

EBB-TIDAL DELTA MORPHOLOGY IN RESPONSE TO A STORM SURGE BARRIER

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Abstract

The ebb-tidal delta of the Eastern Scheldt tidal inlet has been under the influence of a storm surge barrier for the past 25 years. This barrier caused a strong decrease in average tidal currents through the inlet. The morphological response of the ebb-tidal delta is characterized by several different processes: (1) an overall decrease in sediment volume and morphological activity, (2) downdrift reorientation of channels and shoals, (3) a redistribution of sediment between channels and shoals, and (4) a lack of sediment exchange with the basin. Simulations with a process-based model show that the reorientation is a result of changed balance between cross-shore and alongshore tidal currents. The sediment volume decrease is a result of decreased tidal currents in combination with wind waves and a lack of sediment supply.

Key words: Tidal inlet, Eastern Scheldt, ebb-tidal delta, storm surge barrier, morphodynamics

1. Introduction

Tidal inlet morphology can be strongly influenced by large-scale human interventions. A prime example of such an intervention is the storm surge barrier built in 1986 in the Eastern Scheldt tidal inlet in the southwestern Netherlands (Figure 1). This barrier reduced the cross-sectional area of the inlet from 80.000 to roughly 16.000 m². As a result, the tidal prism was reduced by 30% (Vroon, 1994). These hydrodynamic effects in turn caused a change in the morphological behavior of the ebb-tidal delta. As this barrier is the first of its kind ever implemented, it is important to have good understanding of its morphological effects.

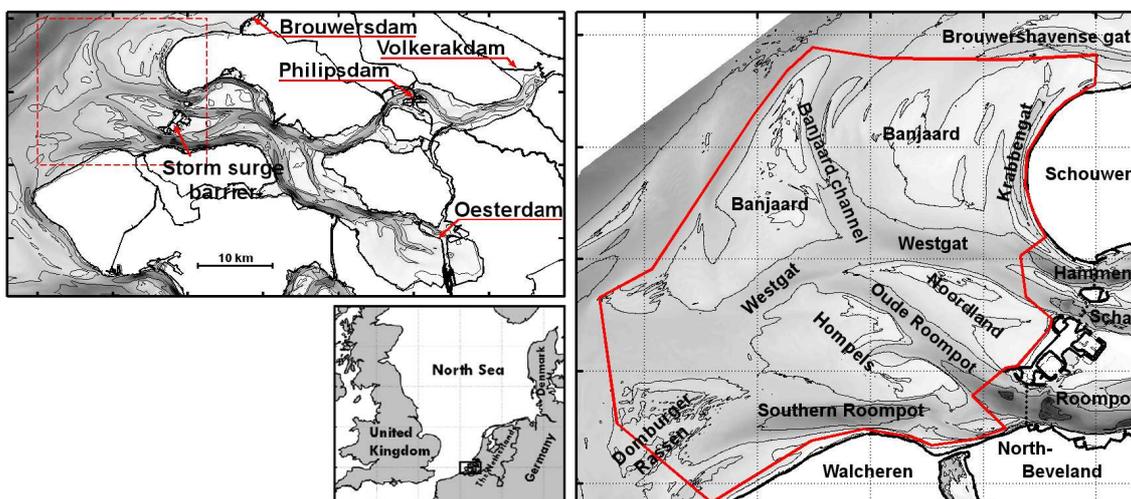


Figure 1: Overview of the Eastern Scheldt Inlet. The red polygon in the right hand side figure is the area taken into account for the sediment budget shown in Figure 4.

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The effects that have been observed in the first 25 years since construction should be regarded as the initial response of the ebb-tidal delta morphology. The research presented in this paper gives an overview of the observed trends, as well as an outlook on possible development of the ebb-tidal delta in the coming decades. This is done by analyzing observed data and applying a process-based morphological model with a simplified geometry.

2. Observations

The Eastern Scheldt (Figure 1) is an elongated tidal basin of approximately 50 km in length and a surface area of 350 km² (Eelkema *et al.*, 2012). The inlet is located between two (former) islands called Schouwen and North Beveland, and consists of three main channels, separated by shoals. The tide, which propagates along the coast as a progressive wave from southwest to northeast, has a mean tidal range of 2.9 meters seawards of the inlet. The long-term mean significant wave height measured offshore of the inlet is 1.1 m, and waves higher than 4 m occur less than 0.2% of the time. The sediment on the ebb-tidal delta consists mostly of fine sand with a median grain size of roughly 200 microns. The grain sizes show a spatial distribution with finer sediment on the shoals and coarser sediment in the channels.

In the nineteen eighties, the Eastern Scheldt inlet was partially closed off from the North Sea with a storm surge barrier (Figure 1). This barrier consists of rows of concrete piers across the three main inlet channels, plus two large construction islands. On both sides of the barrier the bed is protected against erosion by a scour protection which extends about 600 m from the barrier.

The hydraulic effect of the constriction of the inlet was a decrease in tidal range of 20%. Simultaneously with the storm surge barrier, also two back-barrier dams were built in the Eastern Scheldt basin (Philipsdam and Oesterdam, see Figure 1). This was done in order to restrict the decrease of the tidal range by limiting the basin length and thereby increasing the reflection and amplification of the tidal wave (Figure 2). These dams also reduced the basin area from 450 km² to 350 km². The combined effect of these measures was a decrease in tidal prism from 1250 to roughly 900 million m³ per tide.

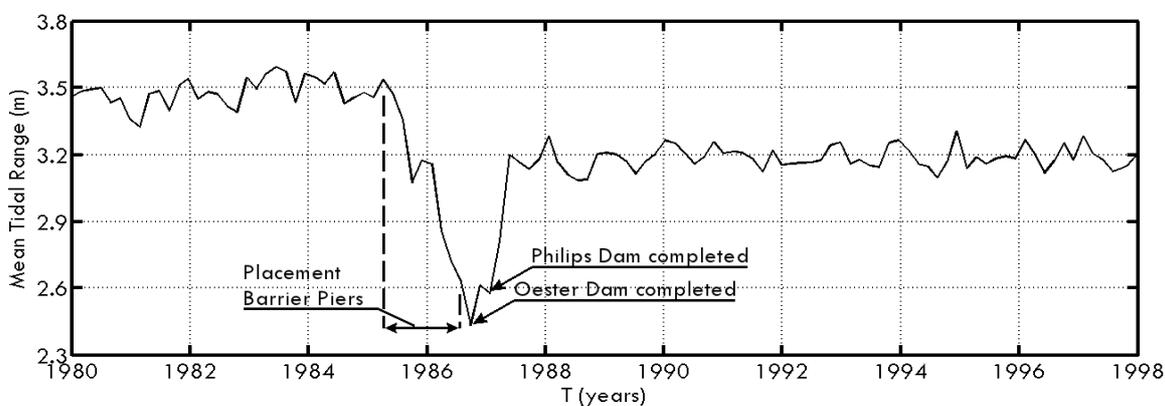


Figure 2: Mean tidal range measured in the central part of the basin.

From the bathymetrical development of the ebb-tidal delta, measured every 4 years since 1960, a view emerges of an ebb-tidal delta that is adapting itself to the presence of the storm surge barrier (Figure 3). The construction of the storm surge barrier caused a clockwise reorientation of the main channels on the ebb-tidal delta, effectively caused by sedimentation on the southern sides and erosion on the northern sides of these channels. Also, the channels running more or less shore-parallel are lengthening in northern direction, and are becoming deeper. This reorientation could be related to the interaction between the alongshore tidal current and the tidal current coming out of the inlet (Aarninkhof and Van Kessel, 1999). According to Sha and Van den Berg (1993), the orientation and protrusion of ebb-tidal deltas are related to the relative phases and strengths of alongshore currents and currents coming out of the inlet. Because the current flowing out of the Eastern Scheldt has decreased in strength, the alongshore current going from southwest to northeast should have become relatively stronger on the ebb-tidal delta. This could explain the clockwise reorientation of most channels and shoals.

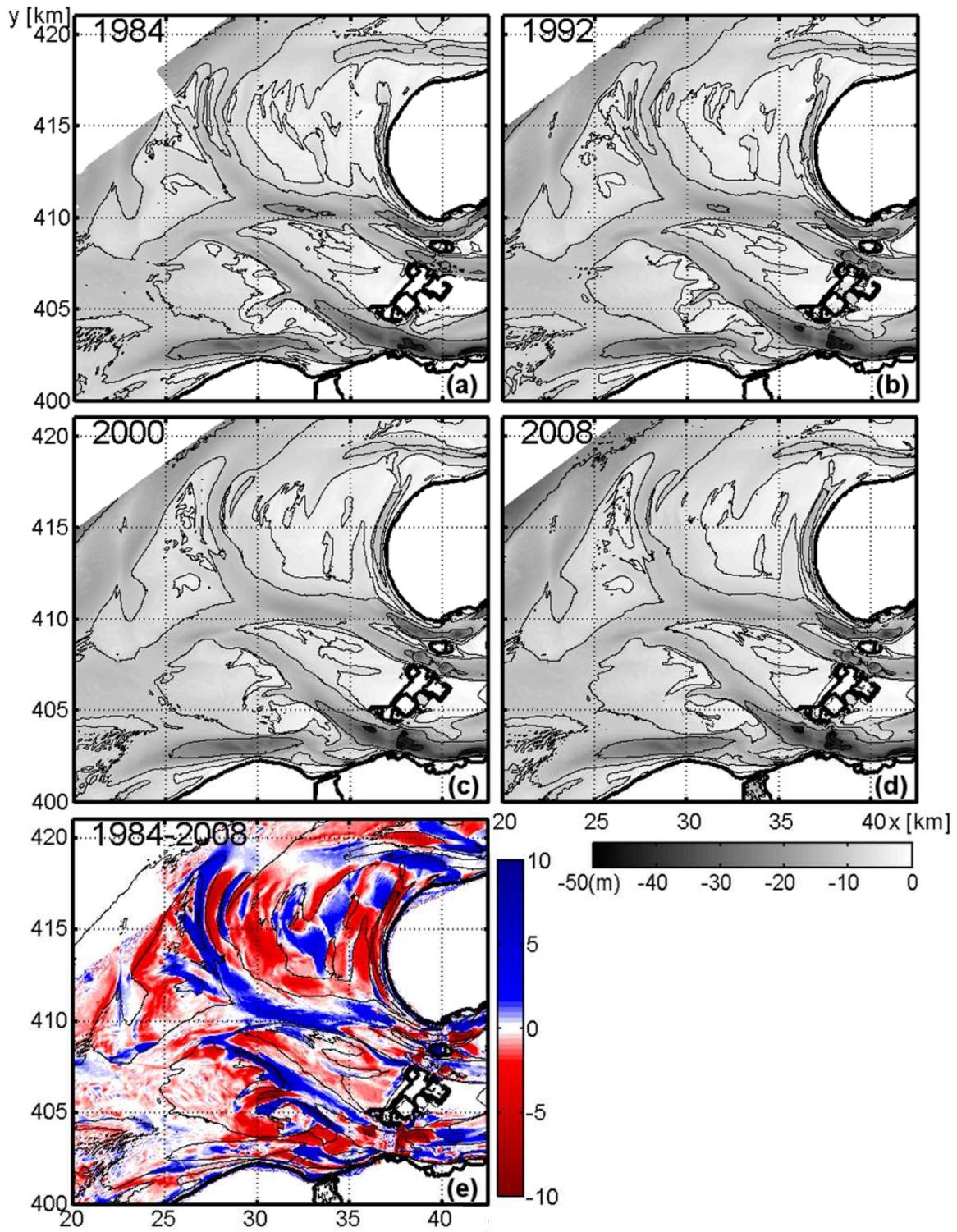


Figure 3: (a through d) Bathymetry of the ebb-tidal delta between 1984 and 2008. (e) Bed-level difference between 1984 and 2008 (red=erosion).

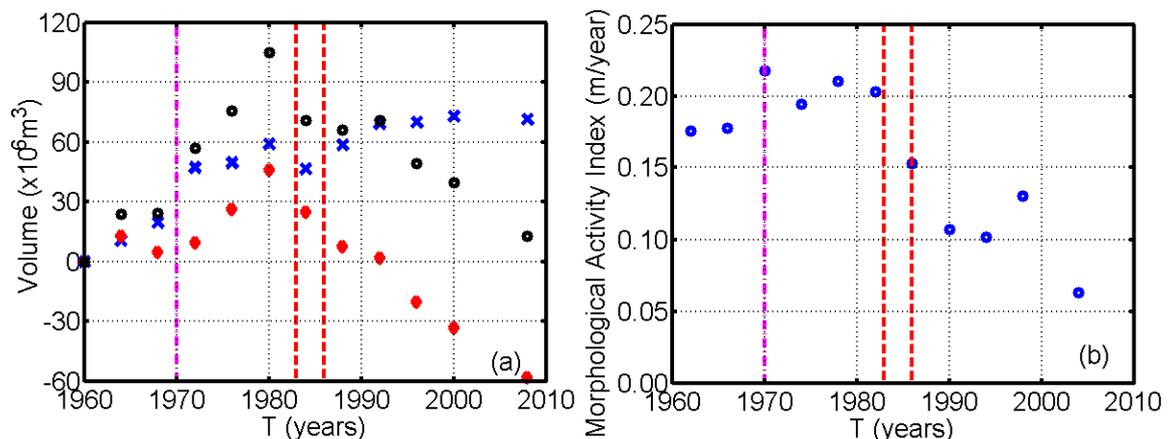


Figure 4: (a) black circles: Total cumulative sediment volume change. Red diamonds: cumulative sediment volume change above 10 m depth. Blue crosses: cumulative sediment volume change below 10 m depth. (b) Morphological activity.

Figure 4a shows the total cumulative sediment volume relative to 1960 (black circles) of the area inside the red polygon shown in Figure 1. The construction of the storm surge barrier marks a clear change in the trend of the sediment volume. Before 1986, the volume grew at a rate of roughly 2 to 3 million m^3 per year, as a result of another back-barrier dam built in 1970. After the storm surge barrier was finalized in 1986, the trend changed into an eroding trend with a rate of roughly 2 million m^3 per year. Between 1986 and 2008 the ebb-tidal delta has lost between 30 and 60 million m^3 of sediment. This trend has not shown any signs of leveling out, and still seems linear. This is consistent with the idea of an ebb-tidal delta sediment volume far out of equilibrium with its tidal forcing. A precise value for the loss is difficult to determine due to inaccuracies in the data (Cleveringa, 2008). The most probable destination for the eroded sediment are the abandoned channels of the Grevelingen ebb-tidal delta north of the Eastern Scheldt, which have been filling up with sediment since the closure of Grevelingen inlet in 1970. The sediment is transported towards the north by the tidal current, which has a strong residual component running from southwest to northeast. However, the bathymetric data of the area north of the Eastern Scheldt cannot account for the entire volume eroded from the ebb-tidal delta.

Another effect on the morphology is a general decrease in morphological activity, which is defined here as the average size of the absolute bed level changes (Figure 4b). After the completion in 1986, the activity decreased sharply and continued to decrease even further after 2000. This indicates that the new situation on the ebb-tidal delta is such that there are hardly any large-scale or high amplitude bed-level changes occurring, and the area is characterized by a slow but continuous development towards a new state. The decline in activity is probably caused by the general decrease in flow velocity over the area. Due to the drop in current velocities the magnitudes of the sediment transports must have decreased also. This decrease in transport is stronger than the decrease in flow, because of the non-linear relation between flow and transport. The strong net erosion of the same area means, that although since 1986 the bed-changes are relatively small, most of them are negative, meaning that erosion is more prevalent than it was before.

The effect of the barrier is also observable in the evolution of the hypsometry (red and blue symbols in Figure 4a). Since 1986, the sediment volume of the ebb-tidal delta above 10 m below mean sea level has continuously decreased, signifying erosion of the shallow parts. The sediment volume below 10 m has increased since 1986, indicating sedimentation in the deeper parts. The erosion on the shallow parts of the ebb-tidal delta does not seem to have slowed since 1986, while on the other hand the volumes of the deeper parts do seem to have reached some sort of stable value.

The shallow parts are suffering net erosion probably because the tidal current is not strong enough to supply the shoals with sediment anymore, and also because the supply from the basin is cut off. However, the tidal current is supposedly still strong enough to transport sediment stirred up by waves away from the shoals. This behaviour is notably different from the ebb-tidal deltas neighboring the Eastern Scheldt to the north, called the Grevelingen and Haringvliet. These two inlets were closed with dams in the nineteen sixties. Their ebb-tidal deltas responded with strong erosion of their seaward fronts and the creation of

large shore-parallel intertidal bars closer to the shore (Steijn *et al.*, 1989). The development of these kind of bars is virtually absent at the Eastern Scheldt. The bars that are there are much smaller and much lower than the bars at the Grevelingen and Haringvliet. The cause of this might be the reduced tidal current on the ebb-tidal delta still being strong enough to interfere with the wave-driven cross-shore transports which would normally build up the intertidal bars.

3. Outlook on possible future developments

The situation around the Eastern Scheldt tidal inlet is quite unique in the way in which the hydraulic conditions have changed in response to the storm surge barrier. This uniqueness also means that it is still unclear what the future morphological evolution of this ebb-tidal delta might look like. The Eastern Scheldt's tidal inlet behaves notably different from other tidal inlets which have been affected by different types of human interventions. This means it is difficult to use other cases as a reference for the Eastern Scheldt. In order to still form an outlook on the possible future morphological development of the Eastern Scheldt's ebb-tidal delta, we have applied an approach which involves letting a process-based numerical model create its own bathymetry similar to the Eastern Scheldt's, and then apply human interventions to see how the modeled bathymetry reacts to these interventions.

For this study, a process-based numerical model (Delft3D, see Lesser *et al.*, 2004)) will be applied. The model application is designed and applied in accordance with the 'realistic analogue' modeling strategy, as described by Roelvink and Reniers (2011). In this modeling strategy, the goal is not so much to reproduce the exact same bathymetry as found in reality. Instead, the goal is to let the model create morphology with similar patterns as found in reality, and to use this model as a numerical laboratory to study the effects of interventions in a more qualitative way (e.g. Van der Wegen and Roelvink, 2008; Dastgheib, 2012).

The model domain consists of a rectangular area, 60 km long and 25 km wide, representing the open sea and coast. Halfway along this coast, the Eastern Scheldt basin is attached (Figure 5). This basin has the same geometry as the real Eastern Scheldt basin. This geometry is adopted because it should make this model more comparable to the real situation around the Eastern Scheldt. The size of the grid cells varies between 150 by 150 m in the inlet to about a kilometer near the boundaries.

The initial bathymetry of all simulations consists of a uniform sloping bottom with a depth of 0 m at the landward end, linearly increasing to 15 m in the inlet. Seaward of the inlet, the depth increases linearly to 20 m over a distance of 12.5 km (Figure 5). The initial bed composition consists of an even mixture of three non-cohesive sediment fractions of 100, 300, and 500 microns.

The model is forced by a combination of water level boundaries on its alongshore edge and Neumann boundaries (i.e. water-level gradient boundaries) on its cross-shore edges. All other boundaries are closed. The only tidal constituents considered are the M_2 tide and its first two harmonic overtones M_4 and M_6 . Values for these constituents were derived by nesting this detailed grid in a much larger and coarser model covering the southern North Sea (Roelvink *et al.*, 2001), and calculating the amplitudes and phases of the Neumann boundaries following the method described by Dissanayake (2011). This configuration of boundary conditions results in a progressive tidal wave running from south to north along the coast. The model produces a tidal amplitude at the inlet of 1.3 m, which is very similar to the average tidal amplitude measured seaward of the Eastern Scheldt inlet in reality. In combination with the surface area of the basin this tidal amplitude results in a tidal prism of roughly 1500 million m^3 /tide, which is comparable to the tidal prism in the Eastern Scheldt by the time of closure.

The morphological model with this geometry is first run for three hydrodynamic years with a morphological acceleration factor of 200. Thus, the model simulates 600 years of morphological evolution. This simulation will serve as a baseline simulation. The effects of a storm surge barrier are investigated by implementing a barrier in the bathymetry after 400 years, and then letting this new simulation run for another 200 morphological years. The effects of the modeled barrier become apparent when results of this altered simulation are compared to the last 200 years of the unaltered baseline simulation.

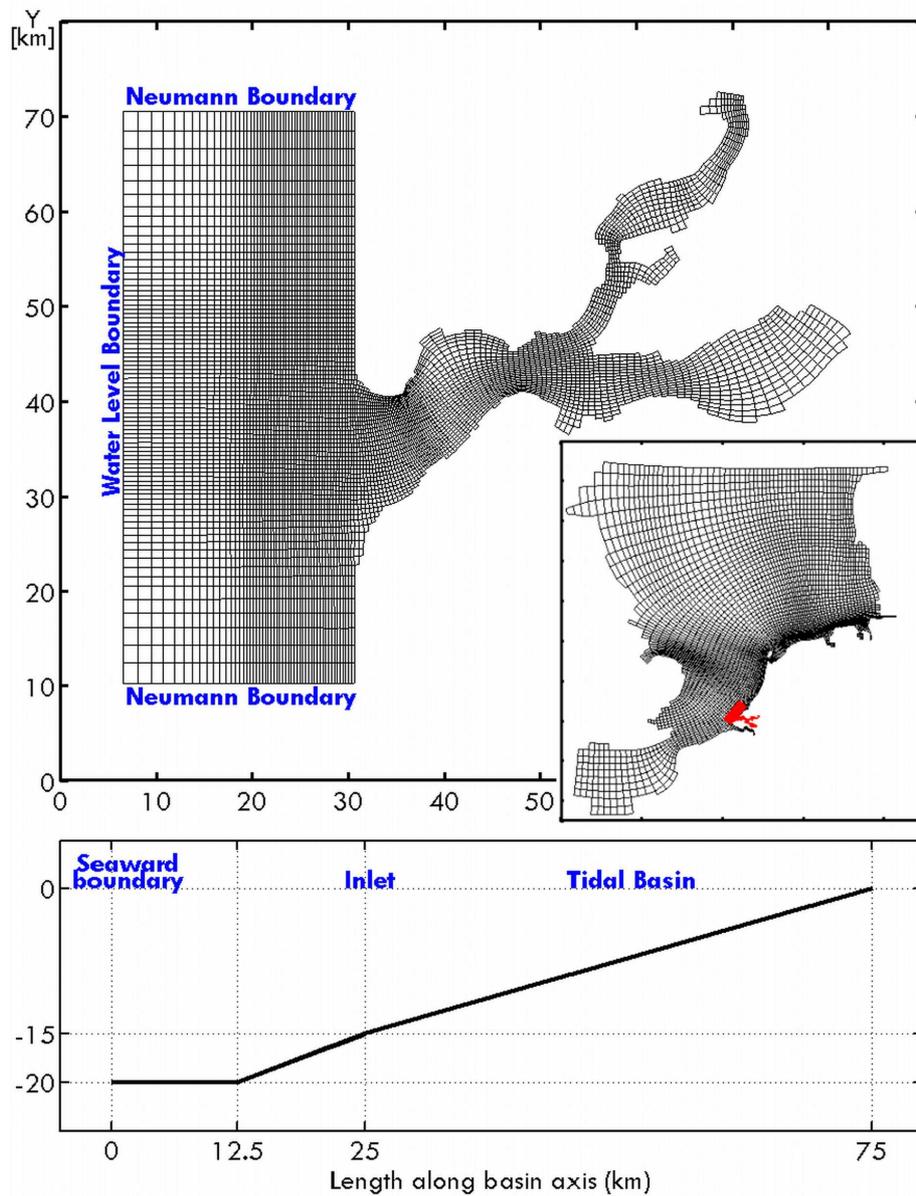


Figure 5: Model domain and initial bathymetry.

After 400 years of computed morphology, a barrier is implemented in the bathymetry. This barrier consists of three elements: (1) dry points across the islands at the barrier's location, (2) decreased depths in the channel openings, and (3) non-erodible layers on both sides of these openings, which act as the scour protection. The dry points have the same effect as the construction islands by cutting off the flow over these tidal flats. The decreased depths in the remaining channel openings act as the sills and piers of the barrier by significantly reducing the cross-sectional area (Figure 6). These openings are also made non-erodible. The total size of the openings has been calibrated to cause the same relative decrease in tidal amplitudes as the real barrier, which reduced the tidal amplitude by 20%. The total reduction of cross-sectional area is 81%. Apart from the barrier, also the back-barrier dams (Oesterdam and Philipsdam) have a serious effect on the tidal range and prism, because they reduce the basin length and basin area. These dams have been incorporated in the model by placing a thin dam which reduces the basin area by 22%. The total decrease in tidal prism in the model is roughly 30%.

The wave forcing is kept simple, with a single wave, in shore-normal direction on the western boundary which stays constant in time. The significant wave height and period are the same as the average wave

height and period measured offshore of the Eastern Scheldt tidal inlet: $H_s = 1.4$ m, $T_p = 4.5$ s. The evolution of the wave field is simulated using online coupling of the SWAN model (Booij *et al.*, 1999) with the Delft3D FLOW-module. The wave field computed with SWAN is updated every 60 minutes.

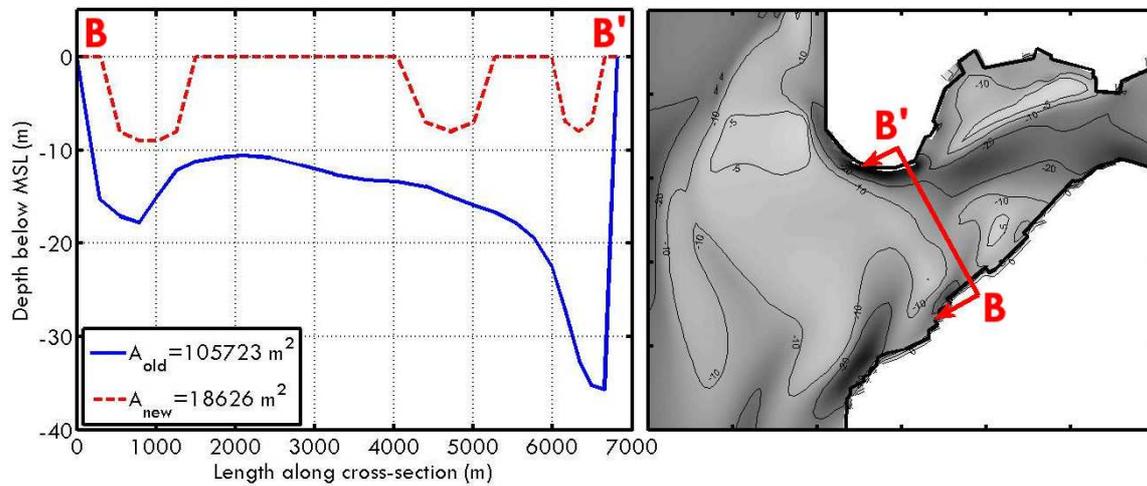


Figure 6: Modeled inlet cross-sectional area before and after implementation of the storm surge barrier.

4. Results

Before the model can be used to give an outlook on future developments, first we need to check whether the model reproduces the morphological trends observed in reality.

The modeled channel-shoal pattern of the ebb-tidal delta behaves as expected: The baseline simulation creates an ebb-tidal delta with a large shoal on its northern side, and the main channels towards the south (Figure 7). This ebb-tidal delta is somewhat wider than in reality, which might be because the real ebb-tidal delta is bordered by other ebb-tidal deltas, while on the other hand the modeled ebb-tidal delta is far less limited in its growth. When the storm surge barrier is implemented after 400 years, there is virtually no sediment exchange with the basin anymore. The ebb-tidal delta is being pushed northward, which seems to confirm that the model is able to reproduce the general channel-shoal pattern and the effect of the barrier on this pattern.

However, when the modeled sediment budget is studied more closely, important discrepancies are observed. First of all, the total cumulative sediment volume stays more or less stable after implementation of the storm surge barrier (dashed line in Figure 8), while in reality the ebb-tidal delta started to erode. The sediment volume below 10 m depth seems to decrease in the model, while in reality these parts gained sediment. More importantly, the areas above 10 m depth should have started to erode after implementation of the barrier. Instead, in the model these parts show hardly any response to the inclusion of the storm surge barrier. Apparently, the total sediment volume in the model is predominantly affected by the fact that there is no more sediment supply from the basin. The lack of erosion of the shallow parts then results in an overall stable total sediment volume.

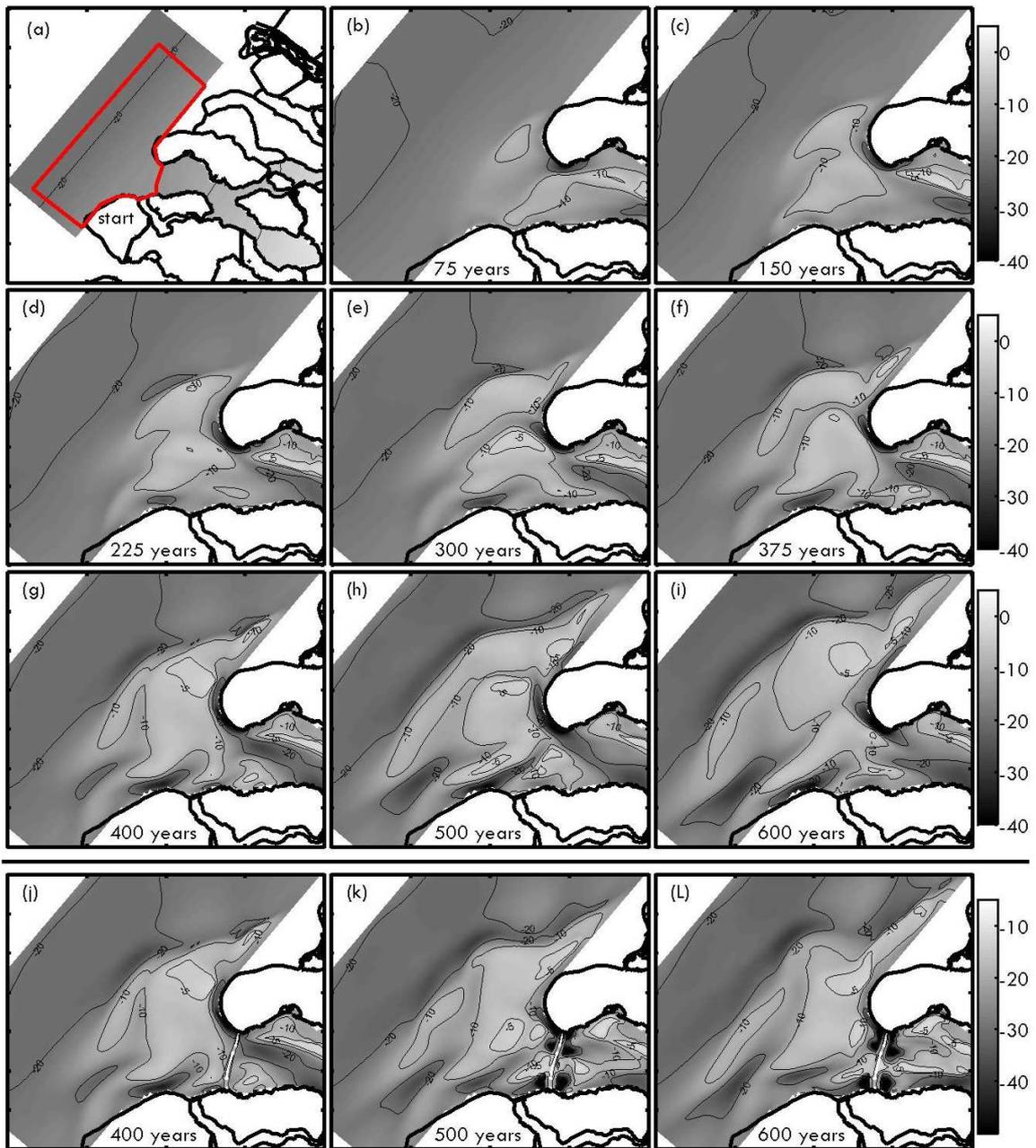


Figure 7: Modeled morphology of the ebb-tidal delta. (a) Initial bathymetry. The red polygon is the area used for calculating the sediment budgets in Figure 8. (b through i): Morphology of the baseline simulation. (j through l): Last 200 years with storm surge barrier and backbarrier dams.

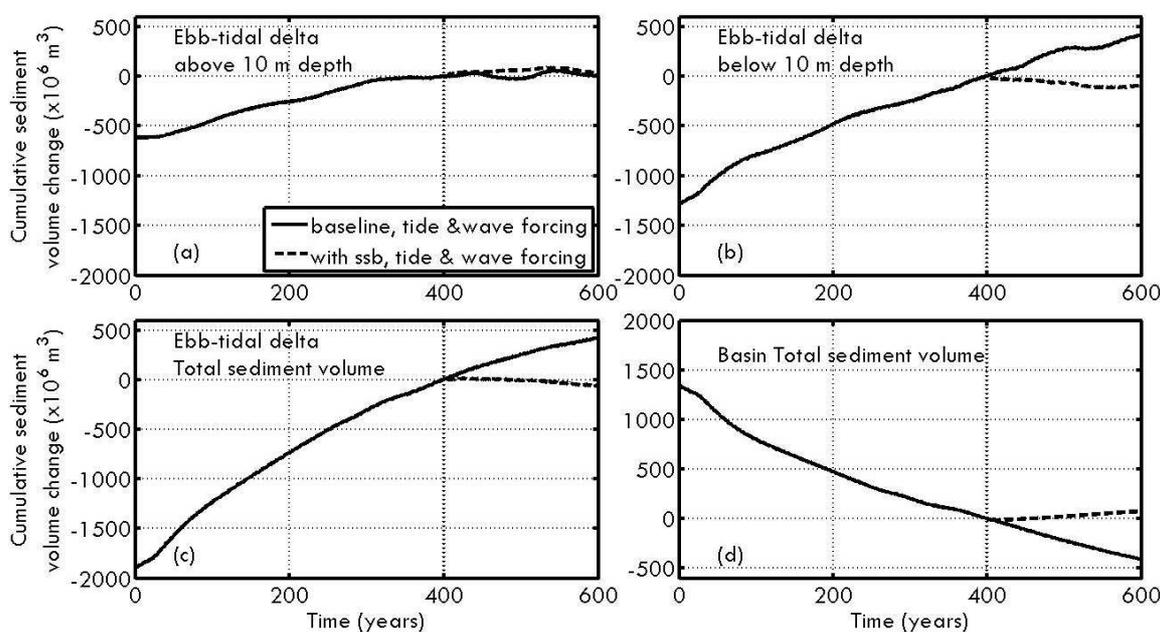


Figure 8: Modeled sediment budgets of the ebb-tidal delta. (a) Cumulative sediment volume changes above 10 m depth. (b) Cumulative sediment volume changes below 10 m depth. (c) Total cumulative sediment volume changes. (d) Cumulative sediment volume changes in the basin.

5. Discussion & Conclusions

The Eastern Scheldt Storm Surge barrier has been in place since 1986. The initial response of the ebb-tidal delta consists of a reorientation of the channel-shoal pattern and a redistribution of sediment, both on the ebb-tidal delta itself as well as towards its adjacent coastline. The ebb-tidal delta's sediment volume has been steadily decreasing, even though the morphological activity is relatively low, and there is virtually no exchange of sediment with the basin behind the barrier. The reorientation is most likely caused by the alongshore tidal current becoming stronger relative to the cross-shore tidal current coming out of the inlet. The redistribution of the ebb-tidal delta sediment consists of sedimentation in most channels, and erosion of the shoals and swash platforms.

Because of the uniqueness of this situation, it is unclear what the future morphological evolution of this ebb-tidal delta might look like. The model applied in this study was not able to reproduce some of the observed morphological trends of the ebb-tidal delta. Because of this inability, the model cannot help us in answering our questions regarding what the ebb-tidal delta might look like in the future.

There are several possible causes behind the shortcomings of the model. First of all, the wave climate applied in this study is highly schematized, consisting of just a single significant wave height and a single shore-normal wave direction. In reality, waves can come from multiple oblique directions. However, Dastgheib (2012) already states that the variation of wave directions is not a determining factor in the reshaping of an ebb-tidal delta, but the relative importance of waves and tidal forces are essential.

This leads us to a more probable cause: The model does not reproduce the proper balance between wave-driven and tide-driven sediment transports. Our hypothesis about the observed erosion of the shoals is that the tidal currents are no longer capable of transporting sediment towards the shoals. However, these currents are still strong enough to transport sediment away from the shoal, aided by waves which stir up the sediment. In the model, apparently, these transports directed away from the shoals are underestimated, resulting in a lack of erosion on the shoals, and a lack of sedimentation in the channels.

Yet another possible cause for the model's shortcomings is the choice for two-dimensional depth-averaged computation. This means that certain wave-driven cross-shore processes such as undertow, wave streaming and wave asymmetry are not incorporated. These processes might play a role on top of the shallow swash platforms on the northern side of the ebb-tidal delta, especially during low tide. A further

indication for this hypothesis is the observation of sand waves on top of these shoals, which migrate westward in cross-shore direction. It remains to be seen how these cross-shore processes might contribute to the overall lowering of the shoals.

The Eastern Scheldt tidal inlet has been under the influence of the storm surge barrier for more than 25 years already, and major morphological changes have already become apparent. However, the morphological response observed until now is most likely only the initial response to the intervention. The sediment surplus on the ebb-tidal delta is still very large, and the lack of sediment exchange with the basin means that it will take longer than most other ebb-tidal deltas to reach a new morphological equilibrium. What this new equilibrium might look like, and what the implications might be for coastal maintenance remains to be researched.

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