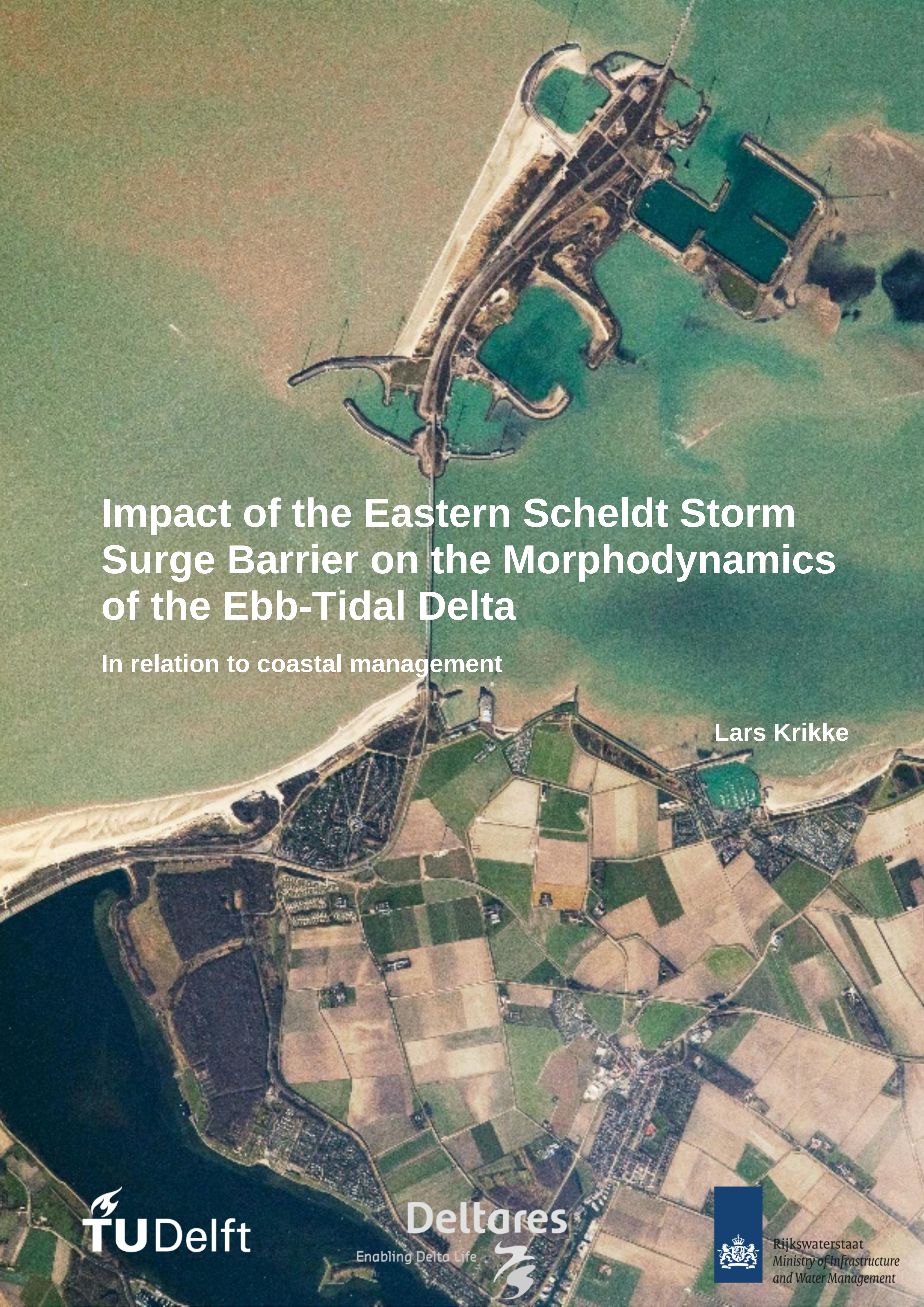

Impact of the Eastern Scheldt Storm Surge Barrier on the Morphodynamics of the Ebb-Tidal Delta

In relation to coastal management

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Deltares
Enabling Delta Life

Rijkswaterstaat
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Impact of the Eastern Scheldt Storm Surge Barrier on the Morphodynamics of the Ebb-Tidal Delta

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By

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Abstract

Threatened by rising sea levels and other climate change induced hazards, there is an increased need for coastal flood protection, such as storm surge barriers. However, the construction of such barriers may lead to unwanted coastal changes. This thesis examines the effect of the Eastern Scheldt storm surge barrier on sediment pathways and the implications for coastal erosion. In addition, possible sediment-based interventions to redirect the current with the aim of reducing coastal erosion were investigated. First, a literature study was performed to provide historical context on the natural and human induced development of the ebb tidal delta. A data analysis on the sediment budget of the ebb tidal delta was performed, which showed that from 1960 to 1987 the ebb tidal delta gained sediment, from 1987 to 2010 it lost sediment, and from 2010 to 2019 it gained sediment again. A numerical model in Delft3D FM was used to produce sediment transport vector fields over a morphologically representative tidal cycle, which were then visualized using SedTRAILS. The research found that the barrier decreased the strength of the ebb current on the entire ebb tidal delta. The Roompot Zuid has a predominantly ebb-dominant character before the barrier in 1976 but changes to a flood-dominant character due to the construction of the barrier, which weakened the ebb-current. In 2019, part of the Roompot Zuid regained an ebb-dominant character. The Schaar van Onrust also became flood-dominant due to the barrier, eliminating the sediment-retaining effect the ebb dominated current in this channel. This shift indicates that sediments that previously stayed in front of the coast of Noord-Beveland are now redistributed further along the coast in south western direction, which led to a sediment deficit and erosion at the coast. The tested interventions seem to induce little structural changes in the tidal currents. The removal of sediment causes the sediment transport patterns to converge into the dredged area, suggesting deposition. Therefore the tested interventions do not seem effective from a coastal management perspective. The approach used here may also be useful for the assessment of sediment transport impacts at other sites where the construction of similar barriers is being considered.

Contents

1 Introduction

1.1 Context

The Netherlands' coastal system consists of three subsystems: the Wadden Sea in the north, the Holland coast in the middle, and the delta area in the south. The Eastern Scheldt is part of the delta area (see Figure 1.1), which is characterized by several peninsulas, tidal inlets, and river outlets. The delta area is important for various functions, including economic activities such as fishing and recreation, and for nature and flood protection. The coastline, including its shoreface, beaches, and dunes, plays a crucial role in protecting the hinterland from storm surges. In 1953, a large storm surge breached the dikes in this part of the Netherlands at multiple locations, resulting in the flooding of an area of 1500 km^2 and over 1800 casualties. This disaster led to the initiation of the Delta Plan, which included the construction of dams and storm surge barriers in the delta area, partly or completely closing estuaries and channels to reduce the length of coastline requiring protection (Watson & Finkl, 1992).

The interventions in the delta area resulted in changes to the hydrodynamics and morphology. The Haringvlietdam prevents seawater from entering the estuary, but retains its river discharging function through sluices. Initially, the Grevelingen was completely disconnected from the North Sea, but for environmental reasons, the connection was reopened using a sluice. The Eastern Scheldt has retained its connection to the sea through the storm surge barrier, which is only closed when necessary. However, the size of the basin and inlet have changed significantly, affecting the hydrodynamics and morphology. The Western Scheldt basin was relatively unaffected due to its function as an entryway to the port of Antwerp. The effects of these interventions can still be observed today, particularly in the ebb-tidal deltas, which are important for sediment transport and wave breaking. A better understanding of the impacts of human interventions on sediment distribution processes, particularly in the Eastern Scheldt ebb-tidal delta, is needed.

1.2 Study area

In Figure 1.1 an overview of the location of the delta area as well as an indication of the ebb-tidal delta areas is given. The Eastern Scheldt (indicated with number 3) is adjacent to the Western Scheldt ebb-tidal delta in the south (4), and to the Grevelingen ebb-tidal delta in the north (2).

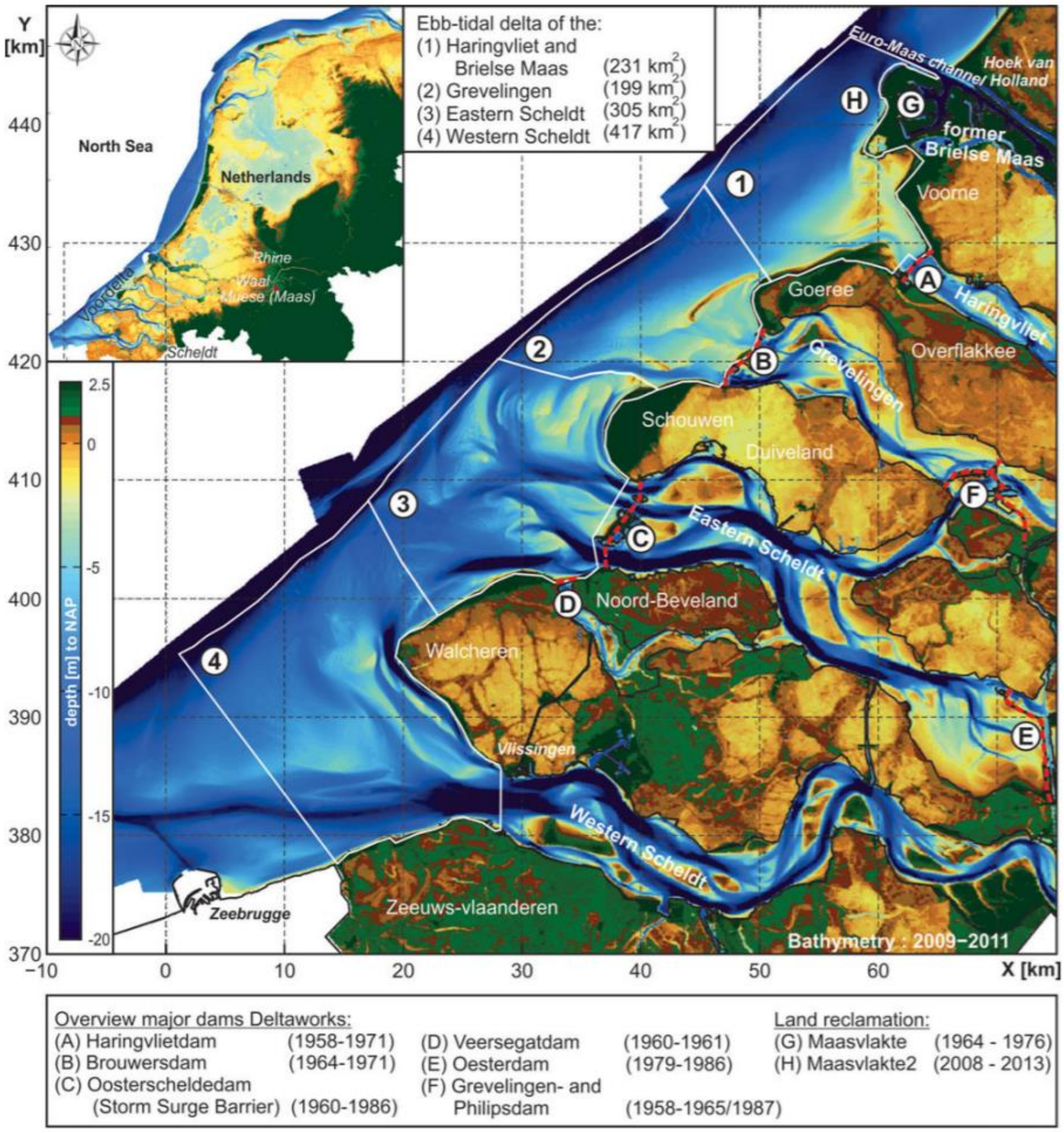


Figure 1.1: Overview of the Dutch Delta, the estuaries which form the Voordelta. The red dashed lines indicate the major dams constructed as part of the Delta Plan. The white lines are an indication of the boundaries of the ebb-tidal deltas of the respective estuaries. Depths are given in m relative to NAP (Normaal Amsterdams Peil), the Dutch ordenance datum which is about present-day mean sea level (MSL). Elias et al., (2017).

Figure 1.2 provides an overview of the channels and shoals of the outer delta of the Eastern Scheldt. The mouth of the Eastern Scheldt is separated by the island Neeltje Jans, which is connected to the shoal Middelplaat. North of Neeltje Jans, there are two main channels: Geul van Roggenplaat and Hammen. The seaward side of these two channels join at the Westgat channel on the outer delta. The Westgat channel splits into a northern and a southern channel, separated by the Banjaard shoal. The northern channel is called the Geul van de Banjaard and the southern channel remains as Westgat. In between the Geul van de Banjaard and the coast of Schouwen, there are two shoals: Petroleumbol and Zeehondenplaat. Adjacent to the coast of Schouwen, a continuous channel has formed known as Krabbengat, which is connected to the Bolle van het Nieuwe Zand shoal on the north side and to the Krabbenplaat shoal on the south side.

South of Neeltje Jans lies the Roompot channel, which splits in the Roompot Zuid and the Oude Roompot. The connection between the Roompot Zuid and the Oude Roompot passes a shallow area of sandbanks. Between the Roompot Zuid and the coast of Noord Beveland lies a narrow yet deep channel called the Schaar van Onrust. The sandbank at the north side of the Schaar van Onrust is referred to as Onrust. The Roompot Zuid channel ends at the shoal area Domburger Rassen, which is also the outflow area for the Oostgat channel from the Western Scheldt (the Oostgat channel is not included in Figure 1.2). The Oude Roompot is connected to the Westgat on the seaward side. The shoal Noordland lies between the Westgat and the Oude Roompot. At the southwestern side of the Oude Roompot the Hompels shoal is located (Elias & Quataert, 2021).

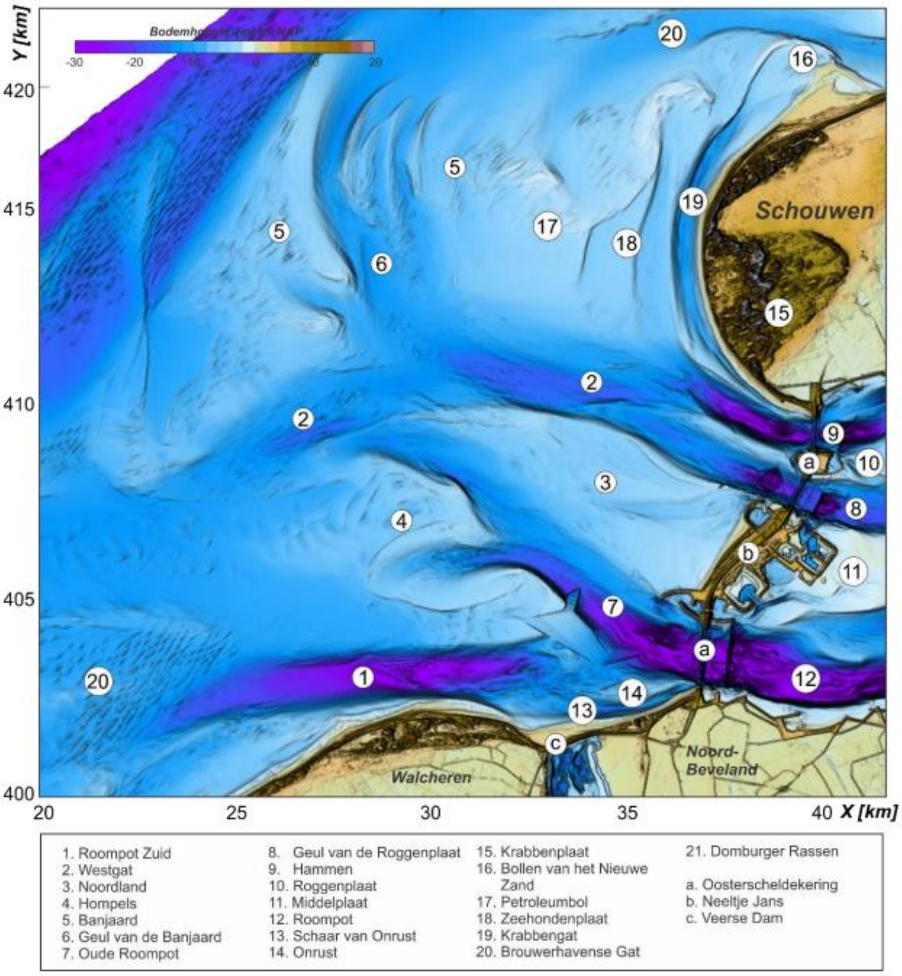


Figure 1.2: An overview of the channels and shoals of the Eastern Scheldt ebb-tidal delta based on the 2019 Vakloding (Elias & Quataert, 2021)

1.3 Problem Statement

Interventions performed in the Delta area over the past decades have led to changes in the hydrodynamic and morphodynamic environment of the inlets and the outer deltas. These changes can locally lead to erosion or accretion of the adjacent coastlines. At Noord Beveland for example, a small channel called the Schaar van Onrust has over the past decades migrated towards the coast. Another example is Verklikkerplaat, a sandbank at northern part of Schouwen. This sandbank has most likely formed due to the extension of the Krabbengat channel which increased since the closure of the dam. This led to the formation of a "sand-motor"-like development with local erosion occurring at the tip near the Verklikkerplaat. These examples show how interventions influencing hydrodynamics on a larger scale can lead to local problem areas.

Effects such as the erosion of the coastline at Noord Beveland need to be mitigated by Rijkswaterstaat, for example by applying nourishments. In the past attempts have also been made to divert the tidal flow using morphological dredging in the shallow area between the shoals Hompels and Onrust. Based on an extensive analysis of the morphological developments (Elias & Quataert, 2021), the erosion of the coast at Noord-Beveland was clearly explained. Because of the landward migration of the shoal Onrust, the Schaar van Onrust is being pushed into the shore, eroding the beach. These developments are being influenced by large scale changes in the morphological system, which are most likely linked to the construction of the Eastern Scheldt barrier in 1986. A possible explanation for this is that the barrier diverted the tidal flow from the Roompot Zuid through the Oude Roompot. This could have resulted in the southward movement of the Hompels, trapping the Schaar van Onrust between the Hompels and the coast. The goal of this study is to better understand how the large-scale processes are leading up to the erosion at Noord-Beveland. In this respect the focus will lie on the influence of the Eastern Scheldt barrier on the large-scale changes in the morphological system, and the influence on the behaviour of the system today.

As the coastal erosion described above forms a problem for Rijkswaterstaat, potential mitigation efforts are worth considering in addressing this issue. It is hypothesized that by strategic dredging tidal volume through the Schaar van Onrust can be reduced, resulting in less erosion at the coast (de Groot, 2002). Redirection of the tidal flow can thus potentially be used to reduce erosion at the coast. In the past attempts were made to manipulate the tidal currents, however, never successful. As a second part of this research it will therefore be investigated whether it is possible to redirect the current. The options we will focus on are to (1) fill up the Schaar van Onrust, (2) connect the Oude Roompot with the Roompot Zuid, and (3) a combination of the two.

1.4 Research Questions

Based on the problem statement, the following to the following research questions were formulated:

What was the influence of the Eastern Scheldt barrier on the sediment transport pathways at the seaward side of the barrier and how can this knowledge be used for future coastal management at the coast of Noord-Beveland?

To answer the research question, sediment transport pathways will need to be investigated in three time instances, leading up to the following sub-questions:

1. What were the sediment pathways just before the construction of the barrier?
2. What were the sediment pathways just after the construction of the barrier?
3. What are the sediment transport pathways under present day average conditions (~30 years later)?
4. How did the changes in the morphological system lead to erosion at Noord-Beveland?
5. Based on this, what would be needed to redirect the tidal current through the Roompot-Homples?

1.5 Approach

To meet the objectives, we began by conducting a literature review on the development of the Eastern Scheldt and its ebb-tidal delta, as well as the erosion mitigation efforts that have been implemented on the coast of Noord-Beveland in recent decades. We then analysed data on the sediment budget of the ebb-tidal delta. Finally a numerical model was used to create sediment transport vector fields. These vector fields were then visualized using SedTRAILS to identify the sediment transport pathways. We used an existing model of the Eastern Scheldt developed by Deltares for this purpose.

2 Literature Review

2.1 Tidal inlets

An opening along a barrier coastline which connects the sea to a tidal basin is called a tidal inlet (Fitzgerald et al., 2002). Key components of a tidal inlet are the ebb tidal delta, the inlet gorge, adjacent coasts and the back-barrier basin. An important characteristic of a tidal basin is the tidal prism, which is defined as the amount of water which has to flow through the tidal inlet in one tidal cycle. The tidal prism is determined by the surface area of the basin and the tidal range. The tidal prism determines the minimal stable cross-sectional channel area of the inlet, as well as the sediment volume of the ebb tidal delta (O'Brien, 1931).

The ratio between the wave and tidal energy determines the geometry of an ebb-tidal delta, as waves tend to push sediment in shore-ward direction whereas tidal energy tend to do the opposite (Hayes, 1979). As a result of littoral drift, sediment can bypass tidal inlets from the updrift coastline towards the downdrift coastline. There are several types of sediment bypassing, and is determined by the ratio between the littoral drift and the tidal prism (Bruun & Gerritsen, 1959).

The propagation of a tidal wave in the tidal channels on ebb-tidal deltas is often not symmetric, meaning the ebb-period is not equal to the flood-period. This is also referred to as tidal asymmetry, and it is often the main driver of net sediment transport through tidal channels. This is because the same amount of water has to pass through the channel in a different amount of time, leading to a different current velocity during ebb and flood. As the current velocity is proportional to sediment transport this leads to net sediment transport. As the phase velocity for shallow water is proportional to the square root of the water depth, the high tide in open waters generally propagates faster than the low tide, resulting in flood-asymmetry (and thus a flood directed net sediment transport). This depends however on the geometry of the tidal channels, which can be such that the net sediment transport is ebb-dominated (Dronkers, 1986).

2.2 Characteristics Eastern Scheldt

2.2.1 Tides

Since the Eastern Scheldt no longer discharges fresh water as a river, the main forcing mechanisms are tides and waves. The tide is semi-diurnal and propagates from south to north along the Dutch coast. The average tidal range at the mouth of the Eastern Scheldt close to the barrier is 2.5m. East of the barrier the tidal range increases to an average of 3m at the Grevelingendam and 3.4m at the south-east end of the Oesterdam (Vroon, 1994). In the basin, the maximum current velocities vary between 1 and 1.5m/s. On the shallow shoals the maximum velocities are smaller, between 0.2 and 1.5m/s. In the Eastern Scheldt basin current velocity and surface elevation of the tidal wave are almost 90 degrees out of phase, giving the wave a standing character. The Eastern Scheldt is ebb-dominant. On the ebb-tidal delta, the Oude Roompot, Westgat and Krabbegat channels are ebb-dominant. The Southern Roompot channel and the Hompels shoal is flood-dominant. The tidal prism of the Eastern Scheldt is about 900 million cubic metres (Mm^3) since the construction of the barrier (de Bok, 2001).

2.2.2 Waves

The wave climate manly consists of locally generated wind waves. Between 2005 and 2010 a mean significant wave height is 1.1m was observed at the Schouwebank station. Waves higher than 4m occurred less than 0.2% of the time. From the west-southwest the mean significant wave height is 1.3m with a mean wave period of 5s. The largest waves in the area can reach above 6m. During such conditions a considerable surge of water levels can occur (over 2m). This elevated water level allows larger waves to propagate over the ebb-tidal delta introducing significant sediment loss at the adjacent coastlines. In Figure 2.1 a wave rose is presented from observations between 2005 and 2010. The two main wave directions are southwest (225 to 270 degrees) and northwest (315 to 360 degrees) (Eelkema, 2013). Note that in the model of this study waves are not included, because the main direct impact of the barrier on ebb tidal delta is tide-related. It is however important to note that waves do play a role in sediment transport.

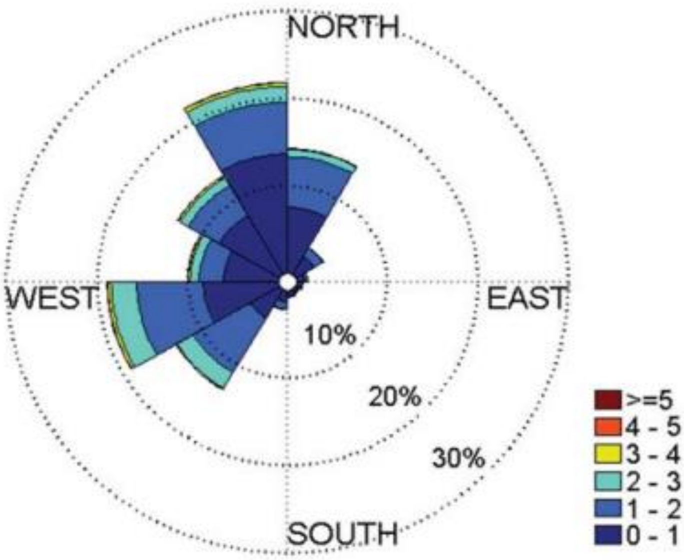


Figure 2.1: Wave rose at Schouwenbank station. Units on the colorbar are in meters. (Eelkema, 2013)

2.2.3 Sediment

The sediment of the ebb tidal delta of the Eastern Scheldt consists mainly of sand. In the channels coarser sediment with a median grain size (d_{50}) between 250 micrometer (μm) and $400 \mu m$ is found. On the shoals finer sediment is found with a median grain size smaller than $250 \mu m$. In the scour holes close to the barrier yield the coarsest sediment, with a median grain size above $400 \mu m$ (see Figure 2.2: Median grainsize (d50) on the ebb-tidal delta. The contour lines indicate the depth in m below MSL and correspond to the 2008 bathymetry. Units on the color bar are in microns.) (Eelkema, 2013).

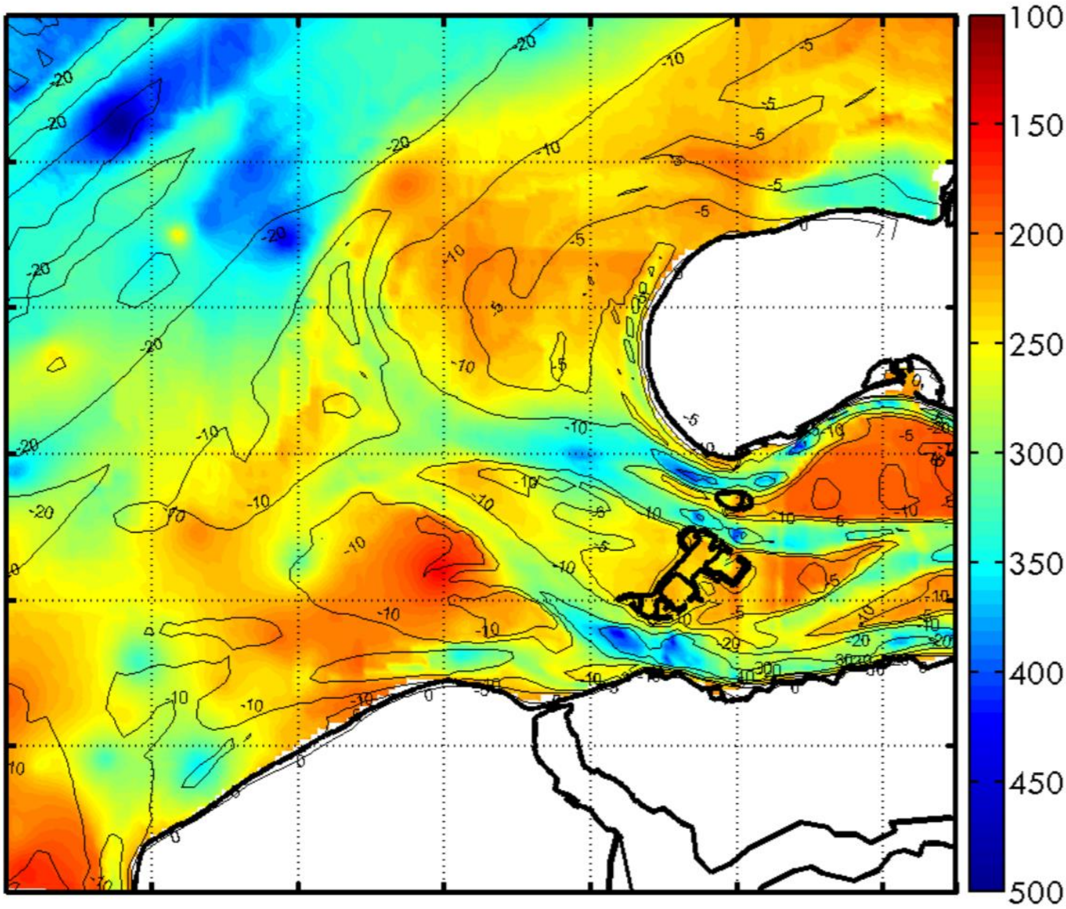


Figure 2.2: Median grainsize (d_{50}) on the ebb-tidal delta. The contour lines indicate the depth in m below MSL and correspond to the 2008 bathymetry. Units on the color bar are in microns. (Eelkema, 2013)

2.3 History of the Eastern Scheldt

2.3.1 Pre-1960 Delta

By the year 1960, prior to the start of the execution of the Delta Plan, the Eastern Scheldt was exporting large amounts of sediment. According to (Eelkema, 2013), this process started around the year 1530, when the polders of South-Beveland inundated. As a response to this inundation the channels in the Eastern Scheldt estuary started deepening, exporting sediment out of the estuary on to the ebb-tidal delta. Figure 6 shows the bathymetry of the ebb-tidal delta between 1827 and 1953. By that time the ebb-tidal delta was morphologically still highly active. The Eastern Scheldt was still exporting sediment and deepening its channels in 1953.

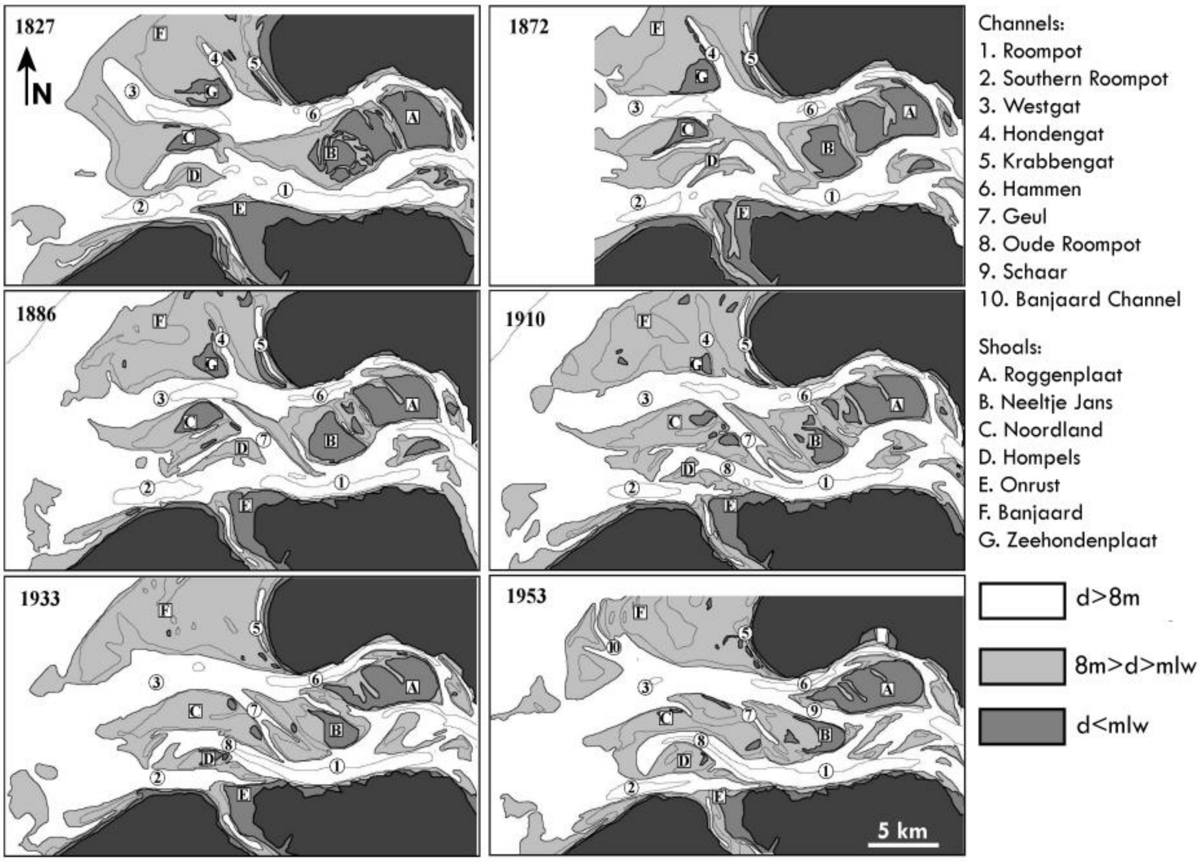


Figure 2.3: Development of the ebb-tidal delta from 1827 to 1953. (Haring, 1978)

2.3.2 Changes Eastern Scheldt between 1960 and 1986

The first step of the Delta Plan was the closing of the Veere inlet by construction of the Zandkreek dam in 1960 and the Veere Inlet dam in 1961 (see Figure 1.1 for the location of the dams and their years of construction). The closing of this relatively small inlet had little impact on the Eastern Scheldt inlet system, and only induced some local changes around the area where the inlet was connected to the Southern Roompot channel (Eelkema, 2013). In 1965 the Grevelingen dam was finished, cutting off the connection with the Eastern Scheldt and the Haringvliet. This turned the Grevelingen into a tidal basin and its tidal prism was reduced by 14% (Haring, 1978). However it is assumed that the effects on the hydrodynamics and the morphodynamics of the Eastern Scheldt were relatively small due to the fact that the dam is located on a tidal watershed between the Grevelingen and the Volkerak channel (Eelkema, 2013). In 1969 the Volkerak dam was constructed, shutting off the connection between the Haringvliet and the Eastern Scheldt. With this, the Eastern Scheldt ceased to discharge fresh water as well. According to de Bok (2001) the tidal prism increased by about 7% within a year. Moreover the tidal wave in the northern branch of the Eastern Scheldt changed to more of a standing wave. Before the construction of the Volkerak and the Grevelingen dam erosion of the channels was already happening, however the dams increased this process (Eelkema, 2013). The result of this was an increasing amount of sediment being exported out of the basin, with a yearly average of between 1 $Mm^3$and 2 Mm^3 between 1960 and 1984 (Louters & van den Berg, 1998).

In 1969 the construction of the Eastern Scheldt barrier began. An artificial island was constructed in the middle of the tidal inlet, situated on the tidal flats Roggeplaat and Neeltje Jans (Eelkema, 2013). At first, the plan was to completely shut off the Eastern Scheldt from the sea, using a dam. However, in the 1970's protest arose against this plan as it would disrupt local fisheries and destroy important ecological habitats. In 1974 the decision was made to build a storm surge barrier instead of a dam. This way the estuary would stay in connection with sea, remaining its function of a tidal inlet. During high storm surges the barrier would be closed to protect the hinterland. In 1986 the storm surge barrier was finalized.

The tidal flow of the Eastern Scheldt is directed through 3 main channels, being the Roompot, Schaar and Hammen. There used to be a fourth channel before 1972 but was closed off during the construction of the Island Neeltje Jans. Measurements between 1965 and 1982 have shown that the Roompot channel took 49% and 55% of the total discharge during flood and ebb respectively (Eelkema, 2013). In 1982 both the flood and ebb discharges through the Roompot increased to 60% (de Bok, 2001).

The increase in tidal volume between 1960 and 1986 caused the main channels in the inlet to scour, and lengthened as well as deepened the adjacent ebb channels. The construction of the islands on the tidal flats enhanced the scouring of the main channels in the inlet (Eelkema, 2013). The larger sediment export from the basin has led to an increasing volume of the ebb tidal delta in the 1970s (Cleveringa, 2008).

2.3.3 Eastern Scheldt between 1986 and 2019

The Eastern Scheldt storm surge barrier has caused the effective cross-sectional area of the inlet to decrease from approximately $80.000\,m^2$ to $17.800\,m^2$. As a result, a large amount of turbulence and energy head loss is present at the barrier, inducing a reduction of tidal range of about 20% (Vroon, 1994). The storm surge barrier has led to significant changes in equilibrium state of ebb-tidal delta, with influence on both volume and shape. The morphological activity on the ebb tidal delta was low but persistent, leading to persistent erosional and sedimented areas (Eelkema, 2013). Between 1980 and 2010 the total area has lost about $150\,Mm^3$ of sediment. Most of these losses, circa $90\,Mm^3$ have been observed at the Banjaard and the Hompels shoal (above -10m average water depth) (Elias & Quataert, 2021). In deeper parts, some accretion has been identified, however this is less than the erosion of the shallow parts. From 2010 until 2019 the morphological changes seem limited. Since 2010 sediment volumes have increased with around $40\,Mm^3$, most of which has ended up in the Banjaard and Westgat channel (Elias & Quataert, 2021).

It is not clear where the $150\,Mm^3$ of lost sediment has gone. The Eastern Scheldt has been blocked by the barrier, not allowing sediment exchange with the ebb tidal delta. The Grevelingen as well as the Western Scheldt ebb-tidal delta have lost sediment since 1986 (Cleveringa, 2008). Also, the dunes have not been growing significantly, and processes to transport large amounts of sediment seaward are absent (Eelkema, 2013).

The channels and shoals in the ebb tidal delta have reoriented. This is a consequence of the change of the relative strength of the alongshore current versus the current coming out of the inlet. The latter has decreased, increasing the relative strength of the alongshore current. Therefore the channels have rotated clockwise (Eelkema, 2013).

In Figure 2.4 an overview is given of the large scale morphological changes in three time periods (1960-1980, 1980-2010 and 2010-2019). It is observed that between 1960 and 1980 the outer delta had a net sediment increase whereas between 1980 and 2010 there was a net sediment decrease. Between 2010 and 2019 the outer delta has gained sediment again.

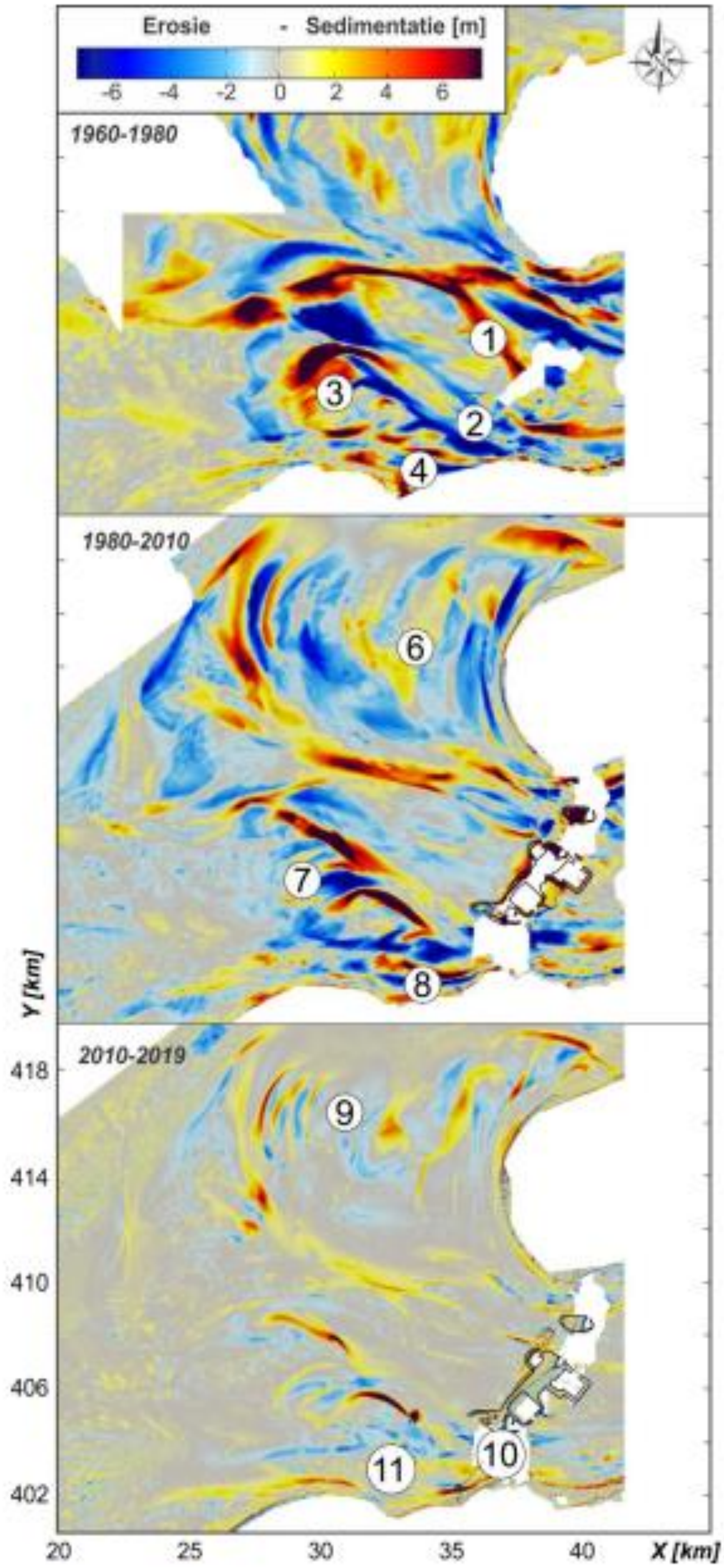


Figure 2.4: Overview large scale morphological changes 1960-1980, 1980-2010 and 2010-2019 (Elias and Quataert, 2021)

2.4 Summary of the morphological development of Noord-Beveland and Breezand

This section contains the main findings of a study performed in 2021 by Elias and Quataert (2021) on the morphological development of Noord-Beveland and Breezand.

2.4.1 Beach Noord-Beveland

The beach at the Banjaardbeach (see Figure 2.5) has been prone to erosion for many years, resulting in the exceedance of the BasisKustLijn (BKL), which is a reference line introduced for coastal management purposes. As a consequence the beach has to be nourished every four to five years. The width of the beach has a high recreational value and is in certain areas relatively narrow. Although the recreational value of a wider beach is recognized the main concern for Rijkswaterstaat and the municipality of Noord-Beveland is the exceedance of the BKL.

The Banjaardbeach has been structurally eroding between transect 180 and 300 since 1972. The origin of this erosion is the migrating shoal the Onrust and the channel the Schaar van Onrust. The channel has steadily been migrating landwards between 1960 and 1990, eroding vast amounts of sediment from both the beach and the foreshore. Without the frequent nourishments by Rijkswaterstaat the channel would have most likely migrated further into the shore threatening to exceed the BKL.

It is likely that the migration is related to the construction of the storm surge barrier, which has triggered large morphological changes in the inlet. The dominant erosional mechanism here is the tide. At the beach of Noord-Beveland, the tidal current is the main cause of the erosion, especially around transects 180-300, the location where the Schaar van Onrust is close to the beach. Longshore tidal currents pick up sediment from this area and deposit (part of) it westward at transects 100 – 140. This leads to a widening of the coast near the foot of the barrier.

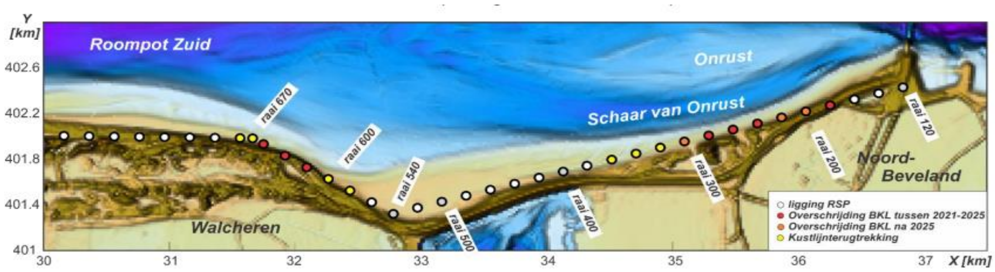


Figure 2.5: An overview of the coast of Noord-Beveland (transect 120-500) and Walcheren (transect 540 – 570). Red dots indicate an expected exceedance of the BKL between 2021-2025. The orange dots indicate an expected exceedance of the BKL after 2025. The yellow dots only indicate coastline retreat. The white dots indicate the location of the RSP. The Banjaardbeach is between transect 180 and 300. Breezand is between transect 520 and transect 720.The veerse dam is located between Breezand and the Banjaardbeach. (Elias & Quataert, 2021)

2.4.2 Beach development transect 260-280

From the detailed analysis of the cross-sections of the beach between transect 260 and 280 it was concluded that the beach erosion will most likely continue. It must be noted that it is assumed that the frequent nourishments in this area will continue (on average once every three years). Without these nourishments there would be no beach in this area. Because of the position of the channel the beach is relatively small. This results in a limited amount of sediment per nourishment with the need for frequent nourishments as a result. How frequently these nourishments must take place exactly depends on the volume of the nourishments as well as natural circumstances such as storms. On average MKL moves around 15m seawards after each nourishment, followed by a yearly retreat of 5m.

Observations from 2014 onwards show that the steepness of the channel side around transect 260 is reducing. In the short term this will not limit erosion, however it may be an indication that the conveyance through the channel is reducing relative to the Roompot Zuid. On the long term reduce erosion of the beach.

2.4.3 Beach/foreshore development Breezand

Also, around Breezand, between transect 600 and 700, there is a risk of exceedance of the BKL. Here one concern is the structural erosion due curvature of the coastline. Between the coast of Walcheren and Noord-Beveland the angle of the coastline changes abruptly causing erosion near transect 640 and sedimentation near transect 540 due to accelerating and decelerating tidal currents. This way the coastline is converging to a smoother transition (see Figure 2.6). For such a smooth transition the coast around transect 640 will have to erode further. On the short term (5-10 years) it is therefore expected that the beach around transect 640 will keep on eroding.

Although erosion is a problem, another phenomenon happening around Breezand is the periodic growth of the beach. This is due to the sediment supply from the northwestern side of Walcheren. Sandbanks form and fold around the coast on the west side of transect 800. The sandbanks wash ashore between transect 700 and 800, resulting in a temporary surplus of sediment to be spread along the coast. The location of the coastline in 2021 is most likely related to the period around 2007 in which the sediment supply at the western side of Walcheren was low. In 2018 a new bank landed between transect 700 and 800 but has yet to reach Breezand. In 2019 a new large bank has been observed in the bathymetry which will likely supply Breezand with sediment in the near future (see bathymetry of 2019 in Figure 2.6).

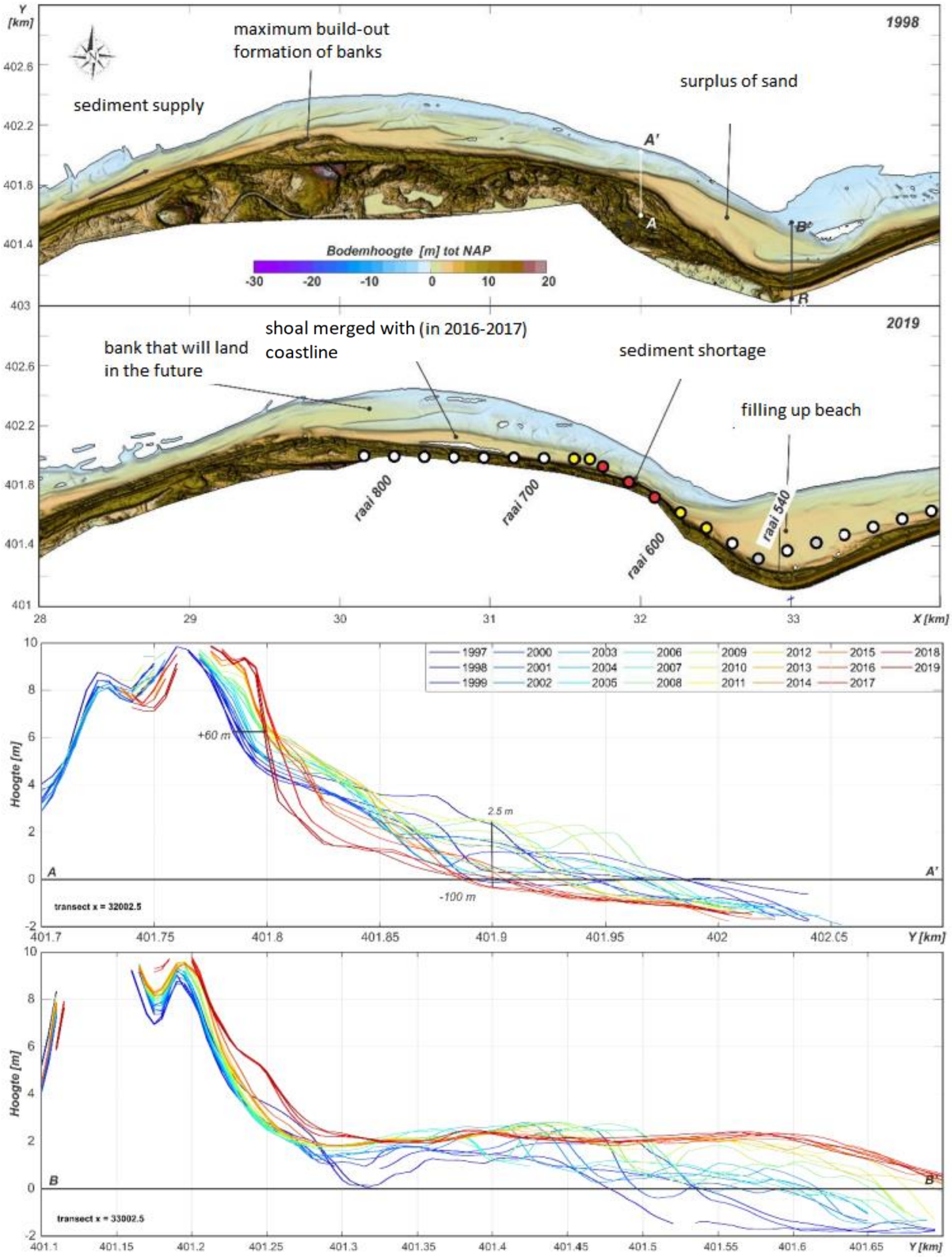


Figure 2.6: Overview form LiDAR measurements for 1998 and 2019 (top two images), and the development the bottom height in crossections A-A'and B-B' (bottom two images). (Elias & Quataert, 2021)

2.4.4 Nourishment of the channel side in 2013

First, the nourishment of the channel side mainly functioned as filling for the channel itself. The depth of the channel at transect 260 reduced with 5m since the nourishment, reducing the correctional area in its turn. This partly reduced the tidal flow (through the Schaar van Onrust) and hence the erosion caused by tidal flow. The reduced channel depth is present even years after the nourishment.

The sides of the channel also show that the flow through the channel has been decreasing. Between 1990 and 2013 the sides of the channel were relatively steep. This allowed the channel to be close to the beach making it effective transporting sediment. Since the nourishment in 2013 the reduced flow cannot maintain the steep channel sides with a gentler slope as a result. This is an indication that the longshore transport has been reduced. On the short term however, this has not yet resulted in a reduction of the erosion of the beach as the losses perpendicular to the beach slightly increase. Until the channel is in a new equilibrium these seaward losses will continue. On the longer term the erosion will decrease, but as long as there is a channel adjacent to the beach it will not completely disappear. Nourishment will therefore also be necessary as long as the channel is present. Nevertheless, by decreasing the flow through the channel the frequency or size of the nourishments may be reduced.

2.5 Findings deepening of the ebb-chute Roompot-Hompels

Between 1993 and 2008 morphological dredging was tried as a means to reduce erosion along the coast of Noord-Beveland. The idea is that alternative routes for (tidal) currents are created by removing sediment. In this case, sediment was removed from the shallow area between the Roompot and the Roompot Zuid. The most important conclusions from (van der Werf et al., 2010) are summarized here.

The morphological dredging deepened the Roompot-Hompels and increased the ebb-dominance of it, partly because dredging was done from the ebb-side. When the morphological dredging was applied, the aim and expectation was that it would lead to a breakthrough of the ebb-shield between the Roompot and the Roompot Zuid. This however did not happen. It was also found that increasing the dredged sediment volume had a positive effect on the preferred morphology. The total volume of dredged sediment was 3 million cubic meters (mcm). This was however not enough to form a connecting channel between the Roompot and the Roompot Zuid. The altering of the system caused the main ebb-flow to go through the Roompot-Hompels and the main flood-flow through the Schaar van Onrust. The decreased ebb-flow through the Schaar van Onrust has made it more flood-dominant. According to (van der Werf et al., 2010) there has been no decrease in coastal erosion due to the Schaar van Onrust since 1993.

2.6 Discussion on literature study

From the literature we can conclude that the southward motion of the Schaar van Onrust plays an important role for the erosion of the coast of Noord-Beveland. The construction of the Eastern Scheldt barrier is thought to have played an important role in this migration. A possible explanation for this is that the barrier diverted the tidal flow from the Roompot Zuid through the Oude Roompot. This could have resulted in the southward movement of the Hompels, trapping the Schaar van Onrust between the Hompels and the coast. By introducing a solid connection between the Roompot and the Roompot Zuid, and simultaneously blocking the Schaar van Onrust, it is hypothesized that the main tidal current can be redirected, relieving the coast of Noord-Beveland of erosion. To test these hypotheses, the impact of the barrier on the sediment pathways will be isolated using a numerical model. Next, the 2019 bathymetry will be adjusted in the model by removing sediment from the Hompels and filling up the Schaar van Onrust, to test whether the tidal flow can be diverted.

3 Data analysis

In this section the sediment budget is presented from 1965-2019. The sediment budget in this period can help to provide quantitative information about the development of the ebb tidal delta from before, during and after the construction of the barrier. The Eastern Scheldt ebb-tidal delta was analysed based on the sediment and erosion areas from 1984 relative to 2019. With this approach accreting and eroding areas since the construction of the barrier can be identified and quantified, and their volumetric trends from prior and after the construction can be analysed. The volumes are extracted from the periodically measured subaqueous Vaklodingen surveys. Due to the varying coverage in the Vaklodingen the volumes above 0m NAP are likely inaccurate. The analysis is therefore limited to the volume changes below 0m NAP (which is about mean sea level), and does not include the beach and dunes.

An overview of the sedimentation and erosion patterns between 1984 and 2019 is given in Figure 3.1. The boundaries between eroding and accreting zones were used to define 20 polygons, which are referred to below. The polygons were defined by subtracting the 1984 bathymetry from the 2019 bathymetry using Delft3D-QUICKIN. The erosion and accretion zones were subsequently divided in polygons manually. In cases where there is no clear eroding or acceding trend near the edge of the considered domain, polygons were subdivided with straight lines. The total volume of the ebb-tidal delta as defined in Figure 3.1 (relative to the volume in 2019) is shown in Figure 3.1.

Starting with the southern western edge of the domain, adjacent to the Western Scheldt ebb-tidal delta (polygon 3), a scattered pattern of sedimentation and erosion is observed. In the south eastern part of polygon 3 the Brouwershavense Gat, and part of the Roompot Zuid is located. Before the construction of the barrier started this area was gaining sediment (Figure 3.1C), whereas from 1980 until 2010 it was losing sediment.

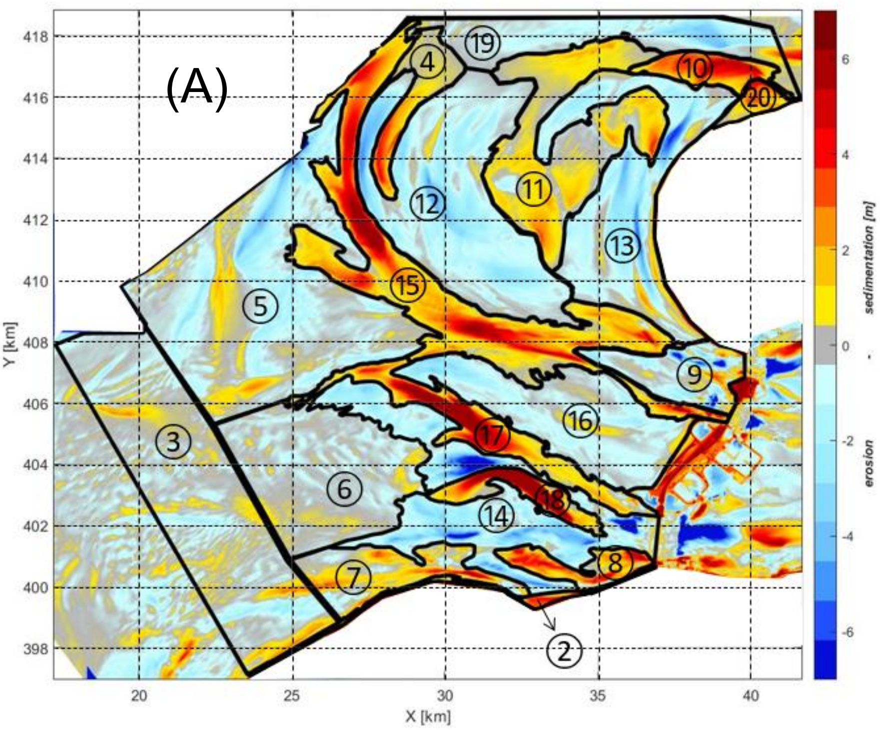
Further North East, polygon 7 includes the nearshore and part of the Roompot Zuid. The amount of sediment in this polygon was fairly stable before 1972. From 1972 to 1976, there is a noticeable increase in sedimentation. Between 1976 and 2010 there is a more gradual trend of sedimentation. Between 2010 and 2019 a fluctuation in sedimentation and erosion is observed, with an initial trend of increased sedimentation, followed by a period of steep erosion, and ending in another steep trend of sedimentation.

Polygon 14 includes the northern part of the Roompot Zuid and the southern part of the shallower Hompels area. Before 1984 it was gaining sediment, after which a steady erosional trends is observed until 2019. In front of the barrier eroding scour holes are clearly visible. The clockwise rotation of the ebb chute is clearly visible in polygon 18, which marks the previous location of the chute. This area accreted, whereas north of it sediment eroded. The Roompot channel has been partly filling up and rotating clockwise as well, visible in polygon 17. The shoal in between the two inlets and west of Neeltje Jans has overall lost sediment (polygon 16).

Polygon 8 includes the current Schaar van Onrust and the Onrust shoal. The shoal has moved landwards and in the channel sedimentation has occurred since 1984. Before this time, the channel was losing sediment.

Polygon 15 includes a big part of Westgat channel and the Banjaard channel. The Westgat channel has been filling up and the Banjaard channels also moved slightly eastwards and reorientated in a more north-south direction. The Banjaard shoal eroded. The Petroliumbol (polygon 11) has gained sediment, and the surrounding Zeehondenplaat (polygon 13) and Banjaard shoal (polygon 12) eroded somewhat. In polygon 19, in front of the northern two inlets erosion has taken place.

The shoals and channels directly in front the southern inlet, including polygons 8, 14, 18, and 17 have overall gained 1.5mcm. The deeper parts of the southern end of the ebb-tidal delta (polygons 3, 5 and 6), lost 56.5mcm, of which the majority of the loss occurred in polygon 5 (42.4mcm). The polygons in front of the northern two inlets (16, 9 and 15) had a net increase of 57.6mcm. and polygons 4, 10-13, 19 and 20 overall lost 53.8mcm. The net sedimentation/erosion of the ebb tidal delta was -50.1mcm from 1984 to 2019. The overall trend from 1984 until 2010 was erosion, whereas from 2010 until 2019 the ebb tidal delta gained sediment again.



(B)

Selected polygon	Volume change 1984-2019 [mcm]
2	-16.1
3	-7.0
4	8.2
5	-42.4
6	-7.1
7	8.1
8	11.4
9	-7.4
10	15.8
11	20.0
12	-59.0
13	-38.7
14	-66.1
15	84.5
16	-19.5
17	34.3
18	21.9
19	4.5
20	4.4
Total	-50.1

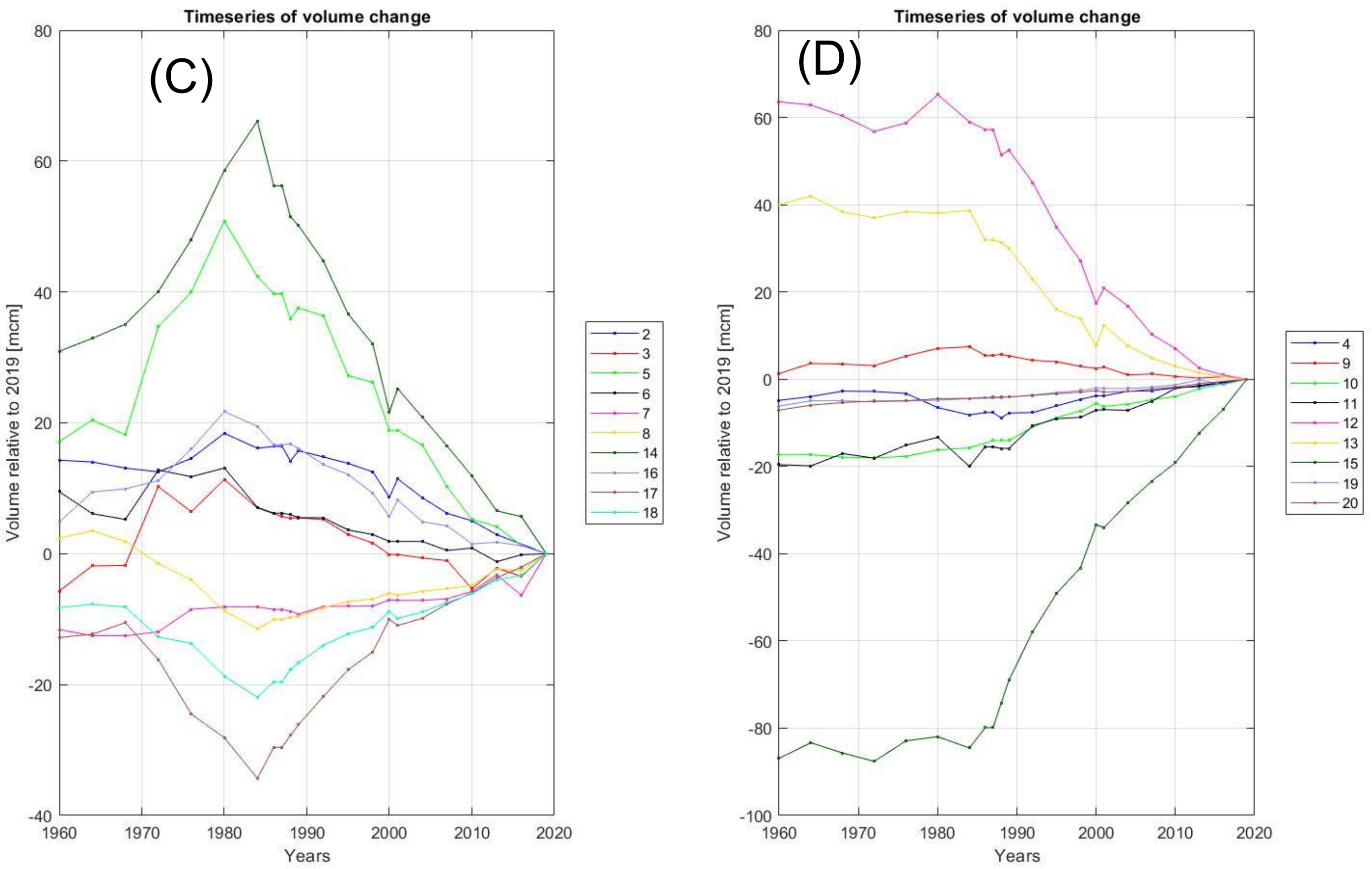


Figure 3.1: Overview erosion and sedimentation patterns .In (A) the erosion and sedimentation from 1984 to 2019 divided in sedimentation and erosion polygons. In (B) the net sedimentation/erosion of each polygon is stated. In (C) and (D) the volume of each polygon relative to 2019 is shown over time.

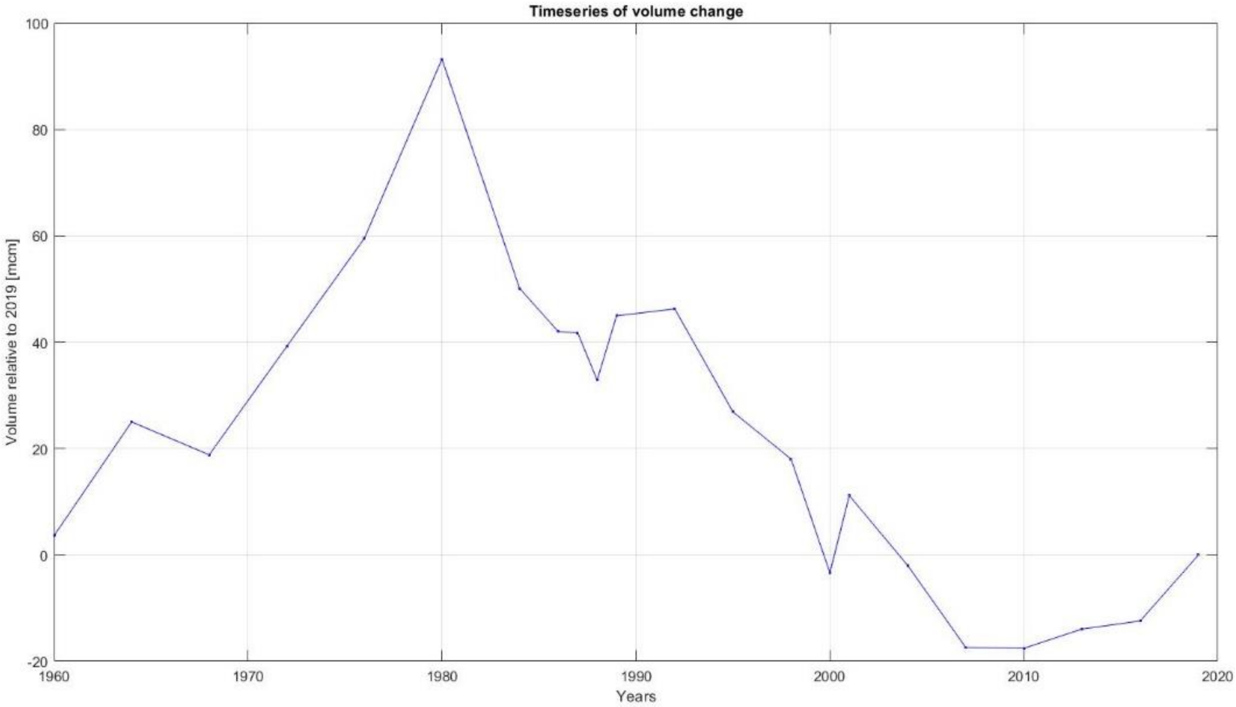


Figure 3.2: Volume of the total eastern Scheldt ebb-tidal delta relative to 2019. Volumes are in million cubic meters (mcm).

4 Modelling Study

4.1 Method

In this study, the 6th generation D-HYDRO model of the Eastern Scheldt has been used (described in detail in section 4.2) (Tiessen et al., 2019). First, a simulation has been conducted using bathymetry data obtained from Vaklodingen measurements taken in January 1976, prior to the start of the construction of the Eastern Scheldt barrier (which began in April of the same year). To account for bathymetric changes unrelated to the barrier's construction, the simulation has been run both with and without the barrier in place. This has allowed for a comparison of the sediment pathways before and after the construction. Additionally, two runs have been conducted using bathymetry taken shortly after the completion of the barrier's construction in 1986, using Vaklodingen measurements from 1987. These runs were also conducted with and without the barrier in place to consider the impact of the construction on the sediment transport pathways. A final run using the most recent available bathymetry (from 2019) has been conducted to understand the current sediment transport pathways and their relation to past large-scale morphological changes.

To reduce computation time, a representative tidal cycle has been selected to represent the yearly average sediment transport. This was done in two stages: first, the tidal signal for an entire year was modelled without considering sediment; then, a representative month was chosen and modelled with sediment, from which the representative tidal cycle for sediment transport was selected. This tidal signal can be used for all relevant bathymetries. The Delft3D FM model has produced the sediment transport vector fields, which have subsequently been employed to calculate the particle trajectories using SedTRAILS. The results have been analysed to understand the connections between the observed changes and the erosional patterns at Noord-Beveland and how to address them.

Important to note is that waves are excluded in this modelling study. Although waves are important for sediment transport on the ebb-tidal delta, this study focusses on tide-driven transport because tide was identified as the driving mechanism of coastal erosion at Noord-Beveland (Elias & Quataert, 2021). Therefore we are particularly interested in the influence the barrier had on the behaviour of the tidal channels with regard to sediment pathways.

4.2 Model Setup

4.2.1 Model domain

Figure 4.1 provides an overview of the model domain. The distance from the middle of the island Neeltje Jans to the seaward boundary is approximately 13km (C-D). At the southwestern edge of the domain, the distance from the coast of Walcheren to the seaward side is 6km (A-B). At the north-eastern edge, the distance from Schouwen to the seaward side is 3km (E-F). The distance from the southwestern edge of the domain to the north-eastern edge is approximately 23km (F-G).

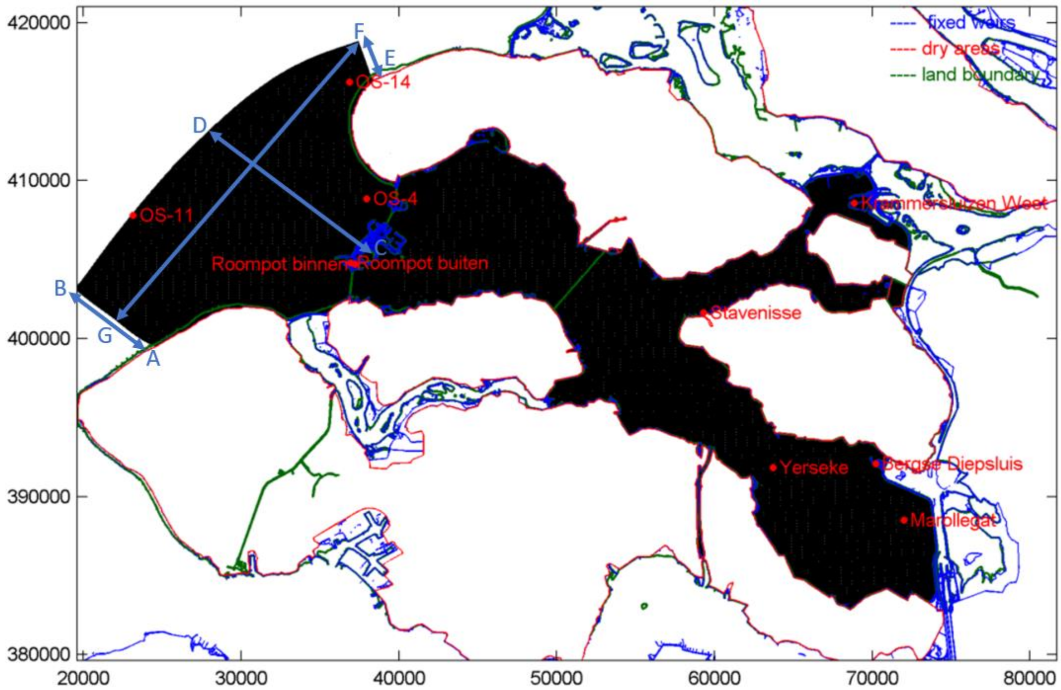


Figure 4.1: Overview the D-HYDRO Eastern Scheldt network with the locations of the waterlevel measuring stations. Distances: A-B = 6km, C-D = 13km, E-F = 3km and F-G = 23km. (Tiessen et al., 2019).

4.2.2 Grid

Several methods of grid generating were researched in a study performed by (Tiessen et al., 2019). The grid generation method that was used for the grid in this study was based on their conclusion and is described in this section.

At the three parts of the barrier (Hammen (north), Schaar (middle) and Roompot (south)) fully regular triangular grids were generated which aligned with the barriers. The grid size was chosen such that each gate is described by one grid cell. For the inner part of the domain (bounded by the norm trajectory line from the Baseline database and the Eastern Scheldt barrier) and outer part of the domain (bounded by the Eastern Scheldt barrier and the open boundary at the seaside) fully regular triangles were also generated. To align the dams, dikes and other constructions near the Rammegors, Bergse Diepsluis and the Krammersluizen with the grid, partial grids were developed to later be connected to the other parts of the overall grid. The model boundary was based on the norm trajectory line from Baseline. This boundary was converted to a polygon and refined to 50 meters. Subsequently a partial grid was made between this line and the regular triangular grid of the inner part of the domain. An opening was kept between these two grids, which was filled with triangular grid cells. This ensures a final grid with as much regular triangles as possible, which guarantees proper smoothness, orthogonality and aspect ratio of the grid. In some areas irregular triangles are however necessary to handle transitions between areas with different orientations and/or resolution (Tiessen et al., 2019).

4.2.3 Bed levels

The bed levels used in the modeling study are obtained from Rijkswaterstaat using the Vaklodingen protocol. The Vaklodingen data is interprolated on a predesigned grid which is divided into map sheets of 10 km x 12.5 km with a resolution of 20 m. (Elias et al., 2016) The pre-barrier bed level was surveyed in 1976, prior to the construction of the storm surge barrier. Although the barrier was finalized in 1986 and bed level surveys were performed in 1986, 1987 and 1988, only the 1988 survey is used in this study as this is the most complete data set. Lastly, the 2019 Vaklodingen data is used. The Vaklodingen data is interpolated on the model grid. For the years 1976 and 1988 the simulation is run both with and without barrier. The barrier itself is schematized as 63 separate ‘general structures’ (31 for the Roompot, 15 for the Hammen and 16 for the Schaar). In all simulations with the barrier the gates will be open. To simulate the bed protection, a non-erodible layer is introduced perpendicular to the barrier about 500m in both ways. For the simulations without barrier, the general structures belonging to the storm surge barrier were removed from the model, as well as the non-erodible layer. (Tiessen et al., 2019).

4.2.4 Boundary conditions

At the open boundaries of the model water levels are specified at 8 locations (see Appendix A for locations). The timeseries on the sea boundaries were obtained from Rijkswaterstaat Zee en Delta (RWS-Z&D). The boundaries were derived by shifting the ratio between the M2-tide and the phase from location OS11 and OS14.

4.3 Representative tidal cycle

To reduce computation time for the simulations the complex time series of the water levels and flow velocities is replaced with a simplified tide. This representative tidal cycle was selected such that the residual sediment transport vectors as simulated by the complex time series are equivalent to the results of those found with the chosen morphologic tide. Finding the representative cycle will be done in two steps. First the representative month will be determined based on the hydrodynamics only. This is done to reduce computation time. The representative month will then be run with sediment to find the representative tidal cycle based on the sediment vector fields.

Figure 4.2: Model domain with the cross-section through which we consider the discharges and fluxes in this chapter indicated as a pink line with an arrow in streamwise direction. The arrow points in the direction of the positive discharges/fluxes.

4.3.1 Hydrodynamics

First the tidal motion is simulated over a sufficiently long period (one year). The year chosen in this case is 2016, with the assumption that the variation of the computed discharge between different years is negligible (hence the computed average yearly discharge can be used for all years that we consider in this study). A cross-section is chosen through which the tidal motion will be investigated. The chosen cross-section is shown in Figure 4.1. This cross-section is representative for our case because it is relatively close to the area of interest and the tidal flow through this cross-section also must pass the channels we are investigating.

First a timeseries of the discharge and area of, the cross-section during the year was extracted from the model. When analyzing the cumulative discharge of this timeseries it is notable that the beginning of the timeseries (from January to April) shows a non-linear trend whereas the rest of the year is linear. The cause of this is unclear. An earlier study from 2009 (Boom, 2016) of a site close to the Eastern Scheldt (measuring location 'Brouwerhavense Gat 2') concluded that the representative tide is in the summer months. This was based on the ratio between the consecutive spring and neap amplitudes within their dataset, compared to the yearly average of this ratio. The spring-neap cycle closest to the yearly average was considered the representative spring-neap cycle. Therefore, to avoid using non-representative data from the timeseries, we will not use the data from the nonlinear part of the cumulative discharge.

With the resulting timeseries of the discharge and the area of the cross-section, the average flow velocity (v) through the cross-section is computed. With this average flow we can get an indication of the sediment transport capacity throughout the year by considering the bedload as well as the suspended sediment transport. The bedload and the suspended load are approximately proportional to the velocity to the third and fifth power respectively. First, we take the timeseries of v^3 and v^5 combined and smoothen it by taking the moving mean of one tidal period (24 hours and 50 minutes), shown in Figure 4.3. Next, the moving mean of the tidal period is smoothened by taking the moving mean of one month, which is shown in Figure 4.4. We compare this moving mean of one month with the year average mean of v^3 + v^5, seen in Figure 4.5. Based on this the moment of which the yearly mean is closest to the monthly mean is determined to be '23-Aug-2016 20:10:00'. Therefore, based on this hydrodynamic analysis of the tidal motion the representative month starts on August 8th, at 20:10:00 and ends on September 7th at 20:10:00.

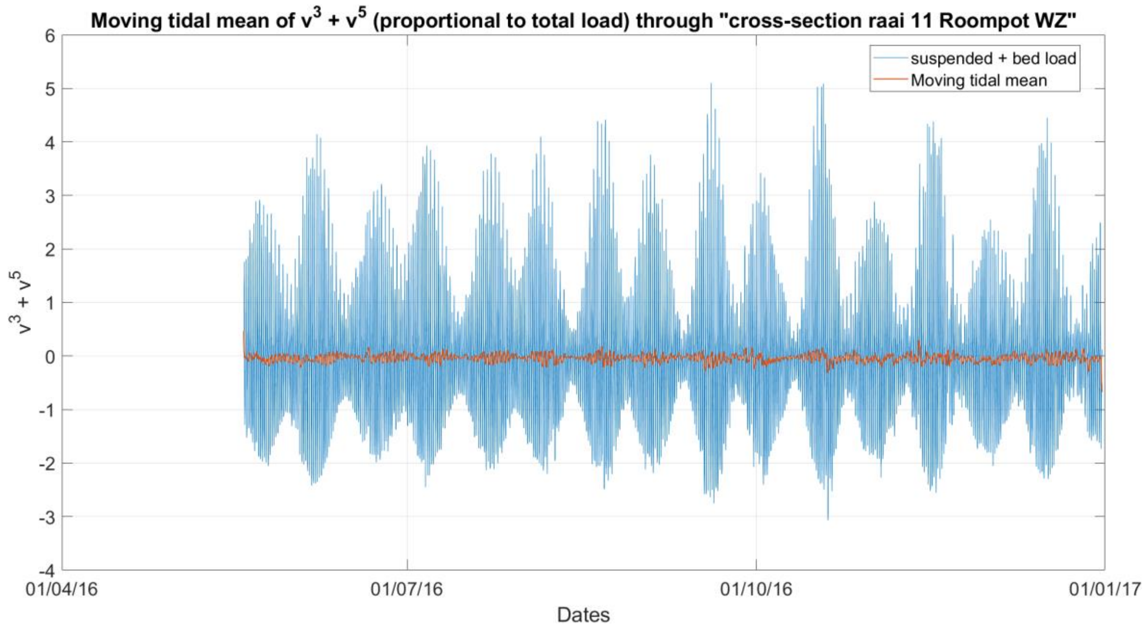


Figure 4.3: An approximation of the suspended + bed load and the moving mean per tidal cycle through the cross section in Figure 4.2.

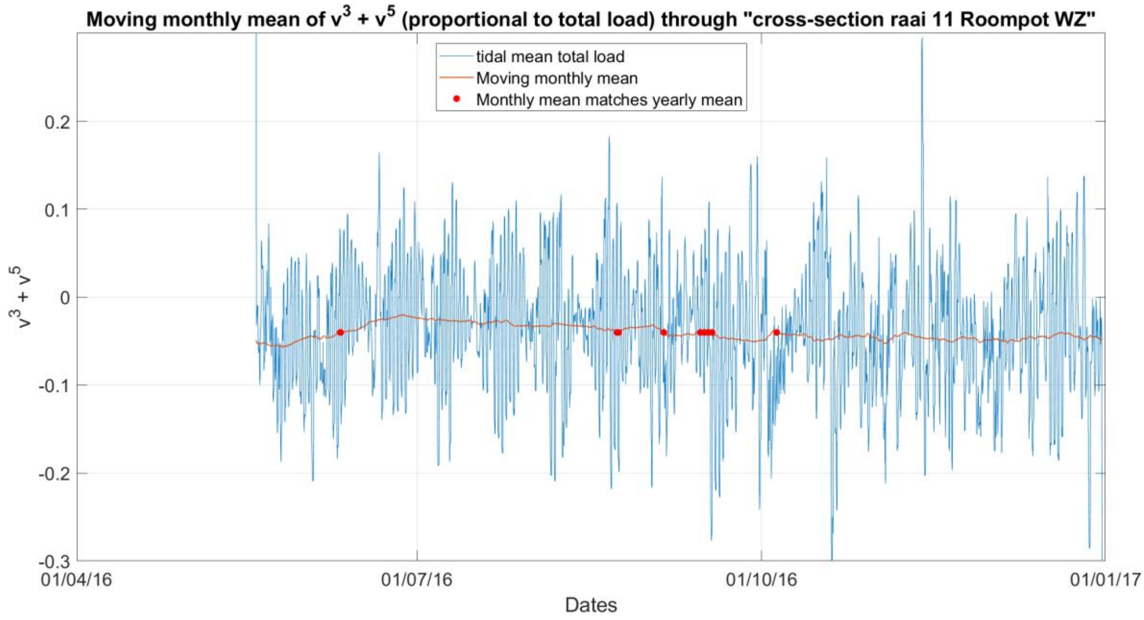


Figure 4.4: An approximation of the moving tidal mean and the moving monthly mean of the total load through the cross section in Figure 4.2. The red dots indicate the points in time were the monthly mean matches the yearly mean.

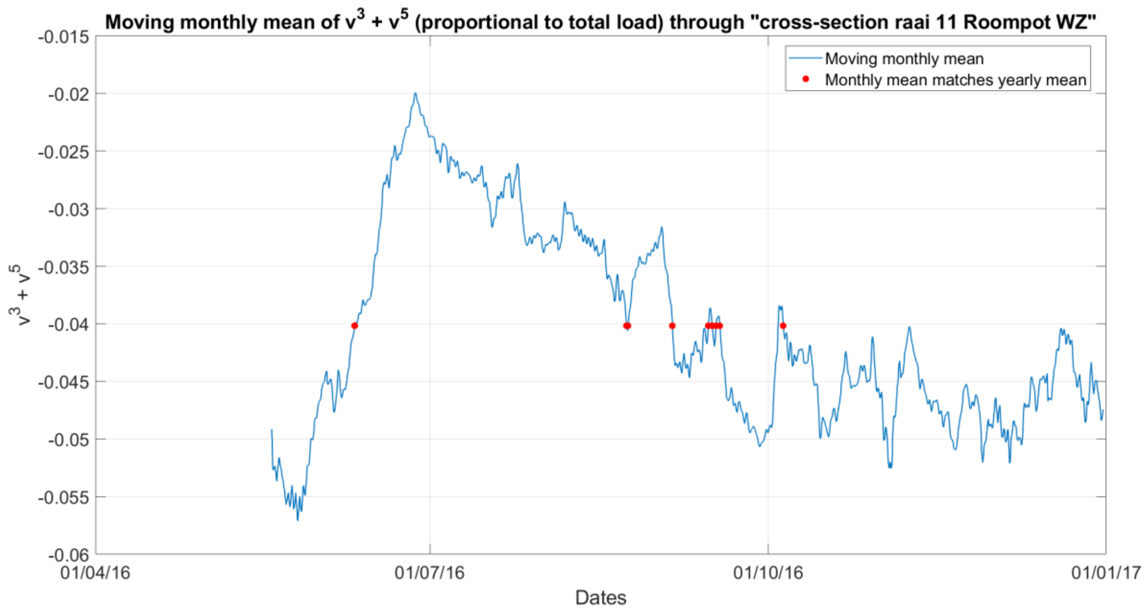


Figure 4.5: An approximation of the moving monthly mean of the total load. The red dots indicate the points in time were the monthly mean matches the yearly mean.

4.3.2 Sediment vector fields

After the representative month was selected based on the hydrodynamics, a simulation was performed during this month however with sediment included in the model. To find the representative tidal cycle in terms of sediment vector fields the average sediment vector field of the previously selected spring neap cycle was computed first. Next, of each output timestep (1/8th of a tidal cycle, approximately 3 hours and 10 minutes), the average sediment vector field of the past tidal cycle was computed. These vector fields were compared to the monthly average vector fields. Based on this comparison a selection of best represented tidal cycles was made (Figure 4.7).

The final step in picking the representative tidal cycle has to do with the accuracy of the SedTRAILS computations. These computations use the selected tidal cycle multiple times (depending on the selected runtime in SedTRAILS). A discrepancy in transport between the beginning and end of the selected tidal cycle can therefore give an increasingly inaccurate representation of the sediment pathways as the runtime of the computation increases. Therefore, it is important to pick a tidal cycle in which the transport at the beginning is as close to the transport at the end as possible. Based on this the tidal cycle considered most representative for the yearly average sediment flux is shown in Figure 4.. This cycle starts on August 23th at 02:40:00 and ends August 23th at 15:20:00. As can be seen in Figure 4.8 the sediment flux in the beginning and end of this cycle are both approximately zero.

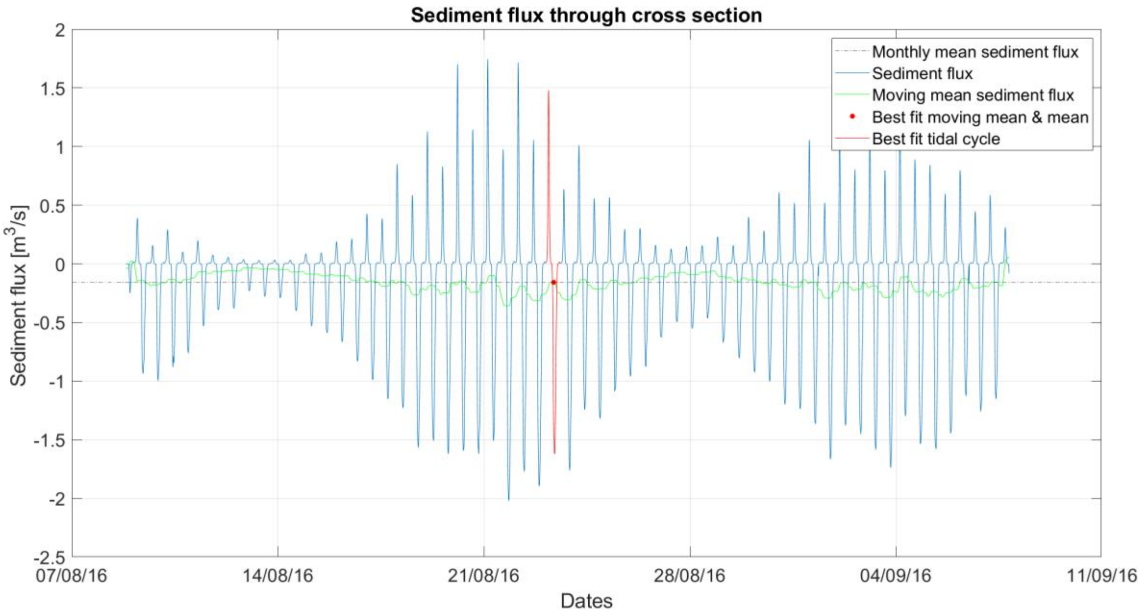


Figure 4.6: Signal of the sediment flux through the cross-section in Figure 4.2.The red dot indicates the moment in time in which the moving mean of the sediment flux coincides with the monthly average mean. The red line is the tidal cycle of which the red dot represents the mean (the red dot is exactly halfway of the cycle of the red line).

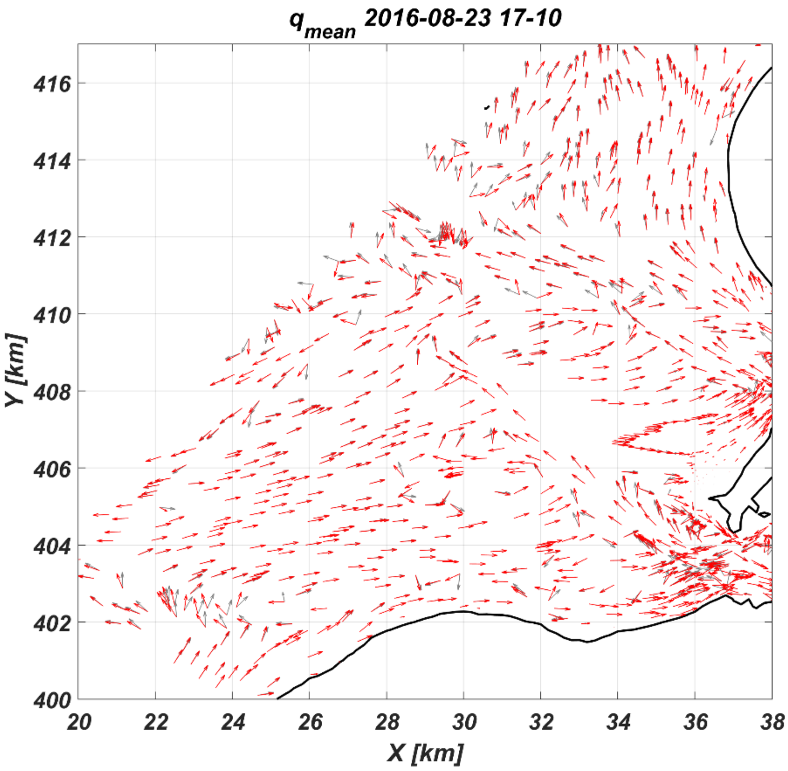


Figure 4.7: A visual representation of sediment vector fields, in which the grey arrows represent the monthly average sediment vector fields and the red arrows the sediment vector fields of the chosen tidal cycle.

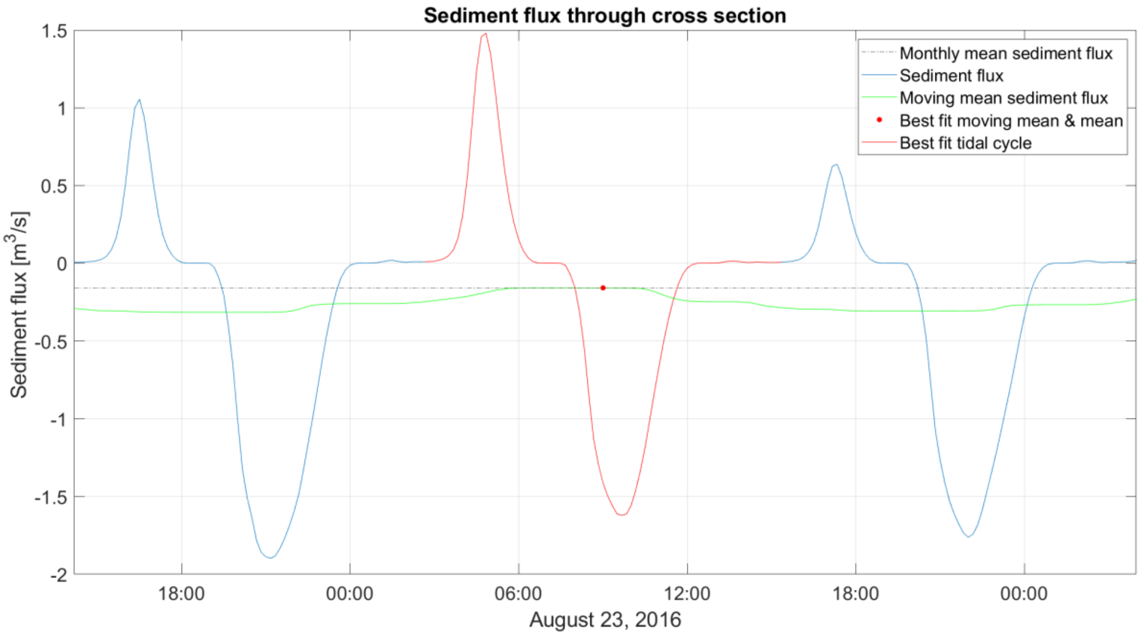


Figure 4.8: Chosen tidal cycle based on sediment flux through the cross section in Figure 4.2.

4.4 Morphological interventions

To investigate the possibility to redirect the tidal current, two interventions were implemented in the bathymetry to redirect the current. One intervention entails a nourishment in the Schaar van Onrust of $4Mm^3$. The other intervention is aimed at creating a connection between the Oude Roompot and the Roompot Zuid by the removal of $8Mm^3$ of sediment (see Figure 4.9). The two interventions were first tested separately and then simultaneously.

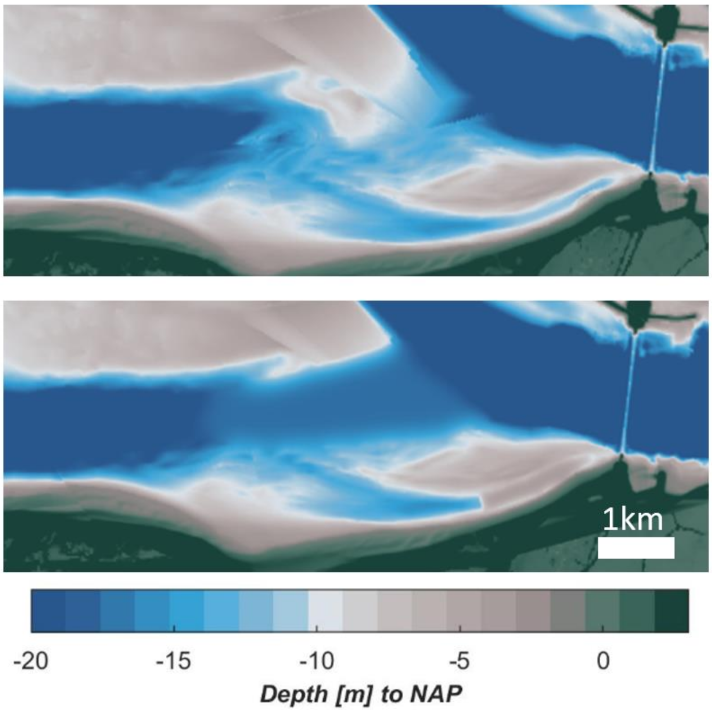


Figure 4.9: Top: 2019 Bathymetry. Bottom: 2019 bathymetry with interventions.

5 Results

In section 5.1, the year 1976 is considered (excluding the barrier) followed by the year 1988 and 2019 (both including the barrier). The main transport patterns will be discussed extensively. Apart from the introduction of the barrier, all parameter settings, boundary conditions and bathymetry are kept the same in this comparison. In section 5.2, the changes in the sediment pathways due to the barrier and the bathymetry will be discussed. Section 5.3 provides a more detailed representation of the sediment pathways near the coast of Noord Beveland. Finally, in section 5.4 the tested interventions will be presented.

5.1 Transport patterns on the ebb-tidal delta

5.1.1 1976 (excluding barrier)

The 1976 ebb-tidal delta without the barrier in place can be divided into 5 areas based on exchange of sediment between these areas (see Figure 5., note that all 'areas' referred to in this section refer to the areas defined in Figure 5.1). Zones with divergent or non-convergent parallel paths were used to determine boundaries between the numbered areas (separated by the white dotted line). The separation of these areas do therefore not necessarily align with the morphological elements such as channels and shoals. This is because in different parts of the morphological elements a different tidal dominance prevails. The Oude Roompot channel for example, is partly in Area 2 and partly in Area 3, as some parts of it are ebb-dominated (transporting sediments seawards) and some are flood dominated (transporting sediments into the estuary).

Starting from the south-western side of the domain the North Sea tide delivers sediment in north-eastern direction roughly parallel to the coast. On the southern side of Roompot Zuid channel a flood-dominant character prevails, leading sediment outwards. Further out the sediment pathways are directed back towards the Oude Roompot though the northern side of the Roompot Zuid and over the shoals of the Hompels (Area 4). In the north-east side of the Roompot Zuid, in front of the former inlet of the Veerse Gat, a striking pattern is observed (Area 1). Sediments from the Roompot Zuid follow an flood-dominant trajectory, and from the Schaar van Onrust and the Hompels an ebb-dominant trajectory. Where these trajectories meet an eddy is observed. Sediments within this tend to stay here.

North of the Roompot Zuid particles follow two different trajectories. Closer to the coast the particles are brought with the North Sea tide towards the Hompels and end up in the large eddy of the ebb-chute (Area 4). Further away from the coast, particles picked up by the North Sea tide as well but end up in the Oude Roompot where the particles are picked up by the dominant ebb-current of the channel.

Particles based in the central and southern part of the Oude Roompot propagate seaward with the ebb-dominant current. A minor part is directed back to the Hompels through the ebb-chute channel. In the Northern part of the Oude Roompot , close to the location of the barrier, particles are following a circular path due to an interaction between ebb- and flood-dominant currents (north-western part of Area 2). Towards the middle they are transported seawards, before they are being redirected back to the estuary. A small portion of particles are also trapped in the eddy that is formed.

At the end of the Roompot channel, at the southern tip of Westgat some particle trajectories are caught up in an eddy, whereas others are picked up by the North Sea tide again until the dominant ebb-current of the Westgat takes over and delivers the sediment Banjaard shoal and the Geul van the Banjaard.

In the north western part of the inlet near Neeltje Jans, sediments from the Geul van the Roggeplaat follow a seawards trajectory up until the Westgat, due to ebb-dominance. Here flood-dominance takes over transporting the sediments back to the estuary through the Hammen.

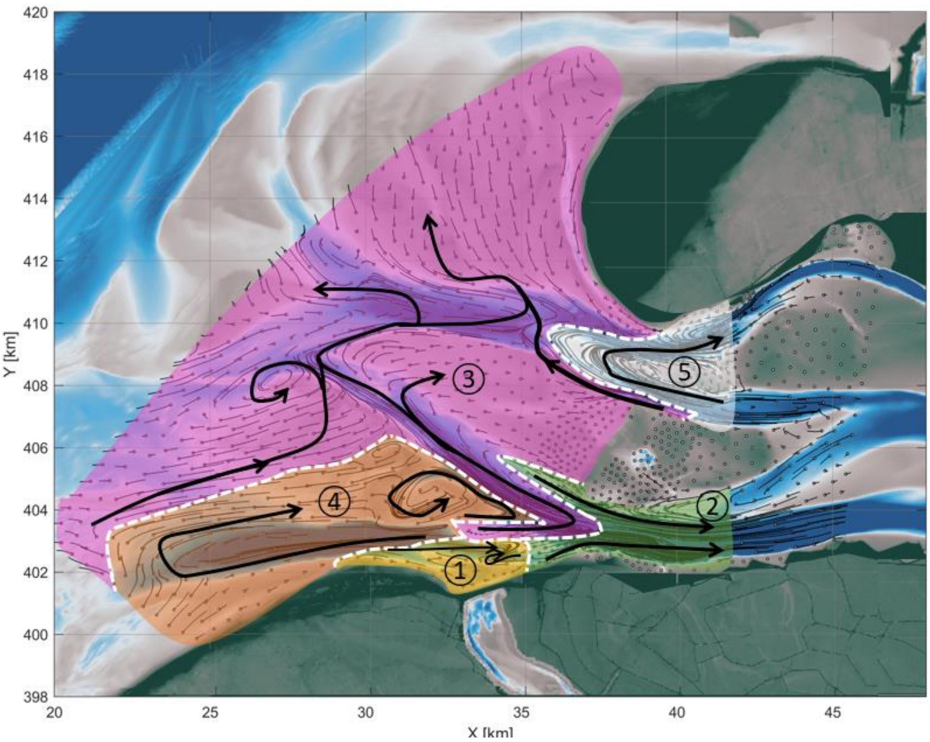


Figure 5.1: 1976 bathymetry without barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.1.2 1988 (including barrier)

The sediment pathways belonging to the bathymetry of 1988 with the barrier included are presented in Figure 5.2. Note that, in this section any reference to the ‘areas’ refer to the areas defined in Figure 5.2.

Starting from the south-western part of the ebb-tidal delta, the Roompot Zuid is transporting sediment along the coast towards the southern part of the Hompels (Area 1), to the narrow shallow area between the Oude Roompot and the Roompot Zuid. Apparently, almost the entire Roompot Zuid has become flood-dominant. North of the Roompot Zuid, a narrow band of sediment pathways is transported with the North Sea tide to the ebb-chute of the Oude Roompot (Area 4). From the southern part of the Hompels sediments are delivered to the Oude Roompot, of which the center and southern part still has an ebb-dominant character. North of Area 4, the pattern is still largely similar to the 1976 situation.

Along the coast, the Schaar van Onrust has now become flood-dominant until all the way up to the Roompot Zuid. Sediments are delivered from south of the former inlet of the Veerse Gat, through the Schaar van Onrust to the estuary (Area 2).

In the north eastern part of the Oude Roompot, sediments are no longer passing the barrier (Area 6). In this Area, towards the centre of the Oude Roompot, sediments follow a seawards trajectory (ebb-dominant), before circling back towards the barrier. Since they are not passing the barrier here anymore, they are ‘trapped’ here.

At the Geul van de Roggeplaat, sediments from the seaward side of the barrier are still ejected seawards. However, they are not being transported back to the eastuary through the Hammen anymore. Instead, once being picked up by the flood-dominant Westgat channel, they follow a trajectory towards the Zeehondenplaat, the shallow area eastwards of Schouwen. Seawards of the barrier at the Hammen channel, sediments are no longer passing the barrier, but instead are trapped in an eddy-like pattern (Area 5).

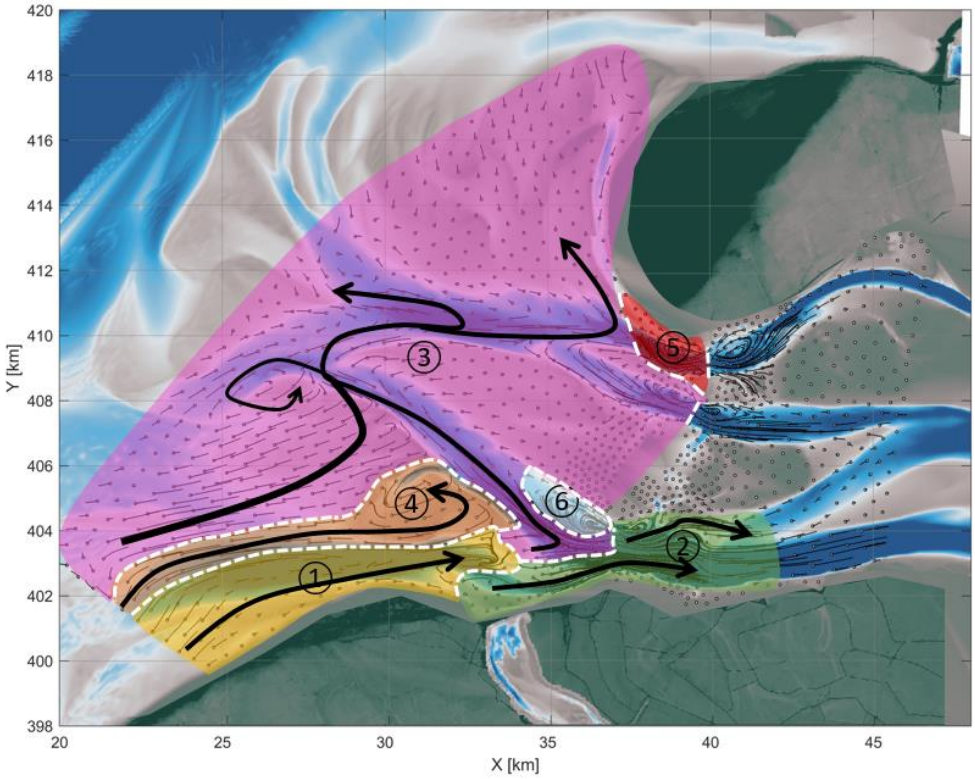


Figure 5.2: 1988 bathymetry with barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.1.3 2019 (including barrier)

The sediment pathways belonging to the bathymetry of 1988 with the barrier included are presented in Figure 5.3. Note that, in this section any reference to the 'areas' refer to the areas defined in Figure 5.3, except if mentioned otherwise.

Starting in the south western part of the ebb tidal delta, a large part of the Roompot Zuid is still flood-dominant. In the north eastern part of the channel however, sediments are delivered to the Roompot Zuid from the Hompels area, meaning a small part of the channel is ebb-dominant at this location (Area 1). The Schaar van Onrust is still flood-dominant, although sediments do not pass the barrier anymore. Instead the pathways show an eddy-like pattern at the southern edge of the barrier (Area 2).

North of the Roompot Zuid the pattern is still largely similar to the 1988 pattern. As the ebb-chute of the Oude Roompot has migrated seawards however, a larger part of the sediments coming in from the south western part of the domain end up here (Area 4). Sediments from the Hompels are still delivered to the Roompot, although a large part of the sediment paths end up in the ebb-chute than in 1988. The ebb-dominant part of the Oude Roompot still has an ebb-dominant character (Area 3, in between Area 4 and 6).

At the Geul van de Roggeplaat, a small portion of the sediments are 'trapped' in the eddy-like pattern in front of the barrier. The rest of the sediments here are still following a seawards trajectory. The north side of the Hammen channel now also has an ebb-dominant character.

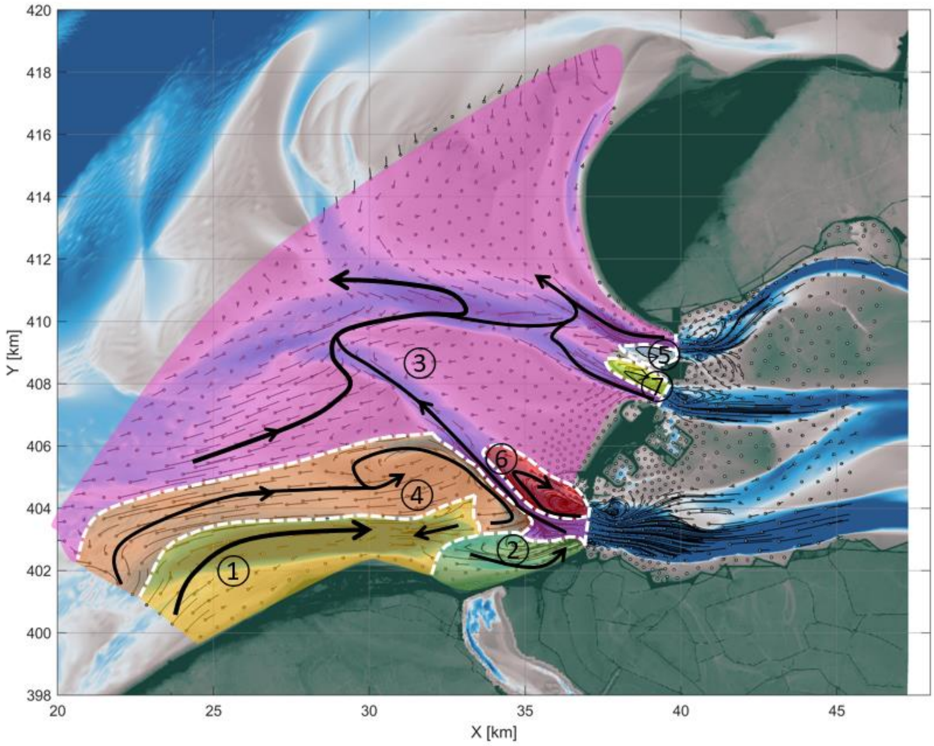


Figure 5.3: 2019 bathymetry with barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.2 Changes in transport patterns

5.2.1 Effect of the barrier

To investigate the influence of the storm surge barrier we compare the sediment pathways with and without the barrier in place, using the 1976 bathymetry. For convenience, Figure 5.1 is incorporated in as the top panel in Figure 5.4.

Starting with the Roompot Zuid it can be seen that the barrier induces a stronger ebb-dominant character. The southern part of the channel, close to the coast, still shows ebb directed sediment transports, but to a significantly lesser extent. Also, just south of the Hompels a new region of converting sediment pathways appears (south eastern end of Area 1 in the bottom panel of Figure 5.4). Secondly, the entire Schaar van Onrust has become flood-dominant. Without the barrier, part of the Schaar van Onrust was ebb-dominant, resulting in an eddy-like pattern close to the Onrust shoal (south eastern side of Area 1 in the top panel of Figure 5.4).

In the ebb-dominated channels and shoals (especially the Oude Roompot, the Petroleumbol, the Zeehondenplaat and the Banjaard shoal), it is clearly visible that the barrier has a reducing effect on the ebb current. The sediment pathways in these areas have significantly shortened, indicating that particles travel less far in the same amount of time. Also, a narrower part of the Oude Roompot delivers sediments from the barrier seawards.

As can be seen by the appearance of Area 6, sediments from the north side of the Oude Roompot do not pass the barrier when it is in place. At the northern two inlets (the Hammen and the Geul van de Roggeplaat), a similar effect is observed, with two eddy-like patterns emerging on the seaward side of the barrier (Areas 5 and 7).

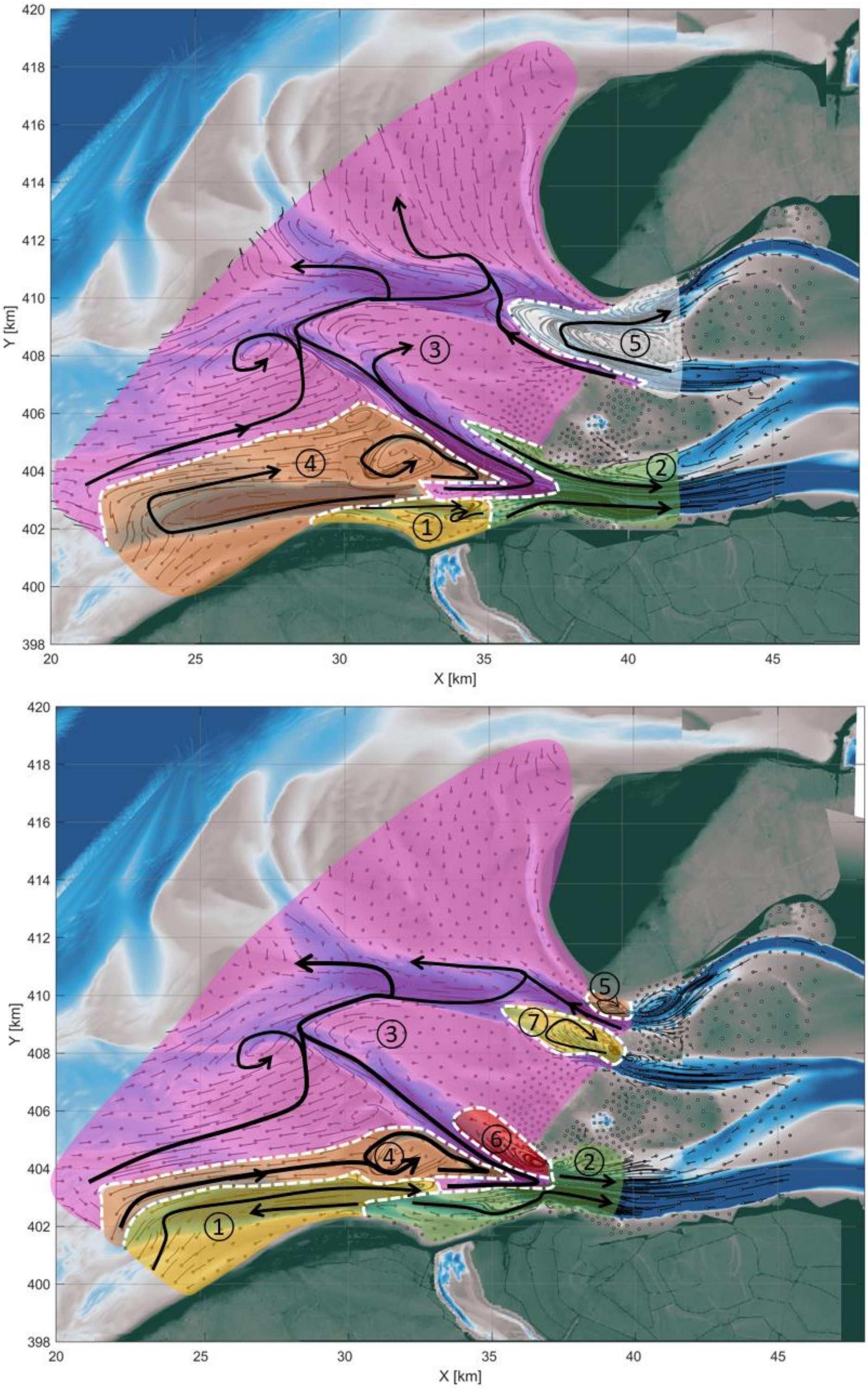


Figure 5.4: Top: 1976 bathymetry without barrier. Bottom: 1976 bathymetry with barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.2.2 Effect of the evolving bathymetry

When we compare 1976, 1988 and 2019, all with the barrier included, we observe a couple of effects on the sediment pathways. Firstly, in 1976 the southern part of the Roompot Zuid is still ebb-dominant. However, the northern part of the channel has become flood-dominant. In 1988 the channel is entirely flood-dominated. In 2019 however, the south western part of the channel is partly ebb-dominant again. The Schaar van Onrust is flood-dominated with all three bathymetries.

Another striking aspect is the ebb-chute of the Oude Roompot. The amount of sediments that come in from the southern part of the domain and end up in the ebb-chute, is largely determined by how far the ebb-chute is located seawards. In 2019 the ebb-chute has migrated seawards, ‘catching’ a significantly bigger part of the sediment trajectories that come in from the south compared to 1976 and 1988.

5.3 Detailed analysis Oude Roompot

This section intents to show more detail of the sediment pathways close to the coast of Noord-Beveland by zooming into this area. This allows for a larger density of sediment source points to be used in SedTRAILS. Although the sediment pathways should not be different from the larger scale representations in the previous paragraph, the higher density of sediment source points that was provides a more accurate representation of the sediment pathways and the sediment sharing cells.

5.3.1 1976 (excluding barrier)

At the northern tip of Walcheren, close to the coast particles are transported eastwards along the coast through a small channel (Area 5 in Figure 5.5) following the flood-dominant current, towards a sandbank located between the Roompot Zuid and the Schaar van Onrust. From this sandbank, particles are then ejected towards the middle of the Schaar van Onrust and then follow a path in flood-dominant direction. In the middle of the Schaar van Onrust, eastwards of the former inlet of Veerse Meer, there is a sediment vortex is visible. West of this vortex the Schaar van Onrust is flood-dominant whereas eastwards it is ebb-dominant. This ebb dominance prevails eastwards until the shoal Onrust, of which the south western tip is flood-dominant but the rest is ebb-dominant. These diverging sediment pathways is represented in the boundary between Area 5 and 2. East of this boundary the Schaar van Onrust is flood-dominant as well.

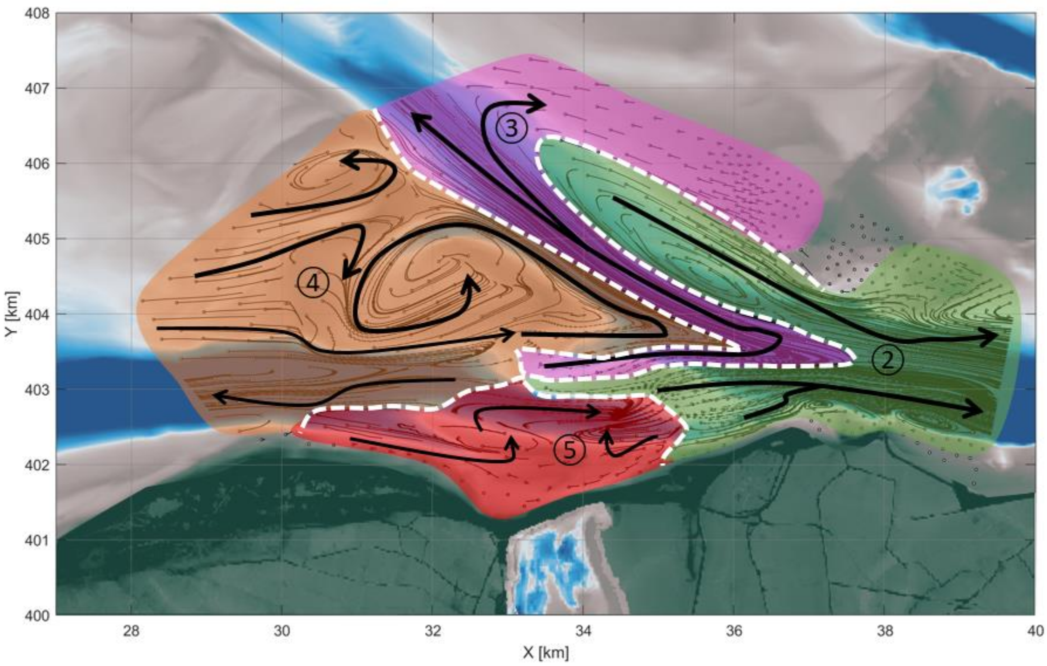


Figure 5.5: 1976 bathymetry without barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.3.2 1987 (including barrier)

The southern part of the Roompot Zuid has become more flood-dominant (see Figure 5.6). Particles form the Roompot Zuid are now transported towards western part of the Roompot-Hompels connection (eastern part of Area 1). With the barrier in place the sediment vortex in the Schaar van Onrust has disappeared. The southwestern tip of the shoal the Onrust is still somewhat ebb-dominant, but most of Schaar van Onrust is now flood-dominant. Only in directly in front of the former inlet of the Veerse Meer, close to the coast, some particle trajectories are moving in ebb direction, before they are ejected towards the middle of the channel where they are picked up by the flood-dominant currents.

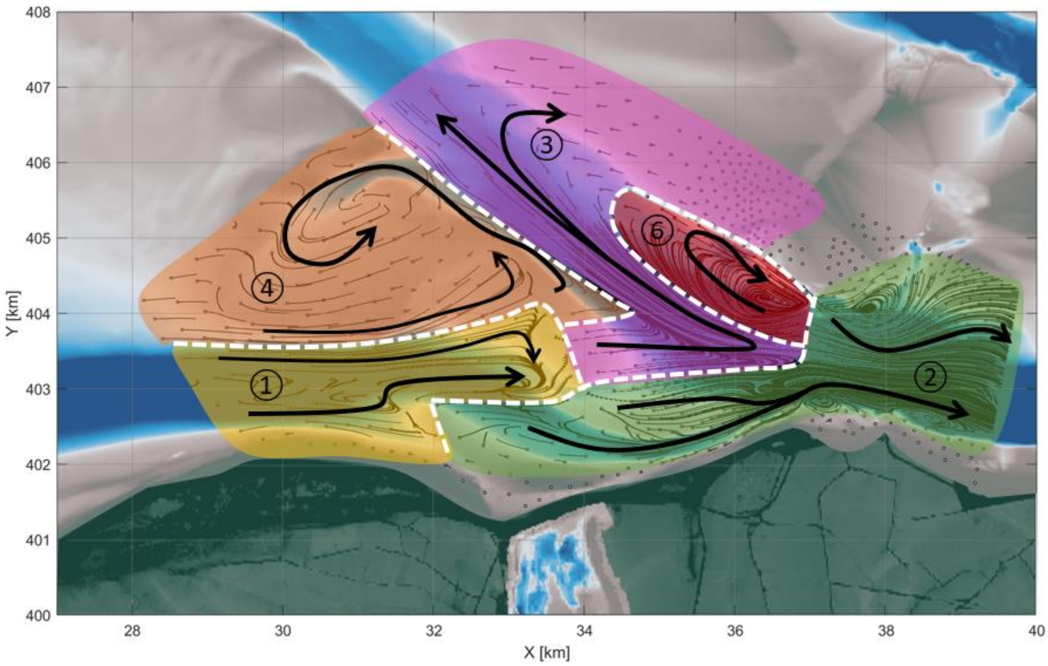


Figure 5.6: 1988 bathymetry with barrier. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

5.3.3 2019 (barrier included)

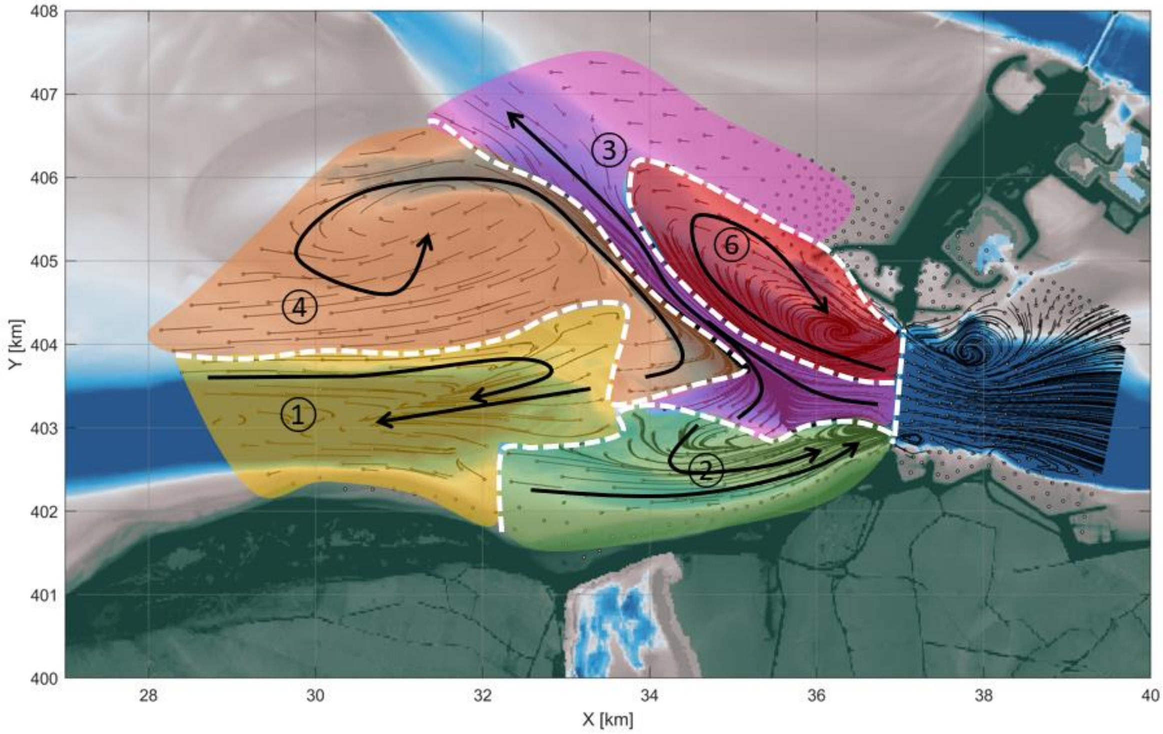


Figure 5.7: 2019 bathymetry zoomed in on the Roompot channel. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

The eastern part of the Roompot Zuid has partly become ebb-dominant (see Figure 5.7). The sediment trajectories lead from the shallow part of the Roompot-Hompels connection in western direction through the Roompot Zuid (Area 1). The North side of the Roompot Zuid is still flood-dominant, until particles are picked up by the ebb-dominant current. Furthermore, the shoal Onrust has moved towards the coast, and particle trajectories from the north side of the shoal are moving in southwestern direction before they are picked up by the flood-dominant current in the Schaar van Onrust. At the southern side of the barrier, in Area 2, a sediment vortex can be identified.

5.4 Interventions

Starting with the nourishment in the Schaar van Onrust only (see Figure 5.8). The most striking effect of this intervention sediment vortex that it creates just north of the shoal the Onrust (Area 7). Without the intervention, sediments were already following a circular trajectory starting north of the Onrust shoal, but apparently the flood-dominant current was strong enough to transport the particles to the southern tip of the barrier. With the reduction of tidal volume through the Schaar van Onrust due to the nourishment, the flood dominance on the north side of the shoal Onrust reduced such that particles now stay within Area 7.

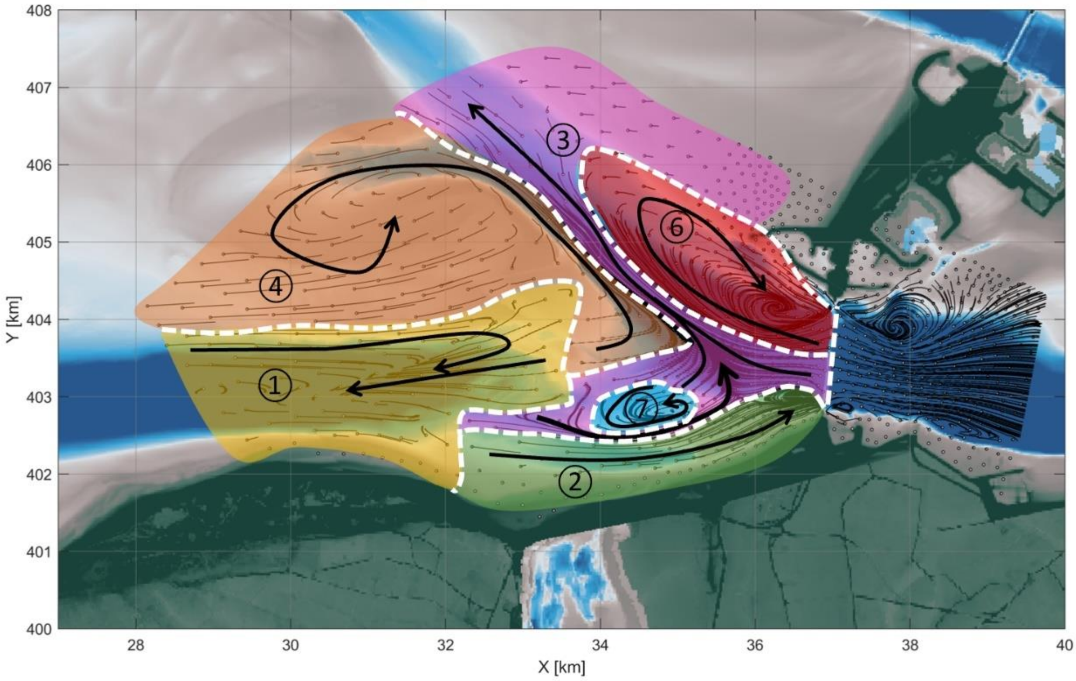


Figure 5.8: 2019 bathymetry with the implemented nourishment zoomed in on the Roompot channel. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

The removal of sediment creates a large sediment vortex at the northern side of the Roompot-Hompels connection (Figure 5.9). Without the removal of sediment (Figure 5.7), sediment trajectories from the location of the tested dredged area lead to four different sediment sharing cells (Area 1, 2, 3 and 4). With the implemented removal of sediment however, all source points that fall within the dredged area show particle trajectories that lead into the sediment vortex. Moreover, several trajectories that end up in the vortex start outside of the dredged area. Starting west from the dredged area, a bigger part of the Roompot Zuid has now become flood-dominant, delivering sediments eastwards to the Roompot-Hompels connection were they then are transported north towards the vortex. Sediments from the northern side of the Onrust shoal follow a northward trajectory to the sediment vortex also. Lastly, sediments from the south western part of the Oude Roompot that were previously delivered through the ebb-chute to Area 4, and through the Oude Roompot seawards (Area 3), now follow trajectories towards the vortex.

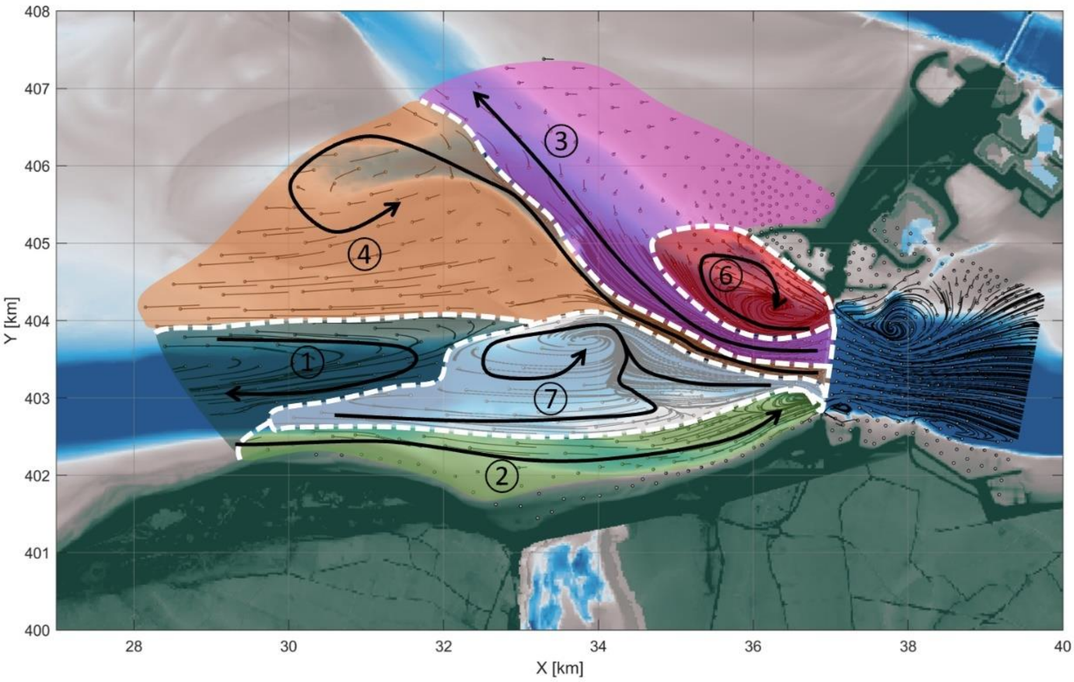


Figure 5.9: 2019 bathymetry with the implemented removal of sediment zoomed in on the Roompot channel. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

With both of the interventions tested simultaneously (sediment removal at the Roompot-Hompels connection, and a nourishment at the Schaar van Onrust), the effects of the separate interventions can still be identified. The south side of the Roompot Zuid has become flood-dominant (see Figure 5.10), which was also observed in Figure 5.9. Particles in this part of the channel follow two trajectories. One trajectory (Area 2) follows a path along the coast into the Schaar van Onrust. The other trajectory (Area 7) leads towards south side of the dredged area. Towards the middle of the Roompot Zuid the channel is ebb-dominant, and towards the north it is flood-dominant (Area 1). At the location of the dredged area, a sediment vortex appeared (Area 8). Sediment trajectories in this Area originate from the northern side of the Onrust shoal.

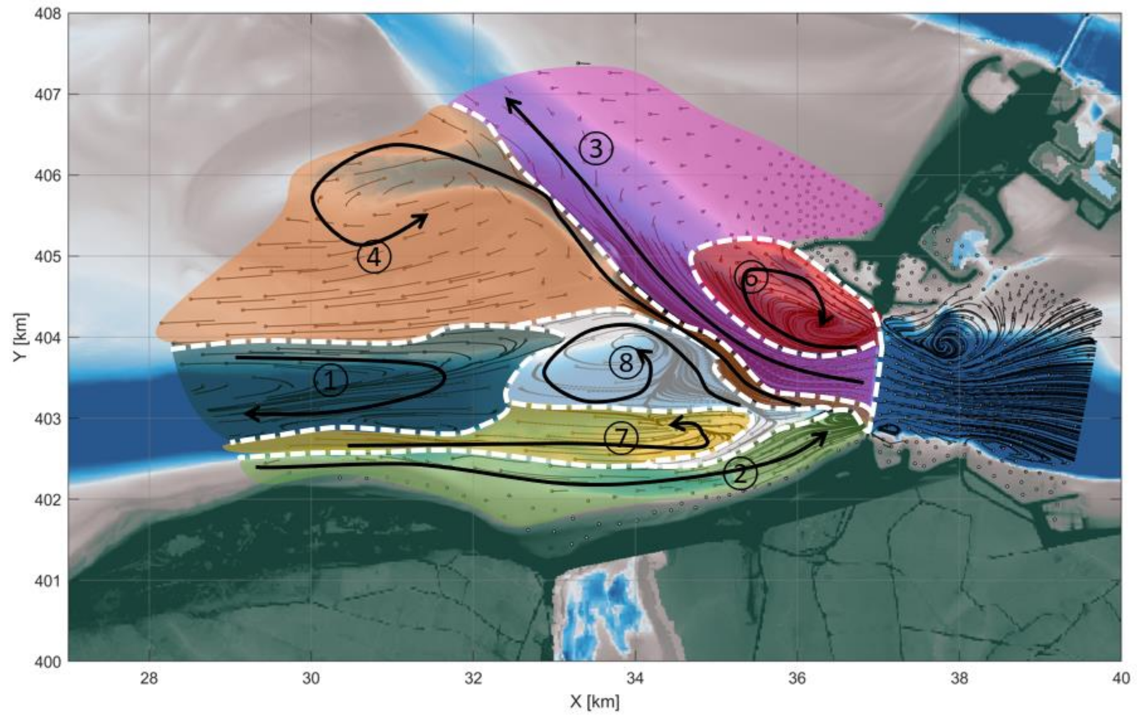


Figure 5.10: 2019 bathymetry with interventions. The dotted white lines indicate boundaries between divergent or non-convergent parallel paths. The black arrows indicate the main sediment pathways.

6 Discussion

6.1 Interpretation of results

6.1.1 Effects storm surge barrier on sediment pathways

In this study the direct effect of the storm surge barrier on the sediment pathways has been isolated. The results show that the barrier has certain effects on the pathways regardless of the bathymetry that has been tested. When we analyse the main sediment transport trajectories based on their ebb- and flood-dominance we see 4 striking developments.

Firstly, the Roompot Zuid has a predominant ebb-dominant character in 1976 before the barrier was built (see Figure 6.1). In 1988, this has changed to a flood-dominant character due to the construction of the barrier. The barrier apparently weakened the ebb-current especially in the middle of the channel. In 2019, the bathymetry changed in such a way that the eastern side of the Roompot Zuid has become ebb-dominant. This is possibly due to the widened gap between the shoal Onrust and the rest of the Hompels area.

The weakening of the ebb current can also be observed in the Schaar van Onrust. Before the construction of the barrier part of this channel was ebb-dominant, allowing a sediment vortex in the channel south of the shoal Onrust. The construction of the barrier caused the Schaar van Onrust to be completely flood-dominant in 1988, which was still the case in 2019. Whereas in 1988 sediment trajectories were still able to pass the barrier, this was no longer the case in 2019, which caused a sediment vortex to emerge just south of the barrier at the boundary of the Oude Roompot and the Schaar van Onrust. Furthermore, in 2019, at the north-western tip of the shoal Onrust, a short sediment trajectory is transporting sediments west, to the Schaar van Onrust. This ebb-dominant trajectory could support the movement of the Schaar van Onrust further into the coast, as sediments are transported from the northern side of the shoal and end up at the south-eastern side of the shoal.

Another development is the increased flood-dominance in the Westgat. The reduced strength of the ebb-current caused by the construction of the barrier causes the flood-dominance in the channel to stretch further into the channel in north-eastern direction 1988. As a result, the ebb-dominant trajectory that originates in the Geul van de Roggeplaat ends up further towards the coast of Schouwen.

Lastly, the northern part of the Hammen has become ebb-dominant and the shoal between the Hammen and the Geul van de Roggeplaat has accreted, resulting in two separate sediment vortexes in front of the two northern inlets. These vortexes are still present in 2019.

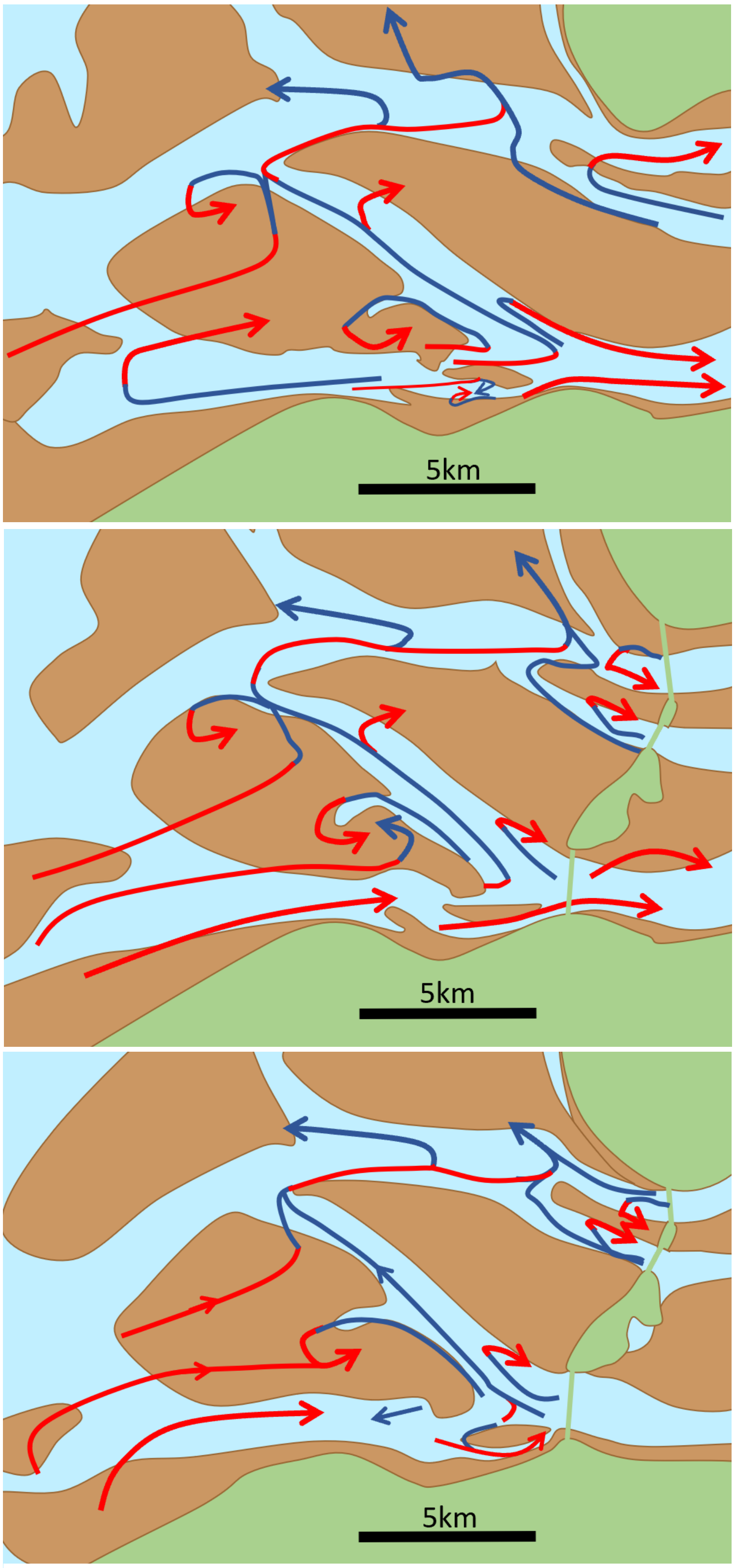


Figure 6.1: Schematization of the main ebb- and flood-dominant sediment transport trajectories in 1976 (top), 1988 (middle) and 2019 (bottom). The red and blue arrows indicate flood- and ebb-dominant transport pathways respectively.

6.1.2 Implications for the coast of Noord-Beveland

In the pre-barrier situation, a part of the Schaar van Onrust is ebb-dominant. This resulted in a sediment sharing cell directly in front of the coast of Noord-Beveland. Sediments are redistributed along this part of the coast but stay inside the cell boundaries. As the barrier caused the Schaar van Onrust to become entirely flood-dominant, the cell boundary shifted the boundary of the sediment sharing cell westward. This is indicated in Figure 6.2. Regardless of the bathymetry, the barrier always had this shifting effect on the cell boundary. With the 1976 bathymetry the westward movement of the cell boundary was biggest with about 3.5km (Figure 6.2A). The 1988 showed a westward movement of about 1.5km (Figure 6.2B). When we compare the pre- and post-barrier situation, we see a westward movement of about 2.5km (Figure 6.2C).

This shifting effect of the barrier on the sediment sharing cells indicates that sediments that previously stayed in front of the coast of Noord-Beveland are now redistributed further along the coast. In 1988, the trajectories extended into the basin, as the barrier did not yet block them completely. In 2019 this extend was reduced to the southern tip of the barrier.

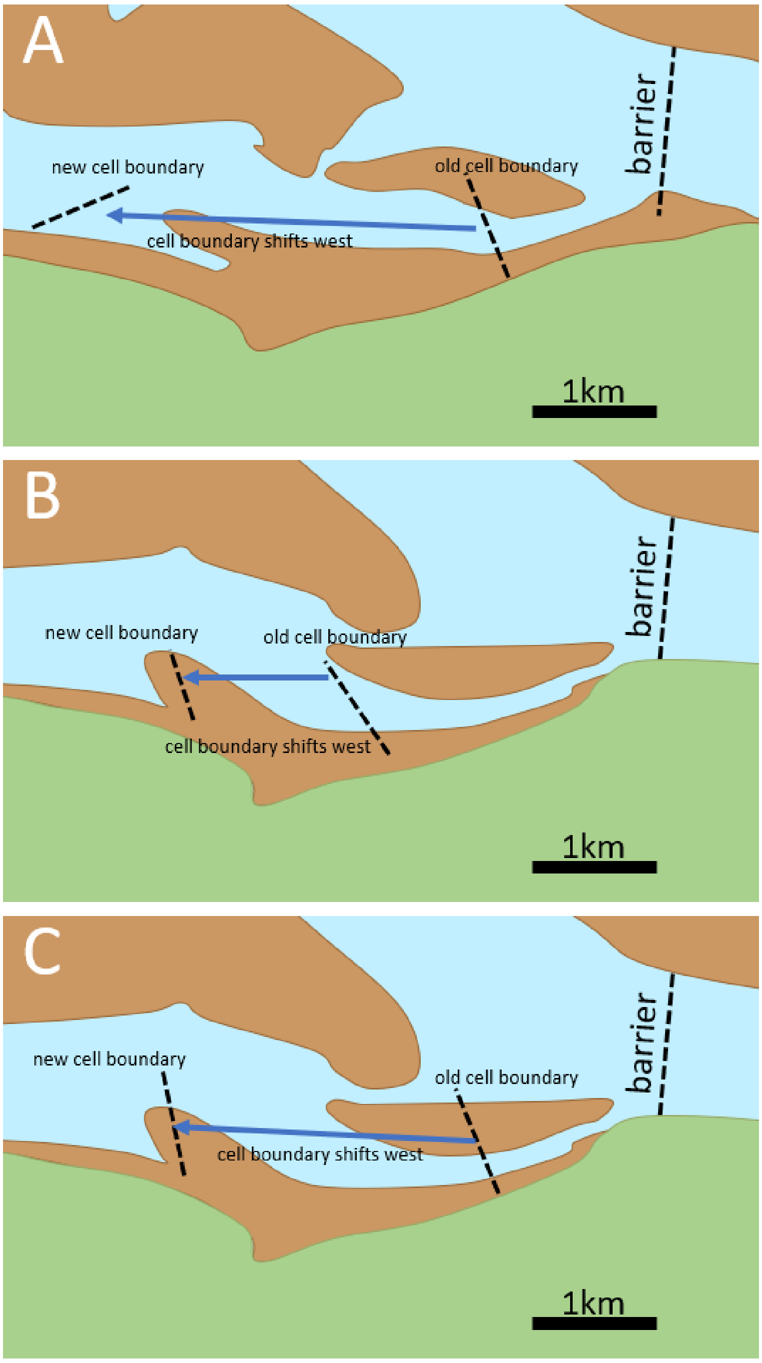


Figure 6.2: Schematization of the sediment sharing cell boundary shift along the coast of Noord-Beveland, with in A the 1976 bathymetry and B and C the 1988 bathymetry. In A and B the 'old cell boundary' represents the cell boundary without the barrier in place and the 'new cell boundary' the cell boundary with the barrier in place. In C the 'old cell boundary' represent the cell boundary with 1976 bathymetry without barrier and the 'new cell boundary' the boundary with 1988 bathymetry with barrier.

The bathymetry has a different effect on the cell boundaries. Without the barrier in place the 1988 cell boundary is about 1km west of the 1976 boundary (Figure 6.3A). With barrier however, the 1988 cell boundary is about 1.5km east of the 1976 boundary (Figure 6.3B). With the 1976 bathymetry, the flood-dominant character of the Schaar van Onrust extends along the coast, passed the shoal separating the Roompot Zuid and the Schaar van Onrust. With the 1988 bathymetry the sediment trajectories in the Schaar van Onrust no longer pass this shoal. This could be due to the fact that the southern part of the Roompot Zuid has become flood-dominant, increasing the volume of the shoal, and rotating it in such a way that sediment trajectories are no longer able to pass it.

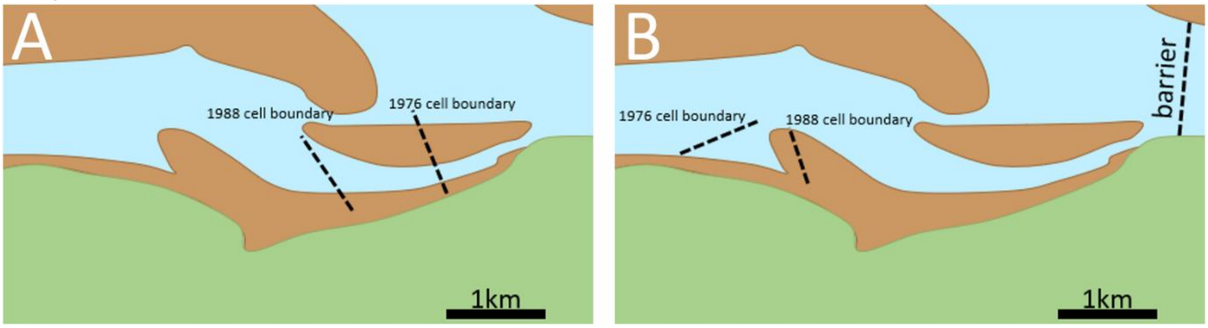


Figure 6.3: Schematization of the sediment sharing cell boundary shift along the coast of Noord-Beveland. A represents the cell boundaries in 1976 and 1988 without the barrier in place. B represents the cell boundaries in 1976 and 1988 with the barrier in place. Both images show the bathymetry of 1988.

6.1.3 Implications for coastal erosion

Close to the coast the barrier has a clear effect on the sediment pathways. The extended influence along the coast is an indication that the flood directed tidal currents have a stronger effect on the sediment along the coast because of the barrier. Because of the disappearance of the ebb-dominant part of the Schaar van Onrust, the area over which sediment is distributed along the coast has increased. It is likely that the ebb-dominant part of the Schaar van Onrust kept a larger part of the sediments available for the coast at that particular location. The disappearance of this sediment retaining force has therefore likely led to a sediment deficit at the coast, leading up to erosion.

6.2 Morphological interventions

To investigate the response of possible morphological interventions, four scenarios were compared, shown in Figure 6.4. When just the nourishment is applied, it mainly has an effect on the flood dominance on the north western side of the Onrust shoal. Without the nourishment sediments from this part of the shoal were delivered over the shoal towards the southern tip of the barrier, where the sediment trajectories from the Schaar van Onrust end up as well. The nourishment however causes a reduction in the strength of the flood current, as it limits the tidal volume through the channel. In the Schaar van Onrust, this does not lead to a regime change as it remains flood-dominant. The north-western tip of the Onrust shoal however becomes partly ebb-dominant, resulting in a sediment vortex in this location.

The removal of sediment results in concentration of sediment trajectories at the northern side of the Roompot-Hompels connection. It increases the flood dominance in the Roompot Zuid, where sediments are now being delivered to the Onrust shoal, from were they are being ejected north. The north eastern tip of the Onrust shoal has become more ebb-dominant. Sediments are being transported east along the shoal until they collide with the sediment trajectories from the Roompot Zuid. The response of the system to the removal of sediment seems to indicate that the artificially created connection of the Roompot Zuid and the Oude Roompot quickly accretes again and consistent connection of the two channels is not achieved. The Schaar van Onrust is still completely flood-dominant. The increased flood dominance in the Roompot Zuid also has an effect on the sediment trajectories in the Schaar van Onrust. These trajectories now extend further along the coast into the Roompot Zuid.

The combination of the two interventions shows a combination of effects of both interventions. The increased flood dominance in the Roompot Zuid caused by the removal of sediment is still present. However, sediments from the north western side of the Onrust shoal are not being transported north, due nourishment in the Schaar van Onrust. Sediments coming in from the southern part of the Roompot Zuid are now trapped in the sediment vortex at the northern western side of the Onrust shoal. Further east of this location, sediments are still being delivered to the dredged area.

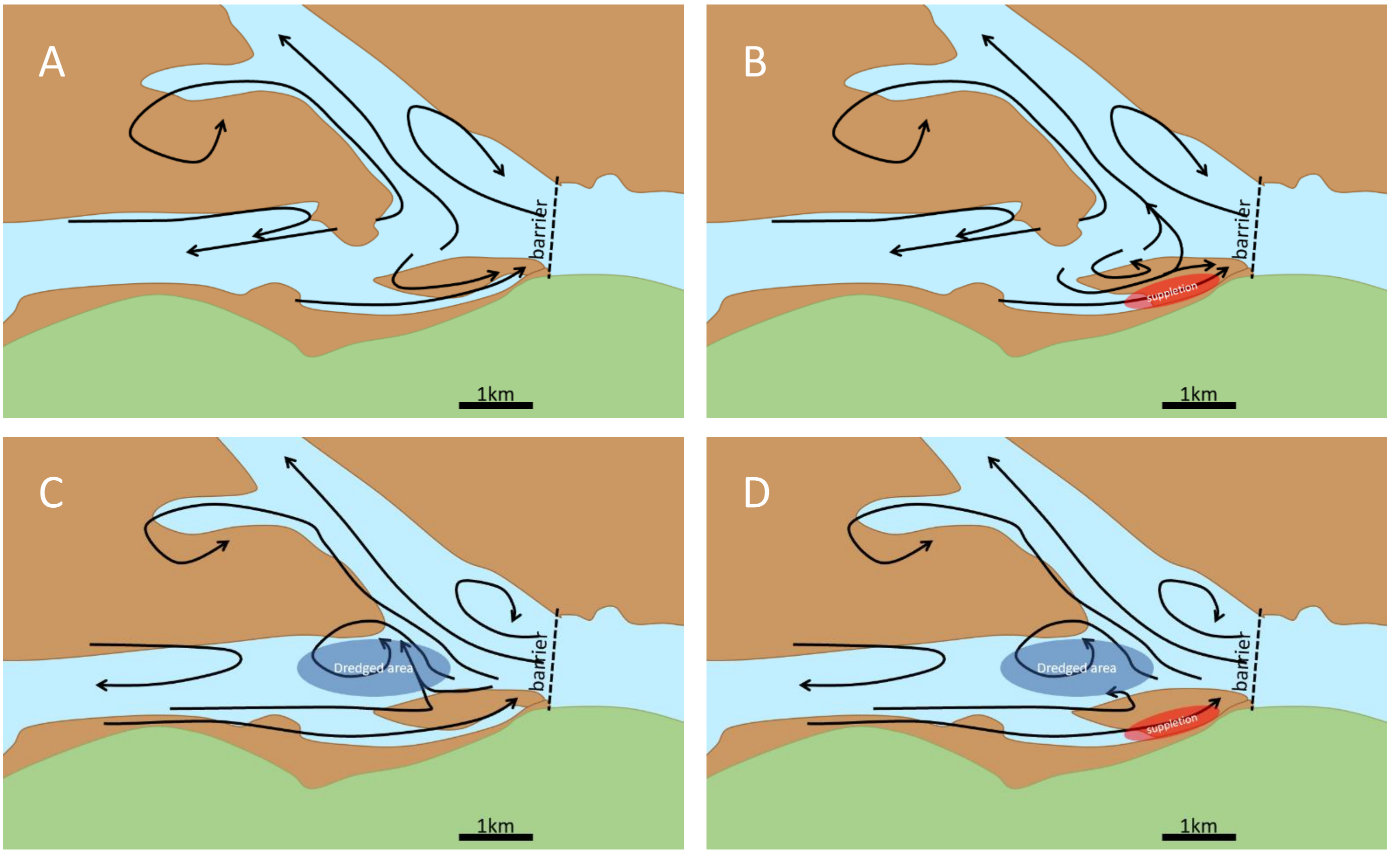


Figure 6.4: Schematization of the main sediment trajectories in different scenarios. A represents the sediment trajectories with the original 2019 bathymetry. B represents the sediment trajectories with a nourishment in the Schaar van Onrust. C represents the sediment trajectories with the removal of sediment from the Roompot-Hompels connection. D represents the sediment trajectories with both the nourishment and the removal of sediment.

7 Conclusion and recommendations

7.1 Conclusion

The objective of this research was to obtain a better understanding of the influence of the Eastern Scheldt barrier on the sediment transport pathways on the ebb-tidal delta, with the aim of using this knowledge for future coastal. This was done using a set of specific sub-questions which will be discussed in this section.

1. What were the sediment pathways just before the construction of the barrier?

Before the construction of the barrier, continuous pathways from the south and north side of the Roompot inlet enter the basin. The pathways emerging from the north side of the location of the basin inlet follow a path outward due to ebb-flow and back in due to flood, forming a vortex at this location. Part of the pathways pass the inlet and are transported further into the basin. At the south-east side of the Oude Roompot, pathways are entering the basin as well. These pathways stretch from along the coast, through the Schaar van Onrust to the inlet, starting from approximately Transect 280, marking the boundary of two sediment sharing cells. Further along the coast, in front of the former inlet of the Veerse Meer another sediment sharing cell is identified, reaching from Transect 280 to approximately Transect 800. This part of the channel is partly ebb-dominant, and partly flood-dominant. Within this cell the converging sediment pathways indicate the forming of a shoal. The ebb-dominant Roompot Zuid has pathways directed seawards until they are picked up and recirculated back in shore-parallel direction towards the shallower Hompels area, by the flood-dominant current that is present north of the channel. From the shallow area between the Roompot and the Roompot Zuid part of the pathways are redirected to the Hompels through ebb-chute of the Oude Roompot. From the shoal Onrust the majority of the pathways are directed to the ebb-dominant middle of the Oude Roompot back to outwards. From the southern tip of the shoal Onrust sediment is directed into the basin. On a larger scale the pathways on the shoals on the southern half of the ebb-tidal delta are mainly directed in north-east direction (flood-dominant), whereas the pathways on the northern shoals are directed north (ebb-dominant). Pathways starting from the inlet entrance of the Geul van de Roggeplaat are directed outwards (ebb-dominant), and then back inwards through the Hammen (flood-dominant).

2. What were the sediment pathways just after the construction of the barrier?

At the north side of the Oude Roompot, close to the barrier, sediment pathways have diverted. No pathways are passing the barrier at this point anymore. The vortex still exists, however sediment pathways don't extend from the vortex back into the basin anymore, creating a separate sediment-sharing cell. At the south side of the barrier, pathways are still crossing it into the basin. The reach from which pathways extend across the barrier has been significantly increased with respect to the pre-barrier situation. This is due to the disappearance of the ebb-dominant part of the Schaar van Onrust. The divergent cell boundary present at Transect 280 moved along the coast past the former inlet of the Veerse Meer to approximately Transect 600. Also a much bigger part of the shoal Onrust, which has moved towards the coast, is part of the sediment sharing cell with pathways reaching into the inlet. From the shallow area between the Roompot and the Roompot Zuid pathways are still directed to the Roompot, either seawards or through the large vortex back to the Hompels area. The Roompot Zuid has become flood-dominant and formed a new sediment sharing cell, with pathways converging at the height of the former inlet of the Veerse Meer. This cell stretches all the way to the southern edge of the domain.

At the two northern inlets, a divergent boundary has formed at the location of the barrier. The Hammen has become partly ebb-dominant, and the Geul van de Roggeplaat partly flood-dominant. In front of both inlets a vortex was formed leaving two separate sediment sharing cells. The main channels are still the main channels. The increased strength of the flood-dominant character in the Westgat channel causes the ebb-dominant sediment trajectories originating from the Hammen and the Geul van de Roggeplaat to end up closer to the coast. The length of the pathways in ebb direction have shorted, induced by the dissipation of energy of ebb flow due to the barrier.

3. What are the sediment transport pathways under present day average conditions (~30 years later)?

The most dramatic changes in sediment pathways are at the coast of Noord-Beveland and around the barriers. At the north side of the Roompot inlet the situation is still similar, with the barrier acting as a divergent boundary for the pathways. In the northern part of the Oude Roompot a combination of ebb-and flood dominance still causes a sediment vortex. At the south side of this inlet the barrier now also acts as a boundary for the sediment cells, with no pathways crossing the barrier anymore. This is most likely due to the scour holes being fully developed near the barriers. In front of the coast of Noord-Beveland a sediment sharing cell has formed that stretches from the barrier to well past the former inlet of the Veerse Meer to approximately Transect 600, as the entire Schaar van Onrust is still flood-dominant. The ebb chute from the Roompot has rotated a little bit more seaward. The north east side of the Roompot Zuid has become ebb-dominant, however the largest part of the channel is still flood-dominant. An ebb-dominant sediment trajectory from the north side of the shoal Onrust is transporting sediment towards the Schaar van Onrust, where the flood-dominant channel transports the sediment towards the southern tip of the barrier and the south-south eastern side of the shoal Onrust.

4. How did the changes in the morphological system lead to erosion at Noord-Beveland?

The disappearance of the ebb-dominant part of the Schaar van Onrust has made the entire channel flood-dominant. Therefore the sediment retaining function of the partial ebb-dominance in the channel disappeared as well, likely resulting in a sediment deficit in this part of the coast. The sediment in front of the coast of Noord-Beveland is therefore distributed over a larger part of coast, without additional sediment trajectories entering the area. This is a direct consequence of the barrier itself, not just due to bathymetric changes. The location of the boundary of the sediment sharing cell stays roughly at the same location up until present day (2019).

The shoal the Onrust has also moved to the coast. This has pushed the Schaar van Onrust into the coast as well, causing coastal erosion. The movement of this shoal is also reflected in the pre-barrier situation where sediment pathways are converging to the post-barrier location of the shoal (the sediment vortex induced by the ebb-dominant part of the Schaar van Onrust).

5. Based on this, what would be needed to redirect the tidal current through the Roompot-Homples?

A large channel connection between the Roompot and the Roompot Zuid as well as a nourishment in the Schaar van Onrust were tested. The nourishment reduced the flood-dominant character at the northern part of the Onrust shoal, resulting in concentration of sediment trajectories here. This reduction of flood dominance likely reduces erosion at the coast, but it does not create a connection between the Roompot Zuid and the Oude Roompot as the Hompels-Roompot connection is relatively unaffected. The removal of sediment from the Roompot-Hompels connection also does not indicate that a stable connection is achieved. The sediment pathways seem to indicate that the system is quickly changing back to the original bathymetry, filling up the dredged area and re-forming the former shoal at the Hompels. A similar result is achieved when the interventions are combined. Therefore a redirection of the current using these intervention seems unsuccessful.

7.2 Recommendations

To keep the shoreline of Noord-Beveland sufficiently wide, Rijkswaterstaat needs to nourish the beach and foreshore on a regular basis. In this study an attempt was made to get a better understanding of the system and explore possible interventions to minimize future nourishment requirements. In the past real life experimental dredging and nourishments have been done with the aim to redirect the current from the Schaar van Onrust to the Hompels-Roompot to reduce erosion at the coast of Noord-Beveland. These experiments were however not successful as a full connection between the Roompot and the

Roompot Zuid never established. In this modelling study, such a solution was further explored. By combining a large nourishment in the Schaar van Onrust with a the removal of a large amount of sediment from the Roompot-Hompels, an attempt was made to redirect the current. When we analyse the sediment pathways the Roompot-Hompels still appears to block the sediment. The removal of sediment causes the sediment transport patterns to converge into the dredged area, suggesting deposition. At the Schaar van Onrust the sediment seems to be redistributed along the coast. The amount of sediment that was removed and supplied in the model was relatively high. To realize such a an intervention in real life would consequently be accompanied with high costs. Since the results do not indicate that the system is substantially changed, as the Hompels-Roompot connection does not hold, such a solution would be ineffective. Alternatively, nourishing the beach regularly as is currently done, is a more suitable solution.

One improvement for future research on the model could be to incorporate multiple sediment fractions in the analysis. This would increase the realism and accuracy of the model by taking into account the different characteristics and behaviors of different sediment types. Additionally, the impact of waves could be incorporated as well in future research. In this study the impact on the tides was investigated, however for sediment transport waves play an important role as well. Lastly, the morphological tide was based on a visual comparison between the sediment vector fields of individual tidal cycles and the average sediment vector field. Other options include a statistical comparison of transport across a large number of cross-sections in the model area, or a mathematical comparison of the direction and magnitude of the transport vectors.

The converging and diverging zones that were distinguished in the results of SedTRAILS were now found manually. In some cases the boundaries of these areas were rather straightforward, however in other cases they were rather arbitrary. A more consistent method to identify sediment sharing cells would be helpful. Also, the current version of SedTRAILS does not tell anything about the volumes of sediment. If we could quantify volumes this could help analyse the evolution of the studied area.

Around the world more human interventions are expected to be implemented in coastal regions in the coming decades. An example of this is the recent developments in the plans for a storm surge barrier in New York. Investigating the impact of such interventions, like was done in this study, before the construction can help to estimate the effects on the coastal zones and prevent problems related to such interventions. Analyzing the sediment pathways using SedTRAILS can help to identify the kind of changes interventions can have in the system. Where there are large changes in sediment pathways one may expect significant morphological changes. Although SedTRIALS cannot be used to volumetrically quantify such changes yet, it can be used to locate were big changes can be expected to help respond to and avoid those changes.

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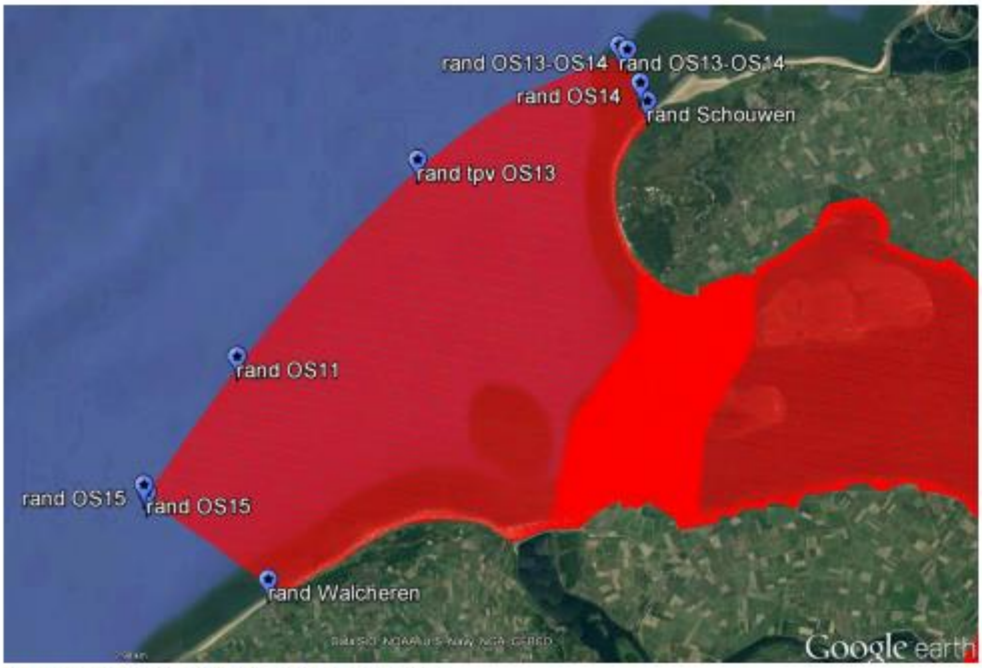
Appendix A

Locations of the measurement stations used in the model. From (Tiessen et al., 2019).

Tabel 4.1 Coefficienten voor afleiden randvoorwaarden voor WAQUA-ScalOost (persoonlijke communicatie met Piet Lievense, RWS-ZD)

Lok	m2-amp	m2-fas		Lok	m2-amp	m2-fas
OS11	132.30	120.4	→	scop1	140.20	117.7
OS11	132.30	120.4	→	scop2	138.40	112.4
OS11	132.30	120.4	→	scop3	138.40	112.4
OS11	132.30	120.4	→	scop4	132.30	120.4
OS11	132.30	120.4	→	scop5	120.50	126.9
BG2	108.30	130.1	→	scop6	112.50	135.6
OS14	119.30	135.2	→	scop7	116.20	135.8
OS14	119.30	135.2	→	scop8	118.20	136.1



Figuur 4.3 Locaties van de open randvoorwaarden

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