Nourishing intertidal foreshore; Improving safety and nature

Part A: Morphological development of the Eastern Scheldt
Part B: the Oesterdam project

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Preface

This report presents the results of my final Master thesis carried out at Deltares. This work completes my double MSc programme in Hydraulic Engineering and Water Resources Management at Delft University of Technology and the National University of Singapore. It covers a background research to the erosion problems in the Eastern Scheldt basin and provides possible designs for a nourishment solution to this problem near the Oesterdam called the Oesterdam safety buffer project. This pilot project is part of a programme by Rijkswaterstaat to find solutions to the erosion of intertidal flats. However, this MSc thesis is no official part of that programme, it stands on its own and the project has only been used as a start for this research.

I would like to thank my daily supervisors at Deltares, John de Ronde and Jaap van Thiel de Vries, for their guidance and support. I would also like to thank the other members of my MSc committee, Prof. dr. ir. M.J.F. Stive, ir. M. Eelkema, N. Volp, MSc and Prof. dr. ir. G.S. Stelling and dr. V. Chua, for their input and their comments on my work. Finally I would like to thank Eric van Zanten and Dick de Jong from Rijkswaterstaat Dienst Zeeland for their enthusiasm and the project visits to the Eastern Scheldt.

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Summary

Morphological development of the Eastern Scheldt

After extensive flooding in 1953, Deltaworks were constructed to protect the Southwest delta in the Netherlands from the sea. In the Eastern Scheldt the open connection to the North Sea was regulated by an open storm surge barrier. The construction of this barrier reduced the cross-section of the entrance. As a result, a smaller volume of water flows into the basin during one tidal cycle. In order to decrease reduction of the tidal range, two compartment dams were constructed (Oesterdam and Philipsdam). These dams ensured that the tidal range remained sufficiently high by reducing the basin surface. However this smaller basin surface further reduced the tidal prism of the basin.

Decrease of the tidal volume has reduced the tidal currents flowing through the channels. The tidal currents are no longer strong enough to transport sufficient sediment onto tidal flats and shoals to keep up with the always present erosion during storm conditions. Consequently tidal flats are eroding and disappear under water.

The intertidal flats and shoals have two important functions in the basin. Firstly, they are valuable habitat and foraging grounds for wading bird species. Many of these are listed species and have to be protected. A second function of flats located in front of dykes is to reduce the wave attack on these water barriers. Rijkswaterstaat has started several pilot project to find solutions to these problems. One location were the flats have both a function for safety and nature is the foreshore of the Oesterdam in the ‘Kom’ in the Southeast of the Eastern Scheldt. At this location Rijkswaterstaat has started a pilot project called ‘the Oesterdam safety buffer’.

Bathymetry data of the ‘Kom’ show the erosive trend of the intertidal flats after the construction of the storm surge barrier in the entrance of the Eastern Scheldt. Some of the sediment has been deposited in the channels in this part of the basin. However sediment volume seems to be missing out of the almost closed system of the ‘Kom’. This loss of sediment can point to a possible error in the bathymetry data. This makes the erosion trends found questionable. That is why two different erosion scenarios are defined.

The high scenario is based on the sedimentation-erosion plots made from the bathymetry data sets. The lower erosion rate scenario is founded on transect measurements throughout the Eastern Scheldt basin. Also taking two different scenarios for the expected sealevel rise in the next 50 years into account, the expected erosion for the next 50 years can be calculated. The high erosion scenario is expecting erosion including sealevel rise of 130cm for the next 50 years. While the low scenario predicts a drowning of the intertidal area due to erosion and sealevel rise of 50cm.

The Oesterdam safety buffer project

The Oesterdam safety buffer project is a project from Rijkswaterstaat dienst Zeeland. It consists out of a nourishment placed on the foreshore of the Oesterdam as a pilot project on finding a solution for the problems with erosion of intertidal area in the Eastern Scheldt.

The revetment on the Oesterdam has been classified as unsafe and is being replaced. The Oesterdam project tries to provide extra safety using measures on the foreshore that cause extra breaking of incoming waves for the next 50 years, even if the foreshore erosion continues. In this way increasing the lifetime of the new revetment. A second objective of the project is to create intertidal habitat, since this valuable habitat is lost due to the erosion processes. The research in this second part of the report, is on finding the most optimal designs for this safety buffer in front of the Oesterdam.

In total seven different designs have been evaluated in this report. Where two high dune designs focus on creating safety and lowering the hydrodynamic conditions at the dam toe in such a way that possibly the revetment on the Oesterdam needs no replacement.
The other 5 designs aim to fulfill both project goals of increasing safety and creating intertidal habitat. Three different design strategies have been found in a workshop namely, a buffer, an equally spread flat nourishment and finally a wave breaking ridge. For all these strategies different profiles have been dimensioned.

During their lifetime, the bedlevel of these nourishments will change. A 1D morphological model called XBeach has been used to model these morphological changes. This model showed that steep slopes become more gentle during their lifetime and it seemed to be that there is a stable slope of around 1:60 to 1:70. When the profile becomes this gentle, the slope becomes very stable and even a large 1/50year storm does not cause large bathymetry changes. For this reason the results of the model for the final profiles are considered to be reliable.

A safety check for the design conditions (1/4000yr) has been done both for the initial profiles, as designed, and for the final profiles at the end of their 50years lifetime, as modeled by the XBeach model. To calculate the overtopping over the Oesterdam the program PC-Overslag has been used. Results showed that all nourishment designs give a smaller overtopping volume of the dam and thus create safety. The high dune design would even reduce the wave impact on the Oesterdam to such a large extent that is possible that the old revetment would have been qualified safe. Nourishment designs with steep slopes deform largely during their lifetime, decreasing the wavebreaking and increasing the overtopping during a design storm.

When evaluating the designs for both safety and nature, it showed that a Flat design is most optimal for both nature and safety. Also this design can considered to be very robust because there is only a slope at the edge of the nourishment. .

1 General introduction

1.1 Problem description

The Eastern Scheldt is a former estuary located in the south-west of the Netherlands in the province of Zeeland, Figure 1-1. The connection to the river Scheldt was cut off completely in 1867, turning the estuary into a tidal basin with an open connection to the North Sea. Large flooding in 1953 was the motive to develop new plans to improve safety in the South West delta; the Deltaplan. This plan consisted out of several large regulating structures, the Deltaworks, that were constructed between 1954 to 1986. In the Eastern Scheldt an open storm surge barrier that regulates the connection to the sea in combination with smaller compartment dams was constructed. During high storm surge levels on the North Sea side the barrier can be closed, protecting the basin from high water levels.

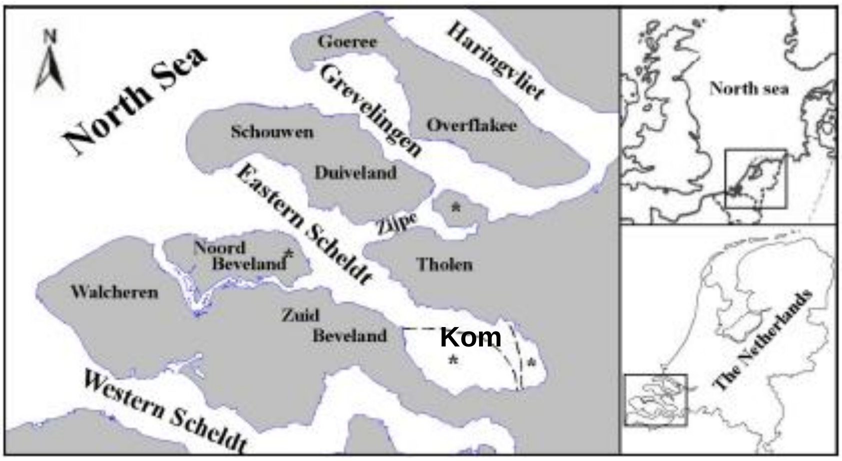


Figure 1-1 Eastern Scheldt basin from (Eelkema, Wang et al. 2009)

Due to construction of the storm surge barrier and compartment dams, the Eastern Scheldt has a smaller tidal volume flowing in and out. Reduced tidal currents transport less or no sediment onto the shoals anymore. Because the erosive conditions (storms, waves) have not changed the net balance is disturbed. The building and erosive transport on intertidal flats are not equal, resulting in a net transport of sediment of the shoals.

The loss of height of intertidal areas causes two problems in the Eastern Scheldt. Firstly, intertidal habitat is lost. Wader birds have less time and less area to forage for food on the flats. Secondly, waves no longer break on the shallow foreshore in front of dykes and dams surrounding the tidal basin. Higher waves can impact on the water barriers. This means to keep the dykes safe, mainly revetments (most sensitive to higher wave impact) need to be renewed, now or in the future. The Oesterdam safety buffer project is a combined solution for both of these problems.

1.2 Research approach

This MSc-thesis is on finding optimal designs for the Oesterdam safety buffer, part B of this report. To get an insight into the processes and morphological development in the Kom basin of the Eastern Scheldt, first part A of the research has been carried out.

1.2.1 Part A: Morphological development Eastern Scheldt

Part A contains both a literature study and a bathymetry analysis to investigate the morphological changes in the basin in the last 40 years. Chapter 2 contains the results of the literature study to the effects of the Delta works. It gives an overview of the basin development before and after the Delta plan was implemented. Hypotheses on the morphological development after construction of the barrier are stated. Chapter 3 presents the results of the bathymetry research. This chapter will confirm or reject the hypotheses stated in chapter 2. It also proposes possible future scenarios on the morphological developments in the future. Chapter 4 and 5 are respectively the conclusions and the discussion on the reliability of the used data and therefore the reliability of the conclusions.

1.2.2 Part B: Oesterdam project

In part B designs are developed for the foreshore nourishment of the Oesterdam safety buffer project. Part B starts with a description of the Oesterdam safety buffer project in chapter 2. In chapter 3 the design strategy is described and the generated designs are presented. Next, the results of the morphological development of the nourishment designs during their lifetime is shown in chapter 4. A safety assessment of the designs in made in chapter 5, after which an evaluation of the different designs can be made in chapter 6. Finally chapters 6 and 7 state the conclusions and recommendations of the Oesterdam project.

1 A Introduction Part A: Morphological development Eastern Scheldt

1.1 Effect Delta works

Figure 1-1 Deltaworks in the Eastern Scheldt

The Delta works in the Eastern Scheldt consisted out of the Eastern Scheldt stormsurge barrier and several compartment dams. The construction of the storm surge barrier narrowed the entrance of the basin. The entrance was chocked; a smaller volume of water can flow in during one tidal cycle, the barrier blocks part of the flow. In order to minimize the reduction of the tidal range two compartment dams were constructed, the Oesterdam and the Philipsdam. By reducing the basin surface the tidal range remained sufficiently high. However, the dams decreased the tidal prism of the Eastern Scheldt even further because less water is needed to fill and empty the smaller basin.

This large loss of tidal volume has reduced the tidal currents flowing through the channels. These currents are now no longer strong enough to transport sufficient sediment onto tidal flats and shoals to keep up with the erosion during storm conditions. Consequently tidal flats are eroding and slowly disappearing under the low water level.

These tidal flats and shoals have two important functions in the basin. Firstly, they provide valuable habitat and foraging grounds for wading bird species. Some of these are endangered species and have to be protected. A second function of flats located in front of dykes is to reduce the wave attack on these water barriers. The flats are part of the safety level; if they erode, the wave impact on the dykes will increase. The dams and dykes would then no longer pass the safety check carried out by Rijkswaterstaat every five years. This means that stronger dykes or revetments would be needed in the future.

1.2 Research question

This research focuses on the East branch of the basin, known as the ‘Kom’. Erosion rates are high in this area, and the intertidal area has both a nature and a safety function. However, there is little knowledge on the exact morphological developments in this part of the basin.

In this research, the morphological development of this branch is investigated. The main research question for this part A of this thesis is;

What is the expected morphological development of the eastern branch of the Eastern Scheldt in the next fifty years?

Sub-questions are;

- *How has it developed since the construction of the storm surge barrier?*
- *What is the erosion rate of the Oesterdam foreshore?*
- *How will the basin develop in the next fifty years?*

2 A Eastern Scheldt and Deltaworks

This chapter aims to give an overview of the hydrological and morphological effects of the Delta works in the Eastern Scheldt basin as been described in several reports and research articles. After this literature research hypotheses on the morphological behavior of the intertidal area in the east branch are formulated.

2.1 Eastern Scheldt basin

The Eastern Scheldt is a tidal basin located in the Southwest Delta in the Netherlands. The historic formation of this delta and the Eastern Scheldt basin is described in more detail in Appendix I to this report.

The Eastern Scheldt bathymetry of 1968 in Figure 2-1 shows the channel system in the Eastern Scheldt before the construction of the deltaworks. The channels and shoals in the basin are clearly visible. The Eastern part of the basin, also known as the Kom is very shallow, with two channels extending into the flats, the Marollegat and the Westgat or Mosselkreek (A). Near Wemeldinge (B) two channels are flanking and a forking behavior of the flood and ebb channels appears a little West from Tholen (C).

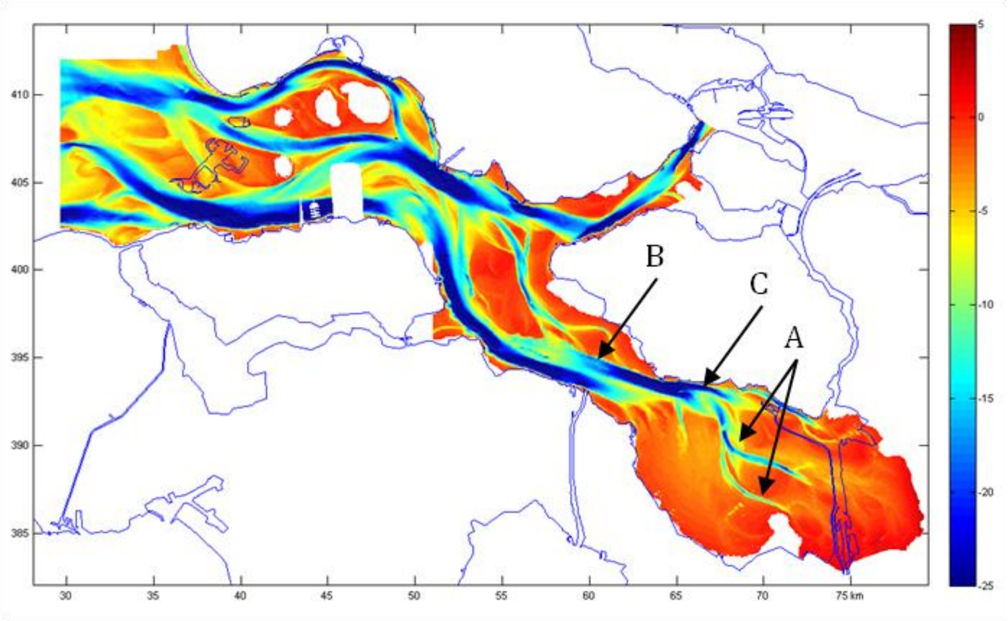


Figure 2-1 1968 bathymetry Eastern Scheldt

2.2 Deltaplan

Figure 2-2 Flooded areas during the 1953 flood

2.2.1.1 1953 flood (31st January 1953)

In the night of 31st of January 1953 a large storm caused extensive flooding, large areas of Zeeland were inundated and many lives were lost, see Figure 2-2. After this disaster, the Delta plan was implemented, aiming to protect Zeeland against the dangers from the sea by constructing dams in the sea arms. Constructions started in 1958 with the Zandkreekdam. Originally also the Eastern Scheldt was meant to be cut of entirely from the North Sea, however between 1960-1970 both nature organizations and the shellfish community opposed to the closing of the tidal basin and removing all tidal influenc. After several different plans (Baptist, De Mesel et al. 2007), it was decided in 1974 to built the works as they are known today. An open storm surge barrier in combination with compartment dams to ensure sufficient tidal range. (Vroon 1994; Hesselink, Maldegem et al. 2003; Arcadis 2009)

2.2.1.2 Delta works

Figure 1-1shows the delta works built in the Eastern Scheldt basin. Constructions in the Eastern Scheldt started in 1960 with the Zandkreekdam and the works were finished in 1987 when the Philipsdam was closed.

2.2.1.3 Different stages in construction Delta works

The Delta works were constructed in several different stages, see Tabel 2.1. Initially it was also planned that the Eastern Scheldt storm surge barrier fully and permanently blocked the entrance of the basin, as the Brouwers- and Grevelingen dams do. However, under pressure from both nature and shellfish organizations, the storm surge barrier was made open to the tide. (van den Berg 1986; Hesselink, Maldegem et al. 2003; Van Winden, Tangelder et al. 2010)

Tabel 2.1 Stages and hydrodynamic effects (Mulder and Louters 1994; Vroon 1994; Louters, van den Berg et al. 1998; Arcadis 2009)

Year	Stage	Effects Eastern Scheldt characteristics
1958	Starting construction Delta project	
1960	Zandkreekdam	
1961	Veersegatdam	Cutting of Veerse meer from the North Sea
1964	Grevelingen dam	Cutting of northern reach from the Grevelingen estuary. Increasing tidal volume (+7.6%), adding part of the Volkerak to Eastern Scheldt.
Spring 1969	Volkerak dam including sluices to regulate riverflow	River inflow cut off, turning Eastern Scheldt from estuary into tidal basin. Resonance of tidal wave in Northern branch, further increasing tidal prism.
mid-1985 april-1987	Storm surge barrier and two compartmentalization dams	Large hydrodynamic effects Reducing cross-sectional area mouth from 80.000 to 17.900 m2, at Yerseke decrease in tidal range/volume of 25%
Mid-1985		Cross-sectional area mouth reached critical 35.000 m2
Mid-1986		Cross-sectional area 17.900 m2
Oct/Nov 1986	Closure Oesterdam, at Marollegat (6 june 1985) and Tholensegat (23 okt 1986)	Reducing basin area Barrier gates had to be lowered, because of unexpected high velocities in Schelde-Rijn channel, no increase tidal range.
April 1987	Closure Philips dam	Due to the Oester- and Phillipsdam, the basin area reduced from 452 km2 to 351 km2. Intertidal area was lost both due to these dams as well as due to the reduced tidal range, 183 km2 to 118 km2.

2.3 *Effects Delta works*

Even though the new design of the storm surge barrier kept the tidal regime, the hydraulic work had great impact on the hydrodynamic characteristics. Some of these effects were predicted by Kohsiek, Mulder et al. (1987). The impact of changes in these characteristics on the morphodynamic characteristics and the impact on the intertidal areas

2.3.1 Changes in hydrodynamic conditions

2.3.1.1 Tide and tidal currents

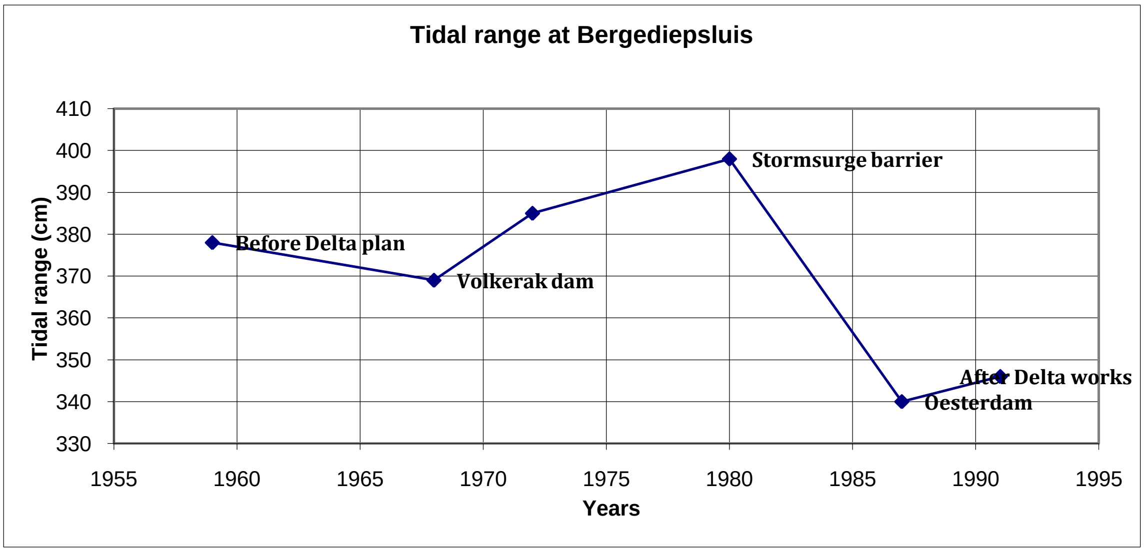


Figure 2-3 The tidal range at Bergesiepsluis in Kom basin from 1959-1991

Due to the construction of the Eastern Scheldt storm surge barrier, the tidal prism and currents in the basin were affected. During the course of the construction works, tidal volume first increased due to the Grevelingen and Volkerak dams (1964-1969). Only when the cross-sectional area of the entrance was smaller than the critical 35.000m^2, the tidal prism reduced (mid-1985) to a volume smaller than the initial tidal prism (Vroon 1994), shown in Figure 2-3. The construction of the compartment dams reduced the surface of the basin. This reduction of basin area further reduced the tidal volume of the Eastern Scheldt, but it caused an increase of the tidal range (1986-1987), see Table 2.2 and Figure 2-3.

Table 2.2 Tidal prism and tidal range (Louters, van den Berg et al. 1998)

Year	**Tidal prism mouth (Mm^3)**	**Tidal prism 'Kom' (Mm^3)**
1530 (St. Felix)	750 → 1130	
1959	1130	
1968	1180	530 (Wemeldingen)
1972	1250	410
1980-84	1189	425
1987	837	290

Decrease of tidal prism also reduced the velocities of the tidal currents. The largest reduction occurred in the northern and eastern branches of the basin, as Figure 2-4 and Figure 2-5 show. In the east branch of the basin, ebb tide velocities show a stronger decrease than the flood tide velocities. The flood tide also reduces over the entire Kom basin, while the ebb tide mainly reduces in the channels. The reduction of the tidal prism also increases the residence time of the water. In the east branch the residence time has increased from 1.5 months to 3 months. (Vroon 1994)

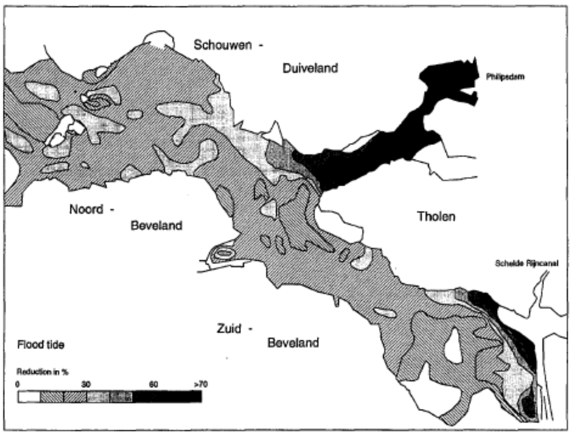


Figure 2-4 Reduction of the flood tidal currents (%) after Delta plan from (Vroon 1994)

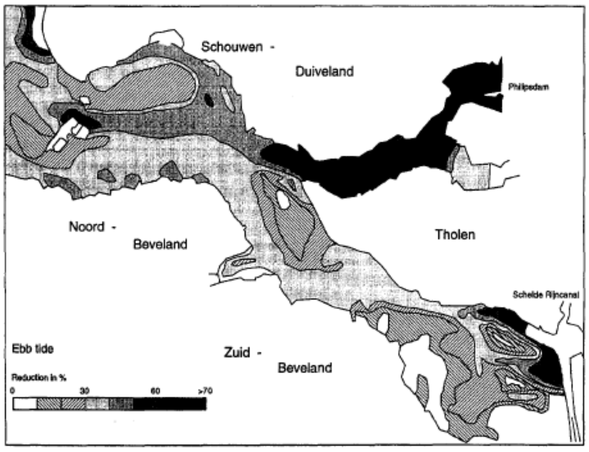


Figure 2-5 Reduction in ebb tidal currents (%) after Deltaplan from (Vroon 1994)

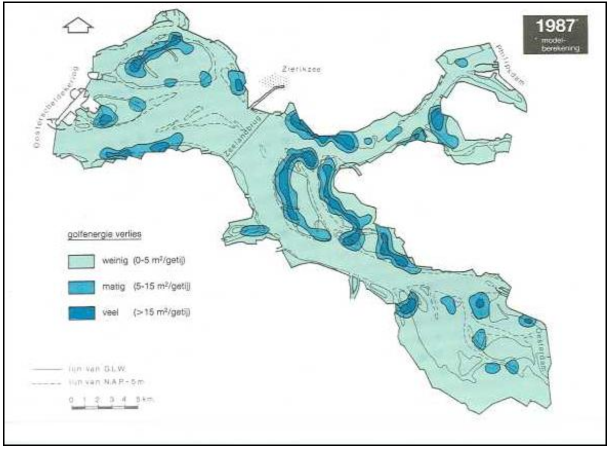


Figure 2-6 Wave energy loss (m2/tide) during WZW winds (Kohsiek, Mulder et al. 1987) Model calculation (HISWA)

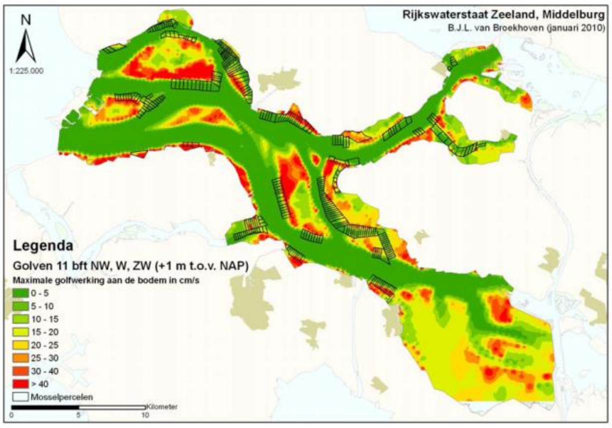


Figure 2-7 Maximum wave energy (cm/s) at bottom during NW, W, ZW 11 bft, +1m NAP (van Broekhoven 2010) (SWAN)

2.3.1.2 Waves

As waves are generated locally in the basin and the wind regime is unchanged, not much will have changed in the wave regime. Only near the storm surge barrier, due to less wave penetration, waves will have decreased due to the storm surge barrier.
If high intertidal flats would erode, the wind generated waves will get higher and longer (Royal 2006). this means that also wave impact on dykes is affected by the changes in morphology. In addition lowering of the intertidal foreshore means that higher waves will no longer break on these shallow areas. The dykes surrounding the tidal basin will have to withstand a more severe wave impact. .

Where waves dissipate and loose energy, they stir up sediment and cause erosion. As the tidal range has become smaller, this means that waves are dissipating in a narrower intertidal zone. The increase in wave dissipation would increase the erosion in this zone. Kohsiek, Mulder et al. (1987) expected that because of the smaller transport capacities due to the reduction in tidal currents, the erosion would not increase significantly. However, this might have been a wrong assumption, as it is found (Royal 2008) that large areas of intertidal shoals are being eroded.
In van der Hoeven (2006) results from a SWAN-model describe how loss of height of the intertidal flats on the Galgeplaat gives larger water depths on the shoals resulting in less shear stress by waves. This effect would decrease the stirring of sediment by waves.

However, the velocities of the currents (tide and wind induced) and with that the transport capacity remains the same. It is expected that the trend of erosion will decrease in time.

In Figure 2-6 the dissipation of wave energy is plotted, this shows locations where high waves arrive on shallow shoals and break. Figure 2-7 shows locations with high bottom orbital velocities from waves coming from Northwest, West and Southwest directions. This figure also highlights locations where high waves arrive at shallow shoals, causing up stirring of the sediment. In the two figures presented below the overall patterns look similar. All highlighting the exposed locations, where a long wind-fetch results in high waves.

2.3.2 Sand deficit of the channels

2.3.2.1 Erosion intertidal flats

Due to the Deltaworks, the tidal prism in the Eastern Scheldt basin has reduced (Table 2.2). The decrease of tidal prism and with that reduction in tidal currents causes a sand deficit in the basins' channels. This happens because the cross-sectional area is no longer in equilibrium with the volume of water flowing through the channel. This relation between tidal volume that is passing and the cross-sectional flow area can be stated as $A_{MSL} = C_A * P_{AB}$ (Bosboom and Stive 2011). Where A_{MSL} is the equilibrium flow area in a certain cross-section AB, P_{AB} is the tidal prism landward of the cross-section AB and C_A is an empirical coefficient.

Figure 2-8 shows the different stages during the Delta plan.. From 1960 to 1970 the Grevelingen- and Volkerakdam caused an increase in tidal volume. The channel system in the Eastern Scheldt responded to this disturbance of the equilibrium by increasing the cross-sectional area of the channels. The strong currents transported the sediment out of the channels onto the intertidal shoals. Between 1980-1990 the construction of the storm surge barrier caused a decrease of almost 30% of the tidal prism. To restore an equilibrium between then tidal volume (m3 of water) the cross-section of the channels will have to decrease.

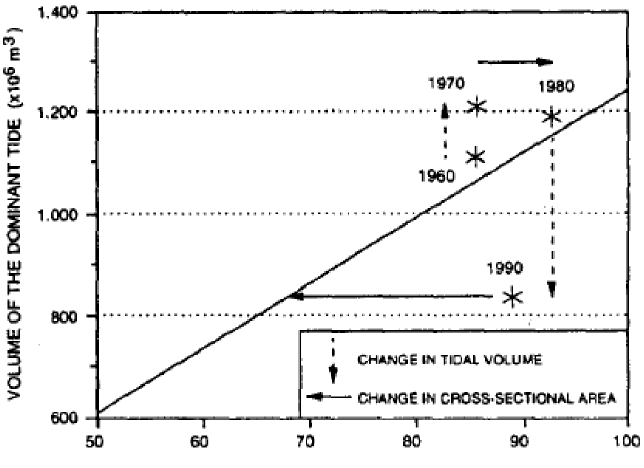


Figure 2-8 Equilibrium relation between tidal prism and cross-sectional area (Mulder and Louters 1994)

When a tidal basin is in equilibrium the sedimentation by tidal currents is in a dynamic equilibrium with the erosion by waves. The Eastern Scheldt is out of equilibrium and until this relation is restored, the tidal currents will be much smaller and have a smaller transport capacity. There will not be sufficient transport onto to shoals to compensate for the erosion during storm conditions, that continues unchanged.

This results in erosion of flats, often also referred to as ‘sand hunger’. However, channels are not actively pulling sediments from the shoals as if they are ‘hungry’. The channels capture the sediment because the cross-sectional area is too large in comparison to the tidal volume passing through the cross-section. The building forces are no longer strong enough to compensate storm erosion, that has always been present.

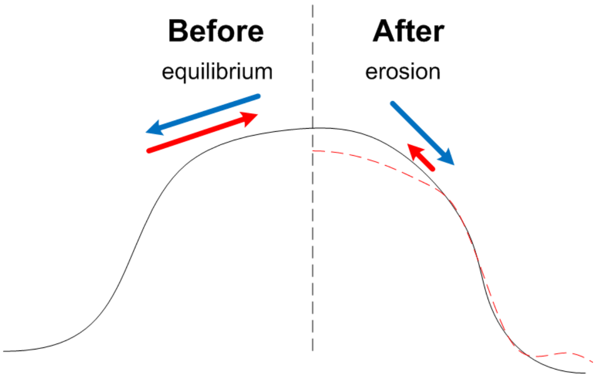


Figure 2-9 Left: building (Red) and erosive (Blue) forces are in equilibrium before the storm surge barrier. Right: The building forces have decreased, overall erosion of intertidal flats.

2.3.2.2 *Sea level rise*

Climate change has two effects on the sea levels. The most well known is the rise of the Mean Sea Level (MSL), expectations range from 0.25 to 0.85 m for the coming century (Deltacommissie 2008; De Ronde, Mulder et al. 2011). However tidal range is also partly affected by climate change and. The High Water levels (HW) will increase with 5 cm/century faster than the MSL rise, while the Low Water level rises 5cm/century slower than the MSL. Each century the tidal range is thus expected to rise with 10cm.

The sea level-rise will affect the Eastern Scheldt in two ways. Firstly, the tidal prism will increase due to the increased tidal range. This effect could counteract the sand deficit of the channels. However, the increase of tidal prism less than 4%. Opposite, due to the sealevel rise the cross-sectional flow area of the channels increase with 3%, increasing the sand deficit. So there is hardly any positive effect on the sand hunger.

Due to the increase in MSL, the tidal flats will be submerged during a longer time of the tidal cycle or even disappear under the water completely (Geurts van Kessel 2004). Yearly 60 ha intertidal area will drown due to sealevel rise (De Ronde, Mulder et al. 2011).

This lost of intertidal area can be compensated when the intertidal flats are increased in height with the same trend as the sealevel rise. Basically the rise of sea level increases the sand deficit of the Eastern Scheldt basin.

2.3.2.3 *Possible solutions*

The sand deficit of the basin due to the abrupt changes by the Delta works is between 400-600 Mm^3 in the entire basin. The current sea level rise adds between 0.4 to 1.5 Mm^3 to this deficit each year. (Mulder and Van Heteren 2009; De Ronde, Mulder et al. 2011) There seems to be hardly natural transport of sediment through the storm surge barrier, this has been assumed to be due to large scour pits. The intertidal areas store almost 140 Mm3 above the LW line (van Zanten and Adriaanse 2008), not enough sediment to restore the equilibrium.

There is no natural solution the sand deficit. In ‘Verminderd getij’ (van Zanten and Adriaanse 2008), possible measures for restoring the equilibrium are discussed. Yet no structural solution that solves the cause of the sand deficit by increasing either the tidal prism or the sand transport through the barrier seems feasible. Only mitigation measures such as nourishment or erosion protection are realistic for the near future.

2.3.3 Changes in morphodynamic characteristics

Loss of intertidal area due to changes in hydrodynamic conditions after the storm surge barrier and the compartment dams is twofold. An almost immediate loss occurred due to the decrease in tidal range and the construction of the compartment dams reducing the basin area. A gradual continuous loss is due to the sand deficit because of the erosion of the intertidal area.

2.3.3.1 Intertidal area

The intertidal area has lost on average 15cm of height in the Eastern Scheldt basin. For the intertidal flats and foreshore this loss of height is also found to be 15cm. This loss of height as resulted in a loss of intertidal habitat (between MHW and MLW) of 9.4km2 in the entire basin and -3.8km2 in the Kom, see Table 2.3. The shallow water area (between GLW and -8m NAP) has increased in both the Eastern Scheldt basin and the Kom due to lowering of intertidal flats. (Hesselink, Maldegem et al. 2003)

In (Royal 2008) a sand balance analysis has showed that from 1990 to 2001 for the areas between -1.5m NAP and +1,5m NAP more than 600 ha of intertidal area has eroded. In the Kom basin the development seems similar, erosion of intertidal area and increase of shallow water area. However, the sand balance for the Kom area is not closed. Between 1990 and 2001 9.6 Mm3 seems to be lost out the Kom system, the report (Royal 2008) is questioning if this loss is real or an error.

Table 2.3 Changes in intertidal area between 1983, 1993 and 2001 after (Hesselink, Maldegem et al. 2003)

		1983 (before)	**1993 (after)**	**2001 (recent)**	**Diff ’93-‘01**
Intertidal area*	Total basin	112.55 km^2	107.96 km^2	103.12 km^2	-9.43 km^2
	Kom	35.03 km^2	33.82 km^2	31.21 km^2	-3.82 km^2
Shallow water**	Total basin	103.67 km^2	109.22 km^2	113.14 km^2	+9.47 km^2
	Kom	10.52 km^2	10.91 km^2	10.93 km^2	+0.41 km^2

**) between MHW and MLW **)between -8m NAP and GLW*

2.4 *Hypotheses on morphological development intertidal area in the Kom*

From literature and known processes, hypotheses on the expected behavior of the east branch of the Eastern Scheldt basin are proposed. These will be tested against the bathymetry data, to see if they are indeed as expected.

a) *In between the finishing of the Volkerakdam (1969) the tidal and before construction of the storm surge barrier (1985), the flats in the east branch ('Kom') were accreting and the channels were deepening.*
The Volkerakdam increased the tidal prism of the Eastern Scheldt. Mulder (1994) states that the morphological gradients in the Eastern Scheldt basin were increasing before the construction of the Delta works. This is because before the storm surge barrier, tidal currents were stronger because of the Volkerakdam and they could transport sediment out of the channels onto the shoals. This building process was stronger that the erosive processes during storm. Note that during one storm events, flats could temporarily decrease in height.

b) As a consequence of the construction of the storm surge barrier (after 1985) the flats are eroding.
The sand deficit of channels since construction of the storm surge barrier, gives smaller tidal currents that are no longer capable of transporting sufficient amounts of sediment onto the shoals to counteract the erosion during storms.

c) The channels, where the eroded sediment is deposited, will gain sediment
Sediment that is eroded from the intertidal flats will deposit in the channels of the system. As the transport capacity of these channel is no longer strong enough to transport sediment onto the shoals as effect of the loss of tidal volume, channels will gain sediment.

d) Erosion is strongest at exposed locations.
At exposed locations (for example Loodijke) waves have most impact. Due to large fetch and the exposed location large waves attack on the shoals. Especially if these are close to channels (transported away) and relatively high (waves have impact on bottom) the erosion rates will be very high.

3 A Analysis morphological development using bathymetry data

This chapter presents the results from the research on the changes in bathymetry in the east branch of the Eastern Scheldt basin. In paragraph 3.1 the found sedimentation-erosion patterns are presented, after which the results on the sediment volume analysis are given in paragraph 3.2After this, data sets from measured profiles in analyzed and erosion trends are extracted from this. Finally, possible scenarios for the future erosion trend are stated and the hypotheses formulated in paragraph 2.3 are being answered in the last two paragraphs of this chapter.

3.1 *Research method*

3.1.1 UCIT

A simple program called UCIT is used to analyze the bathymetry data. With UCIT bathymetry data from different years can easily be compared by making sedimentation-erosion plots or volume balances. The data generated in the program can be exported to excel or matlab for further evaluation.

3.1.2 Vaklodingen data

The bathymetry data used are presented in the ‘Zeeland-20m’ grid. This grid is composed out of sounding and leveling measurement campaigns, sometimes using several surrounding sets to get a full bathymetry grid of the area. These data is not very reliable and contains some known errors. This paragraph presents some of these known errors in order to interpret the bathymetry data correctly.

3.1.2.1 Dataset Zeeland 20m

The different bathymetry datasets for the reference years have been compiled from several sources, both in measuring techniques as well as measuring campaigns. The deep parts have been measured by sounding while the higher parts are measured by leveling or in recent years by laser altimetry. To get a complete bathymetry of the Eastern Scheldt, these different measurements have been compiled. Where laser data was available, this has been used. (Haskoning 2008)

Especially in non-recent data sets, this meant that measurements from different dates had to be compiled to get a full bottom profile of the basin. The small Zeeland-20m grid has been made by interpolating between measured data points.

3.1.2.2 Reliability/Errors

In total four different measuring techniques are used with each of these techniques having their own error band, Tabel 3.1.

Tabel 3.1 Measuring techniques bathymetry data (Haskoning 2008; Paree 2011)

Year	**Level**	**Technique**	**Error band**
Before 2001	Above MWL	Leveling	+/- 5 mm, 'sluitfout'. Individual measuring points can contain larger error
Before 2001	Below MWL	Sounding (waterlevel as reference)	Channels; 25-30 cm Flats; 25- 30 cm Steep slopes; 40-100 cm
After 2001	Above MWL	Laser altimetry	Fault 5 cm, standard deviation 15 cm. 2007;Salt marshes with vegetation; too high. Very wet intertidal flats; too low.
After 2001	Below MWL	LRK-sounding (GPS as reference)	Average 10 cm

3.2 *Sedimentation-Erosion patterns (1968-1983 &1990-2010)*

3.2.1 Before storm surge barrier (1968-1983)

Before construction of the Deltaworks the Eastern Scheldt system was in equilibrium. The start of the Deltaworks in 1958 caused a disruption of this equilibrium. The construction of the Grevelingen and Volkerak dams caused a temporary increase in tidal volume in the Eastern Scheldt. During this phase of the project, intertidal flats increased in height and channels deepened, see Figure 3-1. In Appendix II also the result of the bathymetry changes between 1983-1990 are presented.

3.2.2 After storm surge barrier (1990-2010)

Since completion of the storm surge barrier in 1987 the Delta works have had an opposite impact on the Eastern Scheldt. The tidal prism and tidal range have reduced and the effects of the sand deficit of the basin become visible. In AppendixII a differentiation is made between two stages within this phase, here the bathymetry changes between 1990 and 2010 are shown in Figure 3-2. Where it is clearly visible that the intertidal flats in the Kom basin are losing height.

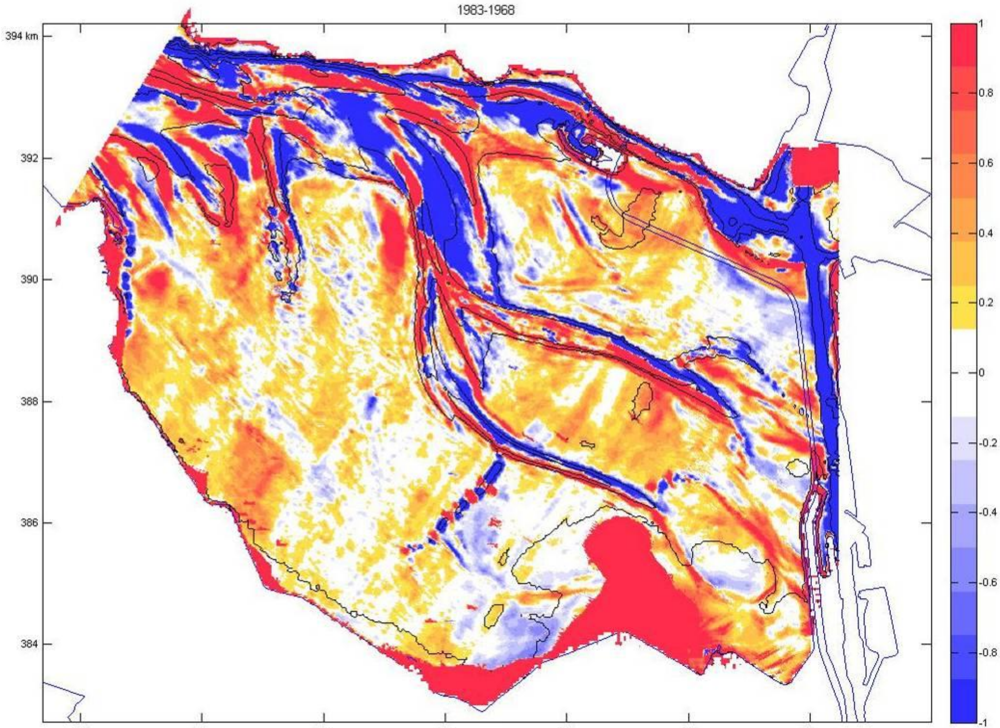


Figure 3-1 Changes in bathymetry between 1968 and 1983, showing erosion(blue) and sedimentation (red) patterns.

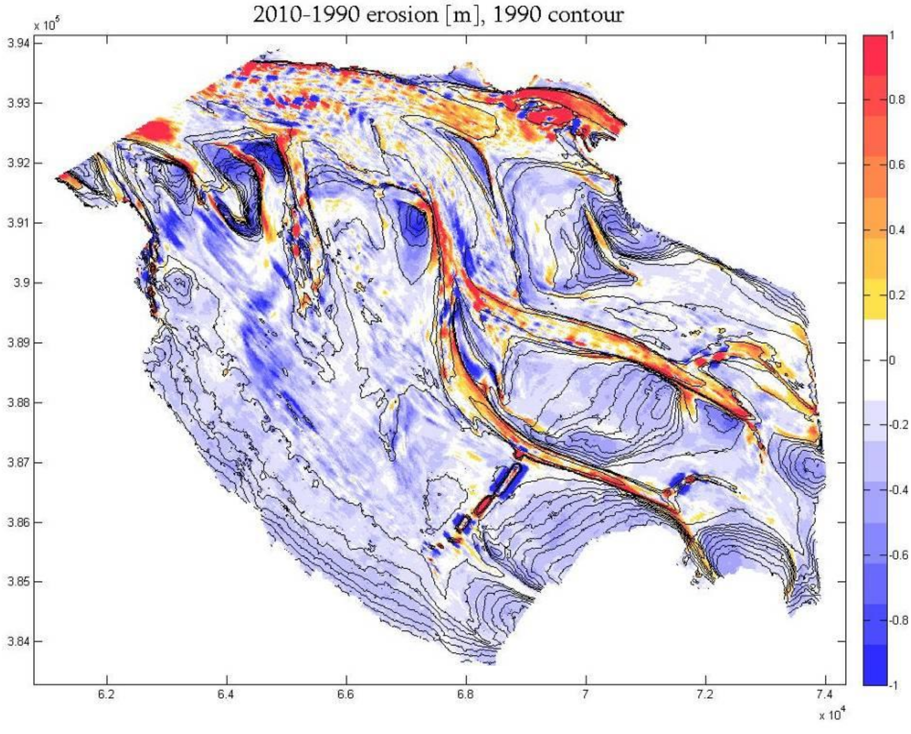


Figure 3-2 Erosion in (m) between 1990 and 2010

3.3 Volume balance

3.3.1 Before storm surge barrier (1968-1990)

As expected, due to the increasing tidal prism between 1968 to 1987, sediment is lost out of the channels and deposited on the intertidal flats (Figure 3-3). Between 1983 to 1990 both flats and channels in the Kom basin are loosing sediment volume. During this phase in the construction, the impact of both the compartment dams and also the narrowing of the entrance of the Eastern Scheldt are affecting the hydrodynamics in the basin. In AppendixII the results of the volume balance are investigated for each flat and channel in the Kom basin.

3.3.2 After storm surge barrier (1990-2010)

When the volume balance of the different flats and channels in the Kom is investigated. Figure 3-4shows that indeed flats are losing sediment volume and that the channels in the basin gain sediment. In AppendixII more results of volume balances for all the separate flats and channels are presented.

The volume balance in the Kom shows that not all the sediment volume that is lost from the flats is found back in the channels. In total 11Mm^3 of sediment seems to be lost out of the Kom basin between 1990-2010. This trend of sediment loss out of the system is visible in the bathymetry data in the entire Eastern Scheldt. It is assumed that there is only little sediment transport trough the storm surge barrier in the entrance because large scour pits prevent large transport of sediment in and out of the basin. The loss of the sediment out of the system therefore points to a possible error in the bathymetry data. More possible explanations for this loss are stated in Appendix II as well as a comparison of the sandbalance to other research done by Royal Haskoning (Royal 2008).

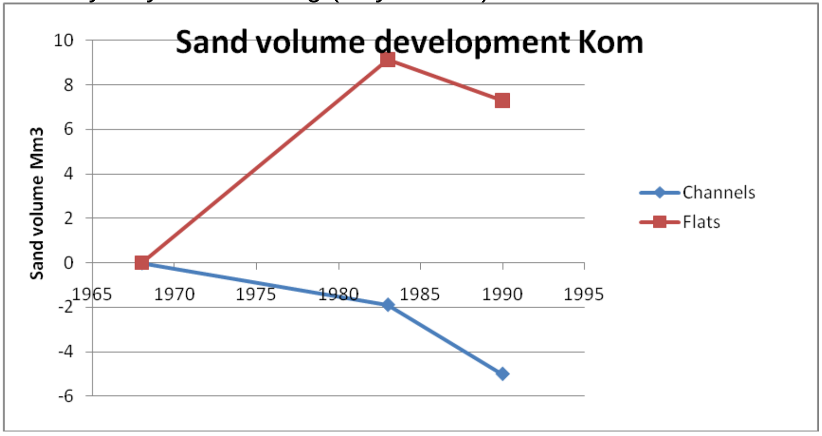


Figure 3-3 Volume balance Kom channels and flats between 1968-1990

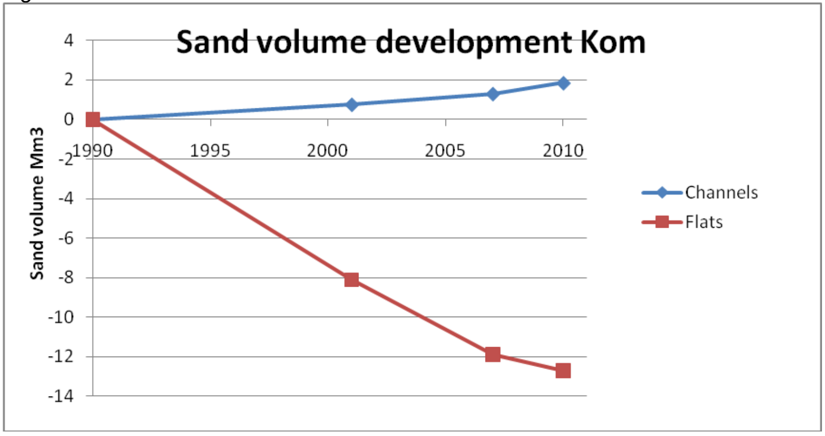


Figure 3-4 Volume balance Kom channels and flats between 1990-2010

3.4 RTK profile measurements

Another data set of bottom measurements in the Eastern Scheldt are transect measurements. These so called ‘RTK profiles’ are straight transects measured by hand using GPS. These data sets are considered more reliable than the bathymetry data sets.

In the Kom basin, a few RTK transects are measured on the Rattekaai and the Krabbendijke salt marshes. For these profiles the yearly trends in mm per year have been determined, these can be used to compare against the bathymetry data (Santinelli 2011).

3.4.1 Locations

All the transects are located in the South East side of the Kom basin, on the higher salt marshes Rattekaai and Krabbendijke. These profiles have been measured yearly starting from 1992/1993 up to 2010.

As the locations in the Kom basin are on salt marshes, they will not represent the erosion rate of the tidal flats because salt marshes are above the normal high water level and have a completely different behavior. That is why the RTK transects for other locations in the Eastern Scheldt are considered in comparison to the bathymetry data as well. This will give more insight into reliability.

3.4.2 Erosion trends

In the analysis (Santinelli 2011) it is found that the transects in the Krabbendijke show little erosion, with a rate of -4 mm/y (Table 3.2). The profile measurements in the Rattekaai salt marsh show an accreting trend of, 1 to 4 mm per year. These trends have been calculated by fitting a trend line through the change in volume of a profile during several years.

The erosion trends are different then can be seen from the ‘vaklodingen’ bathymetry data analysis. Reasons for this are that the bathymetry data is not very accurate, especially the measurements done by laser altimetry on the saltmarshes are known to contain errors. Another reason is the RTK transects are located on the higher area’s of the saltmarshes and they are not representative for the erosion on the lower and more exposed tidal flats in the project area.

Table 3.2 Erosion trends and standard deviation for RTK transects in Kom (Santinelli 2011)

Saltmarsh	**Profile**	**Trend +- deviation (mm/year)**
Krabbendijke	_ssl_5650_1	**-1.2** +- 2.3
	_ssl_5660_2	**-2.1** +- 1.0
Rattekaai	_ssl_5680_1	**-3.8** +- 0.8
	_ssl_5685-2	**+1.2** +- 1.3
	_ssl_5725_4	**+3.3** +-2.0

3.4.3 RTK erosion trends Galgeplaat

The Galgeplaat is an intertidal flat located in the centre of the Eastern Scheldt basin. On this flat RTK profiles are measured. Erosion trends on this flat range between +1mm/y to -14 mm/y, see Figure 3-5.

The vaklodingen bathymetry data show an average erosion trend of -1.6 cm/y. This erosion rates from the RTK measurements on the intertidal Galgeplaat might be representative for the erosion trend of the project area near the Oesterdam.

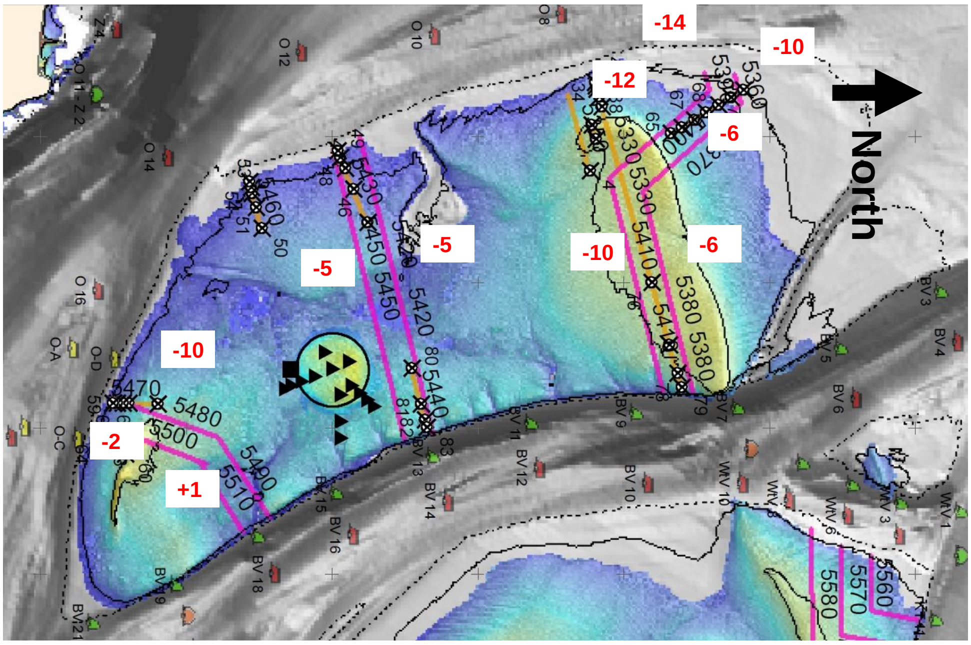


Figure 3-5 Erosion trends Galgeplaat RTK profiles [mm/y] (Santinelli 2011)

3.5 *Scenario's future erosion rate*

To find an answer to the future morphological development of the area, expected erosion rates are defined. Because the bathymetry data sets show an unrealistic sediment loss, the erosion rates found in this research will probably be too high. The RTK transect elsewere in the Eastern Scheldt show a lower erosion. However there are no transect measurement available on the intertidal flats in the project area.
Two scenario's are defined. A 'high' erosion rate and a 'low' erosion rate. Hopefully, with defining these two extreme bands, the truth lays somewhere in between.

3.5.1 High erosion rate from bathymetry data

When dividing the difference in height by the years considered an average erosion rate in centimeters per year can be found. For the Kom basin, erosion rates vary over the area, see Figure 3-6. The maximum erosion speed can be up to -3 cm/y,

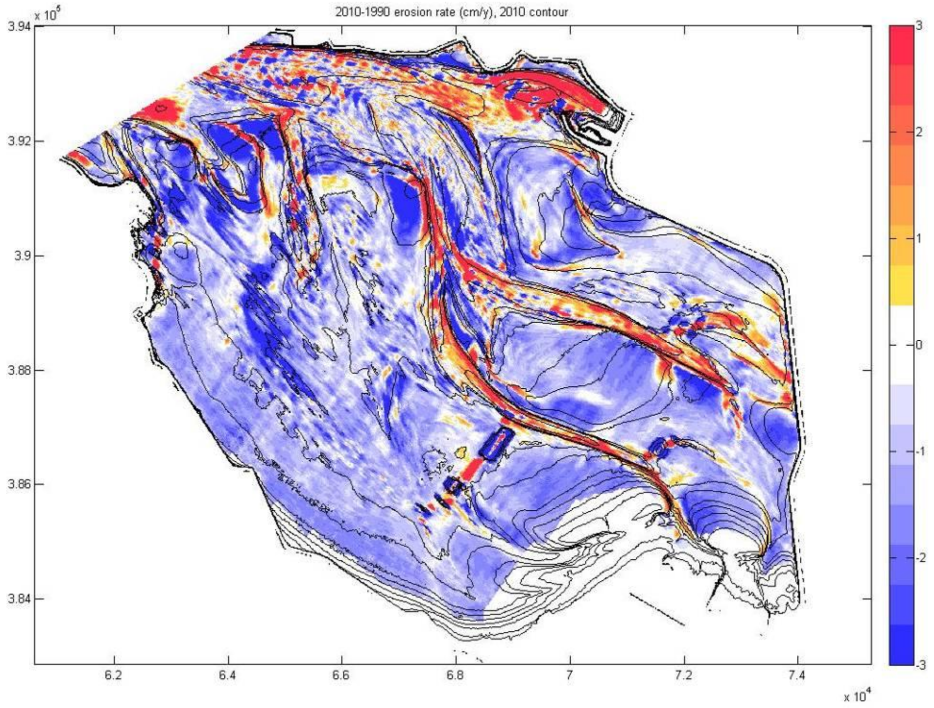


Figure 3-6 Erosion rate (cm/y) for the Kom between 1990 and 2010.

3.5.2 RTK transects conservative scenario

The erosion trends of the RTK profile measurements are lower than the erosion trends seen from the bathymetry data. These RTK trends will give a good conservative erosion scenario.

There are transect measurements made on tidal flats (Table 3.3) for example on the Galgeplaat, in the middle of the Eastern Scheldt. These locations are a good representative for the possible erosion of the intertidal flats in the Kom basin. Transects there show an erosion rate on average of -6mm/y. This trend is assumed to be representative for the Hooge Kraaijer and Oesterdam Flats. Especially since the two locations have the same average erosion rate in the bathymetry data sets. The erosion trend is therefore set at -5 mm per year, this is considered as the conservative or low erosion scenario.

Table 3.3 Erosion trends in other RTK profiles (Santinelli 2011)

RTK profielen **Areas**	**Weighted average of height trend [mm/year]**
Dortsman	**-11**
Galgeplaat	**-6**
Krabbendijke	**-2**
Neeltje Jans	**-10**
Roggenplaat	**-10**
Viane	**-8**

3.5.3 Erosion + Sealevel rise

Besides erosion, also sealevel rise results in a drowning of the intertidal area's. And just as the two erosion rate scenarios for the expected sealevel rise several in the next century high and low scenarios exist. Respectively +0.85m to +0.25m for the next century (De Ronde, Mulder et al. 2011).

Combining the different scenarios of both the erosion and the sealevel rise gives an insight into the expected range of erosion for the next 50 years of the intertidal area in the Kom.

When combining the two different rates, the standard deviation of both scenarios are added by calculating the standard deviation of the total trend using $SD(z) = \sqrt{SD(x)^2 + SD(y)^2}$.

The standard deviation of the total trend, SD(z), is then used to calculate the high and low scenarios of the total trend.

Tabel 3.4 Expected erosion scenarios for next fifty years

	High	**Avg**	**SD**	**Low**
Erosion rate	-2 cm/y	-1.25 cm/y	SD(x)= 0.75cm/y	-0.5 cm/y
Sealevel rise	+0.85 cm/y	+0.55 cm/y	SD(y)= 0.30 cm/y	+0.25 cm/y
		1.8cm/y	SD(z)= 0.80cm/y	
Total rate using sd	2.6 cm/y			1.0 cm/y
Erosion 50 years	**-130 cm**	-87.5 cm		**-50 cm**

4 A Conclusions on morphological development Eastern Scheldt and discussion

Construction of the Delta works have had great impact in the Eastern Scheldt. The reduced tidal currents are transporting less sediment onto the shoals, while storms continue to erode the intertidal flats. As a result, intertidal area is eroding while channels are becoming shallower.

4.1 *Conclusions from literature and bathymetry data*

Effect Delta works (literature study)

The construction of the Eastern Scheldt storm surge barrier in the entrance of the Eastern Scheldt has reduced the cross-sectional entrance by 78% (from 80.000 m^2 to 17.900 m^2). As an effect of this restriction and due to the reduction in basin area by the compartment dams, the tidal prism reduced by 25%. The tidal volume flowing in and out of the Kom basin reduced from 410Mm^3 to 290 Mm^3 (-30%).

The channels cross-sectional area are out of equilibrium with the tidal prism, there is a sand deficit in the system. Tidal currents are no longer strong enough to transport sediment out of the channels onto the shoals. As erosion of the intertidal areas during storm conditions continues unchanged, the net effect is erosion of the intertidal shoals. In the Kom basin the intertidal area has lost 0.15m of height, due to this loss of height 943 ha of intertidal area has been lost.

Bathymetry data research

Before the construction of the Delta works the overall patterns showed deepening of the channels while the intertidal areas accreted. However since the reduction of the tidal prism, the intertidal shoals are eroded.

In the bathymetry data, Figure 3-2, it can be seen that intertidal area is indeed loosing height between 1990 to 2010. The flats and foreshores in the Kom basin shown an overall pattern of erosion (blue).

Some of the eroded sediment deposits in channels or small gullies on the flats, showed in red. However, the volume of eroded sediment is not equal to the deposition in the channels. Between 1990 and 2010 more than 11 Mm3 of sand seems to be lost out of the Kom. This is probably due to an error as it is unrealistic that such an amount of sediment is transported out of this system.

4.2 *Answers* to *hypotheses on morphological behavior*

Based on literature and known processes hypotheses were proposed on the expected morphological behavior in the Kom. After the analysis of the bathymetry data conclusions about these statements can be made.

a) In between the finishing of the Volkerakdam (1969) the tidal and before construction of the storm surge barrier (1985), the flats in the east branch (‘Kom’) were accreting and the channels were deepening.
The bathymetry data from 1968 to 1983 in Figure 3-1 confirms the hypothesis. Before construction of the Delta plan, the tidal prism and currents were strong in the Kom basin due to the construction of the Volkerakdam. Sediment could be transported onto the flats. Indeed from 1968 to 1990 intertidal flats are gaining height and the larger channels show an overall deepening. The channels are morphologically active as sediment is deposited on the outer bends.

b) As a consequence of the construction of the storm surge barrier (after 1985) the flats are eroding.
The data indeed show erosion of intertidal flats since 1990. In the sedimentation-erosion patterns it can be seen that intertidal flats show an overall pattern of erosion (blue). When the sediment balance is investigated, the flats show indeed a loss of volume. This claim can be stated with confidence, because several data sets are available between 1990 and 2010 and this trend is visible in all these plots.

c) The channels, where the eroded sediment is deposited, will gain sediment
This statement is also confirmed by the analysis of the bathymetry data. Both the sedimentation-erosion plots and the volume balance of the channel polygons show an increase in sediment volume of the channels. However, the gain in sediment in the channels is not equal to the loss of sediment from the intertidal flats.

d) Erosion is strongest at exposed locations.
Some of the locations that are high and exposed or in other words have large wave impact, see Figure 2-6 and Figure 2-7, indeed show a relatively strong erosion rate between 1990 and 2010. The high areas at Loodijke are an example of this. This is expected as waves stir up the sediment. However, not all the erosion patterns can be explained by high wave exposure. And vice versa, not all locations that have high wave orbital velocities show large erosion.
This hypotheses can not be confirmed nor rejected. More research needs to be done to explain the erosion patterns found in the Kom basin.

4.3 Answer to research question on expected morphological development

The main research question was;

What is the expected morphological development of the eastern branch of the Eastern Scheldt for the next fifty years?

The expected development is a continuous erosion of the intertidal flats and deposition in the channels. No confirmed statement can be made about the expected increase or decrease of erosion rate for the future because the bathymetry data is unreliable.
For use in my further research an erosion rate of the Oesterdam project location needs to be defined. Two scenarios were chosen and the assumption is made that the erosion rate stays constant for the coming 50 years. The high scenario based on the ‘vaklodingen’ bathymetry data shows and erosion rate of -2 cm/y. The chosen conservative scenario is based on RTK measurements and gives a trend of -0.5cm/y. When also two scenarios for sealevel rise are included, the expected erosion over 50 years is respectively 130cm and 50cm, seeTabel 3.4.

4.4 Discussion data reliability

The used data is not always reliable. Conclusions must be viewed with this in mind. The used bathymetry data sets between 1968 and 2010 show some possible or known errors.

A first great imperfection of these data sets is that the sand balance of the eroded sediment from the flats and the deposited sediment in the channels between 1990 and 2010 shows a net loss of sediment. In total more then 11 Mm3 is missing out of the total Kom polygon. As it is highly unlikely that such a large amount of sediment is transported out of this system, especially now that tidal current have shown to weak to transport sediment out of the channels onto the shoals, this is a serious error.

Another imperfection in the bathymetry data are the known error band of the different measuring techniques used. Moreover since the sedimentation and erosion difference at some locations fall within these error bands, the conclusions made from this analysis must be made carefully. Always realizing this and checking if the showed patterns are in agreement with expectations based on theory.

These uncertainties and possible errors in the data have been considered in the analysis. For example by using two possible erosion scenarios. The final conclusions drawn are reliable, despite the possible unreliability of the used data.

1 B Introduction part B:Oesterdam project

1.1 Problem description erosion intertidal foreshores

Intertidal flats in the Kom are losing height creating problems for nature, loss of intertidal habitat, and safety, less breaking of waves on the eroding shallow foreshores. The revetment on the Oesterdam has been classified as unsafe and needs to be replaced (Arcadis 2010). The foreshore in front of the southern part of the Oesterdam will be heightened with a sand nourishment to compensate for the erosion. Both increasing intertidal area for wader birds and increasing safety by breaking waves on the shallow foreshore. This will also increase the lifetime of the newly designed revetment.

Figure 1-1 Eastern Scheldt compartment dams from (Arcadis 2009)

1.2 Research

1.2.1 Research question

This part B of the report presents the results of the research to the most optimal designs for the safety buffer in front of the Oesterdam. The main research questions that was formulated:

What are optimal designs for a safety barrier in front of Oesterdam that provides safety, while having a positive impact on ecology and limited negative effect on other functions in the surroundings?

Sub questions to reach the answer are;

- *What is the morphological development of the design?*
- *Is the design safe?*
- *Is there benefit for ecology created?*
- *Is the design robust/reliable, will its morphological development be as predicted?*
- *Can we gain knowledge from the design?*

1.2.2 Research method

To find an answer to the above research question several designs have been made. These designs have been modelled using an XBeach model in order to investigate the morphological and hydrodynamic effects of each design.
The safety of the designs has been assessed using the PC-overslag program. With the this program the overtopping and wave runup are calculated and conclusions are drawn on whether these overtopping conditions are allowed. Based on these model results, comparison between the designs has been made.

1.2.3 Framework of this research (Simplifications and Assumptions)

This research is part of MSc thesis and not within the framework of the real Oesterdam safety buffer of Rijkswaterstaat. This means that more freedom is taken for several boundary conditions. It also means that there are several limiting conditions to this research. Results and conclusions in this report have to be viewed with these restrictions in mind.
As time has been a large restriction, several simplifications had to be made.

- Only 1D profile designs are made and modelled
- Model has not been calibrated or validated. Very simplified standard model has been used.
- Designs presented, are not claimed to be optimal.
- Morphological development, is far from realistic. Could be, but no way of checking.

Despite of these simplifications this study can still give a good first insight into possible designs for the Oesterdam safety buffer and conclusions out of this report might be used to determine further investigation to optimal designs for the nourishment.

2 B Oesterdam project

The Oesterdam safety buffer project is a pilot project from Rijkswaterstaat to investigate possible solutions for the eroding intertidal area in the Eastern Scheldt.

2.1 Why the Oesterdam safety buffer project?

Due to the loss of intertidal currents, there is an erosive trend of the intertidal flats in the Eastern Scheldt. For more explanation see part A to this report. To compensate for this erosion, sand nourishments on the flats are most suitable solution in near future. These nourishments will not provide a lasting solution, but at least keeps intertidal flats for the near future (±50 years). (van Beek 2010; Linkit 2011)

2.1.1 Loss of nature and safety

Revetments on dykes and dams surrounding the Eastern Scheldt have tested to be insufficient. Amongst other locations, Project bureau Zeeweringen (zeeweringen.nl) has started to renew the revetment on the Southern part of the Oesterdam, as it was tested unsafe (Arcadis 2010). Due to the expected loss of foreshore height, wave impact will increase in the future (Royal 2008). Meaning that this new revetment might has to be replaced before the end of its lifetime, because the design conditions are underestimated. The hydrodynamic conditions will become larger than the conditions for which the revetment has been design. It is expected that this happens after 20 years.

Due to erosion of intertidal area, also a loss intertidal habitat occurs. Intertidal flats and shoals are important feeding grounds for wading birds. During low tide they feed on small animals living on these flats. Due to loss of intertidal area, these foraging grounds are lost. Not only the area of intertidal area diminishes, the remaining areas are also losing height. Meaning that the flats and shoals are exposed less during a tidal cycle and birds will have less time to feed.

2.1.2 Solution combining safety and nature

The Oesterdam project is a good example where a solution provides both safety and benefit for nature. By applying a sand nourishment on the foreshore, it will break high waves while also creating intertidal habitat.

It is a pilot project that serves as an example to show that foreshore nourishments are a good solution to the problems in the Eastern Scheldt. It will also provide more insight into processes on and effects of foreshore nourishments if the nourishment is monitored. And finally, the pilot project can create a ‘draagvlak’ for future projects that counteract the negative effects of the sandhunger processes.

2.1.3 Project in numbers

Constructions of the nourishment are planned to start at end of 2012 or beginning of 2013.

The project is funded by three parties, Natuurmonumenten (1million euro), the ministery of I&M (Infrastructuur&Milieu) (1.4 million euro) and the province of Zeeland (125.000 euro)

The nourishment is aimed at delaying the necessary maintenance/renewal of the Oesterdam revetment by 20 years.

In total the nourishment is estimated at 600.000 m3. This volume will be spread along a 2km stretch of foreshore.

2.2 Project location

The nourishment is planned on the foreshore at the south part of Oesterdam. Because there erosion is high, and the revetment works are already ongoing.

2.2.1 Bathymetry

The current profile differs at three main locations along the project area.In the North there is a broad flat that is part of the Hooge Kraaijer system, this location is called the Oesterdam flat in this research. It has a most sandy bottom, with not much variation in benthic life present. It is currently a ‘spit’ location where recreational fishermen can dig their bait.

The foreshore south from this broad flat is much narrower. The bed contains more silt and more diversity in benthic life. On both of these flats erosion rates are relatively high. In the most southern part a small saltmarsh is located. Since erosion is very little and the current nature is very valuable and sensitive, there will be no nourishment here.

From the bathymetry data (20x20Zeeland) two representative cross shore cross sections of the two project locations are determined. It can be seen that the Oesterdam flat is almost 1000m wide with an average depth of -1m NAP. While the Kreekrak foreshore is a narrow flat with a relative steep slope.

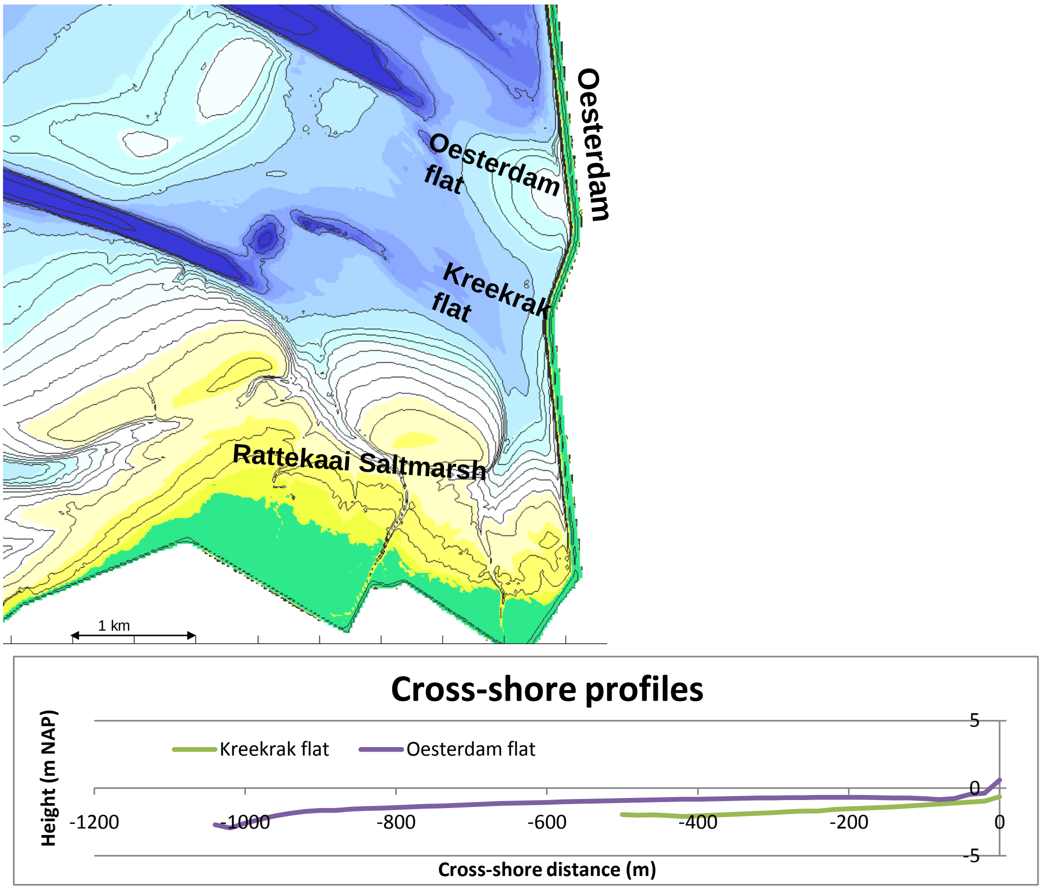


Figure 2-1 Project location. Upper figure; bathymetry from 2010 Zeeland 20x20 data. Lower figure; Cross-shore profiles at Kreekrak (green) and Oesterdam (purple) flat

2.2.2 Oesterdam

The Oesterdam is a primary water barrier connecting two dyke-rings (Arcadis 2009). The dam protect against the outside water of the Eastern Scheldt basin. Behind the Oesterdam, at the landward side lays another waterbody, the ScheldeRijn channel.

The construction of the dam differs over the length of the dam. The general composition of the dam is. (Arcadis 2010; Arcadis 2009), from toe to crest; toe construction, lower table, upper table, berm , upper slope and the highest point is the crest of the dam.

The riprap at the toe protects the toe from erosion and provides support. The toe construction lies between +0.1 and +0.3m NAP. The seaward side of the dam is protected by a revetment consisting out of slags on the lower table and the upper table is made out of Haringmann blocks with a dimension of 50x50x20cm or 25cm placed on clay or at some locations a filter layer. The berm lies between +4 and +5.25m NAP and the crest height between +6 and +7m NAP. The slope of the lower table varies between 1:2,8 and 4,2, upper table 1:2,6 and 4,5.

Near the broadflat Oesterdam location the berm varies between 4.5 and 4.9mNAP and crest between 5.78 and 5.71m NAP.

2.3 Stakeholders

The Oesterdam project has many involved parties. The demands and wishes of these stakeholders need to be taken into account when designing possible solutions for the Oesterdam safety buffer.

The table below (Table 2-1) presents an overview of all stakeholders with their specific demands in the project. The oyster fishery and 'pieren spitters' are have only negative effect from the project, without having direct influence on the project. However, the project will take the interest of them into account, giving a high indirect influence on the Oesterdam project. Both nature organizations and Rijkswaterstaat profit from the Oesterdam project, as both intertidal habitat and safety are increased.

In AppendixIII a more elaborate analysis of the stakeholders in the project is presented. Also the two most important species and the nature policies are described in *AppendixII. These species and policies on ecology also have to be taken into account.

Table 2-1 Overview Stakeholders

Demands on ES system	Stakeholder	Interest in Project	Demand for solution	Effect of project (+/-)	Direct influence (High/Low)	Indirect influence (High/Low)
Fishery	Oyster fishery	None	No disturbance	--	Low	High
	Pieren spitters	None	zoning/ disturbance	--	Low	High
	Commercial fishing	None	No disturbance	0/-	Low	Low
Nature	Nature organizations	Nature	Intertidal habitat	++	High	High
		Nature	No disturbance	--	High	High
Safety	RWS	Safety	Breaking waves	++	High	High
Recreation	other (wind surfing)	None	zoning/ accessibility	-	Low	Low
Shipping	Shipping	None	No disturbance	0	Low	Low

2.4 Boundary conditions and requirements

2.4.1 Hydraulic boundary conditions

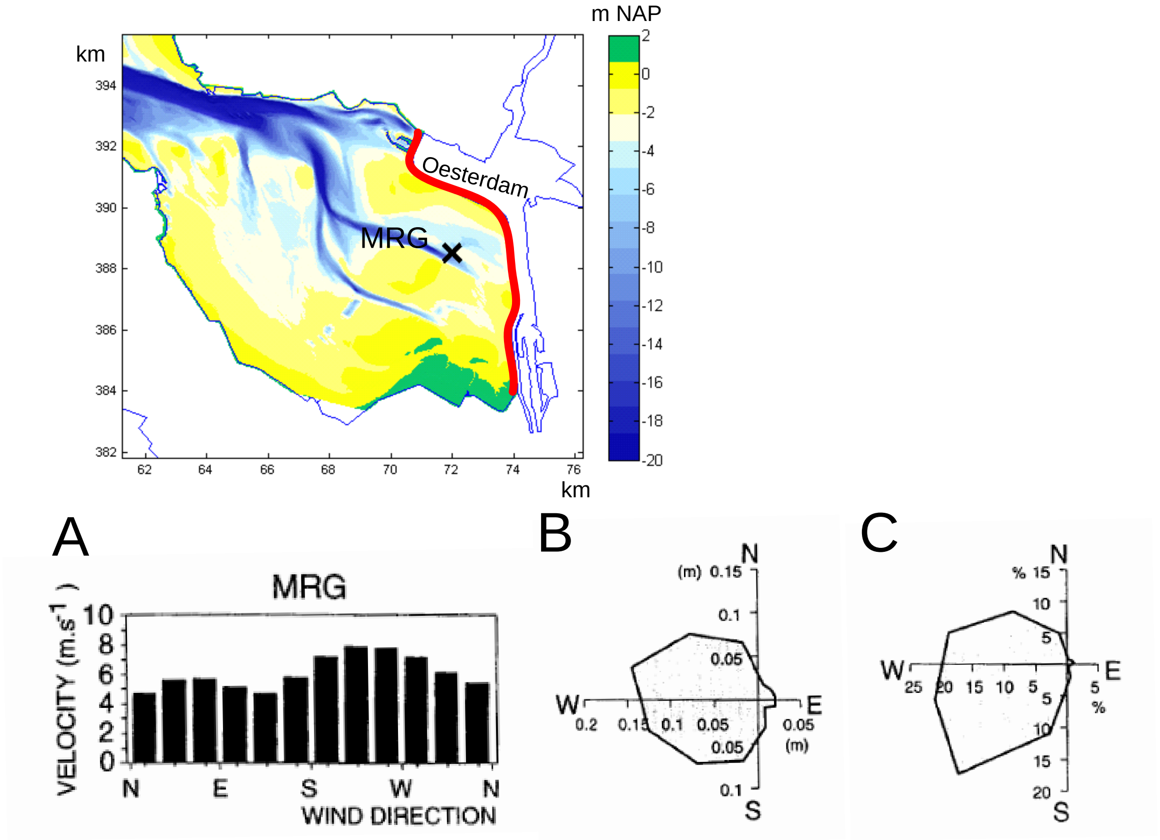


Figure 2-2 Upper figure: Marollegat Measurement station. Lower figure: Wind and wave regime at MRG between 1977-1990 (Louters, van den Berg et al. 1998). A) Wind regime B) Significant waveheight C) Wave energy

Table 2-2 Tide at Oesterdam location, MRG from getij.nl and hmcz.nl.

SWL = +3cm NAP	**High Water (cm +NAP)**	**Low Water (cm +NAP)**	**Tidal range**
Average tide	186	-160	346
Spring tide	214	-165	379
Neap tide	152	-139	291

2.4.1.1 *Average conditions*

The average wind direction (Figure 2-2A) shows that most of the time the winds come from the SouthWest and also the highest wind speeds come from this direction. Because of the Oosterschelde having a orientation NorthWest to SouthEast, highest waves at the Marollegat wavemeasuring station (located near the Oesterdam) arrive from these direction as can be seen from the Wave regime between 1977-1990 (Figure 2-2 B).

Eventhough highest waves are from NorthWest direction, most of the wave energy arrives from the SouthWest, as most of the time winds and waves are coming from that direction. (Figure 2-2 C). Table 2-2 shows the average, neap and spring tidal levels at the Marollegat measurement station.

2.4.1.2 *Storm conditions*

From the results of a probabilistic model that is used to determine the hydraulic conditions near Dutch water barriers (hydra-k) in combination with one year of wave measurements, the following storm conditions have been determined for several storms, see Table 2-3. The conditions are defined in deeper water at the Marollegat (MRG) measurement point.

Table 2-3 Location MRG. Deep water near Oesterdam flat from (Miniserie_van_V&W 2007; van Vuren 2008) en knmi.nl.

Storm exceedance probability (years^{-1})	**1/0.5**	**1/1**	**1/10**	**1/50**	**1/4000**
Wind speed (m/s)	14	16	20	24	33
Hs(m)	0.8	1	1.3	1.4	2
Tp(s)	3.2	3.8	4.2	4.7	5
Waterlevel (m NAP)	tide+ surge 0.8m	tide+ surge 1m	tide+ surge 1.1m	tide+ surge 1.2m	+4m NAP

2.4.2 Morphological boundary conditions

2.4.2.1 *Habitat demands*

The nourishment aims at restoring and possibly creating intertidal habitat, with a focus on foraging grounds for wader bird species, mainly oystercatchers. There are several optimal conditions for this habitat, for wader birds to have sufficient food and be able to feed during most of the tidal cycle.

Height

The height within the tidal range is a very important parameter for creating habitat. More accurately the dry fall duration of a flat is import for wader birds. This is of course both a function of the height of the flat and the water level in time (tide).

Both the feeding time for birds, as the availability of food is depended on the dry fall duration.

The optimal conditions for cockles, the favorite food for oystercatchers are 50% dry fall duration, maximum current velocities of 30 cm/s and fine sandy sediment. (van Zanten and Adriaanse 2008) In Blomert (2002), a correlation between hours of dry fall and bird density has been found in the Waddenzee. (Blomert 2002) The optimal is between 4.0 to 5.0 hrs during tidal cycle (of 12hr 25min), this is between 30-40%.

So the optimal height has a dry fall duration between 30-50% of the time. Using the tidal curve in Kom Eastern Scheldt, this results in a height of **-0.75m NAP to -0.2m NAP**.

Slope

It is important that the created habitat has a very gentle slope. In this way, the tidal level travels slowly towards and from the flat. Birds walk along this waterline to feed. They like feeding in shallow water of maximal a few centimeter. The optimal slope is between **1:100-1:500** (Linkit 2011).

2.4.2.2 *Sediment characteristics*

The sediment on the intertidal shoals in the Eastern Scheldt differs per location. The Oesterdam flat has a mainly sandy bottom. Due to the erosion processes on the shoals, tidal currents have transported the fine silts of the shoals into the channels. On the shoals, mainly sand is left. At some location in the Eastern Scheldt, erosion of the sediments on the intertidal flats have uncovered peat or clay layers. This is not the case at the Oesterdam location. Here an average grain diameter of $D50=150\mu m$ is a good assumption for the sediment characteristics as long as no measurements have been done and because the nourishment will be carried out with unknown sediment from somewhere in the Eastern Scheldt.

2.4.2.3 *Foreshore erosion +Sealevel rise (SLR)*

During the design storm conditions, the sea level rise is not relevant. The closure regime of storm surge barrier determines the water level. That is why the erosion scenario without sea level rise is considered. The two erosion scenarios as described in part A are considered as input for this part of research. To check for safety, the high erosion is most critical and is therefore only considered.

As boundary condition an expected foreshore erosion for the next 50 years of 100cm is used, when sealevel rise is included the erosion +SLR that is expected over 50 years is 130cm.

2.4.3 List of requirements

- Lifetime: the nourishment is designed for a lifetime of 50 years. This means that also after 50 years the nourishment should still break waves sufficiently that the Oesterdam is safe.
- Safety level: The Oesterdam has a safety level of 1/4000 yr storm condition (HR2006).
- The nourishment must be within tidal range in order to create intertidal habitat. In this Master thesis research more freedom has been taken, and also high dune designs will be investigated.
- Total sediment volume: The original project has been estimated at 600.000m3 spread over a stretch of 2km. In this research the total sediment volume is not considered a restriction but it is taken into account in the evaluation of the designs.

3 B Designs safety buffer Oesterdam

To develop the different designs a workshop has been organised to gather idea’s. These ideas and arguments have been used as input for this research. Four different designs strategies have been investigated.

3.1 Design approach

3.1.1 Generating designs

During a workshop (see Attachment IV Workshop report), ideas and possible design strategies for the Oesterdam safety buffer project have been gathered. Participants from Rijskwaterstaat, Hoogeschool Zeeland, Deltares and Technische Universiteit Delft, were asked to generate three different designs where either safety, nature or a combination of the two was the main goal of the nourishment. In total four different general designs were found during the workshop;

- a high dune profile above high water with safety as its main goal,
- a lower buffer profile that combines breaking waves with intertidal area, the buffer will spread during its lifetime,
- a large flat nourishment on the foreshore,
- small wavebreaking ridge placed somewhere infront of the Oesterdam.

In this research the focus is on creating nourishment designs that create more safety. The dune designs are the most extreme example. This strategy goes as far as to wanting to create such a safe system of foreshore+nourishment that there is no need to renew the Oesterdam revetment that has been classified as unsafe (Royal 2008). And that the revetment will still be safe after 50 years.

For each design strategy two profiles with different dimensions are made. Where the dimensions have been found by some iteration, but more optimization of the dimensions is recommended in further research.

3.1.2 Modelling designs (general approach)

The different designs will be tested for overtopping during the extreme storm conditions. Because the sandy profiles will develop morphologically during their lifetime by waves and currents, the profile after 50years of morphological activity can be much altered and needs to be re-checked for safety. So the overtopping is evaluated both on the initial profile and on the expected profile after 50years.

The morphological development is assumed to be caused by two separate processes. The re-shaping of the new nourishment profile by waves and currents. Plus the autonomous erosion trend occurring on intertidal areas in the Eastern Scheldt, as described in part A of this report. To find the developed profiles after 50 years a morphodynamic model called XBeach will be used to model the morphological development (Figure 3-1).

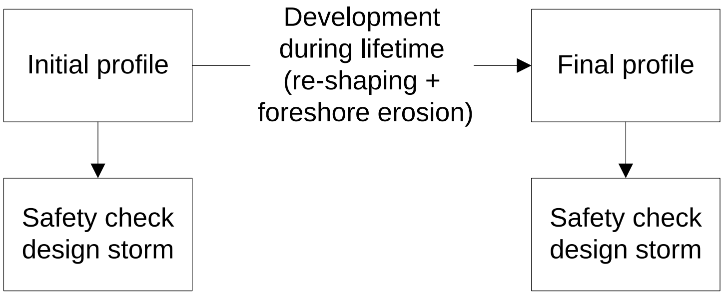


Figure 3-1 General modelling approach

3.1.3 Evaluation designs

The main aim of this research is to create a safety buffer. So safety will be scored highly in the evaluation of the designs. Besides safety, also robustness of the design and the creation of intertidal habitat and disturbance of the current intertidal habitat are taken into account in the evaluation.

To evaluate and compare the different designs a multi-criteria evaluation is carried out. The results are presented in chapter 6.

3.2 Designs

3.2.1 Dune

Aim of this design is to reduce wave height in such a way that even old revetment can withstand the hydrodynamic conditions. The dune will have to be above HW to break waves during storms with high storm surges or during high waterlevels when the storm surge barrier will be closed.

This means that this high dune is not flooded during normal tidal conditions. Creating a high dry dune. This is not similar to the current intertidal Oesterdam foreshore, and it is therefore questionable if such a design would be approved in reality. In this research however, the main goal of this design strategy is to create safety by using a sand nourishment.

For this nourishment design two different shapes of the dune have been investigated. The first is a very high dune, with its height even above the design level of +4mNAP. As it is expected that the dune will be eroded during its lifetime, this height ensures that the nourishment will still break waves during a design storm at the end of its lifetime.

The second lay-out of this dune nourishment is lower. The top of the dune is wider, but the base is smaller, creating a steeper slope of the dune face. This dune will need less volume of sand.

3.2.1.1 Hypothesis development Dune designs

As the smaller dune design has a steep slope (1;25), it is expected that this is not stable. Within the tidal range, waves will attack this slope and a more stable and gentle slope will form. The same process is expected to occur for the larger dune design with a slope of 1:35. But as this slope is more gentle the process is expected to be slower.

Due to the height of both designs being higher than the normal tidal range. The top of the dune remains clear from any wave attack during normal conditions. Above the waterlevel a steep slope will form and horizontal erosion of the duneface will occur.

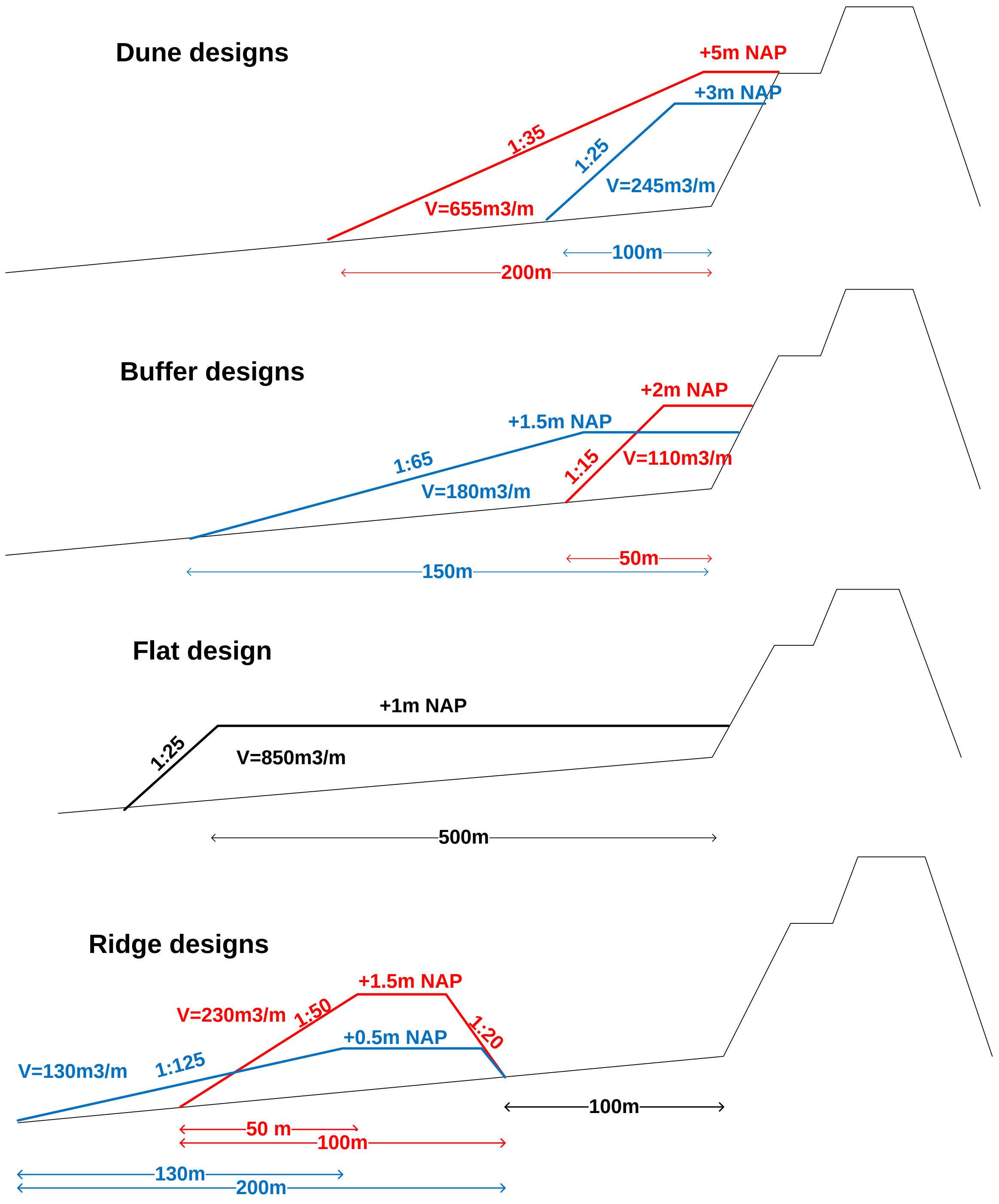


Figure 3-2 Designs for the safety buffer

3.2.2 Buffer

This design consist of a buffer on the foreshore. Sediment will be spread across the foreshore as the buffer slope becomes more gentle. The buffer breaks the incoming waves on it higher top. This height has to be sufficient to break waves, even after its lifetime.

The design also creates intertidal area.

Two different first dimensions. The first design of the buffer is high (+2mNAP) and small. This will give less disturbance of the current intertidal foreshore as the total extend is only 50m from the dam toe. However, it will also create not much intertidal area, if foreshore erosion continues. The height of the buffer ensures that waves will break on the high crest of the nourishment design, even during higher water levels.

The second buffer design is lower with a more gentle and wider slope. It will disturb more interidal area but also create more even if the foreshore erosion continues. The crest of the buffer is lower and wider. Also the slope is wider and more gentle and therefore expected to be more stable during its lifetime.

3.2.2.1 Hypothesis morphological development Buffer designs

Steep slope will become more gentle. This process will go faster initially.

Gentle slope is more stable.

Buffer will break waves. During low waterlevels, waves will break on the slopes. During higher waterlevels, waterlevel reaches dam. Waves will break on shallow buffer crest, but still small waves will reach dam.

During lifetime, slope more gentle, but also loss of height of buffer. Higher waves will reach dam during high water levels.

3.2.3 Foreshore/Flat

Nourish the entire foreshore equally. Like a sheet. The height and cross-shore extend of this flat can vary. Here only one design is presented.

Here a design is presented that has a height of +1m NAP and an cross-shore width of 500m. Note that in this design the flat is assumed to be horizontal.

The slope of the edge of the flat is relatively steep (1:25). This nourishment design creates a large intertidal area, but also buries most of the existing intertidal foreshore. Waves will lose their energy on the very wide shallow foreshore, but are not expected to fully break during higher water levels. As the waterdepth remains relatively large.

3.2.3.1 Hypothesis morphological development Flat nourishment

The steep slope at edge will become more gentle. During lifetime, mostly horizontal erosion of edge. Vertical erosion will be higher then current foreshore erosion because waves have more impact.

Waves will loose energy on the shallow flat but waves will still reach dam. As during high waterlevels the waterdepth is large enough for waves to travel trough.

3.2.4 Ridge

A small ridge is placed somewhere on the foreshore. The aim of this design is to break high waves as they reach the foreshore. While at the same time creating some new intertidal area on the ridge itselft. The ridge also creates a more sheltered area behind it that could be beneficial for nature. As it reduced the wave attack on the sheltered foreshore, it is also reducing the erosion taking place on this foreshore. Both by breaking high waves, but is also prevents sediments from being transported out to the channel.

Two different dimensions

- High steep
- Low wide

Both ridges are placed 100m out of the dam toe. The higher ridge will break more waves initially. But due to its steeper slope, it will not be stable and be eroded faster. The low wide ridge will be more stable due to its steep slope and due to it being low so waves have not much impact. This also points out the downside of this design, as it is too low to have much influence on the waves.

The low wide ridge will create more intertidal area then the high and small design, yet it is also more disruptive as it covers more of the current intertidal foreshore.

3.2.4.1 Hypothesis morphological development Ridges

Ridges are very small and are not expected to have large reduction on the wave height. Also the high ridge has a more steep slope, that will become more gentle.

Exposed to wave side will flatten out. Other side is sheltered. waves will not impact, during low water levels.

During high waterlevels, ridge overflows. Waves will transport sediment from to towards back bay.

The effect on reducing waveheight during storm levels is assumed small to non existing. (note, higher waves, so more reduction possibly?1)

Note that with this 1D profile design, simplification of reality. The 2D design is also important, for how the ‘backbay’ will be filled from the sides etc.

3.3 Optimization designs

The above designs are all simple 1D designs. These designs could be optimized in 2D sense, by varying location and alongshore dimensions. Also other construction concepts could be used in combination with a sandy nourishment for further optimization. And finally, during the construction phase of the nourishment, planning and realization can be done in such a way that there is smallest negative effects on surroundings.

Some of the possibilities are described below, in order to show the reader examples. Most of these ideas are for further research recommendations.

3.3.1 Designs 2D

Also placement of nourishment in 2D sense is important. See workshop report for sketches and arguments. Depending on final design, the nourishment can be placed close to dam or further onto flat. Also variation in this can be made.

The cross-section can also be divers along the nourishment. For example by creating a small bay type on the nourishment. This will be sheltered, filling and emptying every tide, and be a good foraging location for wader birds if very shallow water puddles remain. So even if nourishment high, they still have small puddles they can find food during lower waterlevels.

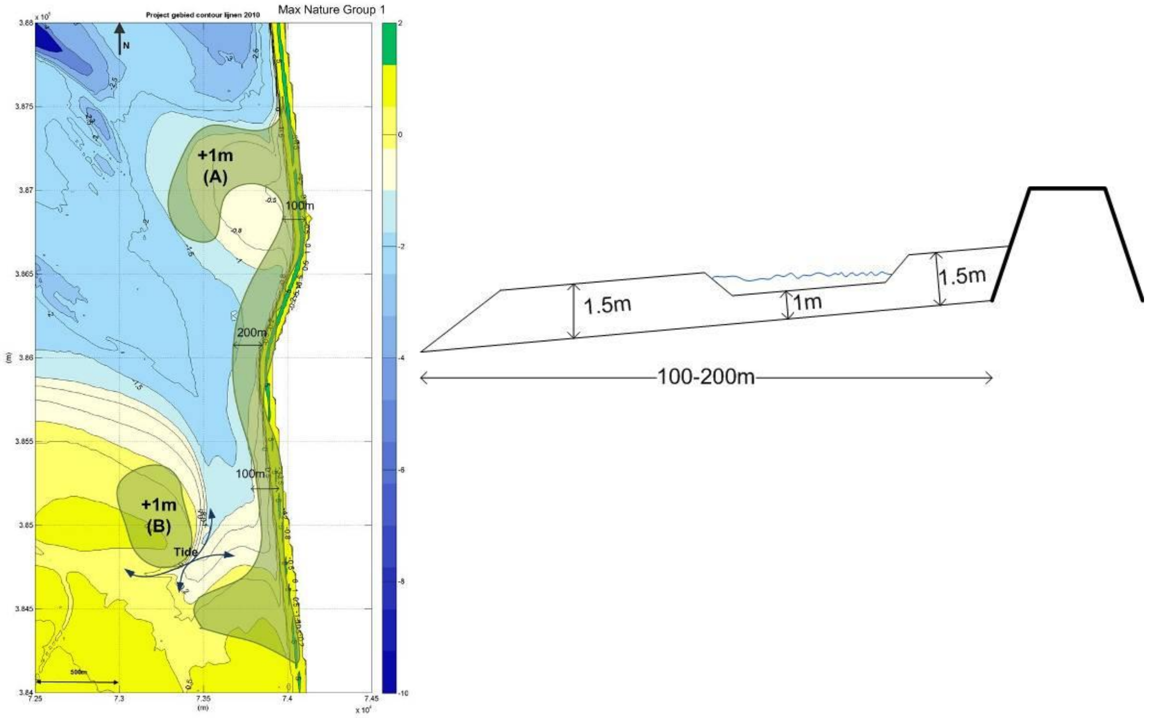


Figure 3-3 Possible optimizations of the nourishment profiles. Left:2D location. Right: Cross-shore profile

3.3.2 Building with Nature (BwN)

The nourishment can be optimized by using additional ‘BwN’ building blocks or concepts. The entire Oesterdam project is a building with nature project, but extra BwN concepts could be added to the project to increase the nature value and the functioning of the nourishment designs. For example erosion could be reduced, increasing the lifetime of the safety buffer.

During the previous mentioned workshop on 10 jan 2012 (Attachment I) a short brainstorm has been held on this, the ideas generated were;

- Boomse klei. This is a very strong and rigid type of clay. Chunks of this could be used as armouring on slopes of the nourishments.
- Oyster or Mussel beds could also be used as prevention of erosion. Also iron cages filled with oyster shells can be used to create small walls that could trap the sediment.
- Crushed oyster shells could be mixed through the sediment to strengthen the sand, resulting in less erosion.

3.3.3 Optimizing ecology in construction phase

During the construction phase of the project choices can be made that results in larger ecological value or less disturbance of the project. Examples of these optimization possibilities are:

- The finishing of the nourishment does not have to be very flat. This saves costs
- The sediment type used has a large influence on the re-colonization of the foreshore.
- Construction method can be optimized, for example bulldozers are very invasive.
- Also the construction period can be optimized, during some months the species are more sensitive for example during their breeding phase (Alkyon 2006).
- Frequent maintenance on the nourishment should be avoided, allowing species to settle on the nourishment.

4 B Modelling morphodynamic development of nourishment designs

This chapter aims to answer the following research questions;

- What is morphological development of the design?
- Is the design robust (effect of grainsize etc?)

4.1 XBeach introduction program & Model

4.1.1 General description

Xbeach is a morphodynamic model that models the hydrodynamics and morphodynamics in a 2DH (depth averaged) domain. The model is developed for modelling dune erosion during extreme storms (eXtreme Beach behaviour). A more elaborate model description and model formulations are given in attachment VI to this report or interested readers are referred to (Roelvink, Reniers et al. 2009).

4.1.2 Using XBeach model in this research

The safetybuffer nourishments are placed around the tidal range and XBeach is a model that has been calibrated and tested for representing the surf zone and dune erosion processes during variable hydrodynamic conditions.

In the surfzone during extreme conditions, short (wind) waves dissipate on the sloping foreshore. However, the long waves generated in the wavegroups do not dissipate and they reach the beach slope or in this case the nourishment slope and Oesterdam. These long waves that reach the nourishment are important in the re-shaping of the profile designs and need to be taken into account when modelling the nourishments. XBeach solves these longwaves and is therefore a suitable model.

That is why the XBeach program will be used to model the morphological behaviour of the nourishment profiles. In this research a 1D-mode of XBeach is used to model the nourishment profiles.

In this research, the program is used to model the morphological development of the nourishment during its 50yrs lifetime. However, XBeach is developed and calibrated for modelling near shore processes such as dune erosion and overwash during (extreme) storm conditions. It must be realized that the model is not calibrated for modelling long term developments during calm conditions.

4.2 Modelling approach

4.2.1 Processes on intertidal foreshore

During their 50 yrs lifetime the morphology of the foreshore and nourishment will be altered. Both during normal calm conditions and during storms with high waves morphological processes will transport sediments and change the bathymetry.

On the broad shallow Oesterdam flat, with the possible nourishment designs relatively close to the Oesterdam, two different processes can be distinguished;

- Re-shaping. The nourishment near the dam will adapt its shape to the hydrodynamic conditions.
- Foreshore erosion. This is the erosive trend occurring on all intertidal areas in the Eastern Scheldt due to the decreased tidal currents. This process results in a net loss of sediment volume from the foreshore into the channels. (See part A to this report)

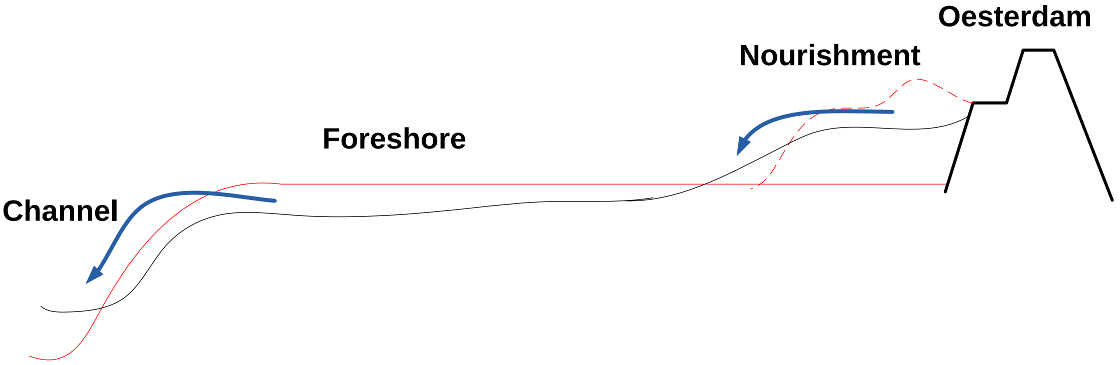


Figure 4-1 Processes on intertidal foreshore

4.2.1.1 *Effects of re-shaping profiles*

Re-shaping of the nourishment will occur because the nourishment adapts its shape to the hydrodynamic conditions. For example, steep slopes will become more gentle due to waves impacting on steep slope and transporting sediment towards deeper water.

It is assumed that the re-shaping process will mainly occur during storm conditions, when waves are sufficiently high to reshape nourishment. This process is similar to dune erosion, when during stormsurge dune face will adapt to a new equilibrium slope.

This reshaping of the profiles can change the way in which the profiles break the high incoming waves during extreme design conditions. And therefore the hydrodynamic conditions at the Oesterdam are affected. Higher impacting waves can change the safety level of the design. That is why the profile development during the 50 years lifetime needs to be modelled and the design safety storm conditions needs to be checked both for the initial designed profiles as for the profiles as they are expected to look at the end of their lifetime.

4.2.1.2 *Effects of foreshore erosion*

Transport of sediment on intertidal foreshores can be both building (onshore transport) or erosive (offshore transport). Generally building onshore transport is associated with calm conditions, when tidal currents transport sediment out of channels onto shoals. While offshore directed transports are assumed to occur during storm conditions. When high waves can stir the sediment and wind induced currents transport the sediment from the flats to the channels.

Due to the lower tidal currents since the Delta works, the building transports on the intertidal flats and shoals in Eastern Scheldt have decreased. It is unknown if they have reduced to zero, if there is even erosion during calm conditions or if there is still some building transport during calm conditions. The netto effect of these reduced onshore transports is erosion of intertidal shoals and flats.

The erosion of the intertidal foreshore means that high waves will no longer break on the shallow shoals. The hydrodynamic conditions at the Oesterdam will change due to this process. That is why this process needs to be included in the simulation of the different nourishment designs if the safety needs to be checked at the end of the 50years lifetime.

4.2.2 Modelling re-shaping nourishment

In order to represent the changes in the nourishment profile by waves and currents an XBeach model will be used. XBeach is a model that has been calibrated and tested for extreme hydrodynamic conditions. In order to model the changes during 50 years, the following modelling approach is used.

The assumption is made that during storm conditions with high waves most of this re-shaping process occurs. Several different storm conditions have been applied to the profile, where the return period of the storm conditions determines the number of storms that have been used to model the development during the entire lifetime.

4.2.2.1 XBeach model set up

The cross-shore profile of the foreshore at the broad Oesterdam flat is used as input. The Oesterdam is modelled by a non-erodable layer. The waterlevel is modelled by an average tidal condition with a storm surge depending on the storm conditions, the offshore boundary is located in deep water (-8m NAP).

In the XBeach model, the loss of wave energy due to wave friction has not been taken into account for now, also windspeeds are not taken into account.

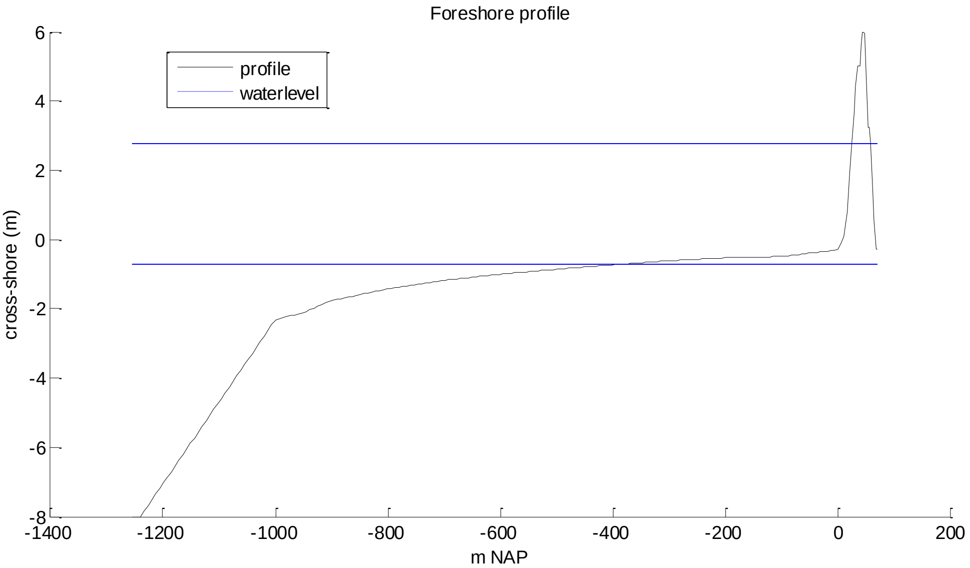


Figure 4-2 Cross-shore profile of the Oesterdam foreshore.

4.2.2.2 1/x yr storms

During the aimed lifetime of 50 years of the nourishment, different storms are expected to occur. Small storms are likely to occur more often during the 50 years than larger more extreme storms.

Storm conditions are expressed by their return period. For example a storm with a return period of 50years means that the corresponding conditions have a chance of 1/50 (2%) to occur during a year, each year. This means that during the lifetime of 50 years, 50yrs*1/50=1, 1 storm with conditions with a 1/50yr exceedance probability is likely to occur. It must be realized that this does not mean that each such a storm will take place at the end of the 50 years lifetime. But that each year there is a chance of 1/50 (2%) that this storm will take place. For a storm with a 1/0.5 years return period, this means that it is expected that such a small storm will occur twice every year, and 100 times during the lifetime.

The different storm conditions from Table 2-3 have been used to model the profile development of the designs. All designs showed that even though during smaller storms the initial change in bedlevel per storm was smaller, due to the fact that smaller storms are likely to occur more often during a lifetime, the total change of smaller storms during the simulation of the entire lifetime had more impact.
However very small storms, with a return period of twice a year, show similar erosion of the design profiles as the 1/1yr storm. The small waves have less impact on the profile, especially when the nourishment slopes are become more gentle and lower during their lifetime. This makes that 1/1yr storm seems to be a good assumption for modelling the profile changes, see Figure 4-3.

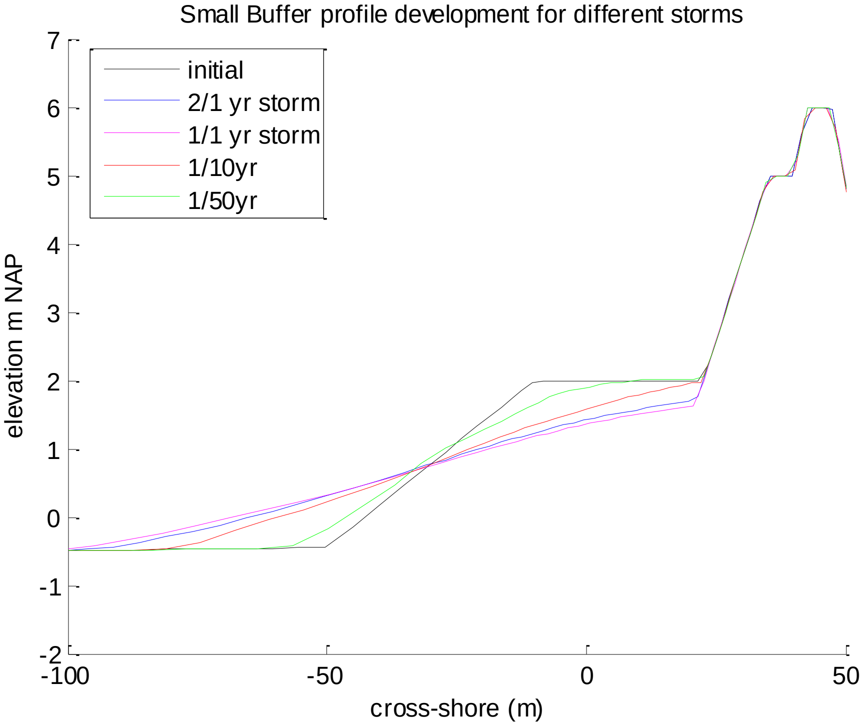


Figure 4-3 example of profile development Small Buffer design

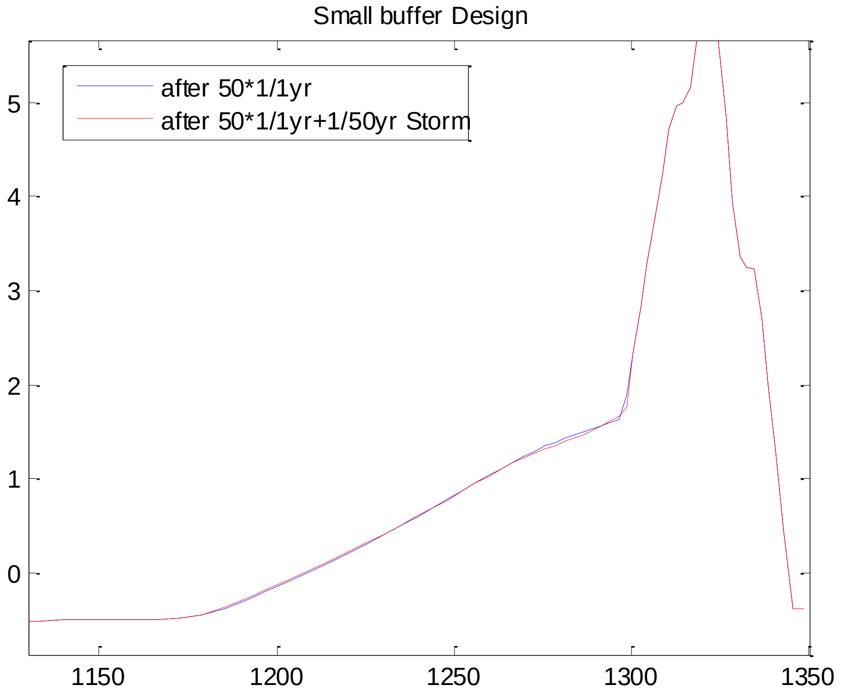


*Figure 4-4 profile of the small buffer design after 50*1/1yr storm before (Blue) and after(red) a 1/50yr storm has attacked the nourishment.*

4.2.2.3 Equilibrium profile

After the model runs with 50 times a 1/1yr storm, all profiles seem to reach an equilibrium state. Those profiles are very stable and do not change much even during severe storm conditions (1/50yr). This makes it likely that the modelled profiles would also be approaching the actual profiles of the designs at the end of their lifetime. (see Figure 4-5)

4.2.3 Modelling Foreshore erosion

The intertidal areas at the project location show an erosive trend, see part A to this report. Two different sets of bathymetry data show different erosion scenarios for the project location. Because the high erosion scenario is most critical for the safety of the Oesterdam system, only this scenario is considered in this research.

The foreshore in front of the Oesterdam is expected to show a continued linear erosive trend for the next 50 years. In the literature and bathymetry data (see part A) the two possible erosion scenarios are hypothesised. These scenarios (1.3m and 0.5m respectively) include the effect of sealevel rise. During normal and smaller storm conditions this sealevel rise and the erosion can be considered as a total change of bed level relative to the waterlevel. During the extreme design conditions (1/4000 yr storm) the waterlevel is determined by the closure regime of the Eastern Scheldt storm surge barrier. In this case, sealevel rise does not affect the waterlevel.

The erosion is included by lowering the bedlevel at the end of the XBeach simulation. In reality the erosion will occur gradually in time. Substracting the total erosion of 50 yrs at end of lifetime is a conservative assumption. Even though waves will break more on the higher foreshore, wave orbital motions also have more effect on the higher bed levels. The last effect is assumed to be larger because of the relatively small waves in the sheltered Kom basin, even during water levels with a high storm surge.

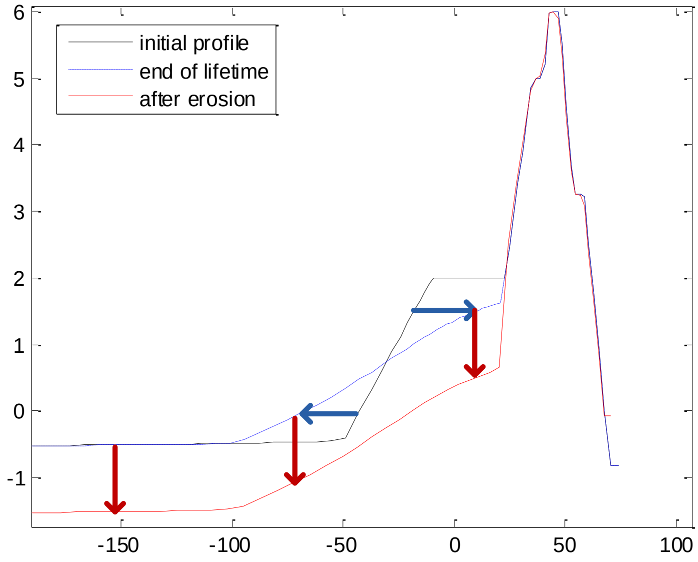


Figure 4-5 Showing initial profile (black),profile at end of lifetime excl erosion (blue) and incl erosion (red) of Small buffer design

4.3 Results lifetime development nourishments (50*1/1yr storm)

The above modelling approach, where 50*1/1yr storm will represent the morphological development of the different nourishment designs during their lifetime, has been carried out for all designs. All profiles develop to a similar gentle sloping profile, where designs with an initial steep slope show more bedlevel changes.

4.3.1 High Dune profiles

These designs were made to reduce the wave height at Oesterdam revetment during design storms. During the smaller storms such as the 1/1yr storm condition, waterlevels are lower than the nourishment crests and waves don't reach the dam. Both designs are above the HW+surge level (=1.8+1=2.8mNAP) and all waves break on the dune designs.

In both designs the steep initial slopes become more gentle for the range where waterlevels reach the nourishment face. During each tide a small volume of sediment is eroded from the slope and deposited in deeper water.

In the high dune design (left in figure), above the waterline a steep dune face where only high waves impact is created. Above this level, the slope of the high dune profile remains unchanged. The initial slope of the profile was 1:35, due to the impact of waves and currents the slope reduces to approximately 1:65.

The profile of the low dune design (right figure) also shows a more gentle slope (~1:50) in comparison to the steep initial profile (1:25). Here the same pattern of a gentle slope within the tidal range can be seen and a more steep slope where waves impact. There is no nourishment above this wave run up level, the nourishment crest shows an horizontal erosion of almost 25m during its lifetime.

4.3.2 Buffer new revetment

The low wide buffer (left) shows much less profile changes than the small buffer design (right). This is according expectations. As the low wide buffer profile has a more gentle initially (1:65) and therefore more stable slope. At the end of its lifetime the profile reaches only slightly more gentle slope (1:70). The low buffer profile is also lower, meaning that during high water levels waves have less impact on the bed level. The top of the buffer is only lowered by a few cm.

The profile of the smaller and higher buffer reshapes much more. The steep slope (1:15) flattens out much and reaches a almost stable slope around 1:60. Because the initial buffer profile is small, the buffer crest is being eroded. The top of the buffer has lost almost 0.5m of height, exposing the non-erodable Oesterdam revetment below.

Both buffer profiles show a reduction of the Hrms by breaking waves. The small and higher buffer design shows initially a larger reduction of the Hrms that reaches the damfoot during High water. However, as this profile is eroded it proves to be much less effective in breaking waves at the end of its lifetime. The low wide buffer initially results in less wave breaking. However, as this buffer profile is very stable during its lifetime. The wavebreaking remains high at the end of the 50 times 1/1yr storm conditions representing the 50years lifetime. The two final profiles show almost a similar Hrms waveheight reaching the damfoot during HW.

4.3.3 Flat

This wide flat profile only shows erosion on the edge of the profile. Where the initial slope (1:25) becomes more gentle and the sharp initial edge more smooth. There is no real erosion on the flat itselft. Notice that as the edge is eroded, the adjacent flat on the right is also slowly loosing some height.

Waves break on the shallow flat. But during high water levels, still some high waves reach dam. The flat reduces waves more than the current foreshore. Both initial profile and final developed profile show a wave reduction of 29% while the original foreshore only shows a reduction of the offshore Hrms of 0.7m to 0.63m (=10%).

As the wavebreaking on the flat design remains unchanged by the changes in the profile, it can be assumed that the small loss of width due to the erosion of the edge is not affecting the wavebreaking. Maybe a smaller flat would result in the same reduction of waveheight.

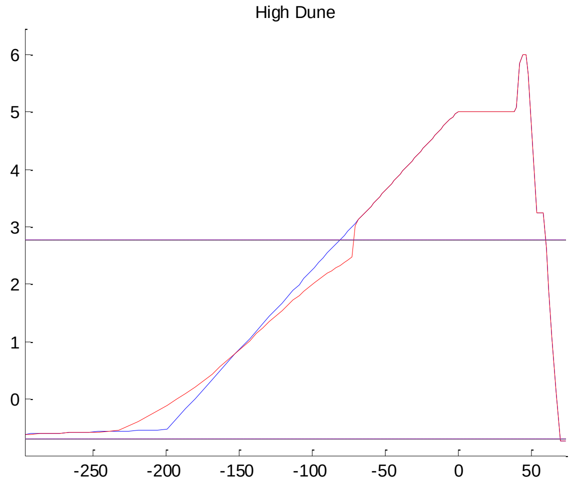


Figure 4-6 High Dune. Initial profile + final+ waterlevels

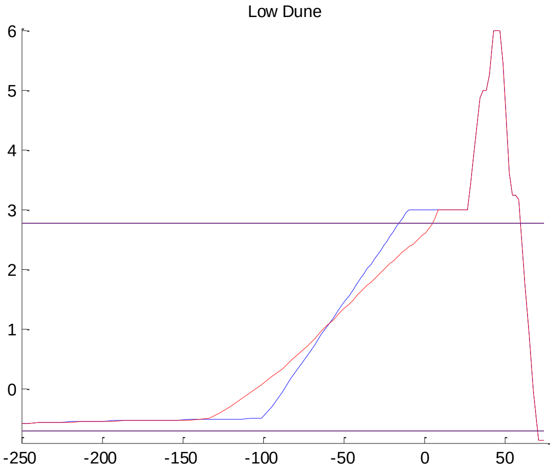


Figure 4-7 Low dune Bedlevel development during 50 tidal cycles 1/1yr storm condition.

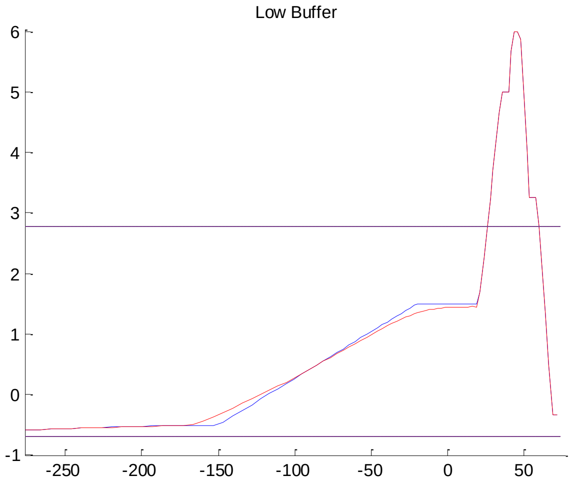


Figure 4-8 Bedlevel change during 50 time 1/1yr storm.

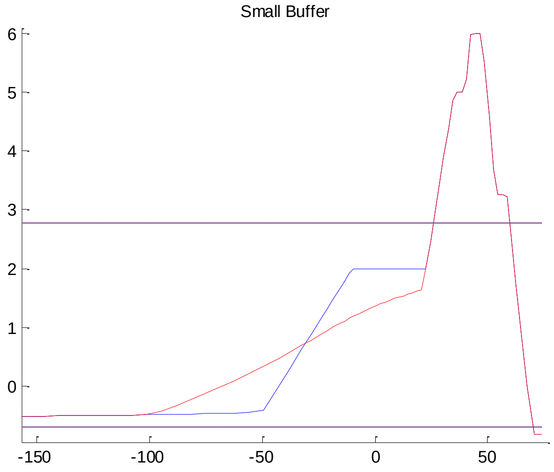


Figure 4-10Buffer Small development 50 yrs

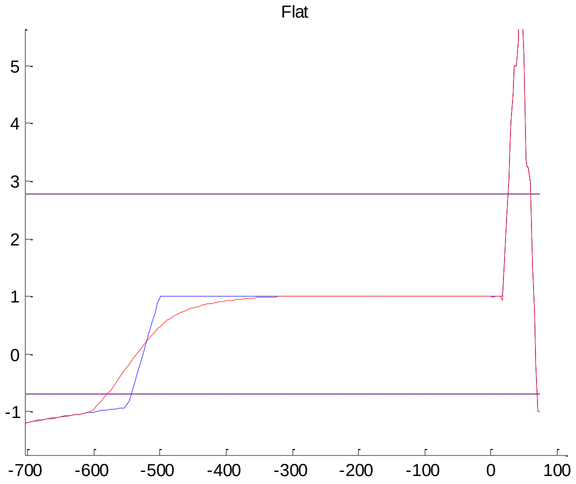


Figure 4-9 Bedlevel during 50 times 1/1yr storm D50=200.

4.3.4 Ridges

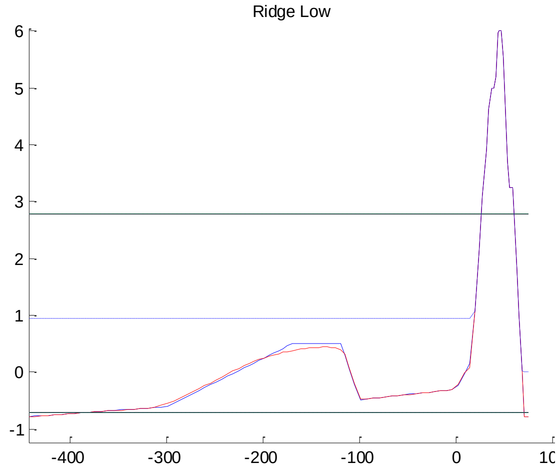


Figure 4-11 Bedlevel during 50 time 1/1yr conditions

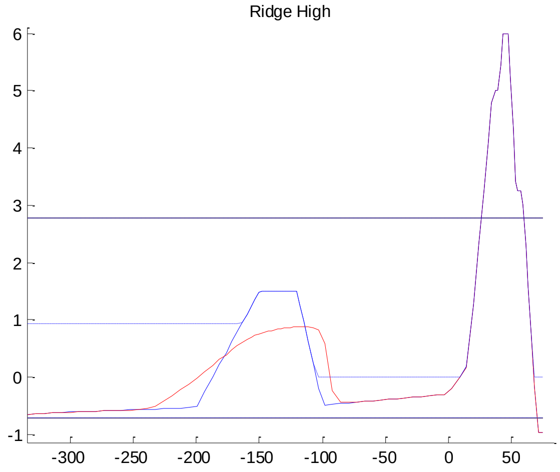


Figure 4-12 Bedlevel during 50 times 1/1yr conditions

The High ridge profile (left figure) shows more bedlevel changes. Most of the deformation ridge occurs during first tidal cycle. Due to the 1D configuration of the model, when tide rises the entire back bay is filled by water flowing over the ridge. Large currents, transporting much sediment, flattening the ridge. Therefore most of the deformation of the high ridge might be due to the model set up, therefore the results of this model are not correct.
With the lower ridge design the initial waterlevel is above ridge, there is no filling of back bay during first tide. (see figures below). The low wide ridge (right figure) is very stable. The initial slope (1:125) on the lefts is already very gentle in the initial profile and hardly changes during its lifetime. The low ridge is also not loosing much height, the crest of the ridge is only lowered by a few centimeters.
Both ridges are not effective in breaking waves during the high water levels of the tidal cycle. The initial profile of the high ridge shows the largest wave reduction, but as this nourishment is flattened during its lifetime, wave reduction diminishes. The low ridge profile shows small wave reduction both with the initial profile as with the final profile.
This design strategy is not further investigated in this research. The 1D modelling approach is not correct for these profile designs. It must be noted that also little impact on safety is expected because the profiles are relatively low and small. Also only small area within intertidal range is being created. In further research, 2D other dimensions, these designs can be more investigated.

4.4 Sensitivity analysis Foreshore erosion in XBeach

4.4.1 0situation foreshore, sensitivity sediment transport

For the foreshore without a nourishment design, the so called 0situation, the sediment transport has been compared for different conditions. Both in waterlevel, waves, sediment characteristics and wind speeds have been varied.
The result show that eventhough some conditions (high waves, small grainsize) results in more sediment transport, the very gentle and broad foreshore does not show large erosion or sediment transport. This was also not expected because the XBeach model is only used to model the re-shaping of the nourishment profiles and not to represent the foreshore erosion.
The foreshore does show some changes in bedlevel but these are mostly only initial adaptations of the edge of the foreshore and near the Oesterdam toe, see attachment VI.

4.4.2 Sensitivity of the Buffer and Flat designs for D50 changes and Hs

For the flat and buffer designs a sensitivity analysis has been done. Where the waveheight and sediment diameter have been varied. The results of varying these two parameters shows the sensitivity of the designs for either changes in the strength (sediment) or load (waves).

In this analysis the results of bedlevel change during one tide are compared. These changes show also an initial adaptation of the profiles. It is not expected that these sedimentation-erosion trends occur every tide. The initial changes are much higher than the changes after a few tides. In Table 4-1the maximum bedlevel change is presented for the different profiles for the different runs carried out. See also attachment III.

As expected, smaller grain sizes or higher waves result in more changes of the initial profiles.

Because the small buffer profile has the steepest initial slope, changes in bedlevel are largest in comparison to the other 2 profiles. However, the profile does not seem much more sensitive to changes in D50 or Hs.

Table 4-1 Results of Sensitivity analysis

	Run1	**Run2**	**Run3**	**Run4**	**Run5**	**Run6**
D50 (μm)	100	150	250	150	150	150
Hs (m)	1	1	1	1	2	3
Buffer Low max sederos (m)	0.025	0.0217	0.0151	0.0217	0.0249	0.0541
Buffer Small max sederos (m)	0.242	0.210	0.176	0.210	0.271	0.291
Flat max sederos (m)	0.1347	0.1127	0.0857	0.112	0.131	0.157

5 B Safety assessment nourishments

Answering research question;
Is the design safe?

5.1 Introduction safety assessment

5.1.1 Safety check Dutch water barriers

Dutch law states that all the primary water barriers have to be checked for safety every 6 years. The ‘Voorschrift Toetsing op Veiligheid’ (2007) is a description of the regulations and guidelines on how the safety of dykes and dams need to be checked.

The hydraulic boundary conditions that have to be used are defined in the (HR2006 (Miniserie_van_V&W 2007)), the safety standards and corresponding boundary conditions are given for some locations on the Dutch coast and rivers. For the Eastern Scheldt, boundary conditions at specific site locations can be determined using Hydra-K. This is a model that is used to translate the hydrodynamic conditions to the specific dyke section that is tested. The Hydra-K model can also be used to find the most critical combination of wave height, period and waterlevel for different return periods.

5.1.2 Overtopping

Dutch water barriers have to be checked for several failure mechanisms. The Oesterdam being a dam at the dutch coast, it needs to be checked for overtopping, stability and stability of the revetment. Since the Oesterdam is primary water barrier but of categorie b, having a connecting function, some overtopping of waves might be allowed. As long as the hydrodynamic conditions at the waterbarriers behind the dam are still safe. When a large overtopping occurs, the revetment on the landward side of the dam also needs to be taken into account in the safety check.

In this research only the overtopping is checked, in further research the other possible failure mechanisms of the Oesterdam need to be tested. Safety check VTV and underlying equations can be found in “Technisch Rapport Golfoploop” (van de Meer 2002). The overtopping can be calculated with the aid of PC-overslag, this module calculates all the formula’s as in (2007) for a specific profile.

Table 5-1 Overtopping conditions from (Verhagen, d'Angremond et al. 2002)

Hazard	Mean q	Max V
Vehicles: Driving at moderate or high speed	0.01-0.05	5-50 at high level
Pedestrians: Aware pedestrian	0.1	20-50
Pedestrians; Trained staff	1-10	500

5.2 Method, modeling approach

5.2.1 Modelling approach

Using the hydrodynamic conditions during the design storm XBeach is used to model both the hydrodynamics and morphological development of the foreshore including the nourishment designs during these design conditions. The output of the XBeach model is taken at the damfoot. The damfoot is considered as the point where the sandy nourishment ends and the

non erodible revetment begins. This point is different for each design, but it also changes during the model run as the sediment will be eroded. Output from the XBeach model at this damfoot are; the exact height of the damfoot, the Hrms at the damfoot, the absolute frequency of the waves (rad/s) and the waterlevel.
XBeach will also model some wave runup on the dam slope. This is not taken into account as the model pc overslag will be used to determine the wave run up. The output parameters from XBeach will be used in the PC-overslag program to calculate the overtopping. The profile used in PC-overslag is depended on the height of the damfoot. The overtopping also depends on water level and profile (berm, crest height etc).

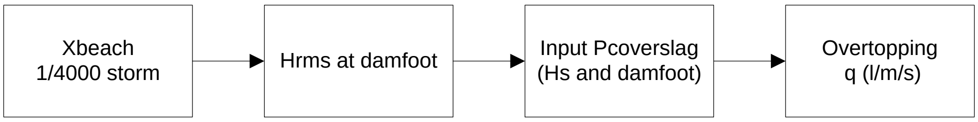


Figure 5-1 Modeling approach Overtopping

5.2.2 Boundary conditions

5.2.2.1 Waterlevel during design storm

The Eastern Scheldt storm surge barrier determines the water level during the design conditions because during the 1/4000 year storm the barrier will be closed. (Klein Breteler 2009)
If the sealevel is expected to rise to +3m NAP or higher during a storm including large storm surge, the barrier will always be closed. When a waterlevel of +2.75m NAP is expected the ‘Beslisteam Sluiting Oosterscheldekering’ is called together to decide if the barrier needs to be closed, basing their decision on weather conditions, tidal information etc.
The storm surge barrier also has a emergency system, in case something goes wrong with the predictions, warning system or operating system. If the measured waterlevel at the outside of the barrier reaches +3m NAP the barrier will close automatically. (rws.nl)
This means that two closure types are considered, a normal closure when the decision to close is made based on predictions of the water level. Or an emergency closure, when the barrier closes due to measured high waterlevels outside the barrier.

Normal closure
When high water levels are expected, the barrier will close. In the following low tide, barrier will be opened. Water level in basin can rise to +2m NAP. If storm continues, barrier remains closed.
Emergency closure
An emergency closure results in waterlevel at Stavenisse of +3.5m NAP. Including ‘scheefstand’ this gives +4m NAP Toetspeil at Oesterdam (HR2006). During the emergency closure the barrier closes automatically when outside waterlevel reach +3m NAP. During first top, water level at Stavenisse reaches +3.5m NAP. This water level is then constant for next 5hrs. After which, outside water level drops, low tide, and barrier is opened to let water flow out. Waterlevel of +1m NAP can be reached at Stavenisse.
It is assumed that drop and rise of waterlevel takes 1 hr when storm surge barrier is opened. Normal tidal range of 3.5m takes 6 hrs to fill/empty basin, but during these extreme conditions water will flow much faster because the difference between the inside and outside waterlevel is larger.

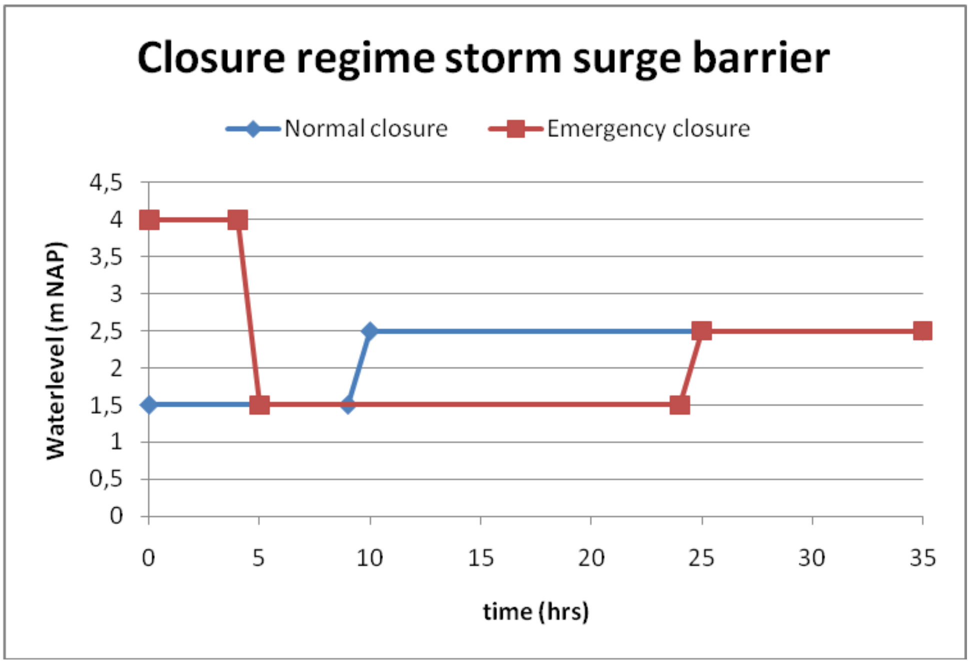


Figure 5-2 Waterlevel at Oesterdam during the two closure regimes after (Klein Breteler 2009)

5.2.2.2 *Wave conditions during design storm*

In the hydrodynamic boundary report (HR2006) the conditions are defined near the dam, approximately at 50m from dam toe. For the XBeach model the boundary conditions need to be known at 1000m offshore of the dam toe in deeper water.

In (van Vuren 2008) the results of Hydra-K output of Hs and Tp at the Marollegat measurement point has been defined, this point is a good representative for the offshore boundary condition in the XBeach model. For an exeedance probability of 1/4000 years this resulted in an Hs of 2m and a Tp of 5 sec.

5.2.3 Model set up XBeach

Both the initial profile of the design as the expected profile after 50 years as modeled by Xbeach (see chapter 4), are used to check for safety. The initial profiles are checked to see if the nourishment designs indeed reduce the hydrodynamic impact on the Oesterdam. The final profiles after 50yrs are used to check if designs are still safe at end of lifetime.

The design storm has a total duration of 35hrs, but only during the first 5 hrs the water level is most critical at +4m NAP (see paragraph 2.5.2) and only these critical hours will be considered.

The wave boundary conditions are defined at the offshore boundary at deep water. As input to the XBeach model are the profiles of the foreshore with the nourishment design and the non-erodable Oesterdam. The reduction of wave friction by bottom friction has been neglected for the moment, this is a conservative assumption.

5.3 XBeach, development during design storm

5.3.1 Morphodynamic and Hydrodynamic behavior

5.3.1.1 Morphodynamics

During the design storm the waterlevel is high. That means that although waves are high, they have not such a big effect on the bottom and low nourishment designs. Also because the model only runs during the first 5 hours of the design storm, not much morphological changes in the nourishment designs are seen.

Ofcourse, the profiles do change somewhat. The most noticeable result during the design storm is that the high waves also transport sediment onshore on the crest of the two high dune profiles. Creating an increase of the bedlevel at the damfoot. This effect is minor however (only a few centimeters) and it is not taken into account for the location of the damfoot.

All other profiles show a similar development, the slopes become a little more gentle and the edges of the initial profiles become more smooth.

5.3.1.2 Hydrodynamics

Even though waterdepths are too large in the 2 nourishment designs that are intended to fulfill the project goals of both safety and nature (Buffer and Flat) to cause large bedlevel changes. The waves do loose energy on these nourishment designs, even during the high design waterlevel. This loss of energy is due to (partially) breaking of the high waves. Note that the loss of energy due to bottom friction is not taken into account. On the steep slope of the Oesterdam, waveheight increass. This is the effect of shoaling of waves as the incoming waves that have not broken on the nourishment reach shallow water ontop of the Oesterdam slope. This effect has not been taken into account because the output of the waveheight has been set at the Oesterdam damfoot.

The Hrms offshore waveheight is even reduced in the current situation without a nourishment. Meaning that even during design high water levels waves loose their energy on the foreshore. Note that the waveheight is higher than the HR2006 design conditions. This might be because there is no loss of energy by wave bottom friction modeled. If the friction factor is taken at fw=0.05, the waveheight at dam becomes equal to the HR2006 condition (Hs=1.45). As fw=0.05 is a realistic value of the friction factor, this gives confidence in the chosen significant waveheight at the offshore boundary.

5.3.2 XBeach output results

The offshore boundary has input of a significant waveheigt of Hs=2m, this is equal to an average waveheight of Hrms=1.41m.

The peak wave period (Tp=5sec) is not changed along the profile, the mean wave frequency is 1.374 rad/s which is equal to Tm=4.6 sec.

Design Hrms offshore = 1.41m	**Hrms initial profile**	**zdamfoot**	**Hrms final profile**	**zdamfoot**
0situation	1.16	-0.3	1.23	-1.3
Dune High	0	5	0.08	4
Dune Low	0.48	3	0.87	2
Flat_1	0.90	1	1.10	0
BufferLow	0.95	1.5	1.16	0.4
BufferSmall	0.83	2	1.15	0.6

The above table shows several remarking results.

- The initial foreshore profile reduces incoming waves even after 50yrs including a 1m lowering of the foreshore, waves are smaller than the offshore waveheight. Ofcourse, due to the lowering of the foreshore, incoming waves are higher than for the current profile.
- The crest of the High dune design has such a height that hardly any waves reach the damfoot. For the developed profile after 50 years, the crest is equal to the water level and only small waves reach the Oesterdam.
- The low dune shows a large reduction of the incoming waveheight. Eventhough the top of nourishment design is below water level, waves loose much energy.
- The Flat and Buffer designs both show more breaking of waves than the current foreshore without nourishment. Even though water levels high and nourishment designs are within normal tidal range. This shows that such nourishment designs can provide additional safety during design storm conditions.
- The small buffer design has the most wave reduction for the initial profile from the three designs (Flat and Buffer2x). However, due to the re-shaping of the buffer profile the wavereduction capacity of the small buffer reduces largely.
- For the final profiles at the end of their lifetime, the Flat has a better wave reduction than the two buffer designs.While the height of the flat nourishment is lower, waves loose more of their energy on the broad flat.

5.4 Run-up calculations

To calculate the wave run-up on the Oesterdam, the PC-overslag program is used. This program calculates the wave overtopping using the dam profile and hydrodynamic conditions at the damfoot.

5.4.1 Model setup PC-overslag

All the wave heights output in combination with the height of the damfoot have been used to calculate the overtopping and wave-run up for the different designs.

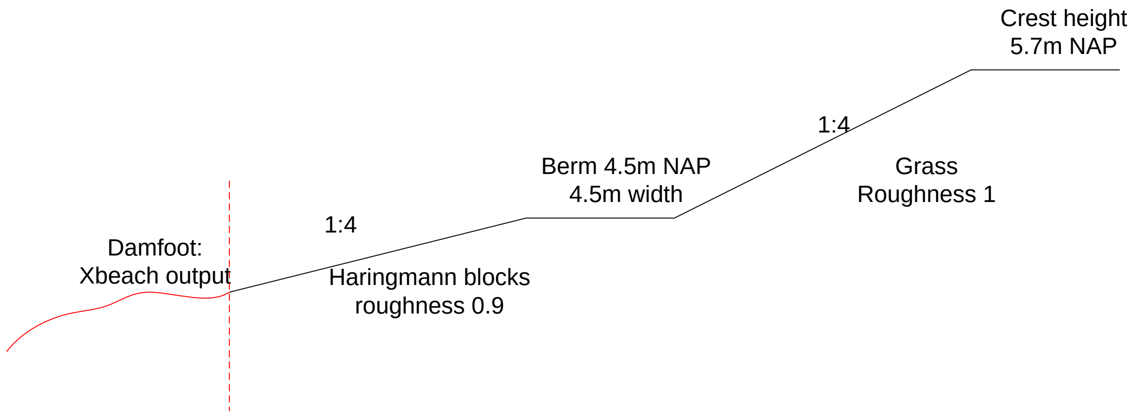
The output from the XBeach model is an average waveheight at the Oesterdam damfoot, a wave frequency and the location of the damfoot. Input of pc overslag is Hm0=Hs and Tp, so XBeach output needs to be translated to this. (Rijn 2011 pg 9.56)

$$H_{m0} = H_s = \sqrt{2} * H_{rms}$$

$$T_p = \frac{1}{freq} * 2\pi$$

The Oesterdam profile is chosen is such a way that it represents the Oesterdam at the project location. As the dimensions of the Oesterdam change slightly over the length of the dam. The most conservative crest height and berm width have been chosen. In this way making a conservative calculation of the overtopping.

The slope is set at 1:4 both for the upper as the lower table. The berm is located at +4.5m NAP and has a width of 4,5m. The crest height is 5.7m NAP. The revetment on the lower table consists out of Haringmann blocks, having a roughness factor of 0.9. The revetment on the berm is assumed to be asphalt and the upper table is covered with grass, both having a roughness factor of 1.



5.4.2 Results overtopping

Design initial profile	Hs	z	Tm1,0	q [l/s/m]	Vmax [l/golf/m]	z%+SWL [m]
0situation	1.64	-0.3	4.57	2.91	604.5	6.30
Dune High	-	5	-	-		
Dune Low	0.68	3	4.57	0.01	0	5.23
Flat_1	1.27	1	4.57	0.97	343.5	6.01
BufferLow	1.34	1.5	4.57	1.23	398.5	6.08
BufferSmall	1.17	2	4.57	0.05	158.5	5.45

Design final profile	Hs	z	Tm1,0	q	Vmax	z%+SWL [m]
0situation	1.74	-1.3	4.57	3.83	717.3	6.39
DuneHigh	0.11	4	4.57	0	-	4.36
Dune Low	1.23	2	4.57	1.56	385.2	6.16
Flat_1	1.56	0	4.57	2.30	522.2	6.23
BufferLow	1.64	0.4	4.57	3,37	560.7	6,36
BufferSmall	1.63	0.6	4.57	3,28	551.1	6,35

Dune designs

- High dune design results in 0 overtopping. This is very safe. Safety of Oesterdam doesn't have to be this safe because on the landward side there is a waterbody (the ScheldeRijn channel) so little overtopping during design storm will be acceptable.
- The Low dune does give overtopping. But the overtopping values are acceptable. The initial profile gives very low q (0.01 l/m/s) but even the final 50yrs incl erosion gives an overtopping of 1.56 l/m/s. Still considered safe for experienced staff to walk. It might be necessary to check dam for other failure mechanisms such as revetment stability or breaching.

Buffers and Flat

- Both the other three designs (Buffers and Flat) reduce overtopping during design storm conditions in comparison to 0 situation. Even after 50yrs including erosion. And all profiles show an acceptable overtopping for experienced staff to walk across the dam. Again, other failure mechanisms need to be checked for this overtopping conditions.

- For the initial profiles the Low Buffer has largest overtopping. Flat reduces waves more and eventhough damfoot is lower, overtopping smaller. Notice that the Small buffer design has much less overtopping for the initial profile however the final profile has an even larger overtopping than then Flat design.

6 B Evaluation of designs

The different designs are evaluated for several criteria using a MultiCriteria Evaluation. Where each design is scored per criteria and by using weighing factors the scores of all the designs are compared.

6.1 Evaluation of designs nature and impact surroundings

The different designs score differently on intertidal area being created and on disturbance of the current intertidal foreshore. Both criteria are effecting the impact on nature of the nourishment designs.
The Flat design buries a large area , giving much disturbance on the intertidal foreshore. The buffer designs cover less area. The dune designs cover less area of the foreshore, however these designs are above the normal high water level. In this way turning intertidal foreshore in a high dry sandy beach. This development is not within the current habitat at the project location, in reality this will not be acceptable.
The Flat design creates much intertidal area even if the foreshore erosion continues as expected. The low buffer design also creates intertidal area within the tidal range even when foreshore erosion occurs in the future. That is why these two designs have the most positive impact on creating intertidal area. The small buffer design only creates a small total area within the tidal range. The dune designs create a high dry area. The low dune design creates a relatively lower foreshore with more total m2 within the tidal range.

	Nature		**Total**
Design	buried area	interidal area created	
Dune High	-	--	--
Dune Low	--	-	--
BufferLow	-	+	0
BufferSmall	+	-	0
Flat	--	++	0

6.2 Evaluation safety; wavebreaking and robustness

6.2.1 Conclusions morphological development, robustness

Overall all profiles with a steep slope become more gentle. The changes are going fastest in the first few tides of the model run and slower as the slopes become more gentle. It seems as if the equilibrium slope is 1:60 to 1:70. All the slopes steeper than this become more gentle and seem to reach this equilibrium slope during the 50 time 1/1yr storm model run.
The buffer low profile is more robust because of its gentle slope. The flat profile is an even more robust design because there is only a slope at the edge of the nourishment. The erosion and flattening of this slope has little impact on the breaking of waves. The flat nourishment is more reliable because even if the slope would be flattened out faster than anticipated by the modelling results, the shallow foreshore still ensures wavebreaking.

6.2.2 Wavebreaking/ Overtopping

The safety of the designs have been evaluated during the design storm conditions. As expected, the high dune designs break most of the incoming waves resulting in very little overtopping. Because the main goal of the dune designs (safety) is different than the project goal of combining safety and nature, these designs are scored separately.

From the flat and buffer designs, the initial profile of the small buffer has the least overtopping volume. However, as the profile is re-shaped and the foreshore is eroded during its lifetime, the results change. For the final profile the flat design creates the most safety, by having the smallest overtopping.

Only the safety scores of the final profile are considered in the evaluation for the designs, because the profiles have to provide safety until the end of their lifetime.

	Safety	**Total**
Design	Initial	**Final**
Dune High	++	**++**
Dune Low	+	**+**
	Safety	
BufferLow	-	**--**
BufferSmall	++	**-**
Flat_1	+	**+**

6.3 Most optimal design(s)

6.3.1 Multi-criteria evaluation

A multi criteria evaluation for the different criteria (Safety, Nature and Costs) has been done to find the most optimal nourishment design for the Oesterdam safety buffer. All the designs have been scored between 1-5 for the different criteria.

The dune designs were made with the intention to reduce the hydrodynamic impact to such an extent that the old revetment on the Oesterdam would be classified as safe. These designs therefore have a very high score on safety but score low on nature. The evaluation is done with this aim in mind. Giving more credit to the safety and costs and little to the impact on nature. Doing this, the high dune design has the highest score.

For the other three designs, the evaluation of safety and nature has been valued equal and the costs of the project has been given less weight in the scoring. With this evaluation the Flat design appears to be the best nourishment profile that fulfils both project goals of combining a solution for both safety and nature.

Design	**Safety**	**x=5**	**Nature**	**y=2**	**m3/m**	**z=3**	**TOTAL**
Dune High	++	5	--	1	655	2	33
Dune Low	+	4	--	1	245	3	31
Design	**Safety**	**x=4**	**Nature**	**y=4**	**m3/m**	**z=2**	**TOTAL**
BufferLow	--	2	0	3	110	4	28
BufferSmall	-	1	0	3	180	3	22
Flat	+	4	0	3	850	1	30

6.3.2 Entire design storm Flat design

Because the Flat nourishment designs seems to be most optimal solution that serves both of the project aim, creating nature and providing safety. This design is checked for overtopping during entire design storm of 35 hrs.

During the design storm, there are three different water levels. During each different condition, the safety of the nourishment + Oesterdam needs to be checked. Eventhough the first 5 hrs have the highest water levels and are most likely most critical. During the storm, the nourishment morphology can change. Resulting possibly in higher waves at end of design storm, although waterlevel is lower.

In total 5 output times, after 5hrs 25 and 35 hrs, all at end of waterlevel. And during the change of waterlevel. Assumed that dropping and increasing water level in Eastern Scheldt basin takes 1 hr.

Overtopping of the Oesterdam when Flat_1 nourishment is present on foreshore. Both for the initial profile of the nourishment and for the final profile at the end of the 50years, including 1m erosion.

The overtopping is highest during the first 5 hours of the designs storm, as expected because then the waterlevel is at its highest. However, the 2% run up height is higher at the end of design storm for the final flat profile, z2% is 2.34m while during the first 5 hours, z2% is 2.30m. However, because of the lower waterlevel there is no overtopping of the Oesterdam crest during the last stage of the design storm.

Flat initial profile:

Time	**Zfoot**	**Tm0-1**	**Waterlevel**	**Hrms**	**Hs**	**q**	**V**	**z2%**	**z+SWL**
5hrs	1	4.57	4	0.90	1,27	0.977	266.5	2	6.01
7.5hrs	1	4.57	2.2	0.50	0,71	0	-	1.89	4.09
20hrs	1	4.57	1.5	0.26	0,37	0	-	1.09	2.59
22.5	1	4.57	1.8	0.33	0,47	0	-	1.36	3.16
35hrs	1	4.57	2.5	0.56	0,79	0.003	-	1.00	4.50

Flat final profile including 1m erosion:

Time	**Zfoot**	**Waterlevel**	**Hrms**	**Hs**	**q**	**V**	**z2%**	**z+SWL**
5hrs	0	4	1.1	1,56	2.675	486.6	2.29	6.29
7.5hrs	0	2.1	0.7	0,99	0.003	-	2.24	4.34
20hrs	0	1.5	0.5	0,71	0	-	1.89	3.39
22.5	0	1.8	0.6	0,85	0	-	2.07	3.87
35hrs	0	2.5	0.8	1,13	0.022	-	2.34	4.84

7 B Conclusions part B

The research question answered in this report is:
What are optimal designs for a safety barrier in front of Oesterdam that provides safety, while having a positive impact on ecology and limited negative effect on other functions in the surroundings?

Sub questions formulated to reach an answer to the main question;

- *What is the morphological development of the design?*
- *Is the design safe?*
- *Is there benefit for ecology created?*
- *Is the design robust?*
- *Can we gain knowledge from the design?*

7.1 Answering Sub-questions

7.1.1 Morphological development

The morphological development during the lifetime of the different profiles is similar, profiles with steep slopes become more gentle. It seems that the profiles reach a stable equilibrium slope of 1:60 to 1:70. Even large storms have no major impact anymore on these gentle and stable slopes.
Naturally the different profiles also show different developments. Because the dune designs are located above the normal high water level, they only show morphological development where the water and waves reach the dune profile. The Buffer designs are located at or below the high water level, showing changes in bedlevel over entire slope.
The flat profile only shows changes at the edge of the nourishment where a steep slope is located. The ridge profiles show an overall lowering of the nourishment, but the 1D morphological approach is not correct for these designs. Because it results in large overwash when the back bay is filled, and the model does not represent the emptying of the back bay basin at the foreshore to the sides.

7.1.2 Safety of design

The original situation without a safety buffer (0situation) shows a large overtopping volume. In (Arcadis 2009) a maximum overtopping volume of 1 l/m/s has been applied, with a note that stability of landward revetment needs to be checked. Because the Schelde-Rijn channel lies behind the Oesterdam, overtopping larger than the normal applied maximum of 0.1 l/m/s is not a problem. The 2.9 l/m/s as found for the current situation is probably too large to be considered safe. This might be because of the overprediction of the hydrodynamic conditions (waveheight) at the dam toe or because the profile considered is a conservative schematization of the Oesterdam.
All nourishment designs show a large decrease of overtopping volume, showing that all the designed profiles provide extra safety. Even during the high design storm water level. The profiles even show a lower or equal overtopping after the 50 years lifetime, including foreshore erosion. The flat design has the least amount of overtopping of the three designs at the end of their lifetime.

The dune designs result in almost zero overtopping for their initial profiles. The morphological developed profiles including erosion show also small overtopping volumes. The low dune design gives an overtopping of 1.5 l/m/s, this overtopping volume might even be considered safe. Again there would be a need to make stability check of landward revetment.

Design initial profile	**q [l/s/m]**	**Vmax [l/golf/m]**	**Design 50 yrs+1merosion**	**q [l/m/s]**	**Vmax**	**final score**
0situation	2.91	604.5	0situation	3.825	717.27	
Dune High	-		DuneHigh	0	-	**++**
Dune Low	0.01	0	Dune Low	1.56	385.2	**+**
BufferLow	1.24	398.5	BufferLow	2.91	604.5	**-**
BufferSmall	0.05	158.45	BufferSmall	3,28	551.07	**--**
Flat	0.98	343.5	Flat_1	2.30	522.2	**+**

7.1.3 Benefit ecology

The high dune profiles are above high water level and will create a high dry beach. This is unwanted as it is no intertidal area. Therefore the dune profiles are considered to have no benefit for nature.

The flat profile creates large intertidal area, both initially and even after foreshore erosion it compensates for foreshore erosion. However, it also buries a large amount of foreshore covering the current intertidal habitat. The low buffer profile also creates intertidal area, but not as much as the flat nourishment does. The small buffer profile only creates a very small intertidal area with a steep slope, these are no optimal conditions for intertidal habitat.

7.1.4 Robust?

Designs with a gentle slope are more robust, the gentle slopes are more stable. The flat design is considered most robust, since only the erosion of the slope at the edge of the nourishment is sensitive to changes. While almost the entire profile of the buffer low consists out of a slope, and consequently the functionality of the design is more sensitive to changes in for example wave height or grain diameter.

7.1.5 Can we gain knowledge from design

All designs will provide different insights in different processes. Key in getting insight is a good monitoring program of the development of the nourishment. Both bathymetry, hydrodynamic and ecological parameters need to be measured during a sufficiently long period.

Both the flat and the two buffer nourishment designs can provide knowledge. The flat profile could give insight on the erosion of higher intertidal shoals, while the buffer profile would provide insight into how sand is spread across the foreshore.

7.2 Answer research question, most optimal designs

Design	**Safety**	**x=5**	**Nature**	**y=2**	**m3/m**	**z=3**	**TOTAL**
Dune High	++	5	--	1	655	2	33
Dune Low	+	4	--	1	245	3	31
Design	**Safety**	**x=4**	**Nature**	**y=4**	**m3/m**	**z=2**	**TOTAL**
BufferLow	--	2	0	3	110	4	28
BufferSmall	-	1	0	3	180	3	22
Flat	+	4	0	3	850	1	30

For the two dune designs a different comparison has been made than for the other three designs because the different profiles were developed for a different goal. The dune designs aim only to increase safety while the other three designs try to fulfill both project goals of safety and nature.

If reducing the hydrodynamic impact on the Oesterdam is the main goal of the nourishment, the high dune design proves to be the best. Even at the end of its lifetime, this profile breaks almost all incoming waves.

The flat design is found to be most optimal to fulfill both project goals of creating safety while having a positive impact on nature. The flat design is also considered to be the most robust profile. However, the initial impact of the design on the foreshore is large, because a large area will be covered. Covering and suffocating all existing benthic life. This is not only a negative impact on the ecology at the foreshore, but also on the ‘pierenspitters’.

Obviously the evaluation depends largely on the different weight factors per criteria. For example, costs are given a low weight in the above evaluation. Seeing that the flat design has a large volume of sediment resulting most likely in higher costs, changing this factor would change the outcome.

8 B Recommendations part B

As this research is not complete recommendations for further research can be made in order to reach a more reliable answer to the most optimal design(s).

8.1 Other designs and dimensions

Only a limited amount of designs and dimensions have been modeled. Dimensions could be varied to find an even more optimal solution. For example the optimal height and width of the flat design can be further investigated. Also a combination of several design strategies can be investigated. For example combining a ridge to create intertidal habitat with a high small dune to provide safety.
Also in 2D placement and dimension need further investigation. Variation in this might give a more optimal design.

8.2 Morphodynamic modelling

- The morphodynamic modeling as done in this research leaves room for improvement. Especially the modeling of the deformation of the nourishment profiles during their 50 years lifetime needs further research.
- As a measuring campaign that includes bed levels, water levels and waves has started up during this research for future research more data is available. With these measurements the modeling of the Oesterdam foreshore could be calibrated.
- It might be necessary to use a 2D model to model the morphodynamic respons of the nourishments both during the extreme storm conditions as during the calm conditions during 50 years. Further investigation needs to be done on whether it is necessary to use a non-depth averaged model to accurately model processes such as wind-induced return currents.
- Also a more elaborate sensitivity study could be done. It might be interesting to see how the profiles develop to their final profiles at the end of their lifetime using different sediment characteristics. Probably the final slopes will be different.

8.3 Ecological optimization

Several construction methods and concepts can be investigated to create more ecological benefit or less disturbance from the nourishments. Some examples are;

- Grain diameter
- Construction type
- Construction phase
- Re-allocating pierenspitters
- Using BwN concepts

8.4 Safety check

In this research only the overtopping has been checked during the design storm conditions. It is recommended that more research is done to the allowable overtopping volumes of the Oesterdam, also regarding the stability of the landward revetment. This might prove if the safety buffer nourishments indeed increase the safety to an allowable standard even after 50 years. For this also the ‘leftover strength’ of the Oesterdam should be taken into account.
Also other failure mechanisms also need to be checked such as revetment stability and geological stability of the Oesterdam and its foreshore.

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