Sea level rise in the Oosterschelde estuary:

A study of the long-term morphological development of a model of the Oosterschelde with accelerated sea level rise if the storm surge barrier is removed

MASTER THESIS

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Preface

This M.Sc. thesis is written as final part of my master in Coastal Engineering at Delft University of Technology. In this report, a study is done to the morphological development of the Oosterschelde estuary with the hypothetical interventions of removing the Storm Surge Barrier (SSB) and applying 2 metre Sea Level Rise (SLR) over a period of 50 years.

During the process of graduating I learned a lot about the functioning of estuaries and especially the Oosterschelde. The scientific way of looking to it broadened my knowledge and gave me more understanding about the fact that current scientific research stands on the shoulders of giants. However, more and more I realise that studying nature is not only a mathematic formula, but that it is wonder too. I wish that knowledge especially to stay with me for the rest of my life.

From this place, I want to thank my graduation committee for the supervision they gave me during this process. From them I learned what it is like to be a scientist: always look further to see how results do have a logical explanation. I learned to be critical all the time, at myself, the model input and the results.

Furthermore I want to thank the people which supported me during this process. Both colleagues, friends and family supported me during this tense period. You remembered me to take a break and you taught me that it is not possible to be always productive. I realise that having you around me is not something to be taken for granted. Therefore, above all I want to thank God that He gave me all I needed, not only during this research process, but during all years of study.

Niels-Jan Wisse, September 2022

Abstract

The Oosterschelde has been an area of morphological change for centuries. Both floodings and human influences have caused the Oosterschelde to have its current shape. During the last century before implementation of the Delta plan (1953) the estuary was still expanding as the channels deepened and the tidal flats increased. With the construction of the Delta works the tidal range decreased with 12 % whereas the tidal prism reduced with 31 %. As a consequence of this reduced tidal motion, the tide is not able anymore to counteract the erosion of the tidal flats which is caused by waves/wind. Therefore, the surface area and the height of the tidal flats reduces ('Zandhonger'). This decrease of tidal area is an undesirable situation as the unique tidal nature of the Oosterschelde provides a lot of functions for both economy (oysters, mussels), ecology and recreation. Furthermore, the Oosterschelde is used as a transport route by cargo vessels.

This research studies the morphological development of a model of the Oosterschelde with two hypothetical interventions: removal of the storm surge barrier (SSB) and applying 2 metre sea level rise (SLR) in 50 years. This is done with four model scenarios: a run with SSB in place, without SLR (1), a run without SSB, without SLR (2), a run without SSB, with SLR (3) and a run with SSB, with SLR (4). This last run was used as sensitivity run in order to see which hypothetical interventions has more impact.

The model results led to conclusions which parts of the model are represented well and which parts of the model need to be improved. The results made clear that current model is promising as the tidal range was modelled correctly for the majority of the Oosterschelde. Also the model represented the tidal prism well compared to the calculated tidal prism (tidal prism = tidal range * wet surface area of the basin – the sediment volume of the tidal flats). It was found too that SLR can be modelled in a correct way by forcing a water level at the boundaries of the model.

It was found that wave activity is an important process with respect to the development of the tidal flats. Therefore, the frequency of the wave computations should be chosen in such way that reliable wave heights are present for each water level during the tidal cycle at all locations in the Oosterschelde. Another key factor which should be improved is the availability of sediment in the model as this determines the (desired) growth of the tidal flats with SLR. Processes/indicators which give information about this availability (ebb/flood dominance, sediment characteristics) can give insight in the development of the tidal flats. With improvement of modelling these two processes it may be possible to improve model capabilities.

Content

1. Introduction

1.1. Research background

The Oosterschelde is an estuary in the province of Zeeland and has an area of 351 km^2. Part of this area consists of intertidal area (104 km^2 in 2001) (Van Zanten & Adriaanse, 2008). Between this intertidal area, channels find their way. The Oosterschelde is one of the last parts of the delta of the Netherlands where tides are present. Other bays are closed off with a dam in order to protect the land against high waters during storm surges. Between the Oosterschelde and the open sea a storm surge barrier (SSB) was constructed in 1986 which protects the coasts of the Oosterschelde from high water levels during storms when it is closed. For such a storm surge barrier was chosen because the tide created valuable nature and made it possible to preserve shell fishery. Besides this shell fisheries many other things are at stake in the Oosterschelde. The tidal flats are valuable for flora and fauna, and the channels are used by the shipping industry to navigate from Gent to Rotterdam. Furthermore, many recreational activities like circular tours and recreational diving take place in the Oosterschelde. Because of this unique ecosystem, the Oosterschelde area is dedicated as Natura2000 area.

With the construction of the SSB the tidal motion was guaranteed in the Oosterschelde. The barrier, however, did cause a change in the tidal influence in the Oosterschelde. One of the current problems is that the tidal flats are eroding due to waves whereas the sedimentation on the tidal flats due to the tides has disappeared ('Zandhonger'). This causes the intertidal flats to fade away slowly (Van Zanten & Adriaanse, 2008). Ongoing worldwide processes as sea level rise can speed up this loss of unique area.

Sea level rise may have influence at another aspect of the Oosterschelde too. The SSB was constructed in 1986 and is designed to close when water levels above NAP + 3.0 metre occur. With sea level rise, it is expected that the SSB will be closed more often. With a sea level rise of 0.6 metre, the barrier will be closed 10 times a year. When the sea level rises further, to 1.25 metre, the SSB will be closed a 100 times a year (Zandvoort M., Zee E. van der, Vuik, V. (2019)). At each closure, vulnerable nature experiences damage. Furthermore, the SSB is designed for a SLR of only 0.4 meter (Rijkswaterstaat, 1985). In combination with the fact that the construction of the SSB caused 'Zandhonger' it may be wondered whether it is desirable to have this intensified closure regime. Furthermore, it must be realised that the level of sea level rise is unknown. Maybe even larger values than 1.25 metre are possible when accelerating factors (melting icecaps) are present. In that case, it may be possible that the SSB cannot fulfil its function anymore. Therefore, it is needed to think about the future of the Oosterschelde when the SSB is not functional anymore.

1.2. Future scenarios

When the SSB is not functional anymore, society has to rethink the safety of the living areas around the Oosterschelde. Furthermore, preservation of valuable nature and other ecosystem services has to be addressed in this process. There are roughly three options to chose from:

- Closing off the Oosterschelde;
- Adjusting the SSB;
- Removal of the SSB (starting point of this research).

Consequences of these options for costs, nature, water safety, transport, economics and morphology are described in short below.

1.2.1. Closing off the Oosterschelde

The first option is to close the Oosterschelde with a dam as is done in other tidal inlets in the area. This can be done by dredging sediment from offshore and put it in the mouth of the Oosterschelde just before or behind the SSB. It is possible to remove the SSB than, but this is not required. Although this seems a relatively simple option, it may be a challenge to close off the scour holes which are present as a consequence of the SSB. With a closure of the SSB first, the high flow velocities in these holes could be reduced in order to ease this process. Regarding the length of the first sea defence nothing changes. Where in the old situation the SSB was responsible for the water safety during storm surges, a dam will fulfil this function in the new situation. The function of the dikes alongshore of the Oosterschelde will become smaller because the new design water level in the Oosterschelde will be lower than the water level which occurs when the SSB closed (NAP + 3 metre). It is expected that a closure dam is a relative cheap option because it does not require expensive investments either in knowledge or in time. Because this option is a simple option, this option can be chosen in an urgent situation and/or when there is low budget available.

It is expected that transport will not be affected because road transport can use the road over the SSB which is still present or a new road over the new dam. Transport over water can proceed too by using the new created lake. Transport from the Oosterschelde to the North Sea can be proceeded by constructing a sluice as is present in the current situation too. As described the water safety along the Oosterschelde will increase. The consequences for morphology will be that the current dynamic bed of the Oosterschelde does not change anymore because the tide is not present anymore. This situation is similar with the situation in the Grevelingen lake. This means that the current tidal nature will disappear due to ongoing erosion. Tidal flats which are not victimized by this process will become islands due to the lack of tidal influence. Together with the Grevelingen lake, the Oosterschelde will become a freshwater lake when it is closed off. Although the Grevelingen lake has valuable nature, the tidal influence in the Oosterschelde creates its own values. Several plants and animals use the tidal flats. Furthermore, the economic valuable shell fishing will disappear when the tidal influence is removed from the Oosterschelde (Staatsbosbeheer). Hence, closing off the Oosterschelde comes at enormous ecological, economical and societal costs.

1.2.2. Adjusting the SSB

Another option is to adjust the SSB in order to anticipate to the changing boundary conditions. When the current SSB is adjusted, an increase in retaining height will be the main adjustment. Another option is to remove the current SSB and place a new one which is fit for future. Both the costs for adjusting and replacing the SSB will be high due to investment costs in new designs. Also high costs in time are expected. It is likely that this option might be chosen when the unique characteristics of the Oosterschelde should be retained while removal of the SSB with strengthening the dikes alongshore the Oosterschelde is not possible.

It is likely that adjustment of the SSB will not influence the cross sectional flow area. For this reason, influence at the morphology or tidal nature is not expected either. While the water safety can increase by this decision, nature needs extra investments in order to maintain the intertidal area as a consequence of the sand demand described above. Examples of these mitigation measures are described in literature (Bruijn, 2012; Van Zanten & Adriaanse, 2008). When this fails, nature and valuable economic activities like shell fishing will still vanish. Consequences for transport are not foreseen because the current transport connections will not be affected.

1.2.3. Removing the SSB

The last option is to remove the SSB. This means that the water safety at the shores of the Oosterschelde should be achieved by increasing the dikes. The costs of the adjustment of 194 km dikes will be high. Costs of the removal of the SSB will be high as well. It is investigated that the net present value for this removal is negative for different levels of sea level rise (Leeuwdrent, 2012). Although this emphasizes that removal is not profitable, it is not a reason to set this option aside. Arguments in favour of this are that it may be good for nature to remove the SSB, it may be possible to use parts of the SSB again for other projects by which the NPV increases. Moreover, taking care of nature does not mean to make something profitable, but to clean up objects from nature when they are not functional anymore. Therefore, this option may be chosen when nature is affected positive by the removal and/or when man wants to remove objects from nature which are not functional anymore.

This option will have several consequences It is expected that a new road connection must be made to replace the current road connection N57 between Noord-Beveland and Schouwen-Duiveland. The transport connection over water can be influenced too, depending on the morphological development of the Oosterschelde. This morphology of the Oosterschelde is expected to change to the same trends as before implementation of the Delta Plan. In the current situation, the SSB blocks sediment transport between the sea and the Oosterschelde. Furthermore, the SSB acts as an energy dissipator in the Oosterschelde. When the SSB is removed this will cause major changes. As is investigated, removal of the SSB will cause increase of intertidal area (Pater, 2012). This is positive for economic activities like shell fishing. The mentioned research, however, did not consider sea level rise. It is uncertain what the effect of sea level rise will be.

1.3. Research goal

Although the three described scenarios are still hypothetical situations, the time is now to investigate how the system will develop and what the consequences are of the different options. This research takes the last option (removal of the SSB) as a starting point and investigates what the morphological consequences are especially when extreme SLR is present. Therefore, the goal of this research can be stated as follows: Evaluating the modelling of the morphological development of the Oosterschelde when the SSB is removed and SLR is considered. In this way this research will contribute to the process of decision-making by providing the consequences of certain policy.

1.4. Starting points

Besides the principle of removing the SSB, this research uses a limited number of other principles. These principles will function as boundary conditions during the further process.

1.4.1. Sea level rise

In 2021 the IPCC concluded in their report that sea level will continually rise. In the most optimistic scenario (SSP1), the sea level will be 50 cm higher in 2100 than the sea level in 1900. They also concluded that this sea level rise can accelerate after 2100 to a level of 3.3 metre in 2300 in a negative scenario. This event can be reduced by implementing sustainability measures. However, it is crystal clear that in the future the sea level will rise (IPCC, 2021).

In this research, predictions will be made what will be the response of the Oosterschelde estuary to sea level rise. Therefore, it is necessary to define sea level rise quantitively. In literature about climate change, different scenarios are defined to agree in terminology, the so-called Shared Socio-economic Pathways. These SSP's define the emissions of greenhouse gasses and the related consequences for nature such as temperature rise and sea level rise. Each of these SSP's is a possible future. Which SSP will be reality is dependent on choices made by policymakers. Therefore, it is hardly possible to choose a most likely scenario.

The KNMI has published a translation of the earlier mentioned IPCC-report with consequences for the Netherlands. With respect to sea level rise, a summary is given in Table 1. Based on this data, different values could be chosen in order to estimate the magnitude of the SLR. However, as this research wants to see effects of SLR, it is decided to choose an high value of SLR of 40 mm/year. This is equal to 2 metre over 50 years. Based on Table 1, this seems an unrealistic value as it exceeds the most extrem scenario (SSP5-8.5). However, as mentioned by (Pycroft, Abrell & Ciscar, 2015) the desintegration of ice sheets can cause extreme SLR especially because ice-sheet melting (and hence SLR) may well be an accelerating process, rather than a linear process. Therefore, a rise in sea level of 2 metre in 2070 with respect to the present sea level is a scenario to take into consideration. A linear approach of 40 mm/year is a first estimate in order to describe what the consequences of this amount of SLR will be for the Oosterschelde basin.

Jaar	2050	2050	2050	2100	2100	2100
Uitstoot-scenario	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Zeespiegelstijging in cm	14-38 cm	15-41 cm	16-47 cm	30-81 cm	39-94 cm	54-121 cm
Stijgsnelheid in mm/jaar	2,8-8,7 mm/jaar	5,2-10,6 mm/jaar	5,8-12,1 mm/jaar	2,9-9,1 mm/jaar	4,4-10,5 mm/jaar	7,2-16,9 mm/jaar

Indicatieve zeespiegelscenario's voor de Nederlandse kust onder verschillende emissiescenario's, rond 2050 (2046-2055) en rond 2100 (2096-2105), ten opzichte van 1995-2014, met zeer waarschijnlijke bandbreedte (90%). Hierbij is de bodemdaling inbegrepen. De definitieve KNMI'23-zeespiegelscenario's kunnen hiervan afwijken, omdat voor KNMI'23 een bredere groep CMIP6-modellen beschikbaar zal zijn.

Erratum: Deze digitale tabel 4 verschilt in details met tabel 4 in de gedrukte versie. Deze digitale tabel is de geldende versie.

Table 1: Consequences of SSP scenarios for the mean sea level for the Netherlands (KNMI, 2021)

1.4.2. Area of the Oosterschelde

When the SSB is removed, the dikes around the Oosterschelde will be primary water defences both during calm conditions as during normative storm conditions. It is likely that these dikes must be strengthened. It is however unknown to what dimensions the dikes must be reinforced. For now, it is assumed that it is possible to strengthen the dikes. A consequence of this assumption is that the area of the Oosterschelde will remain constant.

1.4.3. Area of the inlet

Besides the area of the Oosterschelde, the area of the inlet must be defined. This area has changed due to the construction of the SSB. The tidal flats Neeltje Jans and Roggeplaat have become islands by heightening them. Furthermore, dikes are constructed to withstand the water and land is created to construct the connection to the SSB. In this research, it is assumed that these islands keep their current shape. This is done because other functions (recreation, windmills) have been created after the construction of the SSB.

Although the islands in the inlet will remain, the SSB will be removed in this research. This means that the pylons as well as the sill including the bed protection will be removed. As a consequence, the bed of the inlet will become erodible again. The bridge between Noord-Beveland and Schouwen-Duiveland is not considered in this case because the influence of the pylons at the cross sectional area is small. Moreover, the Zeelandbrug, another bridge in the Oosterschelde, is not present in current models either (Deltares, 2009).

2. Research questions

With the goal in mind, the following research question is formulated:

Research question: *As a result of sea level rise, the SSB in the Oosterschelde will not be functional for future normative conditions and might be removed. To what extent is it possible to simulate long-term morphological development of the Oosterschelde with a process-based model?*

Although this research question does not specify the timescale, it is expected that changes will start rapidly after removal of the SSB. This research does not focus on an equilibrium situation but investigates how the system will develop in the first 50 years after the intervention removal of the SSB. For the study of the impact of SLR, a timescale of 50 years is used too. A process-based model is used (Delft3d) in order to investigate the physical processes behind the model results. The formulated research question is divided into the following sub questions:

Sub question 1: *How has the Oosterschelde developed and what does it look like today (morphology, interests and ecosystem services)?*

In this sub question an overview is given of the development of the Oosterschelde over the last centuries in order to get familiar with the Oosterschelde system. The result will be a thorough literature review with an overview of the development of the Oosterschelde. This result is necessary as input for sub question 2 because that question starts with the current morphology of the Oosterschelde.

Sub question 2: *To what extent is it possible to model the long-term morphological development of the Oosterschelde during calm conditions when the SSB has been removed and SLR is present?*

This sub question will focus on the future of the Oosterschelde. Three model runs will be made to answer this sub question. First, a model of the current situation will be made to validate input parameters. Next, a model will be made without the SSB to look which consequences this has for the estuary. The next step is to add sea level rise to this second model in order to see the development over several decades.

This development will be studied by capturing a moment in time every 10 years after the intervention. At every measuring point hydrodynamic as well morphodynamic indicators are analysed in order to measure the development of the Oosterschelde. These Indicators are further elaborated in Chapter 4. The anticipated development of the Oosterschelde will be used to reflect on the different functions of the Oosterschelde which where studied in the first sub question.

3. Historical development and current ecosystem services

In order to answer the first sub question, a literature review is caried out to research the development of the Oosterschelde and the current state of the Oosterschelde. This sub question states:

Sub question 1: *How has the Oosterschelde developed and what does it look like today (morphology, interests and ecosystem services)?*

This research focusses on how the Oosterschelde developed from main branch of the Scheldt river to an estuary with shoals and channels. Furthermore, with the knowledge gathered, a prediction is made what the consequences are of the interventions which are studied in this research.

3.1. Historical development

For a long time the Oosterschelde was the main branch of the river Schelde. This river flows from northern France, through Belgium and south-western Holland to the North Sea. During the Middle Ages, a new inlet developed and connected to the Schelde river. This inlet which is called Westerschelde scoured more and more and became the main branch of the river. The Oosterschelde thus lost its riverine influence. Two tidal watersheds at Sloe and Kreekrak connected the Oosterschelde and the Westerschelde. In that time, the basin area varied. The basin became smaller due to land reclamations (salt marshes and islands) by local inhabitants. When a large flood occurred, the basin area increased as the land reclamations were inundated again. Extreme events in this period were the St. Felixflood in 1530 and the All-Saints flood in 1532 when the eastern part of Zuid-Beveland was flooded. Especially these floods initiate a process of basin development which resulted in the situation as it is present to this day.

The inundation resulted in an increase in the intertidal area (Figure 1). This caused the tidal prism to increase with at least 50 %. Moreover, more intertidal area means an increase in ebb-dominance (ebb phase lasts shorter than flood phase and as a result, ebb currents are more intense). Both phenomena caused that the basin started to export sediment from the channels. This became especially visible at the mouth of the basin. The scouring process caused the shores of Schouwen Duiveland and Noord-Beveland to erode. As a result of this erosion, the channels of Hammen and Roompot raised (Louters, 1998).

Figure 1: Intertidal area created by two large inundations in 1530 and 1532 in the Eastern part of the Oosterschelde (Topotijdreis.nl)

The increased ebb-dominance caused a waterflow through the tidal watershed between the Oosterschelde and the Grevelingen. As a consequence, the tidal watershed was pushed to the Grevelingen. This also means that the tidal surface area of the Oosterschelde increased into the Volkerak which caused an increase in tidal prism. A consequence of an increase in tidal prism is erosion.

This erosion took place in the Zijpe (see Figure 4 for the location). An increase in tidal prism means that the water volume which flows in and out the estuary during one tidal period increases. The increase in tidal prism and the more or less constant tidal period causes the flow velocities to increase, which causes sediment transport.

As is described above, an increase of tidal influence means erosion of the channels. However, the shoals and marshes are subject to accretion. This can be explained by the fact that the flow velocity is lower at higher grounds. At these locations, eroded sediment from the channels will settle. In this way the shoals are formed.

The ebb-tidal delta is affected too by the changes in the Oosterschelde. As the channels in the Oosterschelde, the channels in this ebb-tidal delta suffered erosion by the increased tidal influence in the estuary. The sediment which eroded from the bay (Zijpe and mouth) caused the ebb tidal delta to grow in seaward direction. This growth became visible when a shoal connected to Schouwen-Duiveland was intersected by new ebb-channels which transported sediment seawards (Berg, 1986; Eelkema, 2013). Until 1867 the Oosterschelde had two connections with the Westerschelde (Sloe and Kreekrak) Over time, both connections silted up. In 1867, Kreekrak was closed off with the Kreekrakdam. The Sloe connection was closed off in 1871 with a railway embankment (Bok, 2001). Since 1850 the Oosterschelde has its current shape. The reason for this fixation is found in the construction of dikes to protect the living area. As of 1850, the Oosterschelde estuary had a surface area of roughly 430 km^2. (Haring, 1978).

During the 20th century the Oosterschelde was used more and more as a location for sand mining. This caused an increase of tidal volume between 1870 and 1960 of roughly 15 % which caused further deepening of the channels as well (Kohsiek, Mulder, Louters, & Berben, 1987). Another major consequence was the development of a third channel in the mouth of the Oosterschelde. This channel, called Schaar van de Roggenplaat, connects Hammen with Roompot. This development is a sign that

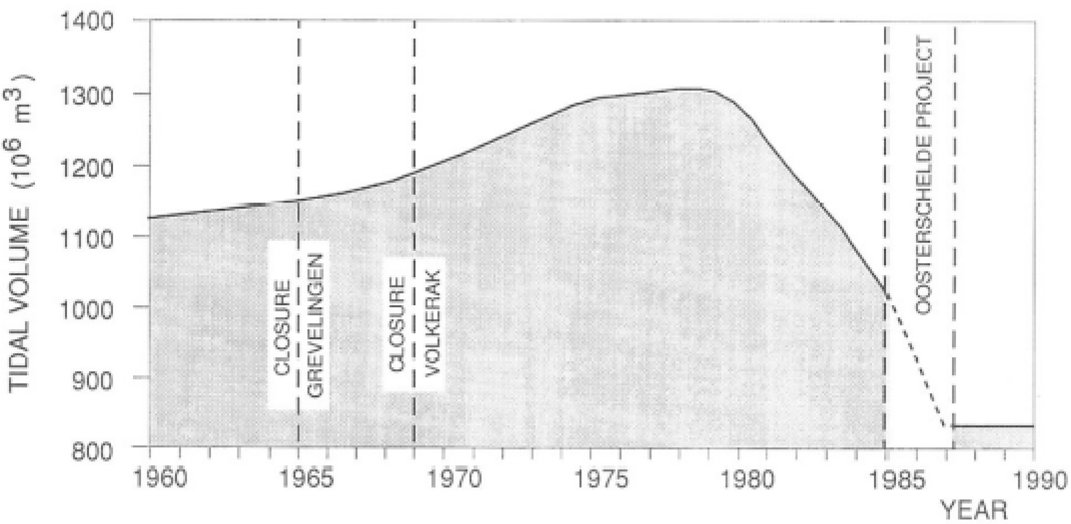


Figure 2: Development of the tidal prism of the Oosterschelde over the years and impact of the Delta plan on the tidal prism (Vroon, 1994)

the Oosterschelde estuary had not achieved a morphological equilibrium in 1950. Other indications for this theorem are the growing tidal volume (or tidal prism) (Figure 2) and the deepening (scour) of the channels (Eelkema, 2013).

3.2. The delta plan

A major storm surge in 1953 caused people to intervene in the Oosterschelde once again. With the Delta Plan the goal was set to close off all the tidal bays to protect the surrounding land against flooding (Figure 4). In the plan, the Nieuwe Waterweg and the Westerschelde were excluded because these were important transport connections to the ports of Rotterdam and Antwerp respectively.

3.2.1. Influences of the delta plan on the development of the Oosterschelde

Because the size of the Delta Plan project was enormous, it was decided to work from small to large. Therefore, the Veerse Gatdam and the Zandkreekdam were constructed first. With these dams the closure of the lake Veere was realised. This closure did not have major impact on the morphology of the Oosterschelde although the tidal prism decreased with 5 % (Berg, 1986). An explanation might be that the location of the closed area was too close to the mouth to impact the rest of the basin.

The next works which were constructed were the Grevelingendam (1965) and the Volkerakdam (1969). Both dams are located in the north of the system. The Grevelingendam was located at the tidal divide between the Grevelingen and the Volkerak. Therefore, it can be said that its influence was relatively small (M. Eelkema, Wang, & Stive, 2012). However, there were noticeable consequences in the system as the dam created a lee zone at the Oosterschelde side which caused an increase in tidal area (Figure 3). Amplification of the tide caused the tidal range to grow with 8 % (Louters, 1998). Furthermore, the tidal prism in the mouth of the Oosterschelde increased from 1,130 million m^3 in 1959 to 1,180 million m^3 in 1968 (Vroon, 1994).

Figure 3: Intertidal area at the south side of the Grevelingen dam (Google Maps)

The closure of the Volkerakdam in 1969 cut the Oosterschelde off from freshwater input from the rivers Rhine and Meuse. Furthermore, the Volkerakdam caused significant changes is the tide. Due to amplification of the tidal wave, the tidal discharge in the Oosterschelde mouth increased with 7 %. In the Northern branch this was up to 60 %. The mean tidal range increased with 2 % in the mouth and 22 % in the Northern branch. This amplification and subsequent increase in tidal quantities caused the Keeten channel to scour (Figure 4). The scoured sediment was deposited at the closed ends of the Zandkreek, Volkerak and Kreekrak. Later on, the dredged areas in the central part of the Oosterschelde were filled with scoured sediment. (Berg, 1986). It was estimated that 40 million m^3 was eroded between 1960 and 1989 due to natural processes against 80 million m^3 due to sand mining in the same period (Louters, 1998).

The consequences of the SSB are studied in Section 3.2.2. At the landward end of the Oosterschelde two dams, the Oesterdam and the Philipsdam, were constructed. Their function is to compensate for the reduced tidal motion caused by the SSB. Because the cross sectional area of the mouth was reduced, less water could flow into the Oosterschelde, and the tidal range reduced. Since this threatened the tidal flats and shell fishing, it was decided to reduce the basin length of the Oosterschelde and thus maintain the tides. Construction of these dams caused the tidal range to decrease only with 13 %. Without these dams, the reduction was 25 %. The tidal prism reduced with 31 % due to the delta works. The back barrier dams contribute for 5 % in this decrease, the SSB for the other 25 % (Mulder, 1994; Vroon, 1994).

The Philipsdam and the Oesterdam where constructed with sand nourishments. However, closure of the last 100 metre was difficult as the tides caused continuous water movement in the gap. This caused the nourished sand to wash away. In order to solve this problem, completion of the dams was postponed until the SSB was finished. With a finished SSB, some gates were closed in order to finish the Philipsdam and the Oesterdam. This caused a reduction in tidal range of 35 % with respect to the original value.

Simultaneously the reduction of the tidal range influenced the salt marshes. Salt marshes are characterized as higher parts of the tidal zone, overgrown with plants. They are dissected by a network of creeks which are bordered by levees. The development of these salt marshes is highly influenced by the action of tides and waves. The character of the salt marsh is dependent on salinity, flooding frequency and flooding duration. The growth of a salt marsh depends on tidal range, surface elevation (gentle slope) and tidal phase. Furthermore, sediment must be available in the water column to let the salt marsh grow. Finally, a small amount of wave energy is needed to make sure that erosion does not take place (De Jong, De Jong, & Mulder, 1994).

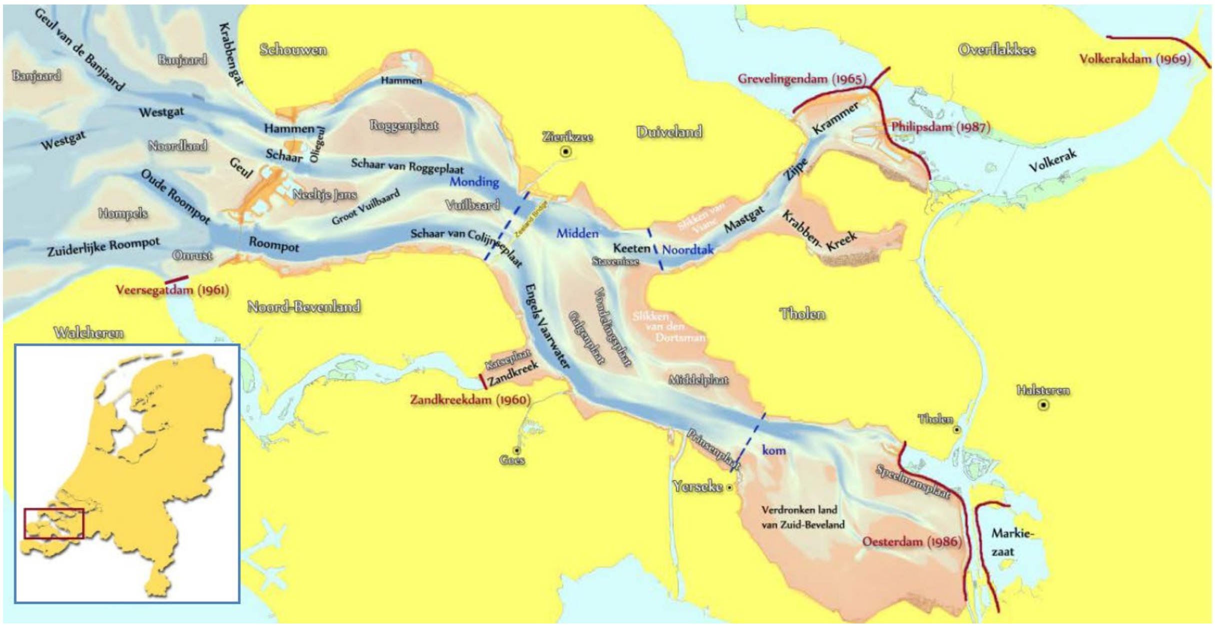


Figure 4: Overview of the Oosterschelde with its tidal flats and salt marshes. The Delta works are indicated by red lines. For the different dams a construction year is given too. Only the SSB is not present in this figure.

Due to a temporal reduction of the tidal range with 35 %, the soil of the salt marshes acidified and ripened. This strong decrease in tidal range caused the wave energy to attack at a lower place of the salt marsh. Because these locations have steeper slopes, erosion accelerated. Moreover, plants on the salt marshes died of a lack of salt water. It was concluded that these processes would occur sooner or later as a result of the tidal range reduction to 88 % of the original values. However, the temporal extra reduction quickened the process of salt marsh degradation. For the long-term a slowdown in salt marsh accretion due to the reduced tidal range and the reduced sediment availability in the channels (52 %-70 %) was expected. It later turned out that this prediction did not match reality.

3.2.2. The SSB and the Oosterschelde development

In the first versions of the delta plan a definitive closure of the Oosterschelde was planned. However, the closure of the Oosterschelde gave rise to many protests by fishermen and nature conservationists. With the closure, the bay, with valuable intertidal nature and valuable fishing grounds, would change to a saltwater lake. This would be disastrous for the nature and fishing grounds. Therefore, it was decided that a storm surge barrier should be built instead. With a SSB, the Oosterschelde area was protected against flooding while the tidal influence remained.

The first step was the construction of three working islands. These working islands were constructed on existing tidal flats Noordland, Neeltje Jans, and Roggenplaat. Two of them, Noordland and Neeltje Jans were connected. What remained where three openings in the inlet: Roompot, Schaar and Hammen (Figure 5). The construction of the working islands reduced the cross sectional area of the inlet from 88.000 m^2 to 73.000 m^2. This reduction caused scour and increased flow velocities in the remaining channels. Next, the construction of the SSB was executed. The remaining openings were prepared to prevent scouring. On the prepared seabed, concrete pillars were placed. Between these concrete pillars sluice gates of 42 metre each are placed. When the water level rises due to a storm (more than NAP + 3 metre) the gates are lowered on a sill which closes off the Oosterschelde. In this way, the saltwater marine life behind the dam is preserved and fishing can continue during calm conditions,

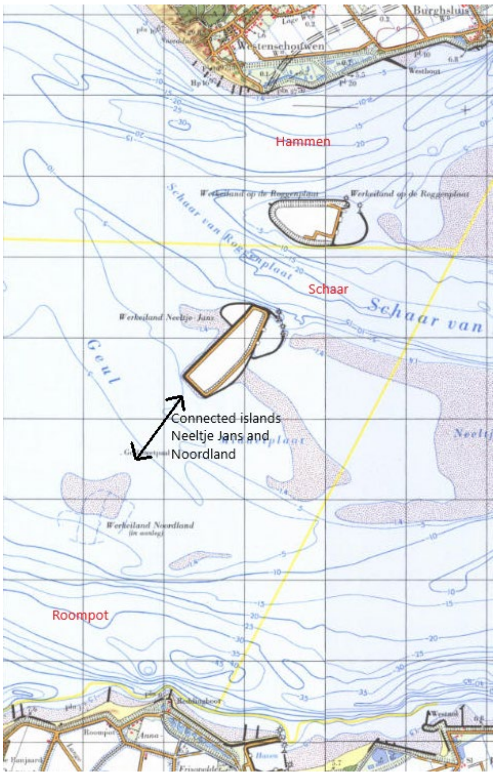


Figure 5: Construction of the working islands which were needed for construction of the SSB (Topotijdreis.nl)

while the land behind the dam is safe during storm surges. Although the Oosterschelde is open in normal conditions, the SSB does influence the hydrodynamic and morphodynamic situation in the Oosterschelde. The placement of the pillars and sill reduced the cross-sectional area from 73.000 m^2 to 17.900 m^2. At the start of the construction, the reduction in the cross-sectional area did not have much influence on the hydraulic parameters because the smaller cross-sectional area was compensated by increased flow velocities in the mouth. Later on, when the cross-sectional area came under a certain threshold of 35.000 m^2 the reduction became noticeable. This value turned out to be critical as turbulence began to cause significant outflow losses. This resulted in a reduction of tidal constituents (Vroon, 1994).

The decrease in cross sectional area caused a decrease in tidal influence. As mentioned, the tidal range and the tidal prism decreased. This led to a decrease in current velocities in the channels. As it will be described in Section 0, this caused erosion of the tidal flats. Furthermore, the reduced tidal range caused plants on the salt marshes to die which consequently led to erosion. To reach a new equilibrium situation, the system began to adapt to a new situation. A reduction in cross sectional area of an inlet means that the channels in the estuary are too large. For the Oosterschelde it was calculated that the amount of sediment which is needed to reach a new equilibrium situation is equal to 400-600 million m^3 (Mulder, 1994). However, the construction of the SSB blocked sediment transport. Therefore, it was (is) not possible to import sediment in the system.

3.2.3. Influence of the delta works on the ebb tidal delta

This blockage of sediment transport between the Oosterschelde and its ebb tidal delta was one of the consequences of the delta works for the ebb tidal delta. Ebb tidal deltas are defined as areas in sea between the open sea and estuaries or lagunes. They develop under the influence of in- and outflow of tidal flows in the estuary and waves from offshore.

The construction of several dams in the back of the Oosterschelde (Grevelingendam, Volkerakdam) increased the tidal prism of the Oosterschelde and caused a rise of sediment export from the Oosterschelde to its ebb tidal between 1969 and 1986 (M. Eelkema et al., 2012). The construction of the working islands in the Oosterschelde caused sedimentation in the lee areas of this islands and scouring in the remaining channels Roompot, Hammen and Schaar. This was caused by the increased flow velocities. When the construction of the SSB was finished, the exchange of sediment towards the Oosterschelde was severely diminished. This had two major consequences. First, the channels of the ebb-tidal delta started to diminish. Because the SSB blocks sediment transport, the tidal flats eroded to fill up the channels. The other result was that the ebb-tidal delta itself became smaller. The lack of sediment supply from the Oosterschelde resulted in erosion of the ebb-tidal delta at the seaward side (Eelkema, Wang, Hibma, & Stive, 2013). Besides sedimentation of the channels, a small rotation of the channels of the ebb-tidal delta in clockwise direction has occurred over time. This can be explained by the change in relative strength of the alongshore and cross shore tidal currents. Due to the SSB the cross shore current decreased in strength. This gives the longshore current more importance (Aarninkhof & Kessel, 1999).

3.3. Empirical relations

In the Sections 3.1 and 3.2 the relation between different hydraulic and morphodynamic parameters is pointed out. In this section an overview of these relations is given to enable making predictions about the reaction of the system when one of the parameters changes.

The first trend which can be distinguished, is the relation between the tidal parameters of an estuary and its size. This relation is seen in the results of the inundation in 1530. The flood caused an increase in tidal prism [P] which caused sediment export and channel creation at the inlet. The cross-sectional size of a channel [A_c] is related tot the total amount of water flowing through it per tide, also known as the tidal prism [P]:

$$\mathrm{A_c} = a * \mathrm{P} + b \quad [\frac{m^3}{tide}]$$

Equation 1 (Louters, 1998)

For the Oosterschelde, it was derived that the coefficients a and b are 12,200 m and $2 \cdot 10^6$ m^3 respectively (Berg, 1986). This relation can be written in another form where Q is the peak tidal discharge:

$$A_c = 1.17 * Q$$

Equation 2 (Berg, 1986)

As mentioned, the behaviour in an estuary is noticeable on the ebb-tidal delta. In the past it was observed that erosion of the estuary led to scour of the ebb tidal delta channels and expansion of the ebb-tidal delta sediment volume. In formula:

$$V_d = a * P^{\beta}$$

Equation 3 (Louters, 1998)

In this formula, the sediment volume of the ebb-tidal delta [V_d] is coupled to the tidal prism [P] of the basin. For the coefficient ß often a value of 1.23 is used. With this formula not only the expansion of the ebb-tidal delta is explained during the last centuries, the size reduction of the ebb-tidal delta as a consequence of the construction of the SSB is explained too as the tidal prism in the estuary decreased.

Another empirical relation which was found relates the channel volume [$V_{channel}$] in an estuary to the tidal prism:

$$V_{channel} = C_v * P^{1.5}$$

Equation 4 (Bosboom & Stive, 2015)

The constant C_v is an empirical coefficient which is $73 \cdot 10^{-6}$ to $80 \cdot 10^{-6}$ $m^{-1.5}$ for the Oosterschelde. With this formula, it can be explained that a decrease in tidal prism caused by the delta works resulted in a reduction of channel volume, which is visible as sedimentation in the channels. Usually the sediment for filling the channels is imported from the ebb-tidal delta. However, because the SSB blocks the sediment transport, the only place where sediment can come from, are the tidal flats. This causes an ongoing process of erosion. The fact that the tidal flats are the only source of sediment is not the only cause for erosion. It is known that tidal movements build up tidal flats by transporting sediment from the channels to higher grounds. Wave attacks counteract this process by transporting sediment from the flats to the channels. Before the construction of the delta works, these processes were nearly in equilibrium (slow increasing trend in area of tidal flats). With the reduced tide however, the accruing trend is diminished whereas the eroding trend stayed at the same level. This causes erosion of the tidal flats as well and is called 'Zandhonger'. In 1987 it was predicted that the channels needed 400-600 million m^3 to stop this process (Kohsiek et al., 1987). Later calculations adjusted this numbers by stating that the Oosterschelde needed 300 million m^3 at that moment (Catalan, 1999). However, the tidal flats consist of only 160 million m^3 of sediment (Hesselink, Maldegem, Male, & Schouwenaar, 2003).

Predictions show that most tidal flats will disappear over time. Yet, at some locations a trend of sedimentation of the tidal flats is observed (Figure 11)(Van Zanten & Adriaanse, 2008).

Per definition, the tidal prism can be coupled to the tidal range. For short estuaries with negligible river discharge as the Oosterschelde the tidal prism is roughly equal to the product of the tidal range (TR) and the surface area of the estuary (A_b):

$$P = TR * A_b$$

Equation 5 (Bosboom & Stive, 2015)

This equation is a geometrical equation as it states that the tidal prism is that the volume between MLW and MHW (tidal range) which has to be filled each tidal cycle. However, in an estuary with tidal flats the sediment volume between MLW and MHW should be subtracted from this value because the locations between MLW and MHW, which are filled with sediment, cannot be filled with water. The (modified) equation states then:

$$P = TR * A_b - V_{sed,tidal\ flats}$$

Equation 6

3.4. Current state of the Oosterschelde

3.4.1. Tidal range

Like the rest of the Dutch coast, the Oosterschelde has a semi diurnal tide. Depending on the location in the Oosterschelde the tidal range differs (Figure 6). The average tidal range for different locations in the Oosterschelde is given in Table 2. These values are determined by averaging the high and low water values of 14 days (one spring neap cycle). For reference, the tides just outside of the Oosterschelde at Roompot Buiten are given. It is observed that the SSB damps the tide (difference between Roompot buiten and Roompot binnen) but that the tides further in the Oosterschelde are higher than at sea. This is caused by the reflection of the tidal wave. Extremes in the tides at spring tides are given in Table 2 between brackets (Rijkswaterstaat, 1994). With an averaged water depth of 15 m, the wavelength of the tide is 540 km. Because the length of the Oosterschelde is 40 km the ratio between the length and the wavelength is around 0.05 (40/540=0.07) the Oosterschelde can be described as a short basin. However, due to decelerating characteristics as the SSB and tidal flats, a phase lag is present (Figure 6).

Location	High tide [cm above NAP]	Low tide [cm above NAP]
Roompot Buiten	155 (186)	-133 (-143)
Roompot Binnen	133 (152)	-121 (-123)
Stavenisse	158 (180)	-139 (-142)
Krammersluizen West	163 (184)	-145 (-151)
Marollegat (Bergse Diepsluis West)	186 (214)	-160 (-165)

Table 2: Tides in the Oosterschelde

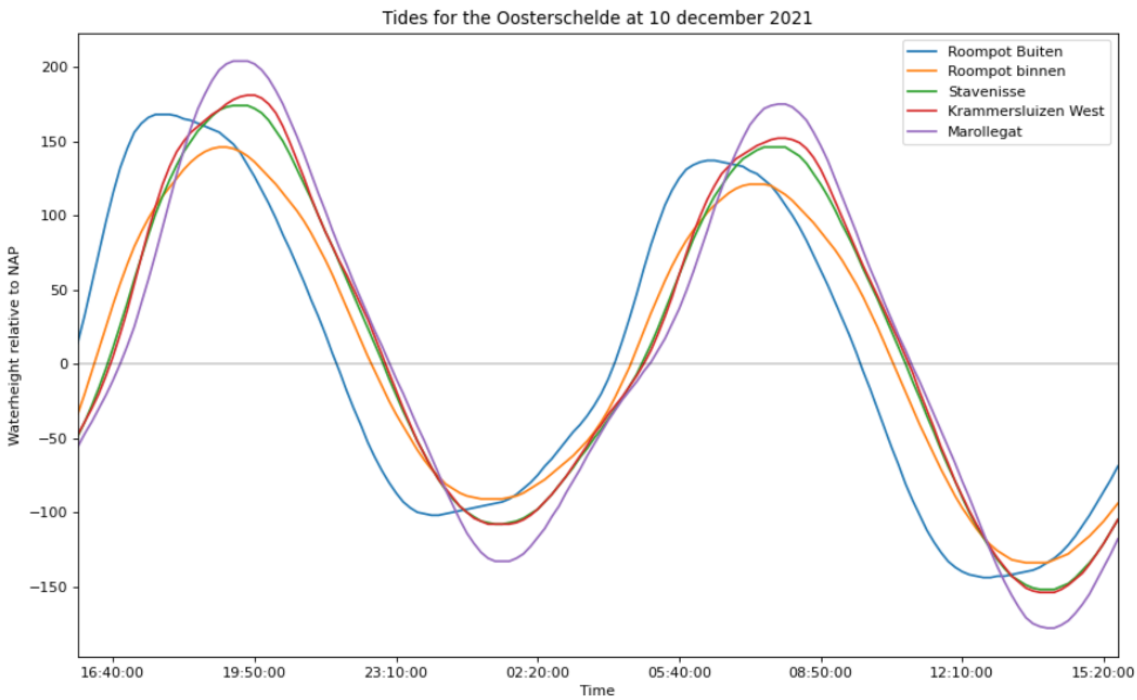


Figure 6: Tides in the Oosterschelde

3.4.2. Tidal prism

Another informative indicator is the tidal prism. This indicator is defined as the volume of water that has to flow in and out through the inlet during one tidal cycle (Bosboom & Stive, 2015). Based on literature, this tidal prism is equal to 880 million m^3 (Hesselink et al., 2003). Measurement data confirm these data although some larger values are present too (Table 3). These measurements are done during so called 13-hours measurements. During these periods, a ship with measurement devices (Acoustic Doppler Current Profiler) sails back and forth over a track. By measuring the flow velocities and flow directions the tidal prism is collected. Over the years the decrease in tidal prism is visible. This decrease is caused by the decrease in channel volume, as the eroded sediment from the tidal flats is deposited in the channels.

Year	1968	1988	1995	1999
Tidal prism [million m^3]	11.80	9.88	9.39	8.41

Table 3: Tidal prism (Rijkswaterstaat, 1999)

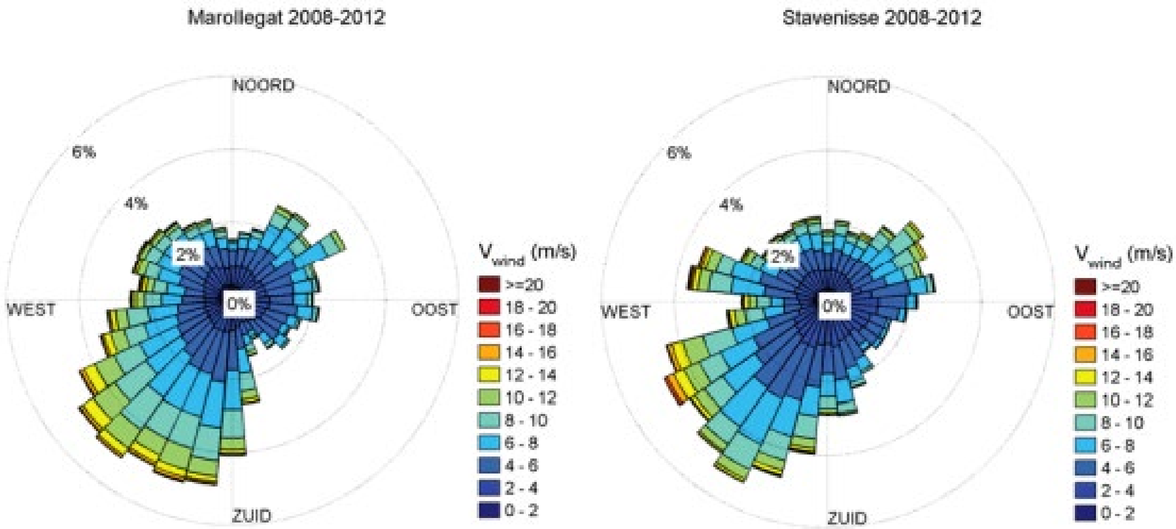


Figure 7: Wind roses for two locations in the Oosterschelde. See Figure 8 for locations (van der Werf, Reinders, van Rooijen, Holzhauer, & Ysebaert, 2015)

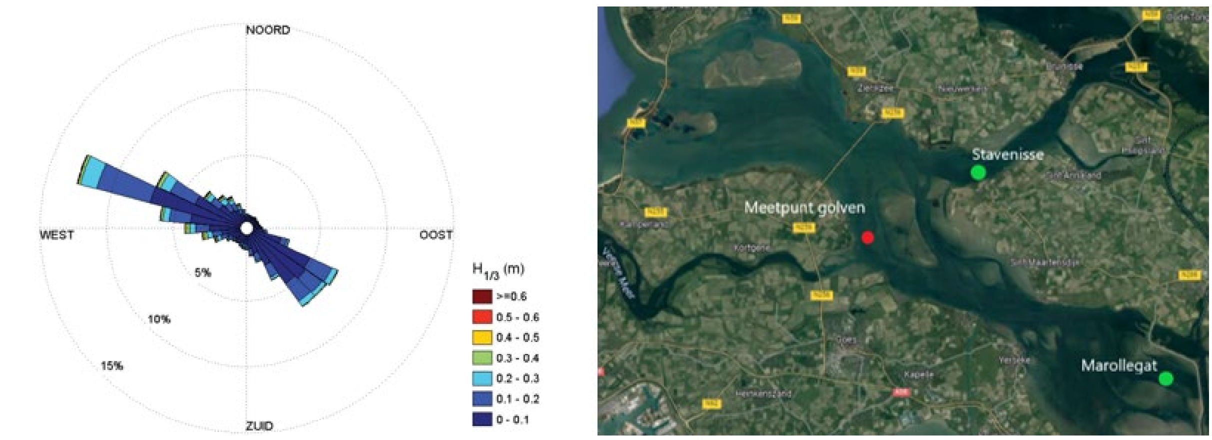


Figure 8: Wave rose Oosterschelde (left)(Van der Werf, Reinders, & Van Rooijen, 2013) and locations of wind and wave measurements

3.4.3. Wind and waves

The waves in the Oosterschelde are predominantly wind waves and locally generated. Almost no waves travel from the North Sea to the Oosterschelde because they are dampened by the ebb tidal delta and the SSB. In Figure 7 two wind roses are given for two locations in the Oosterschelde (Stavenisse and Marollegat) at the centre and at the east end of the Oosterschelde. The predominant wind direction is Southwest. However, there are peaks from Northeast and Northwest present. On average, the wind speed is 6 m/s at the landward end of the Oosterschelde. At the mouth, the wind speeds reach 8 m/s on average (van der Werf, Reinders, van Rooijen, Holzhauer, & Ysebaert, 2015).

As waves are mainly locally generated by wind, local characteristics, such as fetch and refraction by shoals, have a large influence on the heights and directions of waves. This is supported by the fact that wave directions do not follow occurring wind directions. In Figure 8 a wave rose is given for Engelsche Vaarwater. At this location, a channel is present between a tidal shoal and the bank. This makes that waves only occur in Southeast and Northwest directions. The significant wave height is small, between 0 and 0.5 m. During storms, the wind speeds and wave heights are more extreme and have the same direction as the influence of tides is smaller. As it is the governing wind direction, storm winds have west to southwest directions. However, the magnitude is higher. In general, stormy winds are winds with have a magnitude of 17 m/s or higher. A major storm is considered to exist when wind speeds are higher than 24.5 m/s (Van der Werf et al., 2013).

3.4.4. Morphology

The sediment in the Oosterschelde region is prevalently sandy. For the ebb-tidal delta the diameter of the sand is between 150 and 200 microns on the shoals and between 200 and 300 micron in the channels (Eelkema, 2013). For the Oosterschelde diameters are not found in literature. However, from soil samples it is clear that the soil is mostly sandy (64 % sand on average)(Ma et al., 2014). Because there was a sediment exchange between the ebb-tidal delta and the Oosterschelde for a long time, it is assumed that the sediment in the Oosterschelde has roughly the same characteristics although less fine sediment at the ebb-tidal delta is expected as the flow velocities (channels) and wind speeds (flats) are higher. This is confirmed by the sediment characteristics at the salt marshes. Because the Oosterschelde is an ebb dominant tidal basin the current velocities are higher with ebb than they are with flood. This asymmetry in tides causes more sediment to be transported in ebb direction over a whole tidal period. Therefore, it should be expected that there is sediment transport in the estuary from east to west. This sediment transport, however, is not described in literature. It could be possible that the presence of the SSB makes that this transport is not present. However, this is not proved. The construction of the SSB makes that there is hardly any sediment transport between the Oosterschelde and its ebb tidal delta. This sediment blockage and the decrease in tidal range causes erosion at the shoals of the Oosterschelde. On average, the shoals erode with a speed of 50 ha per year. When sea level rise is included, this value increases to 60 ha per year as sea level rise causes the tidal area to drown (Figure 9).

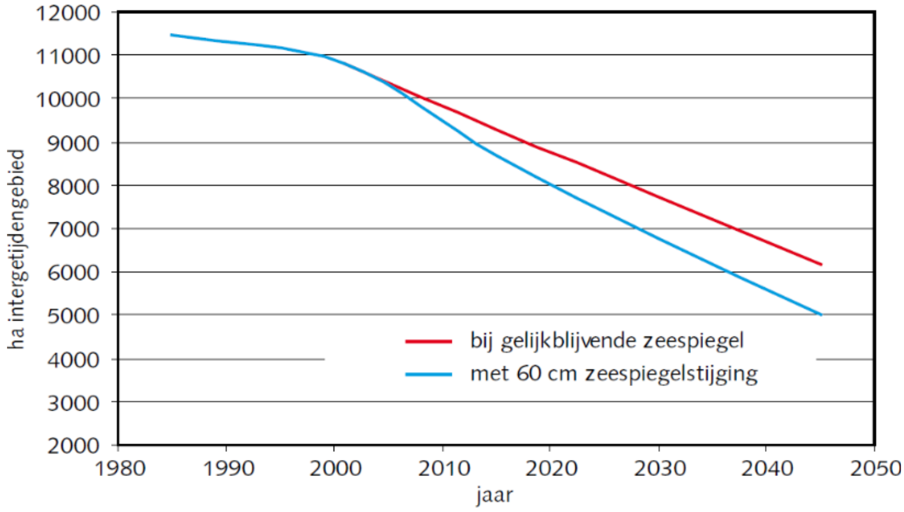


Figure 9: Prediction of the development of the intertidal area (Van Zanten & Adriaanse, 2008)

The decrease in tidal area from Figure 9 is a general picture for the whole Oosterschelde. However, as this process is the most important morphological process in the Oosterschelde ('Zandhonger'), much research is done to de development of the different tidal flats for both surface area, depths (heights) and sediment volume (Van Zanten & Adriaanse, 2008; de Vet, van Prooijen, & Wang, 2017). Below this development is described for the Roggenplaat and Galgeplaat (see Figure 4 for locations). As both studies are based on the Vaklodingen data, it may be expected that the same results are obtained. However, (Van Zanten & Adriaanse, 2008) define tidal flats as the region between NAP-2 m and NAP+2m whereas (de Vet, van Prooijen, & Wang, 2017) use the different MLW and MHW heights per flat as boundary. Furthermore, the latter research covers a larger period. Therefore, differences could be present.

Table 4 gives the development of the surface area of the tidal flats in the Oosterschelde according to literature. Values in the left part are based on (Van Zanten & Adriaanse, 2008). Values in the right part are based on (de Vet, van Prooijen, & Wang, 2017). The decrease of surface area of the Oosterschelde is 9 km^2 between 1985 and 2001. This is equal to 0.56 km^2 per year which corresponds to the value from Figure 9. For the Roggenplaat, a difference is observed between the left and right table. Although the smaller decrease between 1983 and 2012 (right part in Table 4) suggests that the decrease in surface area diminished after 2001, this could be allocated to inaccuracies in the historical data too. For the Galgeplaat, both researches show comparable values. In conclusion, the decrease of surface area of 0.50 % per year is a representative value for the development of the surface area of the tidal flats. However, it must be mentioned that these values differ for the different tidal flats (and salt marshes). The average value of 0.50 % includes salt marshes (see (Van Zanten & Adriaanse, 2008)). Other research (see below) show that decrease is not evident, especially at the salt marshes.

Regarding the sediment volume of the tidal flats a decrease is visible too in both studies (Table 5). As a result of the decrease in both surface area and volume, the height of the tidal flats has to decrease too. This is visible in Table 6. Hereto, both studies show comparable results as (de Vet, van Prooijen, & Wang, 2017) mention that the decrease in height of the studied tidal flats (Neeltje Jans, Roggenplaat, Galgeplaat, Hoogekraaier) is 0.7 cm/year.

Area between NAP-2m and NAP+2m [km2]	1985	2001	Change in percentage per year	Evolution of tidal area (between MLW and MHW)	Percentage change 1983-2012	Change in percentage per year
Oosterschelde	113	104	-0.50%			
Roggenplaat	16	14.9	-0.47%	Roggenplaat	-8%	-0.28%
Galgeplaat	10	9.64	-0.68%	Galgeplaat	-17%	-0.59%

Table 4: Literature values tidal area for the Oosterschelde and two large (important) tidal flats in the centre (Galgeplaat) and Western part (Roggenplaat) of the Oosterschelde.

Sediment volume between NAP-2m and NAP+2m [E6 m3]	1985	2001	Change in percentage per year	Evolution of sediment volume (between MLW and MHW)	Percentage change 1983-2012	Change in percentage per year
Oosterschelde	138	113	-1.13%			
Roggenplaat	32.7	28.1	-0.88%	Roggenplaat	-25%	-0.86%
Galgeplaat	16.8	13	-1.41%	Galgeplaat	-42%	-1.45%

Table 5: Literature values sediment volume and two large (important) tidal flats in the centre (Galgeplaat) and Western part (Roggenplaat) of the Oosterschelde.

Averaged height [m]	1985	2001	Change per year [m]	Evolution of averaged height (between MLW and MHW)	Percentage change 1983-2012	Change in percentage per year
Oosterschelde	0.18	0.32	-0.01			
Roggenplaat	-0.04	0.11	-0.01	Roggenplaat	-20%	-0.69%
Galgeplaat	0.32	0.65	-0.02	Galgeplaat	-28%	-0.97%

Table 6: Literature values averaged height of tidal area and two large (important) tidal flats in the centre (Galgeplaat) and Western part (Roggenplaat) of the Oosterschelde.

However, literature contradict the statement of erosion of intertidal area for salt marshes. This is shown in Figure 10. It was observed that all studied salt marshes show accretion. As described earlier, it was predicted that the salt marshes should erode because the tidal range decreased. It is concluded that this is not the case. An explanation could be that salt marsh height is not only dependent on tidal range. It was found that on mature marshes sedimentation is a balance between tidal and storm sedimentation. On macro-tidal marshes tidal range will have more influence whereas storms will have more influence in micro- and meso tidal areas. For the locations in Figure 10 it was observed that the Rattekaai was most exposed to NW storms. Before construction of the SSB, the sediment concentrations in the Oosterschelde were 3-4 times higher at Rattekaai (Ma et al., 2014).

These observations confirm the hypothesis that even in meso-tidal environment sheltered salt marshes which are protected for storms, are more dependent on tidal range. In short, it can be concluded that salt marshes can survive and grow in the current situation.

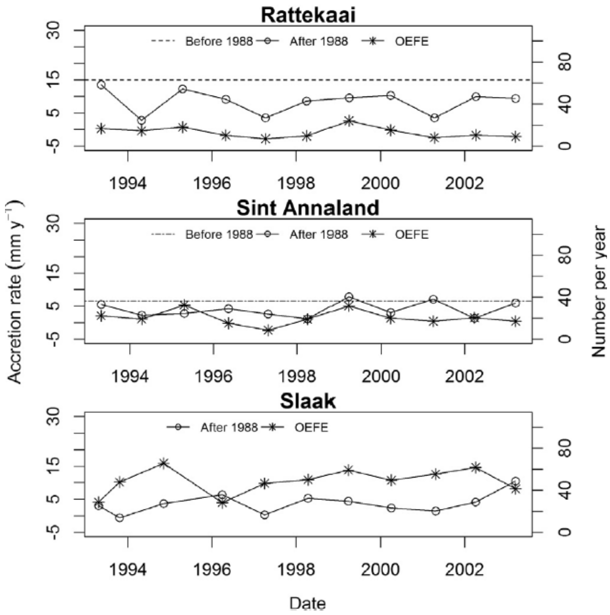


Figure 10: Accretion of salt marshes after construction of the SSB. OEFE: Overmarsh Extreme Flooding Events (Ma et al., 2014)

3.4.5. Influence of sea level rise

An ongoing trend is that the sea level rises. This influences the Oosterschelde. Enhanced sea level rise in the future may speed up the changes which will take place. For estuaries in general, it has been examined that the tidal range of short estuaries with narrow channels and large low-lying areas will decrease under influence of sea level rise (Du et al., 2018). Another study however, which studies the effect of sea level rise on tides and sediment dynamics in the Oosterschelde, states that the tidal range in the bay will increase as a consequence of sea level rise (Jiang, 2020). This can be explained by the fact that the Oosterschelde is a unique estuary with the presence of the SSB which makes that a general theory does not hold. Conversely, sea level rise will influence the SSB too because the closure regime would change. When the sea level rise reaches 2 metre the SSB will be closed 62 % of the time if the same closure standard (NAP + 3 metre) is applied. Furthermore, ecosystem services which use the intertidal flats will be influenced because the intertidal flats will drown. (Zandvoort, 2019). Whether this will also hold for the salt marshes is dependent on accretion rates, land subsidence and the amount of sea level rise (Ma et al., 2014).

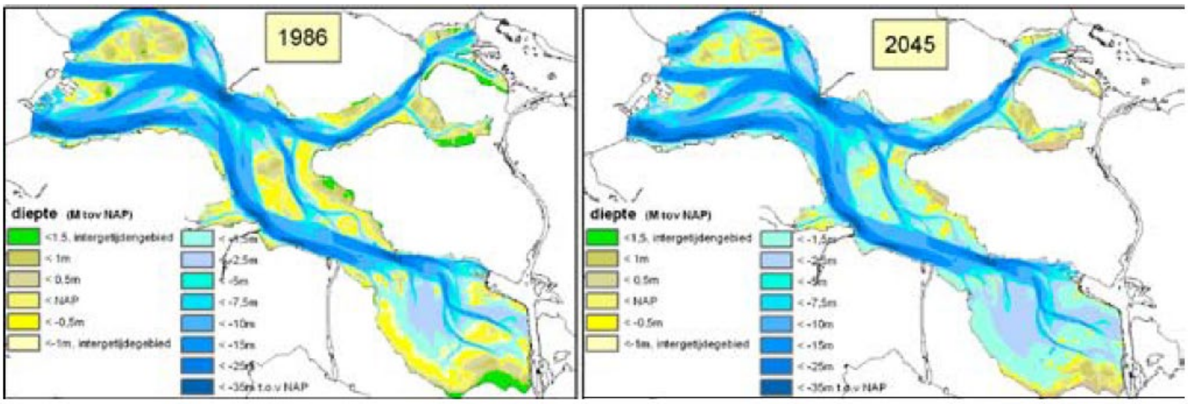


Figure 11: Predicted future of the tidal flats in the Oosterschelde (Van Zanten & Adriaanse, 2008)

3.5. Stakeholder values

As the Oosterschelde is an unique area, it is used in many ways. This section describes how the Oosterschelde is used and what boundary conditions are important to fulfil this usage. The stakeholder values are divided into four categories: transport, recreation, economics, and ecology.

3.5.1. Transport

The Oosterschelde is used by different transport modes. On the road, the connections Oesterdam (4500 movements a day), Philipsdam (6000 movements), Grevelingendam (15000 movements), Zeelandbrug (12800 movements) and N57 (at the SSB) (7500 movements) are important links in connecting different parts of land. Furthermore, the Zandkreekdam (20000 movements) and the Veersegatdam (12000 movements) are links in the transport network (Zeeland, 2019). Regarding boundary conditions, this transport over land does only require transport connections over the Oosterschelde. In the present situation, this is provided by the SSB, bridges and dams. When these connections can be maintained or replaced, vehicle transport is not interfered.

Another important transport mode are the connections for shipping. The Oosterschelde is used intensively by shipping traffic to sail from Gent/Vlissingen to Rotterdam. This industry uses the Kanaal door Zuid-Beveland and the Krammersluizen to sail from south to north or vice versa. Ships use the Oosterschelde between Wemeldinge and the Krammersluizen (Figure 12). In 2014, 40.000 shipping movements were counted at this connection (Atelier-Oosterschelde, 2018). The maximum size of ships which can pass are 195x22.8 metre. The channel must be at least 91.2 metre wide when two ships want to pass each other. The depth of such a channel must be at least 5.6 metre (Rijkswaterstaat, 2017b).

Number	Category	Requirement
1	Transport	Minimal navigation profile of 95x6 metre (width x depth) between Wemeldinge and Krammersluizen

Table 7: Boundary condition transport

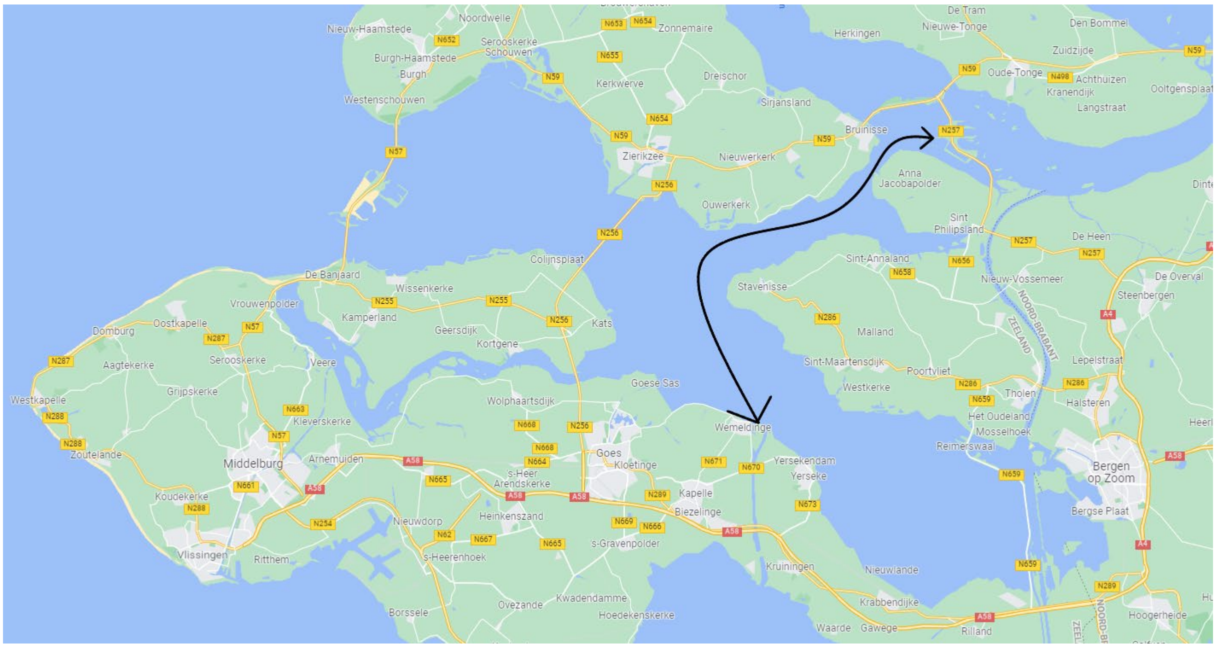


Figure 12: Most important transport connection at the Oosterschelde for shipping

3.5.2. Economics

The transport sector is not the only sector to profit economically of the Oosterschelde. The unique nature of the Oosterschelde ensures that shellfish can grow. The farming of shellfish and the boundary conditions it requires, could also be classified under ecology because it is living nature. Besides, part of the shellfish of the Oosterschelde shall not be fished to ensure the ecological value. However, because most shellfish in the Oosterschelde are intended for consumption, this industry is categorized as an economic value. In total, 56 km^2 of the Oosterschelde is used as area for fishing mussels and oysters. The boundary conditions which are required for the growth of mussels and oysters can be divided into two parts. At one side the biological aspects such as food availability play a role. At the other side, the abiotic conditions (such as current velocity) are important. Because this research does not focus on ecology, it is assumed that hydrodynamic and morphodynamic conditions for both the shellfish and their food are the same. This is confirmed by the fact that good conditions for shellfish, presumes good conditions for the food of the shellfish. Growth of mussels takes place both in the Oosterschelde and the Waddenzee. Because data about boundary conditions in the Oosterschelde is not available, boundary conditions are distracted from data analysis at the Waddenzee. The authors of this article are cautious about using the data for other locations because the combination of wave action and sediment types can differ. However, since in both the Waddensea and the Oosterschelde the blue mussel (Mytilus edulis) is cultivated, the data can nonetheless be useful if handled critically. Therefore, author has decided to use this data, nonetheless. This is be justified by the fact that in both the Waddenzee and the Oosterschelde the blue mussel (Mytilus edulis) is cultivated. Furthermore, not only the quantitative results are collected, also underlying mechanism will be considered.

The boundary conditions are given in Figure 13. The RA at the vertical axes determines the relative appearance of the mussel beds in ha per ha. It is observed that mussels prefer flow velocities between 0.3 m/s and 0.9 m/s. Orbital velocities are ideal below 0.3 m/s but higher than 0. An explanation for these flow velocities could be that sedimentation does not take place. Provision of food can also play a role. Furthermore, the distance to channels is in most cases smaller than 1 km

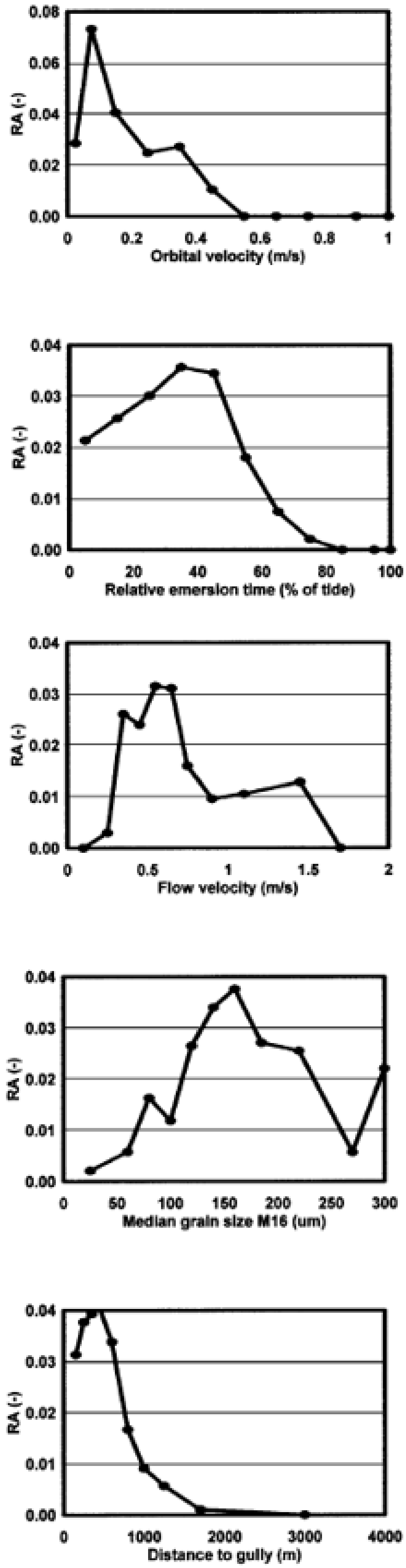


Figure 13: Boundary conditions for mussels (Brinkman, Dankers, & van Stralen, 2002)

and the grow location should not be emerged more than 50 % of the time. As mentioned earlier, there is a correlation between the emersion time and the distance to a gully as a larger distance gives a higher emersion time. The decrease in mussel beds at longer distances from gullies is attributed to decreasing food too. The preferred median grain size does vary a lot. However, silty areas and areas with coarse sand are not desired (Brinkman et al., 2002). In the Oosterschelde mussels can grow fully below the water surface. Therefore, the emersion time is considered as a maximum. Apart from the grain size, the boundary conditions are collected in Table 8. The grain size is not included because the used model does not vary for grain sizes.

The oysters which are grown in the Oosterschelde are Crassostrea gigas and Ostrea edulis. In this research it is assumed that the conditions for both types are the same. Oysters are farmed especially in the east of the Oosterschelde (Henkens, 2012). Oysters prefer a sheltered area with a current velocity of 0.4 m/s maximum and an exposure time of maximal 40 %. Because both mussels and oysters feed themselves by filtering water it is assumed that the orbital velocity for mussels holds for oysters too. (Schellekens, 2012).

Number	Category	Requirement
2	Economics	Ideal abiotic circumstances for mussels are: - Flow velocities between 0.3-0.9 m/s -> low sedimentation rate - Orbital velocities below 0.3 m/s but not 0 -> low sedimentation rate - Distance to channels: below 1000 m; - Relative emersion time: maximum 50 %
3	Economics	Ideal abiotic circumstances for oysters are: - Flow velocities: 0.4 m/s maximum; - Orbital velocities below 0.3 m/s but not 0; - Relative emersion time: maximum 40 %

Table 8: Boundary conditions economy

3.5.3. Ecology

As mentioned earlier, the Oosterschelde is a unique area because of its valuable nature. Numerous species live or forage in the Oosterschelde. Due to the high number of species, it is not possible to consider them all. In compliance with literature it is therefore decided to focus on seals and foraging oyster catchers. These species are chosen because they represent the Oosterschelde well. A general sidenote which can be made is that the process of sand demand facilitates the decrease of species in the Oosterschelde. Therefore, a first boundary condition is that tidal flats should remain in the Oosterschelde.

Seals use the Oosterschelde as their living area. This means that there must be enough food to live. Another essential part of their habitat are resting areas. These areas must satisfy to a few needs. First, the resting area must be above the water level for 2 hours at minimal. Second, the distance between the water and the resting area must be between 100 and 200metre. This means that tidal flats should have widths of at least 200 to 400metre (Henkens, 2012).

The oyster catchers are assigned as a specie which should be maintained regarding the Natura2000 rules. Therefore, it is a valuable specie at the Oosterschelde. This is done because oyster catchers are rare. In Europe, there are only few wintering grounds (Van Zanten & Adriaanse, 2008). Oyster catchers stay on the tidal flats in order to forage. Therefore, the tidal flats must be emerged for 50 % at average (Zwarts, Blomert, Bos, & Sikkema, 2011).

Number	Category	Requirement
4	Ecology	Tidal flats should be present in the Oosterschelde
5	Ecology	Tidal flats should have dimensions of 200 to 400 metre and must be emerged for 2 hours at minimal per tidal cycle.
6	Ecology	Tidal flats should be emerged for at least 50 % of the time.

Table 9: Boundary conditions ecology

3.5.4. Recreation

The Oosterschelde provide multiple functions with respect to recreation. Besides activities at or in the Oosterschelde itself, functions on land are present which have an indirect connection with the Oosterschelde. One can think of biking lanes or museums about the local area. In this research this last category of functions is neglected. It is assumed that these functions will remain even when the Oosterschelde changes because they are used by tourists in Zeeland anyway. Furthermore it is assumed that they do not create boundary conditions which must be considered. Functions that are considered are diving, swimming and sailing.

The Oosterschelde is well known for diving. Some reasons for this fame are the rich marine life, and the different seasons under water as a result of the large temperature differences. Diving is only possible when tidal velocities are low. When the situation in the Oosterschelde changes because the SSB is removed, the tides will change. Although this will influence diving, the low flow velocities during the tide will remain. Therefore, no boundary conditions are distracted for diving.

The same holds for recreational swimming. At different locations along the shores of the Oosterschelde beaches are present where people can swim. Although people prefer sandy, large beaches, these are not present at all locations. Moreover, these beaches can be created artificial by nourishments. For these reasons, no boundary conditions are considered.

Lastly, the Oosterschelde is a popular sailing area. Especially between Wemeldinge and the Zeelandbrug many boats are present during the holiday season. Essential for these vessels are marinas to shelter. Around the Oosterschelde in total 3112 berths are present divided over 15 marinas. As a boundary condition is considered that these 15 marinas must be accessible. A water depth of 2metre is considered. This also holds for the waterway between the Bergsediepsluis to the Roompot locks (east-west connection) (Rijkswaterstaat, 2017a).

Number	Category	Requirement
7	Recreation	Minimal navigation depth of 2 metre at the 15 marinas at the Oosterschelde.
8	Recreation	Minimal navigation depth of 2 metre between Bergsediepsluis and sea.

Table 10: Boundary conditions recreation

3.6. Policy

Because the Oosterschelde is indicated as Natura2000 area, special rules are in place for the area. These rules aim to maintain or foster the living or foraging of designated plants and animals. For each specie, a target value is set. It would go beyond the scope of this research to study all different species and their preferences with respect to living area (Natura2000, 2009). In Section 3.5.3 some boundary conditions for different species are mentioned. Only one boundary condition is considered: the Oosterschelde area has to be an area with channels, tidal flats and salt marshes.

The sand demand forms a major threat for the current situation in the Oosterschelde. Before the construction of the SSB, the tidal influences built up the tidal flats . During storms, waves were responsible for the erosion of the tidal flats. These processes were in equilibrium. After construction of the SSB, the tidal influence waned. This caused an erosive trend of the tidal flats. To stop this trend, several solutions are explored, such as nourishments at different locations (tidal flats, channels, ebb tidal delta), construction of breakwaters and the construction of similar tidal nature at other locations. A long-term solution could be filling the scour holes at the SSB. This ensures that sediment flows into the Oosterschelde as it could not settle in the scour holes. In the meantime, short term protective or reinforcing mitigation measures are necessary (Van Zanten & Adriaanse, 2008).

Over the past years two sand nourishments have been performed. In 2008 a nourishment experiment was conducted at the Galgeplaat, a shoal in the centre of the Oosterschelde. During this nourishment 130000 m^3 was dredged from the adjacent channels (Engelsche vaarwater and Witte Tonnen Vlije) and was dumped in a circular region with an area of 15 hectares. The bottom level of the area increased with one metre to values between NAP – 0.5 m and NAP + 0.5 metre (Holzhauer, Werf, Dijkstra, & Morelissen, 2010). The Galgeplaat has been studied intensively after the nourishment for four years. The nourished area has a higher erosion speed (up to 4 times faster). This is attributed to the higher elevation of the nourished area. Still, the predicted lifetime of the nourishment was calculated at 40 years (van der Werf et al., 2015). Another nourishment experiment was done at the Roggenplaat, in 2019. This shoal is the largest shoal in the Oosterschelde and is located in the West of the Oosterschelde. With the nourishment, 10 % of the total area of the shoal was covered with 1.3 million m^3 of sediment from the adjacent Roompot channel (Rijkswaterstaat, 2019). Because one of the bathymetries used in this study is composed of data from 1-1-2019, this nourishment is not present in the bathymetry (Rijkswaterstaat, 1984-2019).

Number	Category	Requirement
9	Policy	The Oosterschelde area has to be an area with a stable area of channels, tidal flats and salt marshes

Table 11: Boundary conditions policy

3.7. Flood safety requirements

The Oosterschelde is not only an area which provides values and functions to mankind. Because a partly open connection to the sea is present, a flood protection is needed. In the current situation there are two layers of protection for the areas along the Oosterschelde. The first layer is the SSB, which closes when water levels are predicted to reach NAP + 3 metre or higher. The second layer are the dikes which protect the hinterland. These are the dike rings 26, 27, 28, 30, and 31 which failure probability is set at once per 4,000 year (*Waterwet*, 2009). With the presence of the SSB, the dikes along the Oosterschelde can be lower in comparison to a situation without SSB. The current height of the dams and dikes varies but does have an average height of NAP + 6.60 metre (Rijkswaterstaat, 2017a).

3.8. Predicted future development when SSB is removed and SLR is present

With the presented overview of the development of the Oosterschelde under influence of human activity, a prediction can be made about future development with future human intervention. Before the first sub question is answered in the conclusion, this section gives a qualitative description of this future.

As described above (Section 0), there are formulae which describe the relation between hydraulic and morphodynamic parameters like tidal prism, cross sectional area of the inlet and channel volume. Most of these relations are empirical and differ for different estuaries. It is well known however, that an increase in tidal prism causes an increase in cross-sectional area of the inlet. This was confirmed by the historical development of the Oosterschelde. Therefore, when the SSB (including its sill) will be removed, the tidal parameters will increase. As the back barrier dams in the Oosterschelde will not be removed and the work islands will stay, the tidal prism will not recover to the pre barrier situation. In the current situation, the tidal prism is 900 million m^3. When the SSB is removed, the tidal range will increase to a higher value as it was before due to the continued presence of the Oesterdam and the Philipsdam. As the surface area of the Oosterschelde remains constant, the tidal prism has to increase according to Equation 5. The current tidal range at Yerseke is 3.30 metre. When the new tidal range is assumed to be 3.80 metre (which is more than the original 3.70 metre), the tidal prism will increase with the same value: the tidal range has increased with 15 %. Therefore, the tidal prism will increase with 15 % too and will be 1010 million m^3. As a consequence the cross sectional area of the channels has to grow too.

Due to this increased tidal influence the balance between tidal motion and waves changes. As the tidal influence grows, the process of 'Zandhonger' will diminish. Based on the fact that tidal influences grow to values larger than before construction of the SSB, it may be possible that tidal area will grow too. However, extreme SLR could change the situation as tidal flats could drown when the SLR goes too fast. Whether this will be the case for the Oosterschelde with 40 mm SLR per year depends on many parameters as is described by (Wang et al., 2018). For several inlets in the Waddensea critical values are given between 6 and 32 mm per year. It is clear however, that growth of the tidal flats means that extra sediment is needed. For this extra sediment two options are possible:

- Sediment import from the ebb-tidal delta;
- Sediment transport from the channels to the tidal flats (channel deepening).

The first option seems unlikely as the Oosterschelde has been an exporting basin for centuries. Furthermore, it was analysed that the Oosterschelde becomes even more ebb dominant when SLR takes place (Jiang et al, 2020). The second option is more in line with the increasing tidal prism as a larger tidal prism results in a larger cross sectional area of the channels. However, the process of channel deepening cannot be infinite because unerodable layers are present for example. Therefore, it is expected that extreme SLR causes drowning of the tidal flats in the Oosterschelde.

3.9. Conclusion

In the answer to the first research question the story about the development of the Oosterschelde is described. In short, it can be said that the Oosterschelde was a basin which exported sediment in order to get an equilibrium situation until the construction of the Volkerakdam in 1969. The construction of the SSB and back barrier dams Philipsdam and Oesterdam caused the flats to erode into the channels ('Zandhonger'). This is caused by a decrease in tidal motion which makes it impossible to build up the flats. This ongoing trend will bring the system to change drastically if no mitigation measures are implemented. The process of 'Zandhonger' is visible both in decrease of surface area, sediment volume and height of the tidal flats.

As the tidal flats provide numerous services to the ecosystem, its disappearance will have major consequences . Both the economic and ecological services need the tidal flats. Moreover, it can be said that recreation will be influenced as well because the disappearance of the tidal flats means the disappearance of unique tidal nature, which is valuable for tourists too. In the previous sections, boundary conditions are given per category. These boundary conditions are contradictory or double.

Therefore, in Table 12 a selection is made with conditions. These conditions will inform how the relevant ecosystem services are influenced with removal of the SSB and extreme SLR.

In the modelling phase the predicted development should become visible. In the validation run (1990-2020) and reference run (2019-2069) the decrease of the tidal flats should be present in decrease of surface area (average -0.5 % per year), the decrease of sediment volume (average -1.13 % per year) and the decrease of height (average -0.01 m per year). As described in Section 3.8 the future development in the two future scenarios (without SSB and with SLR) will be present in:

- Increase in tidal range (possible to more than 3.70 metre at Yerseke);
- Increase in tidal prism and cross sectional area of the channels;
- Diminished reduction of intertidal area or even growth;
- Drowning of intertidal area caused by extreme SLR.

Number	Category	Requirement
1	Transport	Minimal navigation profile of 95x6 metre (width x depth) between Wemeldinge and Krammersluizen
2	Economics	Ideal abiotic circumstances for oysters are: - Flow velocities: 0.4 m/s maximum; - Orbital velocities below 0.3 m/s but not 0; - Relative emersion time: between 0 % and 40 %
3	Recreation	Minimal navigation depth of 2 metre at the 15 marinas at the Oosterschelde.
4	Recreation	Minimal navigation depth of 2 metre between Bergsediepsluis and sea.
5	Policy	The Oosterschelde area has to be an area with a stable area of channels, tidal flats and salt marshes Requirements for tidal flats: - Emersion time: 50 % at least - Width: between 200 and 400 metre

Table 12: Summary of current ecosystem services in the Oosterschelde

4. Model setup

In this chapter, a description is given of the indicators which are used in order to answer the second and third research question. Furthermore, a description is given of the input in the model and of its validation.

4.1. Indicators

In order to answer the research questions, the model output will be analysed. The indicators which are analysed should describe the development of the Oosterschelde. Furthermore, the predicted development (Section 3.8) and requirements for ecosystem services (Table 12) should become clear. In Table 13 the indicators are mentioned which are studied.

For tidal indicators a period of 14 days is chosen because this period covers one spring tide and one neap tide. The locations which are chosen are distributed at the various parts of the Oosterschelde (Figure 14). For the western part, the station of Roompot Binnen is considered. The station of Stavenisse represents the central part where the station of Yerseke represent the eastern part. The Northern branch is represented by the station of Krammersluizen-West. To make a comparison with the situation at sea, the station of OS4 is studied as well. These measurement points correspond with the official measurement stations as monitored by Rijkswaterstaat. However, during validation of the model it became clear that the results of the measurement points located in a harbour are not representative. Therefore, a point just outside the harbours is considered to overcome this (Figure 15). Furthermore, for the location of Stavenisse a point in the channel is chosen instead of a point at the boundary of the model.

In the indicators related to bed development a distinction is made between different height levels. This distinction is made because it is expected that the height levels of the beds will develop distinctively. Three regions are distinguished: The channels are defined as the locations where the bed level is below MLW. The tidal area is defined as all bed levels between MLW and MHW. All area above MHW is considered to be supratidal parts. For these three categories, both areas and depths are studied. Sediment volumes are studied for the tidal parts only. For the values of MLW and MHW, per scenario (reference, without SLR, without SSB, with SLR, without SSB) an average value is considered for the whole Oosterschelde for each 10 years.

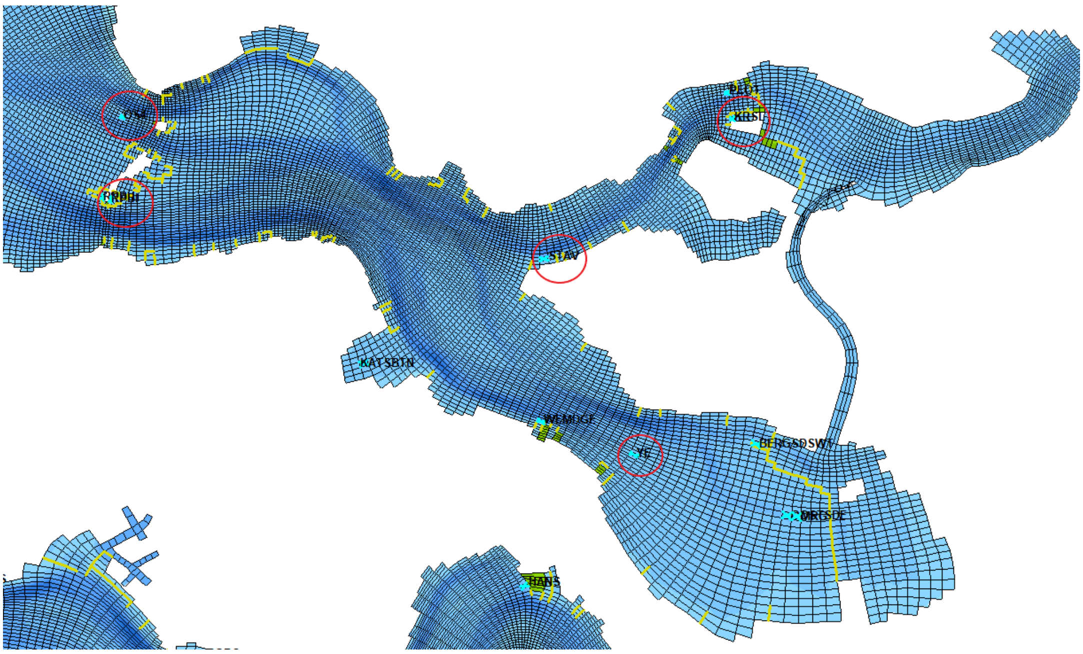
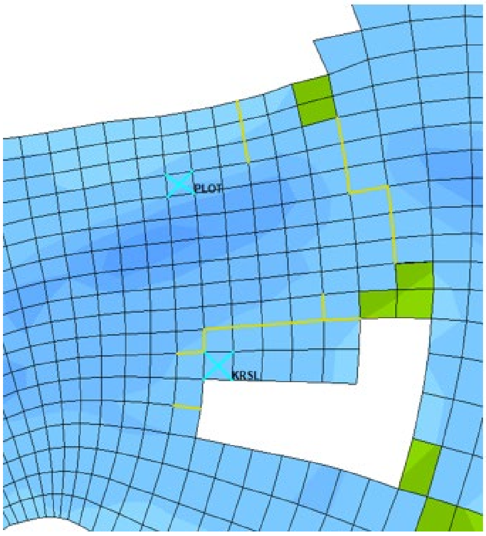


Figure 14: Observation points used in this research to study the tidal range.

In determining the sediment volume, it is possible that the sediment volume for channels, tidal area and supratidal parts is not equal to the total sediment volume. The total sediment volume is measured by summing up all sediment volume above NAP-75 m. For the sediment volumes of the three categories however, the sediment volume is measured with respect to the predefined boundaries. As the tidal area is defined as all bed levels between MLW and MHW, this tidal area is coupled to the tidal range (average difference between MLW and MHW). Therefore, when the tidal range decreases over time, the height zone of the tidal area decreases. Assuming that the surface area of the tidal flats is constant, this has the consequence that the sediment volume of the tidal flats decreases. However, the total amount of sediment in the Oosterschelde is constant.



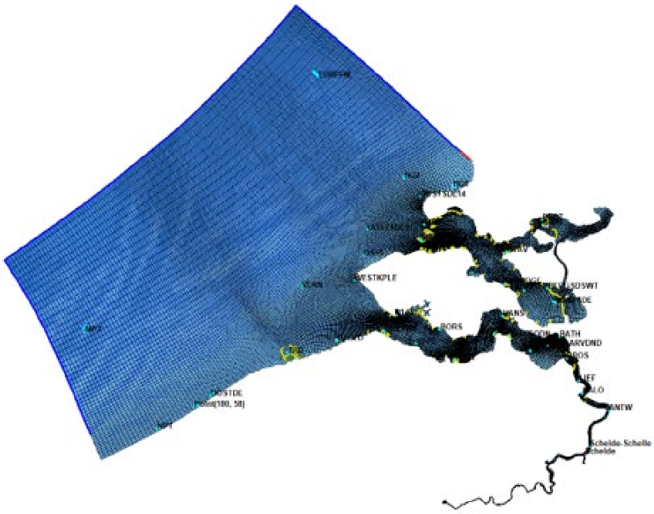


Figure 15: Observation points around a harbour (left) and overview of the KustZuid model (right)

Test parameter	Study by
Tidal influence	
Tidal range	Averaged tidal difference in one spring-neap cycle (14 days) at 5 locations
Tidal prism	Difference between averaged flood volume and averaged ebb volume over 14 days
Bed development	
Area of tidal flats and channels	Development of areas with various levels: - Channels: < MLW - Tidal flats: between MLW and MHW - Supratidal parts: above MHW
Average depths (positive downward)	- Average depth of the channels - Average depth of the tidal area - Average height of the supratidal parts
Sediment volume	- Total volume: amount of sediment above NAP–75 m - Volume between MLW and MHW

Table 13: Indicators

4.2. Model input

The Delft3D model which is used, is the KustZuid model. This model covers the Southern part of the North Sea from the Maasvlakte to the border between Belgium and France (Figure 15). In seaward direction it covers 65 km. Because this model has proven its reliability in several other studies in the Oosterschelde, most parameters are not changed in the model (Eelkema, 2013; Pater, 2012). In Appendix 1 an overview of these standard input values is given. Input which is changed however, is described below. This input can be categorized in two sets: the physical parameters and the numerical parameters.

4.2.1. Physical parameters

Bathymetry

For the different model runs (validation, prediction) bathymetries of the 1990 situation and the 2019 situation are needed. This bathymetry must represent the present bed. For the bathymetry of 1990, different datasets are used to make one suitable bathymetry file. The bed levels of the Oosterschelde are representing the 1987 situation. However, the data of the tidal flats are missing in this file. Therefore, the bed levels for the tidal flats are taken from data from 1983. Both files were provided by (Eelkema, 2013). The data for the ebb-tidal delta and the part of the North Sea which are in the model area, are partly taken from the Vaklodingen of Rijkswaterstaat (Rijkswaterstaat, 1984-2019). Missing parts are supplemented by the 2008 bathymetry which is in the KustZuid model of (Pater, 2012). This choice is made because the missing parts are far away from the Oosterschelde. Moreover, it is known that the SSB blocks sediment exchange from the Oosterschelde to its ebb-tidal delta. This asks for both systems to be independent. The present-day bathymetry of the Oosterschelde and its ebb-tidal delta is composed from vaklodingen of Rijkswaterstaat from 2017, 2018 and 2019 (Rijkswaterstaat, 1984-2019). Missing parts (parts outside the red polygon of Figure 17 are supplemented with the 2008 bathymetry which is in the KustZuid model of (Pater, 2012).

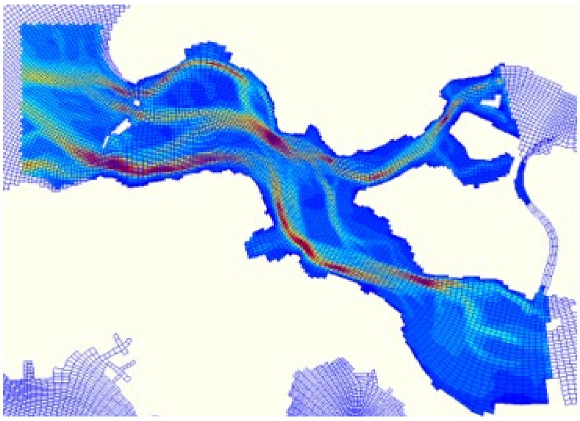
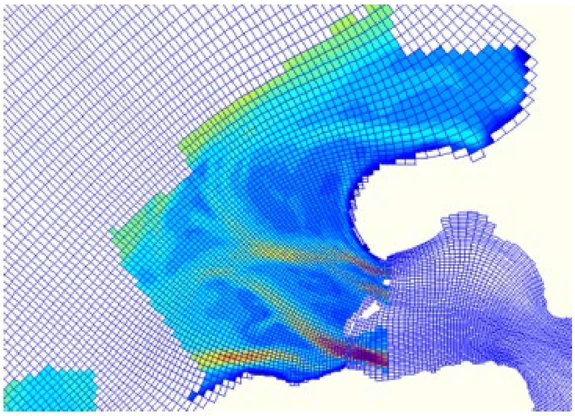



Figure 16: Bathymetry of the vaklodingen 1987 (left) and bathymetry of the vaklodingen 1984 (right)

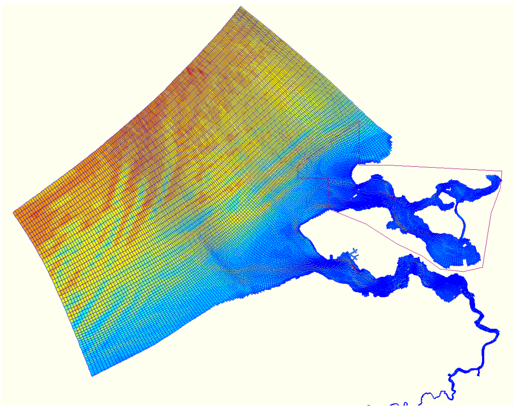


Figure 17: Bathymetry for the future model runs (vaklodingen 2019 in red polygon, rest of the data used from (Pater, 2012))

Wind and waves

In the KustZuid model two types of waves are present. At the northwest boundary of the model a relatively long wave (7 seconds) is present which represents the swell waves (H_s = 1.5 m). In addition, the wind causes short wind waves on a local scale.

The magnitude and direction of the wind are derived from the literature review. From Figure 8 it is observed that the wave heights vary between 0 m and 0.3 m in the Oosterschelde. A wind speed of 6 m/s gives wave heights which satisfy this condition (Figure 18). For the wind direction, the governing southwest wind direction is considered (270°, Figure 7). The influence of different wind directions is studied in Section 4.3.4.

Sediment

In the KustZuid model, sediment is specified as non-cohesive sediment with a median grain size diameter of 200 µm and a density of 2650 kg/m³. During the computations it is possible that tidal flats and channels move. This could lead to transportation of a thick layer of sediment. Because the height difference between channels and flats is around 55metre a sediment thickness of 75 metre is chosen in the model.

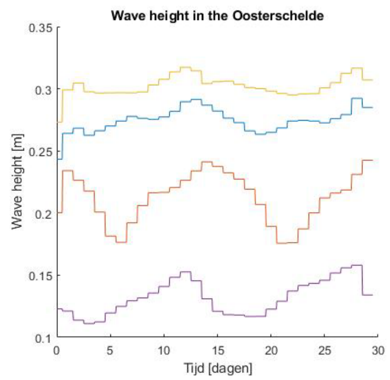


Figure 18: modelled wave heights in the Oosterschelde

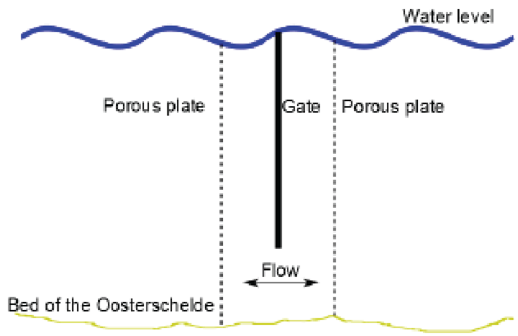


Figure 19: Representation of the SSB in the Delft3d model (Pater, 2012)

4.2.2. Model parameters

Modelling the SSB

The SSB has a large effect on the situation in the Oosterschelde. This SSB is modelled with a vertical gate and a porous plate at both sides of the gate (Figure 19). For further description of the representation of the SSB in the model, the reader is referred to (Pater, 2012). During the validation of the model, some tests are conducted to see how the barrier affects the tides and morphological development in the Oosterschelde.

Timestep

In order to choose a timestep for the model, several runs are performed with a model which represent the development of the Oosterschelde of one month. In these runs different timesteps (1, 2, 5 or 10 minutes) are chosen. When the chosen timestep is too large, the modelled development does not match the actual development. A timestep which is too small gives extra accuracy, but computational time may be unacceptable long. The results of the one month models are compared for significant wave height, tidal range and cumulative erosion/sedimentation at five locations in the model (Appendix 2). It is realised that a model of one month may not give significant development when it comes to morphology. Therefore, the results are studied in a comparative way only to choose the timestep.

With a timestep of 1 minute as base, it is observed that all parameters lose accuracy when the timestep increases. The tidal range is well represented in all timesteps although the moments of highest and lowest water levels move over time. This is caused by the fact that a larger timestep represents the tides less accurate. At each tidal cycle this loss in accuracy adds up. The wave heights were determined once a day. This is represented by the steps in the graphs. Hereto, it is observed that the wave heights differ more when the timestep is larger. A timestep of 10 minutes can give a deviation in significant wave height of 0.05 metre (YE). Although this deviation seems small, it is a deviation of 25 %. When the cumulative erosion/sedimentation is observed, this trend is confirmed. At the station of Yerseke the sedimentation is 0.075 metre for a timestep of 10 minutes. With a timestep of 1 minute it is almost zero. Moreover, the results with a timestep of 5 minutes do deviate too. For most of the locations in the Oosterschelde they are between the results with timesteps of 2 and 10 minutes. However, for the location outside the Oosterschelde (OS4) the deviation is as large as the timestep of 10 minutes. Based on these observations, a timestep of 2 minutes is used in the model.

Morfac

It is well-known that hydrodynamic flows change much faster than morphodynamic developments. Where hydrodynamics (waves, tides) has periods of seconds and hours, bed level changes become significant after months or even years. Therefore, a technique can be used which is called a morphological time scale factor (morfac). This factor multiplies the erosion and deposition at each computational time step with a predefined morfac. In practice this means that the morphological time and the hydrodynamic time will differ. A model run which has a hydrodynamic time of 1 year, will represent a morphodynamic development of n*1 year where n is the morfac.

For the short runs (models of 14 days), a morfac of 1 is chosen. In order to save computational time in the long run models a larger morfac of 25 is preferable. However, as a too large morfac gives the risk that the development is not realistic anymore, a comparison is made (Section 4.3.4) with a smaller morfac of 3. With a morfac of 25, it is only needed to model 2 years of hydrodynamic development which will represent 50 years morphological development. A consequence of this is that interannual tides like the 18.61 year nodal tide are not represented. However, as it is the aim of this research to model general trends in the development of the Oosterschelde, it is not expected that such tidal cycle with a relatively small amplitude (6 cm for the nodal tide) will disturb the occurring trends.

Wave update

In Delft3D, the flow model and the wave model are divided. Therefore, each n timesteps in the flow computation, one wave computation is done. The user must choose a value of n which is small enough to get a realistic representation of the waves in the different states of the tide. At the other side, the value of n should be large to save computational time. Furthermore, for computational reasons, the value of n must be a multiple integer of the chosen timestep. The tide in the Netherlands has a period of 12 hours and 25 minutes. One period of spring tide and neap tide covers 14 days. In order to get wave calculations at different moments in these two tidal cycles one wave is done each 6200 minutes (4.31 days). With this interval, the computations are distributed over the semi diurnal tide. Moreover, there are enough computations in the cycle of spring and neap tide (3 calculations) to represent this cycle as well.

Sea level rise

As described in Section 1.4.1, 2 metre sea level rise is considered in 50 years. Two options are explored:

1. Increasing the depths in the model;
2. Forcing a rise of MSL at the boundaries of the model.

Regarding the first option, increasing depths in a situation could be a definition of SLR. Moreover, in reality it is sometimes *the* definition of SLR as land subsidence is present. In this study however, the area of interest is the bathymetry of the Oosterschelde. Therefore, it seems unnatural to change the area of interest (bottom level) to see what the effect is on the area of interest (bathymetric changes). For this reason, the second option was used to model SLR. With this option, a constant rising level of MSL was forced at the boundaries of the model. This type of modelling SLR will be used both in the long-term models and short term models (14 days).

4.3. Validation

In order to know whether the models represent the development of the Oosterschelde in the right way, a validation is conducted. This validation has four parts:

1. Hydrodynamic indicators (Section 4.3.1): By means of relatively short runs (14 days), the hydrodynamic indicators are assessed:
    a. Tidal range
    b. Tidal prism
2. Morphodynamic indicators (Section 4.3.2): By means of a long run (30 years) the morphodynamic indicators are assessed. In this long run, the bathymetry of 1990 (based on vaklodingen) is used as a starting point. The resulting bathymetry is then compared to the actual bathymetry of 2019 (again based on vaklodingen). By means of comparison, trends in the following parameters are assessed:
    c. Surface area of channels, tidal flats and supratidal parts
    d. Channel depth
    e. Height of tidal flats and supratidal parts
    f. Sediment volumes in channels, tidal flats and supratidal parts
3. Impact of the SSB (Section 4.3.3): By means of a comparison between tidal range for literature values and model results, the impact of the SSB on the tidal range is assessed. By means of a comparison of total sediment volume in the Oosterschelde, the sediment exchange is assessed.
4. Sensitivity analysis (Section 4.3.4): As it turned out that the morphodynamic indicators are not represented well by the long run, a sensitivity analysis is done in order to see what the influence is of several parameters in the model. The following parameters are assessed:
    g. Influence of a smaller morfac
    h. Influence of different wind directions
    i. Influence of different wind speed
    j. Influence of wind/waves (with a model without wind/waves)
    k. Influence of morphodynamic development on hydrodynamic indicators

4.3.1. Hydrodynamic indicators

In this paragraph, both tidal range and tidal prism are validated. The tidal range is validated by comparison of the water levels which have been recorded at the Oosterschelde with the water levels from the model. For each high and low water, the water levels are stored, and differences are calculated. These differences are averaged to obtain the mean tidal range. It must be mentioned beforehand that this comparison comes with some weaknesses. In the models, a maximum wave height of 0.3 metre occurs in the Oosterschelde. In the data that is analysed, actual wave heights and probably some storms are present. As the tidal range is calculated based on water levels, it is expected that the tidal range will deviate a little.

The tidal prism is validated by comparing literature values with model values. The tidal prism is calculated by the difference between the discharges at high and low tide for one spring-neap tidal cycle.

Tidal range

With data from the five monitoring points, the tidal range is calculated for every five years. This is done by averaging all differences between high and low waters. The results are given in Appendix 4. The nodal variations of 18.61 year as well as the influence of the SSB (difference between 1985 and 1990) are visible. In order to compare the tidal ranges two model runs are done with the different bathymetries for 1990 and 2018/2019. Because a rise of the sea level (1.7 mm/year) was observed in the average water level, an extra analysis run is done with a higher average sea level of 51 mm (30*1.7 mm). However, this had no impact on the tidal modelled tidal ranges. The figures of the tidal ranges are given in Appendix 4. In Table 14 the tidal ranges for the various locations are summarized and the differences between model-data, data-data, and model-model are calculated. It is concluded that the model represents the tidal ranges very well as the deviations between model and data are small (<10 %). It is observed that the deviations become larger when the monitoring point is located further east in the Oosterschelde. As the tide is generated at the boundaries at the west end of the model, this indicates that small errors in the model add up further east. Deviations are however considered to be acceptable.

Tidal range								
Location	Model 1990 [cm]	Data 1990 [cm]	Model 2018 [cm]	Data 2020 [cm]	Diff. 1990 model-data	Diff. 2020 model-data	Diff. 1990-2020 model	Diff. 1990-2020 data
OS4	275	284	272	280	-3%	-3%	-1%	-1%
RPBI	271	260	264	257	4%	3%	-3%	-1%
YE	361	333	354	327	8%	8%	-2%	-2%
STAV	321	298	314	296	8%	6%	-2%	-1%
KRSL	332	308	326	304	8%	7%	-2%	-1%

Table 14: Overview of tidal ranges for various locations from measurement data and different short model runs

Tidal prism				
Year	Hesselink et al. (2003)	De Bok (2001)	De Pater (2012)	Model results
1990	8.800E+08	9.250E+08		9.577E+08
2008			1.038E+09	
2018				1.134E+09

Table 15: Tidal prism for literature and model results (last column)

Tidal prism

The tidal prism is an important parameter in the model as it determines the shape of the bottom at a long-term as is stated in Section 0. Furthermore, literature values are known for the tidal prism. The tidal prism is calculated by the difference between the discharges at high and low tide for one spring-neap tidal cycle. From literature it is known that the tidal prism was 8.80 E8 m^3 in 1990 after construction of the SSB (Hesselink et al., 2003). Several values for the tidal prism are given in Table 15. In the last column, the modelled results are given. It is observed that the modelled tidal prism is larger than the actual tidal prism in both this model as in other models. The tidal prism is dependent on the tidal range and the area of the Oosterschelde (see Equation 5). Because both parameters are overestimated in the model, it is in line with expectations that the tidal prism is overestimated too. As a consequence it is possible that the channels will grow over time in the model as the channel volume is coupled to the tidal prism (Equation 4).

4.3.2. Morphodynamic indicators

The second part of the validation of the model is a long run of 30 years (1990-2020). In this long run the morphological development should be validated against the differences between the bathymetry of 1990 and the bathymetry of 2019 in such a way that a long run represents the development of the Oosterschelde in a right way. This development was analysed in Section 3.4.4. For clarification a summary of the trends is given below:

- Decrease of surface area of the tidal flats with 0.5 % per year;
- Decrease of sediment volume of the tidal flats with 1.13 % per year;
- Decrease of height of the tidal flats with 0.01 m per year;
- No sediment exchange between the Oosterschelde and its ebb-tidal delta.

It must be mentioned on beforehand that the model is probably not able to reproduce these numbers because of several reasons. First, the model has a grid which is coarser than the grid of the vaklodingen (20x20 metre). Therefore, some data is lost as the depth is averaged per grid cell. Second, the vaklodingen data has uncertainties in the order of decimetres (de Vet, van Prooijen, & Wang, 2017). As the numbers obtained from literature are smaller than these errors, it is unclear whether observed trends are real trends or measurement errors. For these two reasons, a calculation of the difference in data between the vaklodingen from 2019 and 1990 is not reliable for validating the model. This is confirmed by Figure 20 where the difference is visualised. The fact that differences in model data from vaklodingen do not represent the development of the tidal flats in the Oosterschelde is observed in earlier studies too (Pater, 2012).

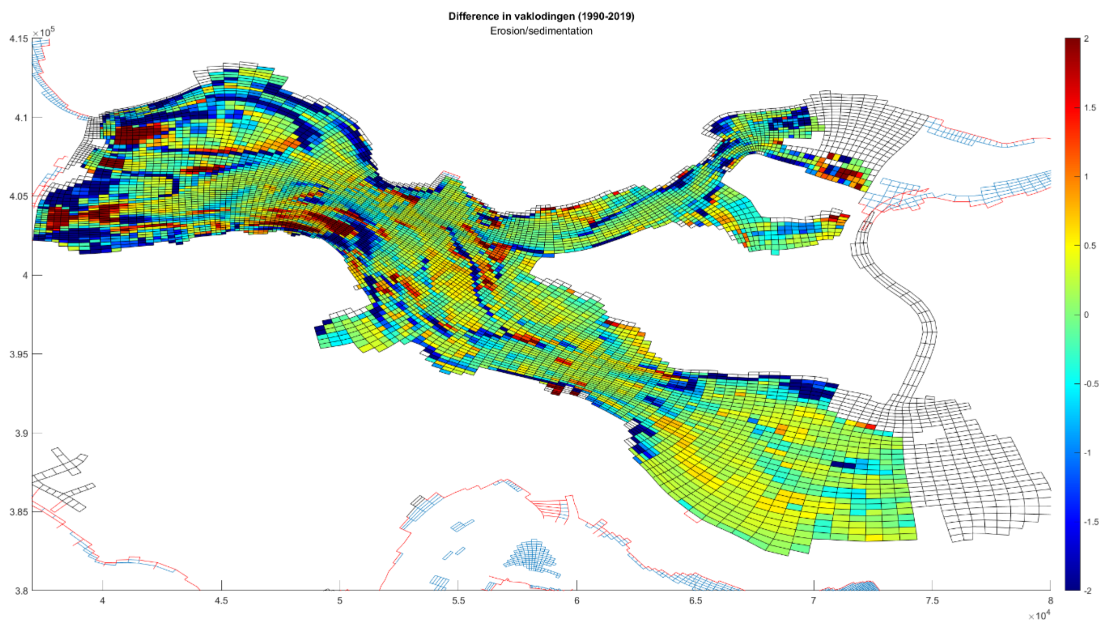


Figure 20: Erosion/sedimentation between 1990 and 2019 (based on vakloding data). Figure shows the differences between these two vaklodingen bathymetries.

Validation run (30 years)

For the validation run of 30 years, the trend values from literature are extrapolated (Table 16) and coupled to the areas of the tidal flats in the vaklodingen (Table 17). In contrast to the values of Table 13, a value of NAP – 1.1 m. is used as boundary between channels and tidal flats for the Roggenplaat. For the Galgeplaat, this value is NAP – 1.3 m. As mentioned earlier, the numbers cannot be seen as reliable when only surface areas, sediment volumes and depths (heights) are observed. Therefore, the validation is also done visual by plotting two dimensional figures of the resulting bathymetry and cumulative erosion and sedimentation.

In Figure 21 the cumulative erosion and sedimentation is given after 30 years development. Numeric results are given in the last column of Table 16. Bathymetries of the start of the simulation (vakloding 1990) and end of the simulation (2020) are given in Appendix 5. It is visible that there is erosion present at the tidal flats as the area decreases from 92 km^2 to 60 km^2. Figure 21 shows that this erosion is present at the boundaries of the tidal flats. Therefore, it can be concluded that waves are responsible for the erosion. However, there are differences between the locations of the erosion. In Figure 24 a plot is made of the erosion and sedimentation of the Galgeplaat (left picture). At the right picture, a cross section is given. It is observed that most erosion is present at the southwest side of the tidal area. This is caused by the fact that only one wind direction (270^o) is considered. Boundaries at the leeward side of the tidal flats undergo less erosion or sedimentation. Variation of wind directions would cause erosion at the other sides of the tidal flats too (Section 4.3.4) with probably a larger decrease in tidal area as consequence.

Indicator	Model vakloding 1990	% decrease per year	Decrease in 30 years according to literature	Predicted values 2020	Validation model
MLW	-1.40				
MHW	1.71				
Areas [km2]					
Channels	290				276
Tidal flats	92	0.50%	13	79.55	60
High parts	8				55
Total	389				391
Volumes [m3]					
Channels	1.82E+10				1.68E+10
Tidal flats	1.11E+08	1.13%	3.09E+07	7.98E+07	1.38E+08
High parts	7.01E+06				2.36E+07
Total	2.57E+10				2.56E+10
Depths [m]					
Channels	13.74				15.47
Tidal flats	0.20	0.01	0.30	0.10	-0.84
High parts	-2.75				-2.16

Table 16: Expected values for surface areas, sediment volumes and heights in the Oosterschelde based on literature and validation model results.

	Indicator	Vakloding 1990	Decrease per year	Decrease in 30 years according to literature	Predicted values 2020	Validation model
Roggenplaat NAP - 1.1 m	Area tidal flats [km2]	10.47	0.38%	1.18	9.29	11.22
	Sediment volume between NAP-1.1 and NAP+2 [E6 m3]	19.94	0.87%	5.21	14.74	35.18
	Average height tidal area [m]	0.11	0.01	0.30	0.41	-1.13
Galgeplaat NAP - 1.3 m	Area tidal flats [km2]	6.97	0.63%	1.32	5.66	4.69
	Sediment volume between NAP-1.3 and NAP+2 [E6 m3]	10.75	1.43%	4.61	6.14	35.18
	Average height tidal area [m]	0.40	0.02	0.60	1.00	-1.04

Table 17: Expected values for surface areas, sediment volumes and heights at two tidal flats based on literature and validation model results.

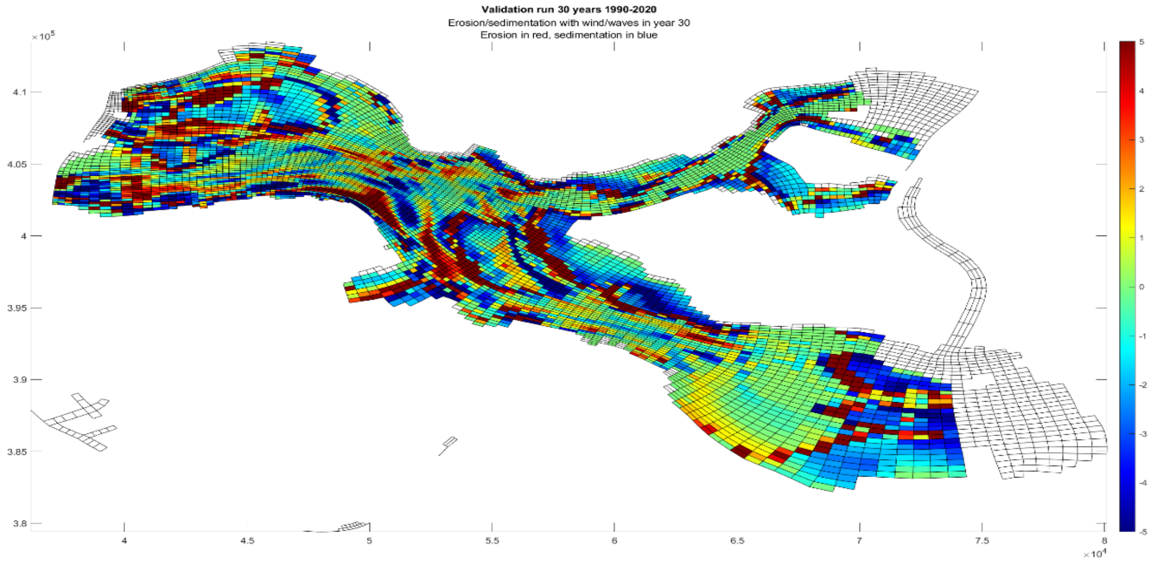


Figure 21: Erosion/sedimentation after 30 years of development for the validation model.

Figure 24 makes it clear that the magnitude of the erosion is large (5 metre or even more). It seems unrealistic that the channels at the boundaries of the tidal flats become this deep. It is possible that this can be allocated to model inaccuracy as gravity will play an important role at locations with a steep slope. With calibration of a bed-slope factor it should be possible to adjust this process. Another cause for these large depths could be that the available sediment is transported to the supratidal parts of the flats, instead of the channels as these supratidal parts accrete in the model.

This is another general observation which is done. Figure 24 shows this trend for the Galgeplaat whereas Figure 21 makes clear that this process is present at other tidal flats too.

In Figure 22 the development of the bed level is given at a location which shows such extreme accretion. As the bed levels increases over time, it can be concluded that this location is dry during certain times in the tidal cycle. When the figure is studied in detail (Figure 23) it is observed that the accretion takes place at that moment when the water level is about to rise again. This means that the accretion takes place when the water depth is small. As (Maan et al. 2018) concludes, at this moment the maximum bed shear stress occurs at this moment. Therefore, the accretion is large during this time. As the height of the waves is determined each 4.31 days, the wave height may be not realistic (too large) during certain times of the tidal cycles, especially at locations with a small water depth. This could be the cause that this accretion is this large. A solution for this problem could be to reduce the time between the two wave calculations to such a level that all water levels of a tidal cycle are considered. Wave calculations with a frequency of half an hour could be a first estimation. However, as this would have an enormous impact on the computation time, this is not done in this study.

Conclusion

Based on the validation run of 30 years it is concluded that a long model run makes that tidal flats shrink in surface area, whereas supratidal parts increase in surface area. Both processes are caused by waves. At locations where erosion of tidal flats is present, the magnitude of the erosion is large. Therefore, for the future development runs, it is expected that this behaviour will be present too.

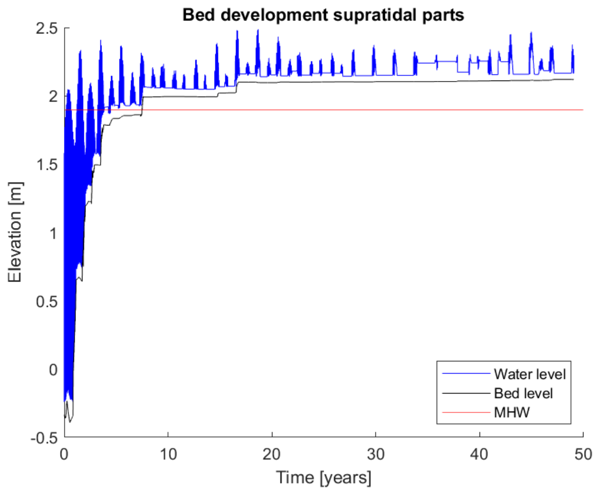


Figure 22: Development of the bed of the supratidal parts.

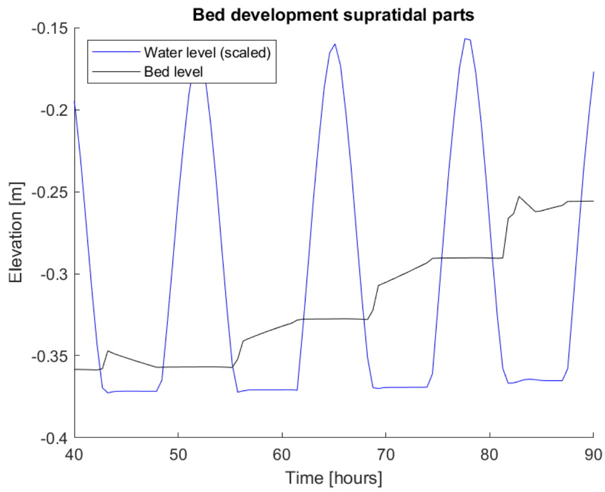


Figure 23: Zoomed in plot of the bed development of the supratidal flats. For clarity the tidal signal is scaled: Water level = 0.1 * original water level – 0.35

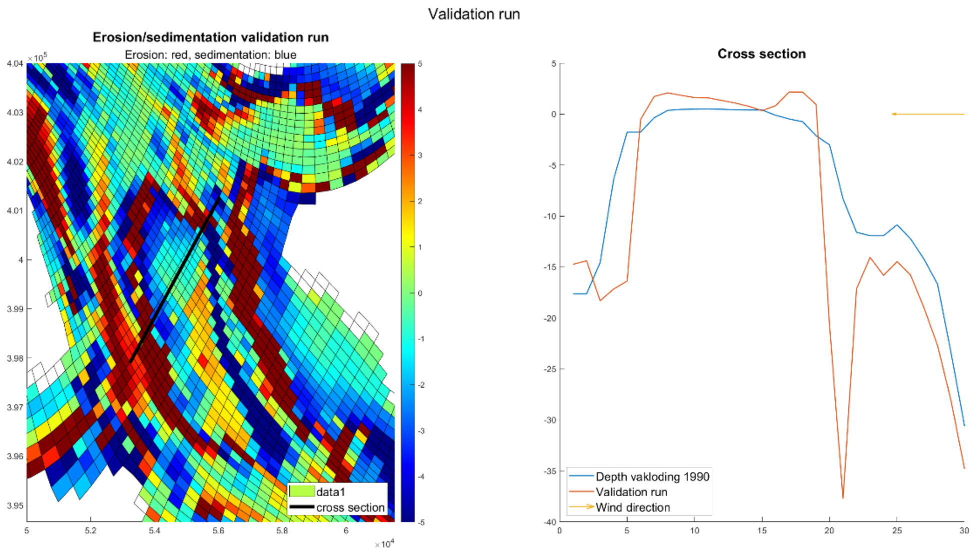


Figure 24: Cumulative erosion/sedimentation Galgeplaat (left) and cross section of bathymetries (right) after 30 years of development in the validation model.

4.3.3. Effect of the SSB

The SSB is represented in a schematised way in the numerical model as described in Section 4.2.2. In order to validate whether the SSB is schematised in a satisfying way, the following model data is collected and compared to literature values:

1. The tidal range at both sides of the SSB by comparing observation points Roompot Buiten and Roompot Binnen;
2. Sediment transport through the SSB.

Tidal range

In Table 18 the tidal ranges for Roompot Buiten and Roompot binnen are given. Both measurement points are located at the former work island Neeltje Jans. Roompot Binnen is located just inside the Oosterschelde, whereas Roompot buiten is located just outside the Oosterschelde. As the tidal differences between these two points are approximately 10 % both for the data as for the model, it can be stated that the SSB has the right amount of friction to dampen the water movement.

Sediment transport

The criterium of no sediment transport through the barrier is measured by studying the total amount of sediment in the Oosterschelde. From Table 16 it is calculated that the difference in total sediment volume is equal to 7.22E07 m^3 over 30 years (0.28 %). This means that the Oosterschelde exports sediment over time. Although this amount seems a lot, it is only 0.18 metre of sediment when it is divided by the area of the Oosterschelde (391E6 km^2). Per year this is equal to 6 mm. When the total amount of sediment is studied in different vaklodingen, a variation is found. For the vaklodingen of 2019 with respect to 1990 the variation is 0.72 % (1.84E08 m^3). This variation could be present because of measurement errors in the vaklodingen. As the variation measured in the long run is less than half the variation between the vaklodingen, it is concluded that the SSB is sufficient capable in the blockage of sediment.

The non-closure of the sediment balance is concluded too in literature (Jacobse, Van der Zel, Arnold, & Hofstad, 2008; Pater, 2012). The uncertainties in the vaklodingen and presence of erosion pits near the SSB are possible explanations of this difference. It is possible that by a different way of representing the SSB in the model, the sediment export would reduce. However, this is not done in this study.

Location	Model vakloding 2019 [cm]	Data 2020 [cm]	Diff. 2020 model-data
RPBU	300	292	-3%
RPBI	264	263	0%
Verschil	-12.00%	-9.93%	

Table 18: Difference in tidal range out- and inside the Oosterschelde for both a short model based on the vakloding of 2019 and measurement data.

4.3.4. Sensitivity analysis

In this section, a sensitivity analysis is done by varying different elements in the model. This is done for two reasons. First, the relative influence of the different elements is explored in this way. Second, it is an attempt to let the validation run represent the morphodynamic development in the Oosterschelde in a better way. Five parameters are assessed:

1. Influence of a smaller morfac
2. Influence of different wind directions
3. Influence of different wind speed
4. Influence of wind/waves (with a model without wind/waves)
5. Influence of morphodynamic development on hydrodynamic indicators

Smaller morfac

As mentioned before, the morfac could influence the development of the morphology in the Oosterschelde. Although a large morfac of 25 is preferred in order to have smaller computational time, it has to be studied whether this large morfac gives results wits smaller deviations compared to a model with a smaller morfac. Therefore, a model is made with a morfac of 3. This model represents 11 years of development (1990-2001).

In Figure 25 a 2D-plot is given of the differences between the erosion and sedimentation with a morfac of 25 and a morfac of 3 for the situation after 11 years development (2001-situation). Blue areas indicate that the model with a smaller morfac gives more erosion whereas red areas indicate that the model with a smaller morfac suffers less erosion (or more sedimentation). Although the model with a morfac of 25 has a lot of erosion at the boundaries of the tidal flats, the model with a morfac of 3 suffers even more erosion at these locations. Furthermore, a model with a smaller morfac has no advantages regarding sedimentation at the supratidal parts of the tidal flats, as these locations are even higher in this model. It could be possible that an averaged continuous wind speed of 6 m/s is too high as in reality smaller wind speeds are present in the majority. Nevertheless, for this study it is justified that a smaller morfac is not preferred above a larger morfac.

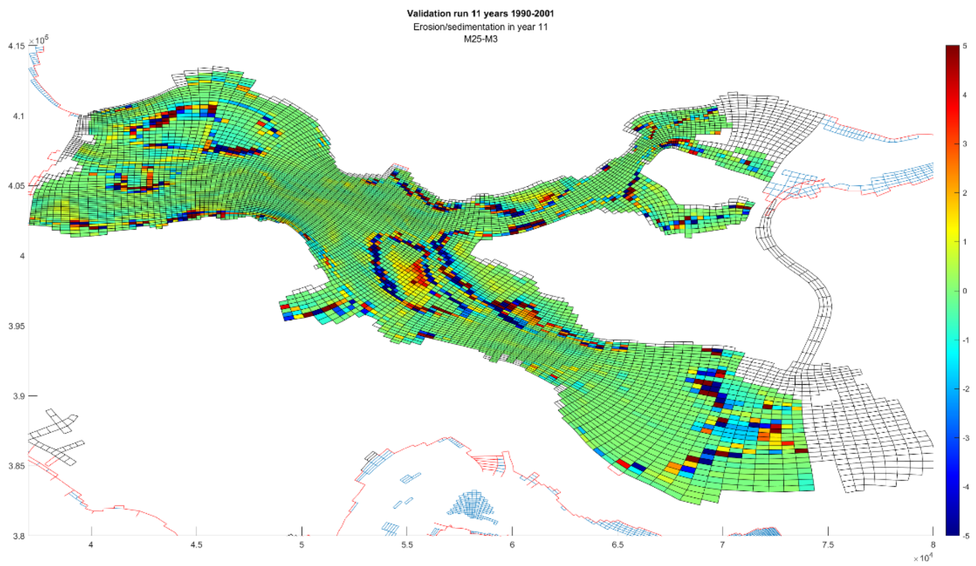


Figure 25: 2D difference plot: erosion/sedimentation M25 minus erosion/sedimentation M3

Influence of different wind directions

In order to see what the influence is of different wind directions on the morphological development of the Oosterschelde, an extra validation run is done. In this run, the wind direction varies in a cycle of 7500 minutes. 60 % of the time a wind direction of 260^o is used. In the other 40 %, a direction of 80^o is used. In Figure 26 and Figure 27 erosion/sedimentation plots are given for the model with uniform and different wind direction. From these figures, it can be observed that the location of erosion is strongly dependent on the wind direction. This is visible at the northside of the Roggenplaat, the northside of the Galgeplaat, and the northside of Het verdronken land van Zuid-Beveland. Erosion occurs in the same direction of the wind, where waves have the possibility to attack at the boundary of the flat. A logical consequence of this principle is that the Slikken van den Dortsman suffers less erosion, as wind directions from northeast are present (80^o).

Another difference is observed at the height of the tidal flats. It is observed that the model with different wind directions causes the flat height to increase more. This is visible at the Galgeplaat. Here a decrease in height is observed at a part of the flat in the model with uniform wind direction (coloured orange). This decrease is not present in the model with different wind directions (coloured blue). This observation confirms the hypothesis that transport caused by wind does play a role in the development of the height of the flat. A last striking difference between the two models is observed at the east side of the Oosterschelde. With a uniform wind direction, almost no changes are observed at Het verdronken land van Zuid-Beveland. Even more erosion is visible at the flats at the westside of the Oesterdam (Hoogekraaier, Speelmansplaten). A model with different wind directions gives the opposite view. Therefore, it can be concluded that the development of specific tidal flats is dependent on specific wind directions which could vary per tidal flat. However, a uniform wind direction can be used when the development of the whole region is studied as the governing process of 'Zandhonger' is present albeit at only one side.

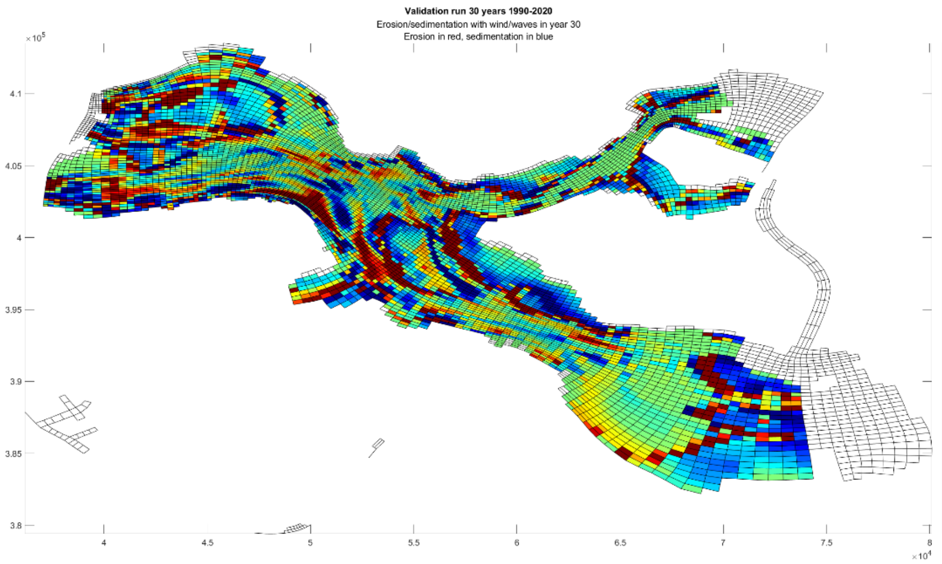


Figure 26: Erosion/sedimentation validation model (repeated)

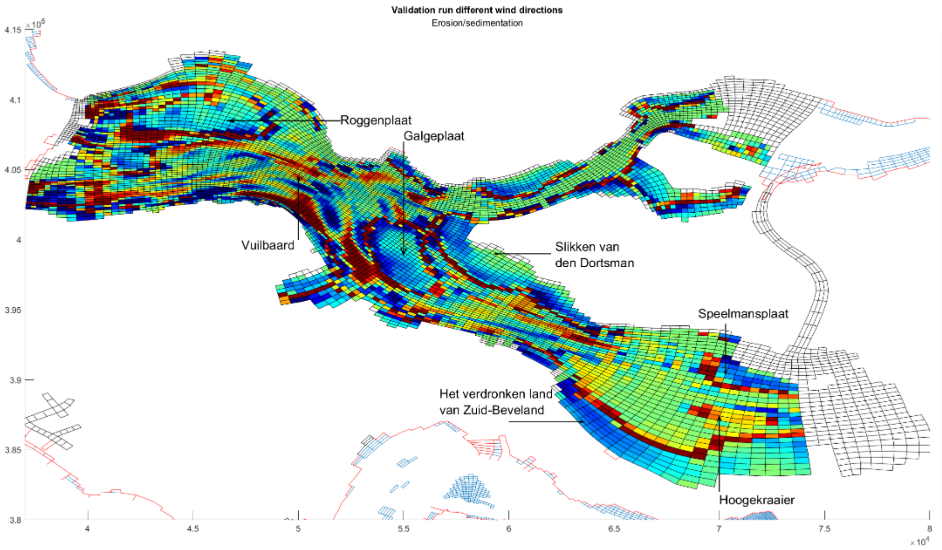


Figure 27: Erosion/sedimentation validation model with different wind directions

Influence of lower and higher wind speed

In order to figure out what the impact is of a lower and a higher wind speed, model runs are performed with wind speeds of 4 m/s and 9 m/s. For the model with 4 m/s, the wind directions vary (same variation as above). In the model with wind speeds of 9 m/s, one constant direction of 270° is used. However, this makes no difference for the goal of these model runs.

In Figure 28 and Figure 29 the cumulative erosion and sedimentation is given for both the model runs. Table 19 gives the development of the surface areas, volumes and depths. Both these models show erosion at the boundaries of the tidal flats and sedimentation at the centres of the tidal flats. For the model with a higher wind speed, this phenomenon is more extreme. In the eastern part of the Oosterschelde for example, the model with 9 m/s shows erosion and sedimentation whereas the model of 4 m/s does not show this pattern. When the numbers are compared, it is concluded that the magnitude of the wind speed is related to the erosion of the tidal flats and the growth of the supratidal parts. This relation is especially visible in the development of the surface area. For the model with 4 m/s, the surface area of the tidal flats changes with -20 % (92 km^2 to 74 km^2). The surface area of the supratidal parts increases with 252 % (8 km^2 to 26 km^2). For the model with 9 m/s, this values are -67 % and 988 % respectively. The original validation model with 6 m/s wind speed, has values in between (- 35 % and + 635 %). Therefore, it is concluded that a lower or higher wind speed does not represent reality better.

Indicator	Model vakloding 1990	Validation model 6 m/s	Wind speed 4 m/s	Wind speed 9 m/s
MLW	-1.40			
MHW	1.71			
Areas [km2]				
Channels	290	276	290	278
Tidal flats	92	60	74	31
High parts	8	55	26	82
Total	389	391	391	391
Volumes [m3]				
Channels	1.82E+10	1.68E+10	1.81E+10	1.69E+10
Tidal flats	1.11E+08	1.38E+08	1.44E+08	6.97E+07
High parts	7.01E+06	2.36E+07	1.16E+07	5.26E+07
Total	2.57E+10	2.56E+10	2.57E+10	2.56E+10
Depths [m]				
Channels	13.74	15.47	14.59	15.36
Tidal flats	0.20	-0.84	-0.61	-0.86
High parts	-2.75	-2.16	-2.21	-2.36

Table 19: Surface areas, depths and sediment volumes for validation models with different wind speeds

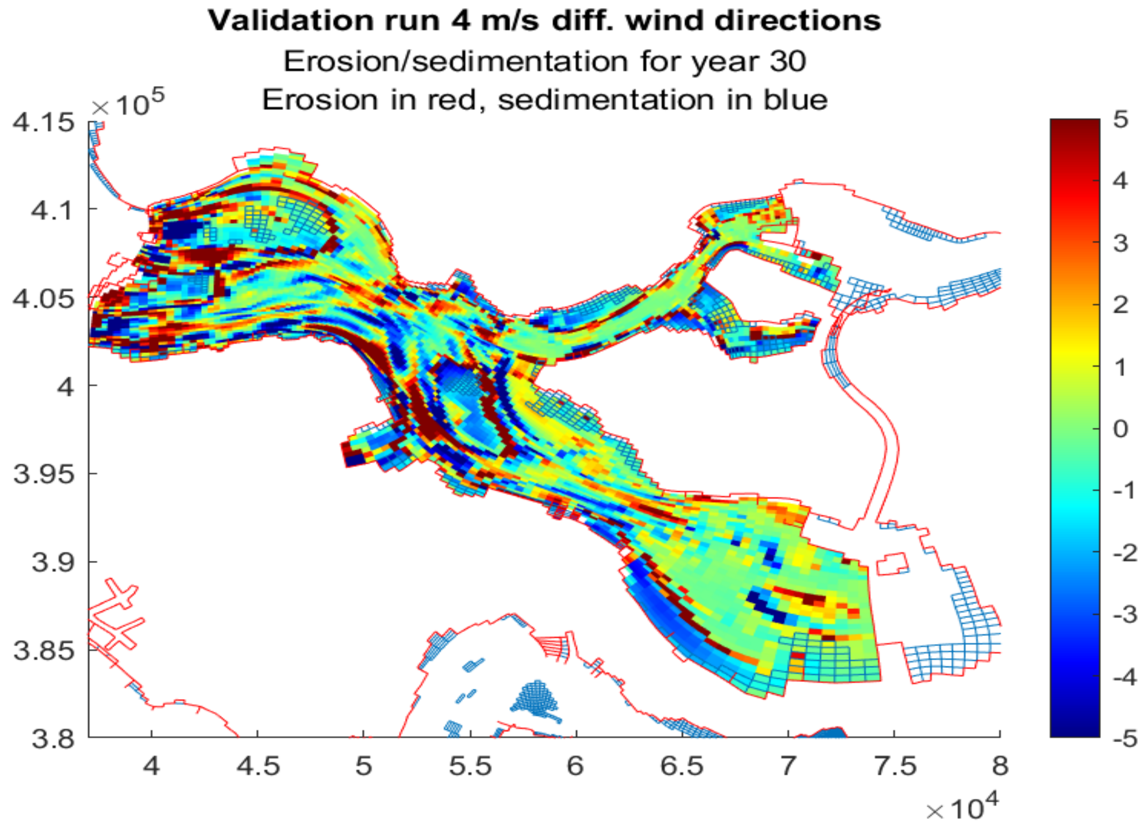


Figure 28: Cumulative erosion/sedimentation after 30 years of development in the validation model for a wind speed of 4 m/s

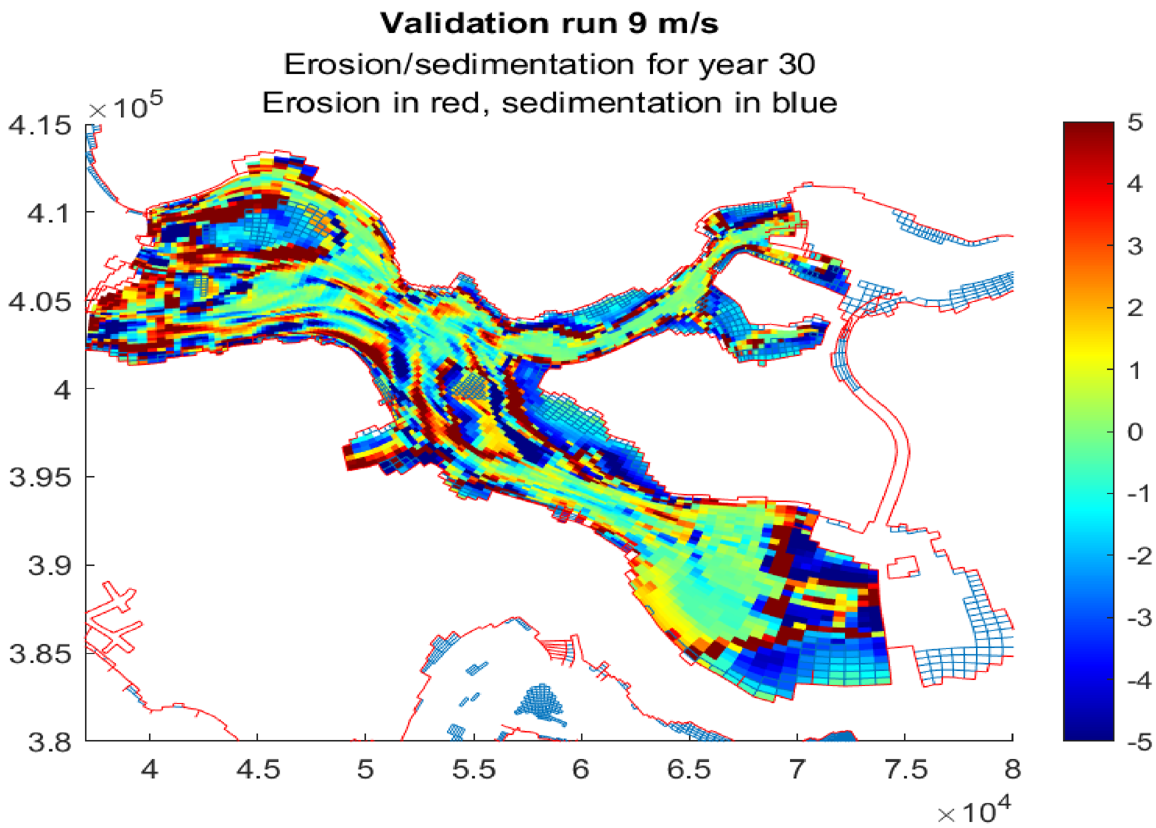


Figure 29: Cumulative erosion/sedimentation after 30 years of development in the validation model for a wind speed of 9 m/s

Model without wind and waves

In order to make a distinction between the flow effect and wave effect in the model, a model run is performed without waves at the boundaries and without wind. The differences are described according to two cross sections (Figure 30). In these cross sections, four lines are visible. In black, green and red, the vakloding, the validation run with wind/waves, and the validation run without wind/waves are given. A blue line is given for the results with only waves. This data is obtained by subtracting the red line (flow + waves) from the green line (only flow).

The first cross section is taken from the centre of the Oosterschelde. At this location a large erosion hole is present in the validation model (between m=50 and m=60) whereas this is not present in the vaklodingen data. The calculated run with only waves (blue line) gives results for this location which fit better in the vaklodingen data. This channel deepening is probably caused by the increasing tidal prism in combination with the lack of sediment from the tidal flats. Another observation is that the drowned tidal flat Vuilbaard (see Figure 27 for location) is represented very well in the model with only waves.

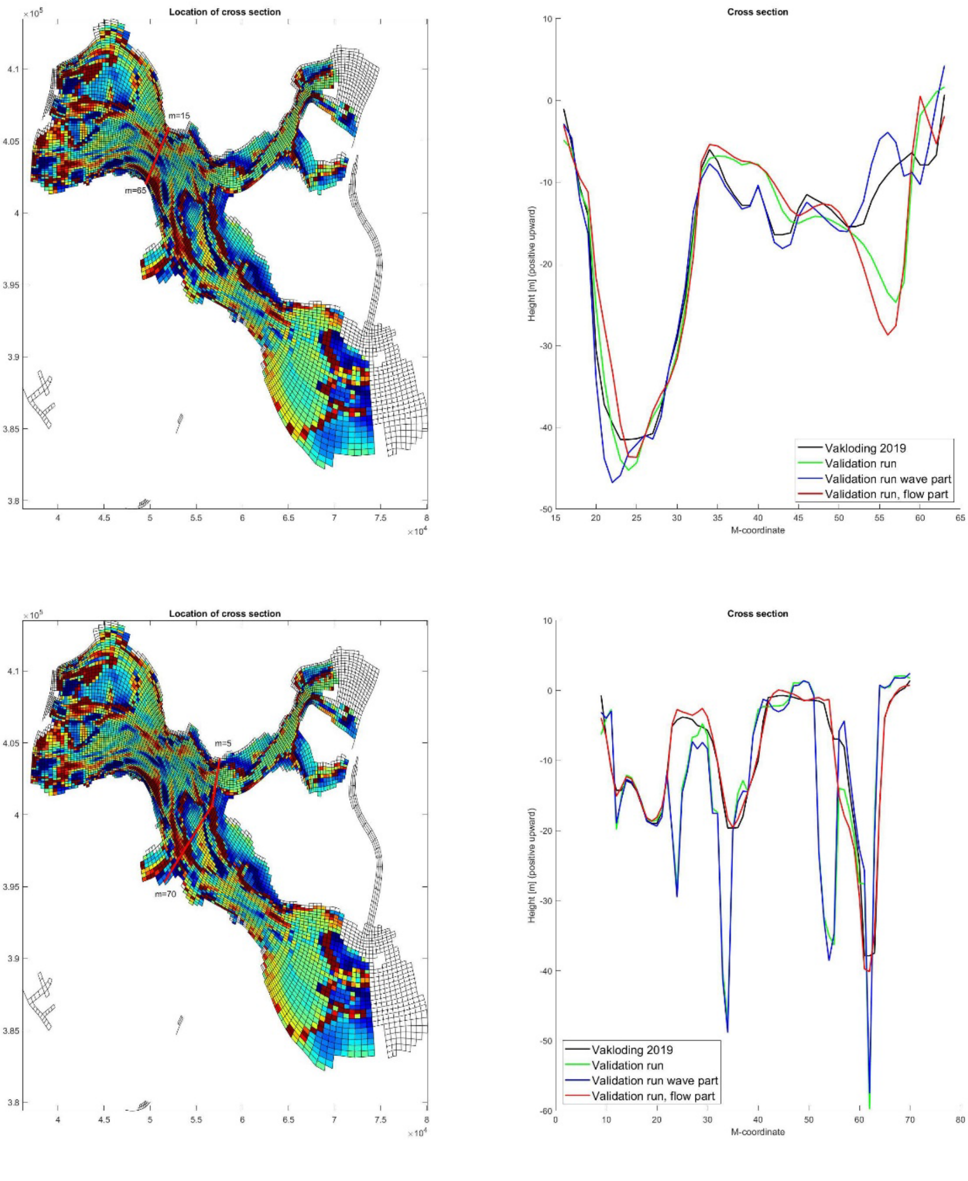


Figure 30: Cross sections in the models with/without flow and waves

It is hypothesized that this is caused by the fact that the waves do not influence the bed as it is too deep, whereas the flow does not influence the bed as it is too shallow.

The second cross section is taken at the Galgeplaat. In this cross section, it is confirmed that the waves (caused by wind) in the model give (too) much erosion at the boundaries of the flats. As mentioned earlier, a smaller wind speed does not solve this problem. As is proved in the model with a morfac of 3, a smaller morfac does not solve this problem either. A possible solution could be to calibrate the model with a bed-slope factor. However, as the trend of erosion at the boundaries is more important than the magnitude of erosion, this calibration is not done in this research.

Short run with new bathymetry
In order to see what the effect of the morphological development is on the hydrodynamics in the Oosterschelde, a 14 day model run is performed with the resulting bathymetry from the validation run. As is described in Section 4.3.1, the difference between the modelled tidal range and the tidal range from the data analysis was smaller than 10 %. Therefore, it can be argued that the tidal range is represented well by the model, when the tidal range differs less than 10 % from the tidal range with the vaklodingen bathymetry.

In Table 20 the development of the tidal prism is given. It is observed that the tidal prism increases in the validation model with wind and waves. This corresponds with the channel deepening (Figure 30). In the model with only wind and waves, a decrease in tidal prism is present because there is no erosion of the channels in this model.

The resulting tidal ranges for the 5 monitoring points are given in Table 21. For the model with both flow and waves the differences increases with respect to the data from 2020. For RPBI and KRSL the differences are large. In Figure 31 the tidal signal is plotted for KRSL. It is observed that the tidal ranges differ more during spring tide. Furthermore, differences are especially present during high tide. This is both the case for both KRSL and RPBI. When a cross section of a channel is plotted, an explanation for this phenomenon is found in the fact that most changes in bathymetry are in the (deep) channels and in the higher parts (Figure 32). During spring tide, this locations get relatively large influence. This causes a larger deviation in the tidal signal.

Furthermore, it was observed that the tidal prism increases in the validation run. Therefore, an increase in tidal range could be expected too. In the model with only waves, the tidal range differs less. This is caused by the fact that no channel erosion is present here. For KRSL, the deviation is smaller as well although the bed development is the same according to Figure 32. However, more north (where the Oosterschelde is more narrow) more erosion of the salt marshes is present in the model with wind and waves (Figure 33). Therefore, the tidal range is larger in this model.

Tidal prism [m3]			
Year	Vaklodingen	Validation run	Only wind/waves
1990	9.578E+08	-	-
2018	1.134E+09	1.172E+09	1.053E+09

Table 20: Tidal prism validation run

Tidal range [m]						
	Data	Vaklodingen (reference)	Validation model incl. wind/waves		Validation model only wind/waves	
Location	2020 [cm]	2018 [cm]	2018 [cm]	Difference	2018 [cm]	Difference
OS4	280	272	287	6%	276	1%
RPBI	257	264	297	13%	278	5%
YE	327	354	370	5%	354	0%
STAV	296	314	343	9%	325	4%
KRSL	304	326	357	10%	338	4%

Table 21: Tidal range validation run

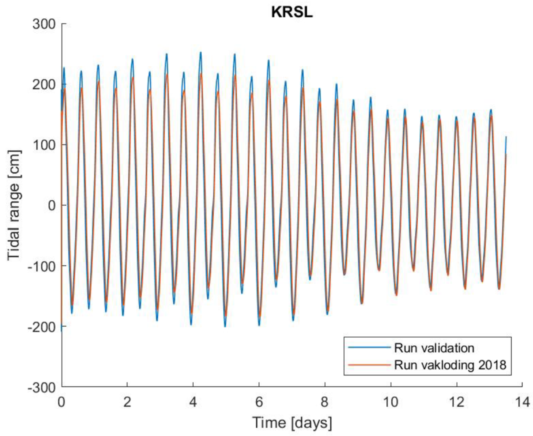


Figure 31: Tidal signal for KRSL

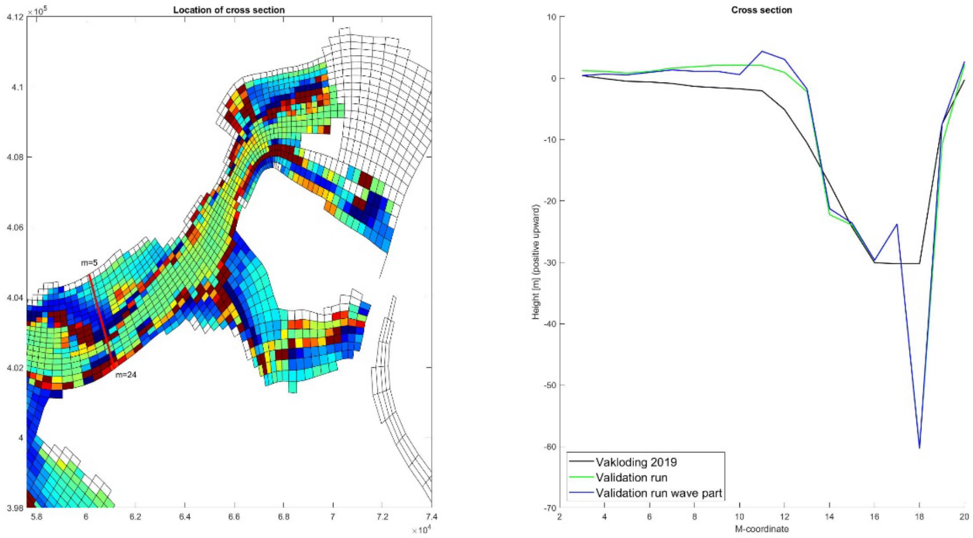


Figure 32: Location of cross section (left) and cross section (right)

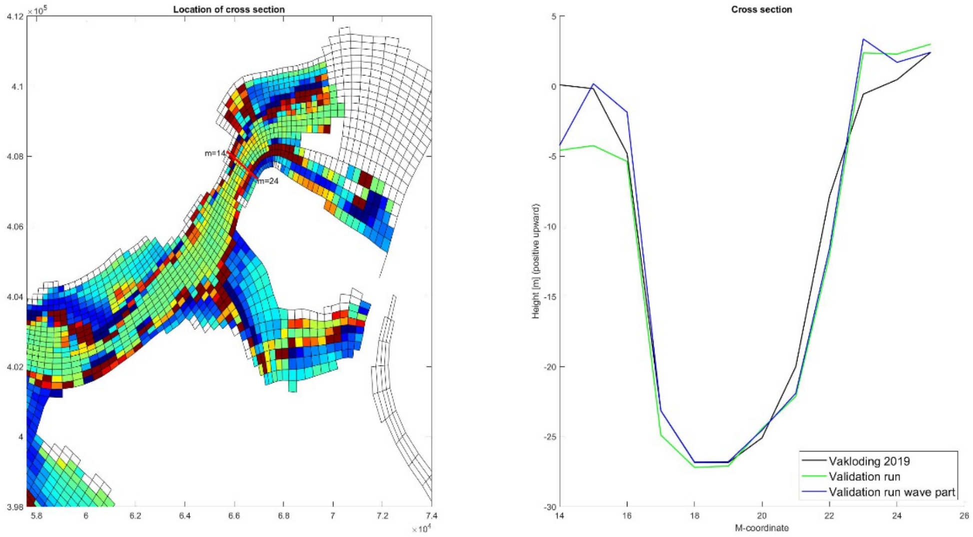


Figure 33: Location of cross section (left) and cross section (right)

4.4. Conclusion

In this chapter, the model setup for the development of the Oosterschelde is described. With model runs of 14 days hydrodynamic parameters of tidal range and tidal prism are validated. A long run of 30 years (1990-2020) is used for validation of the morphological development.

It turned out that the hydrodynamic indicators (tidal range and tidal prism) are represented well in the model when considering the bathymetry based on the vaklodingen of 1990 and 2019. Based on this it can be concluded that the hydrodynamic aspects are represented in a reasonable way in the numerical model. When hydrodynamic indicators are assessed with the resulting bathymetry of the long run, the tidal range increases with a maximum of 10 % with respect to the tidal range at the start of the long run (the 1990 vaklodingen bathymetry). From this, it can be concluded that the modelled change in morphology causes an increase in tidal range.

For the morphodynamic parameters, it turned out that the long run caused the supratidal parts to increase in surface area (+47 km^2). Regarding to literature, this supratidal parts had to decrease as the process of 'Zandhonger' causes the tidal flats to become lower and flatter. Regarding the surface area of the tidal area a decrease was observed in the validation model. This does correspond with literature. However, as the surface area of the channels shows a decrease too (290 km^2 to 276 km^2) the area which is faded from the tidal area is added at the supratidal parts. Therefore, a total decrease in tidal flats (all area above MLW) is not present (increase from 100 km^2 to 115 km^2).

Variations in several parameters (wind direction, wind speed, morfac) did not change this development. It is probable that this phenomenon of increasing supratidal parts is caused by the fact that wave heights (and bed shear stress) are too large when water depths at the tidal flats are small. Therefore, at that moment when the flats are uncovered the accretion is large.

This behaviour of the model should be remembered in the next phase of this research when future scenarios area modelled. Therefore, these trends are summarised below:

Trend	Cause
1. Decrease in area between MLW and MHW, At the boundaries of the tidal flats the erosion has a large magnitude;	Wave action causes this decrease. The large magnitude is probably a model issue as it occurs in the first period.
2. Increase in area and height above MHW;	Significant wave height is too large just before (un)covering of the bed.
3. A small decrease of total sediment volume (± 0.28 % over 30 years);	Representation of the SSB in the model.
4. A small increase in tidal range when the resulting bathymetry of a long run (2020) is used.	Morphological changes in the model. Especially in the first 10 years (spin up effects).

Table 22: Summarised model behaviour

As several model parameters are assessed in this chapter, below an overview is given of the chosen values of these parameters which are used in the future long-term model runs. Parameters which are not assessed/changed, are given in Appendix 1.

- Wind speed: 6 m/s;
- Wind direction: 270^{o};
- Bathymetry: Vaklodingen 2019;
- Representation of the SSB: 2 porous plates with a gate in between;

- Timestep: 2 minutes;
- Morfac: 25;
- Wave update: each 6200 minutes.

5. Future development during yearly average conditions

5.1. Introduction

In order to answer the second sub question, this chapter focuses on the future development during yearly average conditions. This second sub question states:

> ***Sub question 2:*** *To what extent is it possible to model the long-term morphological development of the Oosterschelde during calm conditions when the SSB has been removed and SLR is present?*

This morphological development is described using the indicators as described in Table 13 (Section 4.1). For assessing the morphodynamic indicators, four long model runs (50 years, starting in 2019) are performed (see Table 23). As the focus in these models is on morphological development (long-term), the model results are stored once a model day. Each 4.3 days, wave computations were performed to include the impact of tide and bathymetric changes on the waves. The morphodynamic indicators are calculated for each ten years of development. The first ten years of development gave unrealistic results. These first ten years are considered as spin-up time for the model and excluded from the assessment. The changes during the years are measured against the bathymetry as computed for 2029.

The hydrodynamic indicators (tidal range, tidal prism) are studied with separate models with a model period of 14 days (full neap-spring cycle). As input for the 14 day simulation, the resulting bathymetry from the long run is applied with an interval of 10 years. For investigating the impact of the changed bathymetry on the hydrodynamic indicators, the effect of interannual variations in the tide are excluded. This is done by starting each model run on January 1, 2019. Results for these models are stored every 10 minutes. Although wave impact is not studied with these 14 day simulations, wave computations are done each model day. SLR is modelled in these models in the same way as in the long model by forcing an extra water level boundary condition.

Models with wind/waves
M01: with SSB, without SLR
Z01: without SSB, without SLR
Z11: without SSB, with SLR
M11: with SSB, with SLR

Table 23: Overview of used long-term models. The last model is used as sensitivity model.

In this study the models are marked with characters and numbers (e.g. M01). This codification should be interpreted as follows: The first sign is a character, defining whether the model is with (M) or without (Z) SSB. After this first character, two numbers follow. The first number states whether SLR is present (1) or not (0). The second number defines if wind and waves are present (1) or absent (0).

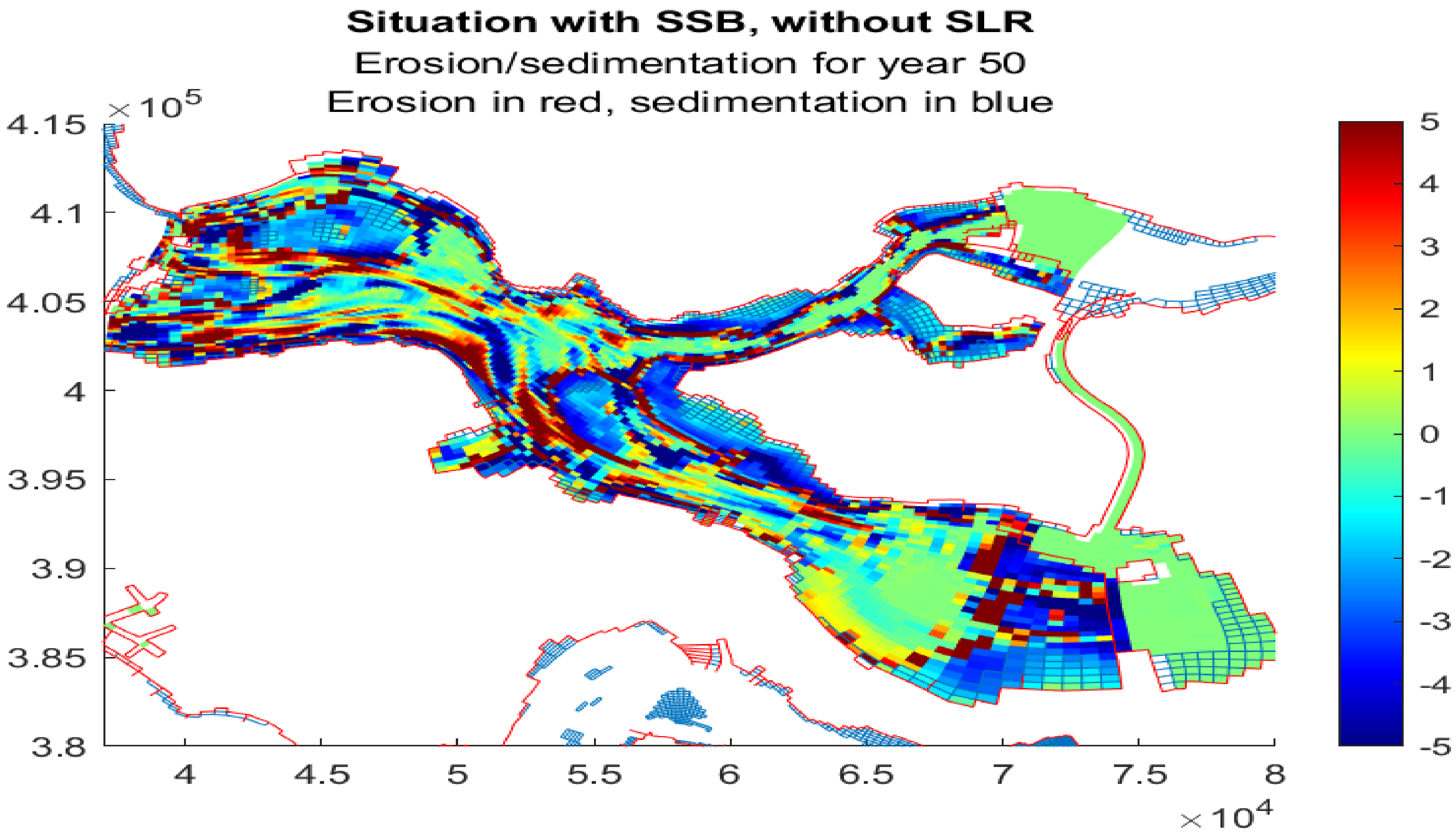


Figure 34: Erosion/sedimentation after 50 years of development for the reference model (M01)

5.2. Model M01: Reference situation (with SSB, without SLR)

In the reference situation, the continuation of the existing situation is simulated (the SSB is preserved and no SLR is considered). The simulated cumulative erosion and sedimentation after 50 years is given in Figure 34. The following four trends were observed in the model results (for the simulated period). The tidal area is defined as the area between MLW (NAP-1.49 m) and MHW (NAP+1.90 m).

The observed trends from the validation model are mentioned below:

1. A decrease in surface area of the tidal flats between MLW and MHW, especially at the boundaries of the tidal flats high erosion rates are computed (see Figure 35 for a conceptual representation of this trend);
2. An increase in surface area and height of the supratidal parts above MHW. (See Figure 35 for a conceptual representation of this trend);
3. A small decrease of total sediment volume (± 0.28 % over 30 years (1990-2019));
4. A small increase in tidal range when a short model run with bathymetry of the validation model is compared to the computed tidal range from the 1990 vaklodingen bathymetry.

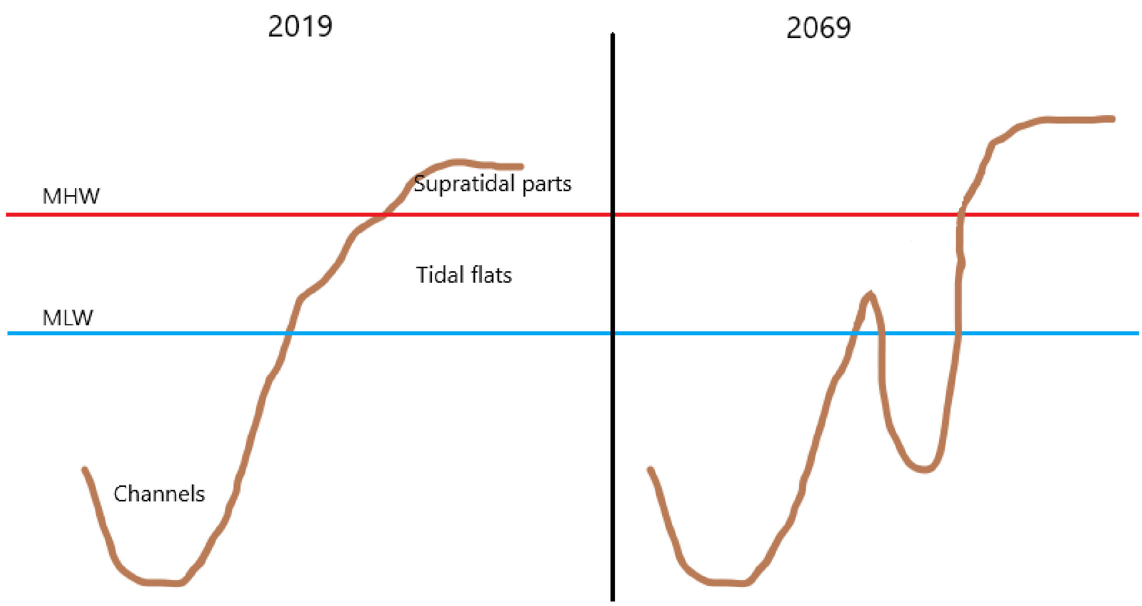


Figure 35: Conceptual representation of observed trends in development of tidal flats in the Oosterschelde.

5.2.1. Trend 1: Surface area of the tidal flats

As can be seen in Figure 34 red areas of erosion area present at the boundaries of the tidal flats. At these locations, the magnitude of erosion is large (more than 5 metre) (trend 1). When the surface area of the tidal flats is studied in more detail (Figure 36) it is observed that the decrease stops after 30 years in 2049 in the model. Furthermore, the height of the tidal flats (Figure 37) starts to decrease in 2049 where it increased in the first 30 years (2019-2049). The sediment volume at the tidal flats shows a change in trend too: in the first 30 years, the sediment volume shows a large decrease. From than on, the decrease has a smaller rate.

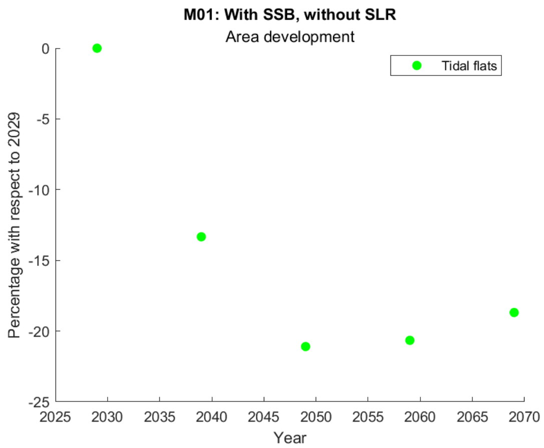


Figure 36: M01: Development of surface area of the tidal flats

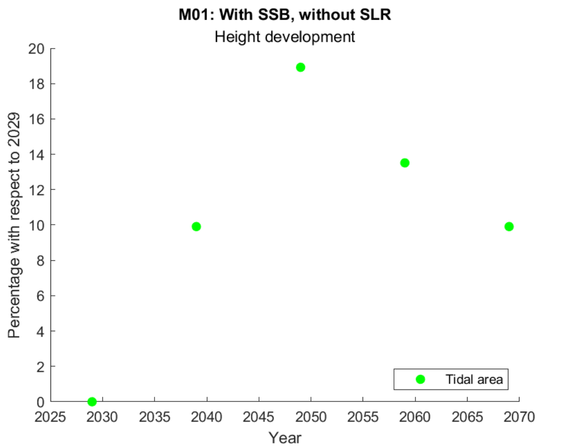


Figure 37: M01: Development of the height of the tidal flats

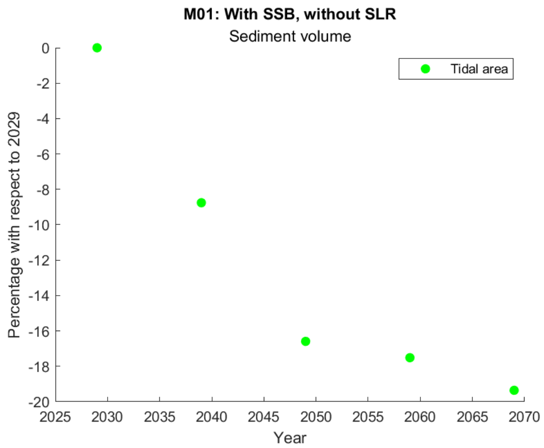


Figure 38: M01: Development of the sediment volume of the tidal area

This change in trends can be explained by the development of the Roggenplaat. Figure 39 shows the surface area of the tidal flats which is disappeared or added to the tidal area over the years. For the Roggenplaat, an increase is visible. In Figure 40 and Figure 41 the development of the surface area and the sediment volume of the Roggenplaat is given. After 30 years, the surface area of the Roggenplaat starts to grow. Moreover, the amount of sediment between MLW and MHW increases. This means that this development is a real growth with sediment from the channels instead of a redistribution of sediment from higher parts to lower parts.

When absolute values from the model are compared, it was observed that the surface area of the tidal flats for the whole Oosterschelde increases between 2049 and 2069 with 2.17E06 m^2. The surface area of the Roggenplaat increases with 2.02E06 m^2. This means that the increasing trend of tidal flat area seen in the entire modelled basin caused by the increase in surface area of the Roggenplaat (Figure 40).

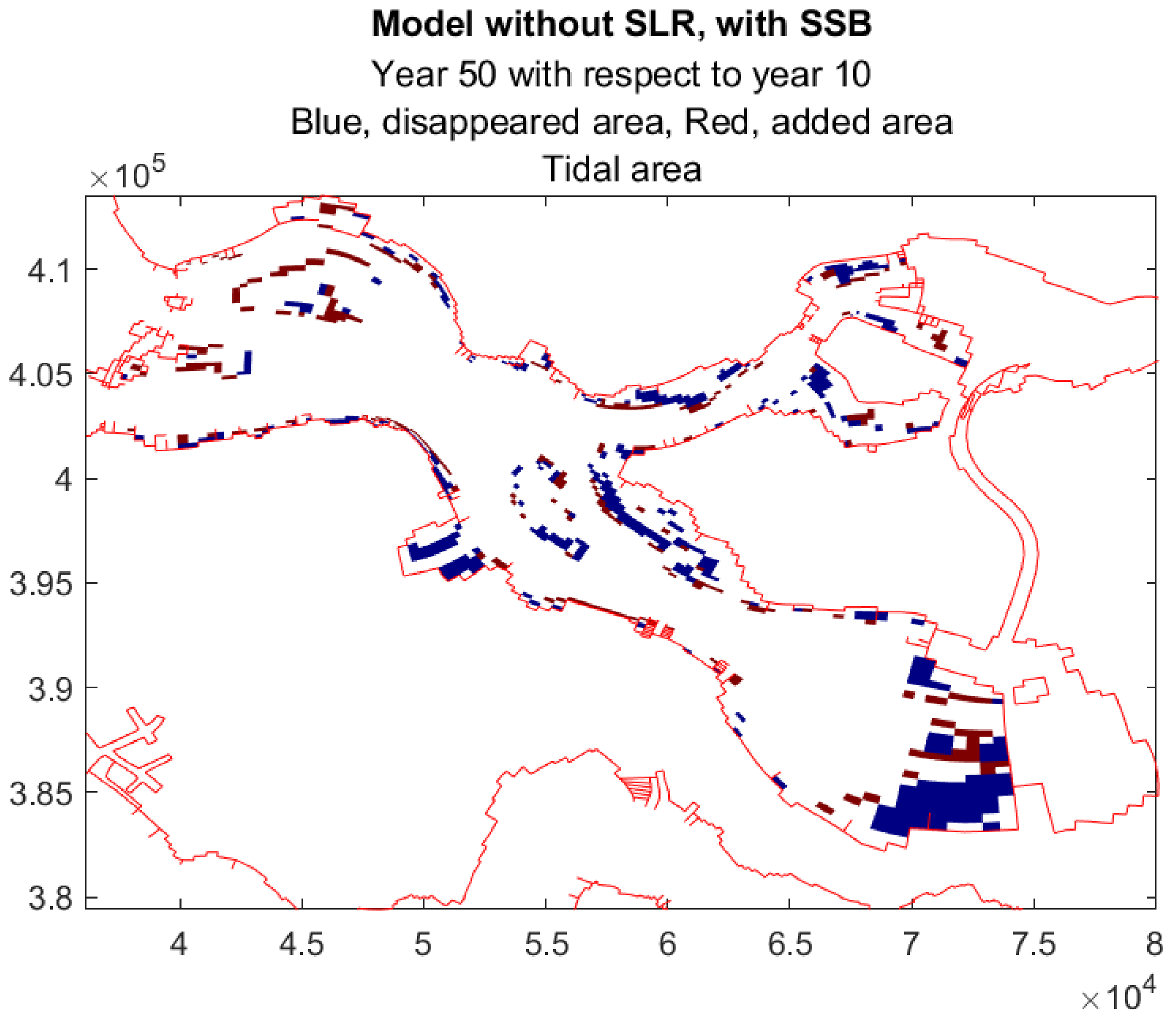


Figure 39: Development of the tidal area in the reference situation after 50 years. Blue areas indicate the tidal area which is disappeared over time. Red areas indicate the surface area which is added over time.

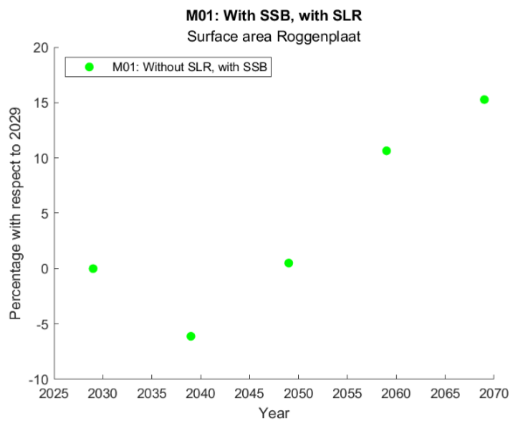


Figure 40: M01: Development of surface area of the Roggenplaat

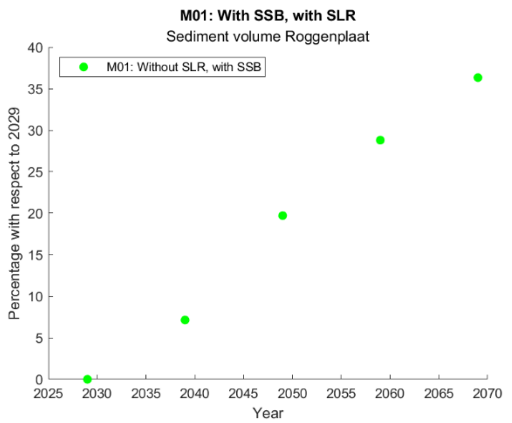


Figure 41: M01: Development of the sediment volume of the Roggenplaat

Another observation in trend 1 was that the magnitude of the erosion is large (more than 5 metre). This should become clear when the development of the channels is studied. In Figure 42 the development of the surface area of the channels is given. Figure 43 gives the development of the depth of the channels. Because the magnitude of erosion is large, it must be the case that deep erosion pits are created in the model. Therefore, the channels should get steeper. As the surface area of the channels decreases, whereas the depth increases, this is indeed the case.

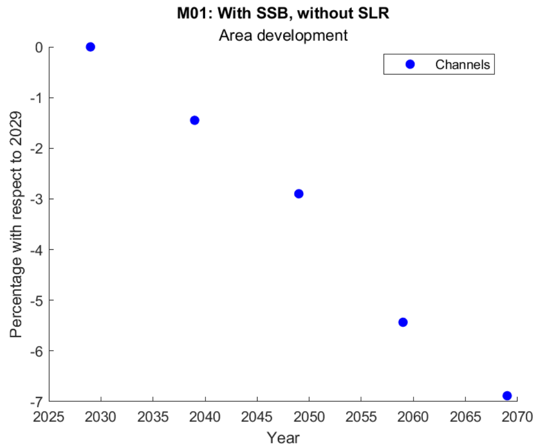


Figure 42: M01: Development of surface area of the channels

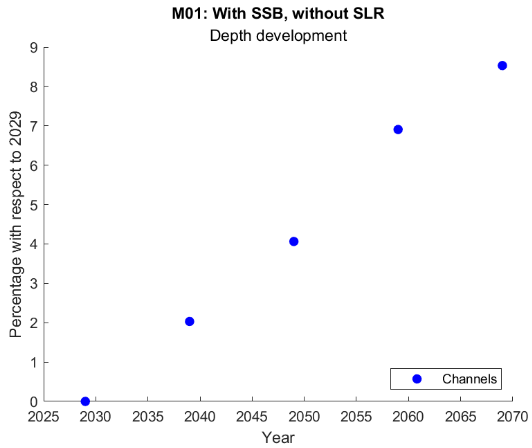


Figure 43: M01: Development of the depth of the channels

5.2.2. Trend 2: Height and surface area of the supratidal parts

The large increase in surface area and height of the supratidal parts in the Oosterschelde is the second trend which was already observed in the validation model (1990-2019). In Figure 34, this increase is visible as the tidal flats show sedimentation in the centre parts (a supratidal part is often surrounded by a zone of tidal area). Figure 44 confirms this observation.

Regarding the height of the supratidal parts there is only minor growth (Figure 45). This can be explained by the fact that the level the supratidal parts is determined by the level of MHW. Sediment only can be transported at locations which are not dry. As MHW is (on average) the highest level where water is present, sediment cannot be transported at higher levels. Therefore, the height increase is small whereas the surface area increase is large.

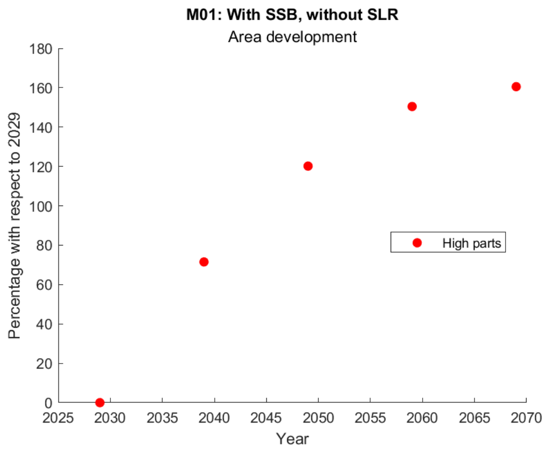


Figure 44: M01: Development of surface area of the supratidal parts

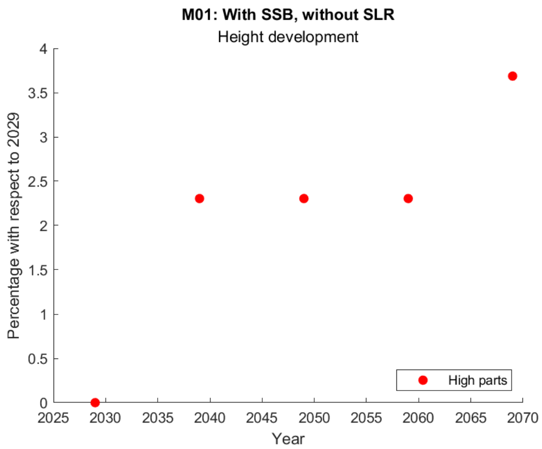


Figure 45: M01: Development of the height of the supratidal parts

5.2.3. Trend 3: Total sediment volume in the Oosterschelde

In Figure 46 the development of the sediment volume in the Oosterschelde is given. In this figure, the trend of sediment export is present (trend 3). However, it must be mentioned that only 0.16 % sediment is exported over 50 years whereas the validation model had undergone 0.28 % sediment export occurred over only 30 years. This difference is probably caused by the fact that bottom protection in this model (M01) is present where the validation model lacked this bottom protection. With this bottom protection no erosion of the bed is possible anymore. When absolute values are considered, it is concluded that this amount of sediment export corresponds with a depth increase of 0.16 m in the channels. This is calculated by dividing the difference in sediment amount by the area of the channels. As the total depth increase in the channels is 1.3 metre, this sediment export of 0.16 metre does not change the observed trend of channel deepening.

5.2.4. Trend 4: Development of the tidal range

In Figure 47 the development of the tidal range over time is given. From the validation it was known that the tidal range increased with 10 % maximum between 1990 and 2019 (trend 4). In Figure 47 this is not observed as the tidal range is constant. However, the difference between the validation model and this reference run (M01) is that in the validation model the tidal range of the start of the simulation is considered (1990) whereas this reference run (M01) has 10 years spin-up time (first data point: 2029 instead of 2019).

However, in Figure 47 values are present from 2029-2069, whereas the validation model had values of 1990 and 2019. The difference is that the validation model. So, in order to see whether an increase has taken place in this reference model, the value from 2029 in Figure 47 should be compared to the 14 day run with the bathymetry of the vaklodingen from 2019 (see Table 21). The average tidal range in this vaklodingen bathymetry of 2019 was 306 cm. In 2029, the tidal range is 333 cm. Therefore, the fourth trend (increase of tidal range with 10 %) is present in this model (M01) too as the tidal range increases from 306 cm to 333 cm. From 2029 to 2069 the tidal range stays constant.

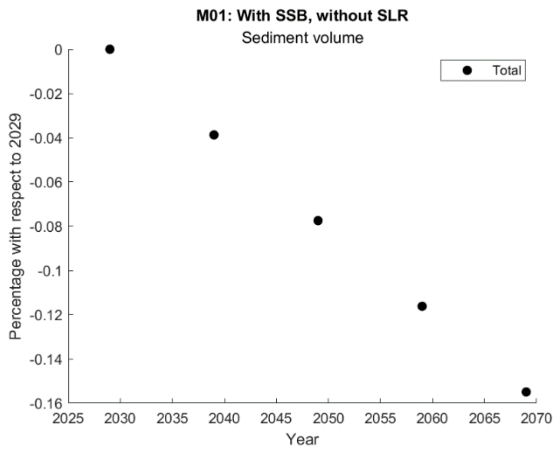


Figure 46: M01: Development of total sediment volume

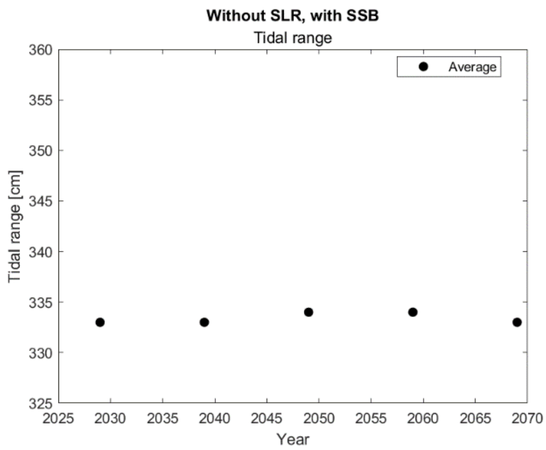


Figure 47: M01: Development of the tidal range

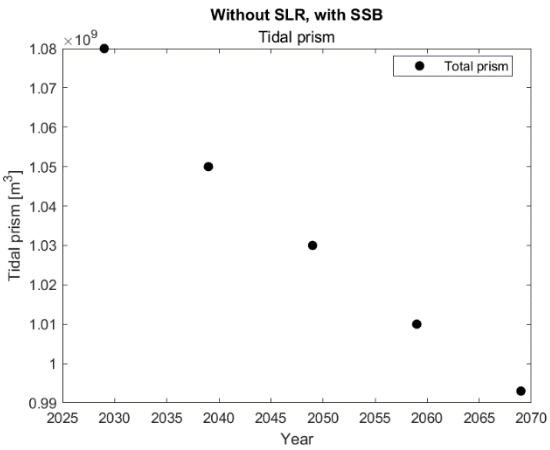


Figure 48: M01: Development of the tidal prism

5.2.5. Development of the tidal prism

Even though the tidal range stabilizes, the modelled tidal prism decreases over time (Figure 48). This is due to increase in surface area of the supratidal parts. As the variation in tidal range is small (MHW and MLW are constant), and the amount of sediment in the tidal area decreases, it may be expected that the tidal prism should grow over the years. However, the tidal prism decreases over time as is shown in Figure 48. This can be explained with Equation 6 (Section 0 and repeated below). The tidal prism is equal to the product of the tidal range and the area of the basin reduced by the sediment volume between MLW and MHW. In Table 24 this tidal prism is calculated. The total modelled area of the basin is equal to 391E6 km^2. This surface area should then be reduced by the surface area of the parts which are above MHWS as these areas are never flooded. Both the calculated tidal prism (based on Equation 6 which is repeated below) and the modelled tidal prism reduce by roughly 8 % in the period between 2029 and 2069 whereas the difference between the calculated tidal prism and the modelled tidal prism stays equal (5 % and 6 %). Therefore, the decrease in tidal prism could be attributed to the increase in surface area of the supratidal parts and the corresponding transport of sediment from the tidal area (between MLW and MHW) to the supratidal parts.

$$TP = TR * A_b - V_{sed,tidal\ flats}$$

Year	MHWS [m]	Tidal range [m]	Surface area above MHWS [m2]	Surface area [m2]	Sed. Vol tidal flats [m3]	TP (calc.) [m3]	Tidal prism (model) [m3]	Diff.
2029	2.10	3.33	1.37E+07	3.77E+08	2.17E+08	1.04E+09	1.09E+09	5 %
2069	2.10	3.33	5.09E+07	3.40E+08	1.75E+08	9.57E+08	1.02E+09	6 %
Diff.						**-8 %**	**-7 %**	

Table 24: M01: Development of the tidal prism in the model with SSB, without SLR

5.3. Z01: impact of removing the SSB

In this section, the development of the Oosterschelde is described for the situation where the SSB is removed in year 0 (2019). Therefore, both the initial changes and the long-term development are important to study.

For the initial changes, the 14 day models with and without SSB are used for 2029. Differences are compared for the tidal range, the tidal prism and (maximum) flow velocities. For the long-term development a comparison is made between the development with SSB and the development without SSB. This is done by assessing the indicators as mentioned in Table 13.

5.3.1. Initial change

Tidal range

Section 4.3.3 already mentioned that the SSB is responsible for extra friction between the sea and the Oosterschelde. As a consequence the tidal range observed in reality is 10 % smaller at Roompot Binnen compared to Roompot Buiten. Therefore, it is logical that an increase in tidal range is observed when the SSB is removed in the model. In Figure 49 it is observed that both the tidal ranges inside as the tidal range at OS4 (at sea) increases. This is logical as the SSB has some impact at the ebb-tidal delta too (Eelkema et al., 2013). Furthermore, the tidal range increases more for the observation points at the landward end of the Oosterschelde (STAV, KRSL). Although the observation point of YE is at land ward direction too, this extra increase is not visible here compared to the observation point in the mouth of the Oosterschelde (RPBI). Furthermore, it is observed that the increase in tidal range that comes with the removal of the SSB is smaller than the decrease in tidal range which was present in the situation with SSB (see Section 4.3.3) Therefore it is hypothesised that the SSB causes less energy loss over time. This is studied in depth in Section 5.5.1.

Tidal prism

Besides an increase in tidal range, the removal of the SSB causes an increase in tidal prism too. This increase is given in Figure 50. The trend that the influence of the removal of the SSB is larger at the landward end of the Oosterschelde is confirmed, as the tidal prism of the Northern part (at STAV) and Eastern part (at YE) increase more than the total tidal prism.

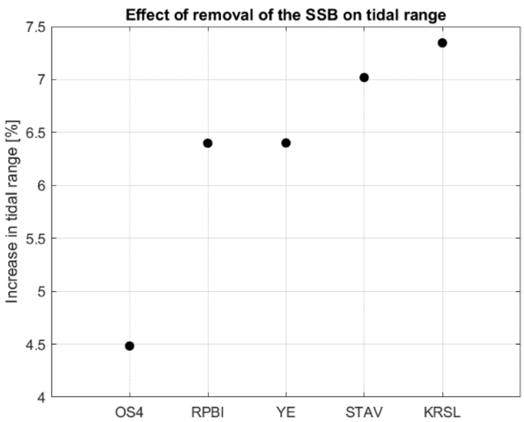


Figure 49: Z01: Initial increase of tidal range because of the removal of the SSB

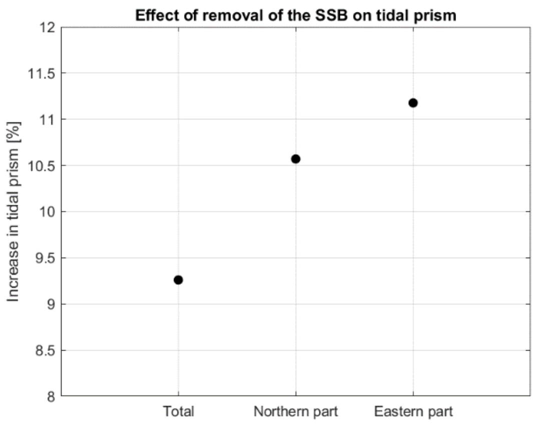


Figure 50: Z01: Initial increase of tidal prism because of the removal of the SSB

(Maximum) flow velocities

As more water must flow in and out the Oosterschelde during a tidal cycle (tidal prism increases) a change in the flow velocities could be expected with the removal of the SSB. In Figure 51 the quotient is given of the flow velocities during the moment of maximum flow velocity for the situation without SSB and the situation with SSB. It is observed that the flow velocities in the channels are larger in the situation without SSB (± 25 %). At the mouth of the Oosterschelde this increases to 60 % for the Schaar channel (middle channel). For the Roompot channel (south channel) increases around the mouth are observed too. Furthermore, it is observed that the increases in the Northern branch of the Oosterschelde are larger than in the rest of the Oosterschelde. This is in line with the observations for the tidal range and the tidal prism in this region.

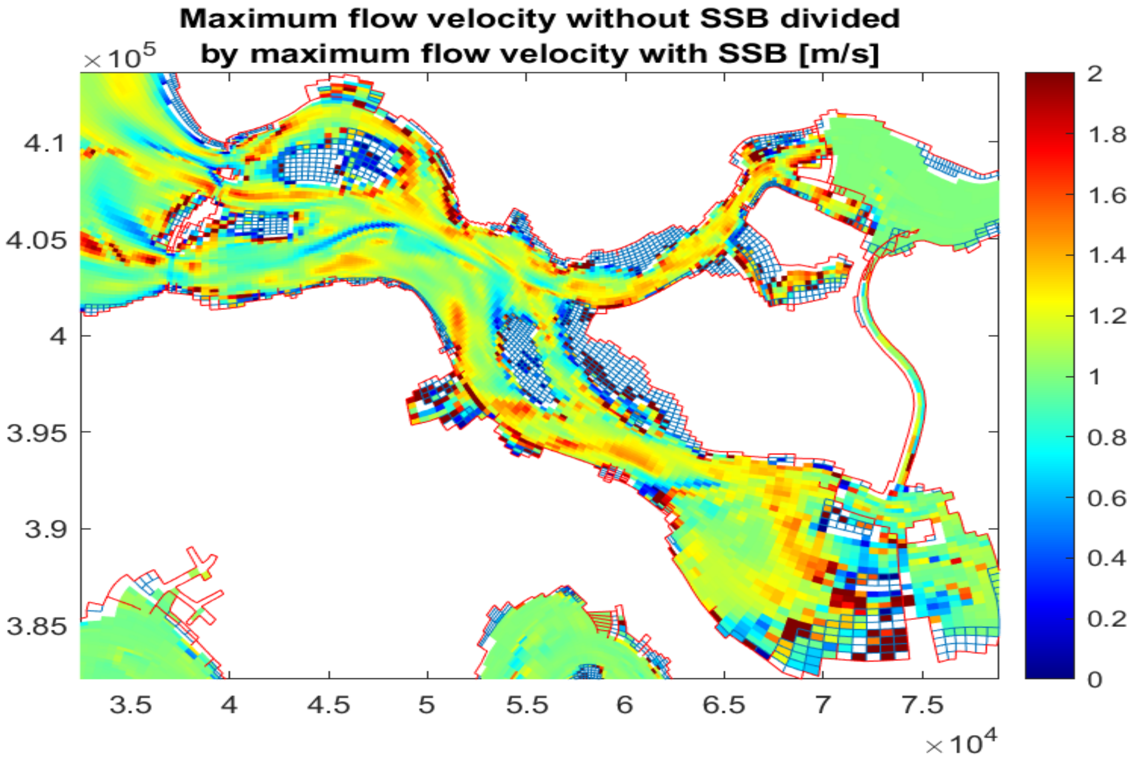


Figure 51: Flow velocities without SSB divided by flow velocities with SSB during the moment of maximum flow velocity (when water level in the Oosterschelde is equal to MSL)

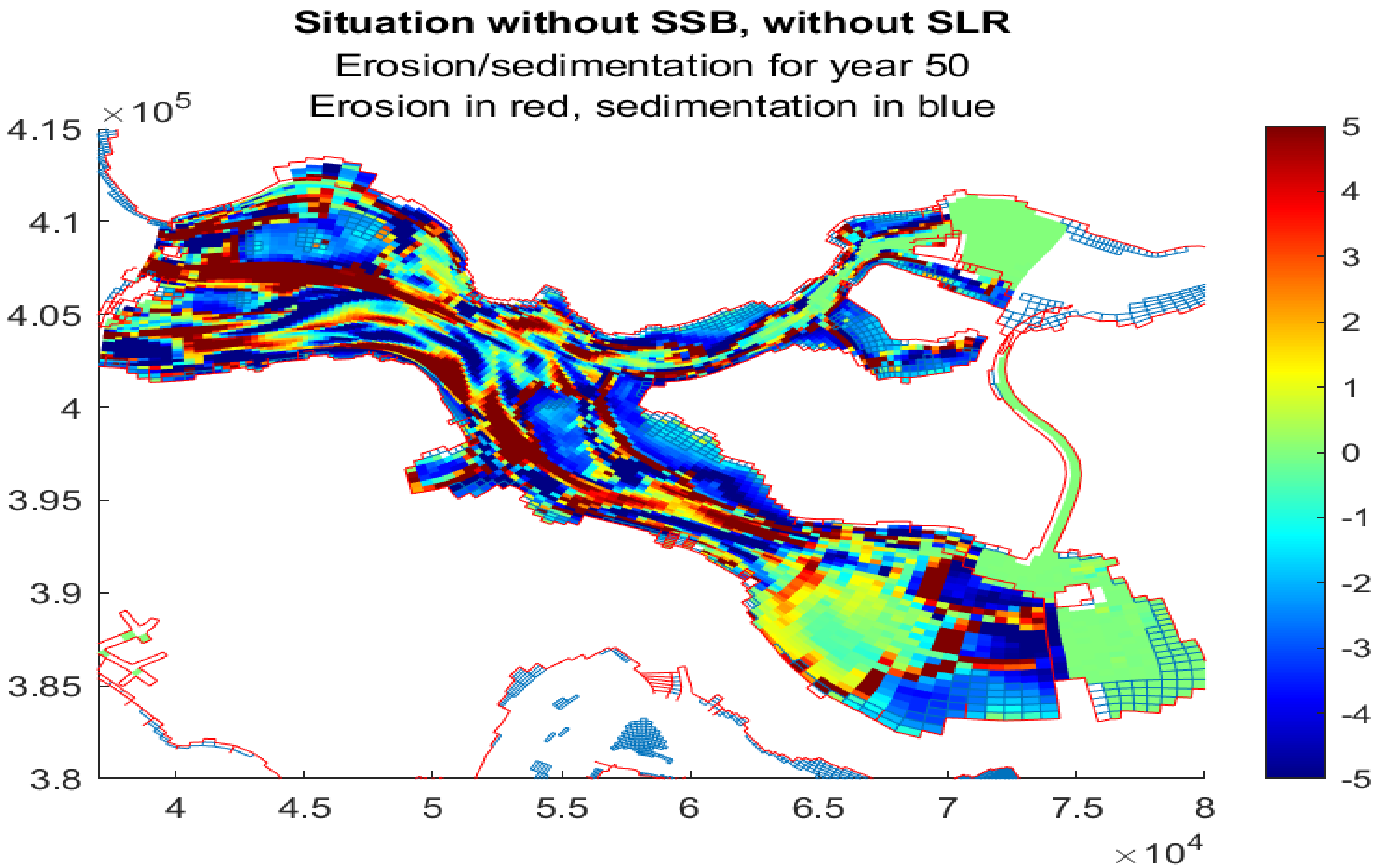


Figure 52: Erosion/sedimentation situation after 50 years of development in the model without SLR, without SSB (Z01)

5.3.2. Long-term development

The long-term development after removal of the SSB in the model is dominated by the increase in tidal prism and tidal range, extra sediment export and a decrease in surface area and sediment volume of the tidal flats. Furthermore, an increase in surface area of the supratidal parts is present.

General morphology

In Figure 52 the erosion and sedimentation are given after 50 years. As was the case in the reference model, some trends from the validation model are observed here too. In this section, the long-term development is described by comparing the development without SSB to the situation with SSB.

	2029	2039	2049	2059	2069
MLW	-1.47	-1.40	-1.36	-1.34	-1.32
MHW	2.17	2.16	2.16	2.16	2.17

Table 25: Z01: Values of MLW and MHW over time. Values are given with respect to NAP and are an average of the MLW and MHW of the 5 observation points

As MLW and MHW change over time, the region where tidal area is defined changes. In order to investigate how this effects changes in the indicators, both results are given for constant MLW (NAP-1.38 m) and MHW (NAP+2.16 m) and varying MLW and MHW (Table 25). The development of the tidal area (surface area, heights, volumes) is given in Figure 53, Figure 54 and Figure 55 respectively.

Regarding the differences between constant and varying boundaries, it is observed that the same trends are present. Values for the surface area and the depth are the same. The development of the sediment volume shows a larger decreasing trend in the scenario with varying MLW and MHW. This could be explained by the fact that the tidal range (which is the difference between MLW and MHW) becomes smaller in this case. Therefore, it is logical that the sediment volume shows a larger decrease.

Tidal area

Compared to the situation with SSB, it can be concluded that there is more erosion of the tidal flats. This is visible in all three indicators: The surface area is smaller in the situation without SSB. Furthermore, the height increase is less, and more sediment is removed from the tidal area (larger decrease). This extra erosion of the tidal flats can be explained by the fact that the tidal range is increased with the removal of the SSB. On average, the tidal range is 3 % larger in the situation without SSB compared to the situation with SSB. Because of this increased tidal range, waves have a larger region where they can attack the tidal flats and more erosion is present.

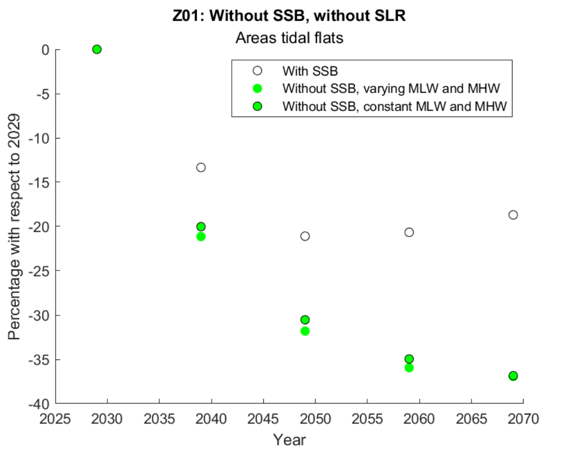


Figure 53: Z01: Development of surface area of the tidal flats

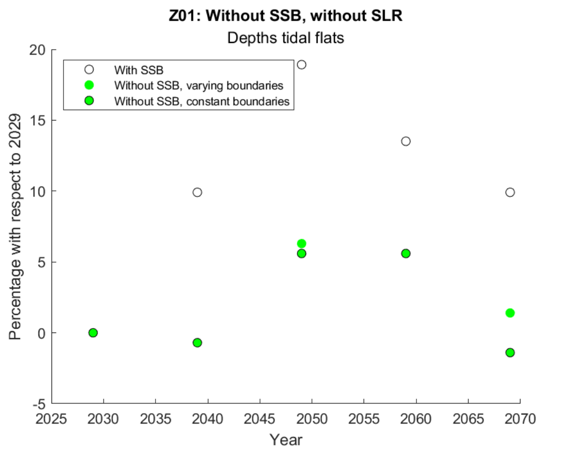


Figure 54: Z01: Development of the height of the tidal flats

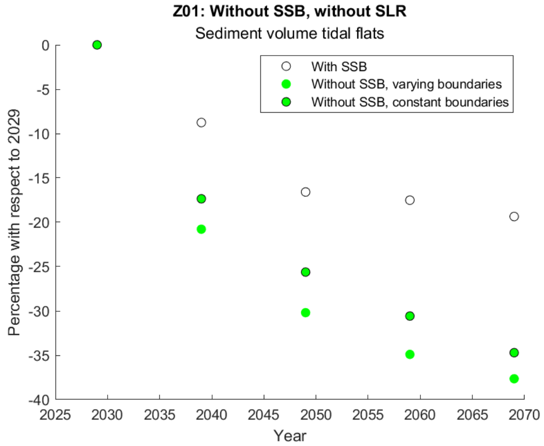


Figure 55: Z01: Development of the sediment volume of the tidal area

Supratidal development

The development of the supratidal parts shows a more extreme increase in both surface area (Figure 56) and heights (Figure 57) in comparison with the situation with SSB. Hereto this trend could be explained with the increased tidal range. This increased tidal range causes more sediment transport which makes that the surface area is larger. Furthermore, the higher level of MHW compared to the situation with SSB makes that the sediment is transported to a higher level. Therefore, the height increase is larger.

Based on these observations, it is concluded that the level of MHW in the model determines the height of the supratidal parts. However, it cannot be concluded that the tidal motion itself is responsible for the growth of supratidal parts in the model as this growth is especially caused by waves (see Figure 22). From literature it is known that tidal motion should be positive for the growth of tidal nature where wave attack causes decrease of tidal nature. This trend is not observed as the surface area of the tidal flats is still decreasing with larger tidal motion. Moreover, when all surface area above MLW (tidal flats and supratidal parts) are considered, the model without SSB shows a smaller growth of surface area than the model with SSB (Figure 59). Although after 50 years the total area is larger in the scenario without SSB, it is suggested that this will change shortly after these first 50 years based on the different growth rate. Therefore, it is concluded that this model does not represent the balance between creation and disappearance of the tidal flats with the tidal motion and wave action respectively.

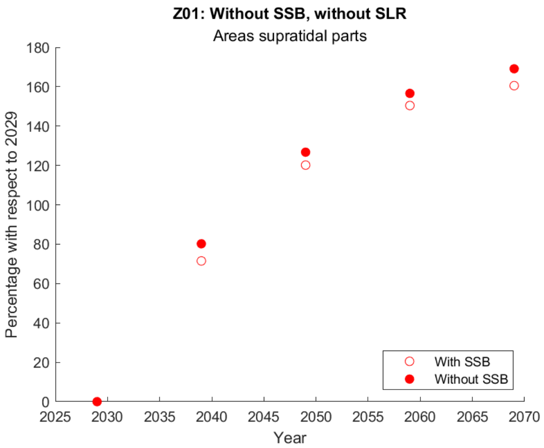


Figure 56: Z01: Development of surface area of the supratidal parts

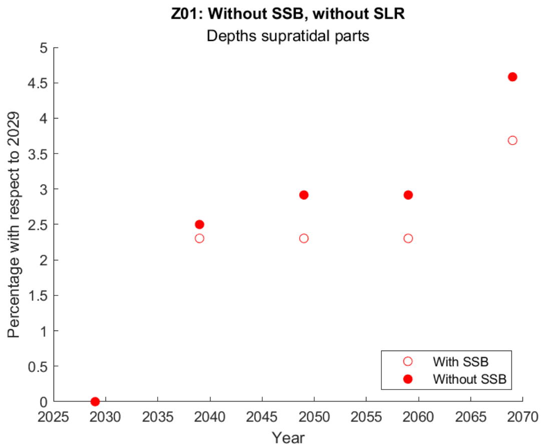


Figure 57: Z01: Development of the height of the supratidal parts

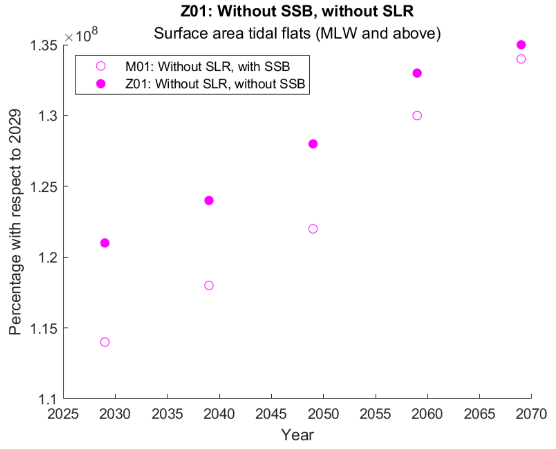


Figure 58: Z01: Development of surface area of the tidal flats (both tidal area and supratidal flats)

Channel development

For the channels, the development of the surface area and depth is given in Figure 59 and Figure 60. It is observed in the model that the surface area of the channels decreases less compared to the situation with SSB. Furthermore, the channels become deeper. This development is also observed in the erosion and sedimentation plot (Figure 52) where large red areas are shown in the channels.

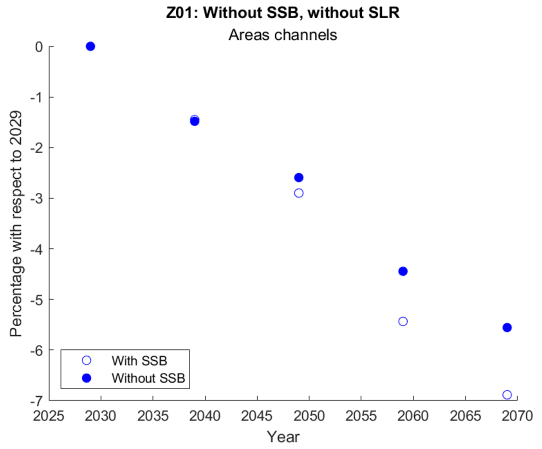


Figure 59: Z01: Development of surface area of the channels

Figure 60: Z01: Development of the depth of the channels

This development should be coupled to the development of the total sediment volume (and the corresponding tidal prism) in the Oosterschelde. Together with the development of the tidal range, the development of these three indicators is given in Figure 61, Figure 62 and Figure 63. As the tidal prism increases with the removal of the SSB (compare Figure 50), the channels are going to adapt to this new tidal prism and will grow in volume. This growth in volume is described by Equation 4. For this reason, the channels decrease less in surface area and become deeper. Consequences of the removal of the SSB are that the flow velocities in the channels are higher and the sediment can transport between sea and Oosterschelde. For these reasons, sediment export is larger in the situation without SSB compared to the situation with SSB.

As the northern part of the Oosterschelde showed more increase in tidal prism and flow velocities, it should be expected that more channel erosion is present in this branch as well. However, this is not the case as Figure 52 shows no erosion in the channels northern branch. In addition, it should be expected that the tidal prism does not decrease as the channels start to export sediment. However, this is not the case either.

Both these observations should be coupled to the development of the supratidal parts in the Oosterschelde, as in the reference situation (M01). In Table 26 the calculation for the tidal prism is given as it was done for the reference situation (M01). Hereto, a decrease in tidal prism is calculated as the supratidal parts in the Oosterschelde cause the surface area of the Oosterschelde to decrease. Both the calculated tidal prism as the modelled tidal prism show a corresponding decrease of around 10-11 %. As the tidal prism decreases, the tidal range shows a decrease too (Figure 62).

The combined development of tidal prism and sediment volume in the Oosterschelde gives rise to the conclusion that the increase of the surface area of the supratidal parts has more impact than the export of sediment on the development of the tidal prism. However, as the SSB is not present anymore, the flow velocities stay larger and the ability to export sediment is still present. Therefore, the amount of sediment keeps decreasing even when the tidal prism is decreases over time after the initial increase (see Figure 61 & Figure 63).

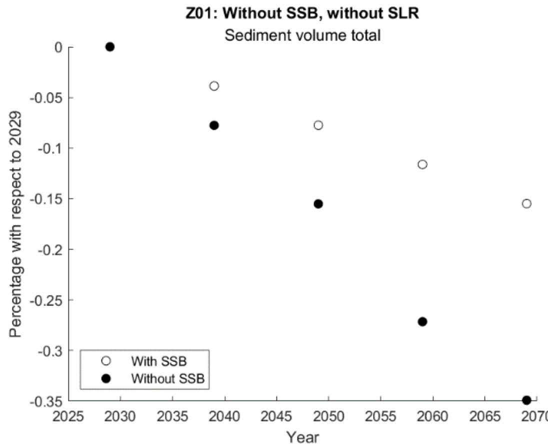


Figure 61: Z01: Development of total sediment volume

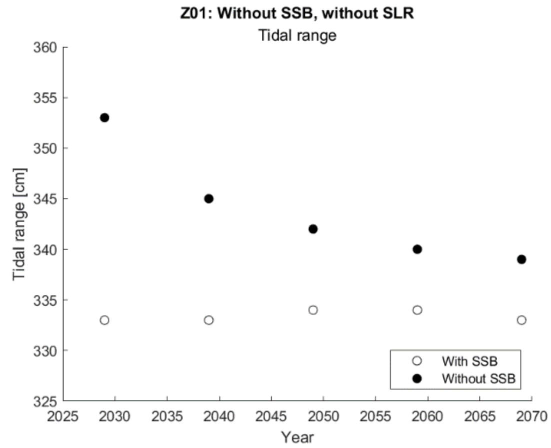


Figure 62: Z01: Development of the tidal range

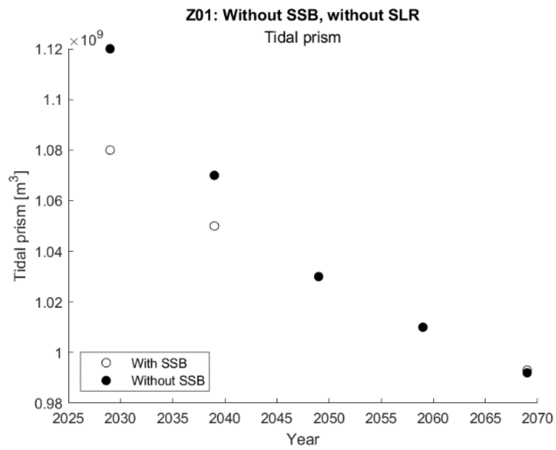


Figure 63: Z01: Development of the tidal prism

Year	MHWS [m]	Tidal range [m]	Surface area above MHWS [m2]	Surface area [m2]	Sed. Vol tidal flats [m3]	TP (calc.) [m3]	Tidal prism (model) [m3]	Diff.
2029	2.42	3.64	2.54E+07	3.66E+08	2.55E+08	1.08E+09	1.12E+09	4 %
2069	2.42	3.49	6.80E+07	3.23E+08	1.59E+08	9.68E+08	9.92E+08	2 %
Diff.						**-10 %**	**-11 %**	

Table 26: Z01: Development of the tidal prism in the model without SSB, without SLR

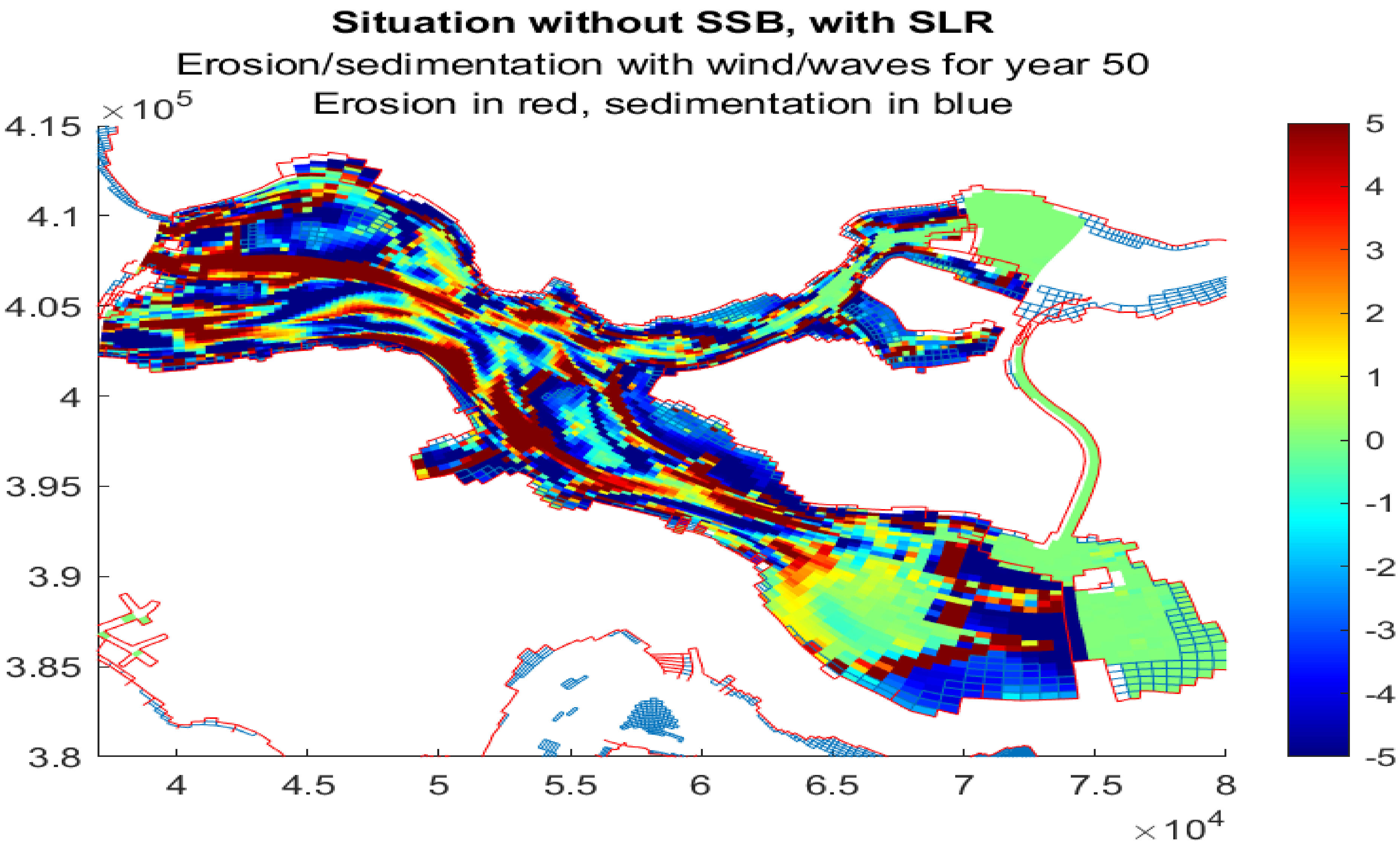


Figure 64: Erosion/sedimentation after 50 years of development for the model with SLR, without SSB (Z11)

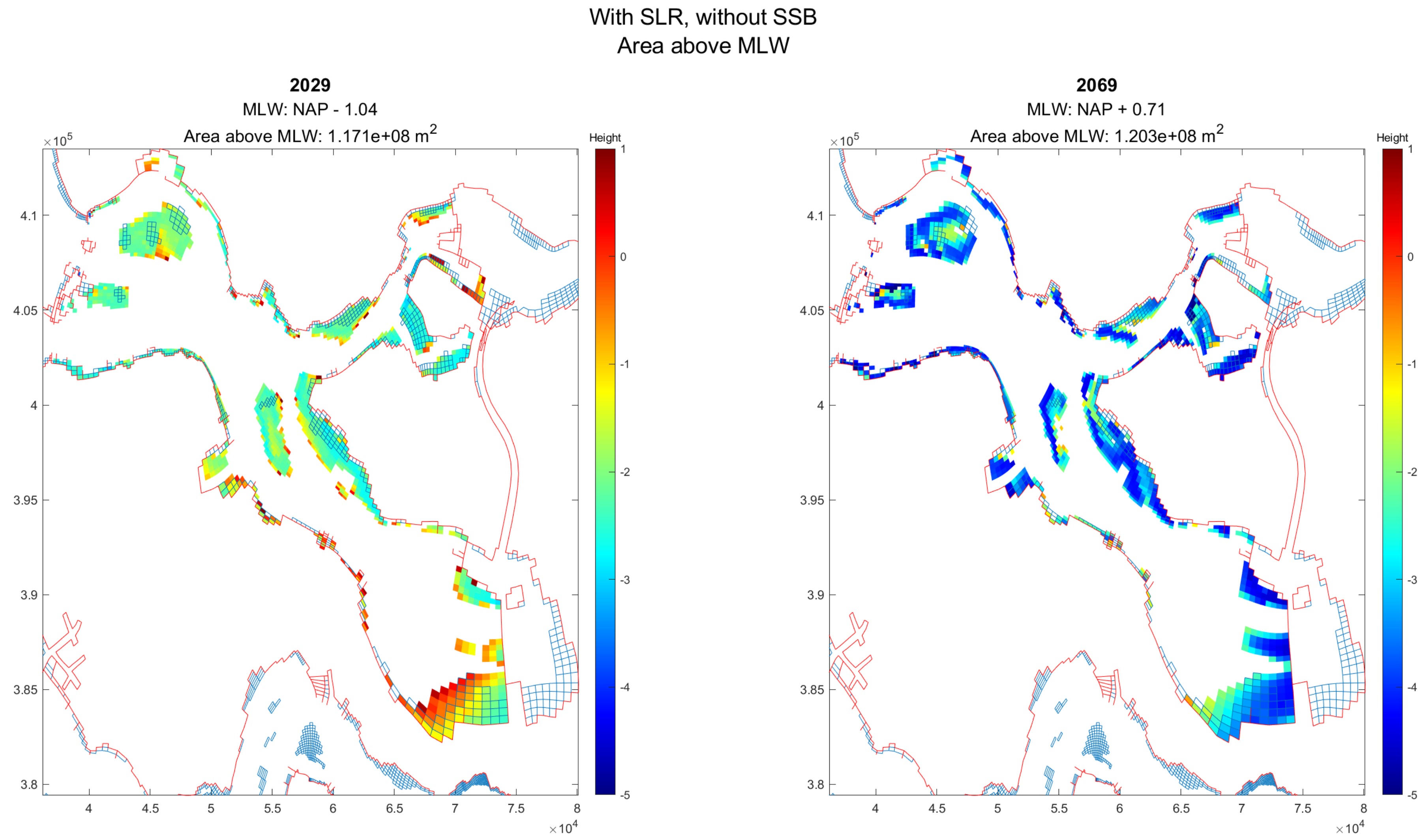


Figure 65: Areas exposed during MLW for 2029 and 2069 in the scenario with SLR, without SSB (Z11)

5.4. Z11: impact of sea level rise

Combining the effects of both barrier removal and accelerated sea level rise results in general in a growth in height of the tidal area and the supratidal parts. This growth corresponds to the growth in MSL. Sediment which is needed for this increase is found in the Oosterschelde itself by a smaller surface area growth of the supratidal parts. As a consequence, less reduction in tidal prism is found.

General observations

For the registration of the height indicators it should be mentioned on beforehand that Delft3d measures the heights and depths with respect to a fixed level. This level is independent of the height of the still water level (MSL). When SLR is applied, the height of MSL increases. However, the depth of the channels does not increase as the reference level of Delft3d is below the new MSL. In order to correct for this shortcoming of Delft3d, the depth of the channels is increased by adding the amount of SLR per decade (0.4 m/decade). In this model run, 2 metre SLR is imposed in 50 years. A direct consequence of this large amount of SLR, is the change of MLW and MHW. In Table 27 the various levels of MLW and MHW are mentioned. As these values change much more than in the situation without SLR, the option to consider one average level of MLW and MHW throughout the whole 50 years is not realistic.

	2029	2039	2049	2059	2069
MLW	-1.04	-0.59	-0.13	0.30	0.71
MHW	2.54	2.97	3.35	3.76	4.15

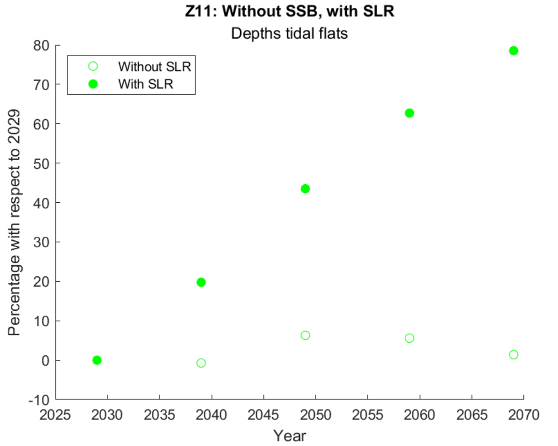
Table 27: Z11: Values of MLW and MHW over time. Values are given with respect to NAP and are an average of the MLW and MHW of the 5 observation points

Height development of the tidal flats

This growth in both MLW and MHW should immediately have consequences for the development of the tidal flats. In Figure 65 a plot is given for 2029 and 2069 with the areas which are exposed during MLW. It turns out that these areas are almost the same, both in location and in surface area. Therefore, it can be concluded that the surface area above MLW (tidal flats + supratidal parts) grows in height with the rise in sea level in this model. This is reflected in the development of the height of the tidal flats (Figure 66) and the supratidal parts (Figure 67) as these show a large increase. Absolute values for this height increase are given in Table 28. It is observed that the height increase is approximately equal to the rate of SLR (0.4 m/decade). However, the height increase reduces over time. This could indicate that the tidal flats are drowning over time with this extreme rate of SLR in the model. Nevertheless, this is not visible in this time span of 50 years. Another option could be that not enough sediment is available over time to make the large grow speed possible.

	1st decade	2nd	3rd	4th
Grow speed of the tidal flats [m/decade]	0.41	0.40	0.37	0.35

Table 28: Height increase of the tidal area (average of tidal area and supratidal parts) over the years



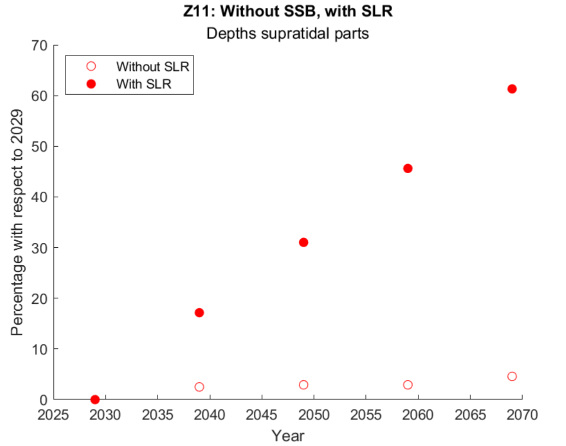
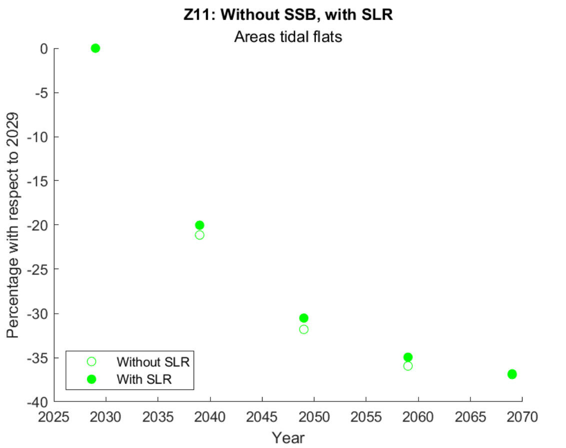


Figure 66: Z11: Development of the height of the tidal flats

Figure 67: Z11: Development of the height of the supratidal parts

In order to make this height increase possible, sediment is needed. Therefore, it would be expected that sediment is imported into the Oosterschelde. Surprisingly, this is not the case (Figure 74). It is the case however that the supratidal flats grow less in surface area compared to the scenario without SLR. In this case sediment for the height increase is available in the model.



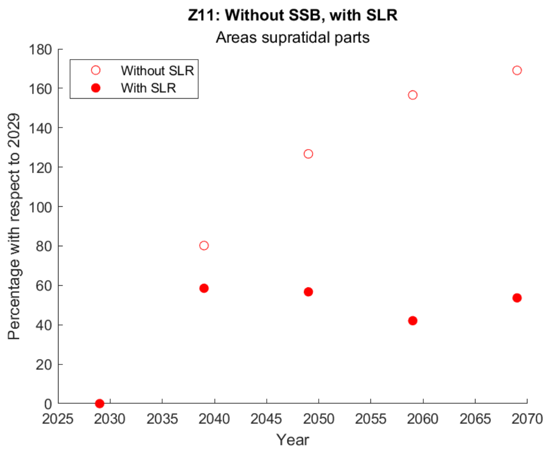


Figure 68: Z11: Development of surface area of the tidal flats

Figure 69: Z11: Development of surface area of the supratidal parts

This gives rise to the conclusion that the development of the tidal parts in the Oosterschelde is independent to the total amount of sediment in the Oosterschelde. In other words: the model does not have the mechanism (tidal asymmetry) to trigger this sediment import. Although tidal asymmetry is no part of this research it can be studied how this tidal asymmetry should change with geometrical characteristics in the Oosterschelde.

As is described by (Friedrichs & Aubrey, 1988) estuarine systems are ebb-dominant when the quotient of the tidal amplitude [a] and the averaged channel depth [h] is smaller than 0.2. When this coefficient is larger than 0.3, the system is flood dominant. Furthermore, the ratio between intertidal storage [V_s] and channel volume [V_c] has impact on whether the system is ebb dominant or flood dominant. In Table 29 the development of this coefficient [a/h] is given. The development of the tidal range and the channel depth are given in Figure 70 and Figure 71 too. Because SLR causes an increase in water level, the channels deepen. Furthermore, the tidal amplitude decreases over time. Therefore, the modelled system becomes more and more ebb-dominant based on [a/h]. As a consequence, it is logical that no sediment import is present. This trend that the system becomes more and more ebb-dominant when SLR is present is also concluded by (Jiang et al., 2020).

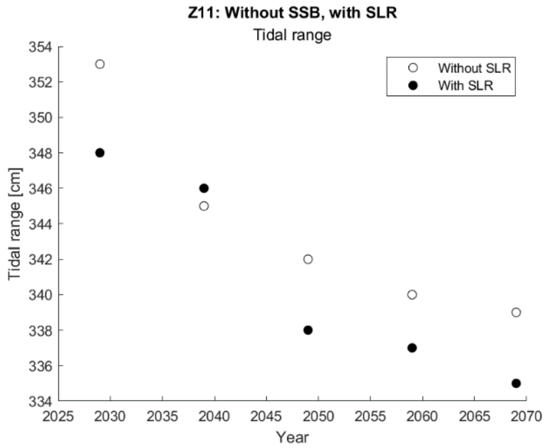


Figure 70: Z11: Development of the tidal range

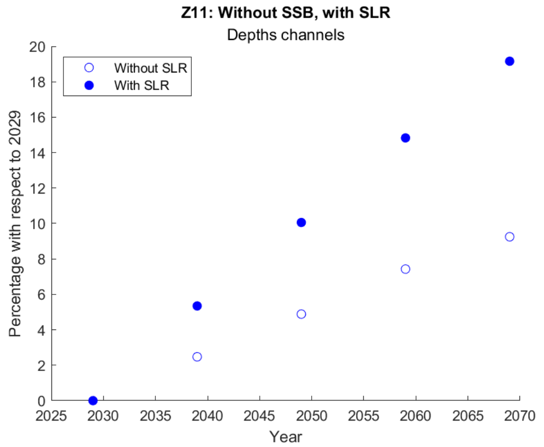


Figure 71: Z11: Development of the depth of the channels

Year	2029	2039	2049	2059	2069
a [m]	1.74	1.73	1.69	1.69	1.67
h [m]	15.71	16.55	17.29	18.04	18.72
a/h	0.11	0.10	0.10	0.09	0.09

Table 29: Averaged tidal amplitude divided by average channel depth for the scenario with SLR, without SSB

The other indicator which determines whether an estuary is ebb dominant or flood dominant is the quotient of the intertidal storage [V_s] and the channel volume [V_c]. The intertidal storage is dependent on the sediment volume of the tidal flats (see Figure 72b and Figure 72c). Due to the decrease in sediment volume of the tidal flats (see Figure 75) the intertidal storage increases. Furthermore, as the channel depth increases due to SLR (Figure 71) whereas the surface area of the channels has only a small decrease (Figure 76), the channel volume increases. So, both V_c and V_s increase over time in the model and dependent on which increase is larger, the quotient of V_s and V_c would change. In the model results, the changes are comparable which makes that the ratio between V_s and V_c does not change significantly over time (see Table 30).

Year	2029	2039	2049	2059	2069
V_s [m^3]	9.00E+07	8.27E+07	7.76E+07	8.89E+07	9.51E+07
V_c [m^3]	4.30E+09	4.48E+09	4.66E+09	4.85E+09	5.06E+09
V_s/V_c	0.0209	0.0184	0.0166	0.0183	0.0188

Table 30: Ratio between intertidal storage and channel volume for the model scenario with SLR, without SSB (Z11)

In Figure 73 the ratio between a/h and V_s and V_c with the corresponding boundaries between ebb- and flood dominance are given. Many relationships for the definition of morphological equilibrium are presented in this figure. For the Oosterschelde, the most reliable relationships are Eq. 22 and Eq. 21 as Oosterschelde data is included in these relationships. (Zhou et al. 2018) give typical values for V_s/V_c and a/h too. These values are larger than the values found in this model. This is studied in depth in Section 6.2.

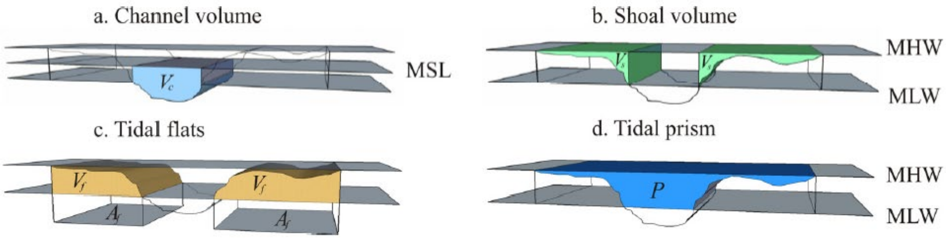


Figure 72: Definitions of channel volume (a), intertidal storage (b), sediment volume of the tidal flats (c) and tidal prism (d) (Dissanayake, 2011)

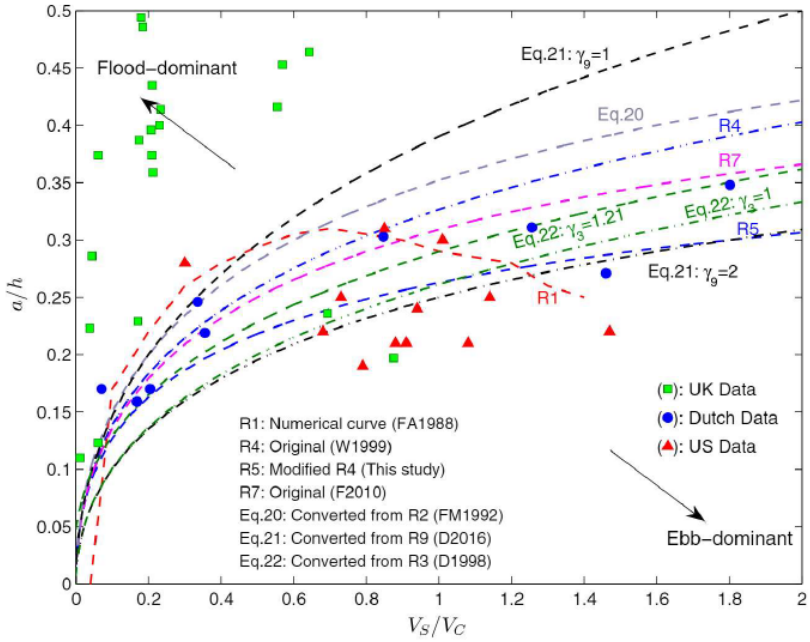


Figure 73: Relationships between Vs/Vc and a/h. The points indicated in red, blue and green represent different estuaries in The Netherlands, US and UK respectively. Eq. 21 is based on (Dronkers, 2016) whereas Eq. 22 is based on (Dronkers, 1998). (Zhou et al. 2018)

Although it was stated by (Friedrichs & Aubrey, 1988) that an estuary is ebb-dominant when [a/h] < 0.2, it is possible that this is not the case for the model of the Oosterschelde in this research as the values for V_s/V_c are very small. However, as sediment is exported from the basin (see Figure 74), it is plausible that the system becomes more and more ebb dominant.

This increased ebb-dominance is visible in the development of the sediment volume (Figure 74) as more sediment is exported. Figure 75 shows the development of the sediment volume of the tidal flats. As the tidal range shows a larger decrease over time and the surface area of the tidal flats is equal with respect to the scenario without SLR, it should be expected that the sediment volume would decrease more. However, as a large increase in height of the tidal flats is present due to SLR, the sediment volume at the tidal flats is larger in the scenario with SLR. Therefore, it can be concluded that SLR has more impact than the decrease in tidal range. This is reasonable as the tidal range only decreases with 0.13 metre whereas the SLR is equal to 2 metre.

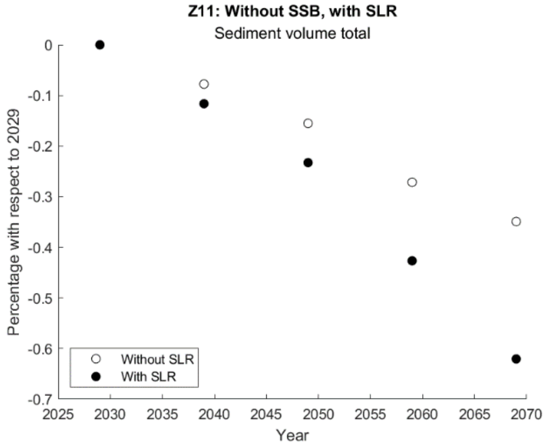


Figure 74: Z11: Development of total sediment volume

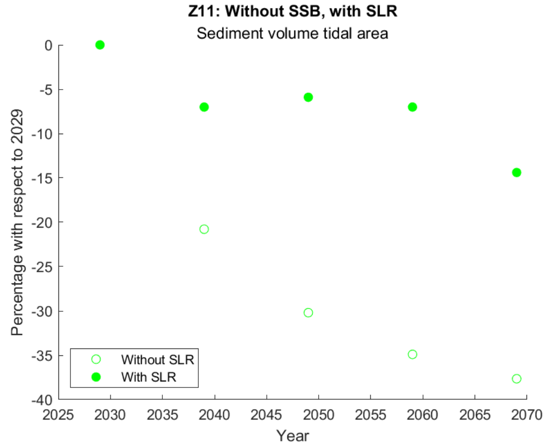


Figure 75: Z11: Development of the sediment volume of the tidal area

In earlier scenarios (M01/Z01) it was observed that the surface area of the supratidal parts increases at the expense of the surface area of the channels. In this scenario (Z11), it was observed that the surface area of the supratidal parts does not increase that much. Because of continuity of the total surface area, the surface area of the channels shows less increase (Figure 76).

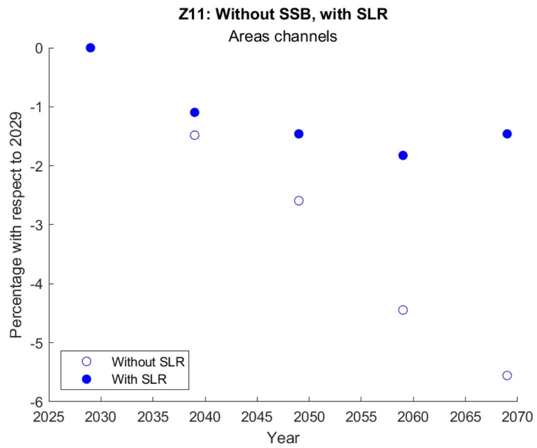


Figure 76: Z11: Development of surface area of the channels

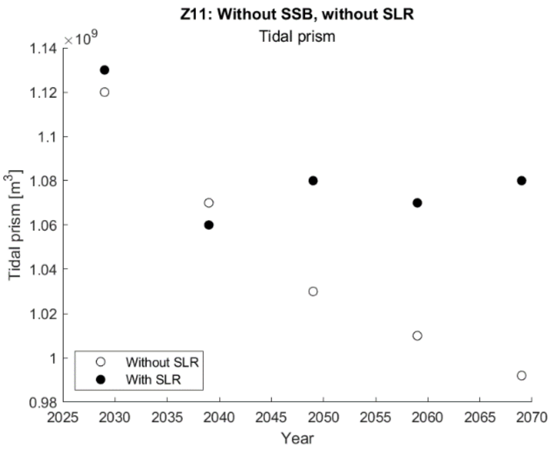


Figure 77: Z11: Development of the tidal prism

Regarding the tidal prism in this scenario, Figure 77 shows that the tidal prism decreases over time both in the scenario with and without SLR. However, in the scenario with SLR, the decrease is less. This is caused by the fact that the increase in surface area of the supratidal parts is less. As a consequence, the wet surface area of the Oosterschelde is larger. In Equation 6 the tidal prism is calculated. Both the modelled development and the calculated development show corresponding results with a decrease of 4 % and 3 % respectively.

Year	MHWS [m]	Tidal range [m]	Surface area above MHWS [m2]	Surface area [m2]	Sed. Vol tidal flats [m3]	TP (calc.) [m3]	Tidal prism (model) [m3]	Diff.
2029	2.79	3.48	2.81E+06	3.88E+08	2.71E+08	1.08E+09	1.13E+09	5 %
2069	4.79	3.35	7.97E+06	3.83E+08	2.32E+08	1.05E+09	1.08E+09	3 %
Diff.						**-3 %**	**-4 %**	

Table 31: Z11: Development of the tidal prism in the model without SSB, with SLR

5.5. Relative impact of model components

During the model phase (described in Sections 5.2, Section 5.3 and Section 5.4), the impact of different model components was studied. With this section (5.5), the impact of different model components is compared in order to see their relative importance in the model.

In Section 5.2, the SSB was present during the whole simulation. Therefore, it can be studied what the impact of the SSB is over time. This is important as the SSB has impact on the tidal range in the model. In Section 5.5.1, the representation of the SSB in the model over time is studied.

Section 5.5.2 makes another comparison, namely the comparison between the development in the Oosterschelde and the development in the ebb tidal delta of the Oosterschelde. With this section, the question is answered whether morphological changes in the Oosterschelde are caused by changes in the ebb tidal delta.

With Section 5.5.3, the impact of removal of the SSB is compared to the impact of 2 metre SLR. In this way, the consequences of both interventions are compared. This is done with an extra model run (M11) where both the SSB and SLR are present. By comparing this new model results with results from previous runs the question is answered which intervention has more impact in the model: removing the SSB or 2 metre SLR.

5.5.1. Representation of the SSB in the model

The modelled morphology seems to have a tendency to reduce the difference in tidal range over the SSB. In Section 4.3.3 the decrease of tidal range (tidal energy) between Roompot Buiten and Roompot Binnen was studied. According to measurements, the difference in tidal range is approximately 10 %. However, during long runs with the SSB (validation run, M01) this difference is not constant. A comparison of the tidal range between different locations is presented to see how the tidal range changes over time. The locations are compared as stated below. Locations in the vicinity of the SSB are visualised in Figure 78 too.

- RPBU-RPBI: see Table 32. Not the original observation points in the harbours as these are disturbed by boundary effects (large bottom changes).
- Roompot channel outside Oosterschelde – Roompot channel inside Oosterschelde: see Table 33;
- OS11 (sea) – Yerseke: see Table 34.

In each table, the tidal range according to measurements is given in red (vakloding value). The value of the validation model corresponds to the modelled tidal range with the bathymetry from the end of the validation model. The tidal ranges from 2029 to 2069 are taken from the M01 model run.

Both in Table 32 and Table 33 it is observed that the differences vary between 2019 and 2029. Between 2029 and 2069 the differences are constant. During the first 10 years the model increases the tidal range at the inside and decreases the tidal range at the outside of the barrier. Therefore, it seems that the model is not able to let grid cells have different tidal ranges when they are close to each other with this representation of the barrier. When observation points far away from the SSB (OS11-Yerseke) are compared, it is observed that the differences are more or less constant. Therefore, the tidal range seems to be modelled correctly for the majority part of the Oosterschelde. Because of this levelling in the proximity of the barrier, the tidal range is larger which makes that waves have a larger zone where it is possible to attack the tidal flats. Therefore, decrease of the tidal flats may be overestimated in this region. The extent of this influence is not known, as no other observation points in the proximity of the SSB are studied.

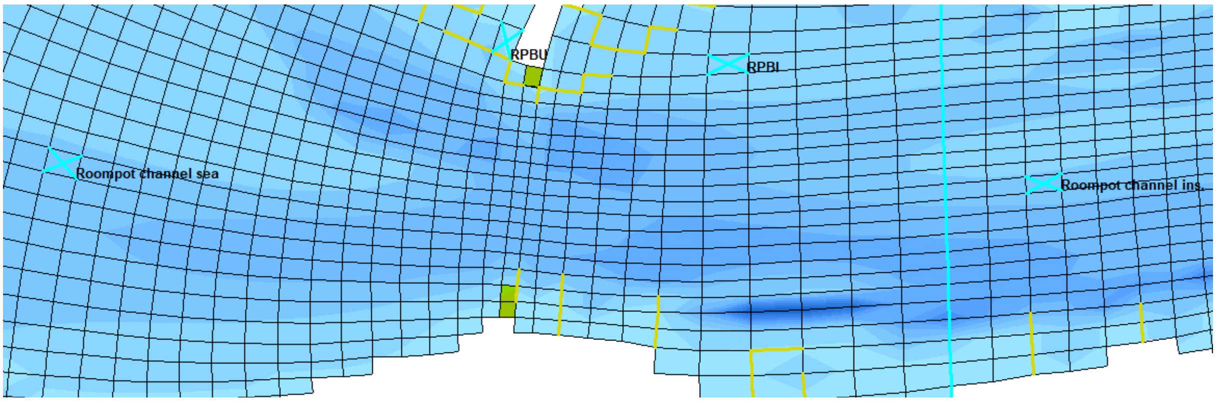


Figure 78: Location of observation points near the SSB

	Validation	2019 (vakloding)	2029	2039	2049	2059	2069
RPBU	296	300	297	299	300	300	300
RPBI	297	269	297	299	301	302	302
Difference	0.30 %	-10.33 %	0.00 %	0.23 %	0.44 %	0.54 %	0.56 %

Table 32: Development of the tidal range at locations RPBU and RPBI (locations chosen outside the harbours)

	Validation	2019 (vakloding)	2029	2039	2049	2059	2069
BU channel	297	286	298	300	301	301	301
BI channel	295	267	294	297	299	299	299
Difference	-0.79 %	-6.64 %	-1.23 %	-1.02 %	-0.87 %	-0.75 %	-0.58 %

Table 33: Development of the tidal range at locations Roompot channel at sea and Roompot channels at the Oosterschelde

	Validation	2019 (vakloding)	2029	2039	2049	2059	2069
OS11	280	279	281	283	283	284	284
YE	370	360	375	374	374	374	374
Difference	31.97 %	29.03 %	33.23 %	32.20 %	32.13 %	32.00 %	31.76 %

Table 34: Development of the tidal range at locations OS11 and YE

5.5.2. Changes at sea vs. changes in the Oosterschelde

In the Sections 5.2, 5.3 and 5.4 the development of the Oosterschelde is described for different scenarios. The development of the ebb tidal delta was neglected as it is beyond the scope of this research. However, it may be possible that changes in this ebb tidal delta affect the development of the Oosterschelde. This may be the case when hydrodynamic parameters (tidal range) show another development or when the development of the bed in the proximity of the SSB differs much from the development of the bed inside the Oosterschelde.

In Figure 79, Figure 81 and Figure 83 the erosion and sedimentation are given for the ebb tidal delta of the Oosterschelde in the different scenarios:

- M01: Reference run, with SSB, without SLR;
- Z01: Model run without SSB, without SLR;
- Z11: Model run without SSB, with SLR.

It is observed that in all three situations, the sediment export of the Oosterschelde leads to sedimentation in the channels of the ebb tidal delta (blue areas). This could be expected as the Oosterschelde exports sediment. Furthermore, the shoals at the ebb tidal delta show the same trend as the tidal areas in the Oosterschelde: erosion at the boundaries of the tidal flats and in the reference situation: some sedimentation in the middle of the tidal flats. Probably less sedimentation is shown at the tidal flats at the ebb tidal delta as the tidal flats in general are lower. This makes that waves have more impact at a larger surface area.

Moreover, it was observed during analysis of the results, that the trend in tidal range at OS4 follows the trend at the other locations of the Oosterschelde (Figure 80, Figure 82 and Figure 84). Based on these observations, it is concluded that the development of the ebb tidal delta, does not disturb the development of the Oosterschelde.

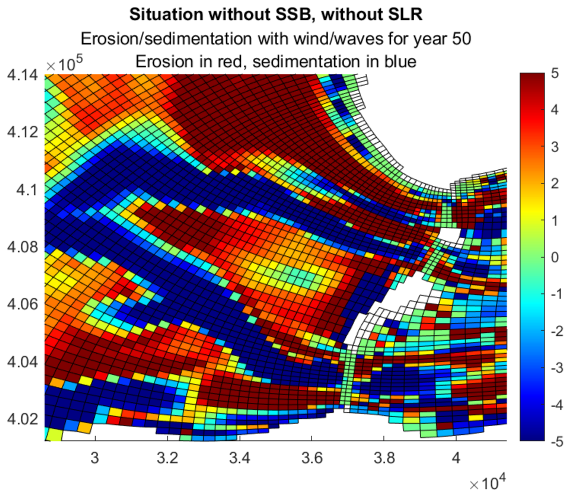


Figure 79: Erosion/sedimentation ebb tidal delta reference situation

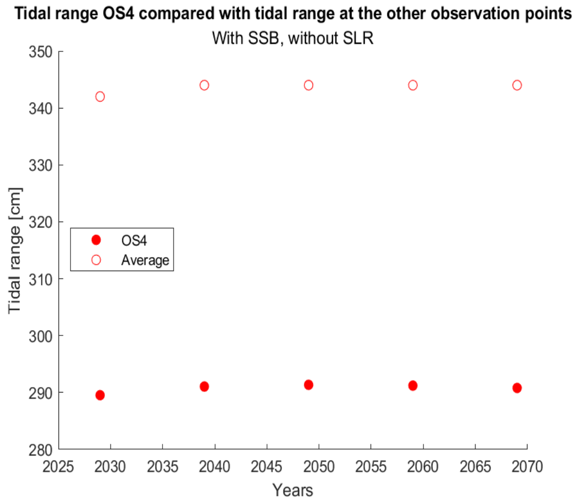


Figure 80: Tidal range OS4 compared with average tidal range for monitoring points in the Oosterschelde (reference model)

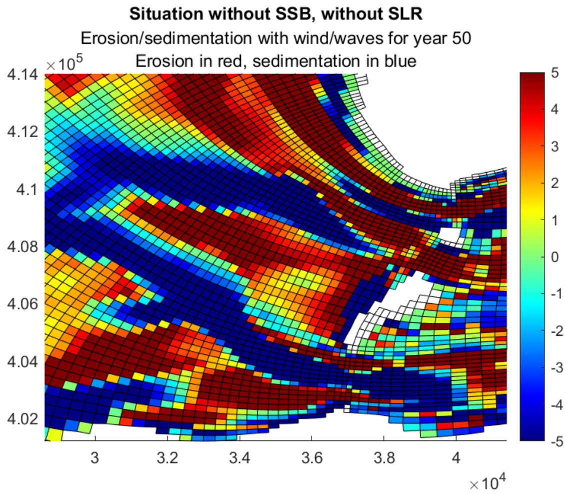


Figure 81: Erosion/sedimentation ebb tidal delta without SSB, without SLR

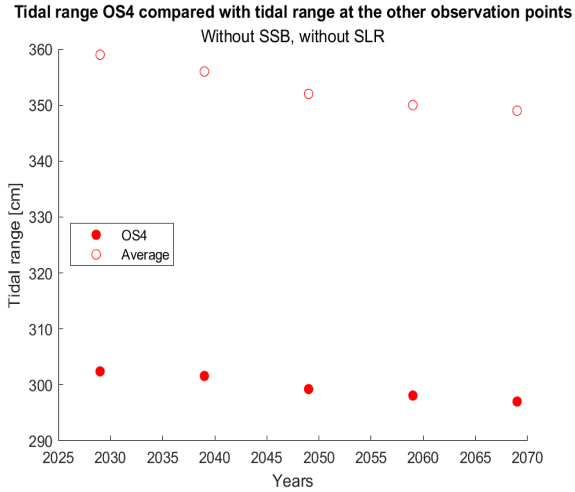


Figure 82: Tidal range OS4 compared with average tidal range for monitoring points in the Oosterschelde (without SSB, without SLR)

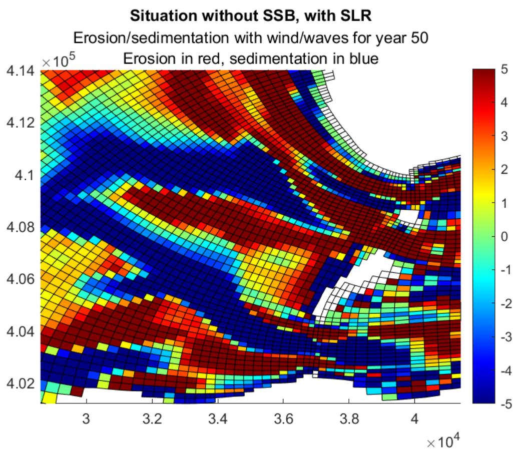


Figure 83: Erosion/sedimentation ebb tidal delta without SSB, with SLR

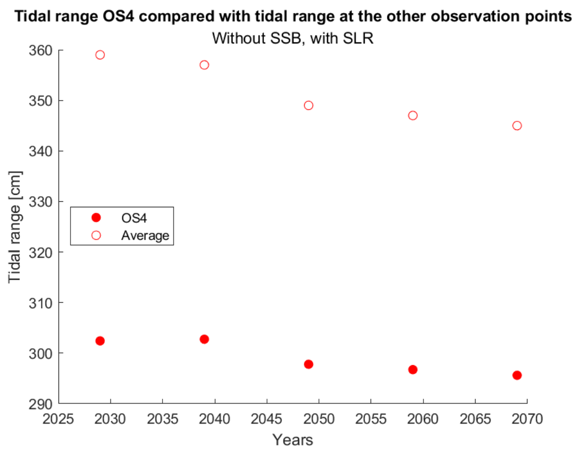


Figure 84: Tidal range OS4 compared with average tidal range for monitoring points in the Oosterschelde (without SSB, with SLR)

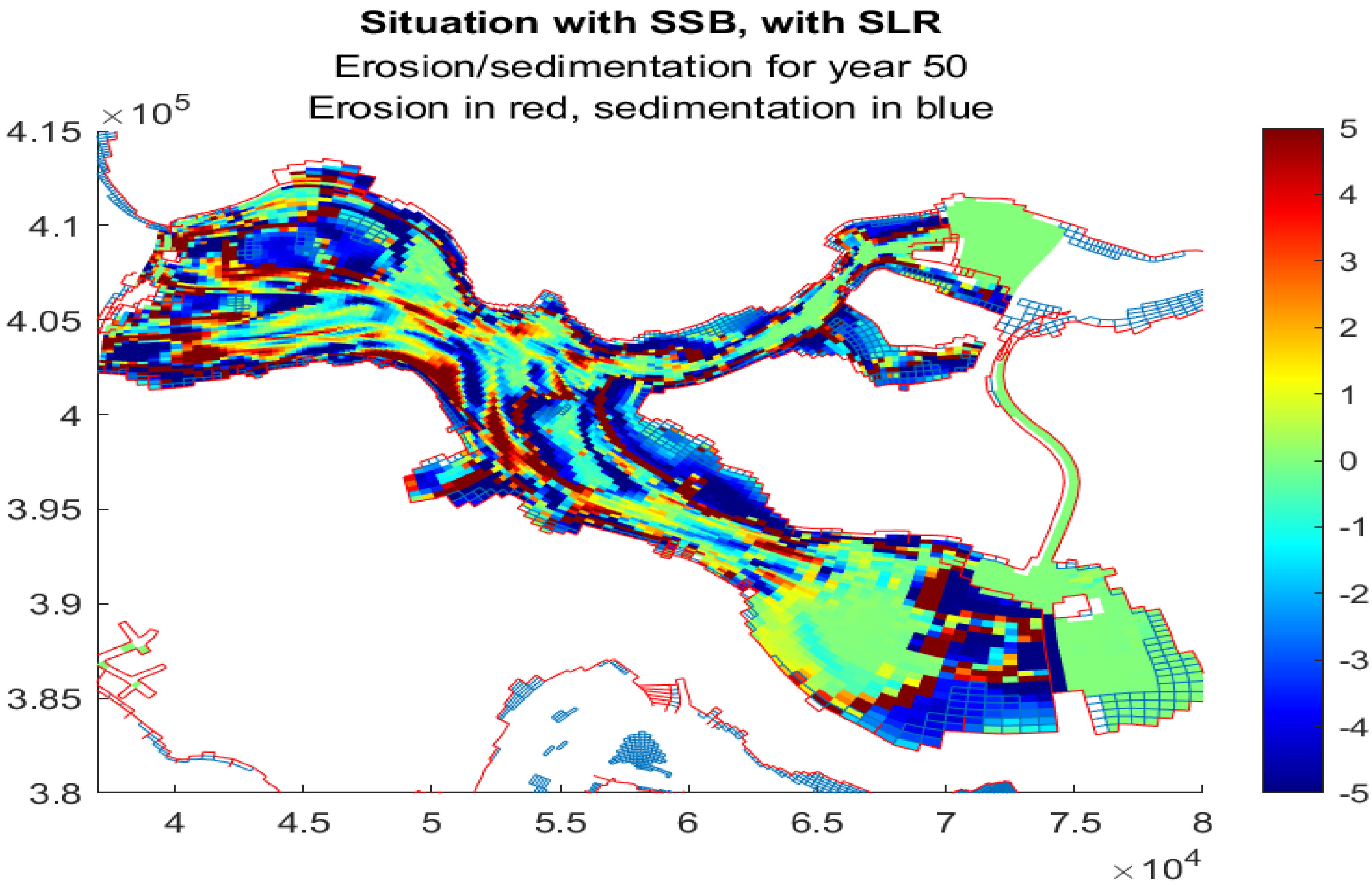


Figure 85: Erosion and sedimentation after 50 years of development for the model run with SSB, with SLR (Z11)

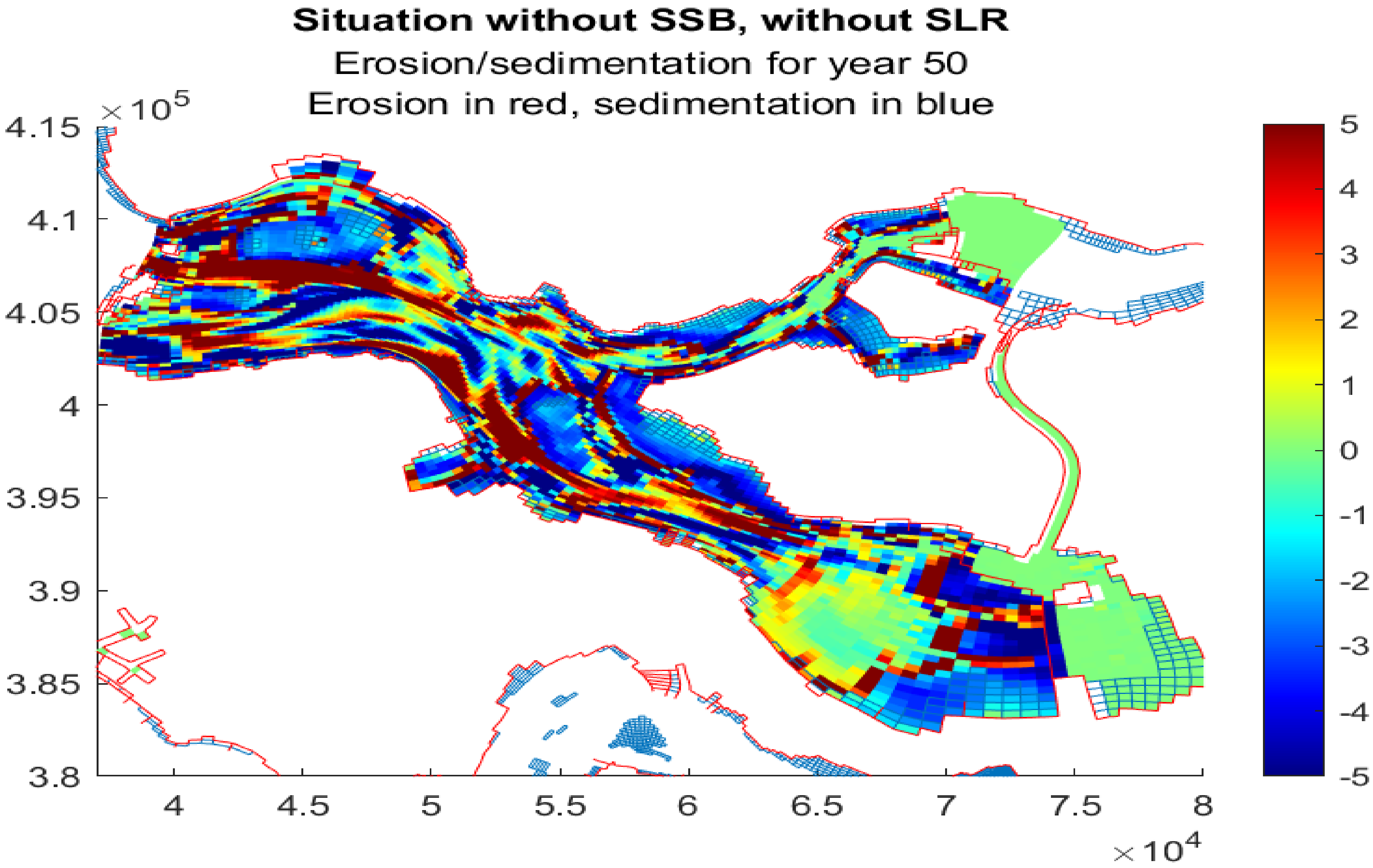


Figure 86: Erosion/sedimentation after 50 years of development for the model run without SLR, without SSB (Z01)

5.5.3. Removal of the SSB vs. SLR

In this study the impact of two interventions in the Oosterschelde is studied. Both for the removal of the SSB and 2 metre SLR model results were obtained. In order to figure out which intervention has the most impact, an extra model run is performed with both the SSB in place and SLR applied (M11). Results of this extra model run are compared to the results of the model run without SSB, without SLR (Z01). In Figure 85 the cumulative erosion and sedimentation are given for the run with SSB and with SLR (M11). In order to compare results, the erosion and sedimentation plot for the model without SSB, without SLR (Z01) is repeated in Figure 86. As it was the case in the previous scenario with SLR (Z11), the levels of MLW and MHW change in the scenario with SSB and with SLR (M11) as well. These levels are given in Table 35.

	2029	2039	2049	2059	2069
MLW	-1.09	-0.69	-0.28	0.12	0.52
MHW	2.33	2.75	3.16	3.57	3.97

Table 35: M11: Values of MLW and MHW over time. Values are given with respect to NAP and are an average of the MLW and MHW of the 5 observation points

It was observed that the height of both the tidal area and supratidal parts increases with SLR in the scenario without SSB (compare Figure 66 and Figure 67 with Figure 87 and Figure 88). This is the case too in the scenario when the SSB stays in place (see Figure 87 and Figure 88). Therefore, in absolute terms SLR has more impact on the model results than removal of the SSB (M11: + 110 % increase in height of the tidal flats, Z01: + 0 % increase in height of the tidal flats). However, as the height of the tidal flats is measured to a fixed level, this is a logical conclusion.

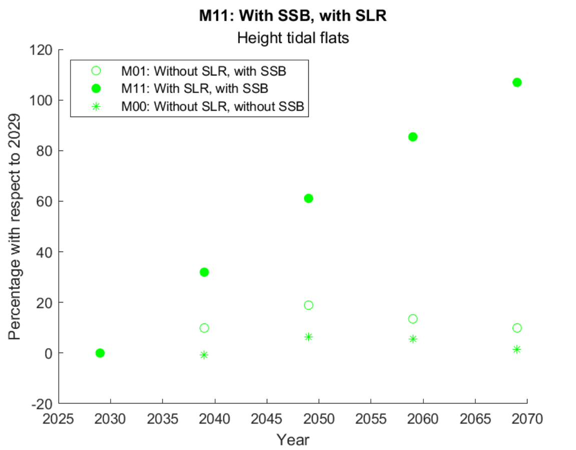


Figure 87: M11: Development of the height of the tidal flats

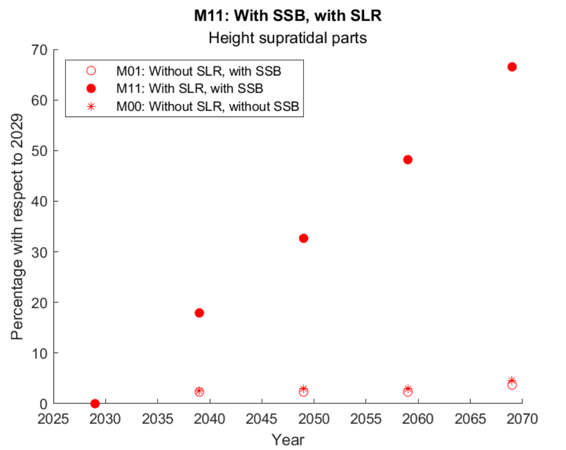


Figure 88: M11: Development of the height of the supratidal parts

When the comparison is made with respect to (the changing level) of MSL, the difference is smaller (Table 36 and Table 37). For both scenarios (M11 and Z01), there is hardly any change in the difference between MSL and the height of the tidal area. Therefore, it is concluded that the height of the tidal area is not dependent on the presence or absence of the SSB. However, this height is dependent on the mean water level in the model. As SLR determines this level, it is concluded that SLR has more impact on the development of the height of the tidal flats (Figure 87) and supratidal parts (Figure 88).

M11	2029	2039	2049	2059	2069
Averaged height of tidal flats [m]	1.97	2.43	2.83	3.19	3.58
MSL [m]	0.62	1.03	1.44	1.85	2.25
Difference [m]	1.35	1.40	1.39	1.35	1.33
Difference [%]	0%	3%	3%	0%	-1%

Table 36: M11: Difference between MSL and the averaged height of the tidal flats and supratidal parts

Z01	2029	2039	2049	2059	2069
Averaged height of tidal flats [m]	1.92	1.94	1.99	1.99	1.98
MSL [m]	0.48	0.50	0.53	0.54	0.56
Difference [m]	1.44	1.44	1.46	1.45	1.42
Difference [%]	0%	0%	2%	1%	-1%

Table 37: Z01: Difference between MSL and the averaged height of the tidal flats and supratidal parts

In Figure 89 and Figure 90 the development of the surface area and sediment volume of the tidal area is given. It is observed that both indicators show the same trend in the scenario with SLR and with SSB. Compared to the reference scenario (M01) it is observed that removal of the SSB causes an extra decrease of surface area and sediment volume whereas SLR causes this indicator to stay constant. Therefore, it is concluded that removal of the SSB has more impact on these indicators.

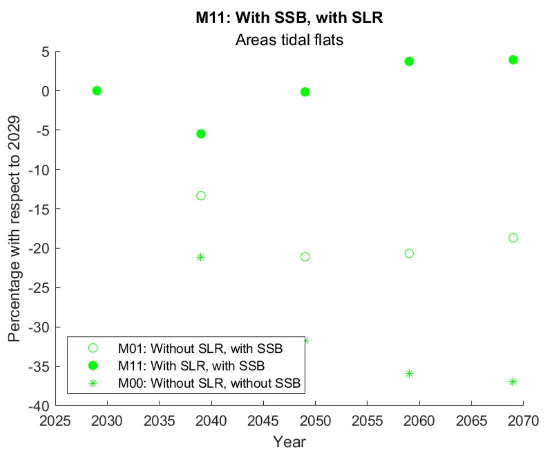


Figure 89: M11: Development of surface area of the tidal flats

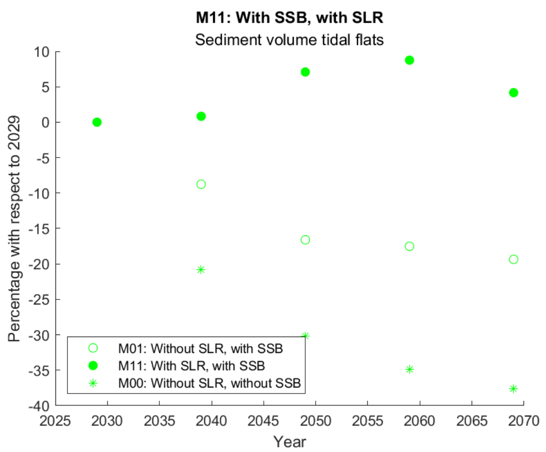


Figure 90: M11: Development of the sediment volume of the tidal area

The surface area of the supratidal parts is plotted in Figure 91. As it was the case in the scenario with SLR, without SSB (Z11) the surface area shows less increase in the model. This can be explained by the continuity of surface area of the parts above MLW (compare Figure 65). As the surface area of the tidal flats stays constant (instead of a decrease), the surface area of the supratidal parts shows less increase.

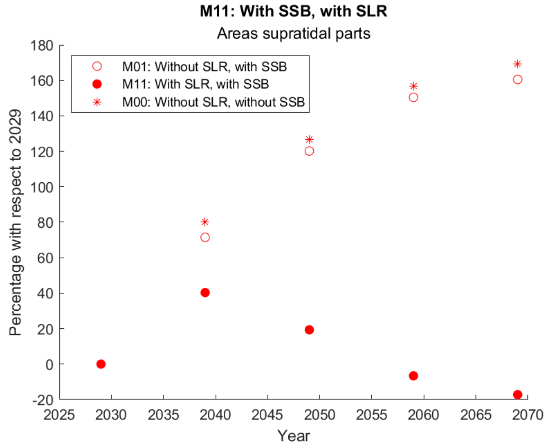


Figure 91: M11: Development of surface area of the supratidal parts

Regarding the channels, the depth increases in the scenario with SLR. However, as described in Section 5.4, the channel depth increases with a rising level of MWL. Therefore, it can be stated that the same development of the channel depth is present for all three scenarios which are present in Figure 93. The surface area, however, shows a different development. Apart from small variations, this surface area is constant. This is a logical consequence of the fact that the tidal flats and supratidal parts exchange surface area. As the total surface area is constant, the surface area of the channels shows hardly any change.

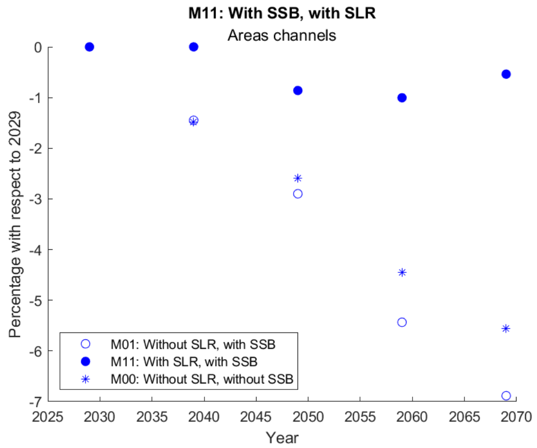


Figure 92: M11: Development of surface area of the channels

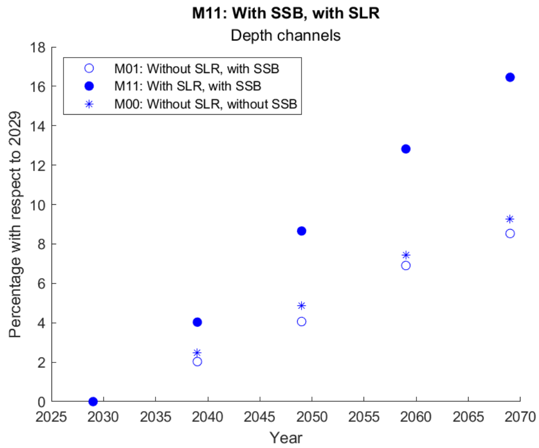


Figure 93: M11: Development of the depth of the channels

When the indicators for the whole Oosterschelde are observed, the differences between the impact of both interventions can be observed. For the tidal range (Figure 95), the presence of the SSB is governing as both the models with SLR (M11) and without SLR (M01) show a constant tidal range. For the tidal prism, the differences are given in Figure 94. From this figure, it is observed that removal of the SSB has no impact on the tidal prism. This is confirmed by the calculations of the tidal prism in Section 5.2 and 5.3 as both models show a decrease of approximately 10 % (compare Table 24 with Table 26). Applying SLR caused the tidal prism to decrease only with 4 % (see Table 31). When SLR is applied in the model with SSB (M11), the decrease is only 1 %. Therefore, it is concluded that removal of the SSB has a larger impact on the tidal prism.

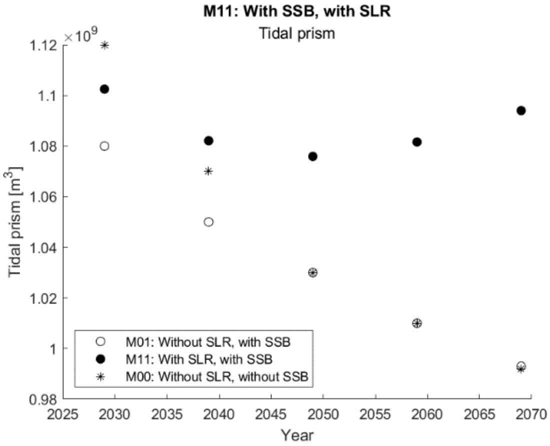


Figure 94: M11: Development of the tidal prism

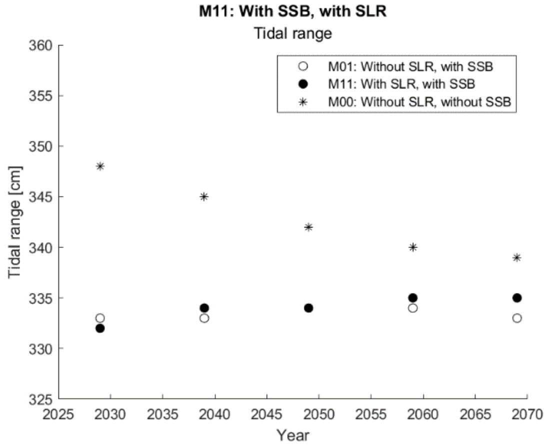


Figure 95: M11: Development of the tidal range

At first glace, when observing the total amount of sediment (Figure 96), it seems obvious that SLR causes more sediment export. However, it was stated that the SSB hampers sediment transport. Therefore, it must be concluded that the impact of the SSB on the blockage of sediment decreases with a rising sea level. This is logical when the representation of the SSB in the model is studied (see Figure 19, repeated below). The 2 porous plates cause energy loss in the model. As these porous plates extend over the whole depth, this energy loss is constant for a rising sea level. The gate is responsible for the blockage of sediment. As this gate is defined with a height from MSL downwards, the relative blockage of the gate decreases with an increasing sea level. As a consequence, less sediment is blocked when SLR is present in a model where the SSB is represented in this way. Therefore, both the values for M01 and M11 should show the same development. Removal of the SSB has more impact on the sediment volume in the Oosterschelde.

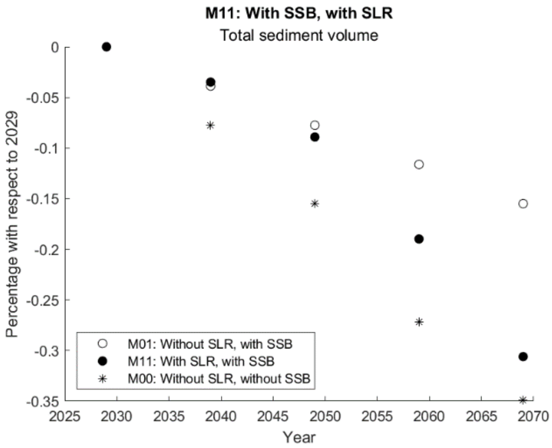


Figure 96: M11: Development of total sediment volume

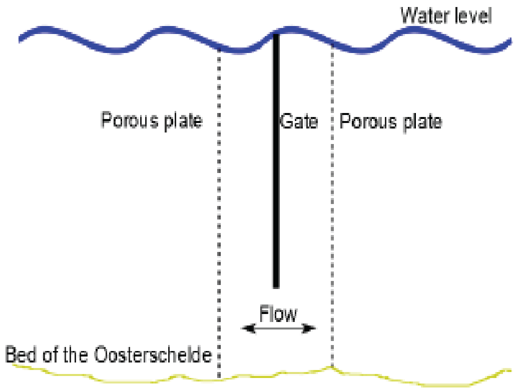


Figure 97: Representation of the SSB in the Delft3d model (Pater, 2012)

In conclusion, it is observed that removal of the SSB has more impact on hydrodynamic parameters (tidal range and tidal prism) than accelerated sea level rise. Furthermore, removal of the SSB has more impact on sediment transport in the Oosterschelde (more export). SLR has more impact on the height of the tidal area (both tidal flats and supratidal parts) as the tidal area grows with the level of MSL. Regarding the surface area of the tidal area, removal of the SSB has more impact in the model. So, in general removal of the SSB does have more impact than SLR. This conclusion will be even firmer when it is realized that this study takes a probably unrealistic high level of SLR.

5.6. Conclusion

In order to answer the second research question, several long-term model runs were done. This section first gives a summary of the observed trends. Second, the research question is answered.

5.6.1. Observed trends

Four different scenarios were modelled:

1. Situation with SSB, without SLR;
2. Situation without SSB, without SLR;
3. Situation without SSB, with SLR;
4. Situation with SSB, with SLR

Some trends in the morphological development were observed in all scenarios:

- Waves cause erosion at the boundaries of the tidal flats;
- The height of the tidal area (tidal flats and supratidal parts) increases due to this wave action. The increase mainly takes place when the cell is at the transition from wet to dry or vice versa. This makes that the surface area of supratidal parts increases;
- As a consequence of this increase of dry cells, the wet surface area of the Oosterschelde decreases. This has the consequence that the tidal prism decreases over time;
- The modelled development in the ebb tidal delta does not disturb the modelled development in the Oosterschelde as the development of the tidal range is the same for both observation points in and outside the Oosterschelde. Furthermore, it is concluded that erosion and sedimentation patterns are the same for both the Oosterschelde and the ebb tidal delta.

Based on the reference model it is concluded that the tidal range is modelled correctly in the majority part of the Oosterschelde. Close to the SSB, the modelled tidal range deviates more as the model has difficulties with an abrupt change in tidal range due to a structure as the SSB.

The impact of the removal of the SSB is clearly visible as the initial tidal prism, tidal range and flow velocities increase. Over time, removal of the SSB has the following consequences with respect to the situation with SSB:

- The level of MHW determines the height of the supratidal parts (dry cells);
- The model does not represent the balance between creation and disappearance of the tidal flats with the tidal motion and wave action respectively;
- The surface area and sediment volume of the tidal flats decrease over time;
- Sediment export is more than 2 times higher after 50 years and is still increasing.

When SLR is added to the situation without SSB, the situation changes (changes given compared to the situation without SLR):

1. Both tidal flats and supratidal parts grow in height with the rising sea level. Over time this increase slows down (less increase per decade); Not enough information is available to determine what the cause of this reduction in grow speed is. Lack of sediment could be a cause (see below). Furthermore, the studied period of 50 years is too short to see whether the tidal area drowns over time in the model;
2. With the growth in height of the tidal area, sediment is needed. In the model, this sediment is gathered by reduction of the increase of the surface area of the supratidal parts compared to the situation without SSB, without SLR;

3. As a consequence of the reduced increase of surface area the supratidal parts, the decrease of tidal prism reduces. So, the tidal prism gets an equilibrium value of approximately 1.08E+09 m^3;
4. No sediment is imported from the ebb-tidal delta in order to facilitate the growth of the tidal area in the model. On the contrary, sediment is exported to the ebb tidal delta with an increasing speed over time. This is caused by the fact that the Oosterschelde becomes more and more ebb dominant in the model.

From the comparison between the impact of removal of the SSB and applying of 2 metre SLR it turns out that

1. The height of the tidal area is not dependent on the presence or absence of the SSB. However, this height is dependent on the mean water level in the model;
2. Removal of the SSB has more impact on the surface area of the tidal area, the tidal range, the tidal prism and the sediment volume in the Oosterschelde.

5.6.2. Answer to the research question

The second research question states:

***Sub question 2:** To what extent is it possible to model the long-term morphological development of the Oosterschelde during calm conditions when the SSB has been removed and SLR is present?*

With this research a first step is taken to model the long-term morphological development of the Oosterschelde. As it is a first step, no perfect model output can be presented as result. However, this research provides insight in the important processes for long-term morphological development. These processes are mentioned below:

- Wave activity is an important process with respect to the development of tidal flats. Therefore, the frequency of wave computations should be chosen in such way that reliable wave heights are present for each water level during the tidal cycle at all locations in the Oosterschelde;
- The availability of sediment is a key factor in possible (or desired) growth of the tidal flats with SLR. Processes/indicators which give information about this availability (ebb/flood dominance, sediment characteristics) can give insight in the development of the tidal flats.

Furthermore, parts of the model are promising as…

- …SLR can be modelled in a correct way by forcing a water level at the boundaries of the model;
- …the tidal range can be modelled correctly for the majority of the Oosterschelde. Only in the vicinity of the barrier it deviates to 10 %;
- …the model shows a good fit with respect to the tidal prism. Deviations between modelled and calculated tidal prism (based on Equation 6) are small.

6. Discussion

In the previous chapters, the numerical modelling results for the long-term morphological development of the Oosterschelde have been described by looking at the large-scale parameters (such as surface area of tidal flats and the tidal prism) and the behaviour of specific areas and parameters in the Oosterschelde. In this chapter the model results are critically reviewed by means of discussing chosen modelling approach (and resulting shortcomings) and the reliability of the model results in comparison with observed trends and developments.

- In Section 6.1, the accuracy of the model is discussed.
- In Section 6.2, the model results are compared with the expected morphological development in the Oosterschelde (based on literature and data). In this way the reliability of the model results is described.
- In Section 6.3 the predicted development of the Oosterschelde is compared to the modelled development.
- Finally, Section 6.4 describes the impact of the development of the Oosterschelde on the different functions in the Oosterschelde.

6.1. Accuracy of the model

The hydrodynamics and morphodynamics in the Oosterschelde are complex. To model all relevant processes accurately a large computational effort is required, which is not proportional to the expected effort for a thesis project. In the modelling approach, several concessions were made in order to have a feasible computation time. In this section, the impact of the made concessions on the model accuracy is discussed by assessing the following elements:

- Feasible computation time: impact of wave computation method;
- Feasible computation time: impact of the timestep of 2 minutes;
- Feasible computation time: impact of the morfac of 25;
- Limited validation time: impact of current validation phase results;
- Limited accuracy of input data: sediment (thickness, size, type)

Wave conditions

In this research, one set of wave conditions was used based on the occurrence of wind waves during daily conditions. These wave conditions were validated against measurements in the channels of the Oosterschelde. As a consequence, the significant wave heights at other depths in the Oosterschelde remain unvalidated. Waves are an important factor in the Oosterschelde as the waves represent the erosion of the tidal area (according to literature and in the model). Together with the tidal motion, which represents creation of the tidal flats according to literature, the waves make that there could be a balance between erosion and accretion of the tidal flats. Model results could become more accurate when a detailed validation on waves is performed.

The frequency of wave calculations is another important model parameter. To save computational time, this frequency was set to 4.31 days. In this way wave computations were done out of phase with the tidal signal. However, it has to be noticed that with this frequency, more than 8 tidal cycles pass within one wave calculation (resulting in a constant wave height over more than 8 tidal cycles with varying water levels). Therefore, it must be concluded that the applied significant wave height is inaccurate. Especially at locations were shallow water and deep water alternate, this has high impact as was described in Section 5.3.2. A smaller frequency (e.g., 0.5 hour) should be applied to have more realistic wave heights during all phases of the tidal cycle.

A next step to describe the development of the tidal flats should be the relation between the significant wave height and the bed level. As (Maan et al., 2018) concludes, the wave height should be coupled to the water depth and the bed shear stress in order to describe the morphological development. For tidal flats in the Westerschelde, it was concluded that maximum bed shear stress (maximum morphological activity) does not occur during high water (when significant wave heights are maximum). Instead, maximum bed shear stresses occur little after or before uncovering. As a consequence, the accretion at the tidal flats is large during these times (this was observed in Figure 23 too for the flats in the Oosterschelde).

Storm conditions were not considered in the long-term simulations. As it is known that storm conditions have an important impact on the erosion of the tidal flats (and with that on the balance between accretion and erosion of the tidal flats) it is important to include storms in the models. To increase the accuracy of the model, storm conditions should be represented by both a larger significant wave height (increased wind speed) as an increased water level (due to set up in the North Sea).

Timestep
The performed model runs (both validation and long-term development) were done with a model time step of 2 minutes. During the validation phase, this timestep was chosen to get a balance between reliable model results and a feasible computation time. The chosen time step of 2 minutes was selected by comparing the results for the tidal signal, significant wave height and cumulative erosion/sedimentation based on a 30-day simulation.

For the tidal signal, it turned out that only minor variations (10 %) are present between model results and measured values. This confirms that a time step of 2 minutes results in a reliable tidal range. However, other indicators (such as the tidal asymmetry) were represented less accurate by the model (meaning that the chosen time step may be too large). This should be kept in mind when follow up research is done.

The timestep has hardly any impact on the computed significant wave height. Based on Figure 101 (see Appendix 2) it is concluded that wave heights are approximately the same for timesteps of 1, 2 and 5 minutes. As mentioned before, the moment of wave computations during the tidal cycle has a lot more impact on the computed wave height.

It was observed that the timestep has a significant impact on the cumulative erosion- and sedimentation rates. In Figure 99 (see Appendix 2) it can for example be seen that erosion- and sedimentation rates at location OS4 varies up to a factor 25 because of the chosen time step. However, when other observation points are observed, less variation is found. Furthermore, it is crude to assume that erosion and sedimentation can be assessed based on a model of one month as morphological changes take place at a larger time scale.

However, the chosen time step does have possible impact at erosion and sedimentation patterns in the Oosterschelde as the stability of the model is linked to the chosen timestep via the CFL-criterion (see Appendix 6 for the description of this CFL-criterion). With the chosen time step of 2 minutes, CFL-numbers have values smaller than 10 in the largest part of the Oosterschelde (for figures, see Appendix 6). In the channels, the CFL-number reaches to values of 20 to 25 (in the deepest parts of the Oosterschelde, the CFL-number even reaches 50). As a result of morphological development and SLR, CFL-numbers in the channels further increase to values of 25 to 35. The remaining question is whether the model results are reliable when it is known that these relatively high CFL-numbers occur. As flow velocities are high in the channels, the sediment transport capacity is large. In combination with large CFL-numbers the accuracy of the bed development in the channels is questionable. At the tidal flats however, the CFL-numbers have reasonable values (<10). As long-term morphological development in the Oosterschelde is mainly about development of the tidal flats, the CFL-number at these locations should be accurate enough. Therefore, it is concluded that the observed model result of the increase of the supratidal parts is not caused by model inaccuracies.

Morfac

In the validation phase, a morfac of 25 was chosen in order to save computational time. The reliability of this choice was assessed with a validation run with a morfac of 3. In this model run with a smaller morfac, the same trends were observed compared to a model run with a large morfac. Therefore, the morfac of 25 was used for the model runs focusing on long-term development (Chapter 5). However, this choice has had consequences. A first consequence is low frequency tidal components are not represented for the modelled period of 2019-2069. As the modelled period starts at 1-1-2019, the tidal signal is present for the years 2019 and 2020. As the nodal tide had a maximum in October 2015, the amplitude of this tidal signal was decreasing during the modelled years and had a value of 0 to -2 cm (Peng, Hill, Meltzner, & Switzer, 2019). This indicates that tidal signals during the 2 modelled years were approximately equal to the average tidal signal during the morphodynamic time scale of 50 years. However, long-term variations in this tidal signal (with an amplitude of approximately 8 cm) are therefore not included. As the amplitude is small, it is not expected that this has and impact on the observed trends.

A second consequence of this large morfac should be coupled to the inaccuracies in the model. As a morfac of 25 is quite large, small inaccuracies in the model can have large impact over 50 years of morphological development. However, as Figure 98 shows, erosion and sedimentation rates are mainly visible in the first 10 years of the simulation. Therefore, this trend is assigned to the spin up time more than to inaccuracies due to the large morfac.

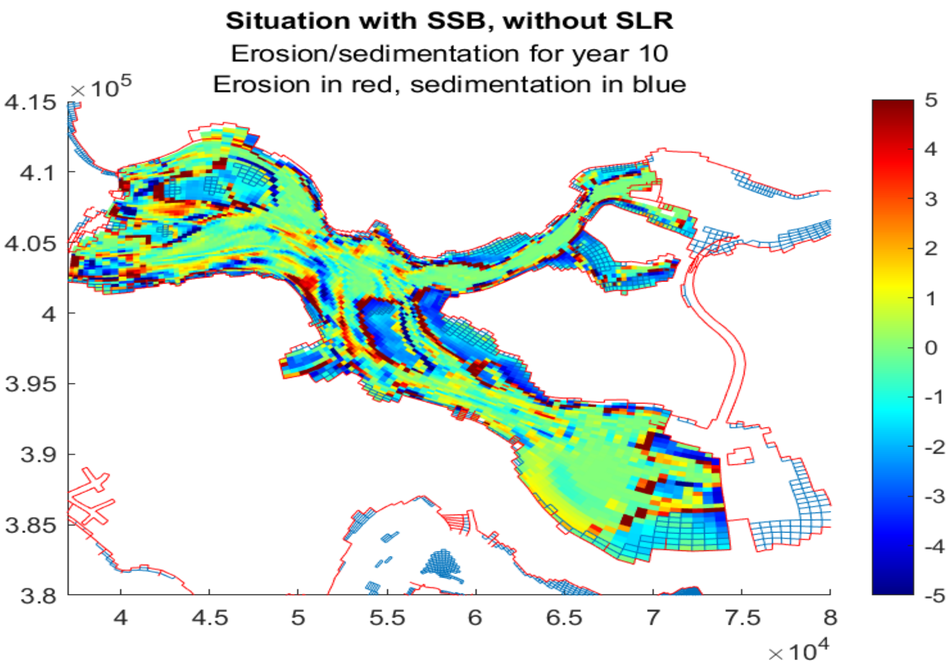


Figure 98: Erosion and sedimentation after 10 years of development in the reference situation (model M01). The large magnitude of the erosion around the tidal flats is visible in red.

Sediment input
For the model runs during this study several parameters representing the sediment in the model are used. During the validation phase (Section 4.3) these parameters are described. For the whole Oosterschelde, a nominal sediment diameter of 200 µm was used with a thickness of 75 metre. Only at the location of the SSB a sediment layer of 0 metre was applied in order to represent the non erodible bed protection. The specific density of the sediment was set to 2650 kg/m^3. These settings did have the consequence that all the sediment in the Oosterschelde was represented by a sand layer of 75 metre. However, this is not realistic as it is known that:

1. Other (smaller) sediment types are present in the Oosterschelde (Kohsiek et al., 1987);
2. Not all locations allow (so much) erosion as non-erodible layers are present (Van Zanten & Adriaanse, 2008);

The absence of small sediment fractions means that sediment transport rates could be underestimated in the models. Sediment particles which are smaller tend to be transported at lower flow velocities. On the other hand, it can be stated that sediment transport rates are overestimated as non-erodible layers are not considered. Because for both facts the spatial distribution is unknown, it is not possible to say at which locations morphological development is over- or underestimated. Therefore, one should be careful to use model results to predict the amount of erosion/sedimentation at specific locations. However, as this is not the goal of this study, this lack of accuracy has probably not influenced the observed trends.

Regarding the thickness of the erodible sediment layer, it can be stated that 75 metre is too much. However, as it could be the case that the location of tidal flats and channels changed as a consequence of the modelled intervention, this amount was needed. However, future studies should use a smaller value, as this shift in location of tidal flats and channels, is not present during the modelled period.

Validation results
During the validation process the model was validated against the ongoing process of erosion of the tidal area in the Oosterschelde. It was observed that this erosion was present in both the validation model and the reference model. However, in both models an increase of supratidal parts was present too causing the total surface area above MLW to increase. As a consequence, the tidal prism decreased. This raises the question to what extent the model does represent reality since it is known that the tidal flats in the Oosterschelde undergo a pattern of height decrease and surface area decrease (de Vet et al., 2017; Van Zanten & Adriaanse, 2008). Therefore, it must be stated that these ongoing trends are not represented by the model. During the model runs in this research for the future development it was known that this height increase of the supratidal parts would have impact on the model results. However, as this thesis project has limits regarding time, it was something to deal with.

A sensitivity analysis was done where both wind directions and wind speeds were varied. As wind causes waves, and waves cause erosion of the tidal flats in the Oosterschelde, this should be parameters which have impact at the erosion pattern at the tidal flats. However, it was observed that both low wind speeds (4 m/s) and high wind speeds (9 m/s) did not have significant impact on the development of the supratidal parts. Also, different wind directions did not change this process. Above it was described that a smaller frequency of wave calculations could be a large improvement of the development of the tidal flats.

6.2. Comparison of the model development and the expected development

This section describes the reliability of the model by comparing the model results to the expected results based on literature. In order to do this, a manual bathymetry is made for the reference situation (with SSB, without SLR). In this manual bathymetry, the expected morphological development based on literature is incorporated. With this new bathymetry, a 14 day model run is performed. Results of this 14 day model run are the tidal range and tidal prism. These indicators are compared to the values of the tidal range and tidal prism based on literature. In this way, the reliability of a model with good representation of the morphological development is assessed for the hydrodynamic indicators.

The manual change of the existing bathymetry (vaklodingen 2019) contains several steps:

1. Calculation of the height of the tidal area (here defined as all area above that certain level in the model) according to literature (Van Zanten & Adriaanse, 2008);
2. Calculation of the corresponding sediment volume and calculation of the corresponding height of sediment in the channels;
3. Change of the height of the tidal area to the calculated maximum height;
4. Change of the depth of the channels in order to close the sediment balance.

These steps come with two important assumptions:

1. The height of the tidal flats is equal in the whole Oosterschelde;
2. The sediment which is removed from the tidal area ends up in the channels in reality. This will reduce the depth of the channels.

The first assumption is a crude one. As it was described in Chapter 3, not all tidal area shows the same development: tidal flats suffer 'Zandhonger' whereas some salt marshes can grow in the current situation. However, as (Van Zanten & Adriaanse, 2008) include salt marshes in their calculation of the height decrease of the tidal flats, all tidal area is lumped together. The second assumption is a more realistic one as it is known that the SSB blocks the interchange of sediment with the ebb-tidal delta. Therefore, sediment which erodes from the tidal area, has to end up in the channels.

According to (Van Zanten & Adriaanse, 2008), the tidal flats decrease in height with 0.8 cm/year based on the period between 1985 and 2001. In Table 38 the results for depths and volumes are given. In total, 0.4 metre of the supratidal parts (0.8 cm per year, 50 years) is eroded (cell D9). When this number is multiplied with the initial area of the tidal flats (both supratidal parts and tidal area, cell B3), the eroded volume of sediment is obtained (cell D6). This sediment volume is divided by the initial area of the channels (cell B2). In this way the depth decrease of the channels is obtained (cell D8).

Expected development of the real Oosterschelde system in the reference situation

A short run is performed with this new bathymetry resulting in tidal range and tidal prism which are given in Table 39. As a consequence of the lack of supratidal parts, the wet surface area of the Oosterschelde and the water volume between MLW and MHW are larger with respect to the 2029 value. Therefore, the sediment volume between MLW and MHW is smaller. This causes the tidal prism increases. In contrast to this increase, the tidal range decreases with 3 cm. Most of this decrease is found at the mouth of the Oosterschelde. As this model run has lowered the bathymetry not only in the Oosterschelde, but in the whole model, it is not possible to say that this decrease has its cause in the Oosterschelde development. Moreover, the decrease is only small.

	A	B	C	D	E
	Indicator	Vakloding 2019	Change per year	Change in 50 years according to literature	Predicted values 2069
1	MLW	-1.47			-1.47
	Areas [km2]				
2	Channels	285	-0.54	-27	312
3	Tidal flats	106	0.54	27	79
4	Total	391			
	Volumes [m3]				
5	Channels	1.788E+10		4.240E+07	1.784E+10
6	Tidal flats	1.420E+08		-4.240E+07	1.844E+08
7	Total	1.802E+10			1.802E+10
	Depths [m]				
8	Channels	-13.84		0.14	-13.70
9	Tidal flats	-0.08	-0.008	-0.40	-0.48

*Table 38 Artificial development reference situation. Change of depth of tidal area calculated based on literature (C9). Change of volume of tidal flats calculated by multiplication of the change in depth by the original area of the tidal flats (D6 = C9 * B3). This volume of sediment is added to the sediment volume in the channels. The depth decrease in the channels is calculated by dividing the sediment volume by the area of the channels (D8 = D5 / B2) Change of area calculated based on literature values (C2 & C3). Areas and depths/volumes are not coupled in this calculation as the steepness of the tidal flats is not considered.*

Year	MHWS [m]	Tidal range [m]	Surface area above MHWS [m2]	Surface area [m2]	Sed. Vol tidal flats [m3]	Tidal prism (calc.) [m3]	Tidal prism (model) [m3]	Diff.
2029	2.10	3.32	1.10E+07	3.80E+08	2.17E+08	1.04E+09	1.09E+09	5 %
2069	2.00	3.28	0.00E+00	3.91E+08	9.53E+07	1.19E+09	1.16E+09	-2 %
Diff.						**14 %**	**6 %**	

Table 39: Development of tidal range and tidal prism with artificial bathymetry in reference situation

Expected trends in the development of the real Oosterschelde without SSB, with SLR
When the SSB is removed and SLR is considered, the situation changes. As described in Chapter 5, SLR causes the following trends:

- An increase of the height of the tidal area with the rising water;
- An increase of the surface area of the tidal area (both tidal flats and supratidal parts) of 17%;
- A decrease of total sediment volume in the Oosterschelde.

It is tempting to make a new bathymetry based on these trends. However, it is not known whether these trends represent reality. Different scenarios are possible:

1. The growth of the tidal area with the rising sea level has to be attributed to the model settings as the erosion/sedimentation patterns due to waves (bed shear stress) are not represented correctly in the model. When this is the case, the tidal flats will drown in reality; sediment is exported, and the tidal prism will grow as the water volume between MLW and MHW will increase;
2. The growth of the tidal area with the rising sea level in the model without SSB is a representation of reality. (Although it may still be the case that the model overestimates the growth of the tidal area) As a consequence of this growth sediment is needed. Therefore, one of the two following options has to be the case:
    a. The tidal area reduces in surface area (the model shows this development);
    b. The tidal area keeps at least its current surface area. In this case sediment import from the ebb-tidal delta or from the channels is necessary.

(Eysink, 1990) mentions for the first option that the loss of surface area of the tidal flats is equal to 0.2 km^2/cm SLR for the Oosterschelde. With 2 m SLR this means that 40 km^2 of surface area has disappeared after 50 years of development. With approximately 100 km^2 of tidal flats in 2019 tidal flats are still present in 2069. However, this approach of the loss of tidal flats may be unrealistic as no maximum of SLR is mentioned whereas it is mentioned in the same article that morphological development lags the development of the sea level. Therefore, it is probable that the number of 0.2 km^2/cm SLR has to be higher when the amount of SLR per year is higher.

The second option is mentioned in literature too (Dissanayake et al., 2012; Eysink, 1990; Van Goor, Zitman, Wang, & Stive, 2003). As the mean height of the tidal flats is approximately MSL, the height of the tidal flats has to increase in this case with 2 metre in this case. Based on the surface area of the tidal flats in 2019 (100 km^2) this means that 2E8 m^3 of sediment is needed. This is equal to 4 million m^3 per year. This is a large (unrealistic) number which means that the system has to change from ebb dominant to flood dominant. However, it was observed that the system becomes more ebb dominant over time (compare Table 29). This increased ebb dominance when 2 metre SLR occurs was confirmed by (Jiang, 2020). Therefore, it is not realistic to expect that sediment import will take place.

The other option (2b) that the tidal area decreases in surface area in order to grow in height, seems to be unrealistic to for two reasons. First, this process is not present in literature for other estuaries/tidal flats. Second, the process that is responsible for the height increase (bed shear stress due to waves) does not give rise to a decrease in surface area as it is mainly responsible for transport in vertical direction.

When the two scenarios are compared, it is most likely that scenario one will be true. Several reasons sustain this as:

- The growth in height of the tidal area in the model is caused by inaccuracies as the model does not represent the occurring wave height (bed shear stress) at small water depths;
- Both the model as literature prove that the Oosterschelde becomes more and more ebb dominant with accelerated SLR;
- Literature proves (e.g., Huismans et al., 2021) that tidal area will decrease with accelerated SLR. Although the rate of decrease and whether it is a decrease in height or in surface area depends on the geometry of the basin, the decreasing trend is visible at all basins;

Expected trends based on morphological equilibrium
It was observed in the model without SSB and with SLR that the Oosterschelde becomes more and more ebb dominant with accelerated SLR. This was confirmed by the decreasing quotient of tidal amplitude [a] and channel depth [h]. The other quotient of V_s and V_c did not change significantly in the model (constant value of 0.018). However, literature mentions a larger value of 0.204 for this V_s/V_c. Three processes/facts could be responsible for this small value in the model:

- Accelerated SLR causes V_c to be larger. As the channel volume is the product of channel depth and channel area, V_c has to grow with a rising sea level as the channels become deeper. In the model, the channel depth increased with 20 % with respect to 2029. As the model has 0.4 metre of SLR in 2029, the increase would be even larger with respect to the start of the model in 2019;
- Due to a low frequency of wave calculations, an overestimation of the wave height is present at the tidal area. Therefore, the erosion at the tidal area (between MLW and MHW) is large and the sediment volume decreases (15 %). Furthermore, the tidal range in the model decreases (4 %). So, the remaining volume which is available for water between MLW and

MHW increases due to sediment volume decrease and decreases due to tidal range decrease. This could have impact at the calculated value of V_s;

- The total surface area in the Oosterschelde is 351 km^2 according to literature. In the model, this surface area is 391 km^2 which is 11 % larger. As the channels cover 70 % of the total surface area, this may have impact at the calculated values.

Despite to the fact that these parameters (channel depth [h], tidal amplitude [a], channel volume [V_c] and intertidal storage [V_s]) are not independent (the channel depth [h] and channel volume [V_c] are related) the parameters influence each other as the system tends to an equilibrium (see Figure 73 for the definition of this morphological equilibrium). Below, expected changes of these parameters are described in order to predict the development of the real Oosterschelde system.

- The tidal amplitude [a] is defined as half the tidal range. As it was concluded that the model is able to predict the tidal range in a reliable way, the tidal amplitude based on the model is expected to be reliable too. Therefore, it is expected that the tidal amplitude will show a small decrease when the SSB is removed and SLR is applied;
- For the depth of the channels [h] it is expected that SLR will cause an increase in depth. Especially with such accelerated SLR as used in this research, no accretion is expected in the channels which could compete with the rise in sea level;
- Above it was mentioned that a decrease of the tidal flats could be expected when accelerated SLR is present. Therefore, the sediment volume of the tidal area will decrease. As a consequence, the intertidal storage [V_s] will increase;
- The channel volume [V_c] will increase too due to SLR. This can be explained by the fact that the depth of the channels increases. Furthermore, as the mean water level at the tidal flats increases (SLR) more surface area will be defined as channel (below MLW). Therefore, the channel volume increases.

Based on these four parameters the quotient a/h will decrease. The development of the quotient of V_s and V_c is unsure as both the nominator and denominator will increase. Based on which increase is larger, the quotient will increase or decrease. When a prediction is made based on morphological equilibrium (see equilibrium lines in Figure 73), V_s/V_c should decrease. However, as accelerated SLR is present, it is questionable whether it may be expected that a system moves to an equilibrium during the period this accelerated SLR is present.

6.3. Review of the predicted development of the Oosterschelde

In the conclusion of Chapter 3, the future development of the Oosterschelde was predicted with 5 statements. This section compares these predictions with the observed development. For each prediction, it is described whether the prediction is correct or not. The predictions were:

- Increase in tidal range (possible to more than 3.70 metre at Yerseke);
- Increase in tidal prism and cross-sectional area of the channels;
- Sediment import from the ebb-tidal delta to the Oosterschelde;
- Growth of intertidal area;
- Slowed growth of intertidal area caused by sea level rise, but no drowning of intertidal area

Tidal range

In the considered future scenarios it is assumed that the SSB is removed whereas the Oesterdam and Philipsdam remain. In such situation, it was predicted that the tidal range would grow. The construction of the SSB caused a decrease in tidal range, the Oesterdam and Philipsdam made the basin shorter which caused an increase in tidal range. Table 40 gives an overview of the tidal range for different situations. It is observed that, according to the model, the tidal range indeed increases to higher values than the original value of 3.70 metre before the Delta works.

Situation	Tidal range at Yerseke [m]
Before Delta works	3.70
Before closure of the SSB	2.75*
After construction of the Oesterdam and Philipsdam	3.30
After removal of the SSB (Z01)	3.77
After 2 m SLR (Z11)	3.68

*Table 40: Development of the tidal range in different situations during past, present and future. *The given value is the value just before construction of the SSB. The impact of earlier delta works is present yet in this value. For more information: compare to (Vroon, 1994) Fig. 8.*

Tidal prism/cross-sectional area of the channels

The tidal prism and cross-sectional area should increase with the planned interventions of removal of the SSB and applying SLR. This increase was not observed in the model as the wet surface area of the Oosterschelde decreased due to an increase in surface area of the parts above MHWS. However, when a model run was performed where this increase is not present (which is the model with manual bathymetry from Section 6.2), the development of a growing tidal prism was enforced.

The growth of the cross sectional area of the channels was not observed in the model without SSB, without SLR (Z01) as the surface area of the channels decreased, but the channels deepened too. When SLR was modelled, the increase of the cross sectional area was observed as the channels deepened as a consequence of SLR (see Figure 76).

Sediment import/growth of tidal area

Corresponding with this increase in cross sectional area in the model with SLR, without SSB (Z11) sediment import was expected as was reasoned in Section 5.4. However, the model did not show this development as the ebb dominance increased in the model. As a consequence, increased sediment export was observed (see Figure 74). Furthermore, it was observed that sediment which was needed to increase the tidal area in height, was picked at the boundaries of the tidal area. Therefore, the tidal area (both tidal flats and supratidal parts) increased less in the scenario with SLR (see Figure 68 and Figure 69). Although this development was predicted in Section 3.9, it cannot be concluded that it is true as it will be more probable that sediment is imported to cause increase at the tidal area in height.

6.4. Impact of Oosterschelde development on functions

In Chapter 3 a description was given of the current ecosystem services of the Oosterschelde. In Table 41 these are repeated for the sake of clarity. This section reflects qualitatively whether the boundary conditions of these functions will be provided when SLR is considered in a situation where the SSB is removed.

Number	Category	Requirement
1	Transport	Minimal navigation profile of 95x6 metre (width x depth) between Wemeldinge and Krammersluizen
2	Economics	Ideal abiotic circumstances for oysters are: - Flow velocities: 0.4 m/s maximum; - Orbital velocities below 0.3 m/s but not 0; - Emersion time: between 0 % and 40 %
3	Recreation	Minimal navigation depth of 2 metre at the 15 marinas at the Oosterschelde.
4	Recreation	Minimal navigation depth of 2 metre between Bergsediepsluis and sea.
5	Policy	The Oosterschelde area has to be an area with a stable area of channels, tidal flats and salt marshes Requirements for tidal flats: - Emersion time: 50 % at least - Width: between 200 and 400 metre

Table 41: Summary of current ecosystem services in the Oosterschelde (repeated from Chapter 3)

For the boundary conditions 1, 3 and 4 a certain navigational profile between different locations in the Oosterschelde is required. As this research uses general values for the development of the Oosterschelde, it would not be reliable to distinguish for the different locations in the Oosterschelde in describing the development of these boundary conditions. Therefore, only a general description is given. The boundary conditions with respect to navigation reduce then to the statement that channels should be present in the Oosterschelde. This is the case in all three modelled scenarios. Moreover, based on the expected development based on literature described in the section above, it is expected that channels will be present in the Oosterschelde.

For the boundary conditions 2 and 5 requirements are set with respect to the tidal flats. In the modelled scenarios, these flats remain even with 2 metre SLR. However, it was observed that the supratidal parts increase in surface area, whereas the tidal area decreases. In other words, the tidal flats become steeper. This may cause a decrease in emersion time.

However, as the modelled development does not correspond to the expected development based on literature, a comparison has to be made with that scenario too. It is expected in reality that the tidal flats diminish (both in height and in surface area) based on literature. This will have a negative impact at the boundary conditions 2 and 5. However, as literature mentions for the tidal area in the Waddenzee that tidal flats do not disappear (Huismans et al., 2021), it may be possible that some tidal flats in the Oosterschelde will remain too.

In present model, the height of the tidal flats grew with MSL. However, each decade less growth was present. This may indicate that tidal flats will drown over time with SLR. Further research has to indicate whether and to what extent tidal flats will drown over time.

7. Conclusions and recommendations

This chapter is divided into two parts. The first section gives answer to the research questions as formulated in Chapter 2. The second section gives recommendations for further research based on the experiences from this study.

7.1. Answers to the research questions

This study aimed to answer the research questions as formulated in Chapter 2. The main research question was formulated as follows:

Research question: *As a result of sea level rise, the SSB in the Oosterschelde will not be functional for future normative conditions and might be removed. To what extent is it possible to simulate long-term morphological development of the Oosterschelde with a process-based model?*

This research question was divided into two sub questions. Below, these sub questions are repeated and answered.

Sub question 1: *How has the Oosterschelde developed and what does it look like today (morphology, interests and ecosystem services)?*

From previous (data) analyses it is known that the Oosterschelde has developed over the past centuries from the main branch of the Scheldt River to a basin with reduced tidal motion because of the SSB. Floodings and human interventions have caused the Oosterschelde to have its current shape. Before implementation of the Delta plan (which started in 1953) the estuary was still expanding as the channels deepened and the tidal flats increased. Construction of the first dams (as part of the Delta works) in the Northern part of the delta (Grevelingendam, Volkerakdam) caused the tidal range and tidal prism to increase, especially in the Northern part of the Oosterschelde. With the construction of the SSB, the tidal range would decrease to a value 40 % smaller than without Delta works. The tidal prism would decrease with 25 %. As this decrease in tidal range would have major consequences for the valuable ecological system, two compartmentalisation dams were built (Oesterdam and Philipsdam). As a consequence, the tidal range decreased with only 12%. However, as these dams shortened the basin, the tidal prism decreased even more (- 31 %).

As a consequence of this reduced tidal motion, the tide is no longer able to balance the erosion of the tidal flats which is caused by waves and wind. Therefore, the surface area and the height of the tidal flats reduces ('Zandhonger'), as observed in decades of field observations. This decrease of tidal area is an undesirable situation as the unique tidal nature of the Oosterschelde provides a lot of functions for both economy, ecology and recreation. Furthermore, the Oosterschelde is used as a transport route by cargo vessels.

Sub question 2: *To what extent is it possible to model the long-term morphological development of the Oosterschelde during calm conditions when the SSB has been removed and SLR is present?*

In order to answer this second sub question a Delft3d model was used. Below the most important results are given. After that, the concluding remarks are given.

Summary of results

This model was validated with a model period of 30 years (1990-2020). Subsequently, four model simulations were performed:

1. Model run, reference: with SSB, without SLR;
2. Model run: without SSB, without SLR;
3. Model run: without SSB, with SLR;
4. Model run, sensitivity: with SSB, with SLR.

In all simulations, waves cause erosion of the tidal flats in the model. This is visible in the decrease in surface area of the tidal area. The height of the tidal flats, however, increases due to wave action: when the cell is at the transition from wet to dry or vice versa the change in bed shear stress is maximal and accretion takes place. Due to this accretion the tidal prism decreases as the wet surface area decreases. However, it was observed in all simulations too that the wave heights are not represented well in the model as wave computations were done with a too small frequency. As a result, waves which are computed for high water conditions (large water depth) are also applied for low water situations (small water depth). As a result of the overestimated wave height / water depth ratio, a large increase in height of the tidal flats was observed in the model. As a consequence a large increase of the tidal flat height was observed in the models.

Below, the most important results are given for each model run. The numbers correspond to the numbers of the model run, as stated above.

1. Based on the reference run, it is concluded that the tidal range is modelled correctly in the majority of the Oosterschelde. Close to the SSB the modelled tidal range deviates more as the model has difficulties with an abrupt change in tidal range due to a structure as the SSB.

2. The removal of the SSB in the model makes that the initial tidal range and tidal prism increase. Therefore, the height of the supratidal parts increases. In other words: the level of MHW determines the level of the supratidal parts. Furthermore, as the SSB is no longer a barrier for sediment, the model shows sediment export. This sediment export is more than 2 times higher after 50 years compared to the reference run and is still increasing (the export of sediment increases over the years). This sediment export could be expected as the Oosterschelde is an ebb-dominant basin where sediment export had been present before construction of the SSB too.

   Before construction of the SSB (1986), there was an equilibrium between tidal motion (positive effect) and wave action (negative effect) on the development of the tidal area. With removal of the SSB in the model this equilibrium is not restored. Namely, in the model there is still a decrease of surface area of the tidal flats. Furthermore, the surface area of the tidal flats (all area above MLW) has a lower growth rate in the scenario without SSB compared to the scenario with SSB (reference run). This indicates that the model suggests that removal of the SSB in the model causes less growth of the tidal flats (all area above MLW) whereas the opposite should be expected based on historical developments. It should be mentioned however, that this decrease in tidal area, even without SSB, is (at least partly) caused by the fact that the supratidal parts show a large increase in surface area.

3. SLR (2 metre in 50 years (0.4 metre per decade)) causes an increase in MSL in the model. Due to the increased MSL, the height of the tidal flats and supratidal parts increases in the model. Over time the height increase slows down in the model (from 0.41 metre per decade to 0.35 metre per decade). There is not enough information available to determine what the cause of this reduction in grow speed is. Lack of sediment could be a cause (see below). Furthermore, the studied period of 50 years is too short to see whether the tidal area drowns over time in the model. This could be possible as the grow speed of the height of the tidal flats and

supratidal parts decreases. However, as bulk parameters are studied in this research, it may be possible too that some flats will remain where other tidal flats will vanish;

In the situation with SLR, sediment is needed to accommodate the growth in height of the tidal area. In order to facilitate this sediment need, less growth (compared to the simulation without SSB, without SLR) of the surface area of the supratidal parts compromises for this growth in height.

As a consequence of the reduced increase of surface area the supratidal parts, less decrease of the tidal prism is observed compared to the model runs without SLR.

No sediment is imported from the ebb-tidal delta in order to facilitate the growth of the tidal area in the model. On the contrary, sediment is exported to the ebb tidal delta with an increasing speed over time. This is caused by the fact that the Oosterschelde becomes more and more ebb dominant in the model. This is confirmed by literature as (Jiang, 2020) shows that the Oosterschelde becomes fully ebb dominant for the same amount of SLR.

4. Sensitivity run: The height of the tidal area is not dependent on the presence or absence of the SSB. This height is only dependent on the mean water level in the model.

   Compared to accelerated SLR, removal of the SSB has more impact on the surface area of the tidal area, the tidal range, the tidal prism and the sediment volume in the Oosterschelde.

Concluding remarks
With this research a first step is taken to model the long-term morphological development of the Oosterschelde. When model results are compared to expected development based on literature it is concluded that no perfect model output is created. However, as this research is a first step, this could not be expected either. Still, insight is provided in processes which play a key role in long-term morphological development. Therefore, the representation of these processes should be improved. These processes are:

- Wave activity is an important process with respect to the development of tidal flats. Therefore, the frequency of wave computations should be chosen in such way that reliable wave heights are present for each water level during the tidal cycle at all locations in the Oosterschelde;
- The availability of sediment is a key factor in possible (or desired) growth of the tidal flats with SLR. Processes/indicators which give information about this availability (ebb/flood dominance, sediment characteristics) can give insight in the development of the tidal flats.

Although a further improvement of space-varying parameters of model input will improve the model too, above mentioned processes are the most important. With improvement of modelling these two processes it may be possible to improve model capabilities. Besides the fact that processes are present which need improvement, parts of the model are promising as…

- …SLR can be modelled in a correct way by forcing a water level at the boundaries of the model;
- …the tidal range can be modelled correctly for the majority of the Oosterschelde. Only in the vicinity of the barrier it deviates to 10 %;
- …the model shows a good fit with respect to the tidal prism. Deviations between modelled and calculated tidal prism (tidal prism = tidal range * wet surface area of the basin – the sediment volume of the tidal flats) are small.

7.2. Recommendations for further research

As model predictions are yet unsatisfactory, recommendations are given to encourage further research to improve understanding of the long-term development of the Oosterschelde.

- The presence of both channels, tidal area and supratidal parts requires that wave calculations are representative for each depth during the tidal cycle at each location. As water depths change relatively fast on intertidal flats, wave predictions are only representative for a limited duration (e.g., half an hour). Therefore, it is recommended to shorten the period between two consecutive wave calculations in the model. A period of half an hour could be a good first estimation;
- In this study, bulk parameters were created as output (surface areas, depths, volumes). Differences in development of these parameters were compared in order to explain the observed developments. In this way an explanation was found for these specific bulk parameters. However, other parameters (e.g. flow velocities, tidal asymmetry) will give more insight in the development of the bulk parameters. Therefore, it is recommended to study other indicators too. In this way, the development of the Oosterschelde can be explained more integrally. When this will be done, it is expected current model settings may be too rough to obtain reliable output (e.g. it turned out that a timestep of 2 minutes was too rough when studying tidal asymmetry).
- This study focused on the development of the Oosterschelde as a whole. As it is known that many parameters vary over the basin (both input (e.g. sediment) and output (e.g. MLW, MHW, tidal prism)) it is recommended to study different parts of the Oosterschelde on their own;
- When SLR was applied to the model (0.4 metre per decade) the tidal flats grew in height with this SLR. However, each decade less growth was present. Further research has to indicate whether this is a model artefact (e.g., related to the limited wave simulations) or what the physical cause of this mechanism is.
- The presence of the SSB in the model has impact on the tidal range. Close to the SSB tidal ranges tend to be the same at both sides of the SSB. This differs from reality as the tidal range is 10 % smaller at the inside of the SSB (in the Oosterschelde). Therefore, the tidal range close to the SSB was not modelled correctly. It is recommended to study the representation of the SSB in order to model the tidal range correctly;

8. Literature

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Appendix 1. Input parameters KustZuid model

Parameter	Unit	Value
Flow parameters		
Tide	-	Forced at the boundaries by specifying water levels (amplitudes) and phases
Gravity	[m/s^2]	9.831
Water density	[kg/m^3]	1023
Air density	[kg/m^3]	1
Horizontal eddy viscosity	[m^2/s]	1
Horizontal eddy diffusivity	[m^2/s]	10
Threshold depth	[m]	0.1
Roughness formula	-	Manning
Bottom roughness	[s/m$^{1/3}$]	0.025
Wave parameters		
Spectrum	-	JONSWAP
Peak enhancement factor	-	3.3
H_s	[m]	1.5
T_p	[s]	7
Direction [nautical]	[degrees]	300
Directional spreading	-	4
Generation mode for physics	-	3rd
Depth induced breaking model	-	B&J model
Coefficient for wave energy dissipation in the B&J model	-	1
Breaker parameter	-	0.73
Bottom friction formulation	-	JONSWAP
Bottom friction coefficient	[m^2/s^3]	0.067
Diffraction	-	False
Wind growth	-	True
Wind speed	[m/s]	6
Wind direction	[°]	270
Quadruplets	-	True
Whitecapping	-	Komen et al.
Refraction for wave propagation in spectral space	-	True
Frequency shift for wave propagation in spectral space	-	True
Sediment transport		
Spin-up interval before morphological changes	[min]	720
Threshold sediment thickness	[m]	0.05
Update bathymetry during flow simulation	-	True
Density of sediment	[kg/m^3]	2650
Dry bed density	[kg/m^3]	1600
Median sediment diameter	[µm]	200

Table 42: Input parameters KustZuid model

Appendix 2. Calibration of timestep

Cumulative erosion/sedimentation

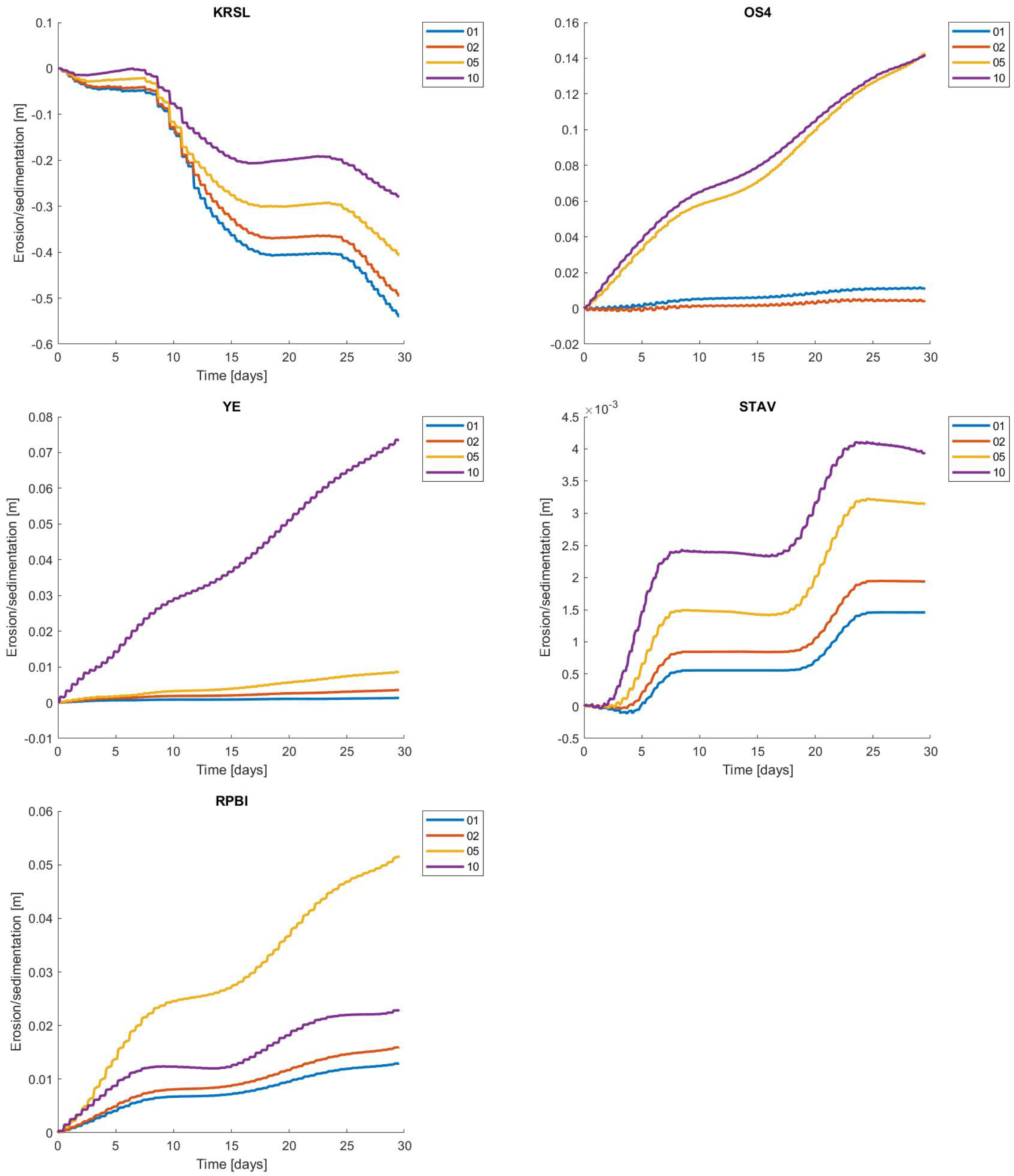


Figure 99: Cumulative erosion/sedimentation for the validation of the timestep

Tidal signal

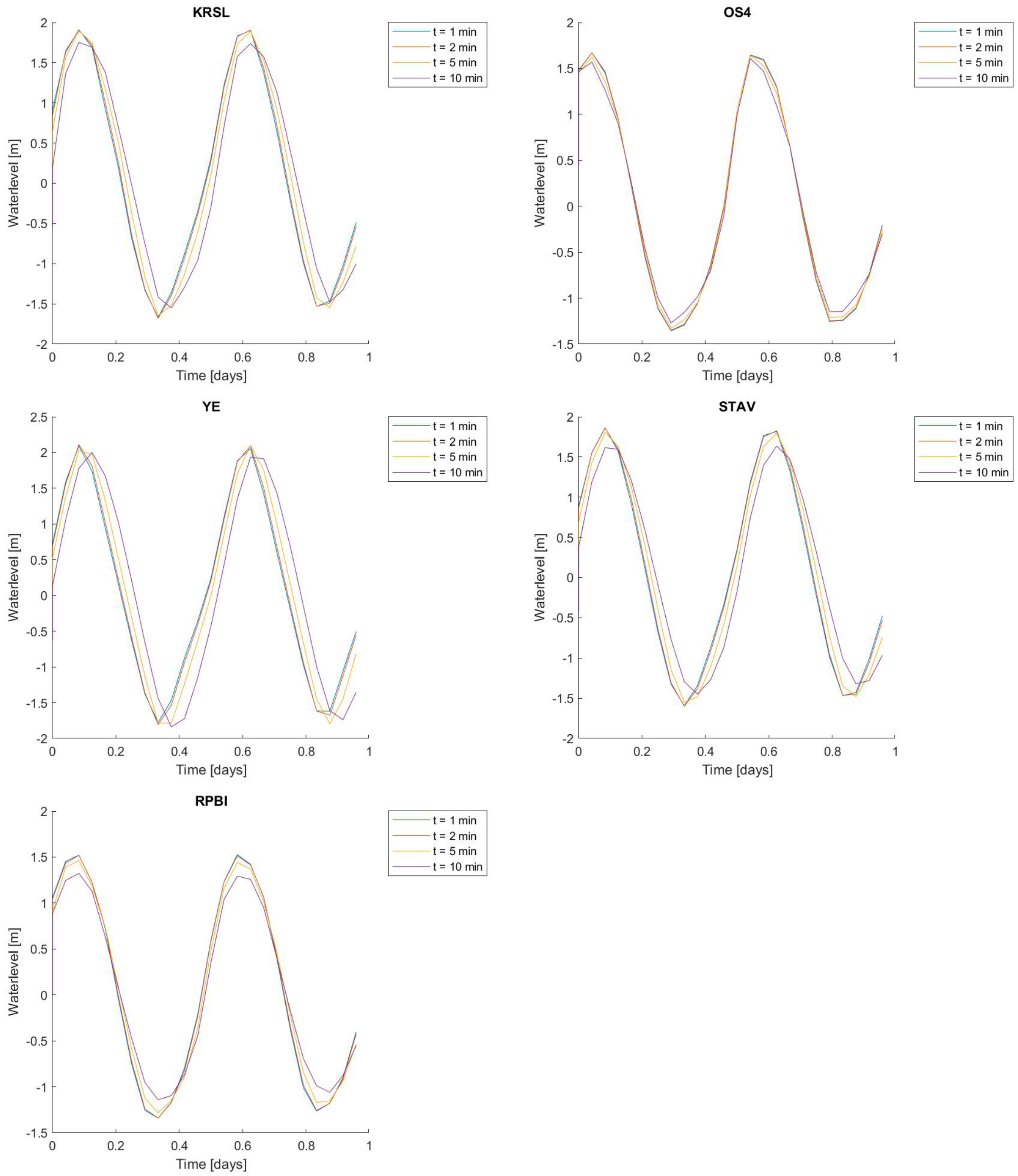


Figure 100: Tidal signal for the validation of the timestep

Significant wave height

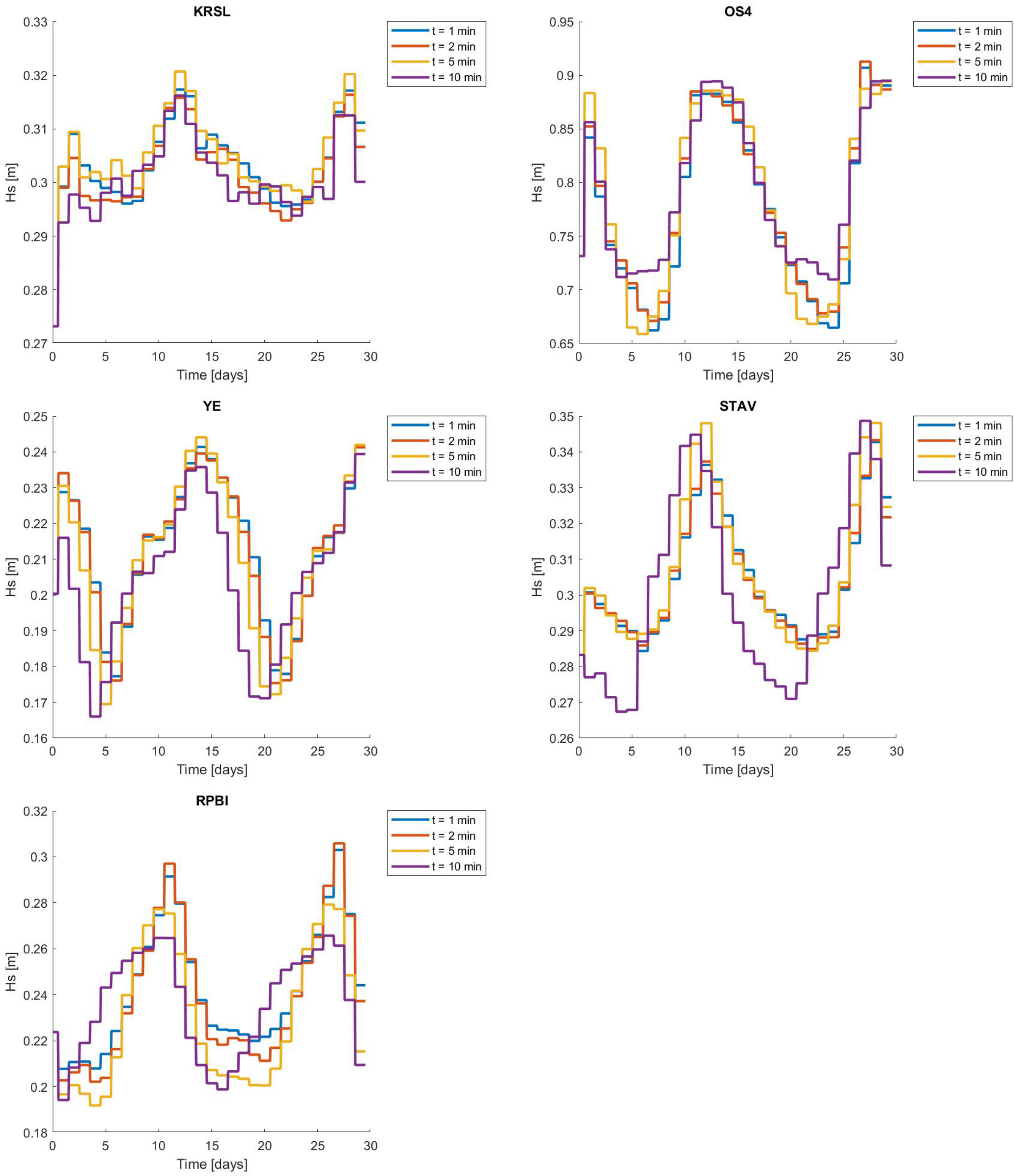
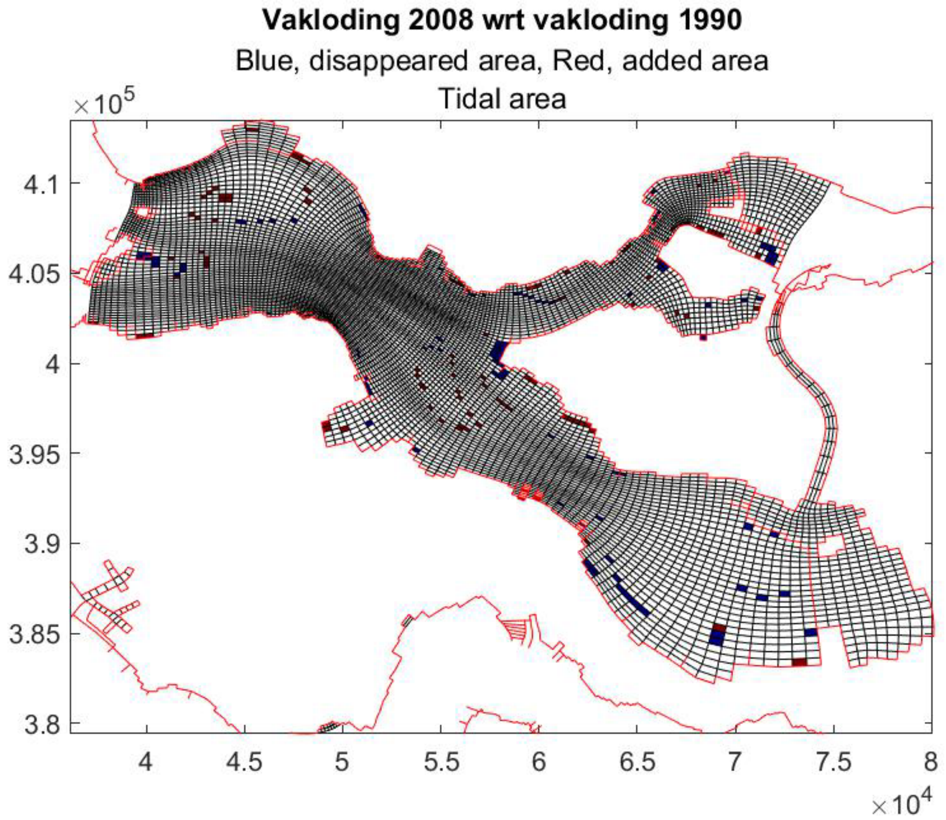


Figure 101: Significant wave height for the validation of the timestep

Appendix 3. Comparison of tidal areas in different years



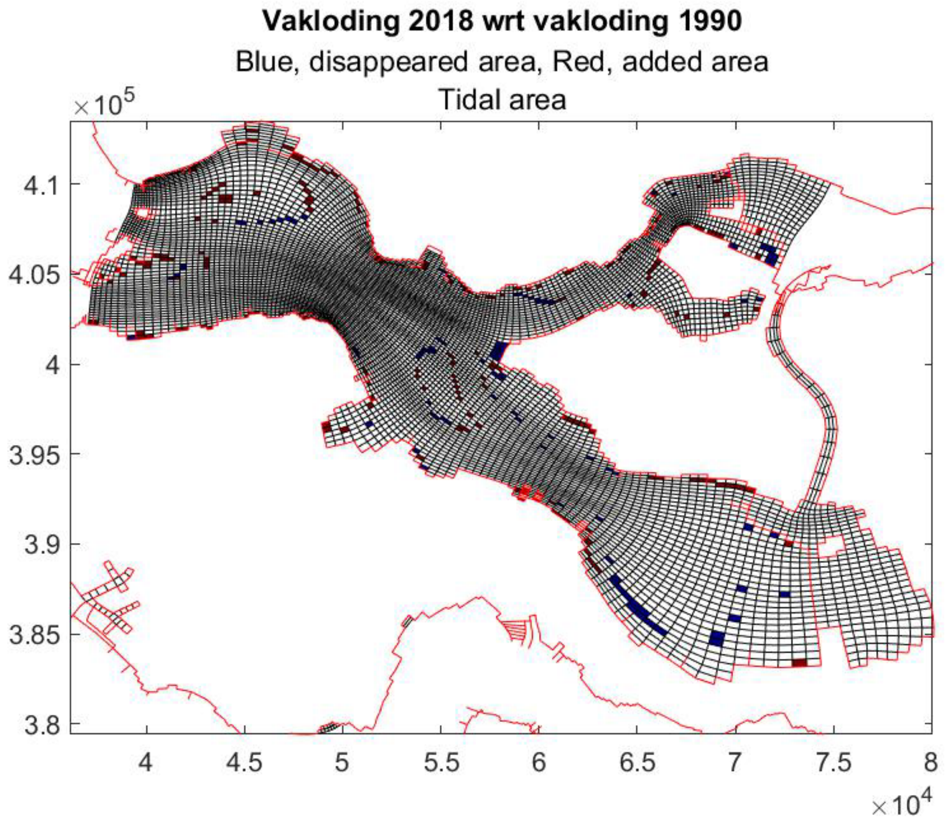


Figure 102: Added and disappeared area between NAP -2m and NAP +2m for 2008 and 2018 wrt 1990

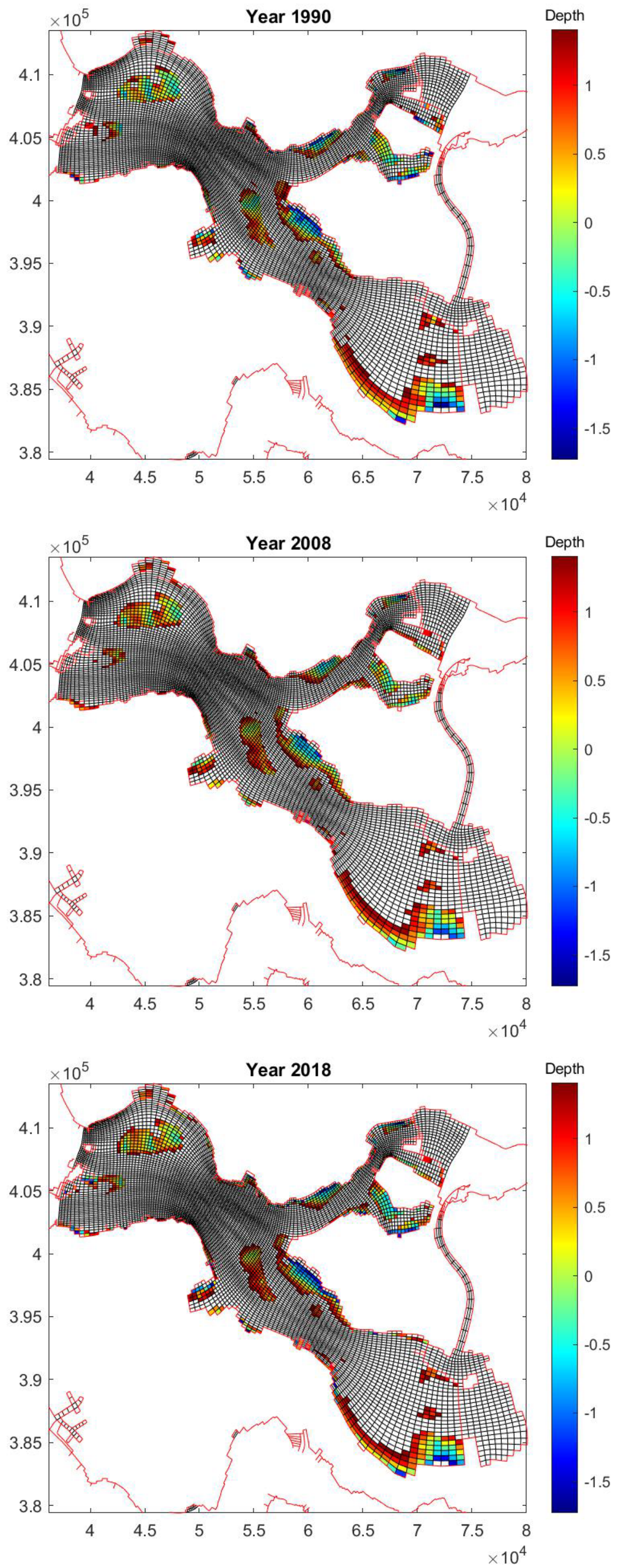


Figure 103: Areas between NAP -2m and NAP +2m for 1990, 2008 and 2018

Appendix 4. Comparison of tidal range

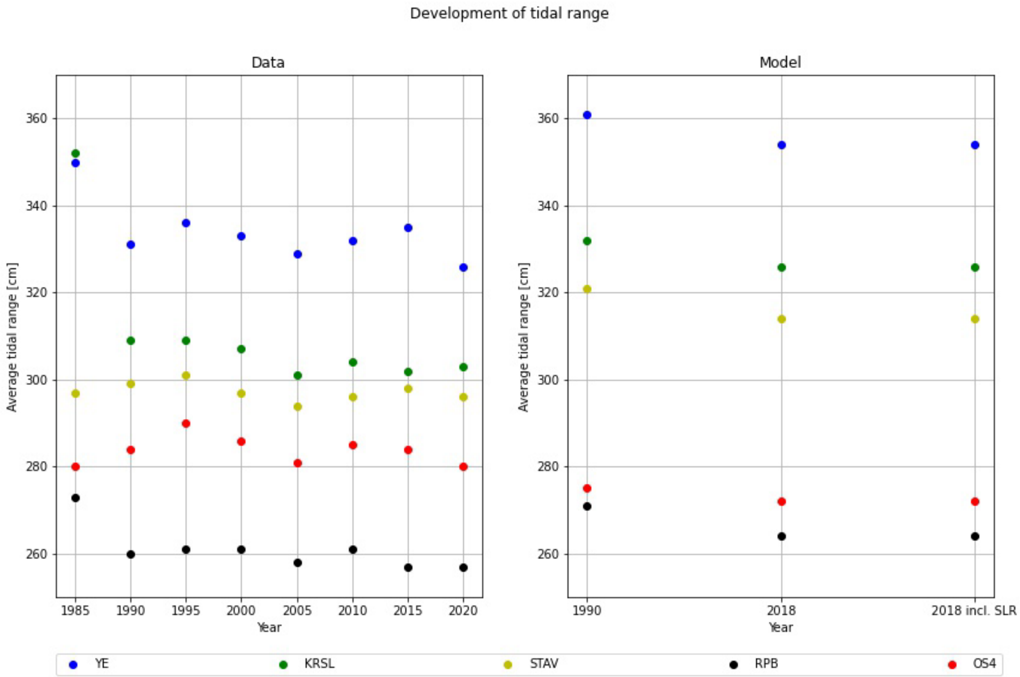


Figure 104: Plots of tidal ranges for different stations

Appendix 5. Depths validation run

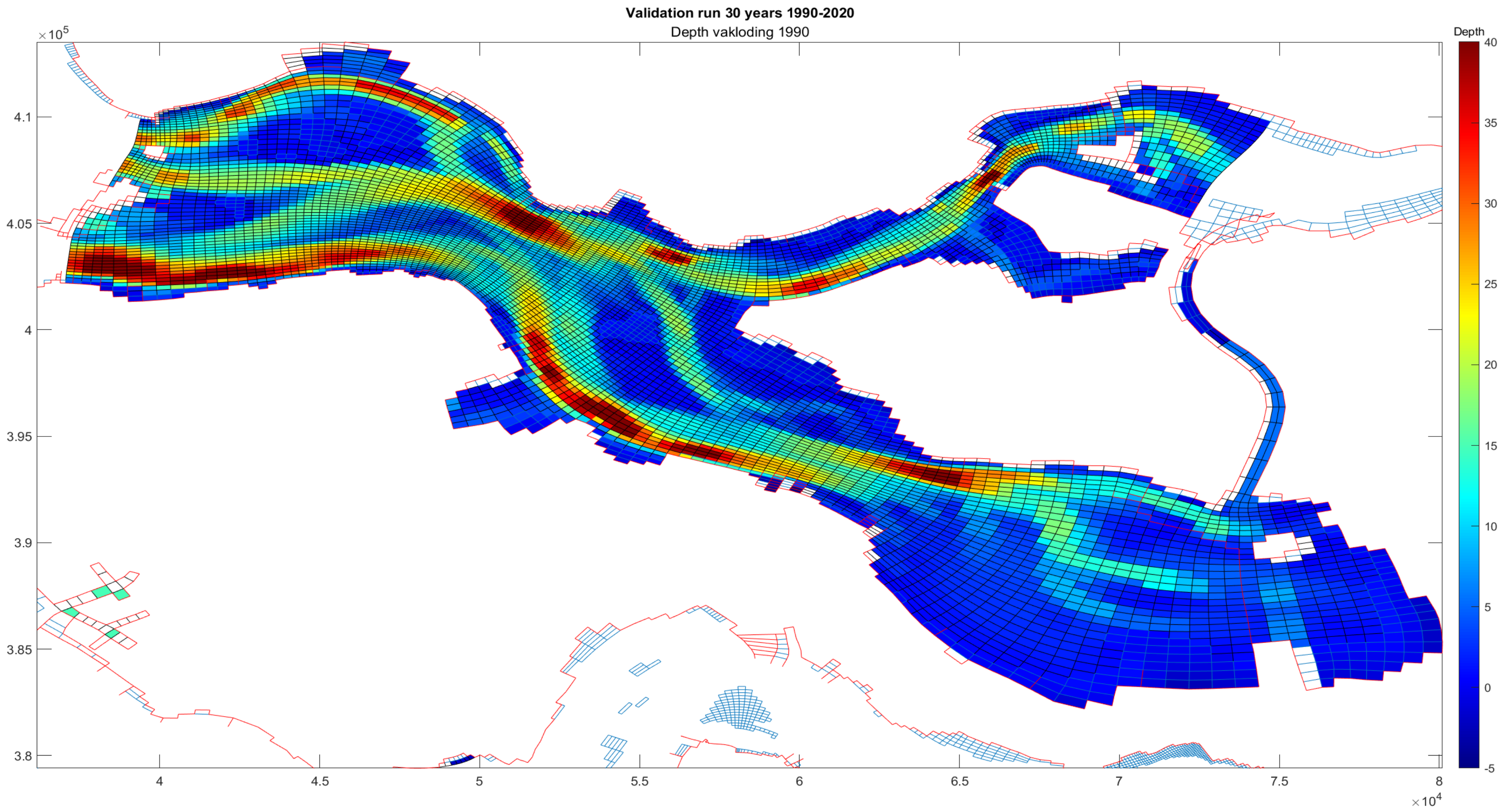


Figure 105: Depth vakloding 1990

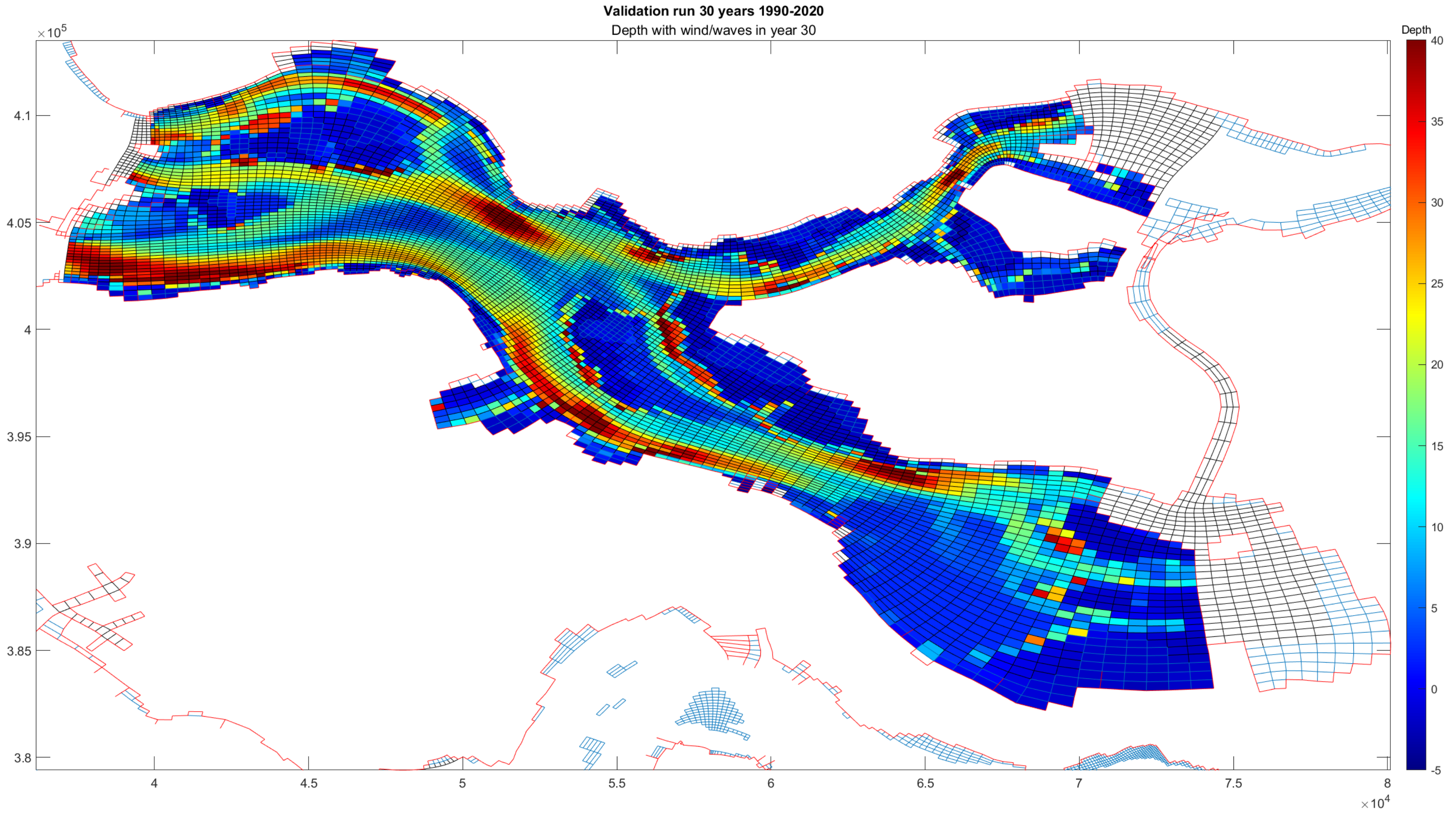


Figure 106: Depth after 30 years of development

Appendix 6. CFL-criterion

The CFL-criterion couples the grid size (in x and y direction) to the depth (z direction) and the time step. As Delft3d uses an unconditionally stable numerical scheme, the time step is not limited in order to obtain stable results. Therefore, the timestep can be chosen on accuracy arguments only. When the CFL-number increases, the accuracy decreases. However, it is difficult to say what the maximum CFL-number is in order to have reliable results. Numbers of 10 to 14 are mentioned in literature as target value (Deltares, 2021; Pater, 2012).

The Courant number is defined as:

$$CFL = \frac{\Delta t * \sqrt{g * h}}{\Delta x, \Delta y}$$

Equation 7 (Deltares, 2021)

In which Δt is the time step in seconds, g is the acceleration of gravity, h is the water depth and $\Delta x, \Delta y$ is the grid spacing in one of the two directions.

Below the CFL-numbers are given for the different bathymetries:

- Vaklodingen 2019
- Z11: without SSB, with SLR

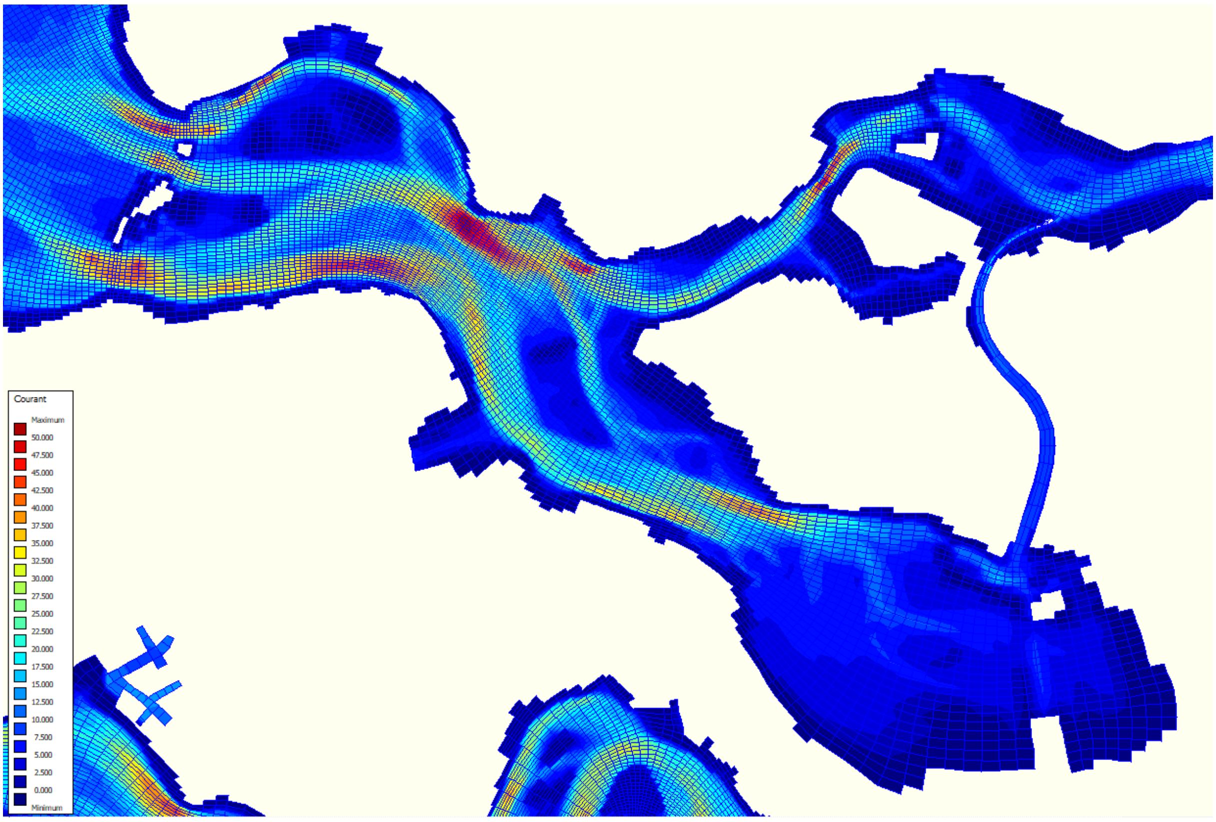


Figure 107: CFL-numbers in the Oosterschelde for the bathymetry of the vaklodingen 2019

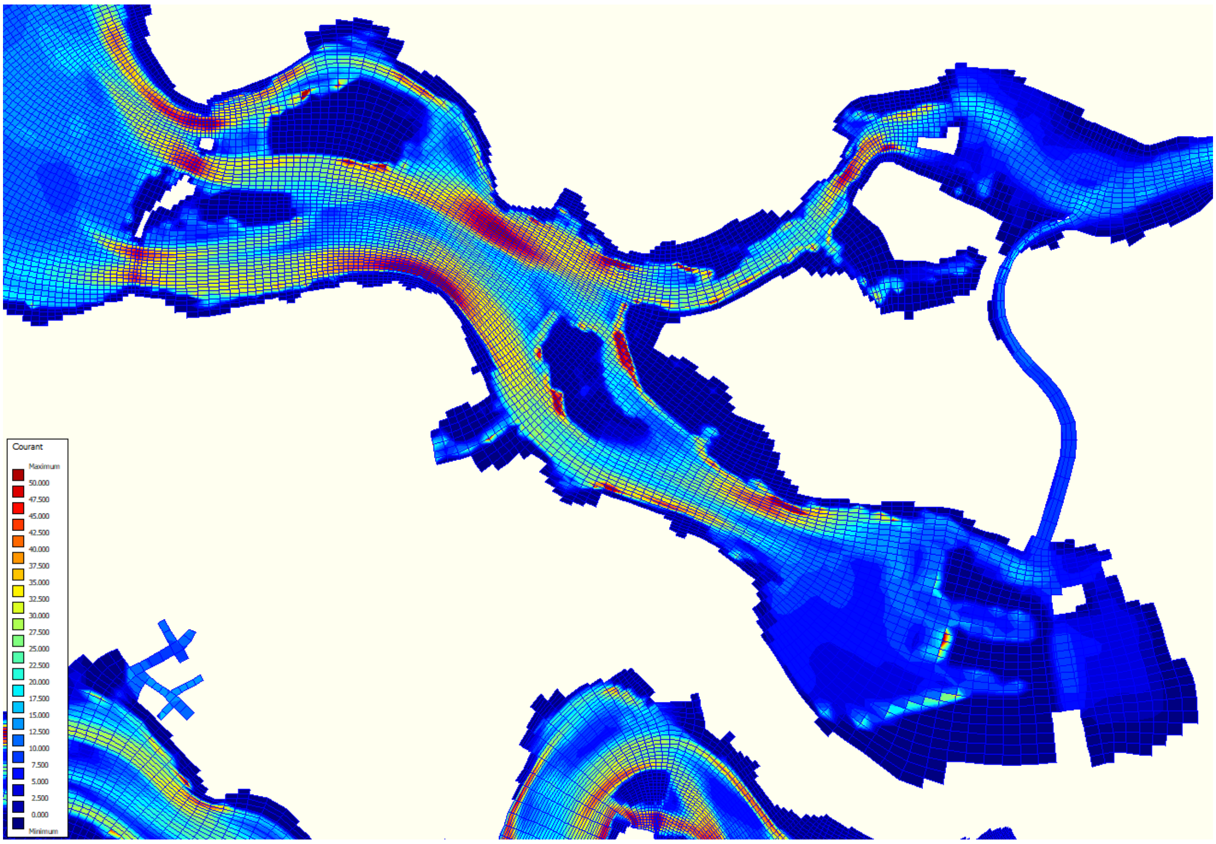


Figure 108: CFL-numbers 50 years after the SSB is removed with 2 metre SLR