# The future of the Oosterschelde with a new inlet channel



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# Preface

This report is written as my master thesis for the master hydraulic engineering at the faculty Civil Engineering and Geosciences at the Delft University of Technology. This thesis is commissioned by Rijkswaterstaat Zeeland.

In this research, a future situation of the Oosterschelde with a new inlet channel through the Neeltje Jans island is explored. This report contains terminology and it is assumed that the reader has some basic hydraulic and coastal engineering knowledge.

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Robbert de Bruijn





### **Summary**

After the storm surge of 1953, the Dutch Delta project was initiated in order to protect the southwestern part of The Netherlands. A storm surge barrier in front of the Oosterschelde and various dams at the back of the estuary were constructed. These interventions led to a large change of the hydrodynamics of the Oosterschelde: a large decrease in tidal volume and flow velocities. This decrease in flow velocities caused a decrease in sediment transport from the channels with about 75%. It is estimated that an amount of 400-600 million m<sup>3</sup> of sediment is necessary to increase the flow velocities, restore the sediment transport from the channels and to obtain a new dynamic equilibrium (Kohsiek, et al., 1987). This need for sand is called the 'sand demand'. At present, the shoal height inside the estuary decreases by erosion. This decrease in shoal height mainly has a negative influence on the protected nature in the Oosterschelde.

The Oosterschelde is a tide-dominated area with low wave heights. The Oosterschelde was ebb dominant and exporting sediment for centuries. All the events and interventions from 1530 up to the construction of Volkerakdam and Grevelingendam in 1969, caused an increase in tidal prism and export of sediment towards the ebb tidal delta. By the construction of the storm surge barrier, Philipsdam and Oesterdam in 1986, the situation changed, the tidal prism decreased and the 'sand demand' started.

This research is aimed at finding a structural solution for the 'sand demand' by opening the storm surge barrier.

In this research the present situation of the Oosterschelde and a future situation with a new inlet channel at Neeltje Jans are analyzed in order to determine if a new inlet channel could influence the hydrodynamics and sediment transport in order to structurally solve the 'sand demand'.

A process based hydrodynamic and morphological model (Delft3D) is used to analyze the present and possible future situations with a new inlet channel. The original Delft3D model of the Oosterschelde, Westerschelde and part of the North Sea has been adjusted and recalibrated to improve the model results for a reliable analysis. The new model has a finer resolution, updated bathymetry, the barrier has been schematized differently, the basin surface area has been adjusted to the land boundaries and the water levels have been recalibrated.

The new model and the methods of Van de Kreeke (1993) and Groen (1967) applied to the present situation of the basin, show that the Oosterschelde is still ebb dominant and would be exporting fine and coarse sediment if the inlet would not block the sediment transport. This ebb dominance follows from the large intertidal area and deep channels. The mean flow velocities are in most parts of the basin in ebb direction. However it should be noted, that the tidal asymmetry in the present situation is negatively 'skewed', but very close to flood dominance. Notwithstanding the ebb dominance, there is no sediment export possible through the inlet. The inlet blocks the sediment transport in both directions mainly because of a 'tidal jet', caused by the small inlet and large tidal prism. Another reason for the sediment block are the scour holes at both sides of the barrier that form a 'sand trap'. This sediment block is positive for the 'sand demand' in the present situation, because sediment export is hindered.

With the new model, model runs with different sizes of the new inlet channel at Neeltje Jans are carried out. Also the whole storm surge barrier has been removed. The tidal prism increases with a new inlet channel and thus increases the flow velocities in the channels. The type of connection between the old channels and the new channel, has a large influence on which areas experience an increase or decrease in flow velocities. The new inlet channel decreases the discharge through the already existing inlet channels, except for the channels it is connected to. The increase in tidal prism and thus flow velocities brings the Oosterschelde closer to the old situation. The higher flow velocities increase the sediment transport from the channels and thus





increase the shoal building. It is not known how much the shoal building is exactly restored. Some channels have such an increase in flow velocities that shoal building occurs again. However, parts of the basin are still not in equilibrium, which can be seen from comparing the old with the new flow velocities and by comparing the tidal prism and the cross-sectional areas of the channels with the empirical relations of Louters (1998) and Haring (1976).

An important disadvantage of an increase in tidal prism is the enhancement of the ebb dominance in the Oosterschelde, by the large increase of the M4 amplitude, M2 and M4 phase difference and mean velocities in ebb direction. This increase in ebb dominance causes more sediment transport in ebb direction. However there is no export possible through the new inlet channel, because also the new inlet channel has a 'tidal jet' that blocks all sediment transport is hindered.

The tidal amplitude increases with a new inlet channel. This enlarges the intertidal area, but does not make the emerging time of shoals longer, because the increase in tidal range makes high water approximately 13% higher and low water approximately 10% lower.

The large-scale effects of the Oosterschelde, like the ebb dominance and 'sand demand' cannot be structurally changed a new inlet channel. However the shoal degradation rate will probably be slowed down with an increase in tidal prism.

A new inlet channel can be combined with an artificially filling up of the channels. This can increase the flow velocities and bring the basin closer to an equilibrium. Model results show that an amount of approximately  $192 * 10^6 \text{ m}^3$  of sediment is in the present situation sufficient enough to create a flood dominant basin. The flow velocities become approximately 30% higher in the first 15 km inside the basin.

When fully removing the storm surge barrier, the old situation is partly restored to an exporting basin. It is questionable if the basin could be made flood dominant by filling up of the tidal channels and retaining of the large intertidal area. Filling up the tidal channels in the 'fully open' situation with about  $600 * 10^6$  m<sup>3</sup> of sediment does not make the basin flood dominant. The mean velocity increases in flood direction, but the tidal area must decrease in order to create flood dominance and import of sediment.

It is recommended that further research should focus on large interventions in order to structurally solve the 'sand demand', rather than small interferences like adjustments to the barrier. Two options to look at, are a combination of a new inlet channel with a partly filling up of the tidal channels and an 'fully opening' of the storm surge barrier with a filling up of the tidal channels. In both situations the safety and costs should be addressed before a decision is made.





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# 1 Introduction

## 1.1 The location and area of the Oosterschelde

The Oosterschelde estuary is located in the southwestern part of the Netherlands (see Figure 1-1). It is part of the Dutch delta coast (referred to as Southewestern Delta), consisting of the Westerschelde, Oosterschelde, Grevelingen and Haringvliet.



Figure 1-1 | The Oosterschelde basin with the names of all the shoals, channels, dams and areas

The main parts of the Oosterschelde described in this report are the inlet, ebb tidal delta and basin (see Figure 1-2). The inlet consists of three inlet channels: the Hammen, the Schaar and the Roompot. The basin is the area from the barrier towards the Philipsdam and Oesterdam. The ebb tidal delta is the area with sand bars and shoals at the seaward side of the inlet.



Figure 1-2 | The Oosterschelde ebb tidal delta, inlet and basin areas





#### 1.2 Problem description

After the storm surge of 1953, the Dutch Delta Project was initiated in order to protect the southwestern part of The Netherlands. As a part of the protection measures in the Delta Project, a storm surge barrier in front of the Oosterschelde and various dams at the back of the estuary were constructed. These interventions led to a large change of the hydrodynamics of the Oosterschelde with a large decrease in tidal volume and tidal range, followed by a large decrease in flow velocities. This decrease in flow velocities caused a decrease in sediment transport from the channels with about 75% (De Jong 2003). A consequence is the present ongoing process, whereby due to waves, the shoals erode, but do not build up again. The eroded sediment is transported to the sides of the shoals and channels, but not back from the channels to the shoals, as it did before the interventions, because the flow velocities will create more sediment transport from the channels to the shoals (see the red arrows in Figure 1-1).



Figure 1-3 | Schematization of the decreasing of the shoals by the 'sand demand'. The black arrows represent the erosion of the shoals and the red arrows indicate the rebuilding of the shoals, which decreased with about 75%, because the flow velocities, indicated by the blue arrows, decreased. Adjusted figure (Hesselink, 2003)

Kohsiek (1987) estimated that an amount of 400-600 million m<sup>3</sup> of sediment is necessary to obtain a new dynamic equilibrium and increase the flow velocities inside the basin. This is called the 'sand demand'. At present the dynamic equilibrium is slowly restored by erosion of the shoals, decreasing the intertidal area inside the estuary. The shoal height decreases, which mainly has a negative influence on nature, safety and recreation (experience of the intertidal landscape). Shoals in front of the dikes should be high and long enough to reduce the wave impact on the dikes (Van Zanten, 2012). At this time, the shoals are still large enough, which means that safety is not yet threatened. Nature however, is already harmed by the decreasing shoal size. In Europe, the Oosterschelde delta is one of the few delta's which is a critical system for large quantities of migratory birds, because of the combination of a large surface area with a tide and lot's of food and nutriments (Brants, 2012). The Oosterschelde is protected by the Natura 2000 nature conservancy law. The shoals are covered by the habitat types 1310, 1320 and 1330, the other parts of the basin by 1160 (Alterra, 2012). On the other hand, nature itself will establish a new equilibrium, which will give room for other animals and organisms. It is estimated that without countermeasures within 40-90 years most of the shoals in the Oosterschelde will disappear (Adriaanse & Van Zanten, 2008).

#### Dynamic equilibrium

When a tidal inlet and basin are in 'equilibrium', they are in a dynamic equilibrium. The flow, waves, sea level and sediment transport are always changing, which causes the inlet and basin to fluctuate around the equilibrium. From now on, with 'equilibrium situation', the dynamic equilibrium situation is meant. The Oosterschelde is not in equilibrium at the moment.





#### **1.3 Context of the research question**

Nature can be left alone, which will bring the Oosterschelde slowly closer to a new equilibrium by a large decrease of intertidal area. Another option is to maintain the current estuary topography with shoals. This can be done by a short term solution, like nourishments or by a structural solution. Recent research is aimed at maintaining the present shoal situation with nourishments and protection of the shoals. A long term strategy (50-100 years) is not yet being investigated. There are several options that could form a long term structural solution. In Figure 1-4 all options from different literature studies are summarized and extended with some additional ones. The optimization of the 'sand demand' can be divided into adjustments to the barrier itself, creating a new opening, a full closure of the Oosterschelde, adjustments inside the basin as compartmentalization or filling up of the channels and the removal of the compartmentalization dams.



Figure 1-4 | An issue tree with the combination of already in literature mentioned and new alternatives to

optimize the 'sand demand'. The green blocks will be the focus of this report.

More and more people start to wonder whether a future situation with an open solution as before the closures, could counter the 'sand demand' and whether this could be an adaptive coastal defense solution. An extra opening in the storm surge barrier could be one of the options to restore part of the tidal volume, tidal range and sediment transport to what it was before the construction of the barrier. Jan Willem Slager (2003) mentioned the option of creating a new inlet channel in the Mattenhaven at Neeltje Jans (Van Maldegem, 2004). This option is mentioned several other times (Reflectiecommissie, 2009). There has never been a profound research on this option. The Deltacommissie (2008) quoted in their report: "If after 2050 the storm surge barrier is not sufficient enough to guarantee the required level of safety, a solution has to be found whereby the tidal dynamics will be maintained or partly restored" (Deltacommissie, 2008). Their preference is a more open alternative (Deltacommissie, 2008). The World Wildlife Foundation shares this preference and states that an open solution is preferred, which can naturally adapt to sea level rise. The treaty of Yerseke 2008 mentions in the context of the solutions for the 'sand demand' that research should focus on the possibilities





of importing sediment from the ebb tidal delta (NationaalParkOosterschelde, et al., 30 Mei 2008). These opinions give rise to the research question of this report.

The Oosterschelde storm surge barrier is constructed for at least 200 years. Only sea level rise can shorten its life span, taking into account that the probability of exceedence of 1:4,000 would not be exceeded. Estimates range, but a conservative estimate is that the storm surge barrier will last till at least 2075 with a sea level rise of 1 meter (Deltacommissie, 2008). However it has to be adjusted with a sea level rise of more than 0.5 m (Deltacommissie, 2008). After this period an open solution could be a realistic option.

#### **1.4 Goal and research question**

Nature habitat protection laws and the future safety form a demand for a solution for the 'sand demand'. In this context, there are many parties that wonder if opening the storm surge barrier could form a structural solution for the 'sand demand'.

The goal of this study is to find a realistic, but futuristic option to open the storm surge barrier as partly proposed by the Delta committee (2008) with the purpose to structurally optimize the 'sand demand'.

#### The main research question is:

• Could a new inlet channel at Neeltje Jans form a structural solution for the 'sand demand'?

#### Sub questions are:

- What is the effect of a new inlet channel on the hydrodynamics?
- What is the effect of a new inlet channel on the sediment transport in the Oosterschelde? And will there be sediment import or export?
- How should the connection be made with the present tidal channels?

#### **1.5 Boundary conditions**

Before this future alternative becomes realistic, the following political decisions have to be made:

- The storm surge barrier is no longer sufficient for the safety of the dikes; This means that either the storm surge barrier will not be adapted to a sea level rise larger than 0.5m, or that there will be a sea level rise of more than 1 m and the storm surge barrier has lost its function;
- The decision is made to open the storm surge barrier for the tide at all conditions, which is necessary to create the new inlet channel without a barrier structure;
- It is decided that in the coming decades most of the shoals are maintained by nourishment and protection. If this is not the case, the optimization of the 'sand demand' to maintain the shoals has no longer a function;
- The transport connection N57 from Schouwen to Noord-Beveland should remain. This means that the concrete pillars of the storm surge barrier will stay. Also the removal of the concrete parts is too expensive.

These decisions imply, that the decisions made before the construction of the storm surge barrier must be reconsidered in this different context.

An increase in tidal range will introduce new water levels and subsequent problems for the existing dikes. Creating an opening will offset the safety of the storm surge barrier during storms, which also introduces risks for the surrounding dikes. In this research the dike safety problem is not assessed as well as the cost aspect that is out of scope.

In the coming years, the present situation will probably be maintained with nourishments and protection of the shoals, which means that the present bathymetry can be used to conduct this research.





It is assumed that all interventions causing a disappearance of nature around Neetlje Jans are possible, because they contribute to the larger ecological problem.

#### **1.6 Research method**

To be able to answer the research questions different research methods are used.

A literature study is conducted to create an overview of all the historical interventions up to the present situation in the Oosterschelde and their influence on the inlet, basin and ebb tidal delta. From this, future responses of the system could be predicted and the model of the present situation could be evaluated.

A hydrodynamic and morphodynamic process-based numerical model (Delft3D) is used to analyze the present situation and the future alternatives. The hydrodynamic changes in the Oosterschelde will be determined from the model results. Also sediment transport patterns can be determined.

Available theories and data about sediment transport and morphology, like tidal asymmetries, empirical relations and measurements are analyzed in order to understand the present sediment transport and to be able to predict the future sediment transport.

The methods of Van de Kreeke and Robaczewska (1993) and Groen (1967) are used to determine the coarse and fine sediment transport vectors in the Oosterschelde and to test the model results for sediment transport.

#### **1.7** Structure of the report

In Chapter 2, the historical development of the Oosterschelde will be addressed. In the first section, the historical developments will be described. The next two sections, hydrodynamics and morphodynamics of the Oosterschelde will focus on specific components of the Oosterschelde system. This chapter concludes with the eventual equilibrium situation and the empirical relations that describe the equilibrium situation.

In Chapter 3, the model that is used and all the adaptations to the original model will be described.

Chapter 4 gives an overview of the model results and analysis of the present situation.

Chapter 5 describes the future situation with a new inlet channel and gives the answers to the sub questions.

This report ends with the conclusion and recommendations for further research.





# 2 System description

This chapter describes the hydrodynamic and morphodynamic situation of the Oosterschelde during history by means of literature. It gives an overview on how the system behaved in the past centuries and how it responded on the different events and interventions.

## 2.1 Historical development of the Oosterschelde

Two large storms in 1530 and 1532 brought the Oosterschelde basin out of balance by eroding the basin and increasing the tidal prism with approximately 50%. This forced the basin towards a new equilibrium with deeper and wider channels and caused sediment export to the ebb tidal delta. In the following centuries the tidal prism increased and forced the channels to become deeper and deeper.

In the 19<sup>th</sup> century, people started to protect the banks against erosion by applying better bank protection. Lateral erosion was hindered and there was a further deepening of the channels in the western part (Van den Berg, 1986).

From 1870 to 1960 dredging and canalization works have been carried out, which had the consequence that the tidal prism increased with about 15%. This created the Schaar channel, that transformed the inlet to a three channel system.

In 1965 and 1969 the Volkerakdam and Grevelingendam were constructed in the back of the basin, which again disturbed the equilibrium by cutting of the Rhine, Muse and Scheldt discharges and by increasing the tidal prism. The Grevelingendam had a minor influence, because it was situated at the tidal divide between the Grevelingen and Oosterschelde. The closure of the Volkerak caused an increase in tidal prism of about 8% and an increase in sediment export from the Oosterschelde. A strong ebb dominant current existed (Eelkema, et al., 2012).

In 1968 most of the flood that entered the Oosterschelde was discharged through the Hammen channel, but most of the ebb discharge was going through the Schaar. This means that the middle channel of the three channel system was the ebb dominated channel and the two others, were mostly flood dominated. This is in accordance with the three channel model by Hayes (1980) (Eelkema, et al., 2012). A new inlet channel can shift this ebb and flood discharge distribution. The Hammen and Schaar channel have shifted a little northwards by the closure of the Grevelingen.

The cross-sectional area of the total inlet was about 88,000 m<sup>2</sup> in 1971. After the damming of the Geul channel in 1972 for the construction of Neeltje Jans, the cross-sectional area decreased by 17% to 73,000 m<sup>2</sup>.







Figure 2-1 | The Geul channel in 1959 (Van den Berg, 1986) projected on the 2011 situation (De Ronde, 2011)

The Geul channel was already sedimentating by the increase in tidal prism. From Figure 2-1 becomes clear that the Geul was a flood dominated channel connecting the Westgat with the Roompot, because the channel ends in flood direction. After the damming, the ebb and flood volumes were distributed over the Schaar and Roompot channels, whereby the Roompot has taken the majority of the volume. There was a loss of discharge in the Hammen channel after 1972 (Van den Berg, 1986).

The next phase in the Delta project would have been a full closure of the Oosterschelde by a closed barrier. However at the end of the 1970s, recognition came for the importance of the tide on nature and especially on the shellfish sector, which led to the decision for an open solution (WNF, 2010). This open solution became the crown of the Dutch Delta works. At that moment one of the requirements was to keep a mean tidal range of at least 2.7 m at Yerseke (Visser, 1986). This requirement was met by decreasing the basin area from 452 km<sup>2</sup> to 351 km<sup>2</sup> by two compartmentalization dams: the Oesterdam and Philipsdam (Vroon, 1994).

Between 1983 and 1986, the Oosterschelde storm surge barrier has been constructed which had a significant influence on the tidal characteristics inside the estuary. In this period, also the Oesterdam and Philipsdam (1986) have been constructed, which decreased the tidal prism with approximately 5% (RIKZ, 2003). The construction of the storm surge barrier caused a decrease in cross-sectional area of the inlet from 64,000 m<sup>2</sup> to 17,900 m<sup>2</sup>, which decreased the tidal prism with 25%, to the ±950 million m<sup>3</sup> it is now. The decrease in tidal prism caused a decrease in flow velocities inside the channels and a decrease of the vertical tide with 13% (Huisman & Luijendijk, 2009). The flow velocities in the Hammen and Schaar channels have declined by 20-40% after the completion of the storm surge barrier in 1986 (Louters, et al., 1998).







Figure 2-2 | Equilibrium relations according to O'Brien and Haring and the situation for the Oosterschelde

Figure 2-2 shows the equilibrium cross-sectional area and tidal prism of the Oosterschelde. To reach equilibrium, the cross-sectional area should increase or the tidal prism should decrease. A decrease in tidal prism could be achieved by decreasing the basin area of the Oosterschelde as the Oesterdam and Philipsdam did. Figure 2-2 shows why such a large (500-600 m) bottom protection was needed to protect the storm surge barrier. Naturally the cross-section of the inlet channels will adapt to the new equilibrium situation, which had to be prevented for a safe foundation of the storm surge barrier. This indicates that an enlargement of the cross-sectional area will have a positive effect on the equilibrium and thus 'sand demand'.

The tidal prism is the volume of water that enters the Oosterschelde during flood or leaves the Oosterschelde during ebb. In formula it is:  $P = V_{HW} - V_{LW}$ . The tidal volume is  $P = V_{HW1} - V_{LW1} + V_{hw2} - V_{LW2}$ .  $V_{HW}$  is the water volume during high water and  $V_{LW}$  the volume during low water. The 1 and 2 in the subscript indicate two following low and high waters. In this definition, that is used in this report, the tidal volume is approximately twice the tidal prism. In literature, a tidal prism of 880 million m<sup>3</sup> after the construction of the storm surge barrier is mentioned. This tidal prism is calculated by multiplying the mean tidal range of Oosterschelde by the water surface area. This is not accurate. RIKZ calculated the tidal prism in 2001 by doing the same calculation, but per grid cell in a fine grid. This gave a more precise tidal prism of about 950 million m<sup>3</sup>. In this report the tidal prism is calculated by averaging the maxima and minima of the cumulative discharge through all the inlet channels. This gives a tidal prism of 953 million m<sup>3</sup> at present.

# 2.2 Hydrodynamics of the Oosterschelde

#### 2.2.1 Tides

The southern North Sea has a semi-diurnal tide, which travels as a Kelvin wave around an amphidromic point that is situated halfway England and the Dutch coast. The tidal wave travels along the Dutch coast from the Southwest to the Northeast. The flood current runs in northern direction, the ebb current in southern direction. The flood velocities are higher than the ebb velocities along the Dutch Coast (De Bok, 2001). The tidal rise is faster than the tidal fall.

The tidal wavelength is about 540 km with a water depth around 15 m ( $\lambda = \sqrt{gdT}$ ). The tidal wavelength compared to the 45 km length of the Oosterschelde basin, makes it a short basin with a reflective tidal wave.

The currents in the Haringvliet and Grevelingen are directly related to the North Sea tide, while the Oosterschelde currents are not (Elias, et al., 2006). The tidal wave and tidal currents are complex due to the distortion by the inlet, bathymetry and reflection. The Philipsdam and Oesterdam increase the reflection of the tidal wave.





In the Oosterschelde mouth, the mean tidal range is 2.9 m, increasing to 3.5 m at spring tide and 2.3 m at neap tide (Eelkema, et al., 2012). The lunar tidal component with a 18.6 year cycle peaked around 1980 and increased the tidal amplitude with 3-4% (De Ronde, 1983).

#### 2.2.2 Wind and waves

The governing south-westerly winds on the North Sea induce a residual northerly flow and sediment transport of fines along the Dutch Coast (Dronkers, 1998). The waves at the Oosterschelde ebb tidal delta are dominated by locally generated waves and have a minor swell component. The governing wave direction is determined by the south-westerly wind direction. The ebb tidal delta reduces the wave height with almost 70% to 0.2-0.5 m. The measurement station OS4 (see Figure 3-6) shows low wave heights, and a large correlation between high tide and higher wave heights and low tide and lower wave heights. This correlation sterns from the reduction of bottom friction on the total water column by a higher water level, increasing the wave height. In Figure 2-3 the wave height and wind distribution inside and outside the Oosterschelde is given.



Figure 2-3 | Wave height and wind distribution inside and outside the Oosterschelde from 1977-1990

(Louters, et al., 1998)

The Oosterschelde is a tide dominated area. The wave height is highly reduced by the ebb tidal delta (especially the Banjaard shoal) and the tidal range is relatively high compared to the wave height. Waves will not be accounted for in the simulations and calculations. Inside the basin there are mainly local generated waves. These waves mainly have an influence on the stirring up of the sediment of the shoals. This influences the shoals erosion, but this is not investigated in this research. Shoal building cannot be modeled correctly, which makes a correct erosion unnecessary. Furthermore, the waves have no significant influence on the hydrodynamics and transport directions.





### 2.3 Morphodynamics of the Oosterschelde

# 2.3.1 The hydrodynamics affecting sediment transport

Sediments are affected by the vertical and horizontal asymmetry of the tide. Tidal asymmetry is a distortion of the tidal wave created by bathymetry, geometry, friction and tide-tide interaction. There are two kinds of tidal asymmetry, namely 'skewness' and 'sawtooth' asymmetry.



Figure 2-4 | The two types of asymmetry: the red line represents the asymmetry around the horizontal axis ('skewness') with higher maximum flood than ebb velocities and the blue line represents asymmetry around

the vertical axis ('sawtooth') with a longer falling than rising period

'Skewness' refers to a phase shift between the horizontal and vertical tide. This can correspond to a shorter ebb than flood duration or vice versa, causing differences between the maximum ebb and maximum flood velocities (see the red line in Figure 2-4). If the flood period is shorter, the mean flood velocities are higher than the mean ebb velocities. This gives averaged over the whole tidal cycle a sediment transport of coarse material in flood direction, because sediment transport is proportional to a power of the velocity larger than 1. This is described as flood dominance. If the ebb period is shorter, the mean ebb velocities are higher than the mean flood velocities, which is referred to ebb dominance.

In this report ebb dominance will be used if the net sediment transport created by the tidal asymmetry and mean flow velocities is in ebb direction. Flood dominance will be used if the net sediment transport is in flood direction.

Flood dominance can be expected if the ratio of the tidal amplitude over water depth (a/h) is large. Longer basins stimulate this effect (Bosboom & Stive, 2011). A basin with large intertidal areas slows down the flood propagation and enhances ebb dominance. Indicators for this enhancement are the ratio of intertidal volume over channel volume  $\frac{V_s}{V_c}$  by Friedrichs and

Aubrey (1988) or the wet surface area at high water over the wet surface area at low water  $\frac{S_{hw}}{S_{lw}}$ .

This can also be expressed by a hypsometric curve, which shows the relation between the bed level and basin area (see Figure 2-5).







Figure 2-5 | Hypsometric curves. (A) represents a basin with a large intertidal storage area and shallow channels (Bosboom & Stive, 2011), (B) represents a basin with little intertidal storage area and deep channels

(Bosboom & Stive, 2011) and (C) is the hypsometric curve of the Oosterschelde, which combines a large

#### intertidal storage area with deep channels (Burt & Allison, 2010)

If the channels are deepened, the ebb duration is shortened with respect to the flood duration, which enhances ebb dominance and sediment export (Dronkers, 1998). In contrast, flood dominance is enhanced by shallow channels, widening of the channels, decreasing the intertidal storage area and a large tidal amplitude (Bosboom & Stive, 2011).

'Sawtooth' asymmetry (asymmetric around the vertical axis) of the tide is described as the difference between the duration of flow reversal from flood to ebb (falling period, also called high water slack) and flow reversal from ebb to flood (rising period, also called low water slack) (see the blue line in Figure 2-4). This asymmetry has a large impact on suspended sediment by creating a residual sediment transport. The amount of suspended sediment settled, depends on the settlement time it has. With a longer falling period than rising period, sediment imported into the basin has more time to settle inside the basin than sediment exported out of the basin has time to settle at sea. This gives a net sediment import of fines towards the basin. In a basin where the length is much smaller than a quarter of the tidal resonance length, sawtooth asymmetry is the dominant form of asymmetry. Shallow channels and little intertidal storage enhances the duration of the rising period and thus export of fine sediment. However a large intertidal storage area creates a counteracting effect. During high water, the water surface and basin area are larger than during low water, which creates more settlement during high water than during low water and thus enhances the import of fine sediment.

*High and low water slack periods* in combination with sediment transport, could be confusing terms. Their original definition is the period that during slack, the water level is neither rising nor falling. In this report the whole falling period (of the horizontal tide) is called high water slack and the whole rising period (of the horizontal tide) is called low water slack. For fine sediment transport almost the whole period of rising or falling water levels is

For fine sediment transport almost the whole period of rising or falling water levels is important. Roughly can be said that If  $\frac{du}{dt_{Falling}} > \frac{du}{dt_{Rising}}$  there is export and if  $\frac{du}{dt_{Falling}} < \frac{du}{dt_{Rising}}$  there is import. To be more precise, if the period when the concentration of the fines in the water column decreases is longer during reversal from flood to ebb than during reversal

from ebb to flood, there is an import of fines. If the period of decreasing concentration in the water is longer during reversal from ebb to flood than during reversal from flood to ebb there is an export of fines.





The astronomical tide and tidal distortion can be described by a series of higher harmonics, as the M4, M6, M8, S4, S6, S8 and many other tidal constituents (see Appendix B for the most important tidal constituents). They all have their own frequency, phase and amplitude.

The tidal propagation velocity is  $c \approx \sqrt{gh}$ . The water depth is different for high and low tide. This gives a shorter ebb or flood period, which is expressed in the M4, M8, S4, S8 and other overtides. Friction slows down the low tide and creates the M6, S6 and other overtides. The M2 and S2 and the M4 and S4 introduce the interaction tides MS2. MS4.

The phase difference between the tidal constituents M2 and M4 is  $\varphi_{m4} - 2\varphi_{m2}$  and describes which type of asymmetry the tide has (Bosboom & Stive, 2011). The asymmetry and its effect are summarized in Table 2-1.

Table 2-1 | Phase difference between the M2 and M4 tidal component and its asymmetry and effect (Bosboom

& Stive, 2011)

Phase difference			
φ4-2φ2 in degrees	Asymmetry	Effect	
0°	Horizontal axis - Skewness positive	Flood dominant - maximum import coarse material	saw-tooth = 0
+ 90°	Vertical axis - Sawtooth	Longer rising than falling period - export of fines	skewness = 0
+ 180°	Horizontal axis - Skewness negative	Ebb dominant - maximum export coarse material	saw-tooth = $0$
+ 270°	Vertical axis - Sawtooth	Longer falling than rising period - import of fines	skewness = 0

For a phase difference of 0° or 180° there is zero sawtooth asymmetry and the 'skewness' is maximal (import of coarse material for 0° and export of coarse material for 180°). For a phase difference of 90° or 270° the 'skewness' is zero and the 'sawtooth' asymmetry is maximal (export of fines for 90° and import of fines for 270°). For all other phase differences, there is a mixed asymmetry of 'skewness' and 'sawtooth'.

Van de Kreeke (1993) gives an expression for the long-term averaged bed load transport of coarse material derived from the horizontal tidal constituents (flow velocity):

$$\frac{S}{c\hat{u}_{m2}^3} = \frac{3}{2}\frac{u_0}{\hat{u}_{m2}} + \frac{3}{4} * \frac{\hat{u}_{m4}}{\hat{u}_{m2}}\cos(\varphi_{m4-2}) + \frac{3}{2} * \frac{\hat{u}_{m4}}{\hat{u}_{m2}} * \frac{\hat{u}_{m6}}{\hat{u}_{m2}}\cos(\varphi_{m4-2} - \varphi_{m4-6})$$
(1)

Where S is the sediment transport  $[m^3/s]$ ,  $\hat{u}$  the amplitude of a tidal current [m/s],  $\varphi$  [°] the phase difference between two tidal components.

This expression holds for the case that the M2 component is the dominant component and the residual flow velocity is small, compared to the M2 amplitude (Van der Kreeke, 1993). These requirements are met for the Oosterschelde.

Only the first three terms are shown here. There are more terms for the S2, N2 and MS4 and K1 components. This method is further explained in Appendix B.

Sediment can also be transported by density, wind or setup driven currents, residual flow patterns, wave driven currents or by sediment hopping. This contribution in the Oosterschelde is not described in this report and of minor influence.

The Groen (1967) expression describes a method to determine the transport of fines:

$$\frac{\delta N}{\delta t} = \alpha (N_e - N) \tag{2}$$

Where N<sub>e</sub> [kg/m<sup>3</sup>] is the equilibrium sediment concentration expressed as:  $N = A(u^2 + v^2)$ , C [kg/m<sup>3</sup>] the instantaneous sediment concentration,  $\alpha$  [-s] is the settling lag time vector between C<sub>e</sub> and C, as  $\alpha = \frac{1}{3} \frac{h}{w_s}$  and A [-] is the proportionally constant depending on the sediment characteristics (Groen, 1967) (Elias, 2006). The water depth has an influence on the settling lag time vector, but is not taken into account. It has a significant effect on the settlement on the





shoals, but not a significant effect on the deep channels. The Groen (1967) method is further explained In Appendix C.

2.3.2 Sediment transport in the Oosterschelde

In this report the terms coarse and fine sediment transport will be used. With coarse sediment transport, bed load transport of the coarse grains (>63  $\mu$ m) is meant. Suspended sediment transport is described as sediment transport of fines (<63  $\mu$ m) consisting of silt and clay.

Measurements of coarse sediment in the Oosterschelde inlet at both sides of the barrier show that sediment import or export is negligible ( (Louters, et al., 1998) and (Ten Brinke, 1993)). Sand concentrations higher in the water column have declined from a few tens of mg/l in 1981 to a few mg/l in 1988 (Ten Brinke, 1990).

The sediment export distribution over the different inlet channels changed over time. In 1968, 40% of the sediment was exported by the Roompot, 35% by the Schaar and 25% by the Hammen. The Roompot has taken 50% on account of the Hammen in 1982 (Eelkema, et al., 2009). In the present situation the sediment transport capacities of the Hammen and Schaar are still smaller than the Roompot (Huisman & Luijendijk, 2009).

At sea, the sediment is transported by the tide along Walcheren and the Zuiderlijke Roompot towards the Oosterschelde barrier. As it cannot cross the barrier, it is expected to transport towards the Oude Roompot channel in the north-west (see Figure 2-6). The longshore sediment transport along the coast is limited. It is estimated that the transport amounts to 20,000-50,000  $m^3$  a year along Walcheren and 5,000-20,000  $m^3$  just in front of the barrier (Huisman & Luijendijk, 2009). This longshore transport is expected to supply the offshore part of the ebb tidal delta.

There is not much known about the coarse sediment transport inside the basin, rather than that the basin was exporting coarse sediment till the construction of barrier and that the shoals are eroding at present.







Figure 2-6 | Sediment transport processes in the ebb tidal delta in 1000 m<sup>3</sup> per year (Huisman & Luijendijk,

2009)

Measurements show that silt ( $8 < d_{50} < 63 \mu m$ ) concentrations in 1987 and 1988 reduced with almost 50% compared to the old situation before the interventions (Ten Brinke, 1989). The measured concentrations of silt are higher during ebb than flood. They are also higher during springtide than neap tide. During flood, the fines are mostly transported along the north and south sides of the channels (Ten Brinke, 1989). Measurements of fine sediment in 1987 showed a net import of silt into the basin of approximately 1 million m<sup>3</sup> a year (Louters, et al., 1998). This is transported in suspended mode. The amount of 1 million m<sup>3</sup> is highly uncertain, because of measurement uncertainties. A small difference of 2.4 mg per liter will change the imported 1.0 million m<sup>3</sup> a year to zero (Cleveringa, 2008). These measurements were all conducted for a short period during moderate weather conditions. It is unknown what impact storms exactly have on the sediment exchange, but their contribution compared to the yearly exchange through the barrier is negligible (Ten Brinke, 1990). Storms probably increase the transport magnitudes by increasing the sediment concentrations. Storms go along with larger wave heights that stir up the sediment. The fine sediment concentrations in the basin are very low and fine sediment is washed out of the shoals by the waves and is transported to the channels.

#### 2.3.3 Sediment availability

The total sediment erosion volume of the Oosterschelde basin between 1969 and 1983 was less than the expansion of the ebb tidal delta (De Bok, 2001). This means that the Oosterschelde basin and ebb tidal delta can import sediment from beyond its own coastal system. However, the sediment supply offered by the North Sea is limited. The sediment surplus of the whole North Sea accounts to almost zero, as most of the river sediment discharges are diminished and there is sea level rise (Mulder, et al., 2010).

The large increase in tidal prism from 1530 to 1983 led to an increase in volume of the outer delta, a shift seawards and an increase of various channels through the ebb tidal delta (Eelkema,





et al., 2009). The total 'sand demand' of the Oosterschelde basin is estimated at 400-600 \*  $10^6$  m<sup>3</sup> by an empirical calculation in the GEOMOR research (Kohsiek, et al., 1987). In this empirical calculation there is no feedback between the new bathymetry and new hydraulic conditions affecting the 'sand demand', which probably will have a significant influence. The predictions of GEOMOR are on the high side according to recent measurements. These measurements give a decrease of ±340,000 m<sup>2</sup> of intertidal area each year, where GEOMOR predicted twice as much (Bekkenrapportage, 1996). This does not mean that the 600 \*  $10^6$  m<sup>3</sup> is not correct, but that the timescales are probably much larger than predicted. With sea level rise the 'sand demand' will grow. A sea level rise of 2 mm/year increases the 'sand demand' in the Oosterschelde with 0.75 \*  $10^6$  m<sup>3</sup> a year (Mulder, et al., 2010). The degradation of shoals amounts to  $1.5 * 10^6$  m<sup>3</sup> a year.

The Oosterschelde does not have a flood tidal delta, because the inlet is tide dominated (low wave height and high tidal range) and the basin has large intertidal areas with deep channels (Hayes, 1980).

The ebb tidal delta now consists of several ebb and flood tidal channels up to 37 m deep and extends up to 15 km offshore with tidal flats around 1-3 m below NAP (Cleveringa, 2008).

A northward longshore sediment transport is depositing sediment on the northern side of the ebb-tidal delta of the Oosterschelde near the Brouwershavensche Gat. On the south side of the ebb-tidal delta erosion rates of 0.9-  $1.2 * 10^6 \text{ m}^3$  a year seem to occur (Cleveringa, 2008). These contribute to the clockwise rotation of the ebb-tidal delta to the north (Cleveringa, 2008). The sandbanks and inter-tidal flats stabilized around 1995. In the years following it showed some regression (RIKZ 2000).

At the moment it is not clear whether the whole ebb-tidal delta is increasing or declining. According to Cleveringa 2008, the most likely rate of erosion and deposition of the ebb-tidal delta lies between -1.2 to  $0.4 \times 10^6$  m<sup>3</sup> a year, which makes it most likely that the ebb tidal delta erodes. This corresponds to the equilibrium theory of Walton & Adams (1976), where the Oosterschelde ebb tidal delta must shrink according to the large decrease in tidal prism.

A tidal prism of 1200 million m<sup>3</sup> corresponds to an ebb tidal delta volume of 960 million m<sup>3</sup>. The current volume of the ebb tidal delta is almost twice as much (1700 million m<sup>3</sup>) and the tidal prism is approximately 950 million m<sup>3</sup>.

The conclusion is that because of the non-equilibrium situation of the ebb tidal delta, it is plausible that the ebb tidal delta still has a large surplus of sediment that could be transported towards the Oosterschelde basin. The exact amount of the surplus is unknown. If sediment import can be created into the basin, this surplus can be used for the 'sand demand' instead of disappearing slowly into the North Sea. Only the surplus of the ebb tidal delta, the pittance of longshore sediment transport and supplemented sediment can be used to appease the 'sand demand'.

# 2.4 Equilibrium situation of the Oosterschelde

It is difficult to determine an exact equilibrium for the Oosterschelde inlet, basin and ebb tidal delta. Empirical relations (2.4.1) give an idea about the equilibrium situation and the adaptations the system must undergo to get closer to this equilibrium situation. A tidal inlet and ebb tidal delta are complex systems with various different timescales. The inlet system acts on different time- and spatial scales than the morphological elements and morphological features like sand riches and migrating bars (Elias, 2006).

The distorted equilibrium situation in the Oosterschelde will result in a sand exchange between the different components and will shift towards a new equilibrium. Nature is now eroding the shoals and filling up the sides of the shoals and channels. This gives another equilibrium situation than the old situation with a large tidal prism.

Currently, the Oosterschelde basin is back to the tidal prism it had around 1850. After 1850 approximately 400 million  $m^3$  of sediment has been exported from the basin towards the ebb tidal delta by the increase in tidal prism, which is almost the same amount as the estimated





'sand demand' (Louters, et al., 1998). Estimates give an adaptation time towards the new equilibrium of the basin of two to four centuries (Louters, et al., 1998). Sea level rise can increase this period.

In the next section the empirical relations concerning the Oosterschelde are described.

#### 2.4.1 Empirical relations

There is a relationship between the tidal prism and cross-sectional area of an inlet. This relation was first given by LeConte (1905), followed by O'Brien (1931, 1969). The general form is:

$$A_{eq} = C * P^q \tag{3}$$

The minimum equilibrium cross-section  $A_{eq}$  of the inlet is related to the tidal prism P and the coefficients C and q (Bosboom & Stive, 2011). This relation with the empirical parameters for the Oosterschelde is:  $P = 12200 * A_{eq} + 2 * 10^6 [m^3/tide]$  (Louters, et al., 1998). The empirical parameters for the Oosterschelde are found by Van den Berg (1986). It is shown that this relation also applies to the channel cross-section compared to the volume passing this cross-section. This relation states that the cross-sectional area of the inlet for the current tidal prism of 953 million m<sup>3</sup> should be 77,950 m<sup>2</sup>. However a larger cross-sectional area will also increase the tidal prism. The present channel cross-section behind the barrier is about 110,000 m<sup>2</sup>. This corresponds to a tidal prism of 1,340 million m<sup>3</sup>.

Haring (1967) found the following empirical relation for the tidal volume and cross-sectional area of the inlets in the southwestern part of The Netherlands (Van Kleef, 1991):

$$A_c = 4.129 * 10^5 * TV \tag{4}$$

This relation is very similar to the relation of Louters.

The empirical relation by Walton & Adams (1976) relates the volume of the ebb tidal delta to the tidal prism:

$$V_{delta} = \alpha_b * P^{1.23} \tag{5}$$

This relation confirms the observation of the reduction of the ebb tidal delta volume after the reduction in tidal prism by the barrier. This also implies that with an increase in tidal prism by a new inlet channel, the equilibrium volume of the ebb tidal delta will increase, which reduces the surplus of the ebb tidal delta available for import into the basin.

In case the maximum and average flow velocities of a channel are known, the following relation can approximate the maximum depth of a channel (Louters, et al., 1998):

$$\frac{Max. Depth Channel}{Average Depth Channel} = \frac{Max. Velocity Channel}{Average Velocity Channel} = 1.8 - 2.1$$
(6)

This relation states that the new opening would never have the same depth along the whole opening.

The last empirical relationship relates the total channel volume to the tidal prism:

$$V_{channel} = C_{\nu} * P^{3/2} \tag{7}$$

In this formula Cv is 76 \*  $10^6$  for the Oosterschelde (Bosboom & Stive, 2011). This gives an equilibrium channel volume for the Oosterschelde of 2.236 \*  $10^9$  m<sup>3</sup>. The present channel volume is bigger.

#### 2.5 Conclusion

The Oosterschelde was an exporting basin for centuries. All the events and interventions up till the construction of Volkerakdam and Grevelingendam caused an increase in tidal prism and





export of sediment towards the ebb tidal delta to restore the equilibrium situation. With the construction of the storm surge barrier and Philipsdam and Oesterdam, the situation changed drastically and the tidal prism decreased.

The Oosterschelde is still out of equilibrium. Approximately  $400-600 * 10^6 \text{ m}^3$  of sand is needed to restore this equilibrium. By an increase in tidal prism, the amount of sand needed is less, but the equilibrium will also be different.

This amount of sediment will bring the Oosterschelde towards a new equilibrium with shallower channels. This does not mean that in the present situation, the basin has changed to an importing basin (see Chapter 4). There is no import or export through the inlet measured, from which can be concluded that the barrier blocks the sediment transport.

Because of the continues increase of the ebb tidal delta and by analysis of the empirical relations, it is plausible that the ebb tidal delta has a surplus of sediment, which can be used for the 'sand demand'. The sediment supply offered by the rest of the North Sea is very limited.





# 3 The model

In this section will be described which model is used and why. Various adjustments have been made to the existing model of the Oosterschelde to create the new model, which complies with the requirements for this research.

#### 3.1 Purpose of the model

In this study, a process based numerical model is used as a tool to assess the present situation and future changes to the Oosterschelde inlet and the effect on the tide and sediment transport. The model should represent 'reality' as good as possible. A 2DH model is necessary to reproduce the spatial differences in flow and sediment transport patterns that are present in the Oosterschelde system. Delft3D is a process-based numerical model that solves water motion, sediment transport and bed level changes with a coupled set of equations. In every grid cell the continuity and Navier Stokes equations are solved. There are simplifications for eddy viscosity, shallow water, incompressible fluid and the Boussinesq approximation, which lead to the shallow water equations.

Future adjustments to the system can easily be implemented in the model grid and schematization, which makes Delft3D a perfect tool to experiment with.

The following questions have to be answered with the model, by comparing the present situation with the future situation (a new inlet channel at Neetlje Jans):

- What are the effects on the tidal prism and tidal range?
- What is the effect of a new inlet channel on the sediment transport?
  - What are the effects on the tidal asymmetry?
  - What are the effects on the tidal jet?
  - o What are the effects on the maximum flow velocities?
- Is sediment transport possible?
  - What are the sediment transport patterns?
  - Where is erosion and where is deposition of sediments?
  - What are the morphological effects of a new inlet channel?

#### 3.2 The model

The model used in this study is the KustZuid model (2DH) in Delft3D (see Figure 3-1). This model is a converted version of the KustZuid SIMONA (WAQUA) model of Rijkswaterstaat. Water levels and flow velocities are almost the same in both models, only the storm surge barrier is modeled differently. The model simulates the water levels and flow at the Southern part of the North Sea, the Oosterschelde and the Westerschelde. The boundary conditions consist of 94 astronomical tidal components.

A nested model of the Oosterschelde has not been used, because a new inlet channel in the Oosterschelde has so much influence on the whole domain, that nesting will not give accurate flow velocities and water levels in and around the Oosterschelde. With a large new inlet channel in the Oosterschelde, at the north part of the Westerschelde inlet, the flow velocities and discharges differ with 5% from the present situation. If the whole Oosterschelde inlet is opened, the difference is even larger.







Figure 3-1 | Overview of the original KustZuid model in Delft3D

# 3.3 Required model accuracy, resolution and adjustments

## 3.3.1 The model requirements

The model must be adjusted to reproduce 'reality' in such a way, to be able to correctly answer the questions for this research. The model requirements are:

- An accurate representation of the phases of the different tidal components;
- An accurate representation of the tidal prism, flow velocities and water levels;
- Accurate sediment transport directions and order of magnitude;
- A good representation of the 'tidal jet'.

The required model accuracy is a correct representation of the M2, M4, M6, S2, N2 and MS4 tidal constituents phase and amplitude, because they contribute the most to the total amplitude and sediment transport. The amplitude of the components may vary with  $\pm$  5 cm compared to measurements of the real water levels. The phase differences between the components must be accurate to reproduce the existing ebb and flood dominance and sediment transport. The phase differences between the measured phase differences by the Hydro Meteo Centrum Zeeland (HMCZ) and the model must be less than 10<sup>0</sup>. The measured water levels by the HMCZ already introduce an uncertainty: they correspond for about 95% with the cosines of the tidal constituents, because set-up, storms and other water level disturbances are included in the measurements.

The aim of the model is not to reproduce the sediment transport magnitudes and concentrations exactly, but rather to show the order of magnitude and the relative changes of the future situation compared to the present situation.

An exact representation of the sediment transport magnitude is not possible by the model, because of the sensitivity to input variations and a lack of sediment concentration data for the calibration and validation of the morphodynamic model. Also long term morphology is difficult to predict, because of the short term process noise and input sensitivity that influences the long term prediction (Elias, 2006).





#### 3.3.2 Model grid and bathymetry

The model grid is refined around the barrier and the grid and bathymetry are adjusted to a more realistic situation.

There were three reasons to refine the existing model grid:

- The grid cells at Neeltje Jans were too large to easily implement different sized openings;
- The grid cells around the barrier were too big to capture all the flow patterns around the barrier including the eddy formation due to the tidal jet;
- The grid cells at the storm surge barrier were too big to capture the exact bathymetry and sill of the barrier. This is necessary to reduce the amplitude and phase errors inside the basin and to model the sediment transport correctly.

The required resolution at Neeltje Jans is at most 150 m wide and the required resolution at the storm surge barrier must be at least 45 \* 65 m for the smallest grid cells. These requirements are met (see Figure 3-3).

The original bathymetry of 2004 is too coarse to use in the detailed model and the bottom protection is not correctly included (see Figure 3-2).



Figure 3-2 | Close-up of the Roompot bathymetry and grid in the old model (left) and the new model (right)

The new model bathymetry consists of multi beam echo sounding measurements from the barrier and bottom protection of January 2011 and bathymetry samples in the rest of the domain of 2010. A close-up of the new grid and bathymetry at the Roompot inlet is given in Figure 3-2. The bottom protection is now included and the barrier has the same sill depth as in reality. Only a single depth layer is used (2DH).

Grid cells at Neeltje Jans are included and other grid cells at the boundaries of the basin are removed, to get a better fit with the land boundaries and a more accurate water surface area (see Figure 3-3).







Figure 3-3 | Adjustments to the model bathymetry and grid in the old model (left) and the new model (right). Grid cells at Neeltje Jans are added and grid cells along the land boundaries are removed

## 3.3.3 The storm surge barrier schematization

By the transferring from WAQUA to Delft3D, the storm surge barrier has got a new schematization. In Delft3D it is modeled as a porous plate only. A porous plate extends as a partly transparent structure into the flow, which exchanges mass and momentum across the plate. A quadratic friction coefficient determines the porosity of the plate (see Figure 3-5).

This porous plate should correspond to the constriction and damping of the flow of the actual barrier pillars.

In the original Delft3D KustZuid model, the inlet channels continue through the storm surge barrier with a continuous depth of around 20 m. This does not correspond to reality, because there is a large bottom protection sloping up towards the barrier and a concrete sill in the barrier that has a maximum depth of 10.5 m in the middle of the Roompot. The barrier has 62 pillars placed on bottom protection with a sill placed on the bottom and beam on top (see Figure 3-4).

![](_page_27_Figure_8.jpeg)

Figure 3-4 | A 3D view of storm surge barrier (left) and a picture of the sill at Roompot 12 (right) (Visser, 1986)

In the new model, the bottom protection and sill of the barrier are included. The exact slope of the scour holes is difficult to reproduce, but an optimum is found between the grid cell size and computational time.

In Table 3-1, the length of the openings of the actual storm surge barrier and model are given. The cross-sectional area is measured up to mean sea level. The new KustZuid model corresponds very well with the actual situation. The original model does not.

![](_page_27_Picture_12.jpeg)

![](_page_27_Picture_13.jpeg)

	Length [m]		Surface [m <sup>2</sup> ]			
	Reality	Original KustZuid	New KustZuid	Reality	Original KustZuid	New KustZuid
Hammen	675	1100	705	4268	13300	4533
Schaar	720	1240	765	4139	14200	4226
Roompot	1400	1760	1421	11991	43290	11849
Total	2795	4100	2891	20400	70790	20607.69

Table 3-1 | Length and surface area of the different inlet channels at the storm surge barrier in reality and models

In Table 3-1, the cross-section including pillars is given below M.S.L. The actual surface area is  $17,900 \text{ m}^2$  instead of  $20,400 \text{ m}^2$ , because the pillars amount to  $2,500 \text{ m}^2$ . This is compensated in the model by implementing a porous plate with a small quadratic friction coefficient, which simulates the actual friction of the pillars and cross-section and reduces the discharges through the openings (see Figure 3-5).

![](_page_28_Figure_5.jpeg)

Figure 3-5 | Storm surge barrier (left) (Google Earth) and schematization of the Roompot with a porous plate

that extends over the whole depth into the flow (right)

The model shows a little difference in discharge of the Roompot and Schaar channels in comparison to the Scaloost model of Rijkswaterstaat. The discharges through the Schaar are a little bit too high and the discharges through the Roompot too low (see Appendix B, Figure 8-1, Figure 8-2 and Figure 8-3). This does not mean that the Delft3D model is incorrect. It does not affect the water levels in the Oosterschelde and has no influence on the comparison between the present en future situations.

There are still imperfections in the Delft3D KustZuid model, which cause an inaccurate modeling of the build-up of the shoals. This will not significantly influence the relative morphological changes that the model will show.

# 3.3.4 The model calibration

The new model is re-calibrated by 5 measurement stations of the HMCZ throughout the Oosterschelde (see Figure 3-6):

- OS11: 15 km offshore of the storm surge barrier;
- OS4: 2 km offshore of the storm surge barrier;
- RPBI: Just inside the storm surge barrier in the Roompot channel;
- STAV: Stavenisse;
- YE: Yerseke.

![](_page_28_Picture_17.jpeg)

![](_page_28_Picture_18.jpeg)

![](_page_29_Figure_2.jpeg)

Figure 3-6 | Measurement stations used for the calibration of the model

During the calibration, the depth of the barrier foundation, the bottom roughness coefficient and the porous plate friction coefficient have been modified.

The best model has a Manning friction coefficient of 0.025  $[m/s^{1/3}]$  in the whole basin, a porous plate with a friction coefficient of 1.5 [-]. Also the horizontal eddy viscosity has been changed. A horizontal eddy viscosity of 1 m<sup>2</sup>/s performed very well. This made no difference with the horizontal large eddy simulation of Delft3D.

The calibration results are shown in Table 3-2. In the first column, the results of the measurement stations are given. In the second column, the results of the original KustZuid model are given and in the last column, results of the new KustZuid model are given. Both models are run for the same period and with the same bathymetry of 2010.

The calibration is carried out with a tidal analysis of the M2, M4, M6, S2, N2 and MS4 components, of which only the M2, M4 and M6 are shown in the table.

The phase does not have to be an exact copy of the original phase, but the phase difference between the M2 and M4 and M2 and other components must match the phase difference of the HMCZ measurement stations.

The result of the calibration is that the M2 amplitudes and all the phases inside the Oosterschelde agree much better with reality. However the phases outside the Oosterschelde and the M4 amplitude has slightly become worse, but this is of minor influence.

A validation of the model by a comparison between the water levels of Yerseke and another HMCZ measurement station (Marollegat) in another month shows the same accuracy (see Appendix A.1).

![](_page_29_Picture_11.jpeg)

![](_page_29_Picture_12.jpeg)

Table 3-2 | Calibration results of the new KustZuid model. Green corresponds best to the HMCZ. The yellow colors indicate the number from the HMCZ. The red and green colors indicate which model is closer to the real amplitudes and phases

	HMCZ	Original KustZuid	New KustZuid Model	
	OS11 (Outside the Oosterschelde)			
Amplitude M2	1.3149	1.317	1.3137	
Amplitude M4	0.1359	0.1271	0.1287	
Amplitude M6	0.0851	0.0719	0.0742	
Phase M2	53.69	47.5	47.15	
Phase M4	116.24	97.62	96.8	
Phase M6	74.57	59.9	59.7	
2φ2-φ4	-8.86	-2.62	-2.5	
M4/M2	0.103353867	0.096507213	0.097967573	
	-	YE (Yerseke	)	
Amplitude M2	1.435	1.4945	1.4463	
Amplitude M4	0.1093	0.0899	0.0785	
Amplitude M6	0.078	0.0832	0.077	
Phase M2	92.18	83	86.59	
Phase M4	212.47	207.5	200.9	
Phase M6	259.15	233	241	
2φ2-φ4	-28.11	-41.5	-27.72	
M4/M2	0.076167247	0.060153898	0.05427643	
		RPBI (Roompot in	nside)	
Amplitude M2	1.1777	1.2305	1.1822	
Amplitude M4	0.0485	0.0304	0.03	
Amplitude M6	0.0309	0.0299	0.0282	
Phase M2	82.9	76	79.35	
Phase M4	152.52	159.22	149.6	
Phase M6	119	101.53	107.42	
2φ2-φ4	13.28	-7.22	9.1	
M4/M2	0.041181965	0.024705404	0.025376417	
		STAV (Stavenis	sse)	
Amplitude M2	1.3439	1.4035	1.3519	
Amplitude M4	0.0756	0.0645	0.0569	
Amplitude M6	0.0325	0.0382	0.0353	
Phase M2	84.66	81.7	84.58	
Phase M4	186.57	198	191.29	
Phase M6	206.13	205	209.19	
2ф2-ф4	-17.25	-34.6	-22.13	
M4/M2	17.77645503	21.75968992	23.75922671	
	OS4 (Middle Inlet)			
Amplitude M2	1.3065	1.3332	1.3144	
Amplitude M4	0.1356	0.127	0.1316	
Amplitude M6	0.0639	0.0486	0.0537	
Phase M2	58.76	57.1	57	
Phase M4	<u>114.63</u>	109.18	108.15	
Phase M6	68.66	72.14	69.37	
2ф2-ф4	2.89	5.02	5.85	
M4/M2	9.634955752	10.4976378	9.987841945	

![](_page_30_Picture_4.jpeg)

![](_page_30_Picture_5.jpeg)

## 3.4 Conclusion

The original Delft3D model was not suitable enough for this research. Therefore the model has been adjusted and recalibrated. All the model adjustments are summarized:

- A higher resolution is implemented around the storm surge barrier and throughout the basin;
- A more realistic schematization of the storm surge barrier has been implemented;
- The bathymetry is updated in the whole domain to 2010;
- A Detailed bottom protection of 2011 is implemented;
- A more realistic schematization of the land boundaries and thus water surface level of the Oosterschelde is implemented;
- A new calibration of the model has been done.

With the adjusted model, different model runs are performed for the present and the future situation. The results of the present and future situation runs will be described in chapter 4.

![](_page_31_Picture_11.jpeg)

![](_page_31_Picture_12.jpeg)

# 4 Results: The present situation of the Oosterschelde

In this section the present situation of the Oosterschelde will be described. First the tidal volume of the present inlet channels is given, followed by the coarse and fine sediment transport through the inlet and inside the Oosterschelde basin.

### 4.1 The tidal volume

Nowadays the Roompot channel is the main discharge channel with a total discharge volume of  $\pm 520 \times 10^6$  m<sup>3</sup> during ebb and flood ( $\pm 1020 \times 10^6$  m<sup>3</sup> in 1 tidal cycle), compared to the Hammen with  $\pm 200 \times 10^6$  m<sup>3</sup> and the Schaar with  $\pm 225 \times 10^6$  m<sup>3</sup>. There are no large differences between the ebb and flood discharges through the channels at present (see Figure 4-1)

![](_page_32_Figure_4.jpeg)

Figure 4-1 | Flood and ebb discharges through the inlet channels from 1965 to 2011

#### 4.2 Sediment transport through the inlet

Measurements show, that there is almost no coarse and fine sediment transport through the barrier (see Section 2.3.2). The main reason is the 'tidal jet' created by the barrier.

The origin of this 'tidal jet' is the basin geometry that has a small entrance compared to the length of the basin. Water flows from all directions towards the inlet during flood and has so much momentum that when it passes the barrier, it cannot spread out fast enough, creating a 'tidal jet' on the landward side (Bosboom & Stive, 2011) (see Figure 4-2)). The reverse process occurs during flood. These ebb and flood 'tidal jets' give, averaged of the tidal cycle, larger ebb than flood velocities at the seaward side of the barrier and larger flood than ebb velocities at the inner side of the barrier. This creates a mean velocity in flood direction at the landward side of the barrier, creating flood dominance. It creates a mean velocity in ebb direction at the seaside of the barrier, creating ebb dominance. This abrupt separation of ebb and flood dominance in the inlet, blocks the sediment transport almost totally.

The 'tidal jet' is visible in the model results (see Figure 4-3).

![](_page_32_Picture_10.jpeg)

![](_page_32_Picture_11.jpeg)

![](_page_33_Figure_1.jpeg)

Figure 4-2 | In and outgoing 'tidal jet' (Bosboom & Stive, 2011)

![](_page_33_Figure_3.jpeg)

![](_page_33_Figure_4.jpeg)

during flood are plotted in black and the red arrows indicate the 'tidal jet' features. The blue colors indicate the

depth

This 'tidal jet' is the main reason, that the barrier blocks the coarse sediment transport through the inlet. The mean total coarse sediment transport in the model and the sediment transport vectors from the method of Van de Kreeke confirm this result (see Figure 4-4). In every inlet channel, at a few points inside and outside the barrier, the depth average velocities are taken and analyzed by the method of Van de Kreeke (see Section 2.3.1 for the method).

At the landward side of the barrier the coarse sediment transport is directed landwards and at the seaward side of the barrier it is directed seawards. At the barrier, there is almost no sediment available, because of the bottom protection and barrier sill, which decreases the sediment transport to almost zero at the barrier.

![](_page_33_Picture_9.jpeg)

![](_page_33_Picture_10.jpeg)

![](_page_34_Figure_1.jpeg)

Figure 4-4 | Mean total transport vectors in black and transport magnitude vectors in purple from Van de

Kreeke

The second aspect that blocks the transport through the barrier, are the scour holes at both sides of the barrier. However, they form only a minor contribution to the sediment blocking. The scour holes at the seaward side of the basin act as a sediment trap during flood and are eroded again during ebb. The same process takes place at the basin side, where sediment is trapped in the erosion hole during ebb and erodes again during flood, which means that no sediment is transported over the sill. Filling up the scour holes will only initiate sediment import if the geometry becomes more flood dominant and if the 'tidal jet' disappears. This also needs to be complemented with a larger bottom protection around the barrier.

Measurements in 1988 showed that sediment transported through the Roompot was mainly transported on the southern side, the outer bend of the Roompot (Jonkers, 1988). This transport is visible in Figure 4-4, where there could be some export at the southern side.

The little net transport that is going through the inlet could be transported inwards in the middle of the Roompot ( $\pm$  50,000-100,000 m<sup>3</sup>/year) and Hammen ( $\pm$  20,000-40,000 m<sup>3</sup>/year) and transported outwards through the Schaar ( $\pm$  12,000-24,000 m<sup>3</sup>/year) (see Figure 4-4).

The coarse sediment transport pattern at the inlet found by Huisman (2009) is confirmed by coarse sediment model runs performed for this research (see Figure 2-6 and Figure 4-5). Only the magnitudes differs with a factor 3 to 5. This difference is caused by the different calibrations of both models, and waves that are not included in the Delft3D model. All the coarse sediment transport is directed away from the barrier. Huisman used a point model instead of Delft3D.

![](_page_34_Picture_8.jpeg)

![](_page_34_Picture_9.jpeg)

![](_page_35_Figure_1.jpeg)

Figure 4-5 | Net coarse sediment transport magnitudes from the model in 1,000 m<sup>3</sup>/year

Fine sediment is also blocked by the barrier (see Figure 4-6 and Figure 4-7). This is also due to the 'tidal jet'. Model runs confirm a little net sediment import of fines if the sum of all three inlet channels is taken (see Figure 4-6 and Figure 4-7).

![](_page_35_Figure_4.jpeg)

Figure 4-6 | Net fine sediment transport through the Hammen and Schaar in 1,000  $m^3$ /year

![](_page_35_Picture_6.jpeg)

![](_page_35_Picture_7.jpeg)


Figure 4-7 | Net fine sediment transport through the Roompot in 1,000 m<sup>3</sup>/year

The coarse and fine sediment transport in the Schaar inlet channel is compared (see Figure 4-8). The coarse sediment follows exactly the 'tidal jet', but fine sediment is also influenced by the mean discharge and flow patterns during flow reversal creating a net discharge direction. The difference between both the fine and coarse mean total transports could be explained by the difference in relaxation time between the coarse and fine fractions. Both the fine and coarse sediment transport is blocked by the inlet.



Figure 4-8 | Mean total sediment transport in de Schaar inlet for fine (left) and coarse sediment (right)

### 4.3 Coarse sediment transport in the Oosterschelde basin

The method of Van de Kreeke is used at different locations in the basin to show, that in the present situation the whole basin is ebb dominant for coarse sediment, except for the small area at the basin side of the barrier due to the 'tidal jet' (see the green area in Figure 4-9). The method of Van de Kreeke is described in Appendix B. All vectors point in seaward direction, which indicates ebb dominance. The numbers in the figure correspond to the dimensionless results of the Van de Kreeke method. This ebb dominance throughout the whole basin follows





logically from the basin geometry that has deep channels and a large intertidal area, which enhances ebb dominance. The main contributors to this ebb dominance are the mean velocity in ebb direction (M0), the M2 and M4 phase difference and the M2, N2 and MS4 phase differences. The mean velocity is a consequence of the stokes drift. The stokes drift results in a water level gradient towards the end of the basin that initiates a return flow (Van Rijn, 2010).

The phase difference between the M2 and M4 components is around 100° in the whole basin and creates a light 'skewed' asymmetry of the tide. This 'skewness' is of minor contribution to the ebb dominance, because 'skewness', has its maximum around 180° and zero around 90° phase difference (see Table 2-1). The phase difference of 100° is close to zero 'skewness' and even close to flood dominance (<90°).



Figure 4-9 | Vectors indicating the sediment transport direction and magnitude throughout the basin

The sediment blocking by the barrier and exporting character of the basin could indicate an accumulation of sediment in front of the basin. However, the sediment concentrations and transport rates are so low, that there is almost no sediment transport towards the barrier (see Figure 4-10). A sedimentation-erosion map over the period from 1983 till 2010 shows that the shoals erode and the channels fill up (see Figure 4-12). There could be some net sedimentation in the front of the basin, but only slightly. The same sedimentation-erosion pattern is found by the model (see Figure 4-11); only the erosion of the shoals is not modeled, because waves are not included.

The sediment concentrations in the Oosterschelde are very low, but there is still sediment transport. When looking at the mean bed shear stress, compared to the Shields criterion for moving bed material, there should be some transport. Delft3D uses the bed form plus the skin shear stress in the calculation of the bed shear stress. This overestimates the real bed shear stress for sediment erosion and therefore a new calculation has been done. The skin shear stress is calculated in the whole domain and is visible in Figure 4-13. This could underestimate the real shear stress a little bit, because turbulence and gravity pull is now underestimated, but it is more realistic than the bed shear stress plotted by Delft3D.

It is clear that there is almost no bed shear stress at the shoals, from which can be concluded that the shoals are primarily eroded by waves.





The shear stress in the channels is between 0 N/m<sup>2</sup> and 0.5 N/m<sup>2</sup>. The critical shear stress calculated by Shields is approximately  $0.11 \text{ N/m}^2$ , which makes sediment transport possible. In Appendix D is described how the bed shear stress and Shields criterion are calculated.



Figure 4-10 | The mean total transport of coarse sediment in front of the basin. The sediment transport vectors are almost zero. Only around the barrier and in the narrowing part on the lower right, there is some sediment transport



Figure 4-11 | The cumulative sedimentation-erosion for a period of 2.5 years in the present situation of the Oosterschelde from the Delft3D model









Oosterschelde for a period of one month in





### 4.4 Fine sediment transport in the Oosterschelde basin

The main drive for the sediment transport of fines is the difference between the falling and rising period of the horizontal tide. This difference has an effect on the difference in concentrations of fines in the water column during ebb and flood and thus on the net sediment transport direction. The phase difference between the M2 and M4 components has a large influence on the rising and falling period. The phase difference between the M2 and M4 tidal component is approximately 100° for the whole Oosterschelde basin, which introduces a longer rising than falling period and corresponds to an export of fines. Furthermore, the transport is influenced by the mean velocities, which are in ebb direction. These two make the whole Oosterschelde basin ebb dominant for fine sediment.

With the Groen (1967) method, the concentrations of fines for a phase difference between the M2 and M4 component of 100° is determined (see Figure 4-14). The Groen method is described in Appendix C. The concentrations during ebb are higher than the concentrations during flood, which creates an export of fine sediment.



Figure 4-14 | Concentration and equilibrium concentration of fines that is representative for the major part of the Oosterschelde for a phase difference between the M2 and M4 components of 100° by the Groen (1967) method. The concentrations during flood are lower, indicating a larger transport of material during ebb than during flood and thus export of fine sediment

The mean seaward velocity has a large effect on the cumulative sediment transport in the Oosterschelde. When the mean velocity is changed from 0 m/s to 0.089 m/s in seaward direction, the cumulative sediment transport is much larger in ebb direction (see Figure 4-15 and Figure 4-16). In large parts of the basin, the mean velocities are in ebb direction, which enhances the export of fine sediment inside the basin. The barrier blocks this transport.







Figure 4-15 | Cumulative sediment transport of fines at a location in the Oosterschelde with a phase difference between the M2 and M4 components of 100° and a mean velocity of 0 m/s. There is some net export



Figure 4-16 | Cumulative sediment transport of fines at a location in the Oosterschelde with a phase difference between the M2 and M4 components of 100° and a mean velocity of -0.089 m/s. The export is much larger than with a mean velocity of 0 m/s

The method of Groen (1967) is also applied to several points inside the basin, which confirm the fine sediment transport simulated by Delft3D (see Figure 4-17). The green arrows show the fine sediment transport directions of Groen (1967). The directions are the same as the Delft3D model run and the concentrations and cumulative sediment transport is in both cases very low. Most of the fine sediment transport is in ebb direction.

It is not known if the large intertidal area, which gives more sedimentation during high water than during low water, contributes to a little net import of fines. This is in any case very limited, as measurements show (see Section 2.3.2).





Figure 4-17 | The mean total fine sediment transport vectors from Delft3D in black combined with the vectors according to the method of Groen (1967). With the extra black arrows, the transport directions of Delft3D are shown. The vectors of the method of Groen correspond very well with Delft3D





### 4.5 Conclusion

The discharge, tidal prism, tidal asymmetry, flow velocities and sediment transport have been analyzed for the present situation of the Oosterschelde.

The tidal prism is about 953 \*  $10^6$  m<sup>3</sup> and there is only a little difference between the ebb and flood discharges through the inlet channels.

The whole Oosterschelde is ebb dominant in the present situation, except for a small area at the basin side of the barrier. This means that coarse and fine sediment transport throughout the basin is directed in ebb direction. However, the sediment concentrations are so low, that there is almost no sediment transport inside the basin. Furthermore, there is no sediment transport possible through the barrier. The barrier blocks a large part of the sediment transport. The main reason is the 'tidal jet' and tidal asymmetry created by the storm surge barrier that form a sediment barrier. Another reason could be found by the large scour holes at both sides of the barrier that form a 'sand trap' for coarse sediment.





# 5 Results: The future situation of the Oosterschelde

In this section, the future situation in comparison with the present situation will be described.

For the future situation a new inlet channel is implemented in the model in the same direction as the old Geul channel through Neeltje Jans (see Figure 2-1). Four different sizes of the new inlet channel are implemented in the model: Geul Extra Small (XS), Geul Small (S), Geul Medium (M) and Geul Large (L) (see Figure 5-1). They correspond to an increase in cross-sectional area of 115%, 150%, 170% and 200%. A larger inlet channel is not realistic, because it is limited by the foundation of the Roompot barrier and Neeltje Jans barrier station and theme park. To get an idea of the limit of the Oosterschelde tidal prism and range, also the whole storm surge barrier and inlet islands are removed in the 'fully open' variant.

In every section a sub question will be answered and the effect on the 'sand demand' will be described.







Figure 5-1 | The model inputs: Present situation, Geul ExtraSmall, Geul Small, Geul Medium, Geul Large and the Oosterschelde 'fully open' with their increase in cross-sectional area compared to the present situation





### 5.1 Hydrodynamic changes of a new inlet channel

In this section the first sub question will be answered.

• What is the effect of a new inlet channel on the hydrodynamics?

This question is divided into the tidal range and the corresponding effect on the emerging time of the shoals, and the tidal prism and the corresponding effect on the flow velocities inside the basin.

### The tidal range

An increase in cross-sectional area of the Oosterschelde inlet will result in an increase of the water levels inside the basin. The tidal range at Yerseke with respect to an increasing cross-sectional area of the inlet by the new inlet channel (Geul XS, S, M and L), is shown in Figure 5-2. The barrier remains the same, only the new inlet channel at Neeltje Jans varies in width. It is visible that a small opening results in a relative larger contribution to the tidal range than a larger opening. The graph shows the historical tidal range in 1960 and the tidal range if the Oosterschelde barrier is 'fully open' when the barrier and all the inlet islands are removed. The Oosterschelde cannot have a larger tidal prism and tidal range then in this 'fully open' situation, because than also the channels inside the Oosterschelde should deepen. This is why this situation is given as the limit. The discrepancy between the historical tidal prism and the 'fully open' situation is the result of the construction of the Philipsdam and Oesterdam. These dams shorten the relative basin length, which increases the reflection of the tidal wave and amplifies the tidal amplitude.





removed. This limit gives a tidal range of 3.9 m with an increase in cross-sectional area of 600%

The tidal range increases throughout the whole basin, but not with the same magnitude. The tidal range increases the most at the end of the basin (see Figure 5-3). At this point, the impoundment by the basin geometry and the reflection of the dams in the back of the basin is the most.

The barrier dampens the tidal amplitude by the high friction of the barrier openings. This can be seen in Figure 5-3 by the decrease in tidal range between RPBU (situated just in front of the barrier) and RPBI (situated just after the barrier). Only if the barrier is completely removed, the damping disappears, as can be seen by the purple line.









channels. The storm surge barrier is situated between RPBU and RPBI. The distances are not to scale!

See Figure 3-6 for the measurement locations

To judge the contribution of the increase in tidal range on the optimization of the 'sand demand', the effect on the different tidal components and the emerging time of the shoals is determined.

The M2 and S2 amplitudes, which mainly determine the total tidal amplitude, increase with about 15%. The M4 amplitude increases inside the basin with almost 100% in case of the large new inlet channel. This increase gives more weight to the M2 and M4 phase difference. Also, the phase difference between the M2 and M4 phase shifts, by a decrease in phase shift of the M2 component (see Figure 5-13). Both phenomena create a more ebb dominant character in the Oosterschelde.

The larger tidal range has no significant influence on the total emerging time of shoals, only on the total area of emerging shoals. The lower shoals have a relatively much longer emerging time, but the emerging time of the higher shoals decreases in comparison to the present situation (see Figure 5-4).







The difference in total emerging time depends on the mean shoal height in the Oosterschelde. The tipping point is at a water level of 0.23 m. The mean water level at Yerseke is 0.044 above M.S.L. The high water levels increase relatively more ( $\pm$ 13%) than the low water levels decrease ( $\pm$ 10%), shifting the mean water level to 0.049 m at Yerseke. This is not a positive effect for the emerging time of the shoals.

#### The tidal prism

The tidal prism of the Oosterschelde increases with an increasing cross-sectional area (see Figure 5-5). The relative increase is the highest with a small increase of the cross-sectional area (Geul XS), as was already seen by the tidal range.



Figure 5-5 | Tidal prism of the Oosterschelde with increasing cross-sectional area of the inlet. The red line represents the historical tidal prism in 1960 and the blue line represents the limit of the tidal prism in the present situation if the barrier and islands are removed





The difference between the historical tidal prism (red line) and the 'fully open' situation (blue line) sterns from the construction of the Philipsdam and Oesterdam whereby the tidal prism decreased.

The increase in tidal prism with a new inlet channel increases the flow velocities through the channels and brings the Oosterschelde closer to the old situation. However, a new inlet channel relieves the flow through the existing inlet channels and decreases their discharge. Water follows the way of less friction through the new opening. An increase of the cross-sectional area of the new opening decreases the discharge through the existing inlet channels (see Figure 5-6).



Figure 5-6 | Decrease in discharge through existing inlets by an increasing cross-sectional area of the new inlet

#### channel

The effect of the decrease in discharge is that not all the flow velocities throughout the basin increase. In case of the 'Geul Large', there are areas that get further away from the equilibrium situation. The flow velocities decrease especially around the Roggenplaat (see Figure 5-7). The dark blue areas experience a decrease in maximum velocity up to 0.4 m/s and the bright red and yellow areas an increase in maximum velocity up to 0.8 m/s. The area where the velocities increase or decrease depends on the connection with the new inlet channel (see section 5.3).







Figure 5-7 | Area's with a decrease and an increase in flow velocities with the 'Geul Large'

The research of Das (2010) showed that shoal building occurs if the tidal flow velocities are as large as before the construction of the storm surge barrier. Flow velocities in the order of 30-40% higher than in the present situation, gave shoal building. The velocities do increase in certain areas with 30-40%, which should bring the basin closer to its equilibrium channel depth and increase the shoal building.

If the flow velocities are compared with the situation 'fully open', which could represent the old situation, it becomes clear that in certain areas they do not differ so much and that they can even become higher with a new inlet channel (see Figure 5-8).



Figure 5-8 | Maximum depth averaged flow velocities in ebb and flood direction in the Present, 'Geul Large' and 'fully open' situation at the measurement location indicated by the red arrow





At the back of the basin, the flow velocities also increase, but they do not come close to the flow velocities of the old situation, represented by the model run where the Oosterschelde is 'fully open' (see Figure 5-9). The main reason are the Oesterdam and Philipsdam.



Figure 5-9 | Maximum depth averaged flow velocities in ebb and flood direction in the Present, 'Geul Large' and 'fully open' situation at the measurement location indicated by the red arrow





To estimate how much closer the Oosterschelde basin comes to its equilibrium, the present situation, the Geul Large and 'fully open' situations are compared to the empirical relations of Louters (1998) and Haring (1967). At different locations in the Oosterschelde, cross-sections of the channels are made for the present and 'fully open' situation (see Figure 5-10).



Figure 5-10 | Cross-sections in the Oosterschelde

The cross-sectional area and 'tidal prism' of the cross-sections has been plotted in Figure 5-11. In the 'fully open' situation, the Oosterschelde comes closer to the equilibrium situation of Louters and Haring, but not all channels do so. The channels at the back of the basin are not closer to the equilibrium, because their discharge is limited by the Philipsdam and Oesterdam. The Geul Large is in between the present and 'fully open' situation and shows that the channels are still far from equilibrium. The cross-sectional area is calculated according to M.S.L.



Figure 5-11 | The empirical relations of Louters and Haring for the equilibrium relation between the tidal prism and cross-sectional area of the channels. Different cross-sections in the Oosterschelde in the present (red dots),





with the Geul Large (green dots) and 'fully open' (black) situations are shown. The 'Open' situation lays closer

#### to the equilibrium situation

All channels in the present situation are far from equilibrium. This does not, according to the empirical relation, make the basin flood dominant and importing. There has been a very large human intervention in the Oosterschelde, which makes it impossible for nature to respond fast to a new equilibrium. The cross-sectional area of the inlet cannot change. According to Dronkers the basin could only be stable if the width and depth are dynamically coupled, which is not the case (Dronkers, 1998). However the tidal asymmetry, especially the M2 and M4 phase difference in the present Oosterschelde is closer to flood dominance than before the interventions.

Nature is creating a more flood dominant basin by decreasing the intertidal area by erosion of the shoals. This would probably lead in the long term to an increase in flow velocities and to an importing basin, just as the empirical relations predict (if there would not be an inlet that blocks the sediment transport). However there would probably not be enough sediment inside the basin to support this internal transition.

The desired equilibrium is one with a large intertidal area and thus enough shoal building. It cannot be predicted with certainty from the model if shoal building would be sufficiently recovered. The model is not sufficient enough to model shoal building. There are no waves included in the model, which form the governing factor for shoal erosion and the model is too coarse to model the building of the shoals (Das, 2010). There is furthermore a lack of sediment data to calibrate the morphology.

From the empirical relations can be seen that even if the Oosterschelde is 'fully open' it is still not in equilibrium. A new inlet channel is further away from the equilibrium than the 'fully open' situation, which means that with a new inlet channel the shoal erosion continues, because nature keeps restoring the equilibrium by shoal erosion. However the rate and timescale on which the shoals erode will be slower and longer than in the present situation, which could be very positive.

An increase of the tidal prism with 20% (Geul Large) brings the channel cross-sections just inside the basin to 85% of the necessary tidal volume, instead of 70% in the present situation, according to the empirical relation of Louters (1998).





### 5.2 Sediment transport in the Oosterschelde by a new inlet channel

In this section the following sub question is answered:

• What is the effect of a new inlet channel on the sediment transport in the Oosterschelde? And will there be sediment import or export?

In the present situation the basin is ebb dominated. The Oosterschelde will become more flood dominant with shallower channels, less intertidal storage area and a larger tidal amplitude. Only the amplitude becomes larger with a new inlet channel.

The new inlet channel is implemented as a very shallow channel (±8-10 m), which should enhance flood dominance according to Dronkers (1998). However the new inlet channel Geul XS is deepened very quickly (see Figure 5-12). The scour hole is 10 m deep after one month and does not continue much further.



Figure 5-12 | The Geul XS channel with the erosion/sedimentation profile after 1 month. The depth averaged

#### velocities during ebb are plotted

The depth of the new inlet channel has no influence on the ebb dominance. The ebb dominance increases in the whole Oosterschelde with a new inlet channel. The largest contribution of this increase is from the mean velocity that becomes higher in seaward direction. The M2 and M4 phase difference becomes larger, which increases the ebb dominance and thus export of coarse sediment (see Figure 5-13). The increase in phase difference between the M2 and M4 components brings the 'sawtooth' asymmetry closer to zero and decreases the export of fine sediment (see Figure 5-13). This is counteracted by the increase of the mean flow velocities in seaward direction.







Figure 5-13 | The change of the M2 and M4 phase difference (φ4-2φ2) with increasing cross-sectional area. The different lines represent different measurement locations in the Oosterschelde, which are representative for the whole basin

This does not mean that there is export of coarse or fine sediment from the basin. All the new inlet channels ('Geul' XS, S, M and L) have a 'tidal jet', which decreases the transport through the new inlet channel to almost zero. In Figure 5-14 and Figure 5-15 the 'Geul ExtraSmall' and 'Geul Large' are shown with the mean sediment transport direction vectors in black and the transport vectors of Van de Kreeke in purple. There is an abrupt separation between the ebb and flood dominant part of the inlet channel created by the 'tidal jet'.



Figure 5-14 | Mean total sediment transport and the sediment transport vectors of Van de Kreeke at the new inlet channel 'Geul XS' show a 'tidal jet' effect







Figure 5-15 | Mean total sediment transport and the sediment transport vectors of Van de Kreeke at the new inlet channel 'Geul Large' show a 'tidal jet' effect

If the Oosterschelde is 'fully open' (barrier and islands removed), the 'tidal jet' disappears and the whole basin becomes ebb dominant (see Figure 5-16). This situation results in an export of coarse sediment of approximately  $2.5 * 10^6 \text{ m}^3$  per year through the whole inlet. This number is uncertain, because of the short term noise of the erosion of the implemented channel.

The sediment transport formula used in Delft3D is the formula of Van Rijn (1993), which is a formula for suspended and bed load transport. Van de Kreeke uses the Bagnold (1966) formula which has a velocity to the power 3.

The mean total transport of fine sediment is also in ebb direction if the Oosterschelde is 'fully open' (see Figure 5-17). There could be an export of approximately  $4 * 10^6$  m<sup>3</sup> per year through the whole inlet if there is enough fine sediment available. This would probably be less in the real situation.







Figure 5-16 | Mean total transport of coarse sediment when the Oosterschelde storm surge barrier and islands are removed. All transport vectors point in ebb direction and generate the export of 2,500,000 m<sup>3</sup> a year



Figure 5-17 | Mean total transport of fine sediment when the Oosterschelde storm surge barrier and island are removed. All transport is directed in ebb direction except for the transport through the Hammen channel





When looking at the net discharges through the inlet channels, they change significantly. The new inlet channel becomes a more flood discharging channel and the Roompot a more ebb discharging channel (see Figure 5-18). This net discharge has almost no influence on the total flood or ebb dominance of the channels.



Figure 5-18 | Net discharge through the inlet channels with an increasing width of the new inlet channel





### 5.3 Influence of the connection with the new inlet channel

In this section will be described what the influence of different connections with the new inlet channel is. An answer will be given to the following sub question:

• How should the connection be made with the present tidal channels?

First, a comparison is made between two connections with the XS channel. One connection is the original Geul XS channel and the other connection is implemented straight, as a parallel side channel of the Roompot (see Figure 5-19).



Figure 5-19 | Two connections of the new inlet channel: one as the Geul XS and the other as a straight side

channel of the Roompot. The flow velocities during ebb are plotted in the figure

From the velocity vectors can be seen, that the straight side channel has a much smoother flow than the Geul XS channel (see Figure 5-19). This smoother flow causes a higher discharge volume through the Roompot side channel in comparison to the Geul XS channel, despite the fact that the cross-sectional area of the channels is exactly the same. The tidal discharge through this channel significantly increases from  $105 * 10^6$  m<sup>3</sup> to  $118 * 10^6$  m<sup>3</sup>, but the discharge through the already existing inlet channels decreases as was already seen in Figure 5-6. This causes the total tidal prism to only increase slightly from  $1,169 * 10^6$  m<sup>3</sup> to  $1,175 * 10^6$  m<sup>3</sup>.

The increase in discharge through the new inlet channel causes an increase in flow velocities and 'tidal jet'. The phase differences between the different tidal components is almost the same in both models.

The connection has a significant effect on the basin areas that have a decrease or increase in flow velocities. A new connection is made between the Roompot and Schaar channel to show this effect (see Figure 5-20).







Figure 5-20 | New inlet channel with a Roompot-Schaar connection with the flow velocities during flood

indicated by the black vectors

In Figure 5-21 and Figure 5-22 the increase and decrease in flow velocities of the Geul XS channel and the Roompot-Schaar connection channel compared to the present situation, are shown. In case of the Roompot-Schaar connection channel, the flow velocities do not decrease around the Roggenplaat, but only in the area just at the basin side of the barrier. This means that a connection, which does not decrease the flow velocities around some of the shoals, is possible.







Figure 5-21 | Increase and decrease in maximum flow velocities during spring tide with the new Geul XS inlet channel. The flow velocities decrease especially around the Roggenplaat



Figure 5-22 | Increase and decrease in maximum flow velocities during spring tide with the new Roompot-

Schaar connection channel. The flow velocities do not decrease around the Roggenplaat

Concluded can be, that different connections have a significant influence on the discharge through the new inlet channel and on the areas inside the basin where flow velocities increase and decrease, but they hardly influence the total tidal prism, the tidal asymmetry and sediment transport.





### 5.4 Filling up of the tidal channels

A structural solution could be found in the filling up the tidal channels, which should enhance flood dominance and increases the flow velocities in the channels, bringing the basin closer to an equilibrium. In this section, filling up of the present situation and 'fully open' situation of the Oosterschelde is explored. In the last scenario the cross-sectional area of the channels is decreased by a filling up of the channels, but the tidal prism is increased by a larger crosssectional area of the inlet.

At first, the present situation is filled up with about  $192 * 10^6$  m<sup>3</sup> of sediment. This amount of sediment is needed to fill up the Roompot channel to 20 m and all the other channel in the basin to a least 15m depth. Most sediment is needed to fill up the large scour holes at the basin side of the barrier and the Schaar van Colijnsplaat. This fill changes almost the whole basin into an importing basin (see Figure 5-25). All mean total transport vectors become directed in flood direction. The main reason is the decrease in mean flow velocities in ebb direction and the tidal asymmetry that changes from a negative to a positive 'skewness'. This is induced by the phase difference between the M2 and M4 components that shifts from  $\pm 100^\circ$  to  $\pm 60^0$ .

The tidal prism and tidal range decrease, but the flow velocities inside the basin increase (see Figure 5-23). The flow velocities increase with about 30% in the first 15 km of the basin.



Figure 5-23 | Increase and decrease in maximum flow velocities with a filling up of the channels with 192 \*  $10^6$  m<sup>3</sup> of sediment compared to the present situation

Another run with a filling up of  $440 * 10^6 \text{ m}^3$  of sediment makes the whole basin importing. All channels are now filled up to at least 10 m depth. This creates even more positive 'skewness' and a mean velocity change in flood direction. However, this flood dominance will not create an importing basin, because the 'tidal jet' will keep blocking the sediment transport through the inlet.

With a fill, the basin is closer to equilibrium, but it is still not in equilibrium (see Figure 5-26). The same cross-sections are used as in 5.1, except for the cross-sections at the end of the basin, which gets away from the equilibrium by a decrease in discharge (see Figure 5-10). With a filling up, the dots do not move vertical, but also horizontal, because filled tidal channels decreases the cross-sectional area, but also the discharge through the channel. This makes the





dots move to the bottom left corner instead of only downwards. In the calculation of Kohsiek is this non linear effect not included.



Figure 5-24 | Filling up the channels in the present situation leads to an import of coarse sediment instead of export



Figure 5-25 | Filling up the channels in the present situation leads to an import of coarse sediment in the whole basin instead of export







Figure 5-26 | Empirical relations of Louters and Haring between the tidal prism and cross-sectional area of the channels of the Oosterschelde (1 to 5 see figure 5-10) compared to model results of the present situation and the the situations fill 1 with a fill of 192 \* 10<sup>6</sup> m<sup>3</sup> and fill 2 with 440 \* 10<sup>6</sup> m<sup>3</sup> of sediment

If the Oosterschelde is 'fully open' and the channels are filled up with about  $600 * 10^6 \text{ m}^3$  of sediment to approximately 10 and 15 m depth, there is still no flood dominance. The tidal prism is decreased in comparison with a 'fully open' Oosterschelde without sediment fill. The mean flow velocity has been increased in flood direction throughout the basin, which logically follows form the shallower channels and les intertidal storage. However the tidal asymmetry is still negatively 'skewed'. An export of coarse sediment is going through the inlet. Furthermore a sort of cell division is visible inside the basin, which could indicate that there is no exchange of sediment between parts of the basin. This fill is not done very accurate, which means that some cross-sections will be too small and others will be too big. This gives a short term exchange of sediment in the basin, which is not representative for the long term morphology. The cell division could be an initial effect of a narrow part of the Oosterschelde.







Figure 5-27 | Filled up tidal channel in the 'fully open' situation with about  $600 * 10^6 \text{ m}^3$  of sediment. There is

still export in the entrance of the basin. The rest of the basin seems to be consisting of sediment cells

The present and future situation with a new inlet channel of the Oosterschelde and the different equilibrium situations are conceptual schematized in Figure 5-28. This hypothetical schematization is not well-founded on findings and facts. However the results from this research speak not against and supply some base for this schematization. On the left, there is the equilibrium situation comparable with the old situation with deep channels and a large intertidal storage area. On the right, there is an equilibrium situations, there could be a lot of other equilibrium situations with among them an 'optimal' equilibrium with shallow and wide channels and a large intertidal storage area.



In the present situation the basin is ebb dominant (below the dotted line). Nature is shifting the present situation slowly to the right equilibrium, by decreasing the intertidal area (erosion of





the shoals), decreasing the ebb dominance and slowly decreasing the tidal prism. A new inlet channel shifts the Oosterschelde at once to a situation with a larger tidal prism and more ebb dominance (see purple star in Figure 5-28). This brings the Oosterschelde closer to the old situation, but the ebb dominance increases.

The oval line delimits the possibilities for the Oosterschelde. The Oosterschelde cannot move parallel or perpendicular to the dotted line, because every change in tidal prism influences the ebb and flood dominance and vice versa. It is not known whether the 'equilibrium situations' are real steady dynamic equilibriums.





### 5.5 Conclusion

For the future situation, different models have been studied. A new channel is implemented in the same direction as the old Geul channel in order to try to create a flood dominated importing channel. The cross-sectional area has been increased four times as the Geul ExtraSmall, Geul Small, Geul Medium and Geul Large channel. Another 'fully open' Oosterschelde model with the whole storm surge barrier and inlet islands removed, is used to show the maximum tidal prism and tidal range in a future situation (with the present bathymetry of the basin).

A new inlet channel increases the tidal amplitude in the Oosterschelde. This enlarges the intertidal area, but does not make the emerging time of shoals longer.

The tidal prism increases by a new inlet channel, increasing the flow velocities inside the basin. It depends on the type of connection with the new channel, what areas experience an increase or decrease in flow velocities, because a new inlet decreases the discharge through the already existing inlets and channels. This increase in flow velocities brings the Oosterschelde closer to the old situation. It is not known how much the shoal building is restored, but in certain areas are the flow velocities so much restored with the Geul Large channel, that shoal building would occur again. From a comparison of the cross-sectional areas of different channels and tidal prisms with the empirical relations of Louters and Haring, can be seen that the equilibrium will not be fully restored and shoal erosion would probably continue, but on a slower rate and longer timescale.

The increase in tidal prism and tidal range increases the ebb dominance of the basin for coarse sediment. The basin stays ebb dominant for fine sediment. However, there is no export from the basin possible, because also the new inlet channels have a 'tidal jet' that blocks the sediment transport. The enhancement of the ebb dominance in the Oosterschelde is caused by the large increase of the M4 amplitude, M2 and M4 phase difference and mean flow velocities in ebb direction.

When the Oosterschelde is 'fully opened', which means that the storm surge barrier and the inlet islands are removed, the damping effect of the barrier on the tidal range disappears and the tidal prism is about  $1,145 * 10^6 \text{ m}^3$ .

The ebb dominance increases by an increase of the mean velocities in ebb direction and phase shift of the M2 and M4 tidal components. This causes an export of coarse and fine sediment towards the ebb tidal delta, which is no longer blocked by the storm surge barrier.

Filling up of the tidal channels decreases the cross-sectional area of the channels, decreasing the discharge, but increases the flow velocities through the channels. It enhances flood dominance. When filling up the tidal channels to at least 20 m depth in the Roompot and 15 m depth in the rest of the basin (total 192 \*  $10^6$  m<sup>3</sup> of sediment), a flood dominated basin can be created. This has however only effect if the barrier is not blocking the sediment import. Filling up the 'fully open' Oosterschelde with about  $600 * 10^6$  m<sup>3</sup> of sediment is not enough to change the basin to a flood dominated basin. The tidal asymmetry is still negatively 'skewed' and sediment is exported through the inlet.





# 6 Conclusion

The history of the Oosterschelde shows that the basin has been exporting sediment for centuries. All the events and interventions, up till the construction of Volkerakdam and Grevelingendam caused an increase in tidal prism and export of sediment towards the ebb tidal delta. With the construction of the storm surge barrier and Philipsdam and Oesterdam in 1986, the situation changed and the tidal prism decreased. The decrease in tidal prism decreased the flow velocities and sediment transport from the channels to the shoals, which caused the degradation of the shoals. The Oosterschelde has a large 'sand demand', needed to restore the flow velocities in the channels and to restore the shoal building.

In this research, the present and future situation of the Oosterschelde are analyzed. For the analysis, a process based numerical model in Delft3D is used. The original Delft3D model of the Oosterschelde, Westerschelde and part of the North Sea has been adjusted and recalibrated to improve the model results for a reliable analysis. The new model has a finer resolution, updated bathymetry, the barrier has been schematized differently, the basin surface area has been adjusted to the land boundaries and the water levels have been recalibrated.

At first, the present situation of the Oosterschelde has been analyzed.

The 'sand demand', as the empirical relations predict, does not make the basin a flood dominated and importing basin. The human interventions made it impossible for nature to adapt fast towards a new equilibrium and towards a flood dominated basin.

The new model and the methods of Van de Kreeke (1993) and Groen (1967) applied to the present situation of the basin, show that the Oosterschelde is still ebb dominant and would be exporting sediment if the inlet would not block the sediment transport. This ebb dominance sterns from the large intertidal area and deep channels. The mean flow velocities are in most parts of the basin in ebb direction. However, it should be noted, that the tidal asymmetry in the present situation is ebb dominant, but close to flood dominance. Notwithstanding the ebb dominance, there is no sediment export possible through the inlet. The inlet blocks the sediment transport in both directions, mainly because of a 'tidal jet', caused by the small inlet and large tidal prism. Another reason are the scour holes at both sides of the barrier that form a 'sand trap'. This situation is positive for the 'sand demand' in the present situation, because sediment export is hindered.

For the future situation a new inlet channel is implemented in the new model. It is implemented in the same direction as the old flood dominated Geul channel, in order to create a flood dominated importing channel. The cross-sectional area of the new channel has been increased in four steps, as the Geul ExtraSmall, Geul Small, Geul Medium and Geul Large channel, to an increase of the cross-sectional area of the present inlet with 200%. Another model with the whole storm surge barrier and inlet islands removed, represents a 'fully open' Oosterschelde. This model is used to show the maximum tidal prism and tidal range with an open inlet and the present bathymetry of the basin.

A new inlet channel causes an increase in tidal prism and following increase in flow velocities, which brings the Oosterschelde closer to its old situation. With a new inlet channel, the flow velocities are in some parts of the basin higher than before the construction of the storm surge barrier. However in most parts, especially in the back of the basin, they do not come close to the old flow velocities. The connection with the new inlet channel has a large influence on the areas where the flow velocities increase and decrease. A new inlet channel decreases the flow velocity through the already existing channels that are not connected to the new channel. The increase in flow velocities optimizes the 'sand demand' if the shoal building in the Oosterschelde is brought back to an acceptable level. To which level the shoal building is restored, cannot be





exactly answered by this research. The empirical relations show that the cross-sectional areas of the channels in the whole basin compared to the tidal prisms are still not in equilibrium with the Geul Large and smaller channels. This means that shoal building is not completely restored and shoal erosion will probably continue with a new inlet channel. However the erosion rate of some shoals will probably be slower and the timescale on which the shoals degrade will be longer.

The methods of Van de Kreeke (1993) and Groen (1967) show that the basin becomes more ebb dominant with a new inlet channel. The reason is the mean flow velocity that increases in ebb direction and the tidal asymmetry that becomes more negatively 'skewed'. This does not make the basin exporting, because the new inlet channel has the same 'tidal jet' as the existing inlet channels, decreasing the sediment transport through the new inlet channel to almost zero. Even the largest inlet channel (Geul Large) has a 'tidal jet'.

Another effect of a new inlet channel is the increase in tidal range, which creates a larger intertidal area, but does not increase the total emerging time of the shoals.

When fully removing the storm surge barrier and inlet islands, the old situation is partly restored to an exporting basin, but the channels are still not in equilibrium according to the empirical relations of Louters and Haring. Shoal erosion will probably continue and approximately  $2,5 * 10^6$  m<sup>3</sup> of coarse and  $4 * 10^6$  m<sup>3</sup> of fine sediment will be exported each year.

Somewhere in between the 'old' situation with deep channels and a large intertidal area, and the equilibrium nature is now going to with a small intertidal area and shallow channels, could be another equilibrium situation, which combines a large intertidal area with shallow channels. This equilibrium could probably be reached if a new inlet channel is constructed in combination with artificially filling up the channels with sediment. Artificially filling up the channels can increase the flow velocities and bring the basin closer to an equilibrium. Model results show that an amount of approximately  $192 * 10^6 \text{ m}^3$  of sediment is enough to create a flood dominant basin in the present situation. The flow velocities are in the order of 30% higher in the first 15 km inside the basin. This could also be done in the 'fully open' situation. A filling up of the tidal channels in the 'fully open' situation with about 600 \*  $10^6 \text{ m}^3$  of sediment to approximately 10 m depth, did not make the basin flood dominant. The mean velocity increased in flood direction, but the tidal asymmetry was still negatively 'skewed'. It is plausible that in an 'fully open' situation the intertidal area must decrease in order to create flood dominance and import of sediment.

The results of this study show that the large-scale effects of the Oosterschelde, like the ebb dominance and 'sand demand' cannot be structurally changed with a new inlet channel. The 'sand demand' and degradation of the shoals can probably be slowed down by a new inlet channel, but this introduces a new dike safety issue and high costs. The tidal prism in the Oosterschelde will probably never be completely restored to the old situation if the compartmentalization dams and storm surge barrier are not totally removed. Shoal erosion will continue, which means that or nourishments will still be necessary in order to maintain the shoals or the shoals will slowly disappear.





# 7 Recommendations

Further research into more options that may form a structural solution to optimize the 'sand demand' should focus on the more drastic measures instead of making small adjustments to the concrete storm surge barrier that increases the flow just slightly.

An issue tree with structural solutions as already shown in section 1.2 is given in Figure 7-1. Adjustments to the barrier, land abutments or rubble mount dams are of too minor influence to the flow, to be successful. A full closure of the basin will stop the little shoal building that is still present and erosion of the shoals by local generated waves will continue. Compartmentalization of the channels is very costly and erosion of the shoals will also continue.



Figure 7-1 | Issue tree with the structural solutions for the 'sand demand' that are still open for research

As a result of this report, there are two options recommended for further research.

A new inlet channel increases the tidal prism, which could be positive for the shoal building. For a more detailed answer, if a new inlet channel would be a solution, more research is needed into the shoals building process and the flow velocities needed for this process. Furthermore, a detailed analysis of the safety and costs should be done. However, the new inlet channel should probably be complemented with a partly filling up of the tidal channels to create an equilibrium for the shoals. Without this filling up of some of the channels, nourishments for some shoals will probably always be necessary.

If a decision is made to construct a new inlet channel, research should be done into the different connections possible, because the connection has a significant influence on the discharge through the new inlet channel and on the areas inside the basin where flow velocities increase and decrease.

Another option could be found in fully opening the storm surge barrier. By doing this, the basin will start exporting sediment and it is not sure whether the shoal building will be restored. This means that this measure should be complemented with partly filling up of the channels, which should create a flood dominated basin that imports sediment. However, before the Oosterschelde is made an importing basin, a profound research should be done into the





availability of sediment at the ebb tidal delta and in the near part of the North Sea. If no sediment is available, the flood dominance does not create import of sediment.

For a more detailed study into this subject, the model could be further optimized by the following improvements:

- A more detailed grid could be used that could simulate shoal building in more detail;
- Waves could be included in the model;
- Storms can be simulated;
- A more detailed calibration and validation could be performed by measuring the horizontal tide and sediment concentrations at different locations.




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## Appendix A Model accuracy

The original model has been refined, the grid has been adjusted and the barrier schematization has changed. The original grid did not correspond with the enclosure file, which made it impossible to do grid adjustments. By creating a new grid and by re-imposing the boundary conditions this problem has been solved. Furthermore the grid cells have a new alignment with the land boundaries and dikes, creating a more realistic water surface area.

The accuracy is influenced by the time step. The time step of the model is set to 1 minute. This gives a Courant–Friedrichs–Lewy (CFL) criterion of:

$$CFL = \frac{\sqrt{gH} * t}{\Delta x * \Delta y} = \frac{\sqrt{9,81 * 25} * 60}{40 * 65} = 0.36$$
(8)

The CFL condition must be smaller than 1-10, which is not a problem (Deltares, 2011).

In Figure 8-1, Figure 8-2 and Figure 8-3 the model is compared with the Scaloost model of Rijkswaterstaat.











Figure 8-2 | Comparison of the Delft3D and WAQUA model instantaneous discharge of the Roompot



Figure 8-3 | Comparison of the Delft3D and WAQUA model instantaneous discharge of the Schaar



#### A.1 Validation of the new KustZuid model

Table 8-1 | Validation results of the new KustZuid model

	HMCZ Maart 2011	Kustzuid Maart 2011	
	MRG (N	/arollegat)	
Amplitude M2	1.4536	1.4778	
Amplitude M4	0.0929	0.0717	
Amplitude M6	0.0767	0.0783	
Phase M2	96.75	89.83	
Phase M4	232.33	210.93	
Phase M6	273.15	246.28	
2ф2-ф4	-38.83	-31.27	
M4/M2			
S2	0.4673	0.4829	
Phase S2	163.11	157.04	
N2	0.3424	0.3228	
N2 phase	68.7	62.74	
MS4	0.0879	0.0681	
MS4 phase	287.71	281.87	
	YE (Y	YE (Yerseke)	
Amplitude M2	1.4027	1.4309	
Amplitude M4	0.0886	0.0731	
Amplitude M6	0.0584	0.0611	
Phase M2	94.05	87.29	
Phase M4	220.79	203.44	
Phase M6	265.85	236.23	
2ф2-ф4	-32.69	-28.86	
M4/M2	0.063163898	0.051086729	
S2	0.4493	0.4669	
Phase S2	159.95	154.08	
N2	0.3307	0.3126	
N2 phase	66.1	60.2	
MS4	0.0845	0.0664	
MS4 phase	278.54	275.89	



## Appendix B The method of Van de Kreeke and Robaczewska (1993)

The method of Van de Kreeke and Robaczewska (1993) is used to assess the order of magnitude and direction of the coarse sediment transport in the Oosterschelde. They assume that the tidally averaged bed load transport sterns from the combination of the M2 tidal component and one of its overtides.

Van de Kreeke and Robaczewska use the velocity time series to determine the M2, M4, M6, S2, N2, K1 and MS4 phases and amplitudes. These are put into the their terms (see Figure 8-4). A time series of 31 days is used in this research to determine all the tidal components correctly.  $\beta$  stands for the phase difference between the M2 and M4 component and is described as:  $\varphi_{m4} - 2\varphi_{m2}$ .

For different locations in the Oosterschelde a summation of terms 1 till 8 is made. Term 4 till 8 are not neglected, because they had a significant contribution. The other terms (9 – 13) did not have a significant contribution and are neglected.

	Expression for dimensionless load transport.	tidally averaged bed-		
Term 1	$\frac{\langle q \rangle}{\iota^3 f} = \frac{3}{2} \varepsilon_0$	M <sub>0</sub> , M <sub>2</sub>		
Term 2	+ $\frac{3}{4}\epsilon_4 \cos\beta$	M <sub>4</sub> , M <sub>2</sub>		
Term 3	+ $\frac{3}{2} \epsilon_4 \epsilon_6 \cos (\beta - \gamma)$	M <sub>4</sub> , M <sub>6</sub> , M <sub>2</sub>		
Term 4	+ $\frac{3}{2} \epsilon_4 \epsilon_2 \cos (\Delta \sigma_1 t + \beta - \alpha_1)$	S <sub>2</sub> , M <sub>4</sub> , M <sub>2</sub>		
Term 5	+ 3 $\varepsilon_2 \varepsilon_0 \cos (\Delta \sigma_1 t - \alpha_1)$	S <sub>2</sub> , M <sub>0</sub> , M <sub>2</sub>		
Term 6	+ $\frac{3}{2} \epsilon_4 \epsilon_3 \cos (\Delta \sigma_2 t + \beta - \alpha_2)$	N <sub>2</sub> , M <sub>4</sub> , M <sub>2</sub>		
Term 7	+ 3 $\varepsilon_3 \varepsilon_0 \cos (\Delta \sigma_2 t - \alpha_2)$	$N_2, M_0, M_2$		
Term 8	+ $\frac{3}{4} \epsilon_5 \cos (\Delta \sigma_3 t - \beta_2)$	$MS_4$ , $M_2$		
	+ $\frac{3}{2}$ $\varepsilon_5 \varepsilon_6 \cos (\Delta \sigma_3 t + \gamma - \beta_2)$	MS <sub>4</sub> , M <sub>6</sub> , M <sub>2</sub>		
	+ $\frac{3}{2} \epsilon_5 \epsilon_2 \cos (\Delta \sigma_3 t + \alpha_1 - \beta_2)$	MS <sub>4</sub> , S <sub>2</sub> , M <sub>2</sub>		
	+ $\frac{3}{2} \varepsilon_5 \varepsilon_3 \cos (\Delta \sigma_3 t + \alpha_2 - \beta_2)$	MS <sub>4</sub> , N <sub>2</sub> , M <sub>2</sub>		
	+ $\frac{3}{4} \epsilon_7^2 \cos 2(\Delta \sigma_4 t - \delta)$	K <sub>1</sub> , M <sub>2</sub>		
	+ $0(\varepsilon^3)$			
	for $u/\hat{u} = \varepsilon_0 + \cos \sigma t + \varepsilon_4 \cos (2 \sigma t)$	$t - \beta ) + \varepsilon_6 \cos \left( 3  \sigma  t - \gamma \right)$		
	+ $\varepsilon_2 \cos (\sigma_1 t - \alpha_1) + \varepsilon_3 \cos (\sigma_2 t - \alpha_2)$			
	+ $\varepsilon_5 \cos (\sigma_3 t - \beta_2) + \varepsilon_7 \cos (\sigma_4 t - \delta)$			
	with $\sigma_1 - \sigma = \Delta \sigma_1$			
	$\sigma_2 = \Delta \sigma_2$ $\sigma_3 - 2\sigma = \Delta \sigma_3$			
Figure 8-4   A	$2\sigma_4 - \sigma = \Delta \sigma_4$ Il dimensionless hed load transpor	t terms (Van der Kroobe 1002)		
iguic 0-T   A	n annensionness deu ioau it allspol	i cermo (van der Mieeke, 1993)		





## Appendix C The Groen method (1967)

The Groen (1967) expression describes a method to determine the transport of fines (Groen, 1967):

$$\frac{\delta N}{\delta t} = \alpha (N_e - N) \tag{9}$$

Where N<sub>e</sub> [kg/m<sup>3</sup>] is the equilibrium sediment concentration expressed as:  $N_e = A(u^2 + v^2)$ , C [kg/m<sup>3</sup>] the instantaneous sediment concentration,  $\alpha$  [-s] is the settling lag time vector.

To solve this expression, the following numerical solution is solved with a matlab script:

$$C^{n+1} = \frac{\frac{C^n}{\Delta t} + \frac{Ce^{n+1}}{\alpha}}{\frac{1}{\Delta t} + \frac{1}{\alpha}}$$
(10)

For the calculation of Ne, the M0, M2, M4 and M6 tidal velocity components are used. This implicit scheme is first order accurate. This does not mean that the scheme is not accurate, because the calculation time step is very small.





## Appendix D Roughness calculation

The bed shear stress gives an indication of the amount of sediment erosion and mobility. Delft3D calculates the bed shear stress over the whole domain. This bed shear stress is determined from a combination of two kinds of roughness: the grain roughness height plus the bed form roughness height. This overestimates the real bed shear stress to compare with the shields criterion for coarse sediment in the Oosterschelde.

In this appendix the difference between the bed shear stress from Delft3D and the 'real' bed shear stress is determined.

At first the chezy roughness value is calculated with the following formula:

$$C = 18\log\left(\frac{12h}{k_s}\right) \tag{11}$$

Where  $k_s$  is k' (the grain roughness height) + k''(the bedform roughness height) Delft3D has as input a Manning roughness value, which can be transformed in a Chezy value with:

$$C = \frac{H^{1/6}}{n} \tag{12}$$

The Manning value of 0.025 [-] used in Delft3D corresponds with:

$$\frac{10^{1/6}}{0.025} tot \frac{20^{1/6}}{0.025} = 58 tot 66 Chezy roughness[\frac{m^{\frac{1}{2}}}{s}]$$

For flat beds (only the grain roughness height), the  $k_s$  can be estimated with (Lambkin, 2012):

$$k_s = 2.5 * D_{50} \tag{13}$$

This gives a Chezy roughness of about 100  $m^{1/2}/s$ , which is larger (smoother bottom) than the value used in Delft3D.

The bed shear stress induced by currents can be calculated with (Deltares, 2011):

$$\tau_{c,b} = \frac{g\rho_0 * u|u|}{C^2} \tag{14}$$

Formula (13) is used to calculate the bed shear stress in the whole domain.

The Shields parameter is 0.035 for a diameter of 2\*10<sup>-4</sup> (Van Rijn, 1993):

$$\Psi_c = \frac{\tau_c}{(\rho_s - \rho_w)gd} = 0.035$$
(15)

With g the acceleration of gravity,  $\rho_0$  the reference density of water, u the flow velocity and C the chezy roughness coefficient. This gives a critical shear stress ( $\tau_c$ ) of ±0.112 N/m<sup>2</sup>.





# Appendix ETidal constituents

The following tidal constituents contribute the most to the astronomical tide:

- M<sub>2</sub> Principal lunar semidiurnal constituent (speed: 28.984 degrees per mean solar hour)
- S<sub>2</sub> Principal solar semidiurnal constituent (speed: 30.000 degrees per mean solar hour)
- N<sub>2</sub> Larger Lunar elliptic semidiurnal constituent (speed: 28.440 degrees per mean solar hour)
- K<sub>1</sub> Luni-solar declinational diurnal constituent (speed: 15.041 degrees per mean solar hour)
- O1 Lunar declinational diurnal constituent (speed: 13.943 degrees per mean solar hour)
- $M_4$  First overtide of  $M_2$  constituent (speed: 2 x  $M_2$  speed)
- $M_6$  Second overtide of  $M_2$  constituent (speed: 3 x  $M_2$  speed)
- $S_4$  First overtide of  $S_2$  constituent (speed:  $2 \ x \ S_2$  speed)
- $MS_4$  A compound tide of  $M_2$  and  $S_2$  (speed:  $M_2$  +  $S_2$  speed)

Source: Virginia Institute of Marine Science 2012, http://web.vims.edu/physical/research/TCTutorial/tideanalysis.htm



