BROUWERSDAM

Morphological analysis of the beach at the Brouwersdam

Master Thesis Report

Section of Coastal Engineering
TU Delft

Final Version
21-07-2013

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Morphological analysis of the beach at the Brouwersdam

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Document	: Main Report
Status:	: Final
Version	: v11
Date	: 21-07-2013
Location	: Middelburg / Zoutelande

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Summary

This thesis focusses on the north-eastward shifting beach at Brouwersdam, which poses a problem for users and stakeholders of the beach. This trend is likely to continue in the foreseeable future and could result in a beach that can no longer fulfil its current functions, like recreation and tourism.

Analysis of bathymetric data from the last decades shows that the systems of the Oosterschelde, Grevelingen and Haringvliet are not in equilibrium, the Delta Works have changed hydrodynamic forcing of the system drastically. As a result, the system is transforming to a new equilibrium, a process that isn't completed yet, nor will it be soon. The time scales of processes like these are in the order of centuries.

For the area around the Brouwersdam the result is that the former ebb-tidal deltas of the Grevelingen and the Oosterschelde are pushed shoreward due to the reduced tidal forcing, therefore wave forcing is becoming more dominant. The former shoals Middelplaat and Kabbelaarsbank were pushed against the Brouwersdam and now form the beach there. Over the last decade, the amount of sediment that is lost in the south-western part of the beach is estimated at around 75,000 m^3 per year and the amount of dry beach is getting smaller.

A morphological model of the area was made to replicate the developments over the last and for the next decade using the SWAN and UNIBEST models. The model set-up consists of a wind- and wave analysis over the last three decades that has been schematized into different wind and wave classes and different tidal conditions, for two different bathymetries (2000 and 2010).

The models are able to reproduce the trend, with dominant southwesterly winds and a beach that shifts to the northeast, but the quantities are different from observations. These differences could be the result of the complex flow patterns in the area. The incoming flood current flows from southwest to northeast and stays close to the Brouwersdam and the beach, while the ebb current stays on the outside of the area and flows in opposite direction. The result is a flood dominated flow pattern along the beach, which has its influence on the dominating transport direction and the models aren't able to replicate this process correctly.

In the near future the characteristics of the system are about to change again. There are plans under development to construct a tidal power plant or an inlet sluice in north-eastern part of the Brouwersdam, which means reintroduction of tidal motion in the Grevelingen. A decision on what solution will be chosen is expected before the end of 2014 and should be up and running in 2020.

There are a lot of different possibilities for the beach; beach nourishments, the construction of a tidal power plant and eventual compensatory measurements will have a profound effect. How the beach will look like in a decade from now is largely up to the responsible (governmental) parties involved, all possible scenario's should be carefully evaluated and it is stressed that cooperation between these parties is vital to find a satisfying solution.

1 Introduction

The subject of this MSc thesis is the beach at the Brouwersdam, located on the border of the provinces Zeeland and South Holland in the Netherlands. The beach is a popular destination for beach recreation and extreme sports like kite buggying and wind- and kite surfing. The beach is shifting north-eastwards and the area of dry beach is getting smaller. When this trend continues, it will lose its functions and might disappear in the future. In this thesis, the problem will be analysed and possible solutions will be reviewed.

This research is carried out at Rijkswaterstaat Zee en Delta in Middelburg in the scope of the Delta Programme, subproject Coast and in collaboration with the municipality Schouwen-Duiveland.

1.1 Project Location

The Brouwersdam is located on the border between the provinces of Zeeland and Zuid-Holland in the south-western part of the Netherlands. The Brouwersdam is a man-made structure damming the former estuary Grevelingen. The largest city in the area is Rotterdam, just fifty kilometres away. Closer to the project location are the villages of Ouddorp, Scharendijke and Renesse, the latter two are the busiest tourist villages in the area and both are located in the municipality Schouwen-Duiveland.

About midway on the Brouwersdam, on the North Sea side, you will find the beach, the main subject of this thesis. The beach is facing the North Sea and therefore subject to its tide, currents and waves. On the east side of the Brouwersdam, you'll find lake Grevelingen, the largest salt water lake in Europe.

Figuur A – Overview map Brouwersdam (Microsoft Bing Maps, 2010)

1.2 Problem description and objectives

The main problem that will be investigated in this thesis, is the ongoing north-eastward migration of the beach at the Brouwersdam. The main objective of this research is to give insight in the problem and evaluate possible solutions. To achieve this, a number of questions will be addressed.

- What is the present-day importance of the Brouwersdam?
- What are the morphological characteristics and developments of the Brouwersdam area in the past and present?
- What are the future morphological developments in the area?
- Which solutions are possible to address the problem of the shifting beach?
- Which other developments play a role when finding a solution?
- What is the best solution for this problem?

2 Brouwersdam, past and present.

In this chapter, a short overview of the Brouwersdam will be given. It treats its reason of existence, its importance for the region and the activities that take place there.

2.1 Brouwersdam, part of The Delta Plan

The south-western part of the Netherlands is a region that made international fame with the construction of the Delta Works. Even declared as one of the seven wonders of the modern world by the American Society of Civil Engineers, these hydraulic constructions protect large parts of the provinces of Zeeland, Zuid-Holland and Noord-Brabant from flooding.

The event that led to the construction of the Delta Works was the catastrophic Flood Disaster of 1953. A heavy north-western storm combined with spring tide led to a very large storm surge on the North Sea. This storm surge propagated into the tidal basins in Zeeland and Zuid-Holland. The dikes in this area were too low and too weak to withstand high water levels and waves. This observation was already made in the thirties, but due to a lack of funds and the intervening Second World War, these dikes were never raised and reinforced. The tragic result was that the dikes couldn't withstand this storm surge and collapsed. The damage was extensive, large parts of the south-western part of the Netherlands were flooded. This disaster claimed the lives of 1836 people, while over 100.000 people lost their homes and property.

After this disaster, it was decided this should never happen again. The Delta Plan was made, the estuaries Haringvliet, Grevelingen and Oosterschelde would be closed off from the North Sea. This would result in considerable shortening of the shoreline, making it easier to defend the land from the sea.

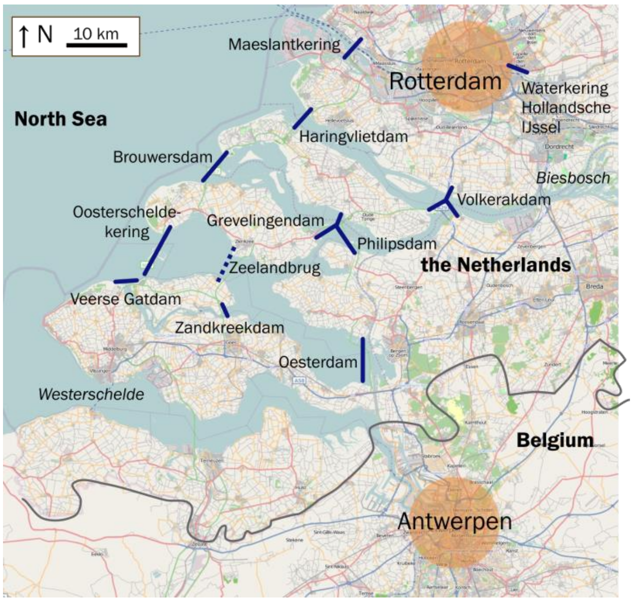


Figure 2.1 - Overview Delta Plan (Wikipedia, 2013)

The seventh project in this series of constructions was the Brouwersdam, which closed off the Grevelingen estuary. The dam itself was completed in 1971, although later a drainage sluice was installed in the dam, which was ready in 1978.

The Brouwersdam connects the former islands of Schouwen-Duiveland and Goeree-Overflakkee. The trajectory of the dam was chosen in such a way that it would cross the Grevelingen over the former ebb-tidal delta, to minimize the amount of materials needed. Large parts of the dam were constructed on the shoals Middelplaat and the Kabbelaarsbank, as can be seen on the overview of possible trajectories in Figure 2.2, the chosen alternative is trajectory I.

When the infrastructure on top of the Brouwersdam was completed in 1973, these shoals became accessible to the public. The shoals got a new function and became a beach. This has become a popular destination for beach tourists and for extreme sports like wind and kite surfing.

The tidal system of the Grevelingen was completely changed and not in equilibrium anymore. As a result the whole system began to change. The former shoals were pushed ashore and the former tidal channels Kous and Brouwershavense Gat were filled up with sediment.

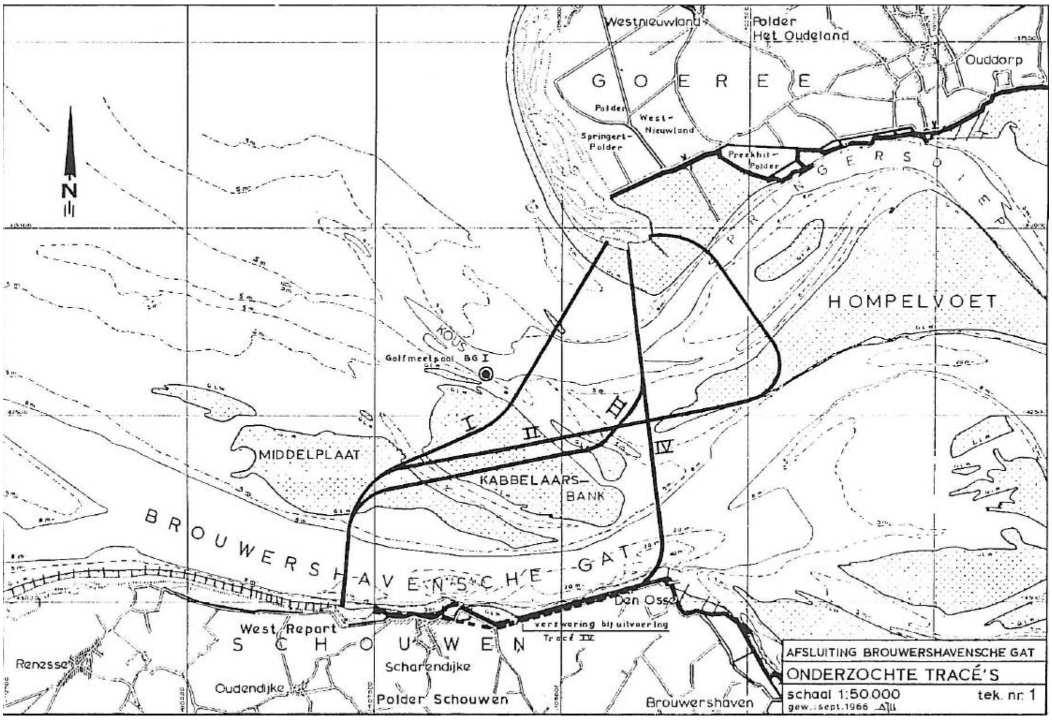


Figure 2.2 - Overview possible trajectories Brouwersdam (Rijkswaterstaat, 1966)

This process isn't completed yet nor will it be soon. It takes a very long time till a new equilibrium is reached. One of the consequences of the system trying to find its new equilibrium is beach erosion. The beach is shifted to the north-east and elongated. The available (dry) beach is getting smaller and it will lose its function if erosion persists. From the point of view of its users and stakeholders this is an unwanted development.

2.2 Beach at the Brouwersdam

The beach at the toe of the Brouwersdam is a fairly long beach, the distance from the dune foot to the low waterline is a few hundred meters, although the biggest part of the beach gets flooded at high tide. The actual dry area is quite small, as can be seen in Figure 2.3. This picture is taken from the northern part of the dam, looking in southern direction.

Figure 2.3 - Situation Beach (October 2012)

In the background of this picture, two beach pavilions can be discerned: De Kous on the left and Natural High on the right. These pavilions are quite large enterprises, with floor areas of around 1200 m^2 each and both house a sport shop, restaurant and a large terrace. The third pavilion was located more southward, but due to the ongoing shift of the beach in north-eastern direction it had to close its doors. It has been relocated to a different beach a few kilometres away: Noorderstand, also in the municipality of Schouwen-Duiveland. This isn't the success the owner hoped for, his business is losing money now. The owners of the two remaining pavilions also fear that their businesses will have to move in the near future because of the ongoing shift of the beach.

The beach itself is used for a number of activities: (beach) recreation, kite buggying and kite and wind surfing. The number of visitors is estimated at 200,000 per year (ZKA Consultants & Planners, 2007). The majority of the visitors go to the beach during summer season, although the season for sporting activities is a bit longer. The picture on the next page (Figure 2.4) was taken in October 2012 and shows a significant number of kite surfers.

Figure 2.4 - Sports Activities around the Brouwersdam (October 2012)

2.3 Area around the Brouwersdam

At the other side of the Brouwersdam, on the side of Lake Grevelingen, there is a large holiday park: Center Parks Port Zélande. This park spans an area of 27 hectares and consists of 700 vacation houses and a large camping. The park itself has all kinds of facilities, like restaurants, shops and a subtropical swimming pool. The number of overnight stays per year is about 800,000 (ZKA Consultants & Planners, 2007).

Also part of the park is marina with more than 800 berths. Figure 2.5 gives an overview of the marina, in the upper right corner you can see the beach, located exactly on the opposite side of the dam. This picture is made in 2008, so in the present day situation, the beach shifted a few hundred meters north-eastwards, moving away from the main road that leads park guests to the beach.

The total economic contribution of the Brouwersdam is estimated at € 46 million per year, making it an important contributor to the area. The contribution of the beach itself is only a smaller part of this figure, however, it is a pillar in the recreational package of the area and further decline of its quality could have its effects on the region as a whole.

Figure 2.5 - Overview Marina Port Zélande (www.centerparcs.nl, 2008)

3 Background information coastal systems

This chapter will give a short overview of the different processes that play a role in the morphology of coastal systems. The focus will be placed on the parts that are important to understand the systems in the south-western part of the Netherlands.

3.1 Tidal inlets

The drowned river valleys or tidal inlets that make up the deltaic systems in the south-western part of the Netherlands are wide at the coast. Large volumes of water enter and leave each tidal cycle, with little or no inflow of river water. This tidal flow carries sediment in and out of the tidal basins, the sediment settles when flow velocities diminish. On the outer edges of the ebb-tidal delta the sediment is pushed shoreward by wave action. The combination of these two processes is the main driving force that shapes the delta coast. The relation between river discharge, waves and tides is a classification made by Galloway (Galloway, 1975) and can be refined further for a situation with tidal inlets with little or no river influence like the Dutch delta coast.

This classification is based on the mean tidal range and the mean wave height (Davis and Hayes, 1984) and is shown in Figure 3.1 (Elias, 2006). It provides a tool to get insight in the dominating force for a given tidal inlet with parameters that are relatively easy to determine.

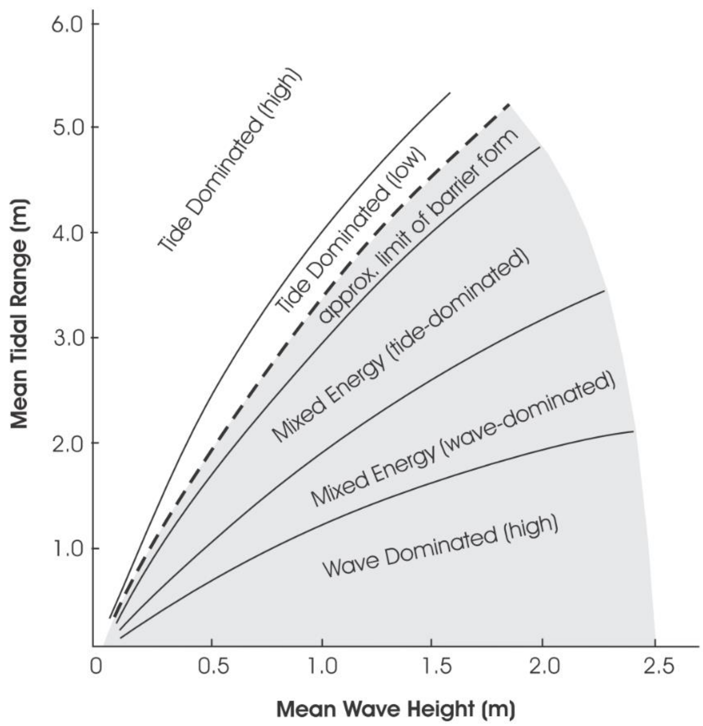


Figure 3.1 - Tidal range vs. wave height (Elias, 2006)

The dashed line in this figure represents the limit for barrier island formation. Above that line the tidal forces dominate and barrier islands aren't formed. It's important to notice that with small values for tidal range and wave height, the lines converge. The result of this is that different types of inlets may occur with little difference in wave or tidal parameters.

The classification on tidal range vs. wave height is a useful property for understanding the morphodynamics of the Dutch delta coast. Man-made changes like the closure of tidal inlets have a big influence on the characteristics of the system, which could result in a shift in the system to a different class, for example from a tide dominated to wave dominated system. Another important aspect is to notice is that a large tidal range not necessarily means that a large tidal delta will develop. There is however a positive relation between the size of the ebb-tidal delta and the tidal prism of the inlet gorge, that relationship was already established (Walton and Adams, 1976). As logical as it may seem, no direct relation is found between the tidal range and the tidal prism.

The relation that was found between the size of the ebb-tidal delta and the tidal prism can be described by the following empirical formula: $V_0 = c \cdot P^{1,23}$

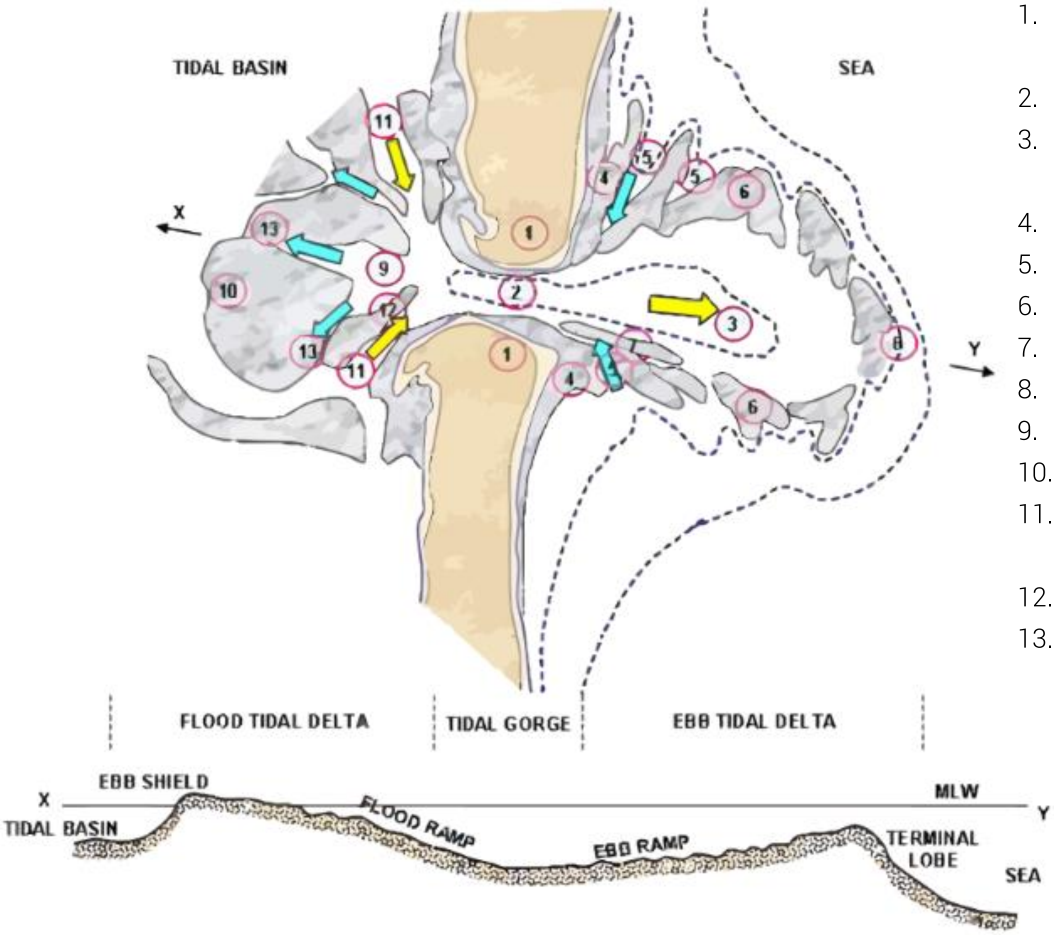
with V_0 the sand volume of the ebb-tidal delta in cubic meters, c is an empirical constant and P is the volume of the tidal prism in cubic meters. between the tidal range and the tidal prism. Changes in hydraulic forcing, leading to a change in tidal prism lead to a new equilibrium situation. When the constant in this formula for a given tidal inlet is known, it is possible to make predictions about the future development of the ebb-tidal delta.

3.2 Layout of a tidal delta

A tidal delta is made up out of a large number of different features, some have been discussed already, others will be discussed in the following parts of this chapter. In the next paragraph an overview of the layout of a tidal delta is given and a brief description of the different features is given. Figure 3.2 provides an overview of a tidal delta.

<u>1.Coastal barrier or spit headland:</u>
The two opposing landforms between which the tidal inlet is situated.
<u>2. Tidal gorge</u>
The part of the tidal inlet between the two opposing landforms, the narrowest part of the tidal inlet system.
<u>3, 5, 11. Ebb- and flood channels</u>
As a result of the in- and outflowing tide, tidal channels will develop over time. Due to the lower water levels during the ebb stage of the tide, the ebb flow will concentrate itself in the main channel. This results in a relative deep ebb channel, oriented perpendicular to the shoreline. Flood will flow in along the flanks of the shoreline, creating relative shallow flood channels.
<u>4. Swash platform</u>
Wide sediment plateau between tidal gorge and ebb terminal lobe or barrier islands.

6. Marginal shoals
Also called swash bars, smaller depositions of sediment on the swash platform created by wave action. These bars tend to move shoreward.
7. Ebb-tidal levee
Also called channel margin linear bars, sand bars parallel to the main ebb channel.
8. Ebb delta terminal lobe
The most distal part of the ebb-tidal delta, where sediment accumulates due to decreasing ebb flow velocities.
9. Flood ramp
Landward inclining bottom slope over which the main flood current is directed.
10. Ebb Shield
The most distal part of the flood-tidal delta, where sediment accumulates due to decreasing flood flow velocities.
12. Ebb spit
Spits created by the ebb-tidal flow, creating a division between the ebb dominant inner channels and the spill-over channels
13. Spill-over channels
Bifurcating channels in the ebb shield created by the inflowing tide.



1. Coastal barrier or spit headland
2. Tidal gorge
3. Main ebb channel and ebb ramp
4. Swash platform
5. Marginal flood channels
6. Marginal shoals
7. Ebb-tidal levee
8. Ebb delta terminal lobe
9. Flood ramp
10. Ebb shield
11. Main ebb dominated inner channels
12. Ebb spit
13. Spill-over channels

Figure 3.2 - Overview Tidal Delta (Smith, 1984)

3.3 Tidal Propagation in the North Sea

The tidal flow enters the North Sea from the Atlantic Ocean in the north and the Dover Straight (*Nauw van Calais*) in the south. This tidal wave is generated by the combined forces of the moon and the sun (and other smaller components) and has its origin in the Pacific Ocean. It takes two days for the tidal wave to propagate into the North Sea. This is also the reason why spring and neap tides happen two days after full or new moon, when the forcing of the moon is respectively at its peak and its nadir.

As the tidal waves enters the basin, it has the characteristics of a surface Kelvin wave. The mechanism and properties of the Kelvin wave can be illustrated by considering a horizontally propagating Kelvin wave in a rotating fluid of uniform finite depth, where the depth is small compared to the horizontal extent of the fluid, like a coastal shelf sea such as the North Sea. The depth of this sea is a lot smaller than the extend of the basin, therefore the fluid rotates due the rotation of the Earth. Such an idealized model is referred to in geophysical fluid dynamics as a shallow water model

The shape of the wave in the longshore direction is arbitrary and is conserved as the wave travels. This implies that the surface Kelvin wave is non-dispersive, and that the wave energy is transmitted at the speed of the shallow water gravity wave (Wang, 2002).

This Kelvin wave is pushed against to the coast and rotates in counterclockwise direction in the Northern hemisphere. The surface elevation of the wave increases with the distance from the origin. This origin is called an amphidromic point, the North Sea has three of these points, as can be seen in Figure 3.3.

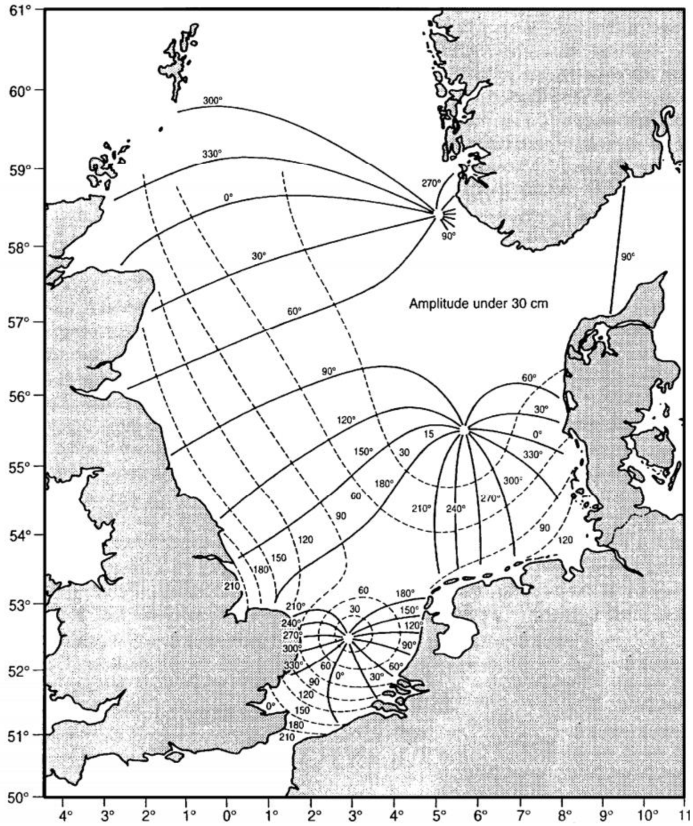


Figure 3.3 - Amphidromic systems in the North Sea (Dyke, 2007)

As a result the tide travels from south-west to north-east along the Dutch coast. In the southwest the amplitude of the wave is at its highest since the distance to the amphidromic point is larger there. For the Dutch delta coast this results in smaller amplitudes when the Kelvin wave travels northeast. This means that the tidal amplitude is the largest at the entrance of the Westerschelde and the smallest at the Haringvliet. Note that this is only true for the wave at the mouth of the estuaries, the propagation of the wave inside a basin can be different due to basin geometry (basin length, depth, resonance).

4 Morphological developments Grevelingen Delta

Figure 4.1 shows the situation of the south-western part of the coast of the Netherlands, the Delta Coast. The map below shows the area around the year 1900 and shows a system that is made up out islands, tidal basins and estuaries. A map that looks completely different nowadays. After the catastrophic flooding of 1953, the system has undergone a number of changes because of the gradual completion of a series of constructions to prevent such flooding would ever happen again: the Delta Plan. Large parts of the system are (partially) closed off from the sea, resulting in major changes in the characteristics of the system. This has resulted in morphological changes, as well on the outer deltas of the system as inside the basins. These changes are still going on, the system is still adapting to these changes and trying to find a new equilibrium. This is a slow process and it can take a few hundred years till a new equilibrium is found. In this chapter the morphological changes of the outer delta of the Grevelingen and its the surroundings systems are discussed. The morphological changes of the beach at the Brouwersdam, the main topic of this thesis, will be treated in the next chapter.

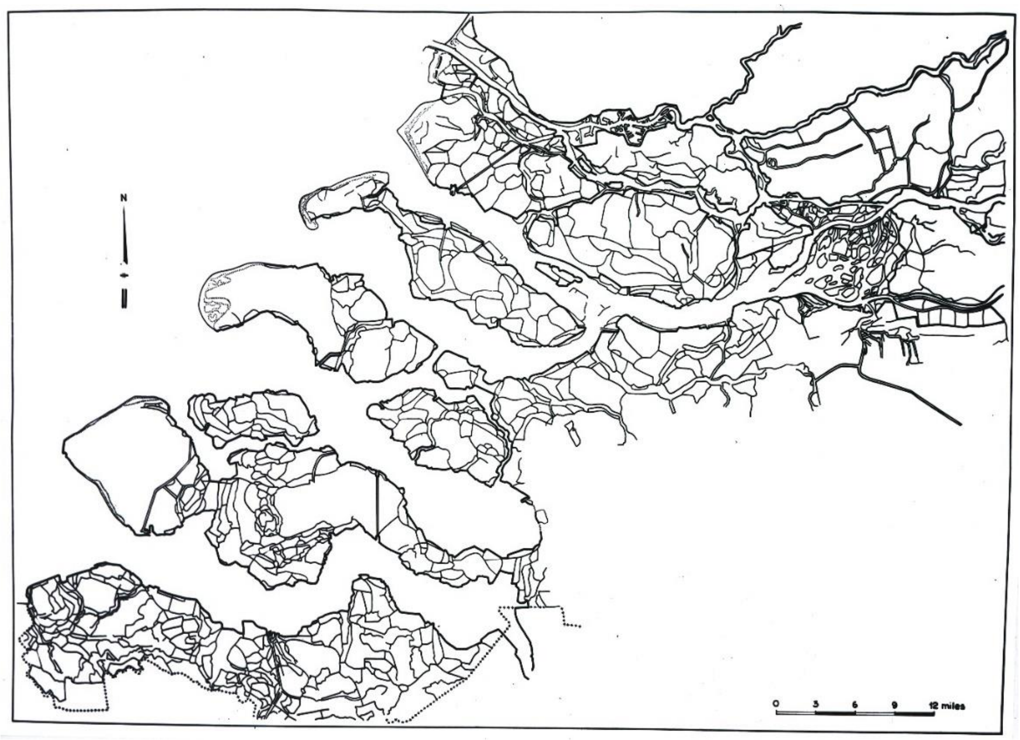


Figure 4.1 - Dutch Delta Coast around 1950 (Rijkswaterstaat Beeldbank)

4.1 Grevelingen before closure

A few years before the first human intervention in the Grevelingen tidal basin, it had a tidal prism of approximately 370 million cubic meters (Van Den Berg, 1987). In size it was about the same as the Haringvliet, but quite a bit smaller than the Oosterschelde and Westerschelde that have tidal prisms of over one billion cubic meters. By then the tidal prism was already smaller than it had been before, over the period 1933-1959 a decreasing trend was observed. The tidal prism of the Oosterschelde was increasing at the expense of the Grevelingen and its tidal prism was already reduced by about 20%. These changes had natural causes but were also influenced by human interventions in the surrounding tidal basins. The decreasing tidal prism shall have yielded a reduction in the size of the ebb-tidal delta (Van Der Spek, 1987).

The first major human intervention in the Grevelingen basin was the construction of the Grevelingendam, closing off the landward side of the basin in 1965, reducing the tidal prism by another 14%. The two main channels, Brouwershavense Gat and Springersdiep, deepened due to increased flow velocities in the basin (Haring, 1978).

The picture below (Figure 4.2) was obtained from the digital archive of the Province Zeeland and gives an overview of the Grevelingen in the year 1959, a few years before the start of the construction of the Brouwersdam that closed of the inlet. The picture is composed of 50x50 cm vertical aerial photos. Above the North Sea the data is incomplete, probably because it served little purpose to make these kind of photos for areas that far offshore.

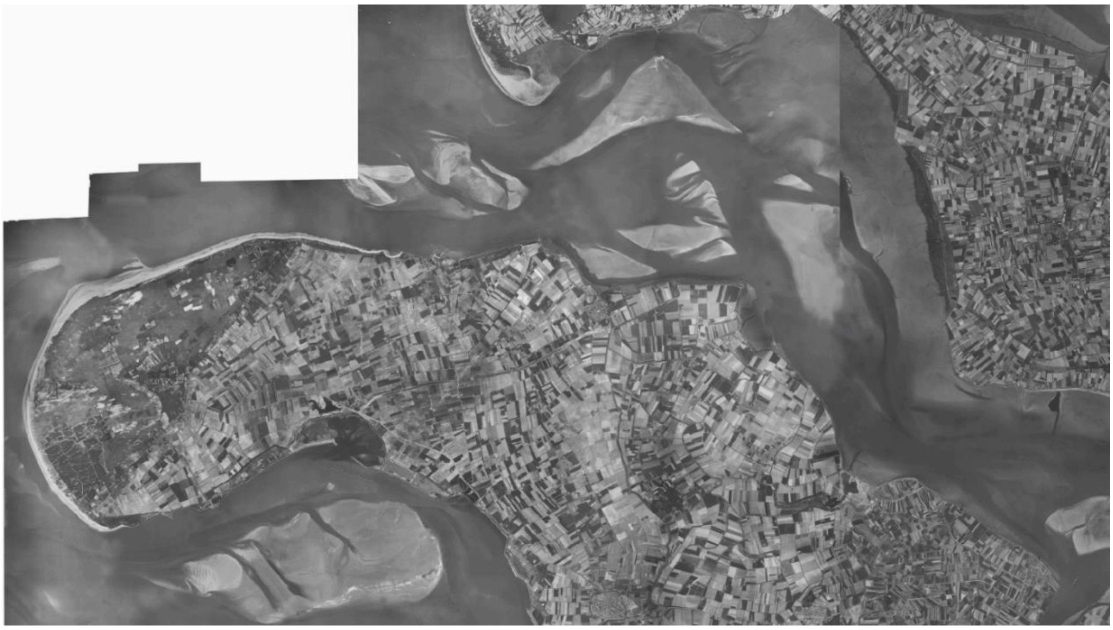


Figure 4.2 - Overview Grevelingen 1959 (Geoweb Province of Zeeland)

The system of channels and tidal flats inside the Grevelingen is clearly displayed in the aerial photo. To provide a better picture of the ebb-tidal delta and its main features, the bathymetry of 1964 is plotted in with the Open Earth Tools in Figure 4.3. Please take note that the underlying Google Earth image is not from 1964 but from around 2005.

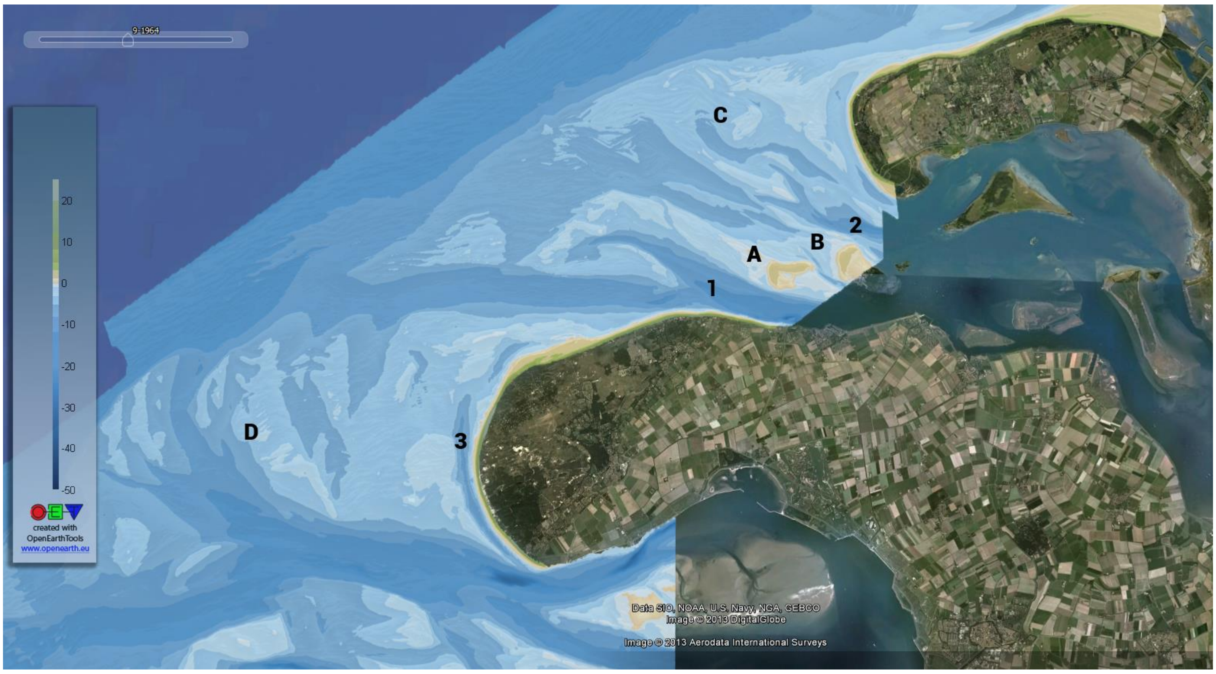


Figure 4.3 - Bathymetry 1964 (Open Earth Tools)

The most important features in the area have been marked, the channels are numbered and the lettering indicates shoals and other parts of the ebb-tidal deltas of the Grevelingen and the Oosterschelde:

1. *Brouwershavense Gat*
2. *Springersdiep*
3. *Krabbengat*

A. *Middelplaat*
B. *Kabbelaarsbank*
C. *Bollen van de Ooster*
D. *Banjaard*

4.2 Grevelingen after closure

After the completion of the Brouwersdam in 1971, the system has changed significantly. This section will discuss the developments of the most important features of the system through the years. The parts on the North Sea side of the Brouwersdam are the most important for this thesis, the developments on lake side of the system are of little interest for this study.

Figure 4.4 shows the bathymetry of the area in the year 1976. A number of trends can already be observed, the size of the ebb-tidal delta of the Grevelingen is shrinking (C). The area is being pushed shoreward due to a decrease in tidal velocities, making wave impact more important. The distal part of the Grevelingen ebb-tidal delta (C) is also changing shape, from a concave shaped profile to a convex profile, associated with a wave dominated forcing (Cronin, 2011). The channels (1,2) are being filled with sediment and the Middelplaat (A) is pushed against the Brouwersdam.

On the south side, around the head of Schouwen-Duiveland, the tidal channel Krabbengat is extending further northward. This channel is being formed due to a water level gradient between the Oosterschelde and the Grevelingen, a feature that is typical for the south-western part of the Netherlands and isn't found in for example the Waddenzee. The development of this channel bears resemblance to that of the Oostgat channel that formed around the head of Walcheren, between the Westerschelde and Oosterschelde.

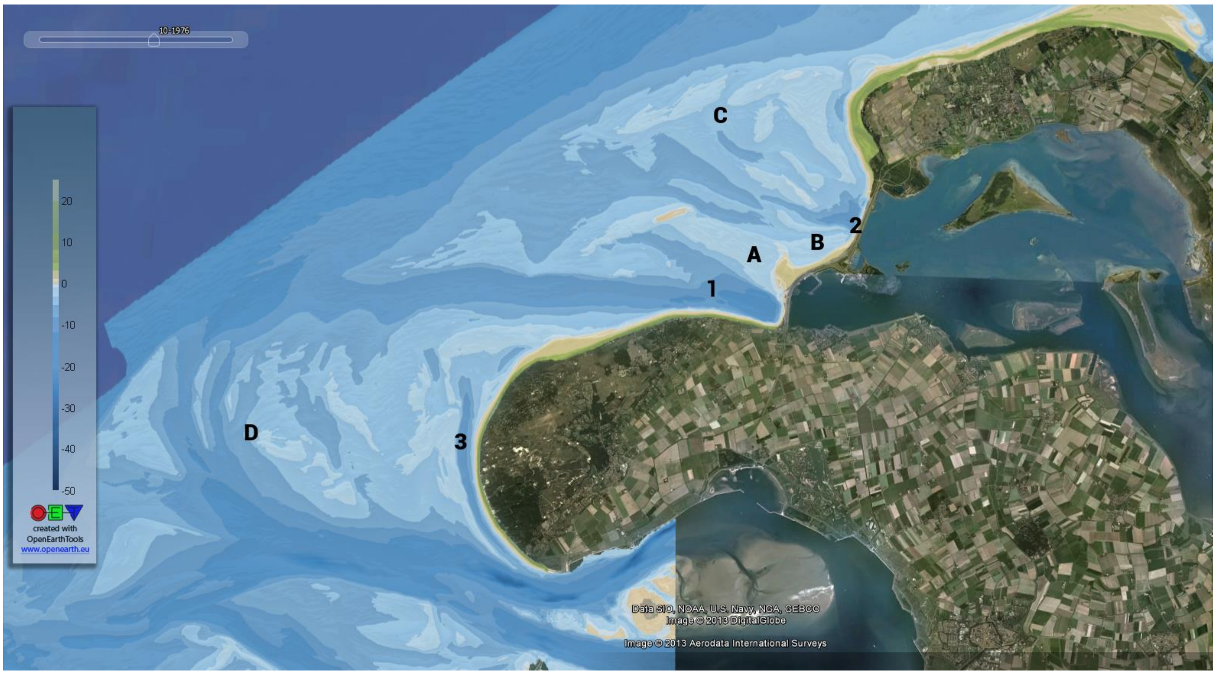


Figure 4.4 - Bathymetry 1976 (Open Earth Tools)

At the end of the eighties, the same trends are still continuing. Figure 4.5 shows the situation in the year 1989, three years after the closure of the Oosterschelde. The Bollen van de Ooster (C) are pushed further shoreward and are beginning to form a continuous intertidal breaker bar instead of separated sub-tidal shoals. The channels (1,2) are further filled in with sediment and Krabbengat channel has extended further northward. The Middelplaat has rotated clockwise towards the coast and is merging with the Kabbelaarsbank. In the next figures, the markings A and B will be omitted because a more detailed description is given in the next chapter.

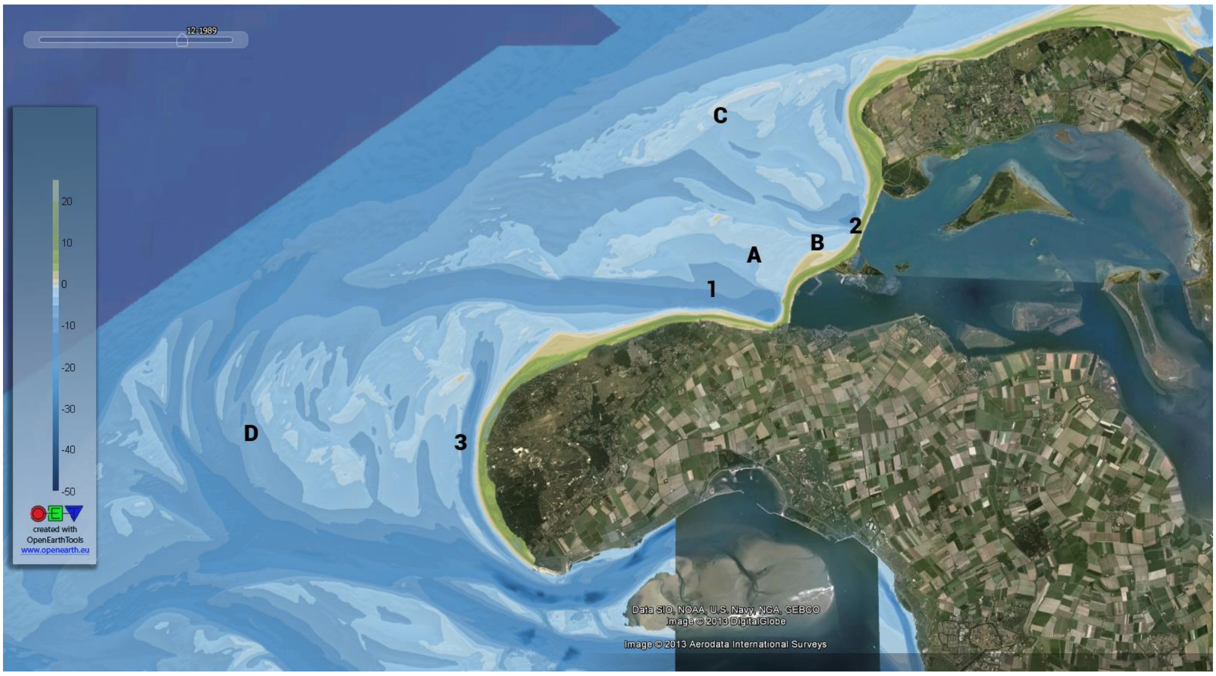


Figure 4.5 - Bathymetry 1989 (Open Earth Tools)

The next two figures (Figure 4.6 and Figure 4.7) show the developments over the last decade, the first bathymetry is from the year 1998 while the second is the most recent bathymetry, made in 2010. The Bollen van de Ooster (C) are being pushed inwards while protruding higher out of the water and becoming more elongated in south-western direction. The area shoreward of the Bollen van de Ooster is being flattened out, the scouring holes of the channels (1,2) near the Brouwersdam are still visible, but are much shallower than a few decades ago. The former ebb-tidal delta is likely losing sediment at a rate of 0,2 Mm^3/year, but the uncertainty in the data is rather large (Cleveringa, 2008)

The eastern part of the ebb-tidal delta Banjaard (D) is becoming smaller and lower in height, a trend that can be clearly seen when comparing the bathymetry of 1998 and 2010. It is migrating northward and is pushed towards the coast of Schouwen-Duiveland, a development influenced by the completion of the Oosterschelde storm-surge barrier in 1986.

The eastern part of the Banjaard is losing sediment and waves are reworking the delta front. The western tip of the Banjaard, separated from the eastern part by the Banjaard channels, shows highly dynamic behaviour and is growing in recent years. However the process of creation and migration of these bars is a cyclic process, bars created on the western tip travel to the eastern side of the Banjaard channel, a process that takes approximately forty years.

The Krabbengat channel is continuing its northward extension and is deepening, showing a distinct increase in cross-sectional area since 1986. This is caused by a change in the balance between the cross-shore and the alongshore tidal currents. The construction of the storm surge barrier decreased the cross-shore tidal currents because of the decreased tidal prism flowing through the barrier, leading to a relatively stronger alongshore tidal current. The result is a northward extension of the Krabbengat and a northward migration of the Banjaard shoal. At the northward end of the Krabbengat, sedimentation is occuring, resulting in a distinct bend in the Brouwershavense Gat (Eelkema, 2013).

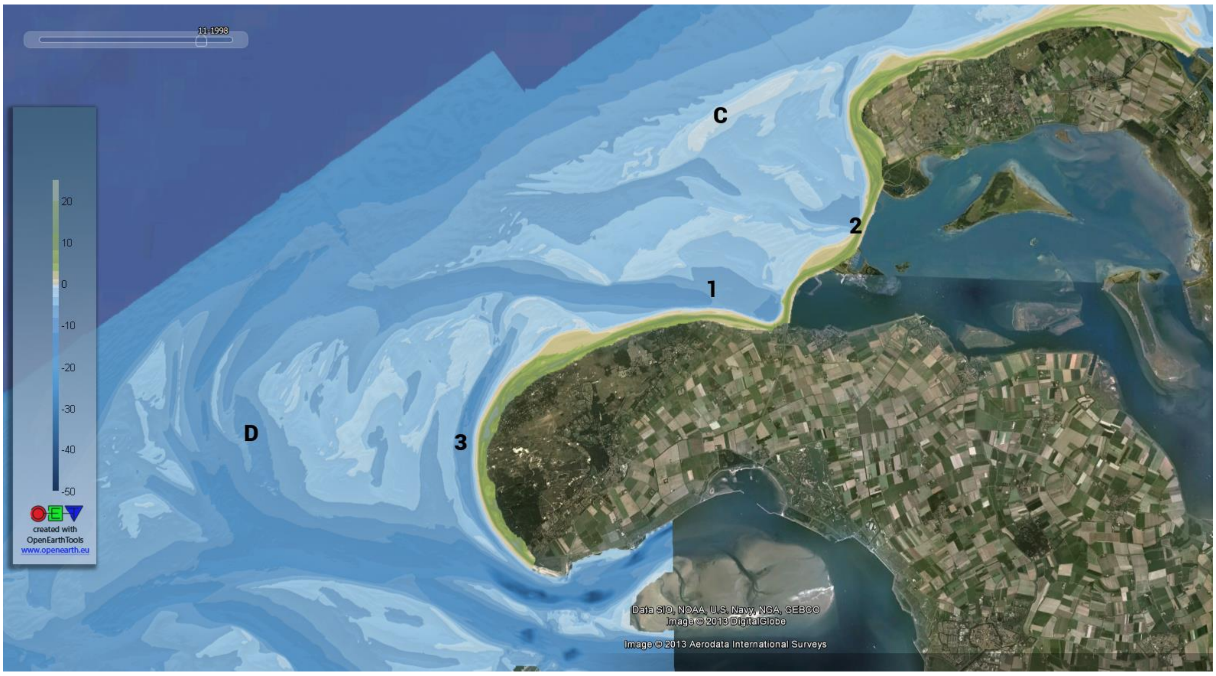


Figure 4.6 - Bathymetry 1998 (Open Earth Tools)

Figure 4.7 - Bathymetry 2010 (Open Earth Tools)

So far, a short history of the most important morphological developments on the west and south-western side of the Brouwersdam has been given. Developments further southward, in the direction of the Wester- and Oosterschelde, will not be discussed, because these subjects are of lesser importance to the area of research. The developments north of the area of research, in front of the Haringvlietdam, will be discussed and a short overview of the developments since the closure of the Haringvliet in 1970 will be given.

Figure 4.8 and Figure 4.9 show the bathymetry of the years 1968 and 2010. The morphological developments in this area are similar to those at the Brouwersdam, the former ebb-tidal delta is pushed shoreward and the former channels are filled in with sediment. However, the number of human interventions in this area is far greater: damming of the Brielse Maas in 1950, construction of the first Maasvlakte in the sixties, construction of the Slufter in 1985 and more recent, the completion of the Maasvlakte II.

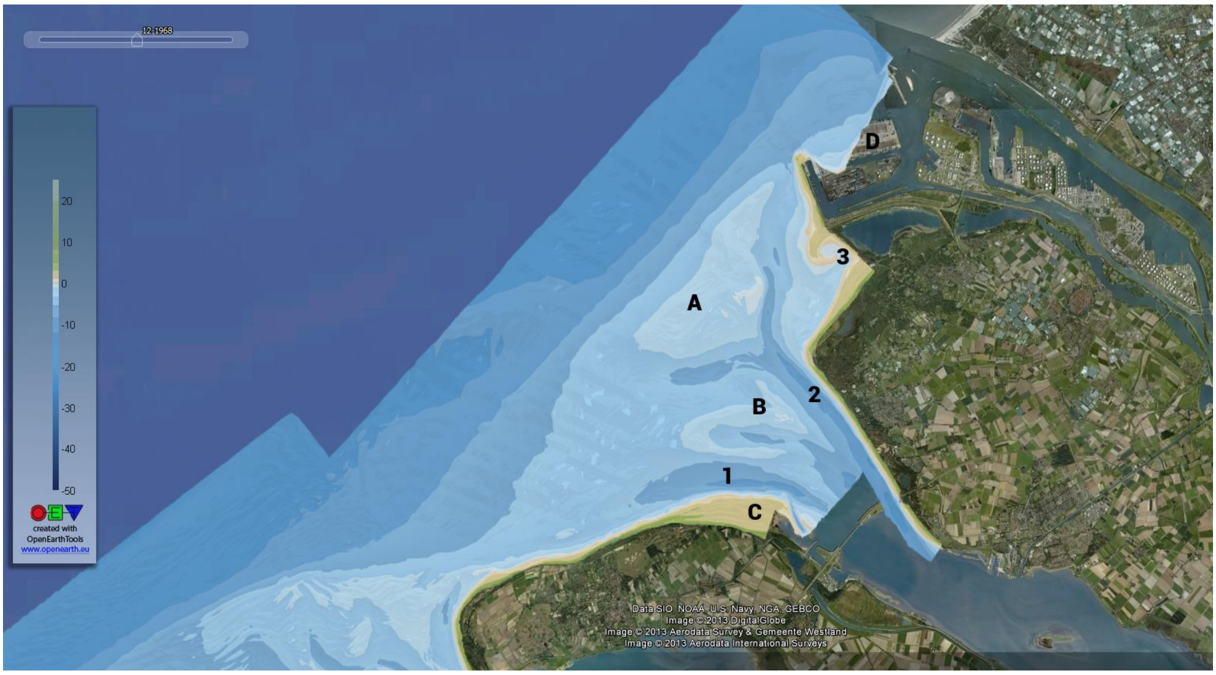


Figure 4.8 - Bathymetry Haringvliet 1968 (Open Earth Tools)

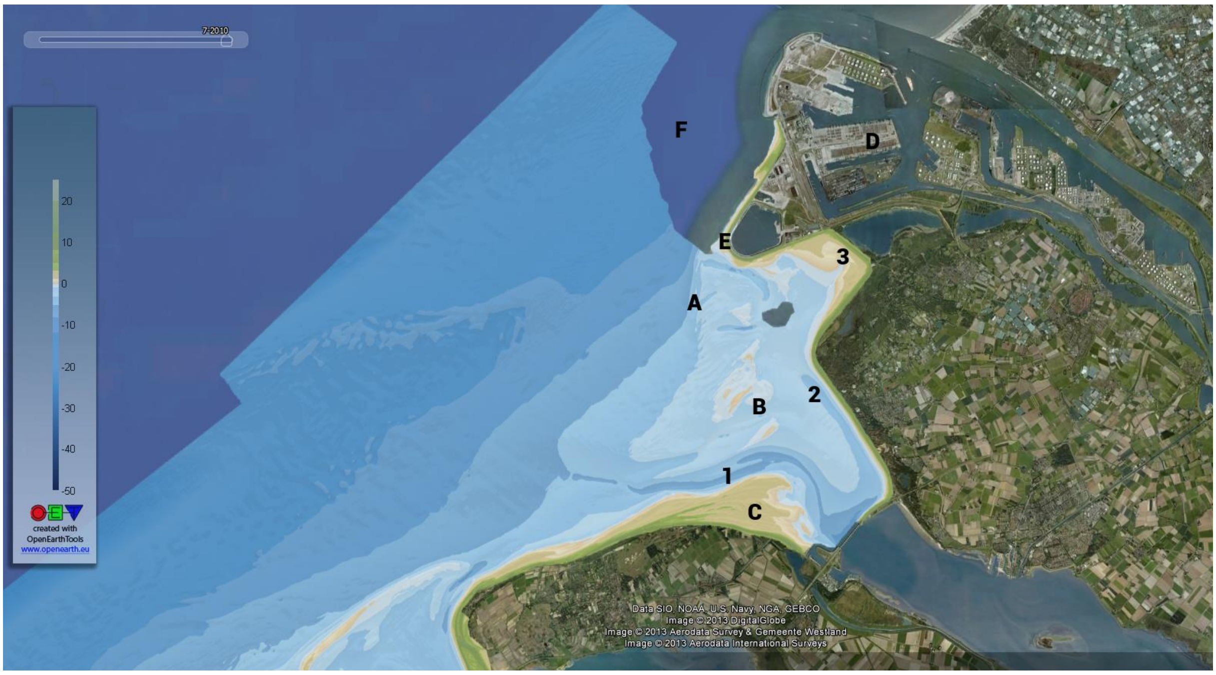


Figure 4.9 - Bathymetry Haringvliet 2010 (Open Earth Tools)

The main elements of the Haringvliet area have been labelled in Figure 4.8 and Figure 4.9, the names of the elements are as follows:

1. *Slijkgat*
2. *Rak van Scheelhoek*
3. *Brielse Gat*

A. *Hinderplaat*
B. *Rak van Scheelhoek*
C. *Kwade Hoek*
D. *Maasvlakte I*
E. *Slufter*
F. *Maasvlakte II*

These constructions all have had an influence on the morphology of the Haringvliet. The area was already gaining sediment before 2004 (before Maasvlakte II) at a rate of approximately 0,5 Mm^3 per year (Cleveringa, 2008).The bathymetry of the year 2010 shows that the former tidal channel Rak van Scheelhoek (B) is hardly visible anymore. The Slijkgat (1) channel is still visible because the sluices of the Haringvliet are discharging onto this channel, but is quite a bit smaller than forty years ago .In the south the Kwade Hoek beach ridge is growing in north-eastern direction, pushing the Slijkgat in the same direction. The former ebb-tidal lobe Hinterplaat (A) is pushed shoreward due to the relative increase of wave action, a feature that also can be observed at the Bollen van de Ooster at the Grevelingen.

The former estuary is nowadays on an even more sheltered location than before the construction of Maasvlakte II (F), so it is likely that the trend of sedimentation of the area continues in the near future. However, what the exact morphological developments will be, has to be seen in the future. The last major change in the system was completed only very recently and it will take a long time for the system to reach a new equilibrium.

5 Morphological Developments Beach Brouwersdam

What today is a beach used by tourists and extreme sports enthusiasts, was till the construction of the Brouwersdam part of the ebb-tidal delta of the Grevelingen tidal basin. The Brouwersdam is built on top of the former shoals Middelplaat and Kabbelaarsbank. Figure 5.1 shows the location of these shoals and the channel. The Middelplaat, the largest channel is situated west of the convex part of the Brouwersdam. The Kabbelaarsbank is in the concave part, separated by a flood channel.

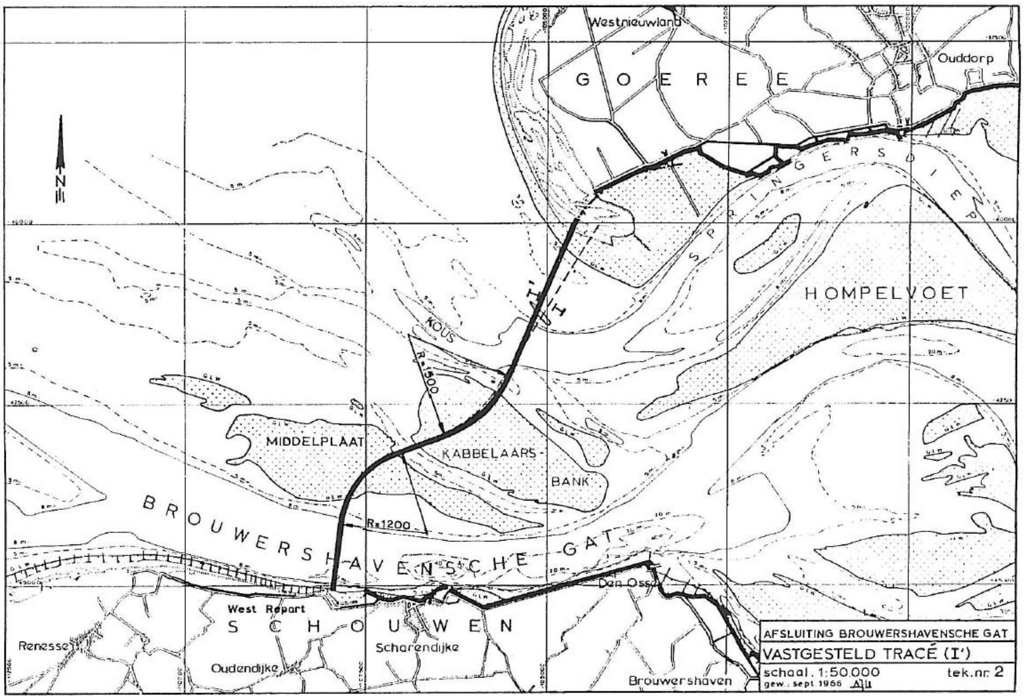


Figure 5.1 - Overview chosen trajectory Brouwersdam (Rijkswaterstaat, 1966)

After the closure of the Grevelingen the hydraulic forcing of the system was changed significantly. The tide couldn't enter the Grevelingen anymore and the incoming tide now propagates from south-west to north-east along the Brouwersdam. Wave action became more important, resulting in significant changes in the bathymetry of the system and significant changes for the beach.

5.1 During construction

The map in the previous paragraph provides an overview of the planned course of the Brouwersdam. This map was made at the beginning of the sixties, the actual construction started in 1964. The first stages of construction were building the sections on the former shoals Middelplaat and later Kabbelaarsbank. Figure 5.3 is taken from an aeroplane, in the foreground Schouwen-Duiveland, on the left the Middelplaat, on the right the Kabbelaarsbank and in the background Goeree-Overflakkee. Figure 5.2 shows a close-up of the Middelplaat, the dike is being made and a dredger with a floating pipe line is supplying sand for the embankment. The dike is made on the eastern part of this shoal, the western part will become what is now the beach.

After the construction of the dam on the shoals, the closure of the tidal channels Springersdiep and Brouwershavense Gat had to take place. The Springersdiep was closed by the sinking of caissons, these caissons were placed onto a sill of dumped rock. The Brouwershavense Gat was too deep to close with caissons, so a different method was chosen: closure by dumping concrete elements. These elements were transported from the shore by a cableway and dumped on site.

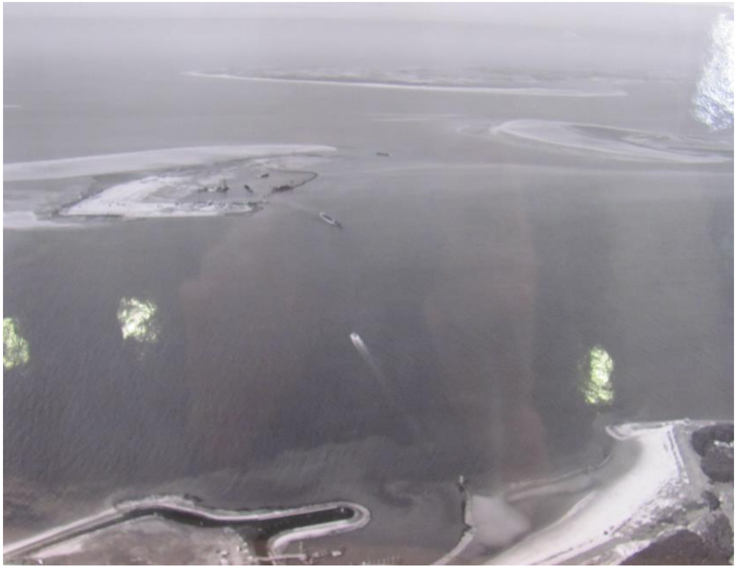


Figure 5.3 - Schouwen-Duiveland, Middelplaat and Kabbelaarsbank (Rijkswaterstaat,1965)

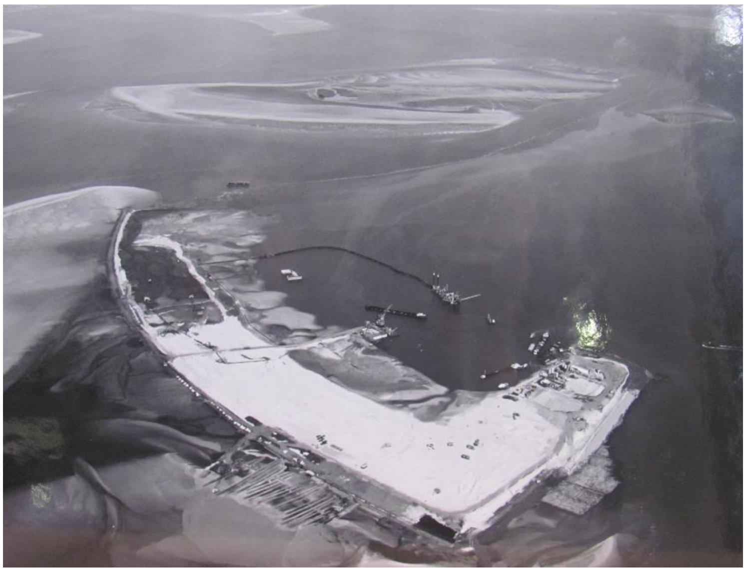


Figure 5.2 - Close-up Middelplaat (Rijkswaterstaat, 1965)

5.2 Period 1972-1981

The amount of data available for this first ten years after construction is rather limited. Echo soundings for the JARKUS rays are available from the year 1981. Before these years, only measurements with levelling instruments were made, so there are no data points below the low water mark. This also means that there are no data points on the Middelplaat.

To get a good view of what happened in the first ten years after construction, other sources of information have been consulted. In this case (aerial) photographs, buried deep in the archives of the 'Zeeuws Archief', the archive of the Province Zeeland and only found after a long search and a bit of luck. One small line in an archive entry confirmed the existence of these aerial photographs and negated the fear that they were lost in time. The archive map contained photos from 1973 till 1980, these were made by a now defunct subsidiary of the Royal Dutch Airlines: KLM Aerocarto, the photos were commissioned by Rijkswaterstaat.

In a later stage of this research, information from Deltares became available in the form of the bathymetries of earlier years. These bathymetries were plotted in Google Earth and have also been incorporated into this chapter.

Figure 5.4 - Middelplaat 1973 (Rijkswaterstaat)

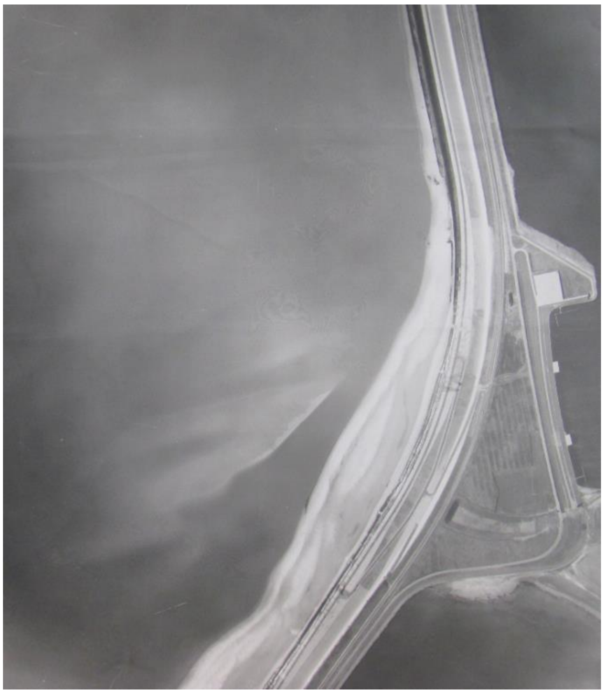


Figure 5.5 - Kabbelaarsbank 1973 (Rijkswaterstaat)

The photo in Figure 5.4 is taken in 1973 and already shows the shifting Middelplaat, Figure 5.5 shows the narrow beach on what was the Kabbelaarsbank a few years before.

A few year later, in 1976 the size of the Middelplaat has increased (Figure 5.6), at least the part above water. Due to wave action sand is transported from the deeper parts of the shoal onto the beach. In the upper-middle part of the image the elongated part of the beach has become considerably less wide then a few years before. The water level at the time the picture was taken could be different, but if that was the case the other parts of the Middelplaat would also appear smaller, so it is fairly safe to say that sediment is lost on that part of the beach.

Figure 5.7 is a picture of the Kabbelaarsbank in 1976. In this picture the changes compared with Figure 5.5 are harder to determine, but when closely examined it becomes clear that the beach is getting narrower on the southwest side and is growing towards the northeast and gets wider there, although it must be noted that the pictures aren't aligned from north to south. The deviation in Figure 5.5 is approximately 30 degrees and 40 degrees in Figure 5.7, both counterclockwise.

Figure 5.8 shows the bathymetry in 1976, the shape of the Middelplaat and the Kabbelaarsbank is very similar to the aerial photos, apart from the rotation of the latter. The former channel Springersdiep is still fairly deep.

Figure 5.6 - Middelplaat 1976 (Rijkswaterstaat)

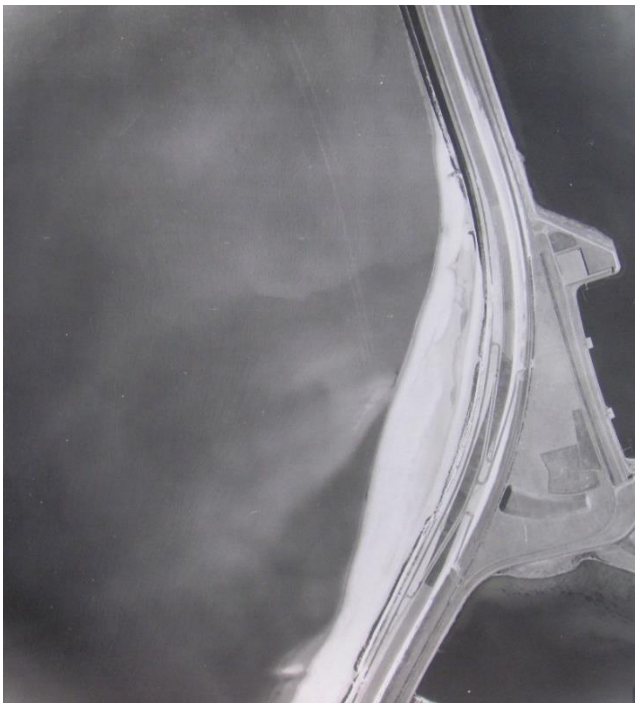


Figure 5.7 - Kabbelaarsbank 1976 (Rijkswaterstaat)

Figure 5.8 - Bathymetry beach 1976 (Open Earth Tools)

1. *Brouwershavense Gat*
2. *Springersdiep*

A. Middelplaat
B. Kabbelaarsbank

In 1977 the construction of a sluice was started. This sluice was constructed to let salt water into the Grevelingen because it was turning into a freshwater lake. The rather wide bulge in the dam in Figure 5.9 is broken up and the sluice is constructed in between. The construction of the sluice was finished a year later.

The discharge through the sluice isn't very large, the difference between high and low water level in the lake due to high and low tide is only 5 centimetres. With a total flow profile of 54 m^2 and a maximum discharge of 140 m^3/s leading to a maximum flow velocity of 2,6 m/s there will be some scouring. However, when the sourcing holes have developed, the exchange of sediment between the lake and system on the sea side is going to be small. This phenomenon is comparable with the Oosterschelde Storm Surge Barrier, although on a much smaller scale. The exchange of sediment is also limited there, only finer particles are exchanged, these particles are mostly mud (Mulder et al., 2010)

Another four years later in 1980 the trend remains the same, the Middelplaat is shifting in north-eastern direction. Figure 5.10 shows this trend clearly. The 'head' of the shoal is moved towards the coast and is slowly starting to attach to the elongated beach of the Kabbelaarsbank, a process that will take a lot more time but it is starting to show here. When comparing the first available measurements from 1974 to 1980 (Figure 5.12 and Figure 5.13) this is visible. The amount of sediment has increased. This can also be seen in Figure 5.9 and Figure 5.10. Also the north-eastward shift of the beach can be seen in the graph, though both developments aren't as clear in the graph as on the pictures.

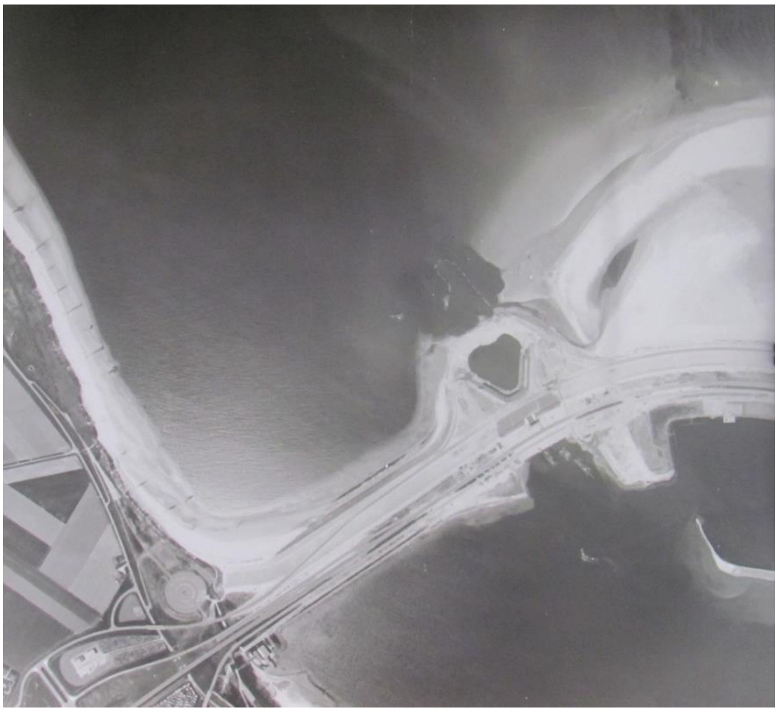


Figure 5.9 - Construction sluice 1977 (Rijkswaterstaat)

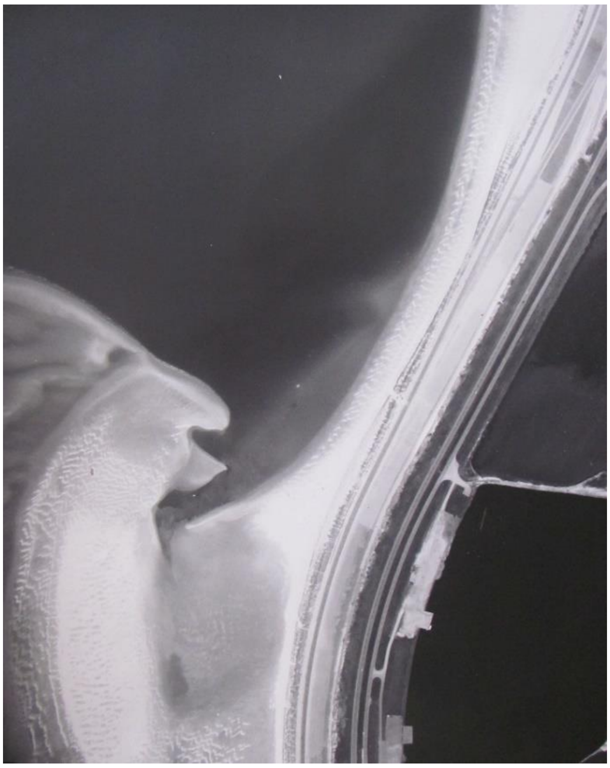


Figure 5.10 - Middelplaat 1980 (Rijkswaterstaat)

While the amount of sediment has increased it is difficult to tell how much this increase exactly was. The data itself seems accurate, the measurements were made with levelling instruments so in theory they should be accurate. The measurements are so-called "JARKUS-raaien", yearly measurements of fixed section lines (profiles) along the Dutch coast.

These JARKUS rays are measured each two hundred meter, in between there are no data points, as can be seen in the graph above. So the amount of sediment per profile jumps from one value to the next while the beach itself is curved instead of a straight line. This induces an error in the calculation of the amount of sediment. How large this error is can't be determined afterwards, that depends on the actual shape of the beach at that time. An overview of the JARKUS rays is given in Figure 5.11

Figure 5.11 - Overview JARKUS rays

The amount of sediment per profile is calculated with a program called MORPHAN, this program is developed at Deltares and is used by Rijkswaterstaat, among others, to monitor morphological developments on the Dutch coast. This program uses the JARKUS data as source data.

To calculate the amount of sediment per profile it is required to set boundaries, there are four possible boundaries: seaward and landward, upper and lower. The seaward boundary in the source data should be the low water mark, but due to changing water levels during measurements this boundary isn't the same for all profiles and also differs per year.

The result of these inconsistencies is that the amount of sediment can't be calculated within exact boundaries, because the end point of the measurement determines this boundary and therefore the measured amount. It is not possible to set an exact seaward boundary because the profiles have large differences in length and thus the limit has to be set to a very low value, rendering comparison useless. When no boundary is set, the program chooses the shortest rays over the specified period for comparison. Although this seems a pretty good compromise, it is important to be aware of the consequences. When sediment is lost, the low water mark moves towards the coast, so the measured profile becomes shorter. So when the shortest profile is chosen, the sediment loss outside the profile isn't taken into account, only the sediment loss in z-direction inside the profile. When sediment is deposited the same effect takes place, but vice versa. This effect also takes place when the measured profile is shorter for other reasons, such as the rising tide during the measurements. The result of this calculation is given in Figure 5.12, the boundaries in z-direction are +15,00m NAP and -10,00m NAP. The lines in the graph have a shape that resembles the actual shape of the beach at that time, but they are very close together and it's hard to distinguish difference between the individual lines, making it difficult to spot the trend over these years. This indicates that this comparison doesn't give optimal results but also that one has to be careful which data and boundaries to choose, because the choice made can lead to very different conclusions about what is happening.

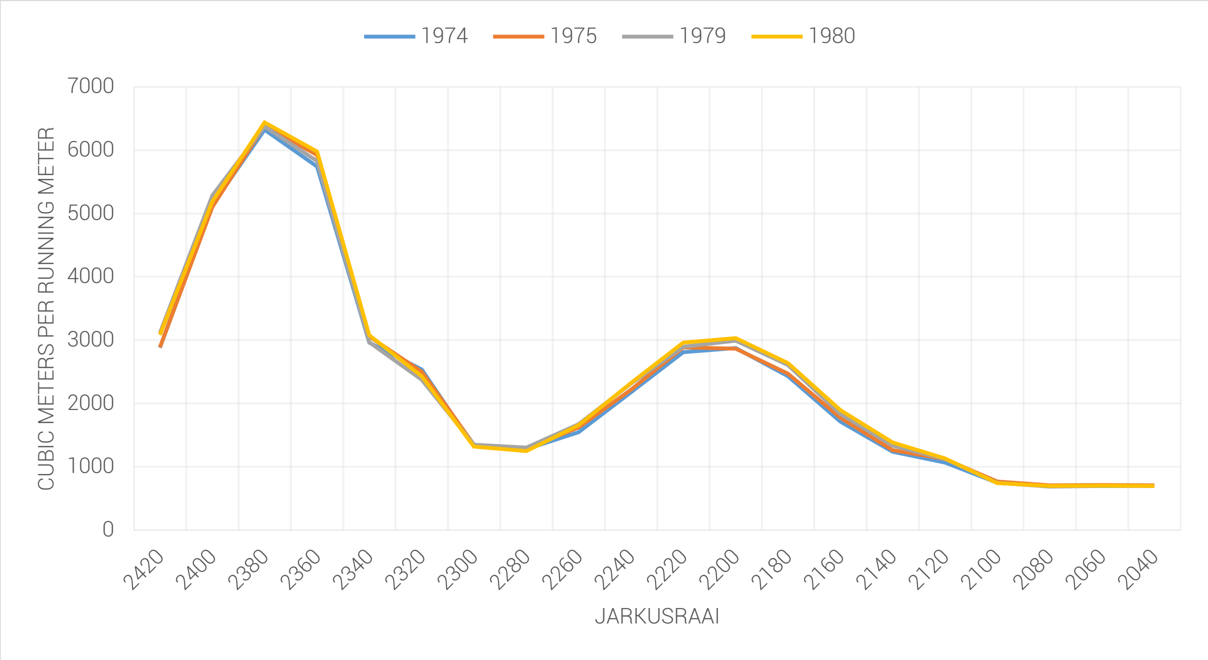


Figure 5.12 - Volume with shortest profile length

A different method is to calculate all sediment per year over all the JARKUS rays. This has the advantage that the length of the profile can be different per year and changes due to erosion or accretion are included. The disadvantage is that changes in profile length due to other reasons like the changing water levels during measurements are also included. The result of this calculation is shown in the graph below and actually provides a better picture of what has happened.

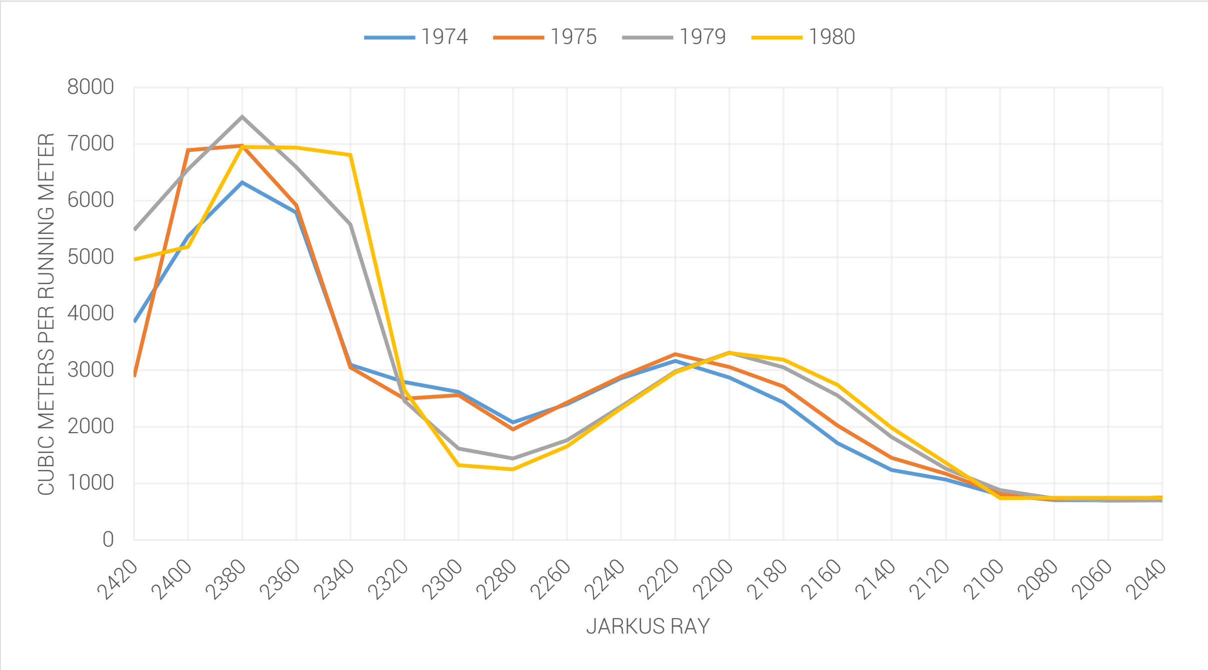


Figure 5.13 - Volume with maximum profile length

A difference between Figure 5.13 and Figure 5.12 is the erosion around profile 2280, which is barely visible in the latter graph. It seems that sediment is transported into the former flood channel, filling it in.

There are large differences between these graphs, which indicates that caution is needed. The difference in sediment quantities between 1974 and 1980 for the two calculation methods is large. The first method shows an increase of approximately 350,000 m^3 while the second method gives an increase of 1,200,000 m^3. So these graphs do indicate the trend, but the actual quantities have a high degree of uncertainty.

5.3 Period 1982-2012

In the eighties the amount of available measurement data increased significantly. From now on not only measurements from land were made, but echo soundings were included in the JARKUS rays. So the amount of data points for each profile increased significantly, which leads to an increase in the quality of the sediment quantity calculations because the errors discussed in the previous paragraph don't play a role anymore.

5.3.1 Volume between +15,00 m NAP and -10,00 m NAP

Now it is possible to make calculations for sediment transport above and below the water level, which should provide a better picture of the transport for different sections of the coastal profile. A calculation has been made for the whole profile, which extends from the Brouwersdam to about 800 meters into the North Sea and ranges in height between +15.00 m NAP and -10.00 m NAP.

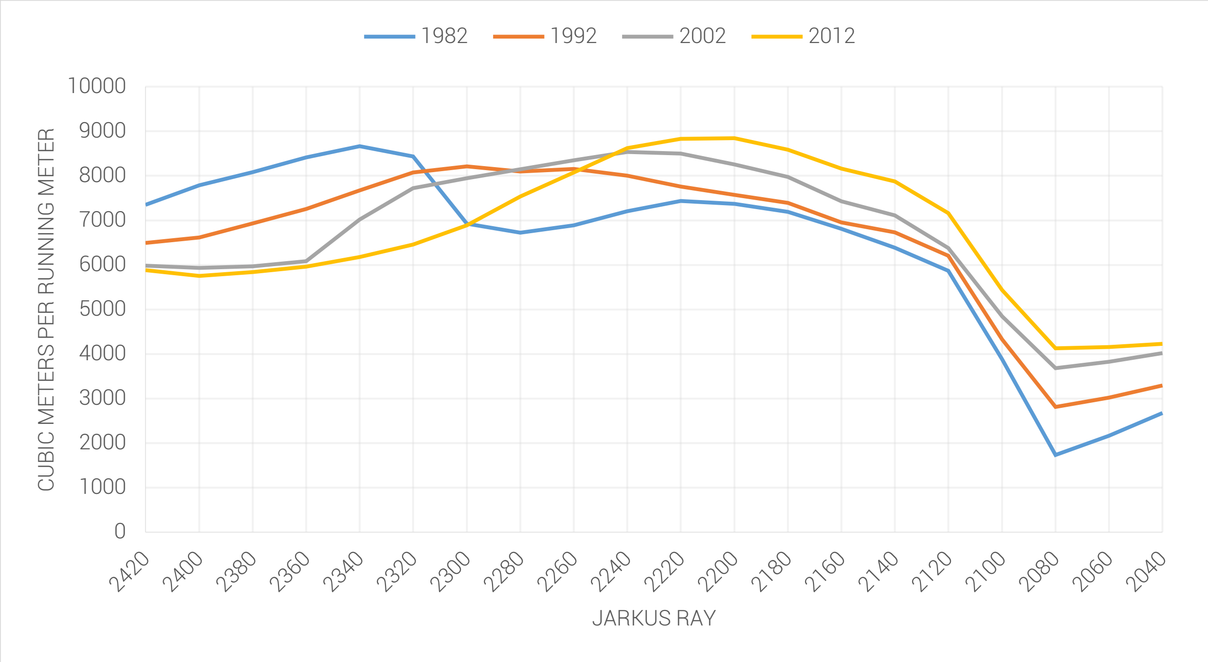


Figure 5.14 - Volume total profile 1982 - 2012

The coastline in the year 1980 is comparable with the year 1982, although the shape of the lines in graph in Figure 5.14 differs a lot from Figure 5.12. The reason for this difference is the increased profile length of the measurements.

What can be observed from the figure above is the gradual shift of the beach to the right, which means a shift in north-eastern direction. Also the trough in the graph around ray 2280, clearly visible in 1982 and the years before, is flattened out in twenty years and is gone in 1992. Figure 5.15 is a picture of the situation in 1987, where the trough is still visible, but the Middelplaat starts to attach to the beach in the convex part of the Brouwersdam. This distinction between the former shoals is still visible, but is slowly disappearing and the shoals fuse together. Between rays 2120 and 2040 the former tidal channel

Figure 5.15 - Aerial photo Brouwersdam 1987 (Rijkswaterstaat Kustfoto)

Springersdiep can be recognized because the amount of sediment in these rays is considerably smaller than in other rays, meaning that the depth in front of this part of the Brouwersdam is larger than for other rays.

The bathymetry of the year 1989 in Figure 5.16 shows a similar picture as Figure 5.15, the Middelplaat (A) has shifted north-eastward and the upper part of the shoal is attached to the former Kabbelaarsbank (B) now. The channels (1,2) are slowly filled in and are much shallower than in Figure 5.8

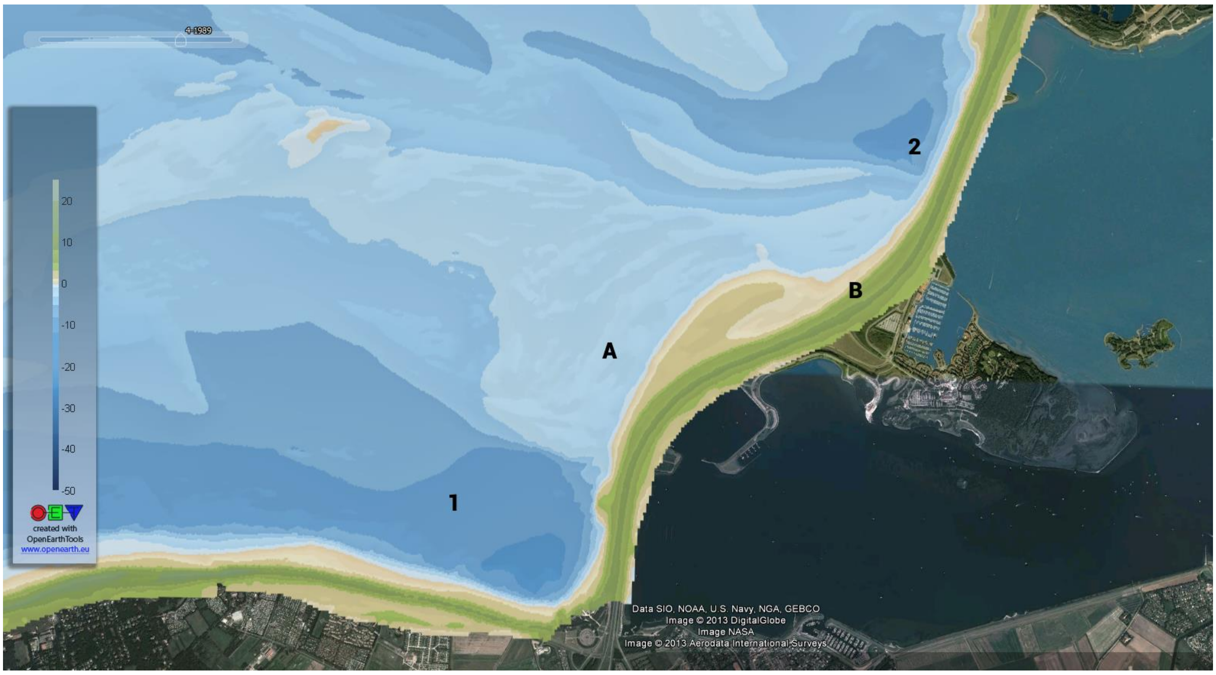


Figure 5.16 - Bathymetry beach 1989 (Open Earth Tools)

The amount of sediment in the measured profiles has its maximum in 1982, there is a small increase in the period 1992-2002, but over three decades almost 1,4 million m^3 is lost. In Figure 5.14 can be seen that the last profiles contain considerably less sediment than the other profiles. This is where the former tidal channel Springersdiep was located. The measured JARKUS rays are shorter than the length over which the channel is deeper than its surroundings, meaning that sediment deposited outside the measured ray in the depths of the former channel leads to a decline in total volume.

	1982	1992	2002	2012
Total sediment (m^3)	27,520,000	26,673,000	26,870,000	26,130,000
Change per decade (m^3)		-847,000	+197,000	-740,000

Table 5.1 - Sediment volume total profile 1982 - 2012

However that is only one part of the story, the other part is the actual problem that stakeholders of the beach are experiencing, the shifting location of the beach and the loss of (dry) beach.

In Figure 5.15 can be seen that the beach is still attached to the dike body next to the dewatering sluice, JARKUS ray 2420. The erosion in that profile between 1982 and 1992 is almost 850 m^3/m and between 1992 and 2002 another 500 m^3/m is lost. Nowadays there is no beach at that location anymore. The volume in that profile in the year 2012 is the volume below the low water mark, all sediment above that level is eroded.

Note that the total amount of sediment available can be chosen arbitrary, the chosen depth of -10 m NAP is only a reference level. In the measured profiles there are no data points below that reference level, but the same can be said for a reference level of -20 m NAP which would increase the total amount of sediment quite substantially. What is important are the changes, because that's the amount that has really been eroded or deposited.

5.3.2 Volume between +3,00 m NAP and -1,40 (Beach)

By setting different boundaries when calculating the available sediment per profile, this development can be shown more clearly. In the graph below the height is set between +3.00 m and -1.40 m, the boundaries on the x-axis are the intersections with the z-axis of the respective heights. The first height indicates the dune foot, the second height is the average low waterline at spring tide called LLWS. Setting these boundaries results in the volume of the actual beach itself.

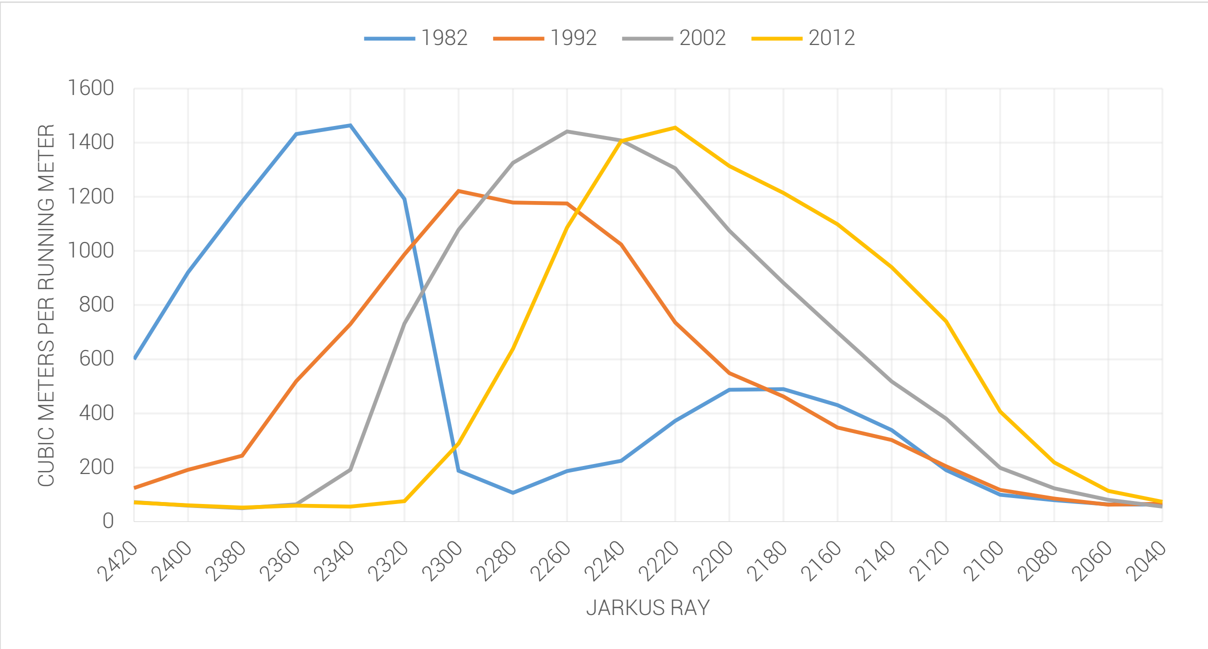


Figure 5.17 - Volume beach 1982 - 2012

This graph shows more clearly what is happening, the continuous north-eastward shift of the beach. In thirty years, the centre of gravity has shifted almost twelve hundred meters and this trends still continues, where the centre of gravity is the profile that has the most sediment in it. Each decade shows a shift of about four hundred meters north-eastward, it is assumed that this trend will continue in the future.

The total amount of sediment in the beach has also changed in this period, the table below shows the values per year. The table shows that the amount of sediment was at its peak in 1982 and that almost 260,000 m^3 is lost since then. A loss of more than 10% is quite substantial. However, there are uncertainties in the data like measurements errors and seasonal variations in beach profiles, it is reasonable to say that the trend is downward over the last three decades.

	Total amount of sediment (m^3)	Change per decade (m^3)
1982	2,318,000	
1992	2,151,000	-166,000
2002	2,188,000	+37,000
2012	2,061,000	- 127,000

Table 5.2 - Sediment volume beach 1982 - 2012

To determine what happened to the total volume over the last ten years, a comparison between the individual years has been made . The graph below shows the shift in north-eastern direction each year, the table below shows the sediment amounts per year.

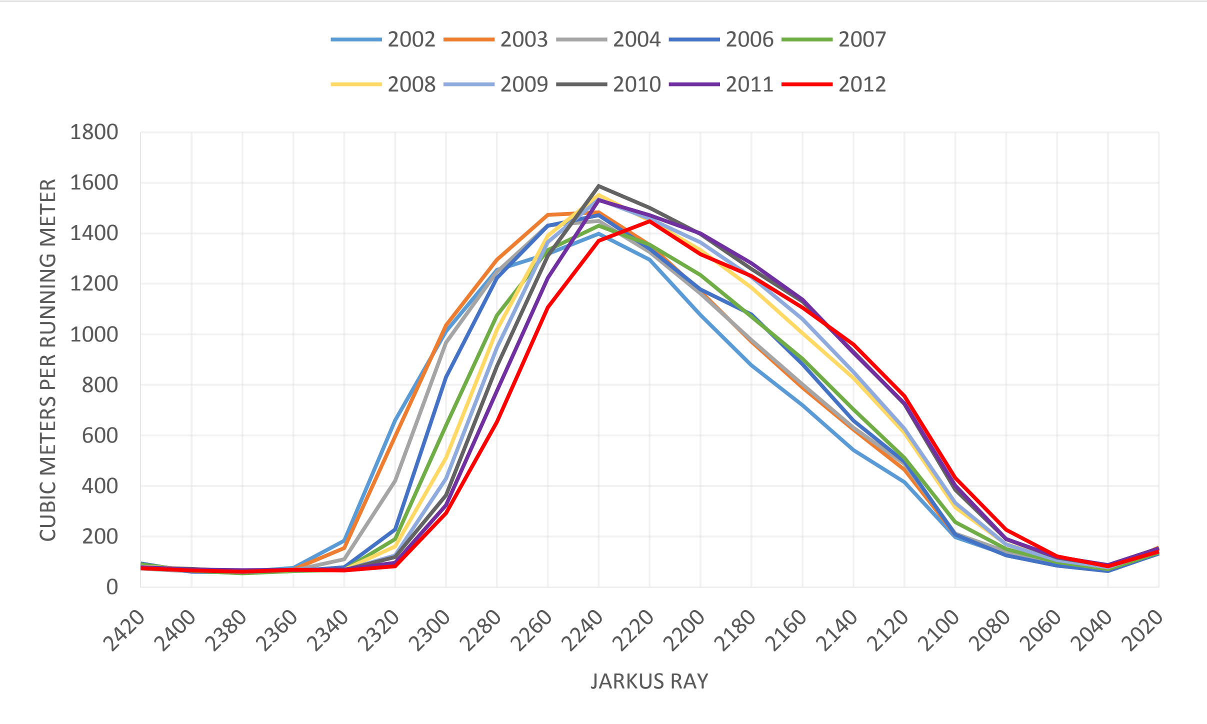


Figure 5.18 - Volume beach 2002 – 2012

	Total amount of sediment (m^3)	Change per year (m^3)
2002	2,188,000	
2003	2,303,000	+ 115,000
2004	2,208,000	- 95,000
2005	No Data	No Data
2006	2,160,000	- 48,000 (difference with 2004)
2007	2,086,000	- 73,000
2008	2,197,000	+ 111,000
2009	2,174,000	- 23,000
2010	2,220,000	+ 45,000
2011	2,164,000	- 56,000
2012	2,061,000	- 103,000

Table 5.3 - Sediment volumes beach 2002 - 2012

Table 5.3 shows that there are large variations per year, the amount of sediment peaked at the year 2003, but the amount of sediment in 2010 isn't much smaller, the difference is about 3%. The last two years show a fairly large decline, but changes of such magnitude aren't uncommon. The years 2006 and 2007 show the same declining trend, but a year later the sediment volume increased again. So the sediment volume does change from year to year, but this amount is fairly stable over the last ten years. However, if this decline continues for 2013 and further, the amount will be at its lowest in the last decade and then the decline could be labelled as structural.

5.3.3 Dry Beach Volume and Area

The changes in sediment volume don't explain the loss of beach that is reported. To do so, the amount of dry beach is determined. The graph below (Figure 5.19) shows the development over the last three decades.

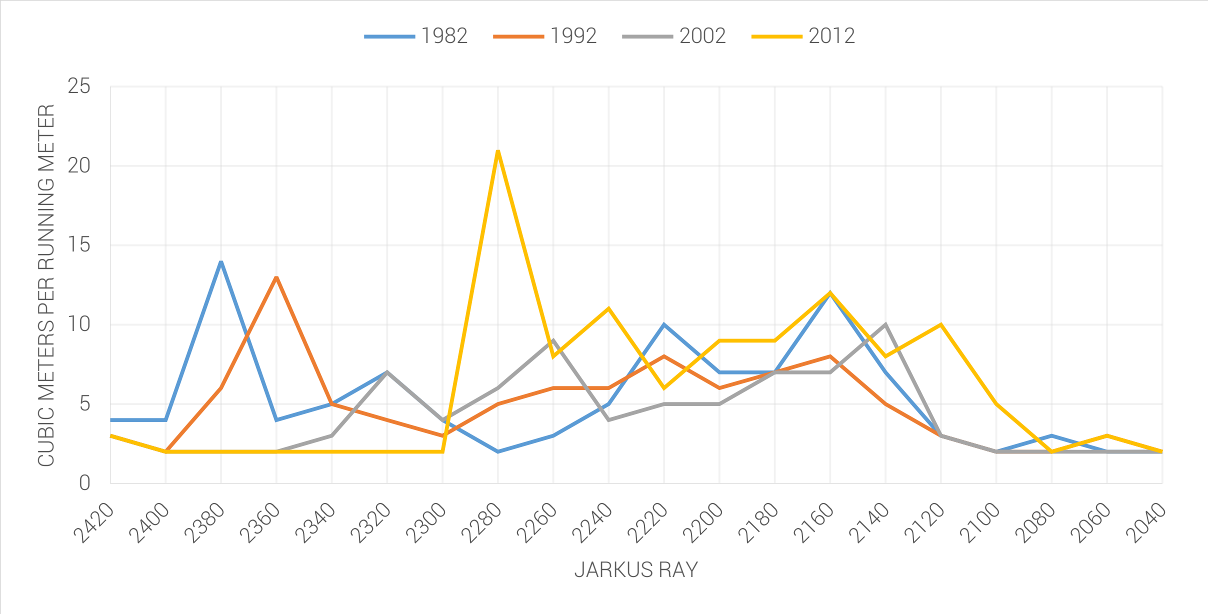


Figure 5.19 - Dry Beach Volume 1982 - 2012

This graph doesn't have much value, the sediment amount in the profiles is rather small and more prone to errors due to this small volume. The large spike in volume in 2012 should indicate a large stretch of dry beach at that place, the volume is a lot bigger than for any other location. While the amount of dry beach has increased on that location (see Figure 5.20), the amount isn't as large as Figure 5.19 suggests. A volumetric approach based on JARKUS measurements doesn't seem to be the best way to determine the amount of dry beach, that's why a different approach is chosen.

That approach is to measure the regression or progression of the dune foot and the high tide mark per profile. In Figure 5.20 the changes in distance per profile are given. While the total change is almost equal to zero, there are some significant changes. The loss of dry beach takes place in a rather small area; three profiles, a length of six hundred meters. The accretion on the other hand takes place in a large area; ten profiles, a length of two thousand meters.

This phenomenon is the actual problem that the users of the beach experience, a wide (in seaward direction) dry beach is eroded and the sediment is transported in north-eastern direction. The accretion takes place on a much longer stretch of coast. This results in a more elongated beach, with only small pieces of dry sand available. From the point of view of the users of the beach this is a loss, it is less attractive for recreation. The resulting beaches are small and have little to no dunes behind them, only the asphalt of the Brouwersdam, which is visually a lot less attractive.

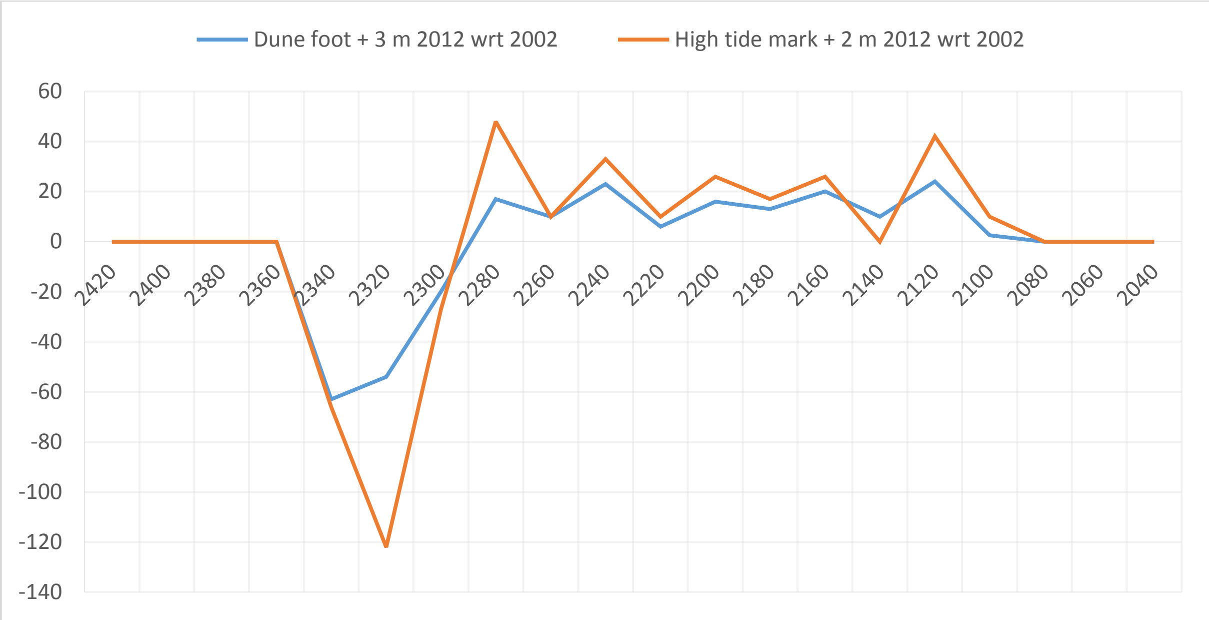


Figure 5.20 - Change of dry beach length per profile

These JARKUS rays aren't the only way to determine what's happened over the past decades. A lot of progress has been made in the field of information technology in recent years. With Google Earth you can have a look at nearly any place in the world you would like to see. When you combine this with height measurements it is possible to plot these datasets onto the location of choice. The resulting images are often easier to understand than graphs with a lot of figures because of the underlying map.

The measurements used to generate these images aren't done yearly like the JARKUS measurements, but only every three years for this area. These measurements are called "Vaklodingen" (Zijpp, 2001). The most recent dataset is made in 2010 and this dataset is compared with measurements from the year 2000.

The first comparison is made between the average waterline (0,00 m NAP) and the dune foot (+3,00 m NAP). In the year 2000 the total area is 82 hectares while in the year 2010 this area is only 66 hectares, a 25 percent loss in area. Figure 5.21 and Figure 5.22 show both areas in bird's eye view. Please note that the underlying Google Earth image is taken in 2005, possible taken during summer season with low tide, judging by the amount of dry sand seen in the picture.

The small coloured dots in the figure on the other side of the dam are small artefacts left over by the filtering algorithm that was made to create these images. These artefacts do influence the measurements, but that influence is rather small. What already could be seen in the previous calculations also shows on these images, in 2000 the beach as bigger and it has shifted north-eastwards.

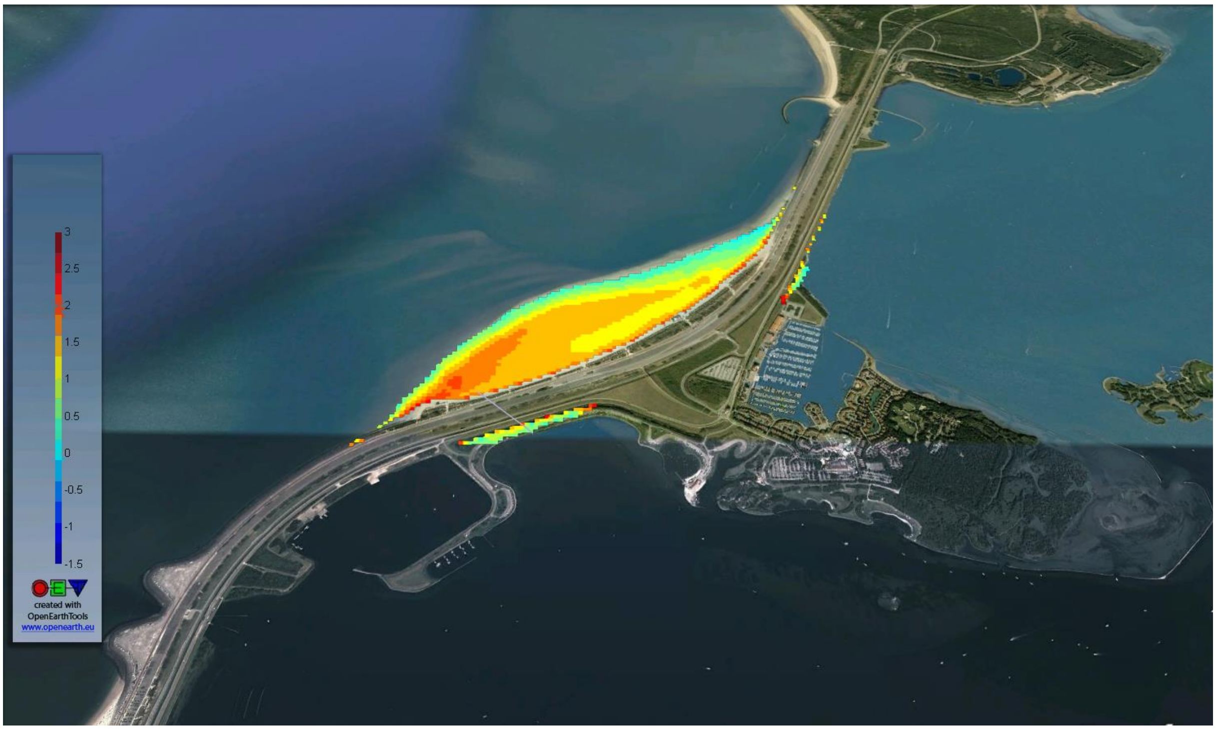


Figure 5.21 - Area between 0 and +3,0 m NAP in the year 2000

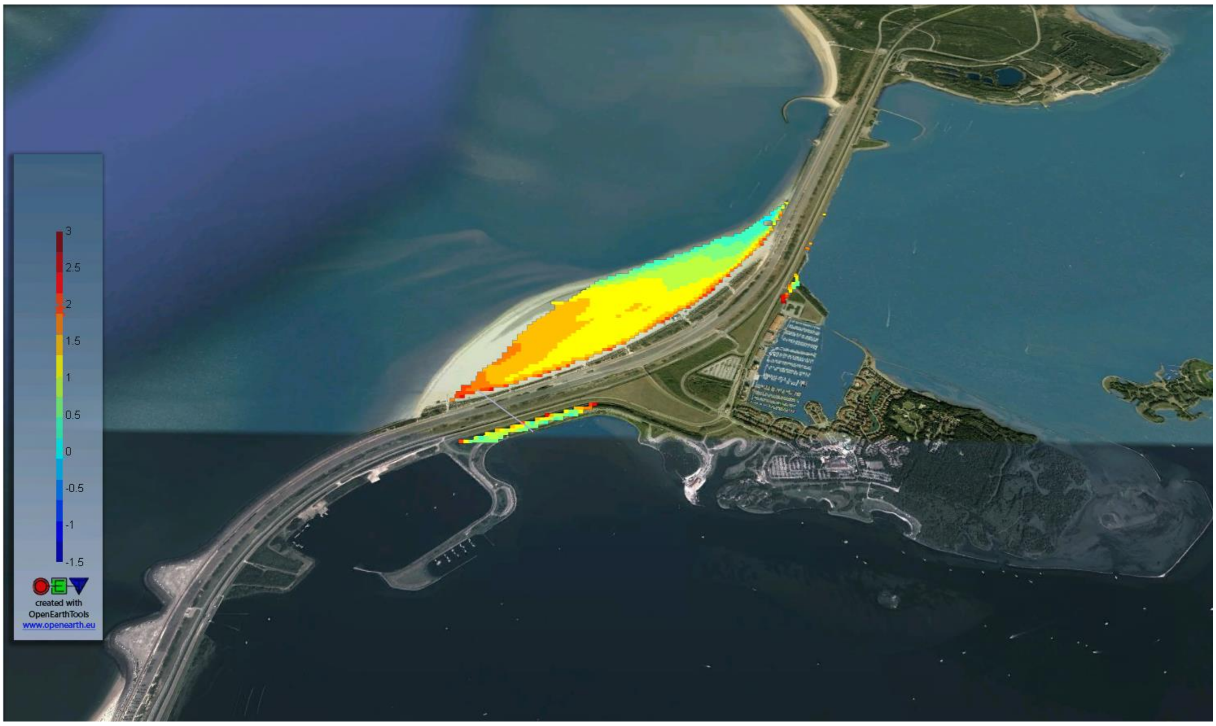


Figure 5.22 - Area between 0 and +3,0 m NAP in the year 2010

The next images (Figure 5.23 and Figure 5.24) show the area of dry beach available, this area is rather small for both years, but also these images do confirm the trend: the beach is getting smaller (lower) and is shifting. The highest points on the beach are not the areas near the dune foot, but the areas near south-western edge of the beach. The heaviest wave attack takes place in this corner (*Appendix C.3 - SWAN model results*), so it's likely that wave action causes this higher build-up of sediment. This phenomena was already observed on pictures taken through the years. The total area in 2000 was 29 hectares, in 2010 only 17 hectares is left.

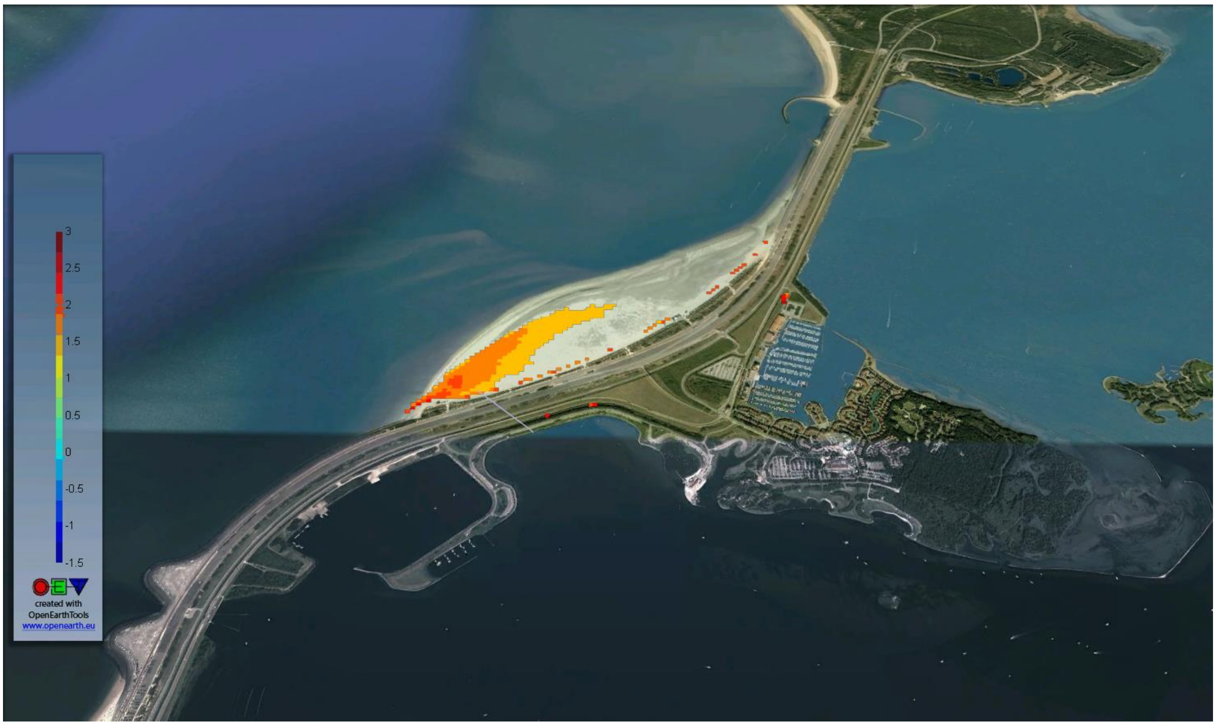


Figure 5.23 - Area between +1,40 and +3,00 m NAP in 2000

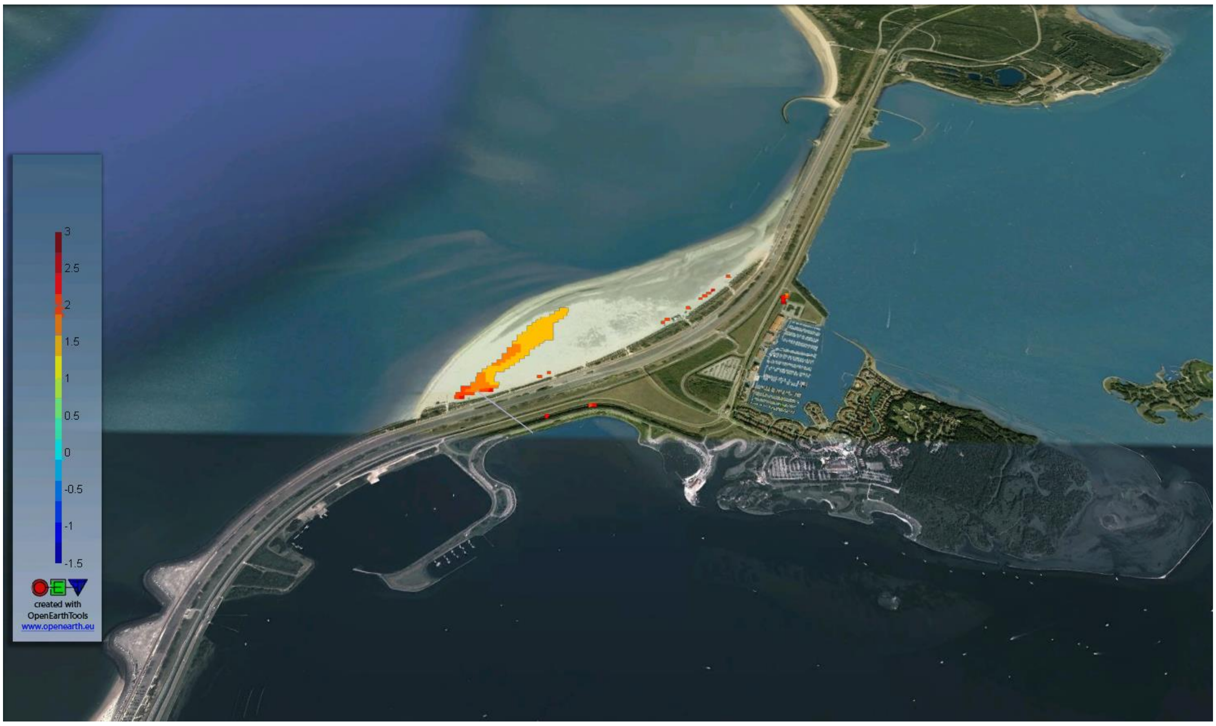


Figure 5.24 - Area between +1,40 and +3,00 m NAP in 2010

5.3.4 Transport between municipalities and provinces

Apart from the changes is total volume and dry beach, the continuous shift of the beach in north-eastern direction is causing problems for entrepreneurs. Their enterprises are located on the beach itself, so in the long run it means the ground is literally washed from underneath their feet. To complicate things even further, the beach is located on the border of two municipalities and the same border is the border of two provinces. This border is located on JARKUS ray 2300, so while in the seventies the majority of the beach was in the municipality Schouwen-Duiveland, nowadays it is in the municipality Goeree-Overflakkee (and thus in the province Zuid-Holland).

	1982	1992	2002	2012
Total sediment +3 to -1.40 [m^3] in Schouwen-Duiveland	1,718,000	907,000	447,000	143,400
Change per decade [m^3]		-811,000	-460,000	-303,000
Total sediment +3 to -1.40 [m^3] in Goeree-Overflakkee	600,000	1,245,000	1,742,000	1,918,000
Change per decade [m^3]		+ 645,000	+ 497,000	+ 176,000
Total sediment +15 to -10 [m^3] in Schouwen-Duiveland	14,975,000	12,527,000	11,376,000	10,551,000
Change per decade [m^3]		-2,448,000	-1,152,000	-825,000
Total sediment +15 to -10 [m^3] in Goeree-Overflakkee	12,545,000	14,146,000	15,494,000	15,579,000
Change per decade [m^3]		+ 1,601,000	+ 1,348,000	+ 85,000

Table 5.4 - Sediment volumes Schouwen-Duiveland and Goeree-Overflakkee 1982 – 2012

Table 5.4 shows this development, more than 90% of the beach in Schouwen-Duiveland is gone nowadays, 1.6 Mm^3 sediment is eroded between the +3,00 m NAP and -1,40 m NAP lines. The erosion in Schouwen is larger than the deposition in Goeree-Overflakkee, only 1.3 Mm^3 is deposited between the set boundaries, which means that sediment is lost to deeper parts, in- or outside the JARKUS rays.

The total volume eroded from Schouwen-Duiveland between +15,00 m NAP and -10,00 m NAP lines is 4,4 Mm^3 (measured rays extend eight hundred meters into the North Sea). On Goeree-Overflakkee, the deposition in these three decades is 3,0 Mm^3. So not only the beach loses sediment, the complete profile loses sediment, which means this sediment is deposited outside the measured rays. The former tidal channel Springersdiep is filling in, but the JARKUS rays don't extend far enough offshore to quantify the amounts of sediment that sink into the former channel. Figure 5.25 shows the situation in 2010 and shows that the area around the channel (2) has become much shallower compared to Figure 5.16. So even without a quantification it is likely that the measured difference in sediment between Schouwen-Duiveland and Goeree-Overflakkee is caused by the filling in of the Springersdiep.

Figure 5.25 - Bathymetry beach 2010 (Open Earth Tools)

6 SWAN Model

In this chapter the process of creating a wave model for the area of interest will be elaborated. First, a description of the SWAN model is giving. Next, the preparatory steps needed for creating this model are given. These steps are analysing the wind and wave climate and creating a bathymetry grid that serves as an input for creating a computational grid. The last step is setting up the model and running different cases.

6.1 Description of the SWAN model

SWAN is a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. However, SWAN can be used on any scale relevant for wind-generated surface gravity waves. The model is based on the spectral wave action balance equation with sources and sinks (SWAN, 2013).

The SWAN model is being developed at the TU Delft and has a long version history, continuously expanding its functionality over the past decades. SWAN is an acronym and stands for Simulating Waves Nearshore. The version used in this thesis is version 40.91 and was specially compiled for use on multi-core computers. This increases the computational speed almost linearly with the number of cores available.

6.2 Wind and wave data analysis

The morphodynamics of a coastal zone are determined by the hydrodynamic forcing on that area. This forcing consists of waves and currents, transporting sediment along the coast. The main driving force behind incoming waves is the wind, although the interaction between wind, atmospheric pressure and the water surface is a bit more complex than that. To predict what will happen to certain stretch of coast, it is important to know what the prevailing winds are and what the velocity of these winds is. (KNMI, http://knmi.nl/cms/content/18185/historie).

Weather data for the Netherlands goes back a long time, the Dutch metrological institute KNMI was established in 1854 and is measuring the weather continuously since then. But even earlier, the famous hydraulic engineer Nicolaus Cruquius began measuring the weather around Delft, as early as 1706. This three centuries long series of weather data is the longest in the world. On a side note, Cruquius was the first to propose a national authority on water management, the same authority who made this thesis possible: Rijkswaterstaat.

6.2.1 Selecting locations

Wave data is measured at several locations along the Dutch coast. Some locations are far offshore, others are located close to the coast. This has its influence on the data that is being produced, wave height and wave direction (among others) change when approaching the coast, traveling into shallower waters. It seems logical to select a location that is as close as possible to the location of interest, the

Brouwersdam. However this isn't exactly the case, wave data that is measured close to the coast has already undergone changes, such as shoaling and refraction, possibly even breaking.

The local bathymetry determines the local wave characteristics. Since the measured profiles along the Brouwersdam are very different from each other, so are the local wave conditions. So you would need a lot of measuring points along that stretch of beach. But that's not feasible in practise, so a different solution is needed. That's where wave models come into the picture, in this case the wave model SWAN is used.

When you feed this wave model with offshore wave and wind data, it is able to calculate the wave characteristics on the points of interest, in this case at the end of every measured JARKUS ray. In the area of the Grevelingen, there are a number of measuring stations available.

Figure 6.1 - Locations measurement stations (Google Earth)

In Figure 6.1 a number of measuring stations are depicted. Three offshore stations and one station closer to the shore. The offshore stations are candidates for providing wave data to the SWAN model.

The Schouwenbank and Brouwershavense Gat 02 stations are part of the ZEGE measuring grid, the "Zeeuwse Getijdenwateren" measuring grid. This grid is operated by Rijkswaterstaat Zeeland. The other two stations are part of a measuring grid MNZ: "Meetnet Noordzee", operated by Rijkswaterstaat Noordzee.

In the past, all stations only measured wave height, later some stations began measuring directional wave information. This directional wave data is needed as input in the wave model SWAN, the model needs three wave parameters: wave height, wave period and wave direction.

For Schouwenbank, this directional information is available from the year 2002 till now. Wave height and period are measured since 1985. This necessary information wasn't available for Lichteiland Goeree. The wave period was only available for the last few years, a period far shorter than for Schouwenbank. The data of the Europlatform has the same problem. So for wave data the best option is the Schouwenbank station.

Apart from wave data also wind data is necessary to simulate incoming waves. Schouwenbank doesn't measure wind data, Europlatform and Lichteiland Goeree do. However, wind data is also measured at Brouwershavense Gat 02, fairly close to the location of research. This location doesn't measure wave direction and is too close to the site for wave data, but for wind data this problem doesn't play a role.

All the data of the ZEGE measuring grid is corrected for errors in the past, like wave buoys that came adrift, were damaged by gunfire (Holthuijsen, 2007) or for other reasons that had an impact on the measured data. For Lichteiland Goeree and Europlatform, the measured wind direction is fairly crude until respectively 2000 and 2004, when wind directions were measured per 10 degrees. For Brouwershavense Gat 02, this was measured per degree since 1982, an order of magnitude more accurate.

With the ZEGE measuring data available in-house and its quality guaranteed by the measuring departments (Meetdienst), the choice was made to combine the wave data of Schouwenbank with the wind data of Brouwershavense Gat. The resulting dataset contains 600.000 measurements, which should suffice to give an accurate representation of the wind and wave climate for the Brouwersdam over the last decades.

6.2.2 Filtering method dataset

The dataset that is used to derive wind and wave conditions for the SWAN model isn't directly applicable. The five measured parameters in this dataset are:

- Wave height H_{m0} [m]
- Wave period T_p [s]
- Wave direction [degrees]
- Wind direction [degrees]
- Wind speed [m/s]

Not all parameters were available since the start of the measurements in the 1980's. Some are incidentally unavailable, because of aforementioned reasons. Some are structurally unavailable until a different type of buoy was placed at that location, like the wave direction that is measured since 2002.

The first filter that is needed, is filtering for the availability of wind direction. If no direction is available, the data is of little use because it can't be put in a bin for the wind direction and needs to be filtered out. The same goes for wind speed, wave height and direction.

There is no filter for missing wave direction values, because this would mean that all values older than 2002 would be deleted. Instead, the data is first divided into wind direction bins and then into wave height bins. The entries without wave direction are bundled with conditions that are very much alike, so that the older data can be used as well.

6.2.3 Wind sea and swell

Before dividing the dataset into classes, a separation is made between wind sea and swell. The former is generated locally, the latter travels into the North Sea basin but was generated in a distant storm. The difference between the two isn't always clear-cut with because the two relevant parameters only give a limited description. Wave conditions with similar wave height and period can be very different. Short, irregular storm waves generated on the North Sea versus long crested swell waves generated far away, both can have a similar significant wave height and wave period.

To split up the dataset in a wind sea and a swell part, the following formula was used:

$$H_s = \left(\frac{1}{4.5}T_p\right)^B + C$$

This formula was developed in the Joint North Sea Wave Project, or short JONSWAP. This research found a maximum wave steepness for wind sea and swell on the North Sea was found, the formula takes this steepness into account to divide waves into wind sea or swell. The original values for the constants in the JONSWAP formula are $B = 2$ and $C = 0$. However, using these values didn't provide a good fit with the data.

A better fit was found with values $B = 1.65$ and $C = -0.7$. A study performed on the neighbouring Oosterschelde, found values of $B = 1.8$ and $C = -0.45$, with the same kind of analysis (Huisman and Luijendijk, 2009) performed on a data of the Europlatform. An additional criterion as applied: only waves with a wave period larger than 5 seconds are considered swell waves. The result of these criteria is a line that splits the dataset in two, a line that has more or less the same shape as was used for the JONSWAP project.

The differences in the values of the formula are due to the local situation, e.g. a changing bathymetry which has its influence on the shape of the incoming wave spectrum. The Europlatform is located on deeper water and a bit further offshore than Schouwenbank, which may account for the differences between the two. However, Schouwenbank is closer to the edges of the SWAN model and therefore its measurements are better suited to be applied as boundary conditions because it is closer to the actual situation.

Figure 6.2 depicts a scatter plot of the dataset and the line that splits the dataset in wind sea and swell.

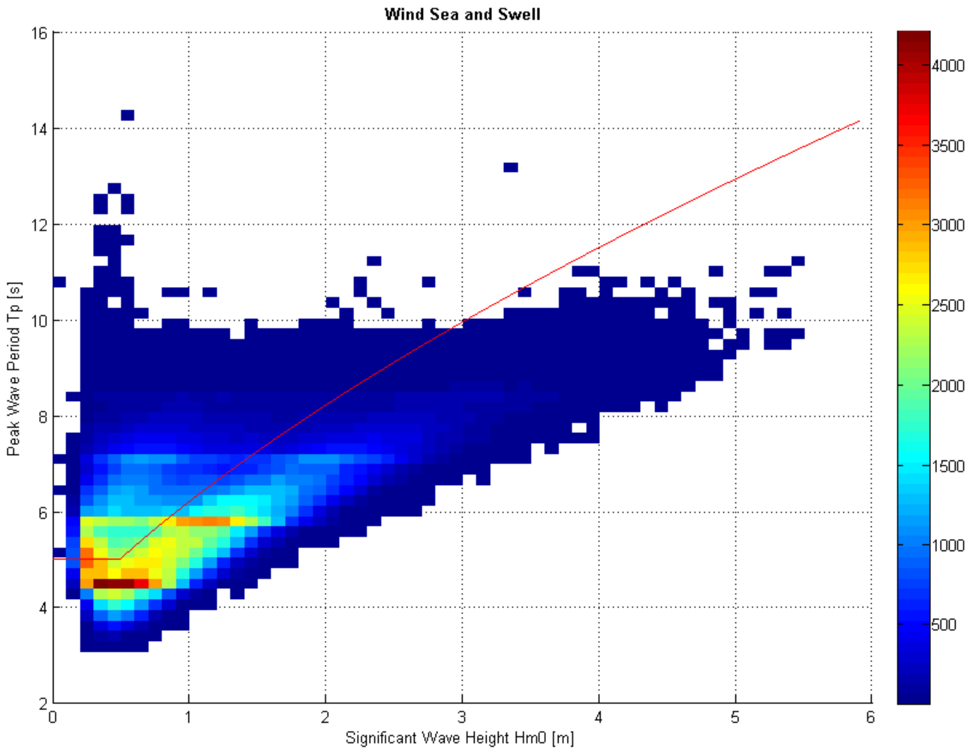


Figure 6.2 - Splitting of wind sea and swell conditions

6.2.4 Classification of scenarios

Now that the dataset consists of two separate parts, the data can be placed in bins for different wind directions and wave heights. First the data is split per wind direction class and then this result is split per wave height class. This analysis is performed with MATLAB, because of the size of the data set. The complete MATLAB code is a few hundred lines long and apart from splitting the data into classes also filters out data that isn't useable or incomplete.

After this process of dividing the dataset over different bins for wind direction and wave height, the other parameters are averaged. Table 6.1 provided an example of a few scenarios that have been made. The full tables for all classes are available in Appendices A.1 - Wind sea classes, and A.2 - Swell classes. A total of 108 scenarios have been made, 63 for wind sea conditions and 45 for swell.

		Avg. Winddir [deg]	Avg. Windspeed [m/s]	Avg. H_{m0} [m]	Avg. Tp [s]	Avg. Wavedir [deg]	N	%	Days	Scenario nr.
Wind direction 240-270 [deg]	$H_{m0} < 0.50$	254,16	4,76	0,38	4,53	270,54	3726	0,960067	3,5042	37
	$0.5 < H_{m0} < 1$	252,88	7,18	0,77	4,96	257,94	11153	2,873759	10,4892	38
	$1 < H_{m0} < 2$	252,45	10,22	1,43	6,00	255,19	18019	4,642899	16,9466	39
	$2 < H_{m0} < 3$	253,59	14,10	2,36	7,15	253,73	5200	1,339868	4,8905	40
	$3 < H_{m0} < 4$	256,35	17,91	3,35	8,17	254,71	629	0,162072	0,5916	41
	$4 < H_{m0} < 5$	258,70	21,70	4,29	8,98	250,83	56	0,014429	0,0527	42

Table 6.1- Scenario's wind direction 240-270 degrees

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6.2.5 Wind roses

In the previous section, the distribution of wind direction and wave heights into bins was discussed and lead to 108 different scenarios that serve as input for the SWAN wave model. All the data is available in the tables in *Appendix A.3 - Wind roses per decade*. However, it is important to understand the basic forcing behind these scenarios, the wind. The prevailing wind direction gives insight into possible dominant sediment transport patterns.

Analysis of the wind data over the available period indicates that the prevailing wind directions are between west and south, the largest bars on the wind rose (Figure 6.3) are those with winds from the south-west. Winds with origins between south and east are the least common.

Due to the large number of observations, wind speeds in the upper bins fall away on the wind rose. To get insight in how storm conditions are distributed among the different wind directions, a second analysis is made for wind speeds above 20 m/s or 9 on the Beaufort scale. Note that the internal empty radius in this figure is a bit bigger, to enhance the visibility of the smaller bins.

The result is displayed in Figure 6.4 and gives more or less the same results, also storm conditions have predominantly south-western directions. The analysis also indicates that storms with directions east to northeast are virtually non-existent.

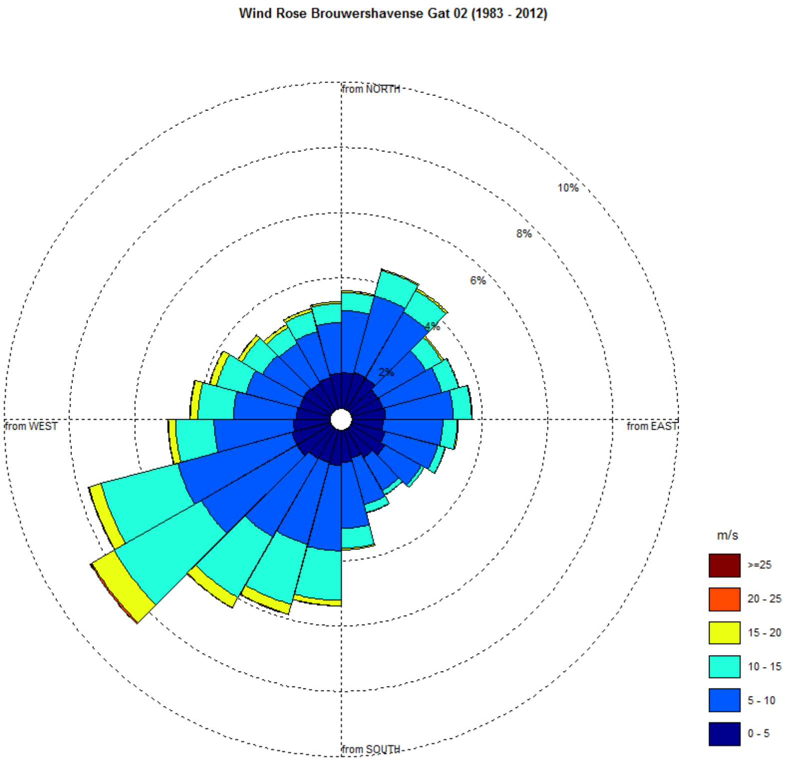


Figure 6.3 - Wind Rose Brouwershavense Gat 02 (1983 - 2012)

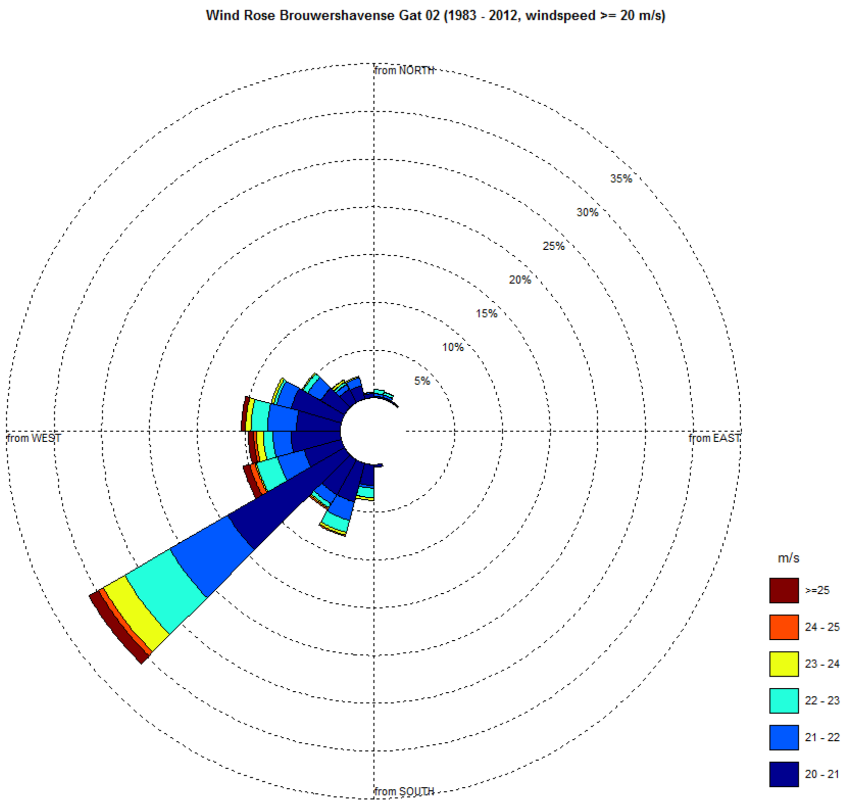


Figure 6.4 - Wind Rose Brouwershavense Gat 02, wind speeds >=20 m/s (1983 - 2012)

These wind analysis have also been made per decade, the wind roses of those results are found in *A.3 - Wind roses per decade*. There are differences between the three decades that these measurements cover, but no significant differences were found. The general picture stays the same. Only for extreme values the differences are somewhat bigger: in the eighties, less values above 20 m/s have been recorded. However, since these measurements started only in 1983, this period is smaller than the others. Storms are extreme events, so it is entirely possible that the difference can be explained by the shorter time period of the measurements. For the simulations in SWAN, the complete period is used.

6.3 Bathymetry data

Periodical measurements of coastal areas and the sea bottom are necessary to understand the behaviour of these systems and to make predictions, on both short and long term. These measurements are used for all kinds of purposes: navigational charts, policy making and for morphological predictions like in this thesis.

When measuring the position of a point in the Dutch coastal system, a distinction is made between coastal measurements ("kustmetingen") and echo soundings made per section of the coast ("vaklodingen").

Coastal measurements consist of echo soundings and height measurements, carried out every year on imaginary lines perpendicular to the coastline, with an intermediate distance of 200 meters. These lines are the previously mentioned JARKUS rays. The echo soundings are made by boat with single beam echo sounding equipment. These measurements are combined with various interpolation techniques to cover the complete bathymetry with a data resolution of 20 by 20 meters. However, this processing has its influences on the accuracy and the resolution of the bathymetry data. A more detailed explanation of this process is given in *Appendix B.1 - Measurement methods and data resolution*.

To set up a computational grid, this bathymetry data is needed as input information. This grid used in the simulations needs to be sufficiently large so that the influence of boundary conditions on the results in the area of interest is as small as possible.

Two grids have been created for the SWAN simulations, a grid of the bathymetry of 2010 and one of 2000. The grids are not of the same size, due to differences in availably of measurements. The grid for 2010 is a more accurate representation of reality, because the measurements are all made in that same year, while for the bathymetry of 2000 data from earlier years had to be used to fill the gaps.

The process of creating the different bathymetry grids for SWAN is further explained in *Appendix B.2 - Bathymetry data*. The resulting grids for the years 2010 and 2000 are found in Figure B 4 and Figure B 6.

6.4 Creating an unstructured mesh grid

The bathymetry of the area around the Brouwersdam is quite complex, the system isn't uniform along the coastline. It is made up out of different elements like breaker bars, tidal channels, shallow parts and beaches. To accurately resolve such a complex bathymetry in a model, the mesh grid for the model needs to be of a high resolution. However, applying a high resolution regular or curvilinear mesh grid to the entire bathymetry will result in increased computational costs, simulation times will become a lot longer.

To address this problem there are basically two options. The first and most used option is the nesting of grids (regular or curvilinear) with increasing resolution. Figure 6.5 shows such an approach, this model was applied to model the sand demand of the Oosterschelde (Huisman and Luijendijk, 2009).This model consists of three grids of increasing resolution and decreasing size, the grid with the highest resolution is applied to the region of interest.

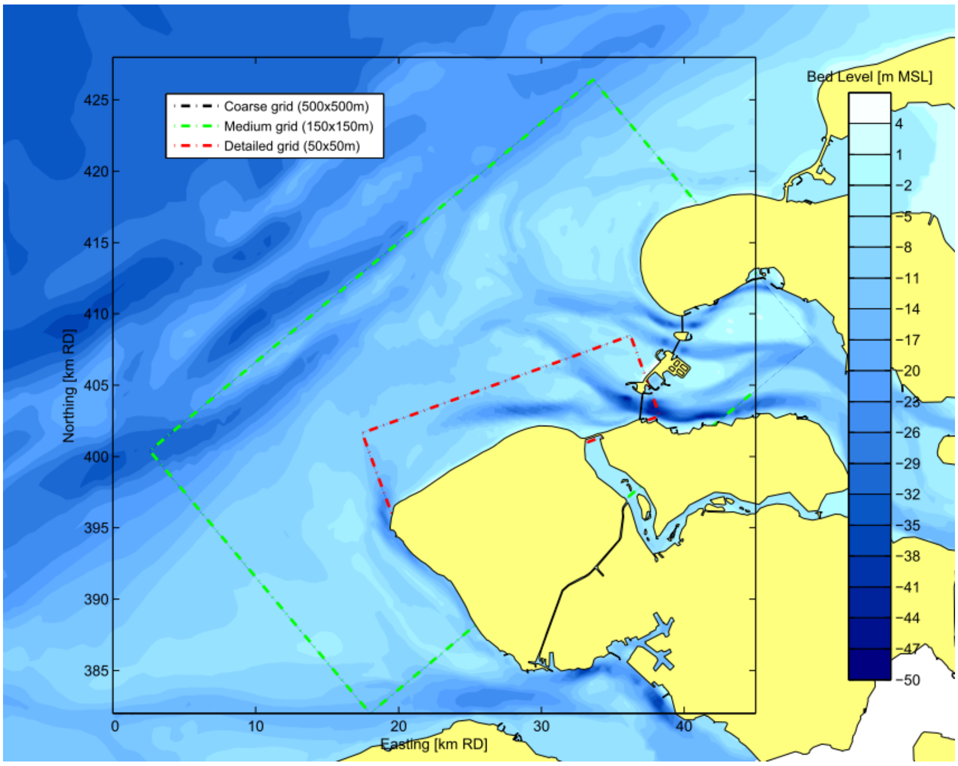


Figure 6.5 - Structured grid with nesting (Huisman and Luijendijk, 2009)

The second option is to construct an unstructured (or irregular) mesh grid. The basic premise behind these grids is that on places with irregular geometry the density of the nodes that make up the grid is increased while on places with a regular geometry the density of the nodes can be lower, making it a more efficient grid option for simulations. Figure 6.6 shows an example of a grid that was made of the area. The figure shows larger grid cells on deeper water while the number of grid cells increases greatly near complex features, such as the tidal channels and around the breaker bar Bollen van de Ooster.

Due to the complex bathymetry around the Brouwersdam, this problem is approached with the use of an unstructured mesh grid. Earlier research (Witteveen + Bos, 2012) led to ambiguous results, near the Bollen van de Ooster the results were good, but near the beach the results were only reasonable, the model indicated the trends but interpretation by experts was suggested by the author.

6.4.1 BatTri processing

Before arriving at the result in Figure 6.6, a number of steps has to be made. One of the tools that is used is a program called BatTri, a program that was developed at Dartmouth College (Dartmouth College, http://www-nml.dartmouth.edu/Software/battri/).This program provided a graphical user interface (GUI) between MATLAB and Triangle. The latter is the program that is performing the actual creation of the unstructured mesh grid and was developed at the University of California at Berkeley (University of California at Berkeley, http://www.cs.cmu.edu/~quake/triangle.html)

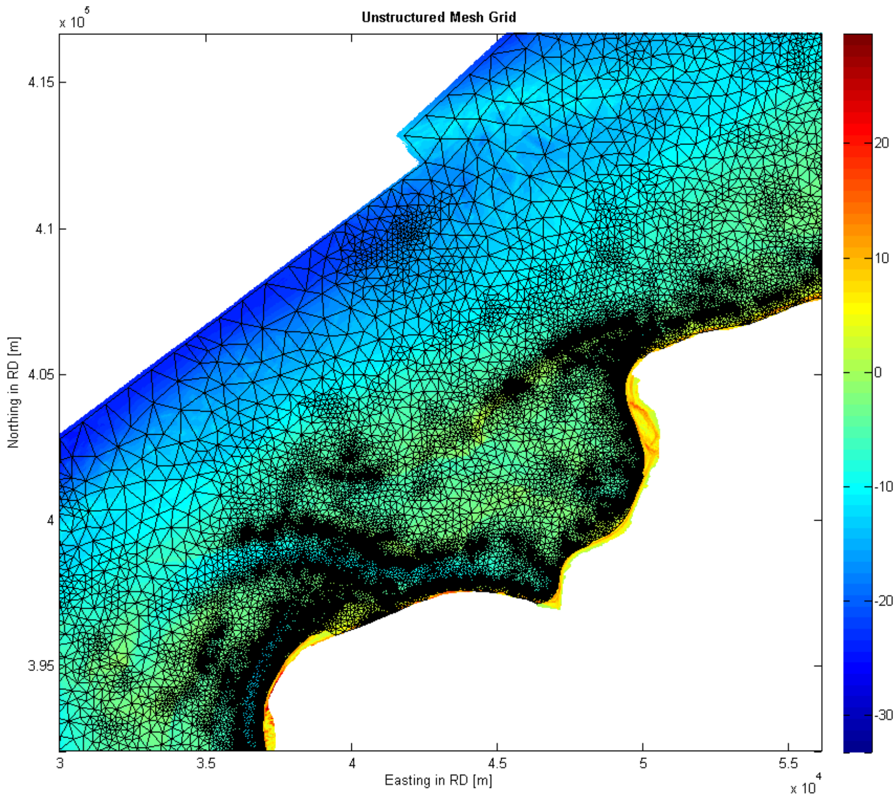


Figure 6.6 - Unstructured mesh grid

SWAN in its current functionality only supports triangular meshes, Triangle performs these triangulations by a process called Delauney-triangulation, a method of triangulation that can be used for performing triangulations on sets of discrete data points like bathymetry data. The method of triangulation has as main property that it maximises the smallest internal angle of every triangle. This property is useful in the field of computational modelling because it minimizes the floating-point error in numerical calculations and is therefore beneficial for the numerical stability of the calculations.

BatTri is able to let Triangle perform Delauney-triangulations in different ways, the user can choose from various methods and is able to set the constraints wherein Triangle has to operate. There are eight available methods in BatTri and each method has several adjustable parameters. The constraints that can be set are depth limits and the maximum number of triangles that can be used. So the number of different grids that can be created is virtually infinite.

However before the actual triangulation is started, one has to set the boundaries between which the triangulation has to be performed. These boundaries can be the lateral boundaries of the dataset but also areas on land or islands that have to be omitted. In this case, the dataset contains many points on land, like dunes with heights almost 45 meters above sea level. These points serve little purpose in the wave model and should be placed outside the boundaries of the triangulation. Figure 6.7 gives an overview of the main steps that have been performed to arrive at a grid that is suitable for a SWAN calculation. Each step contains a number of sub steps, but for clarity they are left out of the chart.

Since the approach with unstructured grid in SWAN seems to be fairly novel in master theses in coastal engineering, all the steps that were performed to create at a suitable grid in are given in *Appendix C.1 - BatTri processing*.

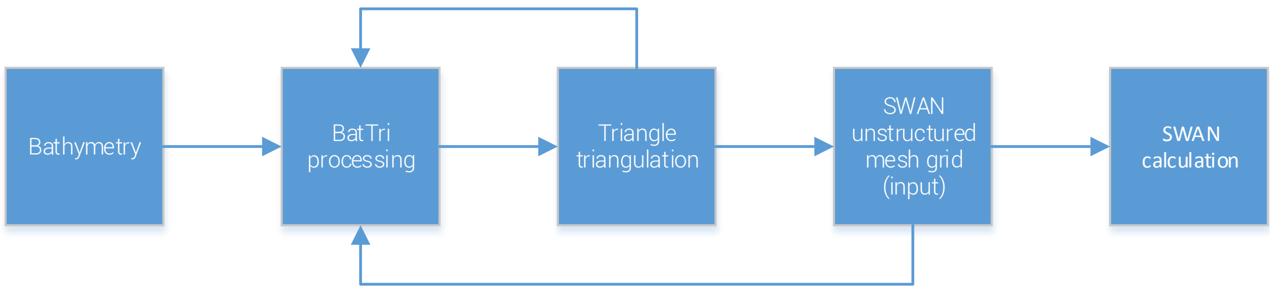


Figure 6.7 - Schematization of steps for SWAN

6.5 SWAN calculations

The North Sea area is an area that is prone to storm surges and water levels can rise to levels much higher than the average level. For a shallow area like the Brouwersdam, a rise in water level of more than three meters above average high tide is possible, resulting in waves that are a lot bigger than average. However these water levels are only possible under very specific conditions, like storms from the north-west combined with spring tides.

More frequent storm events also have their specific circumstances, most storms originate from the south-west, while easterly winds result in the lowest water levels (*Appendix A* :). Linking each wind direction to a certain water level is possible and could be done by averaging the occurring water levels into the wind bins as has been done with the other wave parameters. However, the result would be a bit ambiguous. On the one hand you would see different water levels for different scenarios and you would be able to run all these scenarios in SWAN. On the other hand, the highest waves only occur during high tide due to the limited depth of the basin. The output values of SWAN are the input for UNIBEST, where the water level has to be set again, which would be redundant because these averaged water levels per wind bin already have a tidal component in them. It is theoretically possible to filter out that component so that wind setup remains, but that would require tidal information for the complete measurement series of almost thirty years. That information isn't readily available, therefore other values have be chosen to set the water levels in the SWAN model.

The choice has been made to use three different water levels: average high tide, average low tide and the overall average water level of the nearest measuring station, Brouwershavense Gat 08. These parameters can be found in *Appendix D*, along with extreme value statistics and recorded extreme events for this area. Note that these values are statistics made by Rijkswaterstaat in 1991 and seem old, however these are the latest official statistics available. One might think these values would have been changed due to phenomena like sea level rise, however this doesn't seem to be the case. The values are actually a little lower for the year 2012 than for 1991, but the difference is only a few centimetres. All kinds of reasons are possible, like the tidal forcing that is going through cycles. The lunar nodal cycle for example has a period of almost nineteen years, combined with a lot of other tidal variables it has its effect on the occurring water levels. But also the local bathymetry has its effects on the propagation of the tidal wave inside the area. The values of the year 1991 are still used in tidal tables issued by Rijkswaterstaat and are almost the same as more recent statistics, so for this research the same values are used.

The next step is to perform the calculations for all the different wind and wave scenarios with SWAN. A total of 108 scenarios, 63 for wind sea and 45 for swell conditions for 3 different water levels on 2 different bathymetries.

6.5.1 Model setup and parameters

A number of test runs were made with different mesh refinement method produces to determine which method gives the best results when imposing the same set of boundary conditions on these mesh grids. These test runs were all performed on the grid of the year 2010, the same method that was chosen for that year is used on the grid of the year 2000. The chosen grids are refined using the h-refinement method, this method was chosen because it is the most used method, but the differences between the grids could not adequately be explained. Not only the refinement method but also the number of nodes in the grid led to different results. A comparison of the different grids and the parameters that were used can be found in *Appendix C.2 - SWAN test runs*.

After performing the test runs, SWAN was configured to perform the actual simulations with the different wind conditions found in *Appendices A.1 - Wind sea classes and A.2 - Swell classes*. SWAN normally calculates one scenario at a time and the user is required to enter the parameters for each scenario in the SWAN input file. However entering all the different scenarios by hand is a lot of work and would require you do start a new run every time another one finishes. Once again MATLAB proved to be an invaluable tool. All the wind and wave scenarios are loaded into the program and a script was written to write input files for SWAN, start the first calculation, let it run till it is finished an start the next scenario, a so-called batch run.

The input scenarios for each batch run are different on six parameters, the first five are different for each scenario, the sixth one is only different for wind sea and swell. This parameters are:

- Wind direction [degrees]
- Wind speed [m/s]
- Significant wave height [m]
- Peak Period [s]
- Wave direction [degrees]
- Directional spreading [degrees]

The output files SWAN creates are tables and MATLAB structures, the tables are used as input for the next step in the modelling phase, coastline model UNIBEST. The MATLAB structures are used to plot key data like significant wave heights and wave periods. What is important is that SWAN writes output information for the right locations. These locations are the x- and y-coordinates of the JARKUS rays that serve as base for the coastline model. SWAN load the file with these coordinates and writes tables with the specified wave parameters per location. The 108 scenarios have to run six times, three times per water level and all of that for two different bathymetries. The end result are six full batch runs that will be loaded into UNIBEST, see also Figure 6.8

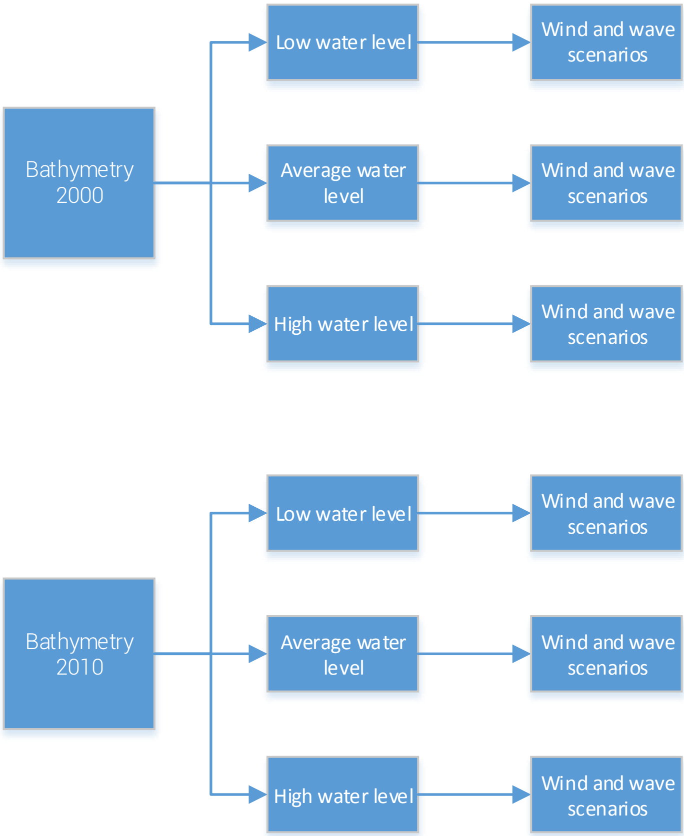


Figure 6.8 - SWAN model scenario's

Apart from parameters that are different for each scenario, the input files for SWAN have to contain which physics the program has to use in its wave calculations. For this study the settings that were used are the following:

- 3rd generation mode for wind input, quadruplet interactions and white capping
- Depth-induced breaking enabled
- Triad interactions enabled
- Diffraction disabled (due to instability issues with SWAN (Enet et al., 2006))

All these settings were used with the standard values as provided by the SWAN manual (SWAN, 2013).

6.5.2 Results

The results of the SWAN calculation are used in the next step of the modelling process, the coastline model. Before arriving at the point, the results of the wave calculations are examined. Not all can be reviewed due to the sheer number, so a number of scenarios is picked and examined. Three scenarios with wind sea conditions, one with swell and all will be compared for both simulation years, 2000 and 2010 as well as for the different water level scenario's.

The first scenario that is picked, is the scenario with the highest offshore wave heights and wave periods, with winds between 300 and 330 degrees (north-west): scenario number 55 in *Appendix A.1 - Wind sea classes*. The second scenario is the most common one, winds between 210 and 240 degrees (south-west) and an average wind speed of 11 m/s and waves between 1 and 2 meters (scenario 33).

Scenario number three is also fairly common one, winds between 30 and 60 degrees (north-east) with an average wind speed of 10 m/s and waves between 1 and 2 meters (scenario 8). The fourth and last scenario that is chosen is the most common scenario for swell waves, waves entering the domain at angle of almost 360 degrees with winds between north and north-east an average wave height of between 0.5 and 1.0 meters (scenario 65). This scenario is found in *Appendix A.2 - Swell classes*.

Graphs of all scenarios mentioned above can be found in *C.3 - SWAN model results.* The graphs show that the wave height near the beach depends strongly on the occurring water level, at high tide waves just in front of the beach are more than twice as high as during low tide. The sand bar Bollen van de Ooster provides shielding from waves for the whole area during low tide, but becomes submerged during high tide. In 2000, the biggest part of this sandbar was submerged, even during low tide, in 2010 the sandbar has gained height and a bigger part stays dry during low tide. At high tide or during storms, it will become submerged again, but the wave height behind it is still less than in 2000.

Waves entering through the former tidal channel Brouwershavense Gat are the biggest source for waves near the beach, the tidal channel is still the deepest part of the area and all figures show that the biggest waves occur there. However, the channel is filling up and this has an effect on the wave height. The models show that waves entering the area are less high for 2010 than for 2000, the difference ranges from 10 to 20%.

Scenario 55, with the highest offshore wave heights of more than 3 meters, leads to waves of about 1,4 meters just in front of the beach during high tides, at low tides this height is reduced to 0.5 meter. This scenario causes the biggest waves near the beach. These waves aren't the most important contributor for the observed sand transport from south-west to north-east because the wave direction of these waves is between 330 and 350 degrees near the beach. More westerly winds like scenario 33, the most common scenario, have a bigger contribution to this transport because the wave directions are between 250 and 260 degrees; a direction that is more aligned with the observed direction of the sand transport. Please note that the wave direction quiver plots are based on a rectangular interpolation of the unstructured mesh grid to reduce the density of the wave direction arrows near the beach, the rectangular grid has a resolution of 100 m x 100 m and the wave directions are modelled during high tide.

Swell waves like scenario 65 originated from a more northward oriented direction and don't penetrate as far into the area, because the Bollen van de Ooster shields the area from these waves. The wave direction is between 350 and 360 degrees, this leads to sand transport in south-western direction, the opposite of the net transport direction.

Scenario 8 and 33 show that on average the wave height in the area isn't very large, wave heights are well below a meter for the most common circumstances. These scenarios also show that the waves at the south-western side of the beach are higher than more north-eastward. All wave scenarios have this characteristic, and although wave heights are fairly low under the most common circumstances, the most sediment is brought into motion at the south-western side of the beach. From the four chosen scenarios, only scenario 33 contributes to the sand transport in north-eastern direction, the other scenarios transport sand in southern directions. However with the predominantly westerly winds and the flood dominated tidal motion in front of the beach directed north-eastwards (Figure 7.3), the net sand transport is in that same direction.

7 Unibest model

In this chapter an analysis is given of the beach at the Brouwersdam using the shoreline model Unibest. The SWAN model output data is used as input for this model. The Unibest model is used for two cases, the first one is a hindcast of the developments of the beach over the last decade, from 2000 to 2010. The second case is a forecast for the developments from 2010 into the future.

The results of the hindcast modelling process will be compared with the actual developments over this period. The simulation process can be performed with different transport formulae, where each formula has its own parameters that can be set. Also physical parameters such as sediment fraction have its influence on the end result of the simulation. A number of simulations with different parameters have been performed to gain insight in the sensitivity of the modelling process on a number of parameters.

After calibrating the hindcast model, the forecast part of the modelling process will be started. The forecast will be executed with the same transport formula as the hindcast model and will be used to give a prediction of the development of the beach for the next decade.

7.1 Unibest

Unibest is a software package developed at WL | Delft Hydraulics and is used for the simulation of longshore and cross-shore processes and related morphodynamics of beach profiles and coastline evolution (Deltares, 2011).

The name of the package is an acronym for UNIform Beach Sediment Transport and the software is used to study the medium to long-term coastal evolution. The model is best suited for wave-dominated coastal systems, the model only has basic implementation of (tidal) currents.

Unibest is a 1D modelling package and has as advantage that long-term evolution of a shoreline can be simulated computationally efficient. The computation time necessary varies from minutes for simple cases to a few hours for more complex scenario's like in this thesis, so this gives the possibility to try different model parameters to gain insight in how the model responds to these changes.

Unibest itself consists of two modules, the LT and the CL modules, short for Longshore Transport and CoastLine. The LT module calculates the transport capacity at every beach transect for several coastline orientations near to the initial orientation of the concerning transect. The output of this module are so-called S-Φ curves, curves that give the transport capacity S for coastal orientations Φ near the initial orientation. The CL module uses the output of the LT module to simulate the developments on the actual coastline and has to be provided with the exact orientation of and the spacing between the individual profiles, in this case the JARKUS rays. Also other spatial features such as revetments can be included in the model, no erosion can occur beyond these points.

7.2 Model setup

The coastline model for the beach at the Brouwersdam is build up out of twenty-one JARKUS rays and stretches from the dewatering sluice southwest of the beach to the small port northeast of it. An overview of the location can be found in Figure 5.11. The rays are not completely uniform, there are differences in the amount of sediment per profile, the beach itself is the most notable representation of that observation, making this coastline a challenging environment to model. However, the long-term trend of this coastline is a very clear one, the beach is shifting north-eastwards, a development that is favourable for this modelling process since Unibest isn't suitable for modelling short-term variations without evident trends.

7.2.1 LT module

The longshore transport module of Unibest is used with different transport formulae to get insight in the differences in sediment transport between them. The formulae used are: Bijker (1971), Van Rijn (1993) and Van Rijn (2004), for a description of the exact formula, reference is made to the Unibest manual (Deltares, 2011).

For calculating the sediment transport capacity, the most important factor is the wave climate. The wave climate is calculated with the SWAN model in the previous chapter. This model calculates the wave parameters at the start of each JARKUS ray and that data serves as input for the LT module of Unibest.

Since the former Grevelingen mouth is a shallow area, the wave height depends on the occurring water level, which varies with tide and also due to storm surges. However, each water level requires a separate SWAN model run, which is a computationally expensive procedure. Therefore the water level has been modelled in three different steps: low, average and high tide, for both bathymetry of 2000 and 2010 (Figure 6.8).

These same water levels are used in Unibest, each water level represents one-third of a year in the simulation run of a year, where each one-third consists of the calculated wind- and wave scenarios. These scenarios can be found in *Appendix A :*.

In the LT module it is possible to set tidal current velocities, however the implementation of these velocities is a very basic one: the velocity is extrapolated over the depth of the profile with the square root of the set velocity. This implementation isn't very well suited for more complex flow patterns like those in the former Grevelingen mouth, which vary significantly with spatial location and tide. A number of simulation runs have been performed without tidal flow and with different flow velocities. Apart from that, the stability of the model left much to be desired when provided with spatially different tidal flow velocities, on quite a number of occasions the program terminated completely without providing any insight in what caused the problem.

7.2.2 CL module

The coastline module of Unibest is the module that gives insight in the actual developments of a coastline by giving the possibility to insert a reference line against which the retreat or advance of a section of coast is measured. The data provided by the LT module serves as base for this simulation. The most important feature of the CL module is the ability to insert features such as revetments, in this case the Brouwersdam, because obviously no erosion can occur when no sediment is left above the closure depth in a transect.

At the ends of the model it is necessary to set boundary conditions, for this simulation the boundary conditions are set to 'angle constant', which means that the coastline is considered to be at a constant angle beyond the boundaries. This is the option that gives the best representation of the real situation, although it is not an exact representation of reality with on the south-western side a dewatering sluice with small groynes and on the north-eastern side the groynes of the small port. The other options however are less suitable, for instance the standard setting 'Y constant', which means the boundary is kept at a fixed location, does not work because in reality sediment can be deposited in the last transect at the boundary.

7.3 Hindcast model results

The aim of the hindcast model is to simulate the shoreline evolution between the years 2000 and 2010. The model results will be compared with the real evolution that has been observed in that decade and the differences between the model results and reality will be discussed. An aerial photograph of the year 2000 (Figure 7.1) serves as reference for how the situation was at the start of the period, a photograph of 2010 is used to compare the model simulations with reality.

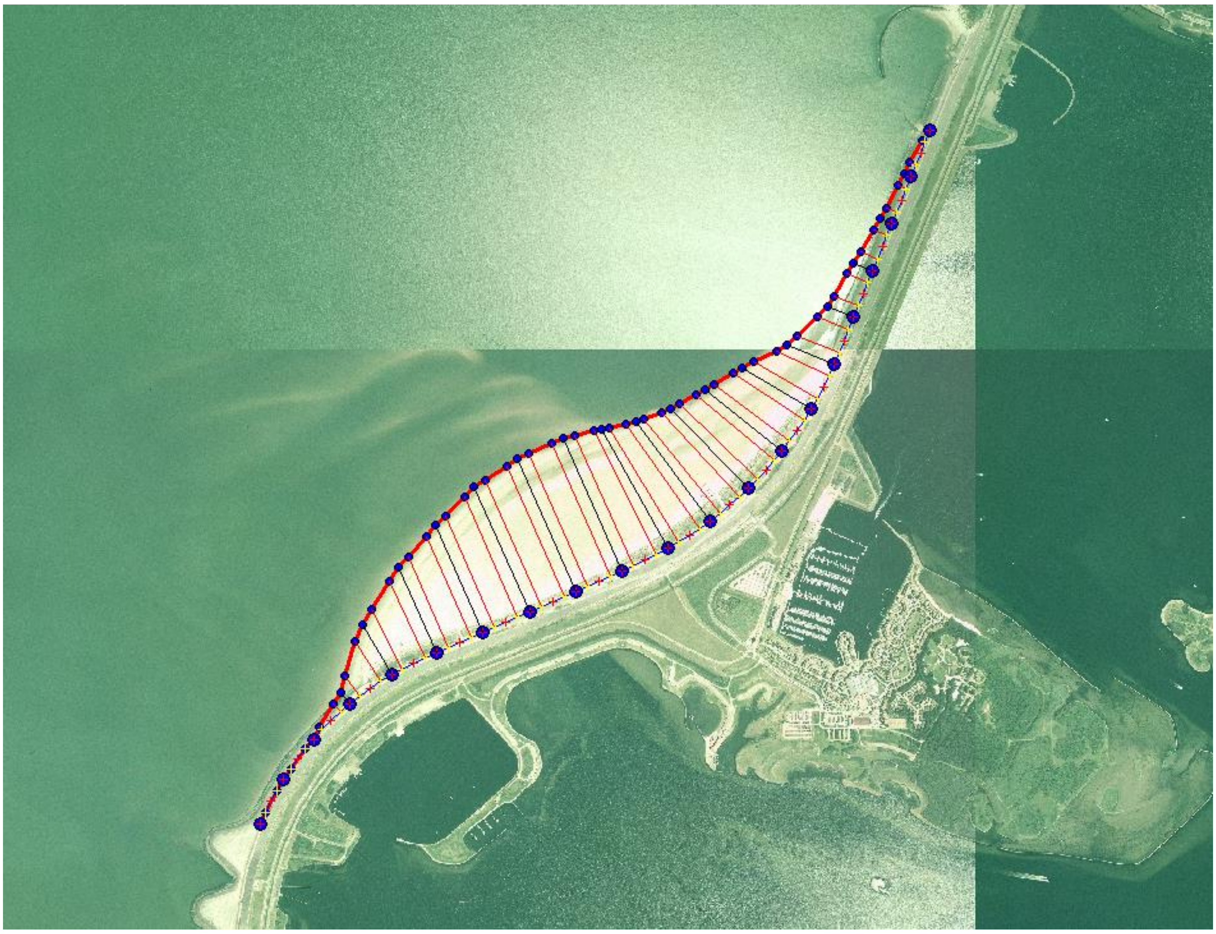


Figure 7.1 - Unibest CL model 2000

The results of ten years simulation time with the three different transport formulae are found in Figure 7.2, the observed erosion or sedimentation is measured against the reference line found in Figure 7.1 that has been drawn on the low water line. The basic settings for the three formulae are the same, no tidal flow velocities and no wind driven currents are enabled in the model.

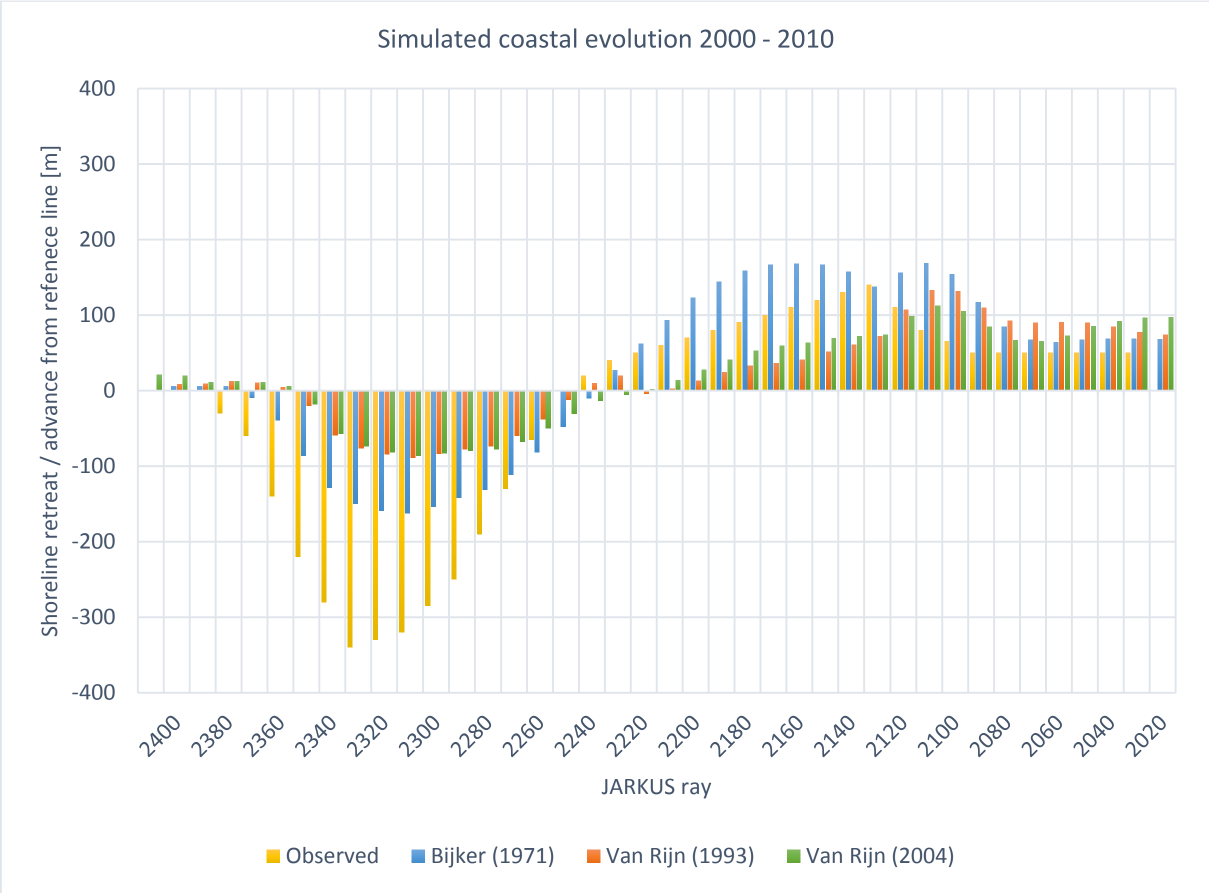


Figure 7.2 - Coastline evolution 2000-2010

The Bijker formula gives the best results for the observed rate of erosion on the south-western side of the beach of the three formulae, although the observed erosion is still larger in reality. Further north, from ray 2200 to 2020, the predicted sedimentation is higher than observed. Overall the formula performs reasonably well, however it is a possibility that the formula is closer to the observed erosion due to its known shortcomings, where the most important one is the overestimation for low transport capacities due to a lack of a beginning of motion criterion.

Van Rijn (1993) and Van Rijn (2004) perform in a similar way, both aren't able to reproduce the observed rate of erosion and sedimentation from ray 2400 to 2140 while both overestimate the erosion on the most northern rays. The centre of gravity of the beach, the transect with the largest sediment volume, shifts north-eastwards in reality and both models are able to replicate that trend but at a slower pace. Between the two, there are differences on individual rays, Van Rijn (2004) is closer to the observed values, making it a better choice.

Apart from the presented results in this section, a sensitivity analysis with different values for sediment fractions, different wave-current interaction formulae and with inclusion of wind driven currents and/or tidal flow velocities has been performed. For the Van Rijn (2004) formula the trends remained fairly stable when choosing realistic values. The Bijker formula on the other hand is sensitive to the inclusion of tidal flow velocity, small changes in the velocity per ray could result in a blow up of the simulation to very large negative or positive values, making the model terminate itself within seconds. Both the Van

Rijn (1993) and the Bijker formula are also sensitive to the inclusion of wind driven currents in the UNIBEST calculation. The results of the simulations where wave driven currents were included are found in Figure E 1.

The conclusion from the hindcast model simulations is that the simulated evolution of the beach is different than observed over the last decade. Although the tidal flow velocities in the tidal channels have been reduced by 45-80% (Cronin, 2011), tidal flow velocities keep playing an important role near the beach. The largest flow velocities are observed at the south-western tip of the beach, the velocities get smaller north-eastwards. Bijker and Van Rijn (2004) both have its strengths and weaker points, however both differ from reality, probably due to tidal flow induced erosion on the south-western side of the beach.

A conclusion that also can be drawn from the observations and simulations is that on locations with larger tidal flow velocities, the hindcast models deviate more from the observed developments than on locations with a smaller velocity. A data analysis of Delft3D data from (Witteveen + Bos, 2012) provides more insight into the occurring tidal flow velocities, as can be seen in Figure 7.3. This figure gives the difference between the minimum and maximum tidal flow velocities per grid point during two simulated spring-neap cycles on the bathymetry of 2010. No model data was available for the year 2000.

The flow pattern around the beach is a complex one, the tidal flow rotates around the beach, which is a pattern that can't be modelled in Unibest. This flow pattern isn't stationary, but undergoes the same spatial shift as the beach, making it even harder to model this phenomenon in a model with only basic implementation for tidal flow velocities like UNIBEST.

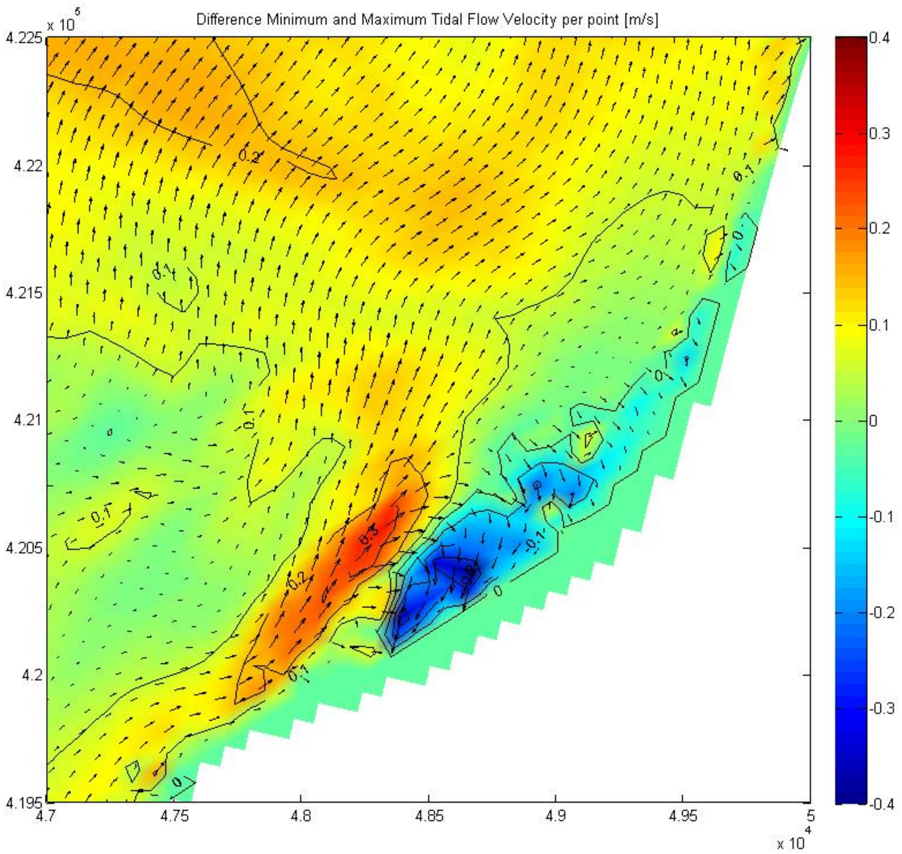


Figure 7.3 - Difference minimum and maximum tidal flow Velocity

7.4 Forecast model results

The aim of the forecast model is to simulate the shoreline evolution from the year 2010 into the future. Bathymetry data from 2010 is used, because that is the most recent information available, so the model has a slight overlap with reality. The model results will be compared with the hindcast model and the JARKUS data from 2010 to 2012. An aerial photograph of the year 2010 (Figure 7.4) serves as reference for how the situation was at that time.

The model results of the hindcast model showed that the Van Rijn (2004) and Bijker transport formulae give the best results when simulating the evolution of the beach during the last decade. This formulae will also be used to make a prediction for future developments, the Van Rijn (1993) formula has little added value over the 2004 formula and these results will be omitted in this section.

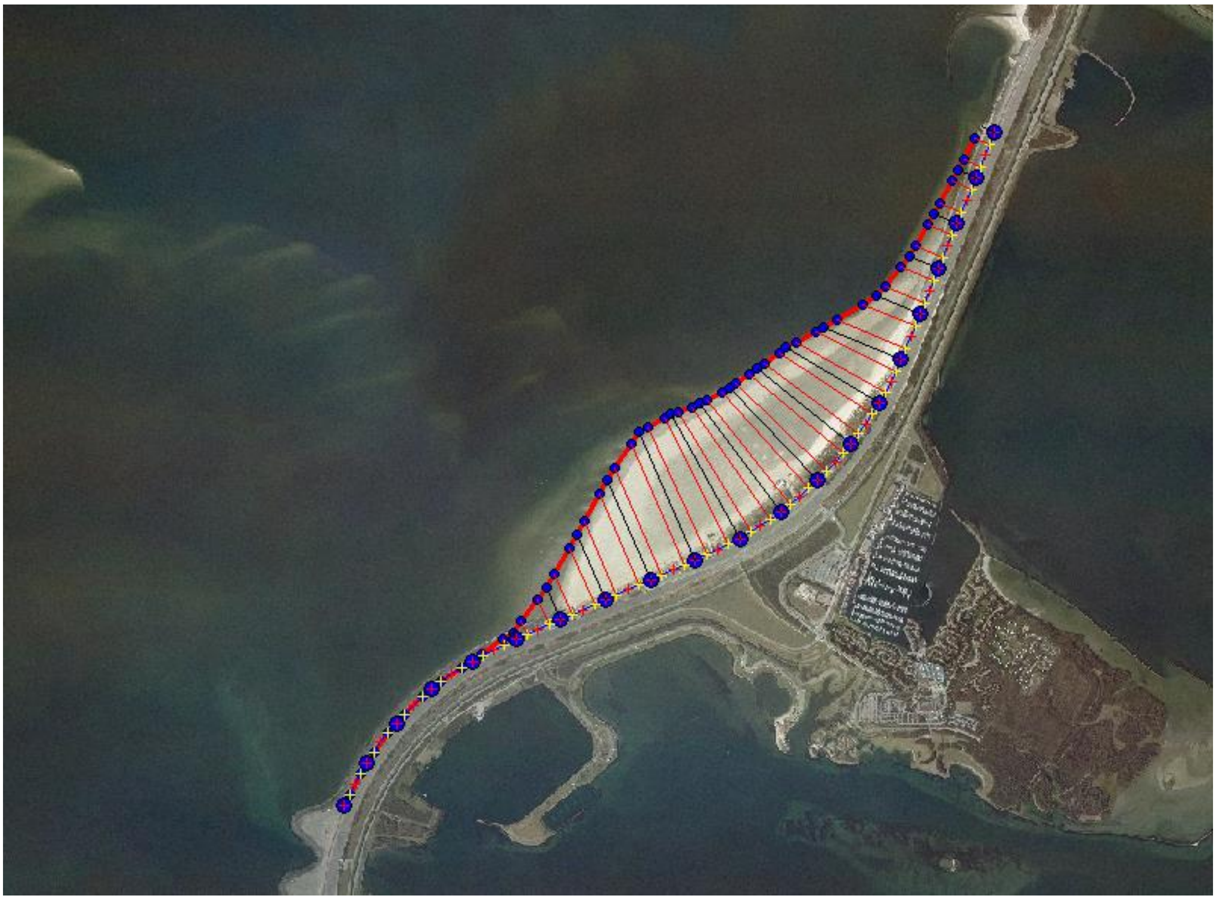


Figure 7.4 - Unibest CL model 2010

Both formulae are used without tidal flow enabled in UNIBEST, the result with wind driven currents enabled can be found in Figure 7.5 , the runs with wind-driven currents enabled can be found in Figure E 2. For both the simulated sand transport is in the same direction as it was for the hindcast model. The amount of erosion and sedimentation is smaller than the model results for the hindcast model. This finding is in accordance of what is found in SWAN model results, the resulting wave heights for the year 2010 simulation are lower than for the year 2000. However, the observed sand transport between 2000 and 2010 was quite a bit larger for the south-western part of the beach than could be simulated with the hindcast model. The premise is that the same conclusion can be drawn for the forecast model, the actual erosion there shall be higher in reality.

Van Rijn (2004) calculates lower erosion and sedimentation than the Bijker formula and also shows little change between rays 2200 and 2140, while Bijker predicts an advancing shoreline on these rays, a prediction that is in accordance with what is observed from 2010 till now.

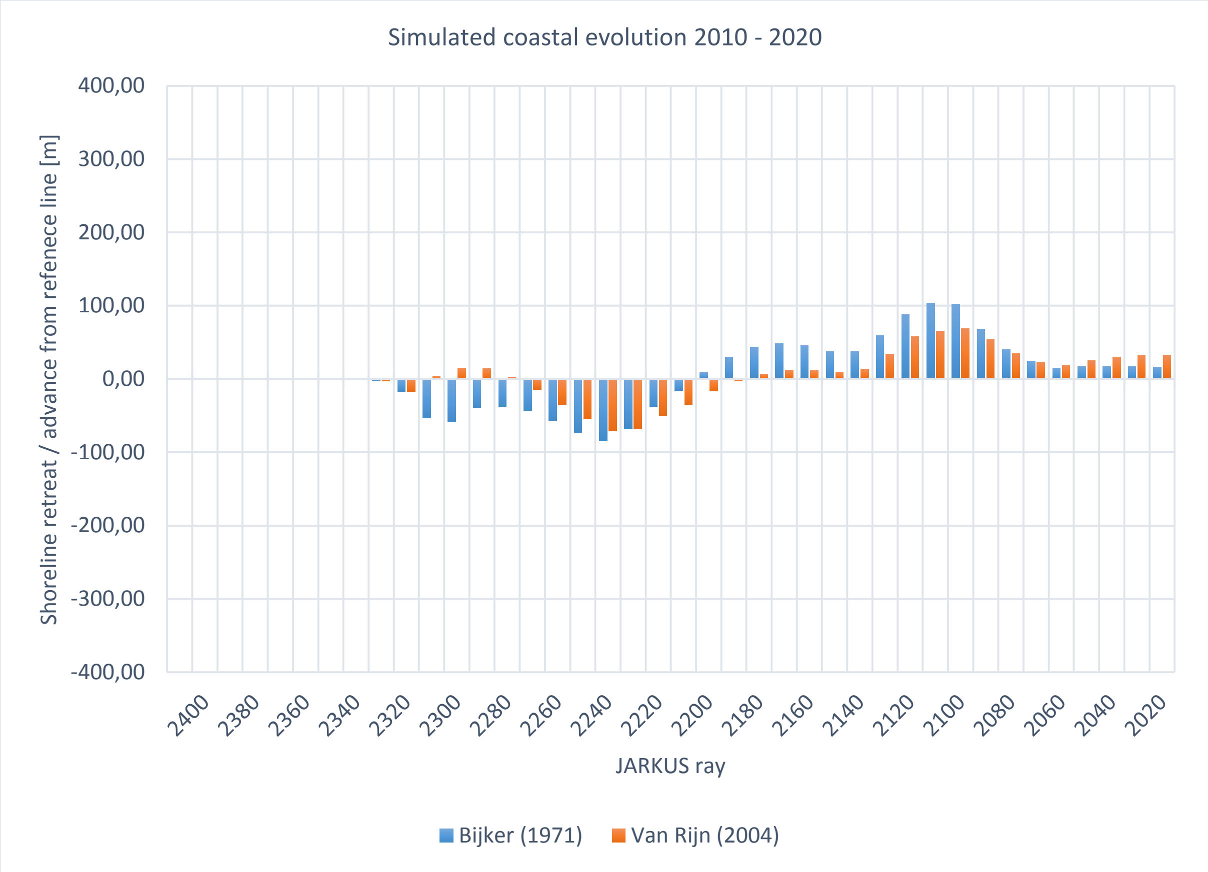


Figure 7.5 - Simulated coastal evolution 2010-2020

When wind driven currents are enabled, the sand transports per ray increase with on almost all rays for the Bijker formula, on average this increase is 30%. For the hindcast model the simulation with the Bijker formula resulted in quite a different erosion and sedimentation pattern, while for the forecast model the shape stays the same.

The results for Van Rijn (2004) are a bit different, the model predicts erosion instead of sedimentation on rays 2300 and 2320 with wind driven currents enabled, which is a better prediction because it is in accordance with observations.

What can be concluded is that results for the forecast model are closer to reality with wind driven currents enabled in UNIBEST, while for the hindcast model this led to different beach shapes and therefore inaccurate results. For both can be said that the modelled net sand transport from rays 2320 to 2200 in north-eastern direction is too small and because the hindcast model already underestimated this amount, it is likely that when the forecast model predicts an even smaller amount, it also underestimates this. The JARKUS data in Table 5.3 support this hypothesis, such a slowdown in transported quantities can't be found in recent data. The sedimentation on the north-eastern side is more in line with recent observations, the forecast model performs better on this section than the hindcast model did.

The forecast model has simulated only ten years into the future, it is possible to let the model simulate further into the future, but extend of the model is limited to the JARKUS rays, there are no measurements more north-eastward because this is where the small harbour is located. The groynes and the harbour basin itself will have an effect on the shoreline evolution. The beach is still shifting in that direction and it is likely that when the rays with the biggest sand volume in them are getting closer to the harbour, the basin will start to accumulate more sediment than it does nowadays. What the exact developments will be is hard to model in UNIBEST, the model isn't suited for complex flow patterns around groynes and in harbours, so no simulations beyond 2020 are provided. What also plays a role is the underlying SWAN grid, the wave heights are modelled on the grid of 2000 or 2010 and the situation is assumed to be stationary for the next ten years of simulation. The bathymetry isn't updated in the SWAN model during wave simulations, while there are changes in the wave characteristics of the area due to changes in the bathymetry (*Appendix C.3 - SWAN model results*)

Also important to note is the location of the former tidal channel Springersdiep (Figure 5.8), the remains of the channel are still deeper than its surroundings. Due to the ongoing shift of the beach, the sediment budget in the northern rays is getting bigger, meaning that the available sediment to sink into the former channel is increasing. When the sediment settles there, the amount of sediment in higher parts of the system like the beach, decreases. The last two years show a decline in the amount of sediment between the low water line and the dune foot (Table 5.3) and also the total amount of sediment over full length of the JARKUS rays shows a large decline over the last decade (Table 5.4).

8 Developments and solutions

The previous chapters have shown that the shifting of the beach in north-eastern direction and the decline in dry beach area are trends that are still continuing and are likely to continue in the foreseeable future. Stakeholders of the beach report that erosion is happening at a higher pace now than it did in the last few years. Despite that this latest trend can't be confirmed by models or data, because there is no data that recent, it underlines that the problem isn't going away by itself.

All parties involved recognize the problem and the general desire is to find a solution. However, the situation is more complex than just the aforementioned problem. There are other circumstances that have to be considered when trying to find a solution. The first part of this chapter will treat the developments that have to be taken into account, the second part of this chapter is about possible solutions to the problem, taking the circumstances mentioned in the first part into account.

8.1 Developments

8.1.1 Flood safety

In 1990 the Dutch government decided that the coastal foundation of the Netherlands shouldn't get smaller due to erosion of this foundation. To achieve this goal, the basic coastline (BKL) was created. The aim is to keep the coastline dynamically stable at that location, when the coast retreats beyond this point, measures have to be taken. The preferred and most commonly used method to counteract this erosion is beach nourishment, when this is not possible, other options are taken into consideration. The eventual goal is, off course, protecting the land from the sea.

Many people have asked why the beach at the Brouwersdam isn't part of this beach nourishment programme, because this is common practice for a lot of beaches in the south-western parts of the Netherlands, also for beaches very close to the Brouwersdam, like the ones near Renesse. The reason is a fairly simple one, but one that isn't very well known: there is no safety issue at play for the Brouwersdam.

The Brouwersdam separates the North Sea from lake Grevelingen and the dam itself provides the necessary safety for the hinterland, so no BKL was established. When the sand in front of the dam that now forms the beach disappears, waves will break directly on the dam, but the dam is designed to withstand these forces and is also high enough to protect the hinterland against extreme water levels. This means that beach erosion isn't considered to be a problem on grounds of safety against flooding. The practical implication is that the official policy of Rijkswaterstaat in this case is that no beach nourishment needs to be provided in the context of flood safety, so solutions have to be sought in other contexts.

8.1.2 Maintenance costs

With the disappearing of the beach in the south-western part of the dam, the underlying asphalt construction and the gabions come to the surface, after being buried by sand the last decades. Wave action that was first absorbed by the sand on top, now needs to be absorbed by the dam itself. Also degradation of the asphalt by sunlight and other weather influences do now play a role, which means that the structure is more subject to wear and tear now.

For now, this problem is mitigated by the fact that in the northeast, parts of the dam are buried by sand due to the shift of the beach in that direction. In the more distant future, this won't be the case, because the beach can't shift any further. Erosion is likely to continue, which means an increasing part of the dam will be laid bare. Rijkswaterstaat has provided figures about the maintenance costs for the asphalt slab and gabions in recent years; the maintenance costs for these parts of the dam are estimated at € 17,500 (Hintzen, 2013).

Apart from maintenance to structural parts of the dam, also maintenance costs are made to keep the roads on the dam sand free. Wind blows sand from the beach onto the roads, which can lead to dangerous situations for cyclists and motorized traffic and therefore needs to be cleaned up. The amount of sand that is blown onto the road is estimated between 2,500-10,000 m^3 per year and leads to a cost of € 65,000, this figure includes the placing of sand reed and osiers on strategic locations.

What can be concluded from these figures is that the costs for keeping the roads sand free are quite a bit higher than for the repairs of the asphalt slab and the gabions. When larger parts of the dam aren't covered by sand anymore, the maintenance costs for the former will decrease while they will increase for the latter. This means that overall maintenance costs will stay in the same order of magnitude, even if the beach disappears, provided that the current methods of repair will also suffice in the future.

There is some debate on which the test criteria should be applied for the asphalt slab (Davidse, 2010), Rijkswaterstaat is of the opinion that this is only a theoretical issue and there is no safety issue at play (Van De Ruit, 2010). If this point of view changes it could become necessary to take more comprehensive measures. A number of options have been examined earlier, including a beach nourishment (Van Der Wal, 2003). The final conclusion of that report is that the current method of repair with riprap and asphalt is the most economical solution, a beach nourishment is the most expensive one but has benefits in other areas such as recreation.

On the long run, maintenance costs could increase because the Brouwersdam is nearing its expected life span of 50 years (Ministerie van Verkeer en Waterstaat, 2007) and it is possible that additional measures have to be taken to meet (future) test criteria. For now however, maintenance costs are an order of magnitude smaller than the expense that would be needed for an eventual beach nourishment and the former is therefore the most economic strategy to follow.

8.1.3 Delta Programme Coast

The title of this section in Dutch is: 'Deltaprogramma Kust', a programme of the Dutch government that has an integral approach for the management of the coast, it does not only focus on flood safety, but combines this with other aspects such as recreational, economic, environmental and social activities. Local governments could sign up projects they thought would qualify for this programme, the municipality of Schouwen-Duiveland did this for the Brouwersdam.

The beach at the Brouwersdam is one of the many projects that have been signed up, but is one of only five projects in the whole country that have been chosen by the project office of the Delta Programme as a so-called 'Voorhoedeproject', front runner projects in which the project office will cooperate. So the importance of the beach is recognized despite no actual safety issue, which is an encouraging sign for all stakeholders that try to find a solution for this case.

8.1.4 Environmental legislation

The area on the North Sea side of the Brouwersdam belongs to marine reserve Voordelta, part of the Natura 2000 nature reserve network in Europe. The Voordelta area is established as nature compensation for the construction of Maasvlakte II and extends from the south-western tip of Schouwen-Duiveland to just below the Maasvlakte. The aim of these nature reserves is to protect vulnerable species and habitats by restricting access during breeding season and setting additional rules for interventions in the area that could have an effect on the natural value of the area.

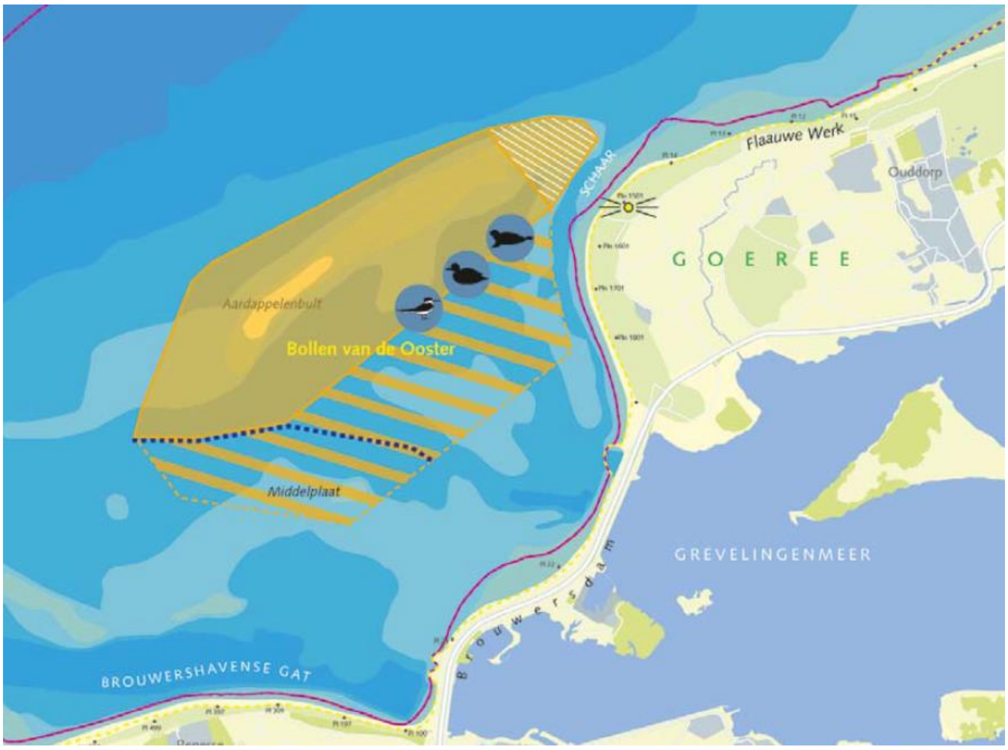


Figure 8.1 - Natura 2000 area Voordelta near the Brouwersdam

The most important species in the area is the so called Sanderling *(Calidris alba)* or 'Drieteenstrandloper' in Dutch, the effects of an eventual interference can be mitigated by taking the breeding season of this bird into account.

Two types of habitats have been designated in the area, Habitat H1110 and H1140. The first are permanently flooded sandbars and the latter are mud and sandbanks and are not permanently flooded. The system is a highly dynamic one and the area of both is fluctuating, the one can transform into the other or vice versa. This means that an eventual expansion of the beach doesn't have to lead to difficulties on the subject of Natura 2000 legislation, because the decrease of Habitat H1110 means an increase in H1140 (Van Sante, 2012).

A purple contour line is drawn around the part of the Voordelta that is located near the Brouwersdam, this contour shows that the beach itself isn't part of the nature reserve. However, this contour has fixed coordinates and because of the ongoing shift of the beach, these don't correspond with the current location anymore. This means that the north-eastern part of the beach is now part of the nature reserve. On the southwest side, where the beach used to be a decade ago, is now sea again. Because the coordinates of the contour are fixed, this part doesn't belong to the Voordelta and in case of a beach nourishment this could mean that this could be carried out on that location and there is no need to comply to the stricter Natura 2000 legislation. However, the legislation for the management plan Voordelta is evaluated and possibly updated in 2014, so an updated contour is a likely possibility.

Apart from what the exact coordinates of the boundary are or will be, it is not likely that a beach or foreshore nourishment will be restrained by Natura 2000 legislation, because the effect of it on the ecosystem will probably be judged as not significant, so the feasibility of such a nourishment doesn't depend on it.

8.1.5 Tidal power plant / inlet sluice Brouwersdam

For the near future, a number of plans are being developed for the Brouwersdam. Plans that can have a significant impact on both sides of the dam, because they change the system quite fundamentally. These plans purport to construct a tidal power plant or an inlet sluice in the Brouwersdam. For both plans this means that an inlet will have to be constructed and a part of the dam will have to be broken up. The proposed location of such an inlet is the north-eastern part of the dam, where the former tidal channel Springersdiep was located (Figure 4.7, Figure 8.2)

Figure 8.2 - Location inlet (Turlings and Nieuwkamer, 2009)

The most fundamental change for the system is the reintroduction of tidal motion in the Grevelingen, although one can argue that there is some tidal motion in the current situation due to the existing inlet sluice, that range is only a few centimetres however. What the tidal range on the Grevelingen will become in the future depends on the chosen solution. For a tidal power plant, the proposed tidal range in the Grevelingen is between 50 and 100 cm while for the inlet sluice a range between 30 and 100 cm is considered ((Witteveen + Bos, 2012) , (Turlings and Nieuwkamer, 2009)).

Both options are yet under consideration and a decision is expected before the end of 2014. An eventual tidal power plant should be up and running in 2020, which means a decision can't be postponed too long, otherwise that deadline will not be met. Also there is still a possibility that neither one of them will be chosen, because both are costly projects, especially in times of economic recession, with estimated costs between 250 and 1500 million euro's. Although that would mean that the water quality in lake Grevelingen will continue to deteriorate and that in its turn would mean that the quality of the water in the lake will not meet guidelines in 2015 (*Kaderrichtlijn Water*), which is also not desirable because it has an adverse effect on the flora and fauna.

When tidal motion is reintroduced on the Grevelingen lake, the bathymetry of the area on both sides of the Brouwersdam will undergo a new series of changes. At the lake side, the former tidal channel is still very deep, with depths up to 20 meters just behind the dam while at the sea side the channel has filled up over the years and the depth there is only about 5 meters. When an inlet is built, the biggest changes will occur at the sea side of the dam, because the former channel will deepen again. How deep such a channel will become depends on the chosen solution, although in general one can say that the bigger the discharge through the inlet, the bigger the channel, both in depth as in width.

Model simulations by Witteveen + Bos showed that the development of the beach in the period 2010-2020 with or without tidal power plant is almost the same, for both scenarios the beach area shrinks quite substantially although the decline with an inlet is a bit larger (Witteveen + Bos, 2012). This means that the sand transport in north-eastern direction will continue for both scenarios and the beach will shrink. With tidal power plant the sediment will be moved to other parts of the system, while without one the sediment will most likeably settle in the depths of the former tidal channel Springersdiep.

For the system at large the changes with a tidal power plant are larger than without, in both cases the system is not in an equilibrium state, but the pattern of channels and tidal flats that will develop as a result of the inlet means bigger changes than without.

What the exact effects on the beach and the system as a whole will be is a question that is hard to answer without knowing what solution will be chosen and how that solution exactly looks like. In the model of Witteveen + Bos, the tidal power plant is modelled as a discharge boundary condition, meaning that constructions like flow guiding are not implemented into the model. It may be no necessity that they are constructed, for example the Haringvliet discharge sluices don't have groynes. However, an inlet is a different kind of construction, where water doesn't only flow out but also needs to flow in. It is possible that groynes are needed to prevent siltation of the access channel and to ensure the required flow velocity for a tidal power plant. They could also be necessary to mitigate the effects of an inlet on popular beaches in the close vicinity, such as the beach at the Brouwersdam.

A groyne between the beach and a future inlet could serve as a means to stop the migration of the beach and hold the sand in place. The shape of the beach would change considerably as it would rotate counterclockwise and be clamped between the groyne and the Brouwersdam. However, the exact behaviour of these kinds of 'hard' constructions is difficult to predict. When a definitive solution for reintroduction of tidal motion on the Grevelingen is chosen, additional model research on this topic is suggested.

8.2 Solutions

8.2.1 Sand nourishment

One of the most obvious solutions to counteract the problem of the ongoing north-eastward migration of the beach and the decreasing amount of dry beach is to perform a beach nourishment. Each year, millions of cubic meters of sand are dredged from the deeper parts of the North Sea and supplied to beaches and on the walls of tidal channels in the framework of flood safety programmes. It is an efficient strategy to defend the hinterland and it is the preferred option of coastal defence of the Dutch government, hard solutions like revetments and groynes are less flexible (future proof) and past experiences haven not always been positive because the effects are difficult to predict and can be serious adverse side-effects like scour holes and erosion downstream. Safety isn't at stake for the Brouwersdam, like mentioned earlier in the previous section of this chapter. This means that funding for a nourishment has to be found on other grounds, like the importance of the beach for recreation and tourism in the area.

Dredging location, workability and costs per cubic meter

Sand that can be used for nourishments has to be dredged from the deeper parts of the North Sea, outside the -20 m NAP depth contour, this regulation is made to ensure that extracting sand doesn't weaken the foundation of the Dutch coastal system. The Voordelta is a large, shallow area, which means that the distance to locations outside that depth contour are at quite a distance from the Brouwersdam. There are some locations inside the Voordelta that are below that depth, but an additional constraint comes into play and that is that dredging inside this Natura2000 area isn't allowed.

This means that a dredging location outside the Voordelta and outside the -20 m depth contour needs to be found. These vessels will enter and leave the area near the Brouwersdam through the Brouwershavense Gat channel, which means that a dredging location southwest of the beach would lead to the shortest possible distances. A designated dredging location in that area is the location Steenbanken and while this is the nearest location, it's more than 30 kilometres away, which leads to considerable turnaround time for dredging vessels.

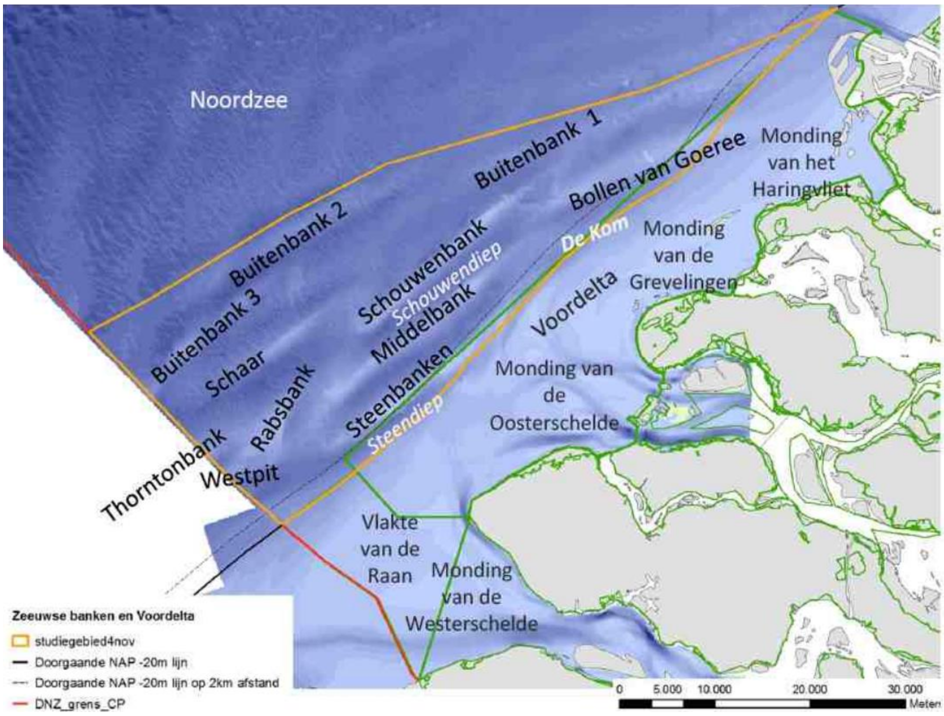


Figure 8.3 - Dredging locations (Cleveringa et al., 2012)

When entering the area through the Brouwershavense Gat, these dredging vessels will try to get as close to the nourishment location as possible. However, large parts of the area are on average only 3.5 meters deep. Most dredgers have a draft that is a lot bigger than the available depth, which means that only small vessels will be able to reach the location and even those can't be fully loaded and will have to operate in a strict tidal window.

This means that other solutions have to be considered, like large pipelines to reach the nourishment location. What is also an option is to dredge an access channel, but the draft of large trailer suction hopper dredgers is more than ten meters, so a lot of preparatory work will have to be performed. Whichever option is chosen, this location will have a more expensive price per cubic meter of sand than locations that are more easily accessible. Consultation with the Waterdienst of Rijkswaterstaat and investigation into comparable nourishment projects in the area have led to an estimated price of € 8,- per cubic meter. This price can't be regarded as fixed however, because it depends (among others) on the market conditions at the time the project will be tendered.

Project budget and nourishment locations

If the choice is made to perform a beach nourishment, there are a number of circumstances to be considered, the most important one is the available budget. In theory every cubic meter of sand that is applied on the beach will slow the migration of the beach down. However, with erosion in the range of 75,000 m^3 per year in Schouwen-Duiveland over the last decade (Table 5.2), the necessary amounts are rather large. Beach nourishments on other beaches, in the context of flood safety, are carried out every four years. If one chooses the same life span for the Brouwersdam and want to keep the beach in place for five years, this means that the estimated costs will be in the range of three million euro. Of course it is possible to operate on a different budget, but one has to keep in mind that for this location the preparatory costs, which are fixed costs, are a sizable part of the budget. Small nourishments will lead to an increased price per cubic meter and vice versa.

The best location to perform a beach nourishment, is the south-western part of the beach. The erosion is happening at that location and if it continues there, the result will be that the businesses at the beach will have to be relocated. A second reason is that the holiday park on the other side of the dam is now directly behind the beach, a further shift northeast will mean that the distance tourist have to bridge will increase, which could have negative consequences for the number of visits. A third reason is the possible construction of an inlet, the designated location is marked in Figure 8.2, marked by "*1. noordelijk sluitgat*", or in English: northern closure gap. The size and exact location of the proposed inlet are unknown yet, but the beach shifted already very close to the marked location. This means that if sand is applied there, it could be in the way of either the inlet itself or for the construction works for the inlet.

Not only the shifting of the beach was identified as a problem, also the area of available dry beach. Filling out the lower parts of the beach is a possibility increase its attractiveness, the amount of sand necessary to do so varies with the chosen width and length over which this measure will be applied. This amount ranges from 5,000 to more than 50,000 m^3, the first number indicating a heightening of the beach to levels above spring tide levels near the beach pavilions and the next number indicating a higher and wider (dry) beach over a length of more than a kilometre. Possible locations have been marked in Figure 8.4, in blue the location on the southwest side of the beach, in orange and yellow possible filling out of lower parts of the beach.

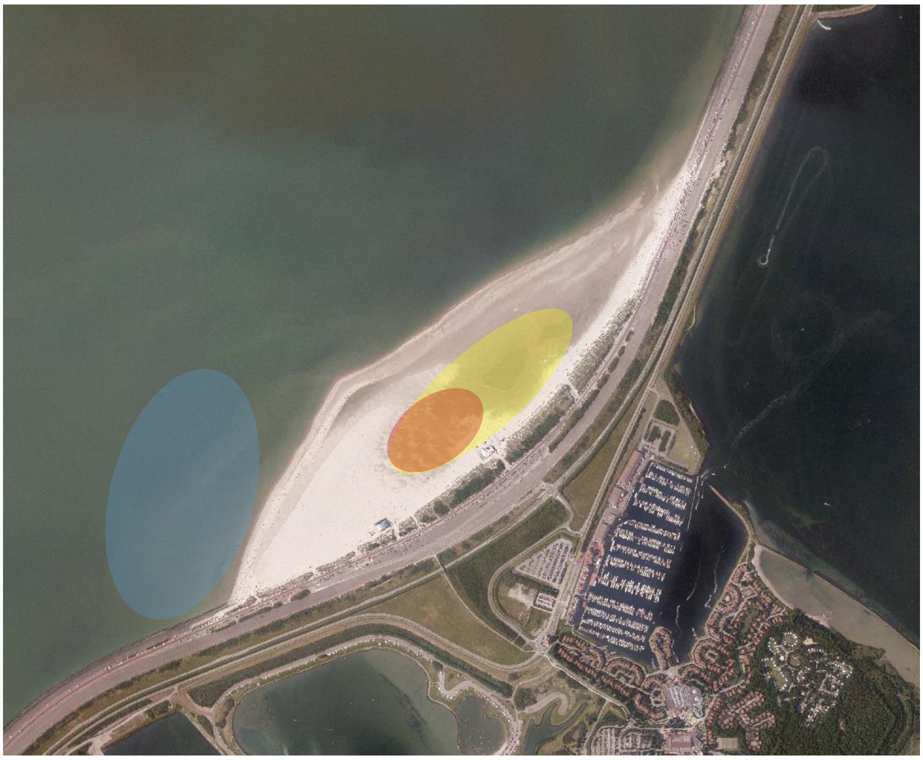


Figure 8.4 - Nourishment locations

Filling out lower parts can be combined with an expansion/buffer in the southwest. The number of possibly combinations is infinite, however the larger the former, the smaller the latter. A compromise has to be found and that compromise will depend on the available budget. An exact design of such a nourishment is omitted in this thesis, the latest available JARKUS data is more than a year old and the design depends heavily on the available budget and the point in time of an eventual nourishment. The most important trend to keep in mind is the loss of sediment in Schouwen-Duiveland, which was on average 75,000 m^3 per year over the last decade. This trend is likely to continue in the coming years and that erosion needs to be counteracted.

When a final nourishment design is made, it is important to keep in mind that in the current situation there is little sand transport to higher parts of the system. The system between the Brouwersdam and the sandbar Bollen van de Ooster is levelling out, former channels are filling in the average height of the beach is decreasing. When large volumes of sand are applied only on the foreshore it is unlikely that the dynamics of the system will not be able to transport enough sediment to higher parts of the system, in this case the beach. The coastal foundation will benefit from the additional sediment, but the amount of sediment in the system is already quite large. It is advised to design a new nourishment in such a way that sand is applied at the place and height where it is desired at that moment, applying on other locations and waiting till the system transports it to the desired location could lead to disappointing results.

Transporting sand back to the beach

Apart from sediment transport by waves, currents and tides, the wind also plays a role in transporting sediment through the system. The smaller sediment fractions are blown from the beach into dunes that are formed on the Brouwersdam, but also onto the adjacent roads. This can lead to dangerous situations for traffic on the dam and therefore this sand is removed continuously. The amount of sand that is removed from the roads per year is estimated at 2,500 – 10,000 m^3 (Hintzen, 2013). Continuous expansion of the dunes can also be undesirable at some locations and also those are removed on a periodical basis.

In the current situation this sand is transported to other locations and used for other projects. It has been suggested by both the municipality Schouwen-Duiveland and the entrepreneurs around the Brouwersdam that this sand is transported back onto the beach. The quantities aren't large enough to fully counteract erosion in the south-western part of the beach, but can be helpful to for example fill out lower parts of the beach for the summer season. Transporting it back to the beach is a solution that can be carried out on the short term, it only needs coordination between the involved parties. The current situation, transporting it to other locations, away from the Brouwersdam, certainly isn't the most ideal one.

8.2.2 Hard solutions

Soft solution are solutions that involve sand or other types of sediment, the main advantage of these kind of solutions is that they aren't fixed. Sand can be removed or relocated relatively easy when results are not what they were expected to be. The opposite is a hard solution, examples of these kind of structures are breakwaters, groynes, revetments and harbour dams. When such a structure is built, its position is fixed. Naturally, these structures can be removed or relocated if absolutely necessary, but the costs of such measures are very high. In principle, the location at which they are built, is the location at which they will stay for a long time, say 50 years or longer.

Hard solutions don't always have the effect that the designers had in mind, like scour holes and local erosion. The exact effect of such a measure is always hard to predict and constructions like these are expensive. When such groynes are constructed, they need to be long and high enough to provide shelter for the area behind them, which means that large quantities of rock and bottom protection are needed. Construction requires specialized (marine) equipment for dredging and rock placement and is sensitive to delays by bad weather conditions, the costs for such projects will in the order of millions.

If such projects would have a guaranteed positive outcome, the consideration could be made that such a one-time expense can be justified. However, the results are uncertain and these hard solutions are not flexible, once they're constructed they stay at that location. Apart from morphological and financial motives, there can be also environmental and recreational motives that are not in favour of such constructions. Natura2000 regulations could classify it as a significant disturbance in the area, but also for water sports it can be a physical obstacle or it can be dangerous because of currents around the tip of the structure.

8.2.3 Timeline for solutions

When a solution is sought, one can look on different time scales to find one. On the short term, a solution can be found by bringing sand that was blown onto the Brouwersdam back to the beach. Such a measure isn't enough to counteract the problem for a significant amount of time however and one has to look on the medium or long term to find better solutions.

On a medium time scale there are some interesting developments in finding budget for a beach nourishment. On the western tip of Schouwen-Duiveland, nourishments are carried out in the context of flood safety every four years. Some of the sediment is blown into the dunes and has a negative effect on the vegetation there. Research will start at the end of this summer to see if it is possible to skip the next nourishment in 2016 and let the dune vegetation recover or expand. This will have a significant morphological effect however and this research will give recommendations on these subjects. If it is possible to skip the next nourishment there, it may be possible to use (parts of) that budget for the Brouwersdam.

On the long term, there are important changes underway, changes that could alter the dynamics of the area once again. How these plans will exactly look like is unknown yet, but the consequences do depend on the exact size, shape and location of plans like a tidal inlet or power plant. There are not only threats for the beach, there are also opportunities. Eventual groynes next to an inlet could hold the beach in place, although that will likely be in a different shape and on a more northern location than it is nowadays. It is also possible that a lot of dredging has to be carried out to create a building pit and that this sand can be transported to the beach.

It is advised to search solutions on the medium term, meaning for the next 5 to 10 years. On the longer term, there are too many uncertainties that could have an effect on the beach. On such a term, the only viable solution is a beach nourishment, which size depends on the available budget. A very large nourishment, in the order of a million cubic meters, would probably last longer than 10 years, but it will be challenging to find such budget. When the decision is made to construct an inlet, the budget of such a project will be in the range of 250-1,500 million euro's and there could be room for compensatory measures. If an additional decline of the beach is expected because of a tidal power plant, it is not unreasonable to expect that there will be a form of compensation.

9 Conclusions and recommendations

9.1 Conclusions

The ongoing shift of the beach in north-eastern direction and the loss of the amount of dry beach is a problem for the users and stakeholders of the beach. This trend is likely to continue in the foreseeable future and could result in a beach that can no longer fulfil its current functions, like recreation and tourism.

Analysis of bathymetric data from the last decades shows that the systems of the Oosterschelde, Grevelingen and Haringvliet are not in equilibrium, the Delta Works and the expansions of the Maasvlakte have changed hydrodynamic forcing of the system drastically. As a result, the system is transforming to a new equilibrium, a process that isn't completed yet, nor will it be soon. The time scales of processes like these are in the order of centuries.

For the area around the Brouwersdam the result is that the former ebb-tidal deltas of the Grevelingen and the Oosterschelde are pushed shoreward due to the reduced tidal forcing, therefore wave forcing is becoming more dominant. The development of the Bollen van de Ooster is a result of this change in hydrodynamic forcing, these former sub-tidal breaker bars are pushed to the shore and are forming a continuous intertidal breaker bar. Behind this breaker bar, the area is flattening out, the former channels Brouwershavense Gat en Springersdiep are filling in. The former shoals Middelplaat and Kabbelaarsbank were pushed against the Brouwersdam and now form the beach that is shifting in north-eastern direction. Over the last decade, the amount of sediment that is lost in the south-western part of the beach is estimated at around 75,000 m^3 per year and the amount of dry beach is getting smaller.

A morphological model of the area was made to replicate the developments over the years 2000-2010 and to simulate the developments in next decade, from 2010-2020. The first step in this modelling process was a wind- and wave analysis over the last three decades to make a schematization that could be used in the wave and shoreline models. The resulting schematization consists out of 108 different wind and wave classes, with averaged values for the wind and wave parameters in that class and the frequency of occurrence of such a situation. The analysis showed that southwesterly winds are dominant, both under normal as under storm conditions.

This schematization was put into the SWAN wave model and the results were calculated for three different water levels (high, average and low tide) and for two different bathymetries (2000 and 2010) using an unstructured mesh grid. The resulting wave parameters for the beach serve as input parameters for the shoreline model Unibest.

The UNIBEST shoreline model calculates the sand transport per JARKUS ray along the beach using three different transport formulae: Bijker (1971), Van Rijn (1993) and Van Rijn (2004) which resulted in a hindcast (2000-2010) and a forecast (2010-2020). For the hindcast model, the amount of erosion on the south-western side of the beach was underestimated, while the sedimentation in the northeast was overestimated. So the model was able to replicate the trends, but the estimated amounts differed from the observed amount, the Bijker (1971) formula provided the best results. The forecast model predicts trends as the hindcast model, but predicts that the sand transport in the next decade will slow down, due to a decreased wave heights near the beach. However, this decrease couldn't be found in the available data from 2010 to 2012 nor in the observations of the stakeholders around the beach, who reported an increasing erosion in the southwest.

The differences between the model results and observations could be the result of the complex flow patterns in the area. The incoming flood current flows from southwest to northeast and stays close to the Brouwersdam and the beach, while the ebb current stays on the outside of the area and flows in opposite direction. The result is a flood dominated flow pattern along the beach, which has its influence on the dominating transport direction and the models aren't able to replicate this process correctly. Also the siltation of the former tidal channel Springersdiep could be of influence because it serves as a sediment sink. However, the deeper parts of the channel are just outside the domain of the JARKUS measurements and therefore the channel isn't fully incorporated into the shoreline model.

In the near future the characteristics of the system are about to change again, there are plans under development to construct a tidal power plant or an inlet sluice in the Brouwersdam. The proposed location of such an inlet is the north-eastern part of the dam, where the former tidal channel Springersdiep was located. This means that tidal motion is reintroduced in the Grevelingen, however the exact tidal range has still to be determined. A decision on what solution will be chosen is expected before the end of 2014 and an eventual tidal power plant should be up and running in 2020. What the exact effect of such solutions will be, depends on the size and design of the solution. However, it is likely that the Springersdiep channel will redevelop itself to accommodate for the in- and outflowing water through the inlet and could lead to increasing erosion of the beach.

A north-eastward shifting and possibly disappearing beach doesn't lead to a safety issue for the Brouwersdam, the structure itself provides the necessary safety for the hinterland and therefore there is no basic coastline (BKL) for this area. The most important consequence is that there are no periodic beach nourishments for the Brouwersdam to counteract the shifting and lowering of the beach. Beach nourishment are the preferred solution in the Netherlands the counteract receding coastlines, but without BKL, there are no funds readily available.

A possibility is to alleviate the costs for maintenance on the dam by keeping the asphalt and toe of the dam buried under the sand by a beach nourishment to minimize the wear and tear through wind, sun and waves. The maintenance costs for the dam consist out of repairs to the gabions and asphalt slabs at the toe of the dam, the removal of sand on the roads on top of it and prevention measures for wind erosion of the beach. The repair costs to the dam itself will increase if larger parts of the dam will be laid bare but on the other hand, the costs made the to keep the roads sand free will decrease. A beach nourishment doesn't lead to lower maintenance costs, it will only reverse the situation: more costs to keep the roads on the dam sand free but lower repair costs. Moreover, the total maintenance costs are an order of magnitude lower than the costs for a beach nourishment, so prevention of maintenance costs through nourishments isn't a viable economic alternative.

A possible solution could be found in the form of the Delta Programme Coast, a governmental program that strives to an integral approach for coastal zones and does not only focus on flood safety but also looks to other aspects such as recreation and economic, social and environmental activities. The Brouwersdam is a front runner project and it is possible that funds for a solution can be found through this project. Rijkswaterstaat is researching the possibility to skip a beach nourishment in a different part of the region, near the Kop van Schouwen and it is a possibly that this budget can be used for the Brouwersdam. The morphological research starts in the fall of 2013 and will give more insight in the feasibility of skipping one beach nourishment in the four year cycle on this location. If that is possible, it is up to the responsible governmental bodies to decide if it is desirable to use this budget for the beach at the Brouwersdam.

Such a nourishment could be best applied on the south-western part of the beach, because this is as far away from the proposed tidal inlet / power plant as possible and keeps the beach on the desired location. The size of the nourishment depends on the available budget and also determines its lifespan. It should be taken into account that the area in front of the Brouwersdam is a shallow area that is hard to reach with big trailing suction hoppers while also the distance to a suitable sand winning location is rather large. This leads to relatively high prices per cubic meter, estimated at around € 8,- per cubic meter for projects that are in the same range as the current projects that are carried out in the area. Smaller nourishments will increase this price even further while larger nourishments will lead to a lower price per cubic meter, but to larger total costs. To counteract a decade of erosion in Schouwen-Duiveland, an amount of 750,000 m^3 is necessary, which would cost around six million euros.

However, the erosion in the southwest is likely to continue in the foreseeable future, so a beach nourishment is no permanent solution, but could alleviate the problems for a number of years. The most important development is the near future is the proposed tidal power plant. Its design and also very important, the requirements that are made to the project and its functioning, determine the developments in the area for the coming decades. Such requirements can for example be that the operator of the power plant has the obligation to keep the beach in its current shape. A different possibility is to construct guiding jetties with a sand bypass, which would lead to a differently shaped beach, but could provide more certainty for its users and stakeholders than the current situation.

There are a lot of different possibilities and outcomes that determine the fate of the beach at the Brouwersdam. The system has undergone numerous changes in the past and in the future it will be no different. How the beach will look like in a decade from now is largely up to the responsible (governmental) parties involved and it is stressed that cooperation between these parties is vital to find a satisfying solution.

9.2 Recommendations

The morphological modelling of the beach at the Brouwersdam presented itself as a challenging task, both in this thesis as in previous studies. The bathymetry data that serves as base data for the various models isn't optimal, it is interpolated from echo soundings and therefore isn't as detailed as one would wish. The area in front of the beach is complex: channels, flats, breaker bars and a shifting beach, which make this area a challenging one for morphological models. These models tend to require extensive computing time and therefore require a simplification of the complete set of events that occur in real life. It also limits the number of model grid points and the model time step, because otherwise it wouldn't be possible to run these models in an acceptable time.

However with the enormous advances in parallelization in (distributed) computing technology, it is becoming easier to acquire computing capacity. With this increased capacity and model optimisations of models of Delft3D, it should be possible to limit number of simplifications or increase the number of grid points. Combined with better measurements like multi-beam echo soundings could lead to a more accurate model, therefore additional and more detailed model analysis is recommended.

When the decision about a tidal power plant or a tidal inlet is made, it is advised to implement the exact design in such a model, including features like flow guiding jetties. This is necessary because the exact design will have a significant impact on how the beach will develop over time.

The last recommendation is about the long term developments in the Grevelingen delta, there are a number of developments that could have significant impact on how the area will look like in the next decades, like the shoreward moving Bollen van de Ooster and the northward extending Krabbengat. In its turn, these developments are influenced by further human influence, like the construction of a tidal power plant, but additional research is recommended.

References

BILGILI, A. & SMITH, K. 2005. BatTri 2-D triangular grid generator (manual). Hanover, NH: Dartmouth College.
CLEVERINGA, J. 2008. Morphodynamics of the Delta coast (south-west Netherlands) - Quantitative analysis and phenomenology of the morphological evolution 1964-2004. Emmeloord: Alkyon.
CLEVERINGA, J., VAN VLIET, F., BERGSMA, J. H. & JONKVORST, R. J. 2012. Zandwinning op de Zeeuwse banken. Culemborg: Bureau Waardenburg.
CRONIN, K. 2011. Grevelingen ebb tidal delta - analysis (internal memo). *2011.* Delft: Deltares.
DARTMOUTH COLLEGE. http://www-nml.dartmouth.edu/Software/battri/.
DAVIDSE, M. P. 2010. Beoordeling toetsresultaten Brouwersdam. Vught: KOAC-NPC.
DAVIS, R. A. J. & HAYES, M. O. 1984. What is a wave-dominated coast? *Marine Geology,* Volume 60, 313 - 329.
DELTARES 2011. Unibest-CL+ Manual - Manual for version 7.1 of the shoreline model Delft: Deltares.
DYKE, P. 2007. *Modelling coastal and offshore processes,* London, Imperial College.
EELKEMA, M. 2013. Eastern Scheldt Inlet Morphodynamics (PhD). Delft: TU Delft.
ELIAS, E. P. L. 2006. Morphodynamics of Texel Inlet (PhD). Delft: TU Delft.
ENET, F., NAHON, A., VAN VLEDDER, G. & HURDLE, D. 2006. Evaluation of diffraction behind a semi-infinite breakwater in the SWAN wave model. Emmeloord: Alkyon.
GALLOWAY, W. E. 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. *Deltas, Models for Exploration - Houston Geological Society*, 87-98.
HARING, J. 1978. De geschiedenis van de ontwikkeling van de waterbeweging en van het profiel van de getijwateren en zeegaten van het zuidelijk deltabekken en van het hierbij aansluitende gebied voor de kust gedurende de perioden 1872-1933-1952-1968-1974. [s.l.]: Rijkswaterstaat.
HINTZEN. 2013. *RE: Onderhoudskosten Brouwersdam (via e-mail).*
HOLTHUIJSEN, L. 2007. *Waves in oceanic and coastal waters,* Cambridge, Cambridge University Press.
HUISMAN, B. J. A. 2013. *RE: Unibest usage (personal communication).*
HUISMAN, B. J. A. & LUIJENDIJK, A. P. 2009. Sand demand of the Eastern Scheldt - Morphology around the barrier. Delft: Deltares.
KNMI. http://knmi.nl/cms/content/18185/historie.
MINISTERIE VAN VERKEER EN WATERSTAAT 2007. Voorschift toetsen op veiligheid primaire waterkeringen. [s.l.]: Ministerie van Verkeer en Waterstaat.
MULDER, J. P. M., CLEVERINGA, J., TAAL, M. D., WESENBEECK, B. K. & KLIJN, F. 2010. Sedimentperspectief op de Zuidwestelijke Delta. Delft: Deltares.
SMITH, D. 1984. The hydrology and geomorphology of tidal basins. *In:* AALST, W. V. (ed.) *The closure of tidal basins.* Delft: Delft University Press.
SWAN 2013. SWAN User Manual. Delft: TU Delft.
TURLINGS, L. G. & NIEUWKAMER, R. L. J. 2009. Verkenning Grevelingen water en getij. [s.l.]: Witteveen + Bos.
UNIVERSITY OF CALIFORNIA AT BERKELEY. http://www.cs.cmu.edu/~quake/triangle.html.
VAN DE RUIT, H. C. 2010. Beheerdersoordeel v4.0. [s.l.]: Rijkswaterstaat.
VAN DEN BERG, J. H. 1987. Toelichting bij de isallobatenkaart Voordelta 1975-1984. [s.l.]: Rijkswaterstaat.
VAN DER SPEK, A. 1987. Beschrijving van de ontwikkeling van de buitendelta's van Haringvliet en Grevelingen. [s.l.]: Rijkswaterstaat.
VAN DER WAL, M. 2003. Versterking teenconstructie Brouwersdam. [s.l.]: Rijkswaterstaat.
VAN SANTE, P. 2012. Quickscan Natuur Brouwersdam. Zierikzee: Gemeente Schouwen-Duiveland.
VISSER, W. 2013. *RE: Bathymetry grids (personal communication).*
WALTON, T. L. & ADAMS, W. D. 1976. Capacity of inlet outer bars to store sand. *Proc. 15th International Conference on Coastal Engineering.* Honululu, HI.
WANG, B. 2002. Kelvin Waves. Honolulu, HI: University of Hawaii.
WITTEVEEN + BOS 2012. Morphologische analyse Voordelta. Rotterdam: Witteveen + Bos.
ZIJPP, N. J. 2001. Controle en bewerking Jaarlijkse Kustmetingen en Vaklodingen. Rotterdam: Mobidata.
ZKA CONSULTANTS & PLANNERS 2007. Concept Economische Visie Brouwersdam. Breda: ZKA Consultants & Planners.

Appendix A :

A.1 - Wind sea classes

			Avg. Winddir [degrees]	Avg. Windspeed [m/s]	Avg Hs [m]	Avg Tp [s]	Wavedir [degrees]	N []	%	Days
Winddir 0-30	*Hs < 0.50*	1	17.28	5.07	0.35	4.55	347.85	3079	0.793356	2.8958
	0.5 < Hs < 1	2	17.31	7.46	0.77	5.01	3.57	5716	1.472824	5.3758
	1 < Hs < 2	3	16.61	9.60	1.40	6.17	2.42	7527	1.939459	7.0790
	2 < Hs < 3	4	15.09	12.21	2.39	7.70	355.34	1688	0.434942	1.5875
	3 < Hs < 4	5	12.65	14.69	3.31	8.81	344.97	351	0.090441	0.3301
	4 < Hs < 5		13.00	17.93	4.37	9.80		25	0.006442	
	5 < Hs < 6		2.00	17.20	5.25	10.50		1	0.000258	
	6 < Hs < 7									
	Hs > 7									
Winddir 30-60	*Hs < 0.50*	6	43.84	5.18	0.34	4.56	359.57	3422	0.881736	3.2183
	0.5 < Hs < 1	7	43.79	7.27	0.77	4.97	17.40	5490	1.414591	5.1633
	1 < Hs < 2	8	44.79	9.77	1.41	6.12	14.91	7587	1.954919	7.1355
	2 < Hs < 3	9	44.61	13.11	2.35	7.47	11.09	1677	0.432107	1.5772
	3 < Hs < 4	10	41.99	15.31	3.30	8.80	4.23	179	0.046122	0.1683
	4 < Hs < 5		40.25	19.13	4.12	10.18		4	0.001031	
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 60-90	*Hs < 0.50*	11	77.42	5.02	0.35	4.57	7.43	3334	0.859061	3.1356
	0.5 < Hs < 1	12	76.29	7.23	0.76	4.96	30.39	6318	1.627939	5.9420
	1 < Hs < 2	13	74.48	10.19	1.38	6.06	24.94	6801	1.752392	6.3962
	2 < Hs < 3	14	70.03	12.93	2.22	7.35	5.75	461	0.118784	0.4336
	3 < Hs < 4		67.17	11.80	3.41	8.50		6	0.001546	
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

Winddir 90-120	*Hs < 0.50*	15	105.96	5.43	0.35	4.49	26.85	4838	1.246592	4.5501
	0.5 < Hs < 1	16	105.56	7.85	0.73	4.74	59.49	6584	1.696479	6.1921
	1 < Hs < 2	17	101.48	11.06	1.26	5.56	58.69	2620	0.675087	2.4641
	2 < Hs < 3	18	99.56	15.41	2.19	6.85	334.71	110	0.028343	0.1035
	3 < Hs < 4		97.67	10.50	3.19	8.57		3	0.000773	
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 120-150	*Hs < 0.50*	19	134.64	5.20	0.35	4.48	326.59	4713	1.214384	4.4325
	0.5 < Hs < 1	20	135.10	7.79	0.70	4.56	144.92	4557	1.174188	4.2858
	1 < Hs < 2	21	136.87	10.88	1.20	5.20	132.40	671	0.172894	0.6311
	2 < Hs < 3		138.00	7.20	2.30	6.93		3	0.000773	
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 150-180	*Hs < 0.50*	22	166.04	5.43	0.36	4.48	228.39	5018	1.292972	4.7193
	0.5 < Hs < 1	23	167.23	7.90	0.73	4.70	207.83	7495	1.931213	7.0489
	1 < Hs < 2	24	170.74	11.43	1.28	5.44	209.58	3384	0.871945	3.1826
	2 < Hs < 3	25	172.43	16.02	2.18	6.32	205.82	97	0.024994	0.0912
	3 < Hs < 4		160.00	6.25	3.84	8.85		2	0.000515	
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 180-210	*Hs < 0.50*	26	195.01	4.98	0.37	4.48	250.55	4540	1.169808	4.2698
	0.5 < Hs < 1	27	195.22	7.75	0.76	4.86	234.23	12165	3.134518	11.4410
	1 < Hs < 2	28	196.71	11.38	1.40	5.80	232.32	15783	4.066756	14.8437
	2 < Hs < 3	29	200.36	15.67	2.28	6.90	231.55	1934	0.498328	1.8189
	3 < Hs < 4	30	202.68	20.37	3.28	7.87	234.31	75	0.019325	0.0705
	4 < Hs < 5		208.00	21.10	4.27	8.50		1	0.000258	
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

Winddir 210-240	*Hs < 0.50*	31	225.76	5.02	0.37	4.49	260.66	4417	1.138115	4.1541
	0.5 < Hs < 1	32	226.44	7.64	0.77	4.93	247.99	12965	3.340651	12.1934
	1 < Hs < 2	33	227.13	11.08	1.44	5.95	243.45	22575	5.816830	21.2314
	2 < Hs < 3	34	228.71	15.03	2.34	7.09	240.87	6874	1.771202	6.4649
	3 < Hs < 4	35	230.00	19.07	3.30	7.99	241.73	561	0.144551	0.5276
	4 < Hs < 5	36	234.35	23.12	4.26	8.76	241.33	43	0.011080	0.0404
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 240-270	*Hs < 0.50*	37	254.16	4.76	0.38	4.53	270.54	3726	0.960067	3.5042
	0.5 < Hs < 1	38	252.88	7.18	0.77	4.96	257.94	11153	2.873759	10.4892
	1 < Hs < 2	39	252.45	10.22	1.43	6.00	255.19	18019	4.642899	16.9466
	2 < Hs < 3	40	253.59	14.10	2.36	7.15	253.73	5200	1.339868	4.8905
	3 < Hs < 4	41	256.35	17.91	3.35	8.17	254.71	629	0.162072	0.5916
	4 < Hs < 5	42	258.70	21.70	4.29	8.98	250.83	56	0.014429	0.0527
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 270-300	*Hs < 0.50*	43	284.18	4.11	0.37	4.61	285.28	2165	0.557849	2.0361
	0.5 < Hs < 1	44	284.37	6.61	0.77	5.07	284.73	5060	1.303794	4.7588
	1 < Hs < 2	45	284.86	9.39	1.47	6.22	289.76	10061	2.592386	9.4622
	2 < Hs < 3	46	285.20	13.04	2.41	7.34	287.02	4421	1.139145	4.1579
	3 < Hs < 4	47	285.96	16.47	3.36	8.19	289.32	1177	0.303274	1.1069
	4 < Hs < 5	48	285.39	19.25	4.32	8.90	285.70	137	0.035300	0.1288
	5 < Hs < 6		286.71	21.86	5.30	9.63		7	0.001804	
	6 < Hs < 7									
	Hs > 7									
Winddir 300-330	*Hs < 0.50*	49	315.03	3.97	0.36	4.61	301.67	1469	0.378513	1.3816
	0.5 < Hs < 1	50	315.17	6.39	0.77	5.11	310.68	3632	0.935846	3.4158
	1 < Hs < 2	51	314.57	8.91	1.47	6.35	314.83	6464	1.665559	6.0793
	2 < Hs < 3	52	314.40	12.20	2.41	7.64	319.67	3111	0.801602	2.9258
	3 < Hs < 4	53	314.63	15.50	3.40	8.65	318.78	946	0.243753	0.8897
	4 < Hs < 5	54	315.19	18.13	4.27	9.28	317.29	145	0.037362	0.1364
	5 < Hs < 6	55	324.33	21.33	5.26	10.78	326.00	6	0.001546	0.0056
	6 < Hs < 7									
	Hs > 7									

Winddir 330-360	*Hs < 0.50*	56	346.27	4.26	0.35	4.59	323.44	1798	0.463285	1.6910
	0.5 < Hs < 1	57	345.73	6.68	0.76	5.04	330.44	3353	0.863957	3.1534
	1 < Hs < 2	58	345.48	8.91	1.46	6.39	339.55	6333	1.631804	5.9561
	2 < Hs < 3	59	344.62	11.94	2.42	7.76	336.86	2804	0.722498	2.6371
	3 < Hs < 4	60	344.12	14.81	3.34	8.81	335.83	709	0.182686	0.6668
	4 < Hs < 5	61	341.23	16.89	4.29	9.83	327.46	96	0.024736	0.0903
	5 < Hs < 6		343.50	20.80	5.27	10.38		4	0.001031	
	6 < Hs < 7									
	Hs > 7									

A.2 - Swell classes

			Avg. Winddir [degrees]	Avg. Windspeed [m/s]	Avg Hs [m]	Avg Tp [s]	Wavedir [degrees]	N []	%	Days
Winddir 0-30	*Hs < 0.50*	62	16.71	3.84	0.34	5.88	335.68	4607	1.187071	4.3328
	0.5 < Hs < 1	63	16.29	5.03	0.74	6.57	352.27	5736	1.477977	5.3946
	1 < Hs < 2	64	15.22	6.48	1.27	7.35	350.84	2418	0.623039	2.2741
	2 < Hs < 3	65	14.19	8.71	2.18	8.82	344.25	59	0.015202	0.0555
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 30-60	*Hs < 0.50*	66	44.18	3.94	0.34	5.91	339.55	4757	1.225721	4.4739
	0.5 < Hs < 1	67	44.31	4.88	0.72	6.56	356.70	4609	1.187587	4.3347
	1 < Hs < 2	68	44.66	6.47	1.27	7.34	357.58	1680	0.432880	1.5800
	2 < Hs < 3	69	43.06	9.33	2.21	8.89	342.77	48	0.012368	0.0451
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

Winddir 60-90	*Hs < 0.50*	70	75.89	3.88	0.35	5.89	341.75	4011	1.033502	3.7723
	0.5 < Hs < 1	71	76.42	5.10	0.71	6.43	4.09	5001	1.288592	4.7034
	1 < Hs < 2	72	74.36	6.63	1.27	7.31	3.92	1599	0.412009	1.5038
	2 < Hs < 3	73	73.12	7.88	2.18	8.93	354.59	25	0.006442	0.0235
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 90-120	*Hs < 0.50*	74	105.89	4.08	0.34	5.90	339.88	4899	1.262310	4.6074
	0.5 < Hs < 1	75	104.74	5.09	0.69	6.50	5.19	4530	1.167231	4.2604
	1 < Hs < 2	76	103.20	5.74	1.21	7.42	1.10	644	0.165937	0.6057
	2 < Hs < 3	77	101.75	10.73	2.12	8.75	358.50	4	0.001031	0.0038
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 120-150	*Hs < 0.50*	78	135.01	4.07	0.34	5.94	327.88	5696	1.467671	5.3570
	0.5 < Hs < 1	79	134.02	4.34	0.67	6.63	345.33	3218	0.829172	3.0265
	1 < Hs < 2	80	133.95	4.00	1.19	7.66	343.29	353	0.090956	0.3320
	2 < Hs < 3	81	141.71	9.73	2.24	9.89	337.29	7	0.001804	0.0066
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 150-180	*Hs < 0.50*	82	165.91	4.25	0.34	5.95	310.07	5045	1.299929	4.7447
	0.5 < Hs < 1	83	166.46	4.79	0.67	6.54	305.90	3110	0.801344	2.9249
	1 < Hs < 2	84	166.24	4.68	1.19	7.61	332.60	331	0.085288	0.3113
	2 < Hs < 3	85	171.00	7.35	2.15	9.63	336.50	6	0.001546	0.0056
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

Winddir 180-210	*Hs < 0.50*	86	194.61	3.82	0.35	5.95	306.11	4294	1.106422	4.0384
	0.5 < Hs < 1	87	195.85	5.13	0.70	6.45	302.96	4154	1.070348	3.9068
	1 < Hs < 2	88	196.20	6.32	1.18	7.40	319.43	714	0.183974	0.6715
	2 < Hs < 3	89	197.33	7.70	2.11	8.57	305.00	3	0.000773	0.0028
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 210-240	*Hs < 0.50*	90	225.92	3.77	0.36	5.91	310.84	4080	1.051281	3.8372
	0.5 < Hs < 1	91	226.24	5.13	0.70	6.46	308.01	5327	1.372591	5.0100
	1 < Hs < 2	92	226.21	6.30	1.18	7.34	315.49	924	0.238084	0.8690
	2 < Hs < 3	93	212.00	7.60	2.04	8.40	317.00	1	0.000258	0.0009
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 240-270	*Hs < 0.50*	94	254.86	3.59	0.37	5.88	309.29	3531	0.909822	3.3208
	0.5 < Hs < 1	95	254.14	4.88	0.72	6.42	316.19	5291	1.363315	4.9761
	1 < Hs < 2	96	256.28	6.44	1.23	7.37	321.61	1549	0.399126	1.4568
	2 < Hs < 3		253.29	8.84	2.24	9.07		7	0.001804	
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 270-300	*Hs < 0.50*	97	284.89	3.17	0.36	5.85	314.31	2586	0.666327	2.4321
	0.5 < Hs < 1	98	285.15	4.39	0.73	6.42	324.31	3982	1.026030	3.7450
	1 < Hs < 2	99	286.35	6.19	1.30	7.48	331.26	1997	0.514561	1.8781
	2 < Hs < 3	100	288.98	9.19	2.15	8.92	331.48	63	0.016233	0.0593
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

Winddir 300-330	*Hs < 0.50*	101	315.67	3.01	0.36	5.87	325.07	2401	0.618658	2.2581
	0.5 < Hs < 1	102	315.39	4.16	0.74	6.50	334.71	3931	1.012888	3.6970
	1 < Hs < 2	103	316.20	6.06	1.32	7.50	338.05	2435	0.627419	2.2901
	2 < Hs < 3	104	316.81	8.82	2.19	8.92	334.47	84	0.021644	0.0790
	3 < Hs < 4		321.00	17.40	3.35	13.10		1	0.000258	
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									
Winddir 330-360	*Hs < 0.50*	105	346.49	3.18	0.35	5.90	329.61	3043	0.784080	2.8619
	0.5 < Hs < 1	106	346.26	4.32	0.74	6.56	344.65	4200	1.082201	3.9500
	1 < Hs < 2	107	345.46	6.15	1.31	7.48	345.40	2640	0.680241	2.4829
	2 < Hs < 3	108	344.93	9.17	2.22	8.94	342.25	92	0.023705	0.0865
	3 < Hs < 4									
	4 < Hs < 5									
	5 < Hs < 6									
	6 < Hs < 7									
	Hs > 7									

A.3 - Wind roses per decade

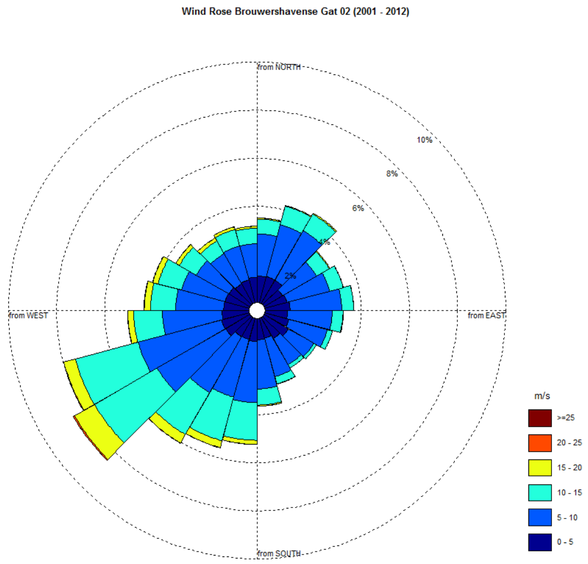


Figure A.1 - Wind rose 2001-2012

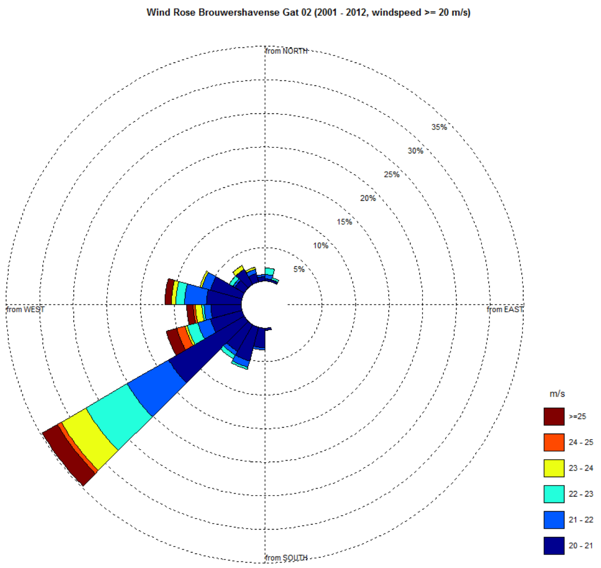


Figure A.2 - Wind Rose 2001-2012 (>= 20 m/s)

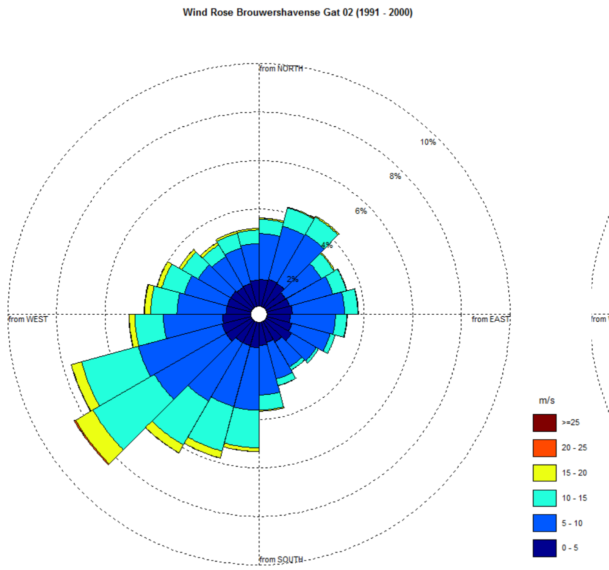


Figure A.3 - Wind rose 1991-2000

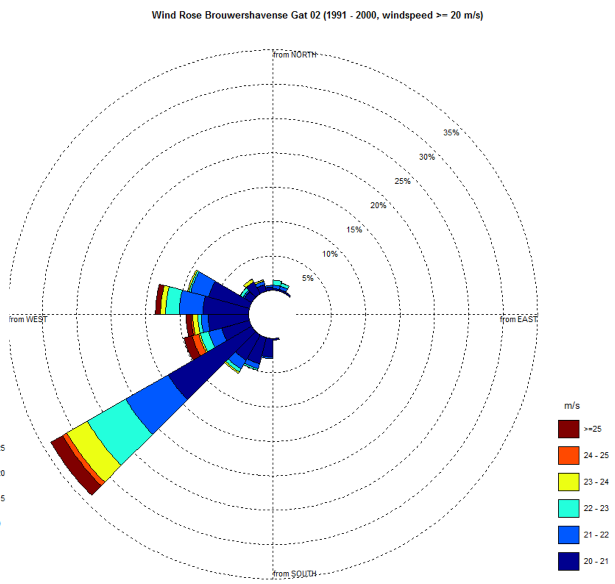


Figure A.4 - Wind rose 1991-2000 (>= 20 m/s)

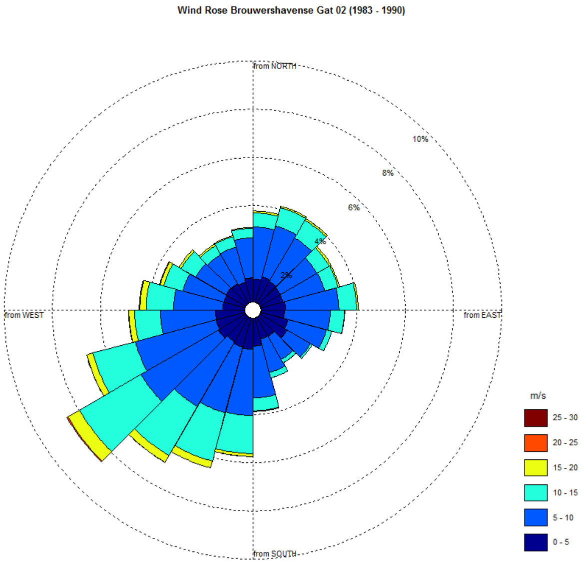


Figure A 5 - Wind rose 1983 - 1990

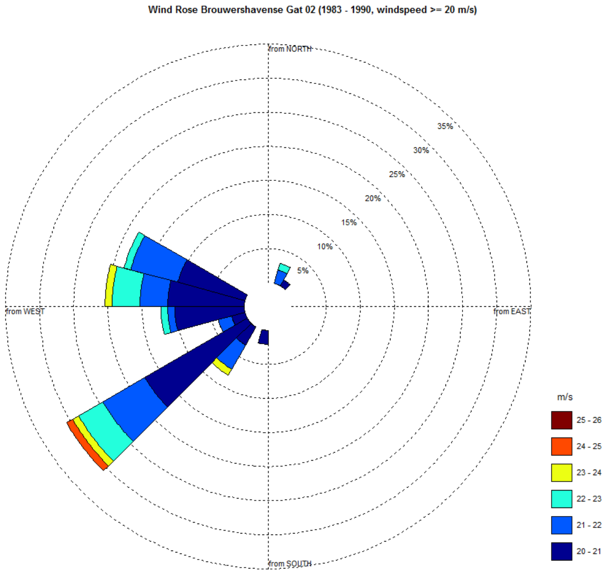


Figure A 6 - Wind rose 1983-1990 (>= 20 m/s)

Appendix B

B.1 - Measurement methods and data resolution

The position of a point in the Dutch coastal system is measured in two steps, coastal measurements ("kustmetingen") and echo soundings made per section of the coast ("vaklodingen").

Coastal measurements consist of echo soundings and height measurements, carried out every year on imaginary lines perpendicular to the coastline, with an intermediate distance of 200 meters. These lines are the previously mentioned JARKUS rays.

In the past, these height measurements were done by hand till and comprise the dry part of the coastal system. Nowadays they are made with laser altimetry by plane and interpolated along the JARKUS rays. The echo soundings are made by boat, these vessels are equipped with single beam echo sounding systems and automated positioning systems that correct for the movements of the ship. By carrying out height measurements on low tide and depth measurements on high tide, it is tried to make the data as complete as possibly.

The measurements per coastal section start where the JARKUS rays end, they start at the toe of the foreshore and extend till the -20 m NAP isobath. They are carried out with the same intermediate distance of 200 meters in this area, in areas with a less complicated bathymetry like the closed part of the Holland coast, the intermediate distance can be up to one kilometre. These echo soundings are performed with the same equipment, vessels with single beam echo sounders.

The term has been mentioned a few times now, single beam echo sounding. This sounding method uses one transducer, a device mounted underneath a vessel that is sending and receiving sound pulses to the sea bottom underneath the vessel. The time between sending and receiving is used to calculate the depth. When a vessel sails along these rays, it only collects data points every few centimetres directly underneath it.

More advanced sounding equipment is multi-beam echo sounding, using multiple transducers to cover a larger area beneath the vessel. This method significantly increases the number of collected data points and gives a more accurate representation of the bathymetry. Figure B.1 shows the difference in data collection between the two sounding methods. Multi-beam soundings require a smaller intermediate distance to cover the complete sea bottom, making soundings more expensive and time consuming. Especially for shallow areas that can only be accessed during a small fraction of the tidal window, it can take a lot of time to measure the complete sea bed.

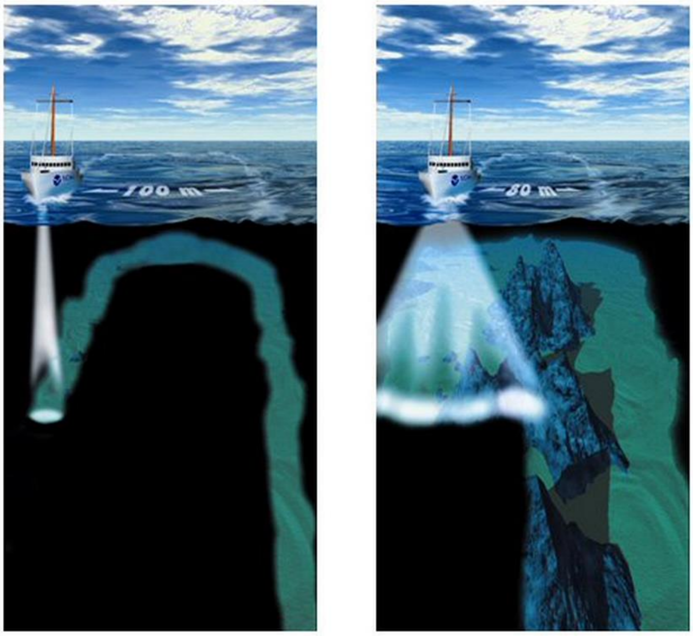


Figure B.1 - Single beam vs. multi beam

The measurements collected by single beam equipment has to be processed by interpolation software to make a full-coverage bathymetry. On the rays the data resolution is too big, with measurements every few centimetres, but between these rays there is no data. Interpolation algorithms are used to make grids with a certain spatial resolution, in this case 20x20 m grids. These grids are very useful for modelling and mapping purposes, but one has to take into account that the data between the rays isn't the actual situation but interpolated data.

The difference between the two can be seen in Figure B 2, divided by a black line. The upper left part of the figure is data collected by the Royal Dutch Navy with multi-beam equipment, the lower right part is data from the "Vaklodingen". The resolution of the navy data makes it possible to see features like sand ripples on the sea bed, details that are lost on the lower part of the figure.

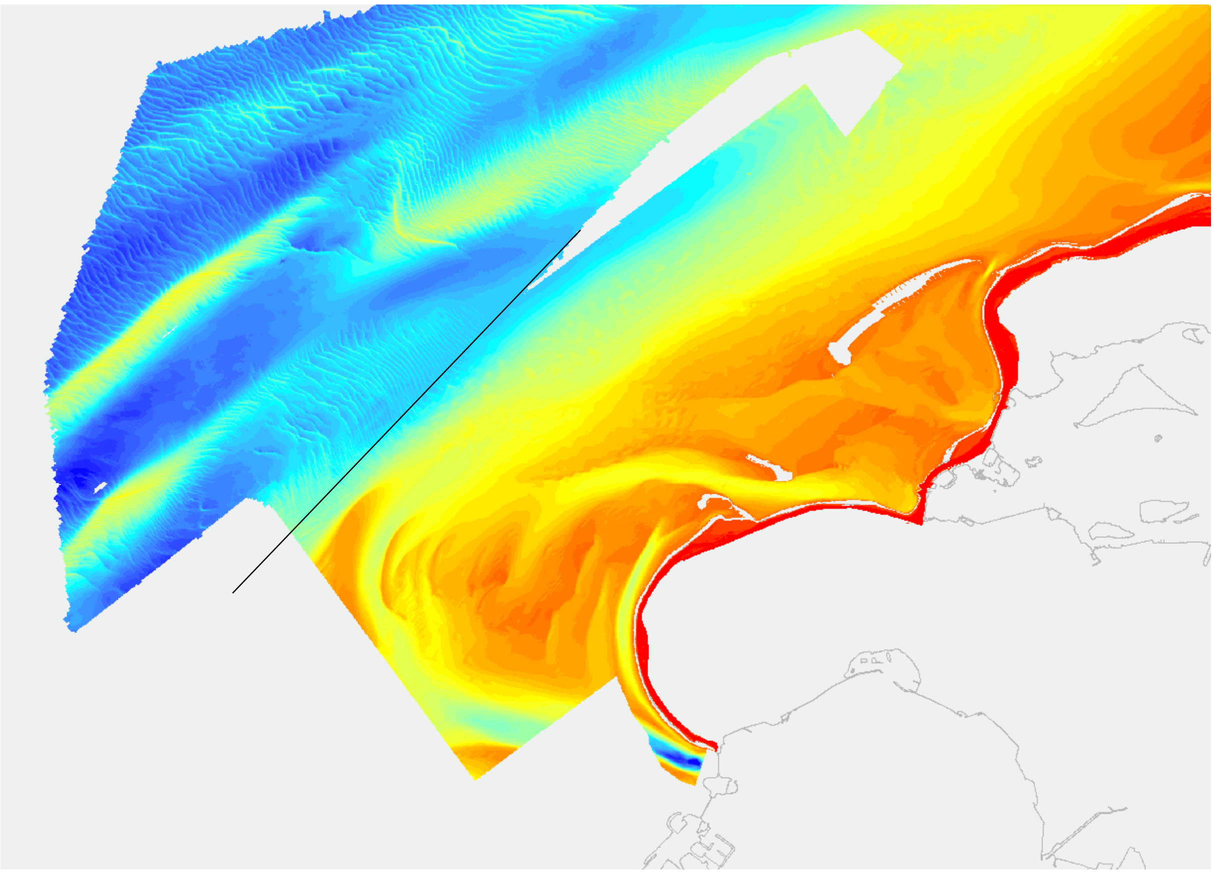


Figure B 2 - Bathymetry with single beam and multi beam measurements

B.2 - Bathymetry data

Acquiring bathymetry data for such a large area isn't as trivial as it may seem, the measurements that are included in grids that span an area of tens of square kilometres are almost always composed of different measurements. These measurements are taken on different dates, with different equipment and processed with different tools.

The first attempts to create a suitable bathymetry grid at Rijkswaterstaat Zeeland took quite a long time. Since the Brouwersdam lies on the border of two provinces, on part of the area falls under the jurisdiction of Rijkswaterstaat Zeeland and the other under that of Rijkswaterstaat Zuid-Holland. Data was requested at both agencies, but stitching the data together without specialized tools was a hard task and resulted in strange artefacts. Artefacts like artificial lines on the places where datasets were seamed together, Figure B 3 shows such an artefact between datasets. The location is the sand bar Bollen van de Ooster, close to the area of interest.

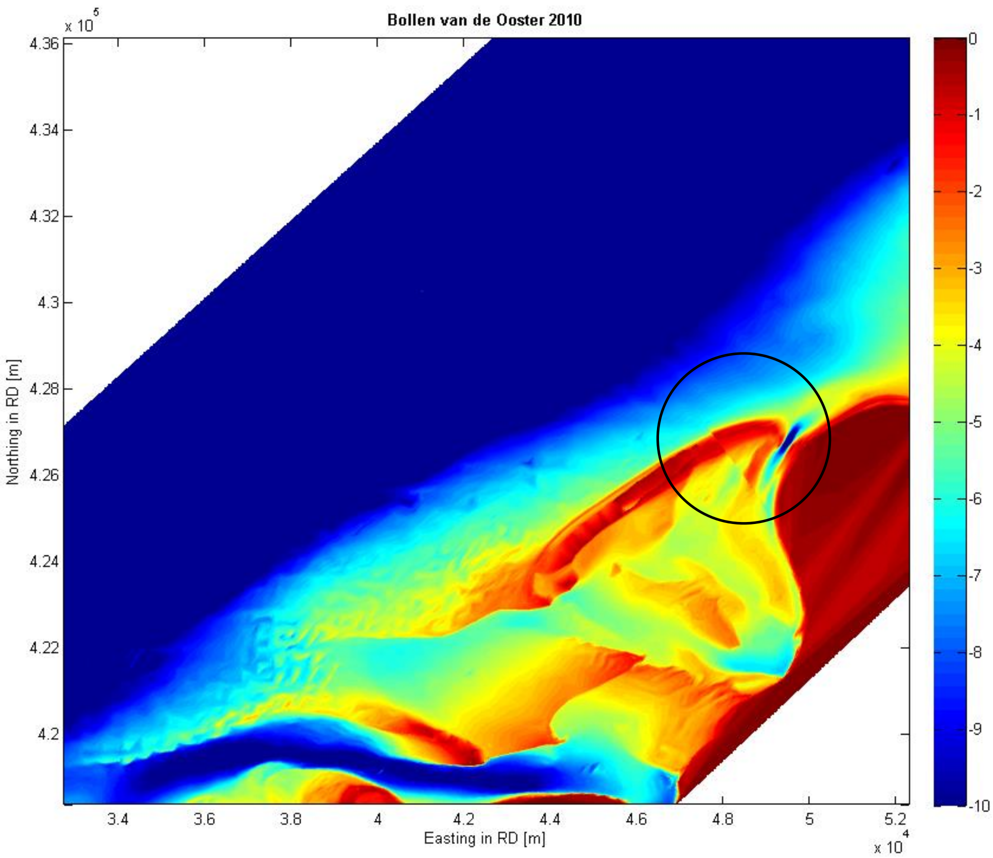


Figure B 3 - Errors Bollen van de Ooster 2010

These differences are quite big, especially for a location this close to the beach. The source data was reviewed by a very helpful college at Rijkswaterstaat Zeeland, but the source of the errors couldn't be found. Then the data was compared with data from other sources and measurements, but the result stayed the same, strange artefacts would surface in the grids.

So after more than a week of work creating grids, writing scripts to import data from different sources into MATLAB and searching what caused the differences, the result was that the differences couldn't be explained.

In the meantime my request for grids of different areas had reached a different part of Rijkswaterstaat, the Waterdienst (Water Service), where they had encountered the same kind of problems before. One of the main problems when comparing data from Rijkswaterstaat Zeeland with data from other parts of Rijkswaterstaat was that different interpolation methods were used, causing a shift on both the x- and y-axis of the data. Only with the original, un-interpolated measurement data it was possible to create correct grids. Since the Waterdienst had re-created all these grids recently and checked them for errors, the task of creating a usable grid became a lot easier.

Grid 2010

The first grid that was created is a grid based on data measured in 2010 and will be used for running a wave simulation that serves as input for UNIBEST to predict future developments. The first grids that were created extended, extended from the tip of Schouwen-Duiveland to just below the Haringvliet. However, after a consultation with an expert at Deltares led to the insight that these were too small (Huisman, 2013). When a grid is too small, errors induced by boundary conditions in the model can travel further into the area of interest. To mitigate this, a larger grid was created.

This grid has been made as large as possible with the available data of the year 2010. This grid extends from Belgian harbour of Zeebrugge to the entrance of the Rotterdam harbour (Figure B 4).

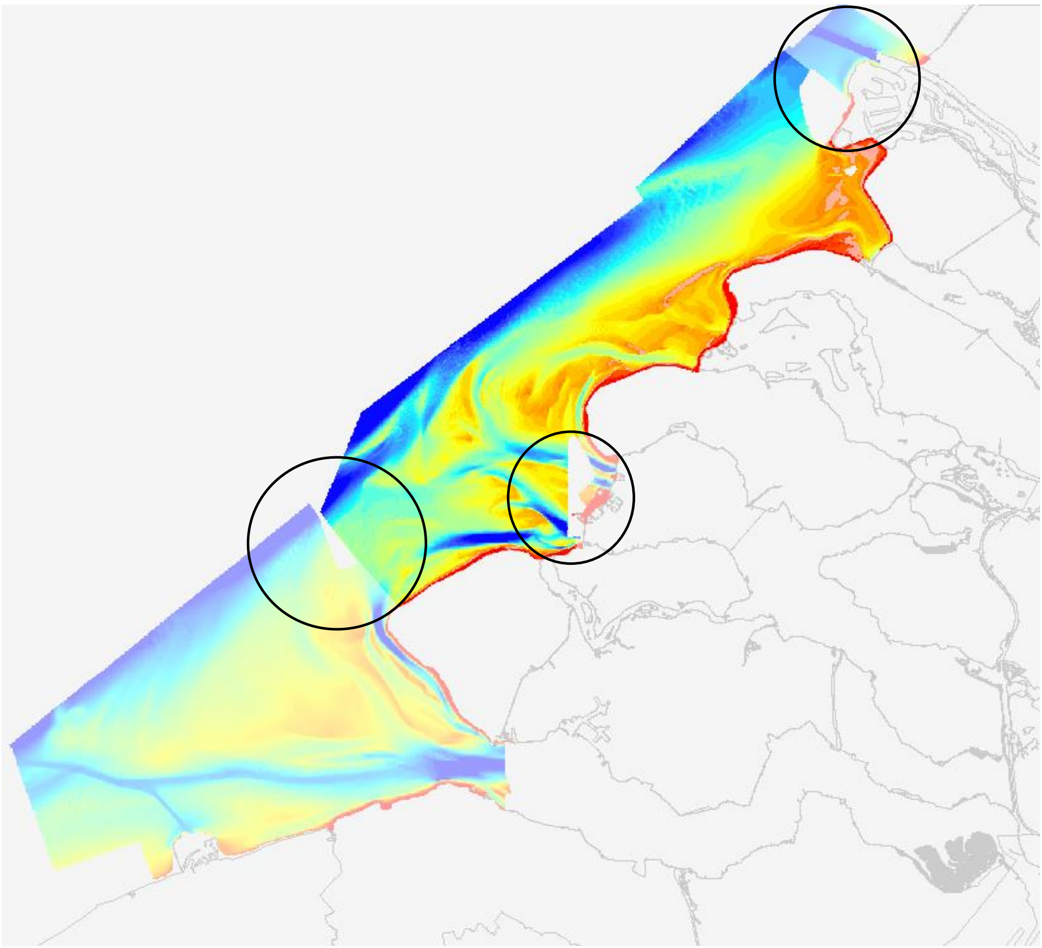


Figure B 4 - Grid 2010

However a small gap in the available data near the tip of the peninsula of Walcheren made it necessary to cut of the remaining data below this line. At the top of the grid the same is done near the Maasvlakte II. Near the entrance of the Oosterschelde, some small areas have been cut off because they serve little purpose and are surrounded by gaps in the data. All the deleted data is shown in faded colours, the bright colours indicate the data is used for as base for the SWAN grid.

Grid 2000

The second grid that was created, is a grid with the bathymetry of the year 2000. This grid is used to perform a hindcast of the developments of the beach in the last decade. The goal was to create a grid that spanned the same area as in 2010, but not all areas were measured that year. So the search was expanded to years around 2000, making a grid that was as much the same as possible. The resulting grid as made in collaboration with the Waterdienst (Visser, 2013) and is constructed from a lot of different measurements. Figure B 5 shows the underlying datasets, ranging from 1998 till the end of 2000.

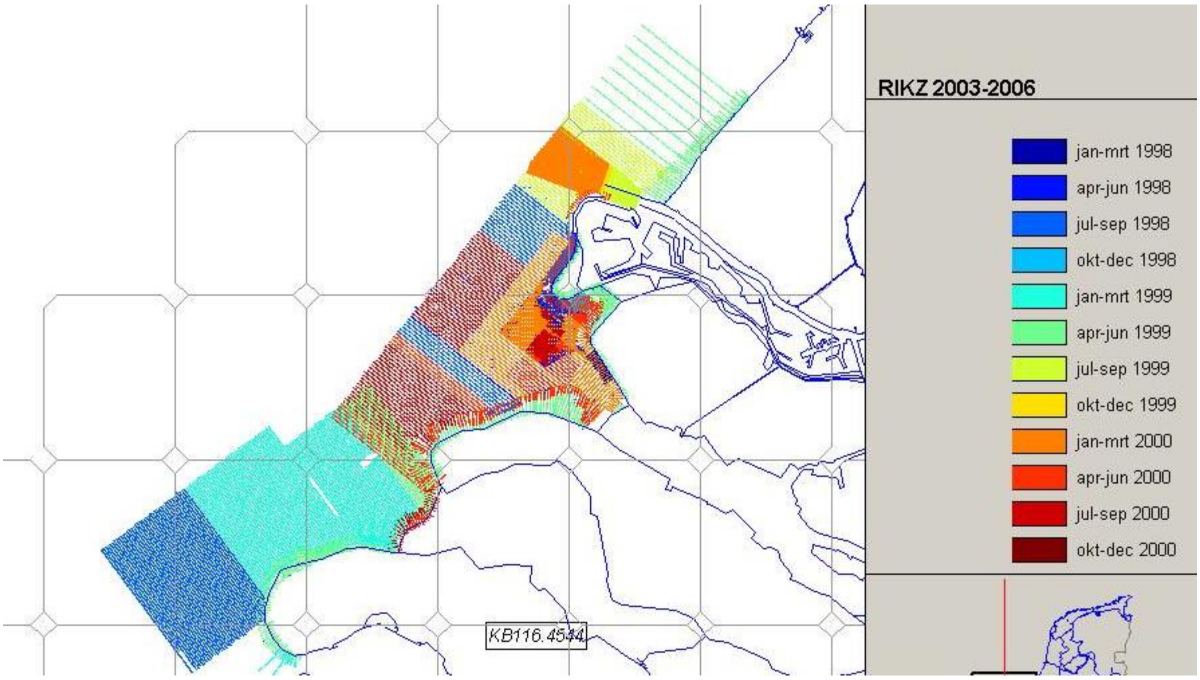


Figure B 5 - Measurements for grid 2000

The final dataset for the year 2000 is the result of 12 different measurements. Around the Brouwersdam they are fairly uniform, but around the Haringvliet it's a patchwork of different datasets measured on different dates. The help in creating this grid was highly appreciated, in hindsight the endeavour of first trying to creating these grids by myself was a task that I shouldn't have gotten myself into. It's a task that you can't perform without the right tools, knowledge and source materials.

On the borders of the datasets, the values from different years will show differences due to ongoing morphological changes between the times of measurements. These values are interpolated by averaging overlapping values to create smooth transitions. The result is a grid that spans a smaller area than the grid of 2010, but still covers a large area around the Brouwersdam. The resulting grid is shown in Figure B 6. In this grid the area above the Maasvlakte II hasn't been cut off, because that didn't exist at the time.

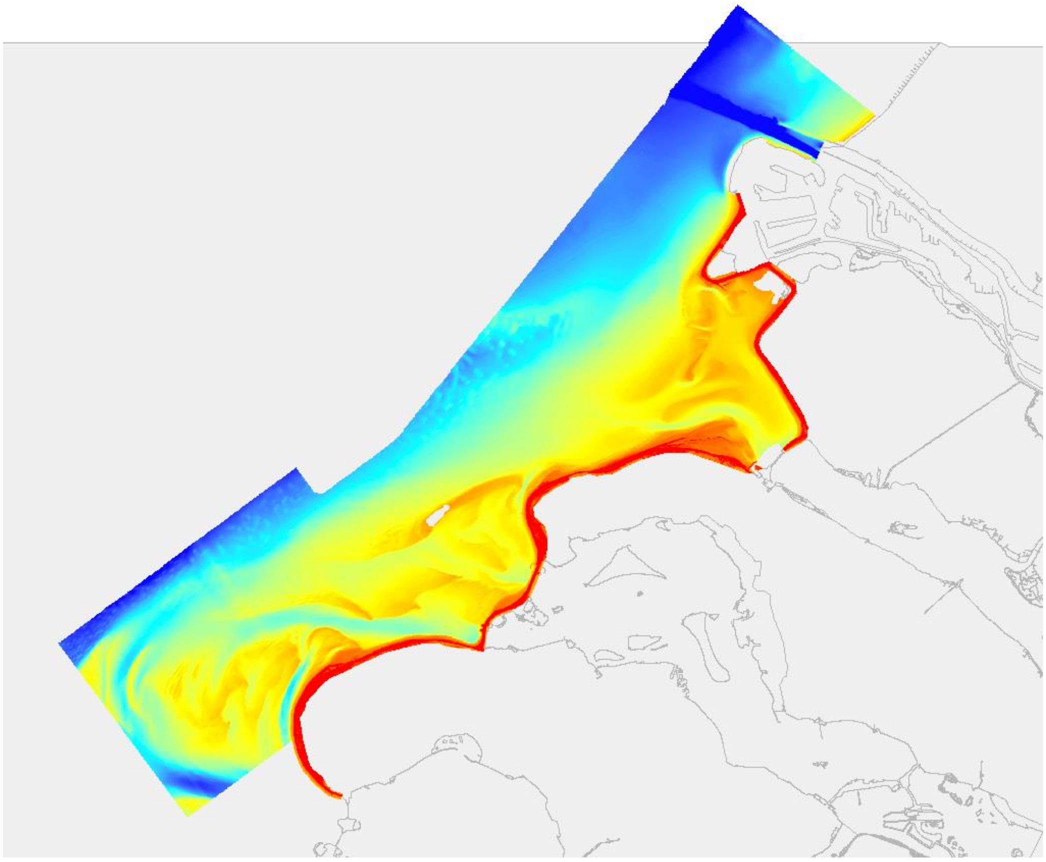


Figure B 6 - Final grid 2000

Appendix C

C.1 - BatTri processing

Creating a boundary file

The first step is creating a boundary points file in BatTri, a so-called .poly-file. This file is made from what BatTri thinks are the outer edges of the dataset. However as stated before, these aren't necessarily the boundaries within you wish the program to do a triangulation. A script was written to cut off all the values above a specified height, in this case above 5 m NAP, to help the program find the boundaries. The result can be found in Figure C 2, where the black line around the bathymetry in the left part of the figure indicates the boundaries and this is the dataset that's loaded into BatTri to make the .poly-file.

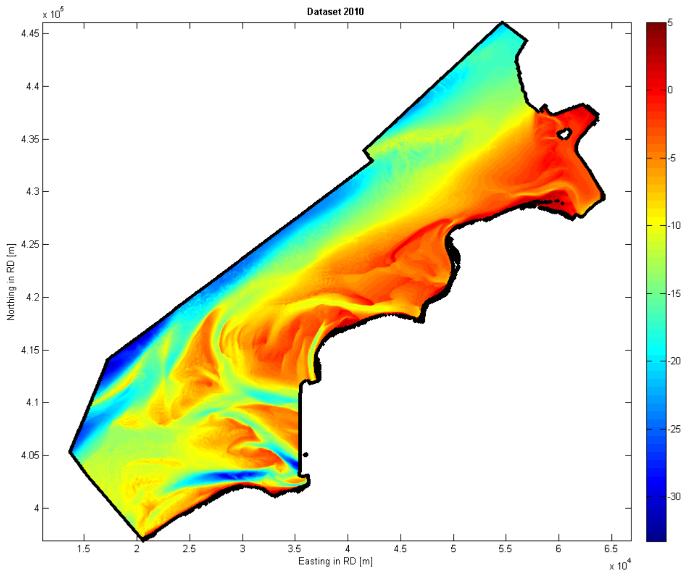


Figure C 2 - Boundaries on bathymetry 2010

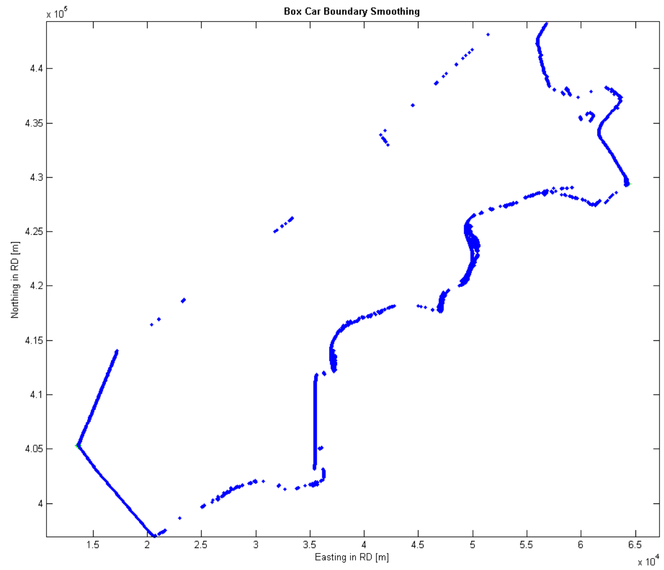


Figure C 1 - Interpolated boundaries

The program BatTri runs inside MATLAB and once the dataset is loaded into this program, all the operations that can be performed in MATLAB are limited to the functions BatTri provides. The blue intermittent contour line in Figure C 1 represents the boundaries. At first sight the results look fairly good, but when smoothed and zoomed in the results are less satisfactory, the results are shown in Figure C 3 and Figure C 4..

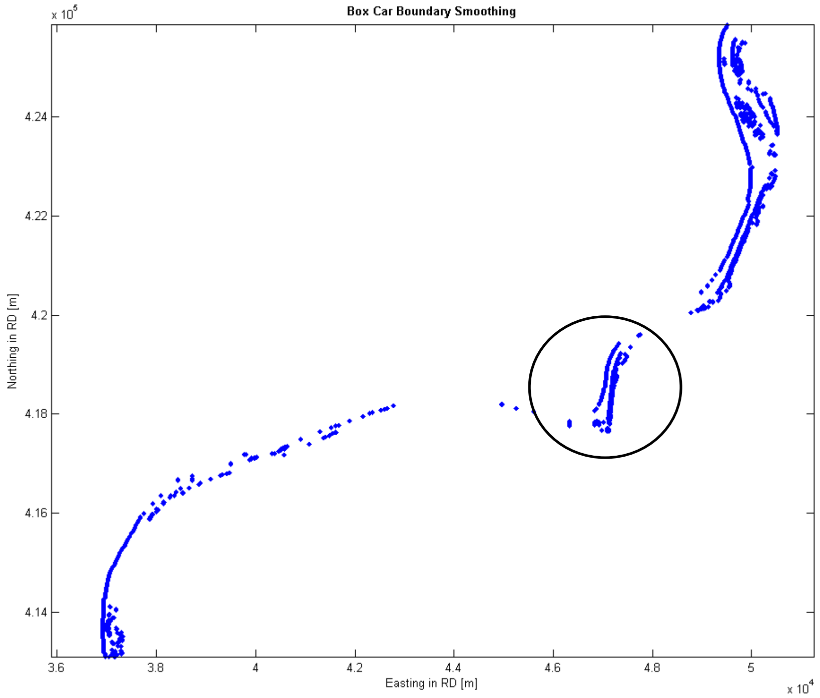


Figure C 3 - Box Car Boundary Smoothing

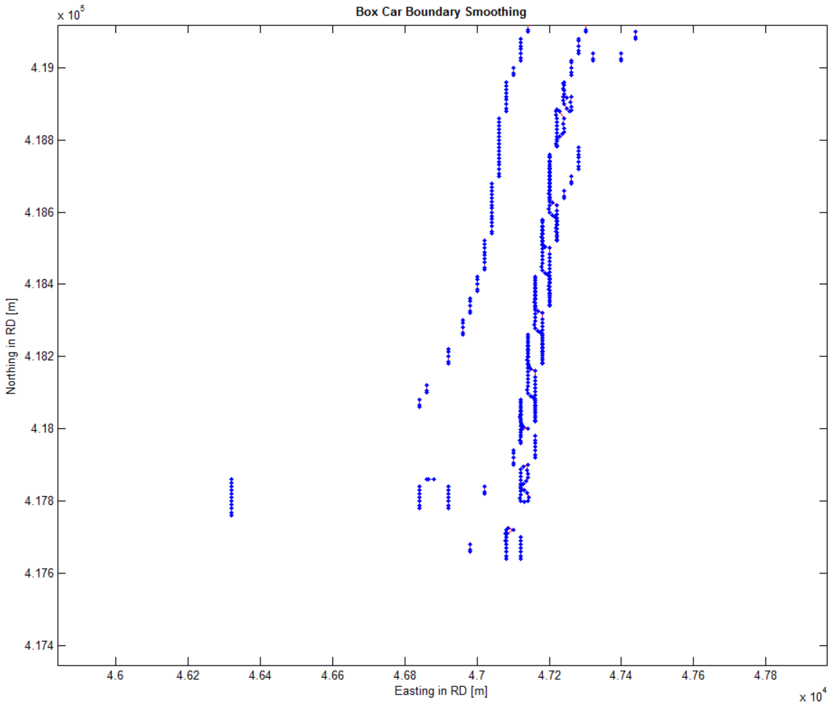


Figure C 4 - Box Car Boundary Smoothing (zoomed-in)

For triangulation, Triangle needs closed polygons. To make a closed polygon, all the dots and lines need to be connected and superfluous parts need to be removed. BatTri does provide the basic tools to perform this operation, but with grids this large and which such a large number of boundary points, it is a challenging task.

Cleaning up superfluous points is the first task at hand, with less points to load, the speed at which BatTri operates significantly improves. When the most obviously superfluous points are removed, it is advised to save your interim .poly-file and go out of the program to plot your results against the bathymetry so check if the results are satisfactory, like in Figure C 2. When inside BatTri, you can't see the bathymetry on the background, so essentially you are a bit flying blind. To get back into BatTri you have to perform about a dozen steps to proceed with creating the .poly-file.

This iterative process of saving your work, checking the results outside BatTri and getting back where you left off is a time-consuming process that is further complicated by the lack of fail-safes and possibilities for error-correction in the program. The program can be terminated by accidentally entering a wrong number that's not in the option list or when trying to save your work and making a typo when entering the location you want to save it. In both examples you need to start over at the last point you successfully saved your work.

The first attempts to successfully create a boundary file took several days, the learning curve of the program is steep and the margins for errors are very small. Once you learn to work with it and learn to make as little errors as possible the speed goes up, but it remains a challenging endeavour.

Grid Triangulation

The next step in the process is the actual triangulation of the bathymetry. This is a two-phase process, first a preliminary (first-cut) mesh is generated. This serves as base and provides the input element area and the depth information that will be used by the next step, the refinement step (Bilgili and Smith, 2005). The dummy bathymetry of the previous step has served its purposes for creating the .poly file, for the next steps the actual bathymetry is used.

For the preliminary mesh generation there are four input variables:

1. Minimum angle constraint: sets a limit to the minimum inside angle (in degrees) that a triangle is allowed to have in the preliminary grid. This constraint is important for SWAN, the maximum internal angle a triangle can have in SWAN is 143 degrees, which leads to the following statement: $180° - 2 \cdot minimum\ angle \leq 143°$
   This results in a minimum angle constraint of 18.5 degrees, but using this value could lead to a different problem, the number of triangles that meet at each vertex should not be larger than ten or smaller than four. This first restriction leads to a minimum angle constraint of 36 degrees, although the possibility that 10 triangles with the same minimum angle of 36 degrees meet at the same vertex is small.
   The second restriction states that the maximum inside angle a triangle can have must be smaller than 120 degrees to ensure there exist no points where less than four triangles meet. For precision in highly refined meshes it is advised to not set the minimum angle too high because this can cause problems with the floating-point precision of the calculation. In all the grids created in this research, the minimum angle constraint is set at 30 degrees, so it is still possible that grids are created that don't satisfy all constraints for SWAN.

2. Maximum element area constraint: this parameter sets the maximum area that an element can have in the preliminary grid and depends on the size of the underlying bathymetry.

3. Maximum number of nodes to add: this parameter sets the number of nodes that can be added to the preliminary grid. This number depends on the size of the grid, the previous constraints and on the available computing time and –resources. In practice, a compromise has to be made between these constraints.
   A number of different scenarios for different years had to be calculated, the goal was to be able to run all the calculations in one week of continuous computing time. So the actual computation time per scenario was allowed to be slightly more than 24 hours.
   After a number of test runs, it was found that the maximum number of nodes for the two grids would have to be around 60.000. With the refinement steps yet to come, the number of nodes for the preliminary gird has to be a lot smaller than this value. When using a maximum element area of 50.000 m^2 the number of nodes for the preliminary grids is about 15.000.

4. Boundary refinement: two options are possible, allow or disallow boundary refinement. Enabling this option will result in a better quality grid, so this option is set to option 1: allow boundary refinement.

After the creation of the preliminary grid, the grid has to be refined to increase the node resolution in the area of interest. In practice, this means increasing the number of nodes in shallower parts of the bathymetry by setting constraints to BatTri to operate only between certain depth contours . The program provides eight different options with each a number of different parameters that can be set. For this research two options were used, the other six options do have its use cases but will not be treated in this thesis because its outside its scope.

The two options that were used are the following:

1. h-refinement: this option relates the maximum element area to the depth linearly with the formula $h/\alpha \geq A$
   In this formula h is the absolute value of the average element depth, the constant *alpha* is a constraint set according to wish and A is the maximum element area.

2. Maximum slope refinement: this option refines elements with a maximum slope larger than a user set value. This option was used to try to improve the resolution on lateral sides of the tidal channels entering the area of research.

For this thesis a lot of different triangulated grids were created, grids with different numbers of nodes and different refinement methods. These refinement methods can also be used in combination with each other and the parameters and depth restrictions can be set by the user.

Before arriving at the two final triangulated grids that were used for the year 2000 and 2010 a number of test runs were performed in SWAN to see what the final result would look like for different mesh refinement options. To be able to perform these test runs, an intermediate step is necessary. The boundaries points at which the different boundary conditions need to applied have to be specified in the generated mesh grid.

This process involves loading the mesh grid into MATLAB and splitting the boundaries in two sections, one section where wave boundary conditions are imposed upon and one section where no conditions are imposed. The first section is displayed with red dots in Figure C 5, the second in blue dots.

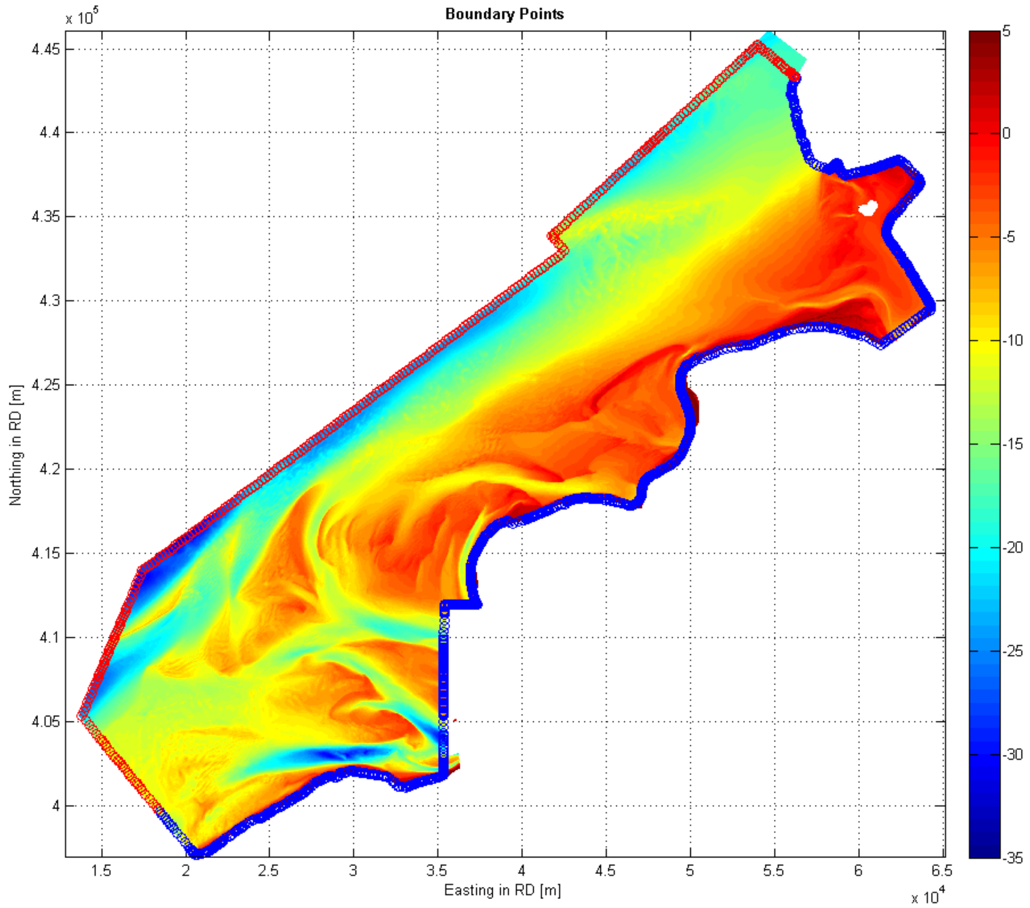


Figure C 5 - Boundary Points SWAN

In the upper right corner the red boundary extends to the Maasvlakte, this area 'sticks out' from the coastline of Holland and the water in front of it is fairly deep. Waves coming from northern directions should be able to travel into the domain, so the wave boundary is set close to the coast. On the lower right side of the figure, the wave boundary doesn't extend to the coast. That corner is a shallow water area and test runs gave unrealistic results when setting boundaries close to the coast. Both boundaries are located far from the area of interest, so errors introduced by the boundary conditions should be minimal.

C.2 - SWAN test runs

The first SWAN test result is the triangulated grid that is used in the definitive SWAN calculations and is created with the first refinement option from *Appendix C.1 - BatTri processing*, the h-refinement method. The second grid is created with the second option, maximum slope constraint and the third is made with both options, where the h-refinement is used on deeper parts and the maximum slope constraint on the shallower parts. The fourth grids is made with the same method as the first grid, but with double the number of nodes. The four different grids are shown in the next figures (Figure C 6-Figure C 9) All the test runs were made on the bathymetry of the year 2010. The same method will be applied to the bathymetry of the year 2000.

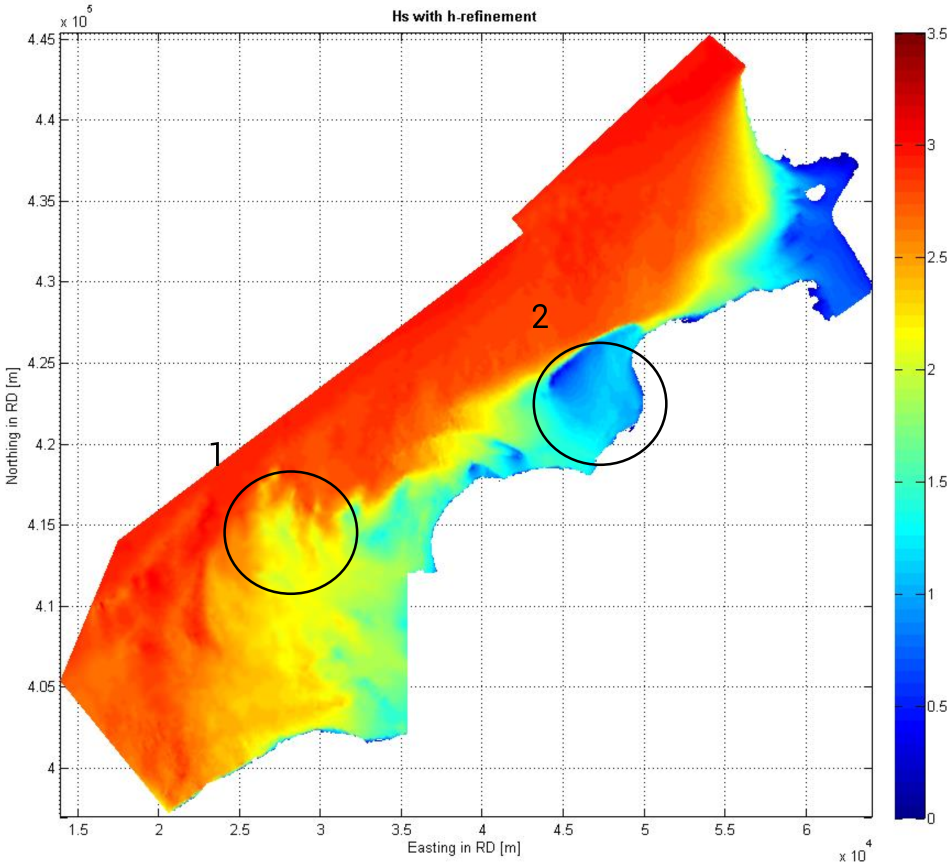


Figure C 6 - Significant wave height on h-refinement grid

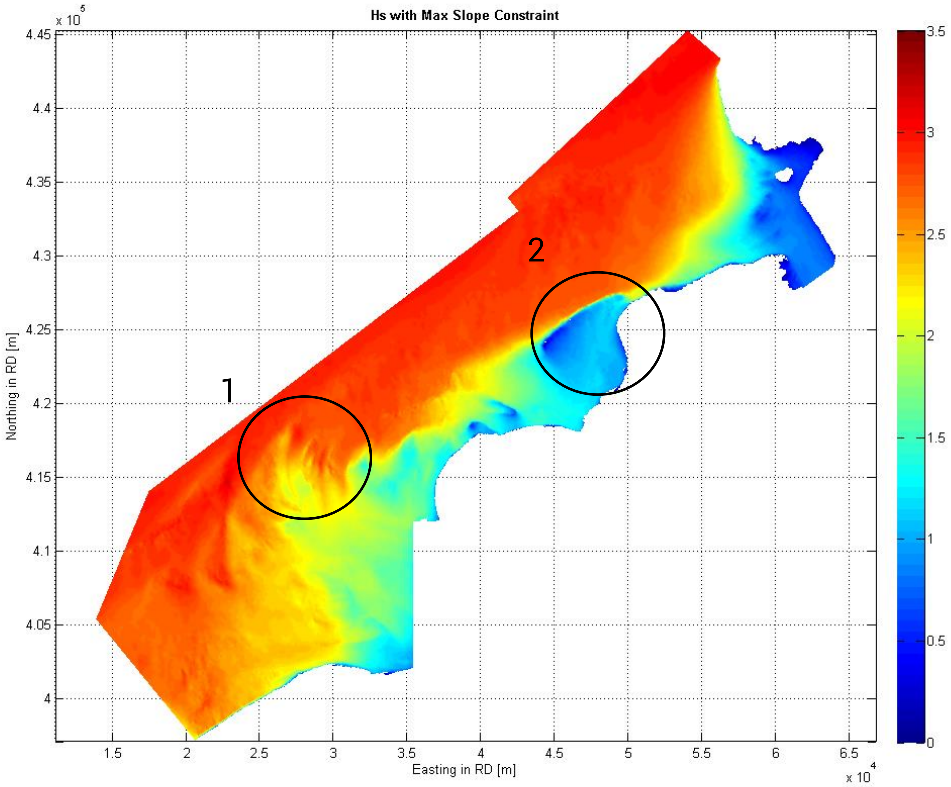


Figure C 7 - Significant wave height on maximum slope constraint grid

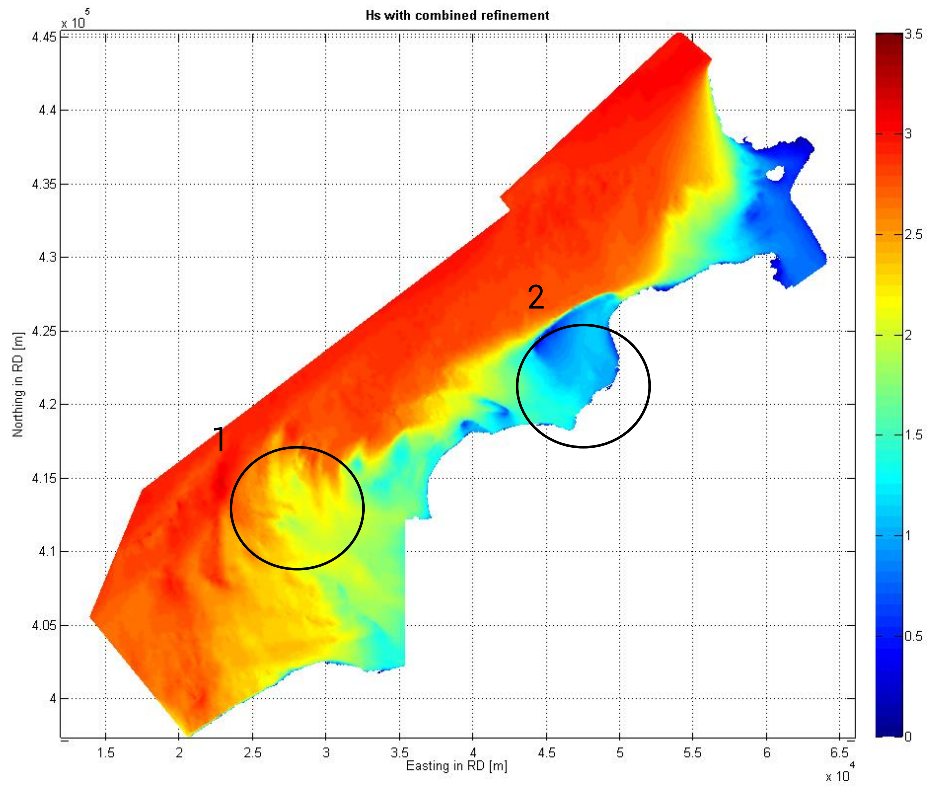


Figure C 8 - Significant wave height on combined grid

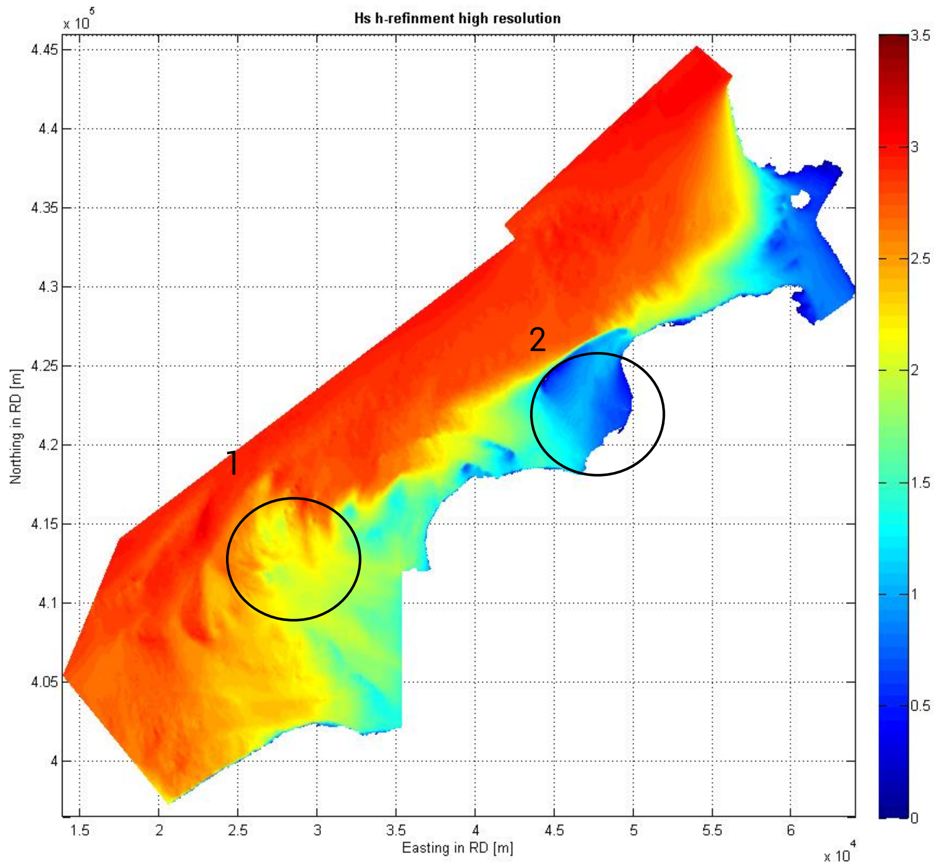


Figure C 9 - Significant wave height high resolution grid

All four figures have two circles in them, this circles denote points that have visual differences between them. In circle 1 the shape of the waves meeting the ebb-tidal delta of the Oosterschelde and entering the tidal channel Geul van de Banjaard is clearly visible, however the actual shape differs per figure. Exact values of the significant can't be given for a common point in the graph due to the unstructured mesh grid. The values exist only per node and those are different for every triangulation. The small differences between the figures would be offset or strengthened by differences in position of the respective nodes because relatively large size of the grid triangles in these parts of the grid. When visually comparing the four circles, in the first figure the channels aren't as clearly resolved, the next three have a sharper shape. This can be explained by the fact that the second and third grid use the maximum slope constrain, which resolves these features better and the fourth has twice the resolution.

The area of interest, the area near the beach of the Brouwersdam, is found in circle 2. All four methods give slightly different results for this area, due to the higher resolution of the mesh grid it is possible to compare points between the different grids. Four points between the in front of the beach have been picked with its respective locations as close to each other as possible, their wave height was compared and the results are given in Table C 1.

Point Nr.	Coordinates	H_s Figure C 6 [m]	H_s Figure C 7 [m]	H_s Figure C 8 [m]	H_s Figure C 9 [m]
1	x=48000, y=423000	1.073	1.066	1.067	0.869
2	x=47000, y=422000	1.105	1.106	1.077	1.006
3	x=46000, y=421000	1.198	1.114	1.159	1.115
4	x=45000, y=420000	1.388	1.361	1.371	1.354

Table C 1 - Comparison SWAN results for different grids

For the first point, the values for the first three figures are all very close with a difference of less than a centimetre, while Figure C 9 shows a significantly lower value. The second point shows more or less the same pattern, the value in this figure is lower than the others , in fact the whole area on the north-eastern side of the beach shows lower wave heights.

The third point gives mixed results, Figure C 7 and Figure C 9 show almost the same value, but both are lower than the others although the results are closer together than on the first two points. For the fourth point, all the values are close to each other, the difference is three centimetres at most.

Grid Choice

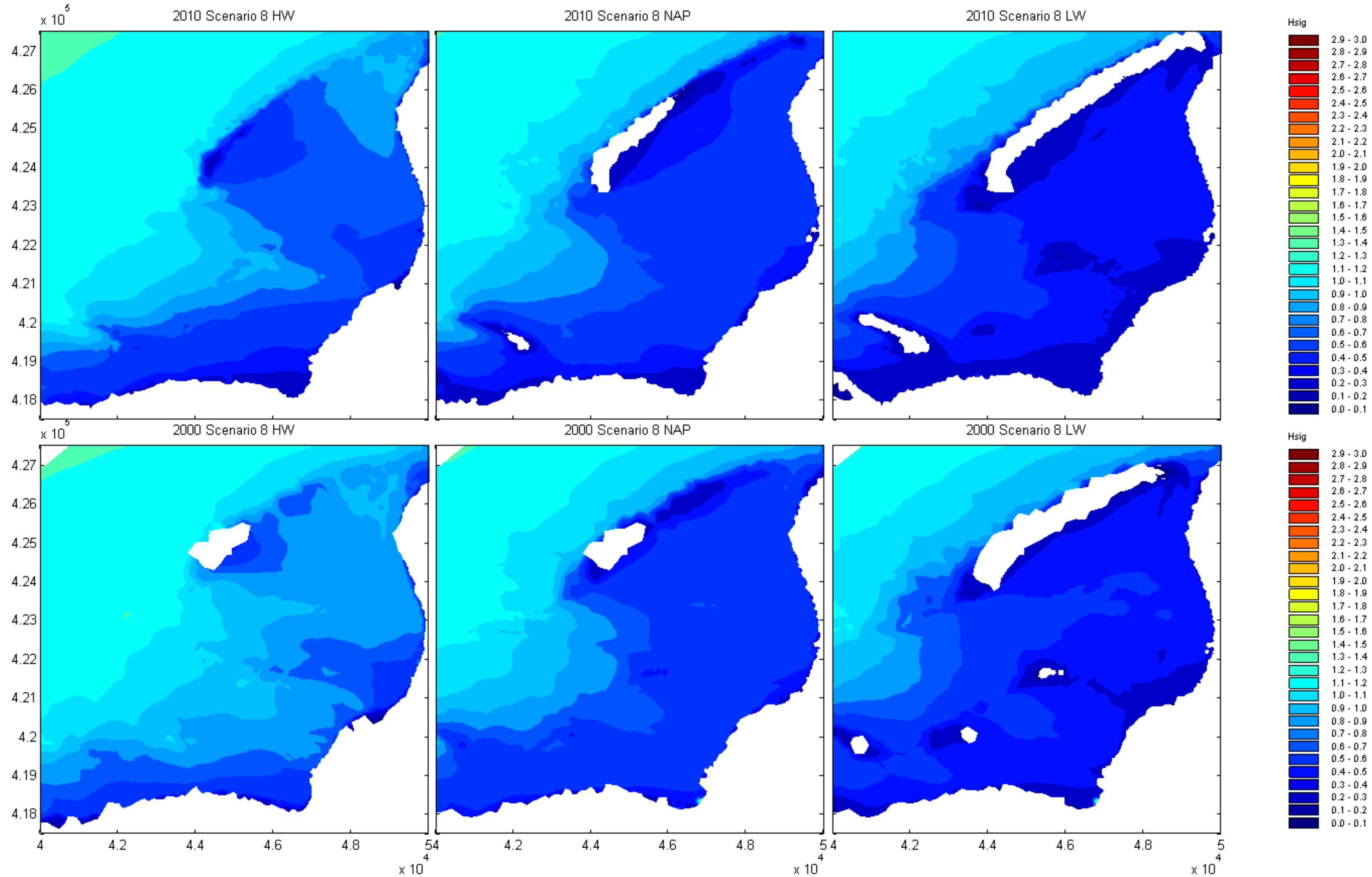
The actual choice which grid to use was a difficult one, for some reason the effect of increasing the number of nodes per grid gives lower wave height north-east of the beach. Closer to the tidal channel the differences get smaller. The wave heights in Figure C 6 are generally among the highest, but finding a clear pattern is difficult. For point 2, Figure C 7 shows the lowest value, but for point 3 it's the highest of the four.

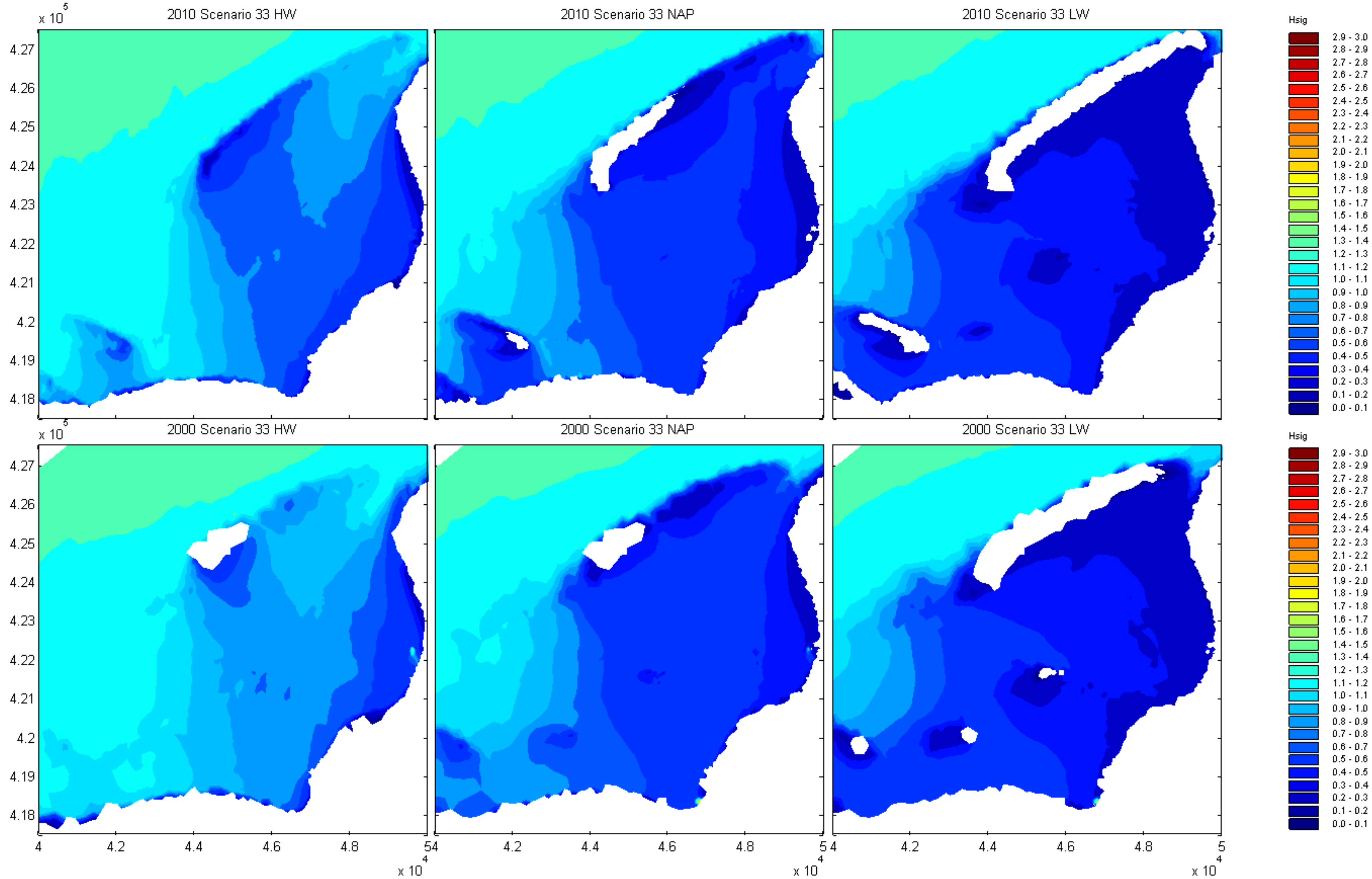
What causes the difference between the tested grids is a difficult question. Quite a number of steps have to be taken and a lot of variables have to be set to arrive at a grid that can be used in SWAN. It is even possible that grids created with the exact same parameters have differences. This problem was encountered a number of times, some grids didn't work in SWAN. The program gave error messages and further examination showed that the number of elements in the grids was slightly different, sometimes a grid had one element more than the other and because of that the calculation couldn't be started. The error message was related to the constraints mentioned in *Appendix C - Grid Triangulation*, where the number of elements in a vertex can't be less than four or more than ten. If this problem occurred, the grid had to be created again, as indicated by the feedback loop in Figure 6.7. So despite the same parameters used for triangulation, the resulting grid can be different.

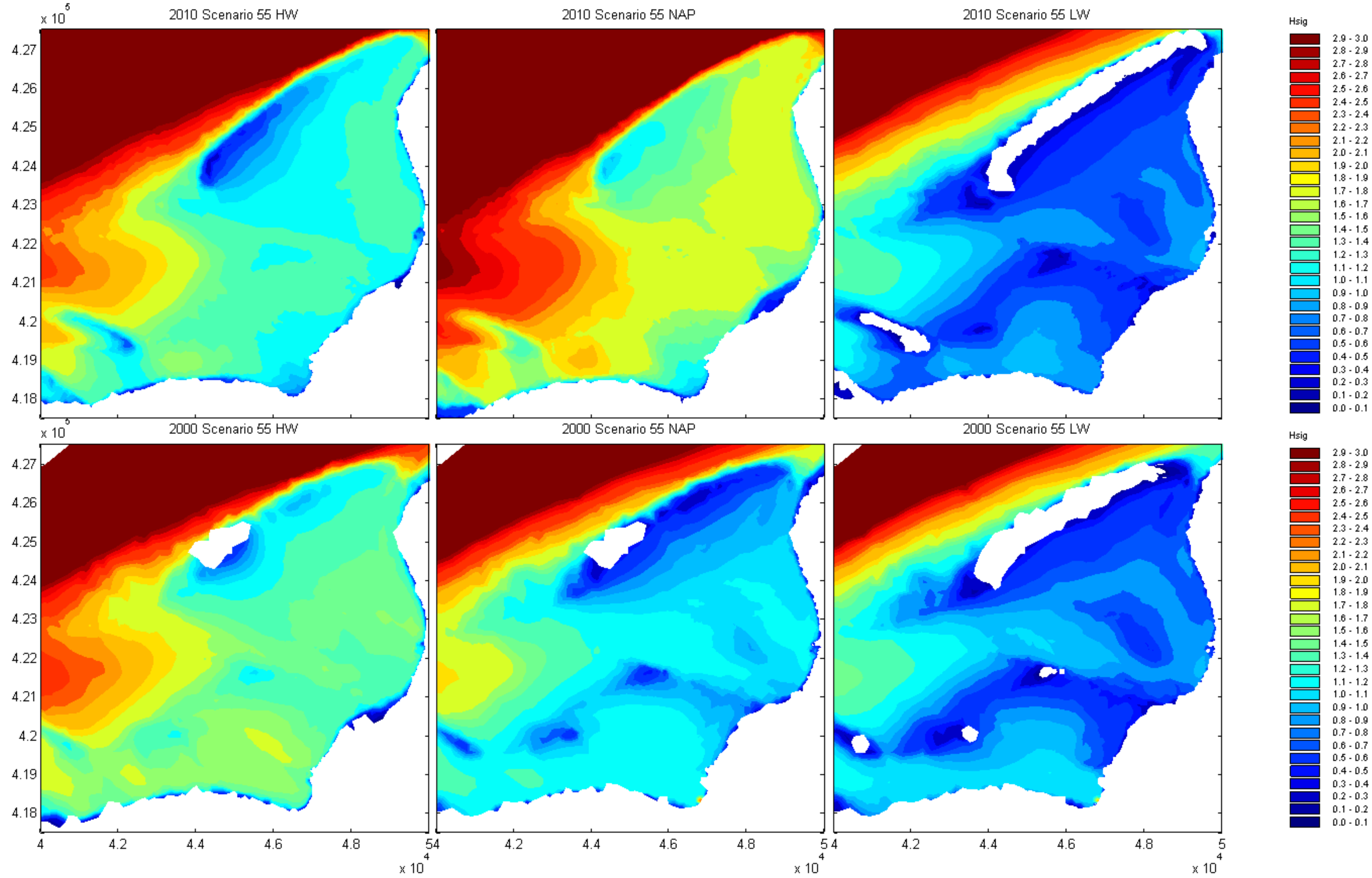
The resulting wave calculations in SWAN shows different results for different mesh grids. Patterns that one seems to observe between different grids can be different when different wind and wave scenarios are tested. Differences are observed for grids with different mesh resolutions and different mesh refinement options. All choices have its influence on the final result and clear patterns haven't been found. One conclusion can be drawn, more extensive research into this subject is beyond the scope of this thesis because there are too much variables involved and the limited time frame forces to set priorities.

The choice for the grid that was used was made in consultation with the person who advised me on the subject of SWAN and an expert at Deltares (personal communication James Salmon, Bas Huisman). James advised me to use the h-refinement method which is the most standard one of the two. Bas advised me to move on because the subject already cost a lot of time and need a whole lot more to figure everything out. These advices combined with practical limitations in computational resources have led to the choice for the h-refinement method with a grid with 60.000 nodes and 120.000 elements for both the bathymetry of the year 2010 as for the one of the year 2000.

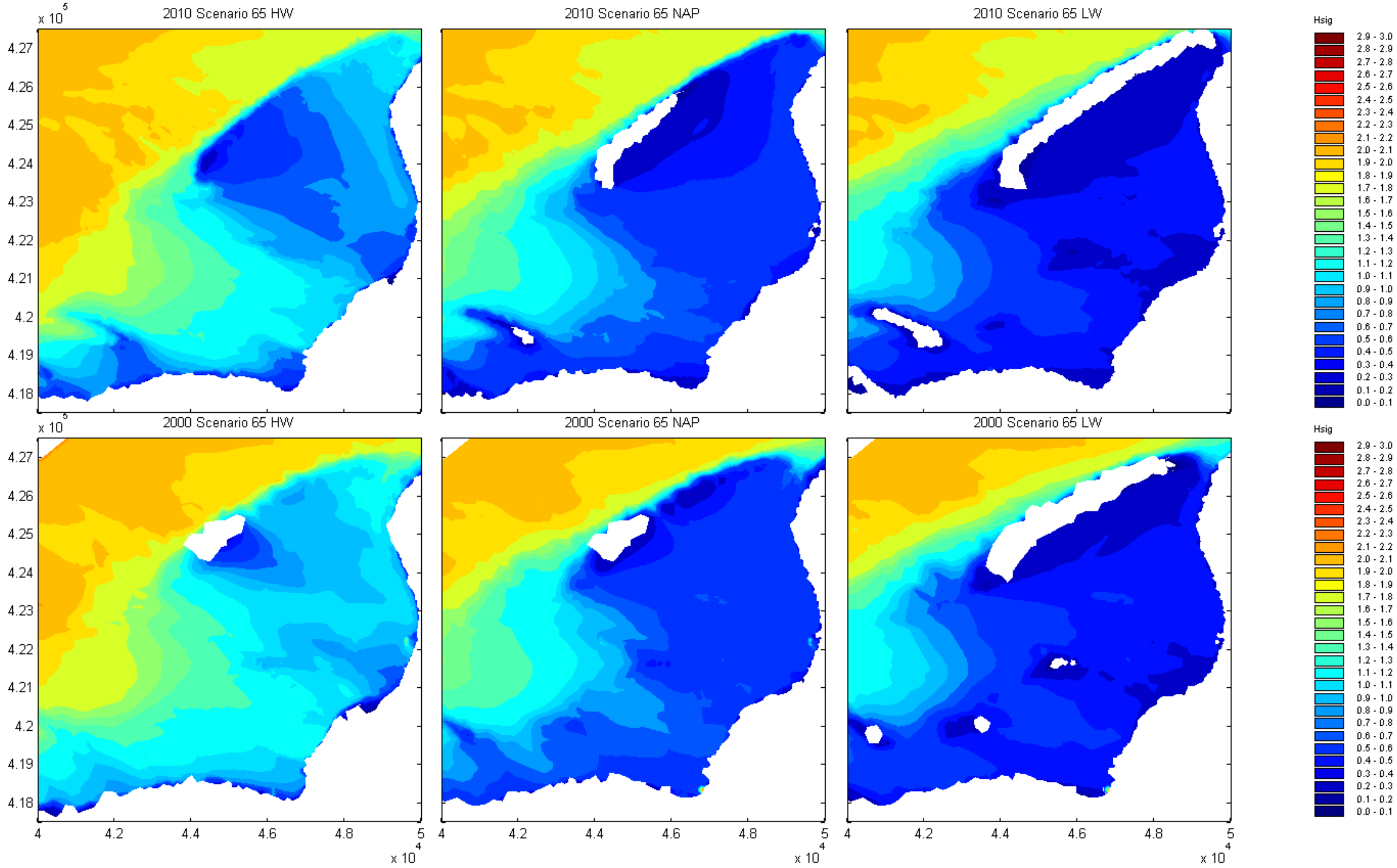
C.3 - SWAN model results

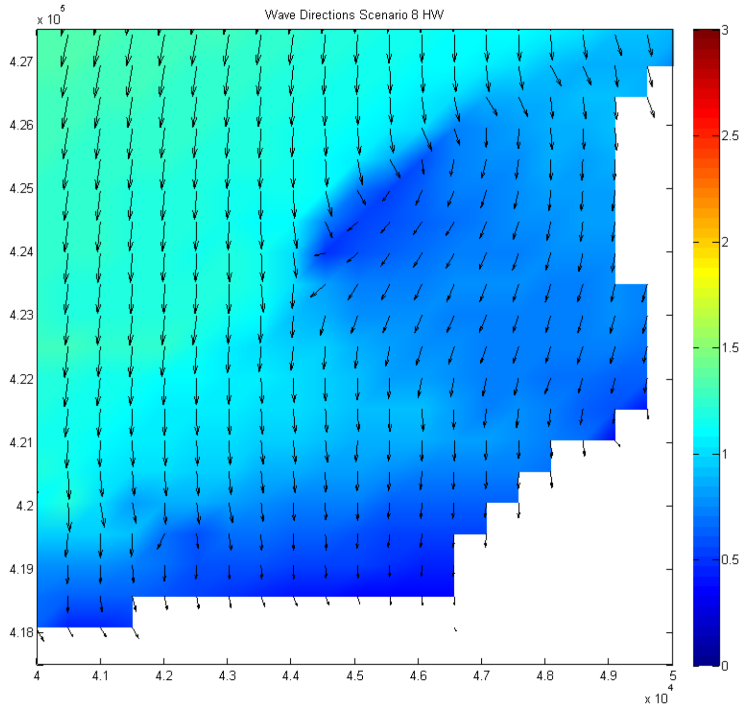


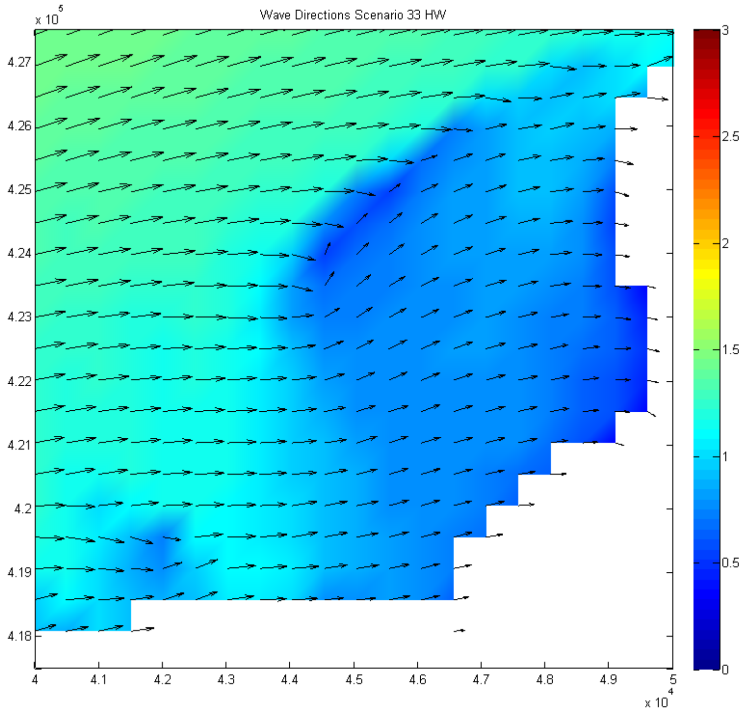

2010 Scenario 33 HW
2010 Scenario 33 NAP
2010 Scenario 33 LW
2000 Scenario 33 HW
2000 Scenario 33 NAP
2000 Scenario 33 LW
Hsig

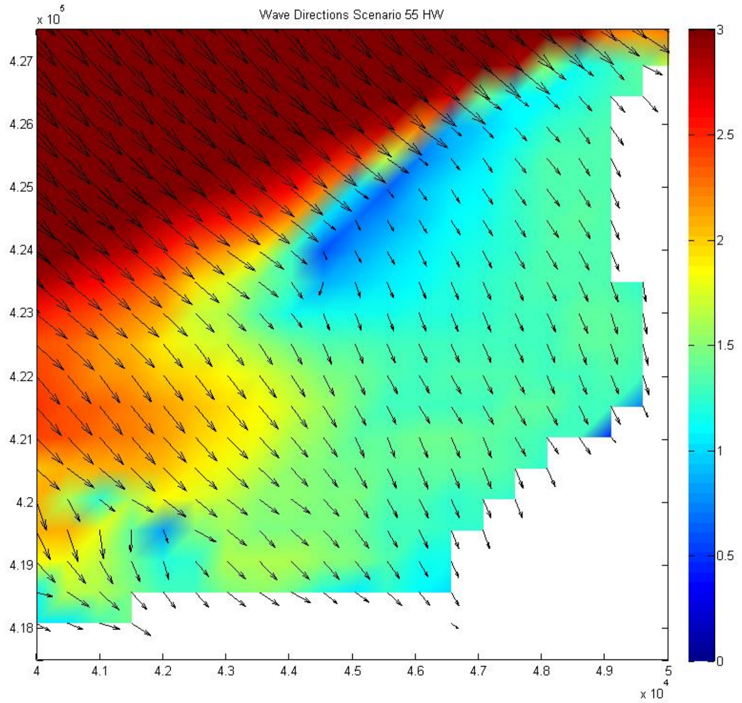


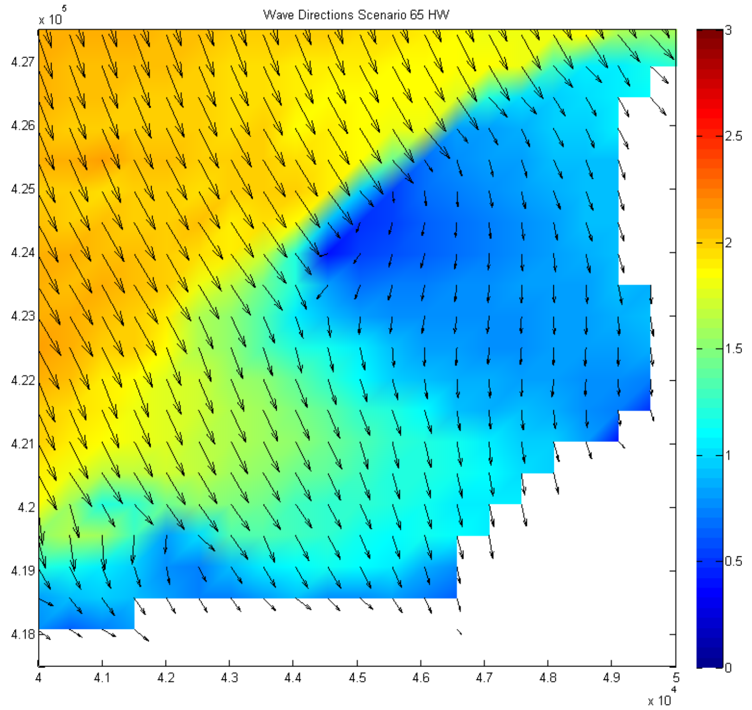
2010 Scenario 55 HW
2010 Scenario 55 NAP
2010 Scenario 55 LW
2000 Scenario 55 HW
2000 Scenario 55 NAP
2000 Scenario 55 LW
x 10^5
4.27
4.26
4.25
4.24
4.23
4.22
4.21
4.2
4.19
4.18
4
4.2
4.4
4.6
4.8
5
x 10^4
Hsig
2.9 - 3.0
2.8 - 2.9
2.7 - 2.8
2.6 - 2.7
2.5 - 2.6
2.4 - 2.5
2.3 - 2.4
2.2 - 2.3
2.1 - 2.2
2.0 - 2.1
1.9 - 2.0
1.8 - 1.9
1.7 - 1.8
1.6 - 1.7
1.5 - 1.6
1.4 - 1.5
1.3 - 1.4
1.2 - 1.3
1.1 - 1.2
1.0 - 1.1
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
0.0 - 0.1


2010 Scenario 65 HW
2010 Scenario 65 NAP
2010 Scenario 65 LW
2000 Scenario 65 HW
2000 Scenario 65 NAP
2000 Scenario 65 LW
x 10^5
4.27
4.26
4.25
4.24
4.23
4.22
4.21
4.2
4.19
4.18
4
4.2
4.4
4.6
4.8
5
x 10^4
Hsig
2.9 - 3.0
2.8 - 2.9
2.7 - 2.8
2.6 - 2.7
2.5 - 2.6
2.4 - 2.5
2.3 - 2.4
2.2 - 2.3
2.1 - 2.2
2.0 - 2.1
1.9 - 2.0
1.8 - 1.9
1.7 - 1.8
1.6 - 1.7
1.5 - 1.6
1.4 - 1.5
1.3 - 1.4
1.2 - 1.3
1.1 - 1.2
1.0 - 1.1
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
0.0 - 0.1


Wave Directions Scenario 8 HW


Wave Directions Scenario 33 HW


Wave Directions Scenario 55 HW


Wave Directions Scenario 65 HW

Appendix D

Source: http://www.rijkswaterstaat.nl/geotool/waterhoogte_tov_nap.aspx?cookieload=true

Brouwerhavensche gat 08 (Noordzee)

Slotgemiddelden 1991.0

Algemene gegevens			
1979	Aanvang waarnemingen		

Gemiddelde waterstanden			
type tij	HW-stand cm + NAP	LW-stand cm + NAP	tijverschil cm
gemiddeld tij	**144**	**-106**	**250**
springtij	**173**	**-115**	**288**
doodtij	**109**	**-92**	**201**
gem. waterstand		**0**	

Gemiddelde havengetallen waarden maansverloop			
type tij cq grootheid	HW-tijd u:min	tijd u:min	LW-tijd u:min
gemiddeld tij	**00:58**		**07:07**
springtij	**00:53**		**06:50**
doodtij	**01:04**		**07:30**
duur rijzing		**06:16**	
duur daling		**06:09**	

Gemiddelde over- en onderschrijdings frequentie per jaar			
overschrijding hoogwaterstanden		onderschrijding laagwaterstanden	
frequentie	stand in cm + NAP	frequentie	stand in cm + NAP
1x per 10.000 jaar	**525**	1x per 10 jaar	**-235**
1x per 4.000 jaar	**500**	1 x per jaar	**-205**
1x per 1.000 jaar	**465**		
1x per 100 jaar	**400**	LLWS 1985.0	**-140**
1x per 10 jaar	**340**		
1x per 2 jaar (grenspeil)	**295**		
1x per jaar	**280**		
basispeil	**525**		
ontwerppeil	**500**		

Bijzonderheden:			
Datum	stand cm + NAP	kenmerkende waarden	periode
27 feb 1990	**330**	hoogst bekende waarde	(periode 1981...1990)
22 jan 1984	**-242**	laagst bekende waarde	(periode 1981...1990)
2 mrt 1987	**439**	maximale rijzing	(periode 1981...1990)
19 mrt 1988	**308**	maximale daling	(periode 1981...1990)

Appendix E

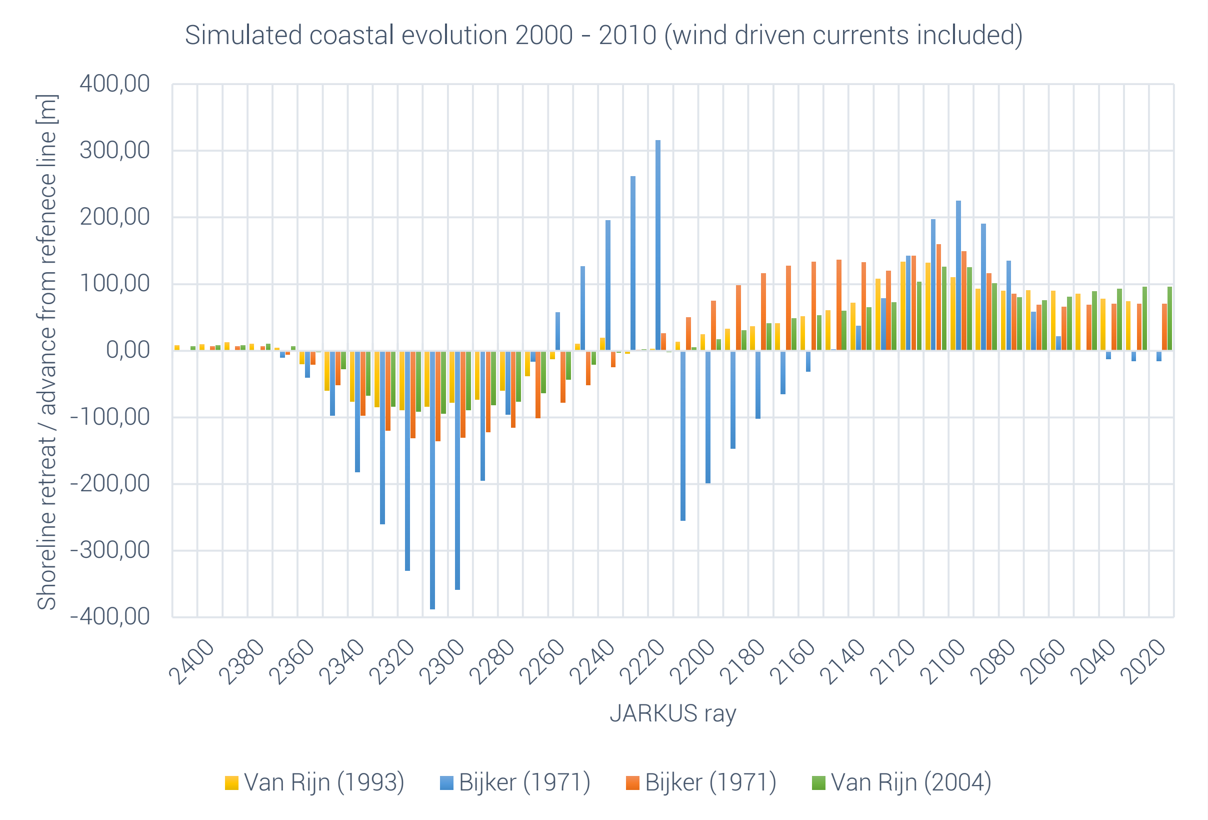


Figure E 1 - Simulated coastal evolution 2000-2010 (wind driven currents included)

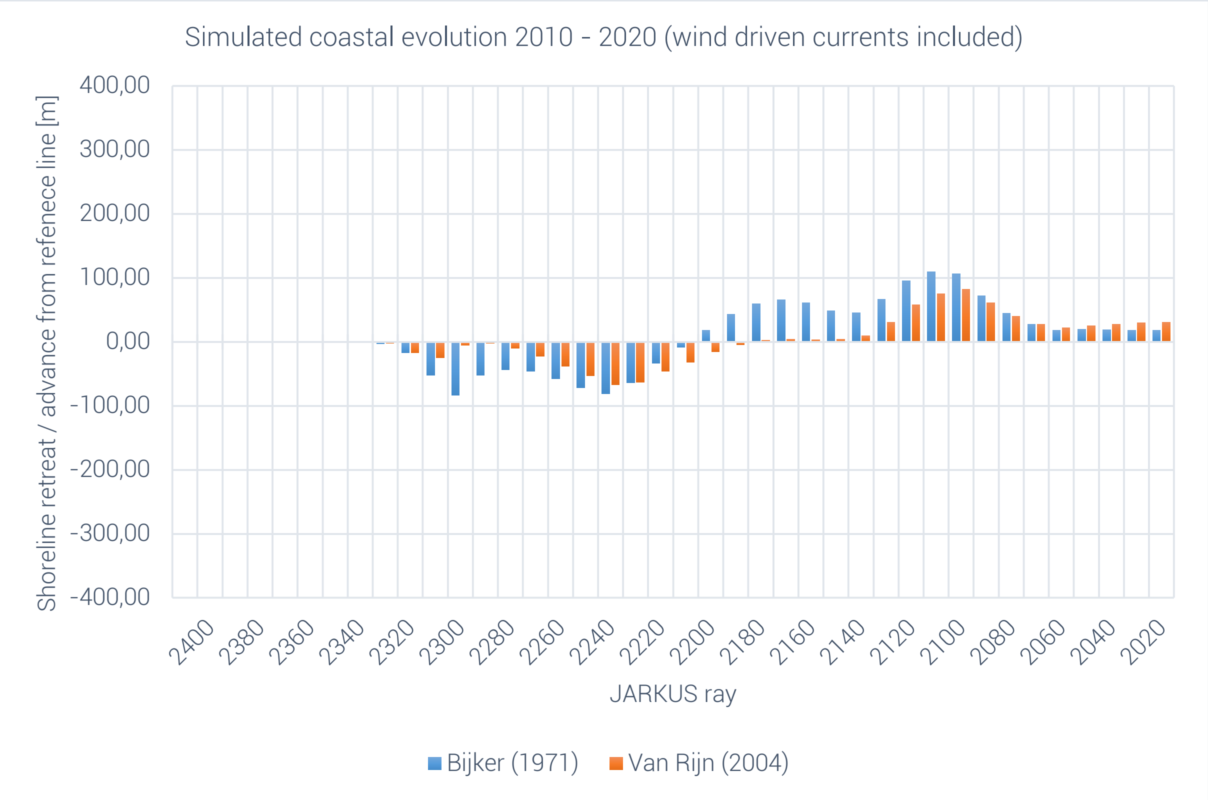


Figure E 2 - Simulated coastal evolution 2010-2020 (win driven currents included)