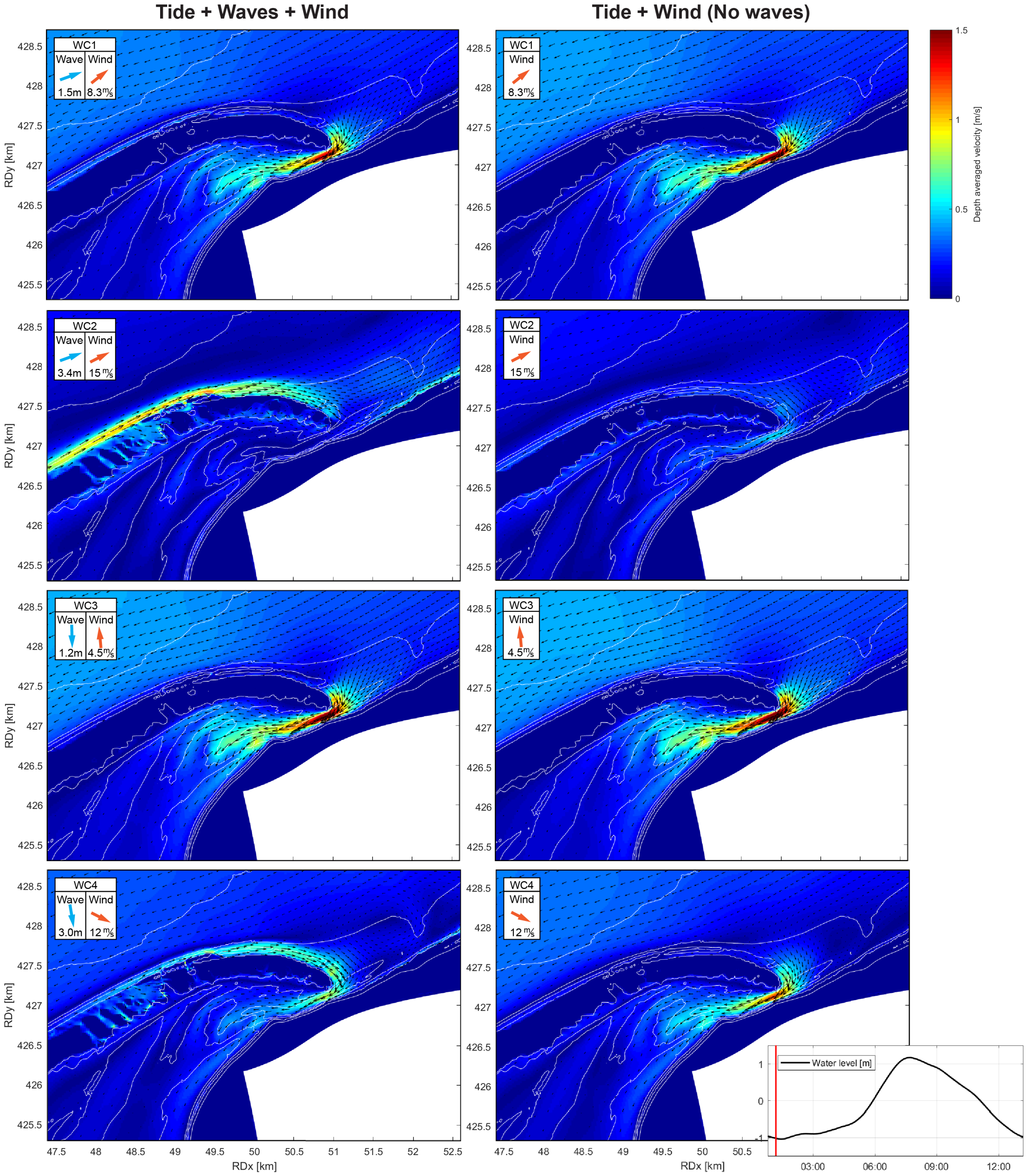

Figure D.11: Assessment of the individual influence of wind and waves in the wave conditions. Pictures on the right show results of the simulation including tide, waves and wind. Pictures on the right show results of simulations without waves.

D.5. Influence of wind direction on the mean wave direction

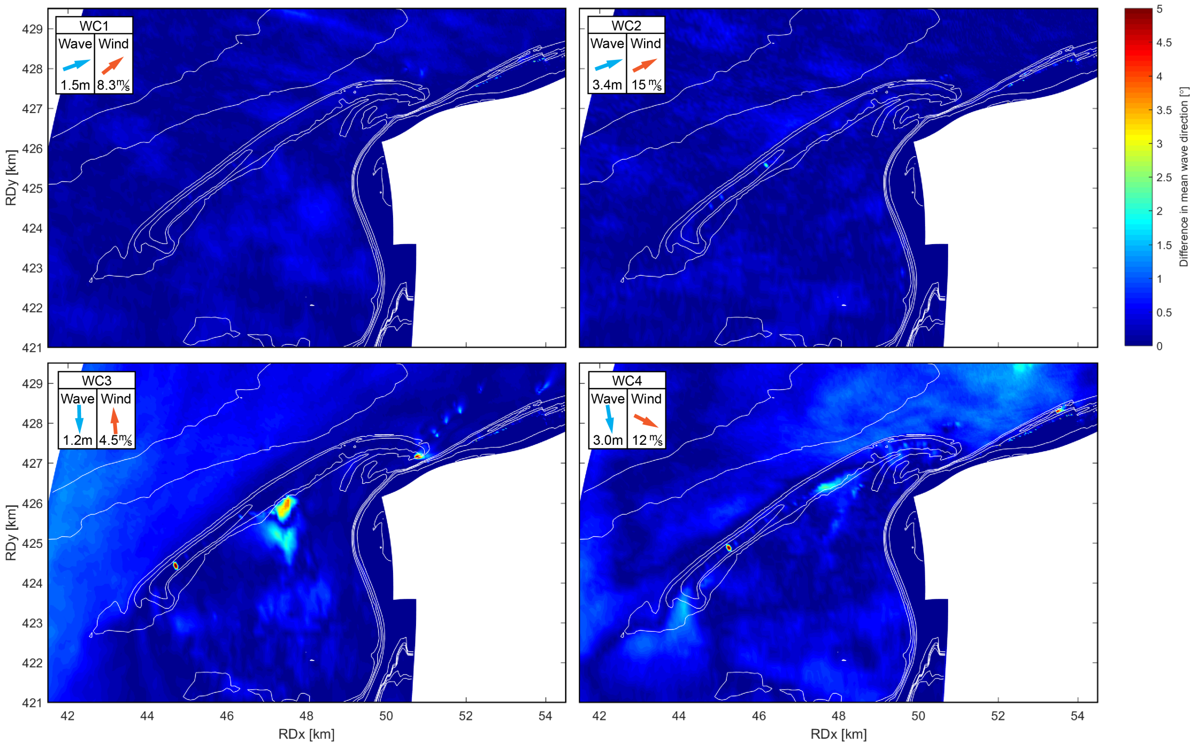

Figure D.12: Assessment of the influence of wind direction on the mean wave direction. This plot shows the difference of the mean wave direction between the simulations with the wind direction shown in the upper left corner and the simulations with the wind direction equal to the wave direction.

D.6. Influence of wind direction on the flow patterns

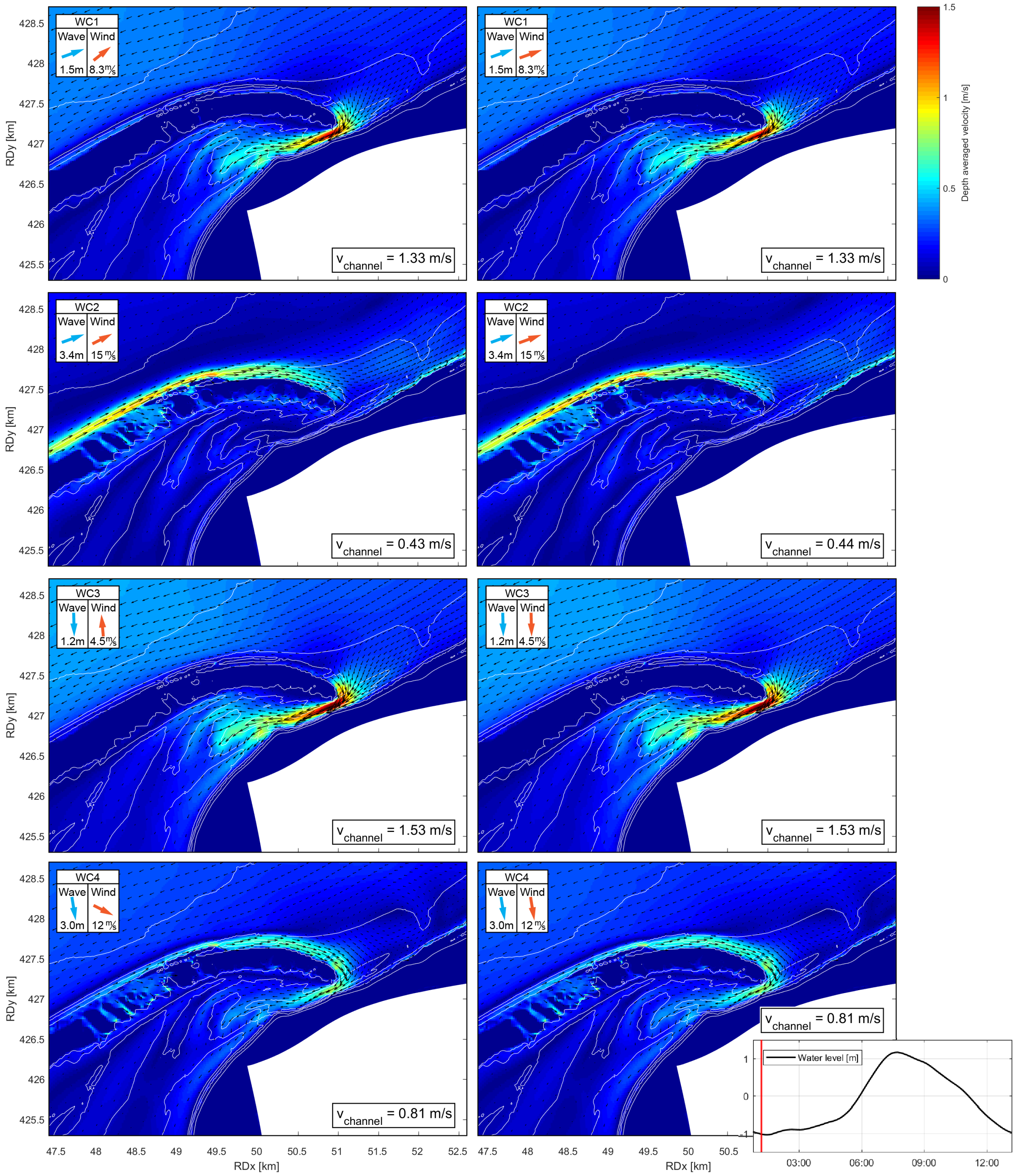

Figure D.13: Assessment of the influence of wind direction on the flow patterns. The pictures on the left show the flow patterns in which the wind direction is based on the wave schematization. The pictures on the right show the flow patterns in which the wind direction is equal to the wave direction. In the lower right corner of each plot, the maximum flow velocity in the Schaar is shown.