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Ebb-tidal delta morphology in response to a storm surge barrier

M. Eelkema[1], Z.B. Wang[2], and A. Hibma[3]
[1] Hydraulic Engineering, Delft University of Technology, P.O. Box 5048, 2600 GA, Delft, The Netherlands, m.eelkema@tudelft.nl
[2]Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands
[3]Ecoshape Building With Nature, Burgemeester de Raadtsingel 69, 3311 JG, Dordrecht, The Netherlands

ABSTRACT

The Eastern Scheldt ebb-tidal delta morphology has been adapting for the past 25 years in response to the construction of the Eastern Scheldt storm-surge barrier in 1986. As a result of the barrier, there has been a decrease in tidal amplitudes, volumes, and average flow velocities, and there is hardly any sediment exchange through the barrier. Bathymetrical measurements of the ebb-tidal delta show multiple effects: (1) an overall decrease in sediment volume, (2) a decrease in morphological activity, (3) sedimentation in most channels, (4) northward reorientation of channels and shoals, and (5) an increase in wave-driven features. Some channels are showing stronger erosion since 1986. This, and the reorientation of other channels could be related to changes in the interaction between cross-shore and alongshore tide. Most of the erosion is located in shallower, wave-dominated regions, indicating that waves have become relatively stronger. The steady erosive trend, combined with the decline of morphological activity, points toward a system dominated by relatively small and mostly negative bed-level changes. This system is still far from any kind of equilibrium, and is steadfastly adapting itself to the new hydraulic forcing regime, even though sediment transport capacities have decreased.

INTRODUCTION

The Eastern Scheldt tidal inlet (Figure 1), located in the south-western part of the Netherlands, has experienced large changes in hydrodynamics and morphology in response to the construction of several dams in its basin (constructed between 1965 and 1970) and a storm surge barrier in the inlet (constructed between 1983 and 1986). This storm surge barrier is open under normal weather conditions, allowing the tide to pass through the inlet, but closes during storm surges. However, even though it was designed as an open barrier, it still has a strong effect on the tidal hydrodynamics, and through that, the morphology of the ebb-tidal delta.

As a result of the storm surge barrier, the average tidal flows inside and outside the basin have decreased (Vroon, 1994). The sediment budget of the Eastern Scheldt basin indicates that ever since the barrier has been in place, the basin has received virtually no sediment from outside. Apparently, the storm surge barrier is acting as a blockage for sediment transport.

This combination of effects has created a unique situation on the seaward side of the barrier: The ebb-tidal delta has experienced decreased tidal flow coming out of the inlet, but exchanges virtually no sediment with its basin. The morphological activity declined, and the sediment volume has decreased. However, it is yet unclear on what time scale the ebb-tidal delta is adapting, nor where the eroded sediment is transported to (Aarninkhof and Van Kessel, 1999; Cleveringa, 2008). The response of the ebb-tidal delta is an important factor in coastal maintenance policy, as we know from looking at other tidal inlets under the influence of human intervention (e.g. Van de Kreeke, 2006; Elias, 2006). Also, knowledge on the behavior of channels on the ebb-tidal delta can be valuable, because some of those channels are positioned very close to the coastline. A shift in the position of those channels might lead to increased coastal erosion.

The goal of this study is to gain understanding of the

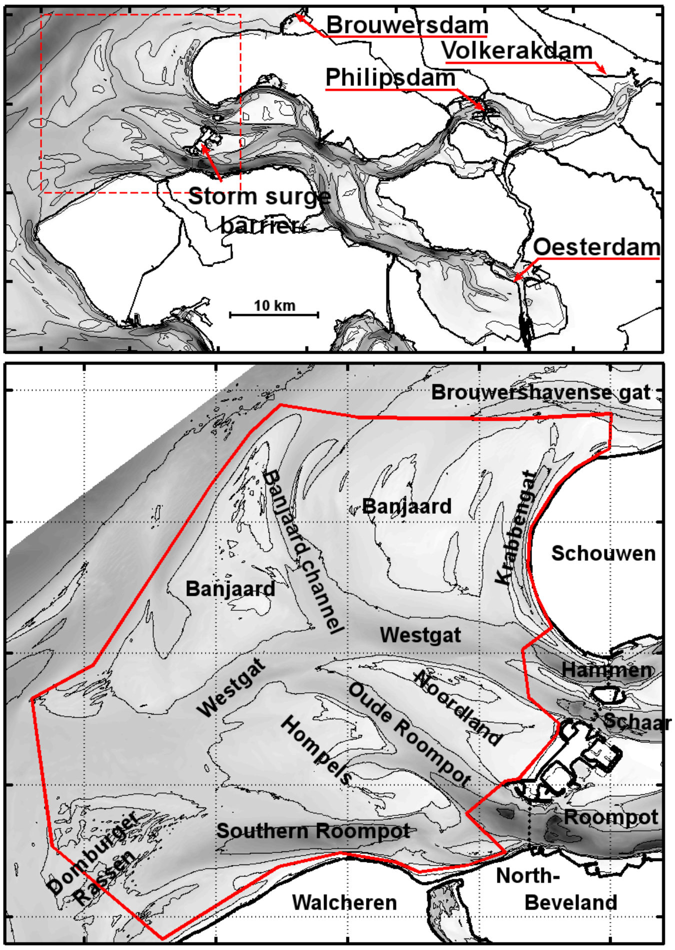

Figure 1. Overview of the Eastern Scheldt inlet. The red polygon in the lower figure indicates the area for which the activity and sediment volume in figures 4 and 5 are calculated.

behavior

of an ebb-tidal delta in response to the construction of a storm surge barrier by studying the Eastern Scheldt Inlet. In this paper we describe the observed morphological development of the Eastern Scheldt's ebb-tidal delta for the period between 1986 and 2008, i.e. the period after completion of the barrier.

STUDY AREA

Eastern Scheldt Inlet

The Eastern Scheldt (Figure 1) is an elongated tidal basin of approximately 50 km in length and a surface area of 350 km^2. Before 1965 A.D., this basin was also connected to two more tidal basins to the north through several narrow, yet deep channels. These connections were closed off with dams in the nineteen sixties as part of the so-called 'Deltaplan', designed mainly to improve safety against flooding. The inlet is located between two (former) islands called Schouwen and North Beveland, and consists of three main channels, separated by shoals. Seaward of the inlet the mean tidal range is 2.9 meters. The total tidal prism passing through this inlet before barrier construction was on average 1250 Mm^3 per tide (de Bok, 2001).

The long-term mean significant wave height measured 20 km offshore from Eastern Scheldt Inlet is 1.1 m, and waves higher than 4 m occur less than 0.2% of the time. The directional distribution shows two distinct wave directions, one from west southwest, and one from north northwest. Both directions are more or less equal in strength.

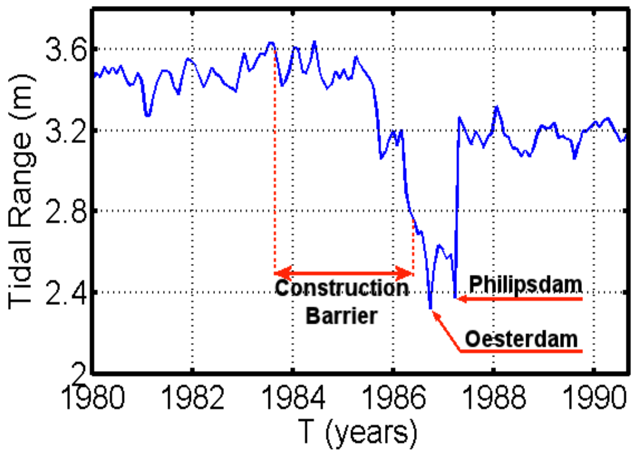

Figure 2. Tidal range measured in the centre part of the basin between 1980 and 1990 (adapted from Mulder and Louters (1994)).

Human Interventions

Between 1983 and 1986 a storm surge barrier was built in the

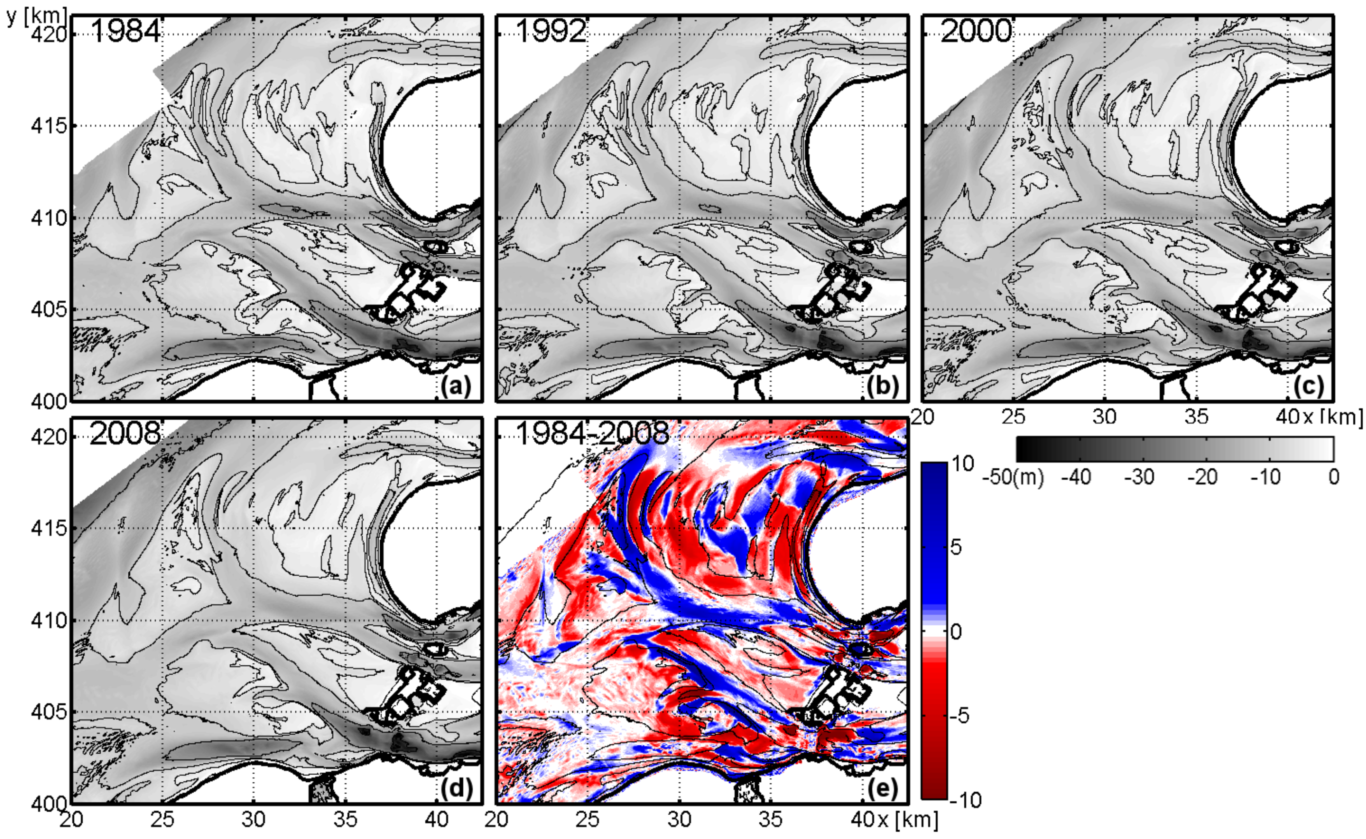

Figure 3. Bathymetry of the ebb-tidal delta between 1984 and 2008. (a through d) Bathymetry measured between 1984 and 2008. (e) Difference in bed level between 1984 and 2008 (red=erosion). Depths and differences are in m.

inlet channels in order to close off the inlet during storms while retaining the tide inside the basin during normal conditions. This barrier decreased the inlet's cross-section from 80.000 m^2 to 17900 m^2 (Vroon, 1994). Simultaneously with the barrier's construction, also two more dams (the Philipsdam and Oesterdam) were built near the landward end of the Eastern Scheldt basin (Figure 1). These dams were constructed 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. As a result of these dams, the total reduction in tidal range was limited to roughly 10% (Figure 2). The tidal prism was reduced to approximately 900 Mm^3 (de Bok, 2001).

MORPHOLOGICAL DEVELOPMENTS

Overall morphology

From the bathymetrical development of the ebb-tidal delta, measured every 4 years since 1960 (De Kruif, 2001), a view emerges of an ebb-tidal delta that is adapting itself to the presence of the storm surge barrier (Figure 3). Due to the drop in current velocities the magnitudes of the sediment transports must have decreased also. This decrease in transport is likely to be stronger than the decrease in flow, because of the non-linear relation between flow and transport. Most of the channels are no longer scouring, and some are becoming shallower. On the shoals, there is an increase in landward migrating saw-tooth bars, and most shoals are eroding and pushed northward (Figure 3e). Also, the seaward front of the ebb-tidal delta is eroding.

The construction of the storm surge barrier has caused a small 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. The growth of the Westgat and Roompot channels in seaward direction has stopped, and both channels are sedimentating in the areas seaward of the scour holes near the barrier. This trend is not seen everywhere on the ebb-tidal delta. Krabbengat and Banjaard Channels are still lengthening in northern direction. Krabbengat channel has also become deeper.

The reorientation of the channels and shoals 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 in and 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.

Morphological activity

The overall decrease in morphodynamics is clearly visible when it is quantified by computing a Morphological Activity Index (MAI), as used by Zimmermann (2009). This index is defined as the mean of the absolute bed-level changes calculated from the bathymetrical data of the ebb-tidal delta from 1960 to 2008 (Figure 4). The MAI is calculated according to:

$$MAI(t)=\frac{\sum_{i=1}^{n}\left|z_{year2}(x_i,y_i)-z_{year1}(x_i,y_i)\right|}{N(year_2-year_1)} \quad (1)$$

in which $t=(year_1+year_2)/2$, and $z_{year1}(x_i,y_i)$ and $z_{year2}(x_i,y_i)$ are the bottom depths with coordinates x_i and y_i measured in $year_1$ and $year_2$, respectively. N is the total number of locations where bottom depths are compared. The area for which the activity is calculated is shown as the red polygon in Figure 1.

In Figure 4 the MAI is shown along with the periods when the Volkerak Dam and the storm surge barrier were constructed. Apparently, between 1960 and 1984 the morphological activity was already quite high as compared to the post-1986 period, indicating that the ebb-tidal delta was still undergoing large changes in response to previous developments inside the basin. This activity increased in response to the implementation of the Volkerakdam and Brouwersdam in 1970, and remained more or less stable during the seventies and early eighties. This activity is mostly due to the increased flow coming from the basin. There was also a supply of sediment coming from the basin, but this supply decreased significantly during the seventies, while the morphological activity persisted (Van den Berg, 1986; Eelkema *et al.*, 2011).

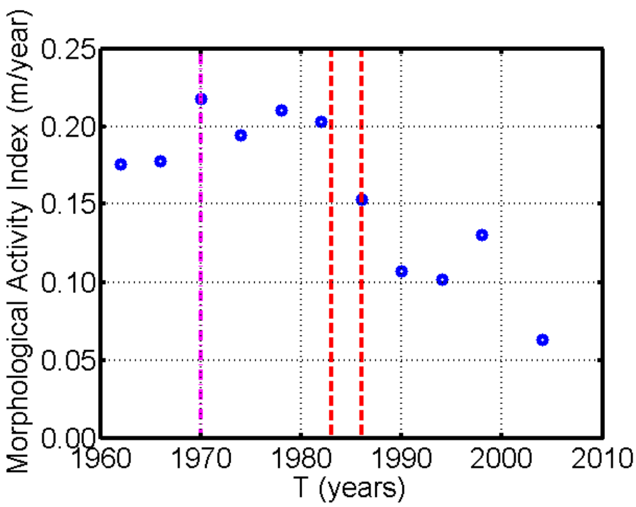

Figure 4. Morphological activity index. The vertical lines indicate the construction of the Volkerak Dam (1970) and the storm surge barrier (1983-1986). The calculation area is shown in Figure 1.

Figure 4 also shows the effect of the storm surge barrier. 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. Because of the non-linear relation between flow velocity and transport, the morphodynamics are diminished much more relative to the hydrodynamics.

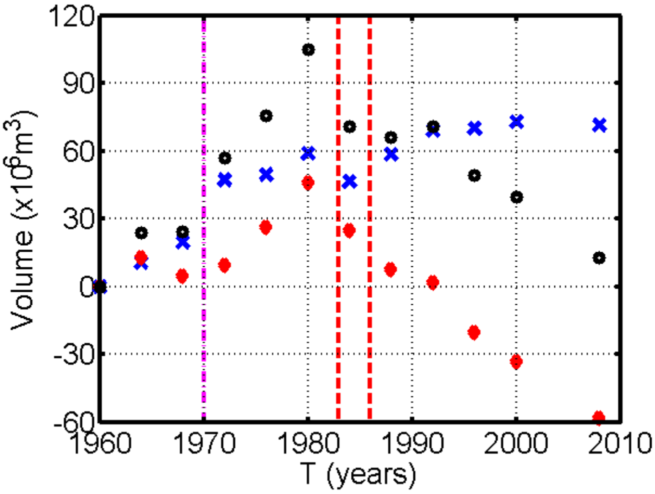

Figure 5. Cumulative sediment volumes relative to 1960. Blue crosses: cumulative sediment volume below -10 m depth. Red diamonds: cumulative sediment volume above -10 m depth. Black circles: total cumulative sediment volume. The vertical lines indicate the construction of the Volkerak Dam (1970) and the storm-surge barrier (1983-1986). The calculation area is shown in Figure 1.

Hypsometric & volumetric evolution

The effect of the barrier is also observable in the evolution of the hypsometry (red and blue symbols in Figure 5). 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. This figure also shows that the sediment volumes lost in the shallow parts are much larger than the volumes gained in the deeper parts, so the ebb-tidal delta as a whole is losing sediment. The erosion of the shallow parts is probably because the shoals are not supplied with sediment by the tide anymore, and waves have started to erode them.

Figure 5 also shows the total cumulative sediment volume relative to 1960 (black circles) of the area inside the polygon shown in Figure 1. Similar to Figure 4, the closure of the Volkerak and the construction of the storm surge barrier mark changes in the trend of the sediment volume. From 1970 onward (closure of the Volkerak channel) the volume grew at a rate of roughly 2 to 3 Mm^3 per year. After the barrier was constructed, the trend changed into an eroding trend with a rate comparable to the rate of growth which existed before 1986. Between 1986 and 2008 the ebb-tidal delta has lost anywhere between 30 and 60 Mm^3 of sediment. 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).

However, this strong rate of erosion seems counter-intuitive, as Figure 4 also shows that the morphological activity is much lower, and the basin is not receiving any of this sediment loss. One way to make the observed behaviors of the morphological activity and the sediment volume consistent with each other, is to say 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.

It is not exactly clear where the eroded sediment ended up (Cleveringa, 2008). The sedimentation in the channels is too small, and the Eastern Scheldt basin has received virtually no sediment since the barrier has been in place. The dunes adjacent to Eastern Scheldt inlet have not grown significantly since 1986. It is also unlikely that the sediment has been transported seaward, as there is no process present which could plausibly transport these amounts of sediment per year. The most plausible location for the eroded sediment are the abandoned channels of the Grevelingen ebb-tidal delta, which has been filling up with sediment since the closure of Grevelingen inlet. However, the deposition in this area could also come from the eroding shoreface of the Grevelingen ebb-tidal delta, and the entire Grevelingen area show net erosion since 1986.

CONCLUSIONS

From morphological observations of the Eastern Scheldt inlet a view emerges of an ebb-tidal delta which is still far from any kind of equilibrium, and which is steadfastly adapting itself to the new hydraulic forcing regime, even though sediment transport capacities have decreased. The initial response of the ebb-tidal delta is characterized by a reorientation of the channels and a redistribution of sediment from the shallow parts towards deeper areas (Figure 6). The reorientation is most likely related to the changes in cross-shore and alongshore tidal currents. The redistribution is most likely an effect of the waves reworking the shoals coupled to the weakening of the tidal currents and associated sediment supply.

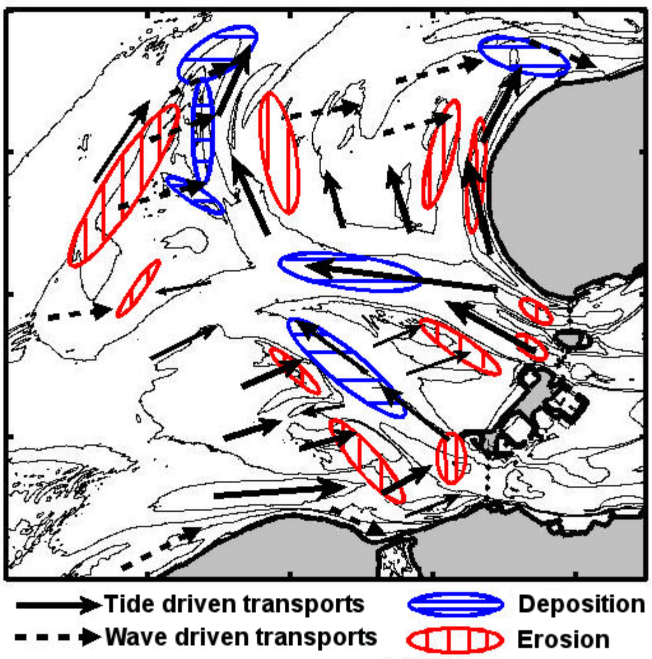

Figure 6. Schematic overview of the main erosion and deposition areas on the ebb-tidal delta.

However, some questions still remain. As mentioned, it is not clear where the eroded sediment ends up. Also, the proposed hypothesis behind the reorientation of the channels related to the alongshore tide remains to be tested. These questions are the subject of ongoing research.

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