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Improving long-term morphological modelling tools

Subreport 1 – Literature Review:
morphology of the Scheldt estuary mouth

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Abstract

This document presents a literature review of the morphology of the Scheldt estuary mouth. In a first part, existing literature on morphology occurring in estuaries is summarized. Specific focus is set on the present knowledge of the characteristics and mechanisms controlling the generation of ebb-tidal deltas. Also the occurrence of elongated tidal sand bars is discussed. Both these features are considered in more detail since the morphology of the Scheldt estuary echoes the presence of these type of marine bottom patterns. Secondly, the historical evolution over the last two centuries of the bathymetry of the Scheldt estuary mouth is discussed together with an overview of anthropogenic measures taken in this region.

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1 INTRODUCTION

The Scheldt estuary is a macro-tidal estuary (tidal ranges of approximately 4 m at the Scheldt mouth), which is located at the border between The Netherlands and Belgium. Providing maritime access to several ports in Belgium and The Netherlands, the estuary has a profound economic value. The bathymetry of the Scheldt mouth is characterized by an extensive shallow area (region of approximately 5x15km, with a depth less than 5m). This region (the “Vlakte van de Raan”) is flanked by two deeper shipping channels. As such, the morphology of Scheldt mouth resembles that of an ebb-tidal delta.

In the framework of several governmental coastal development projects (i.e., Masterplan Vlaamse Baaien), large-scale anthropogenic measures are anticipated near and through the Scheldt ebb-tidal delta. These particular interferences aim to extend the functionalities of both the harbours of Zeebrugge and Antwerp. In order to investigate possible impacts of such measures, Deltares and Flanders Hydraulics Research are presently collaborating within a project that aims to develop (i) a detailed numerical process-based model that is capable of making detailed numerical predictions of the evolution of the morphology of the mouth area, as well as (ii) an idealized model to obtain more insight into the essential physical mechanisms underlying this evolution.

The objective of this report is to summarize the presently existing literature on estuarine morphology in general, and the morphology of the mouth region of the Scheldt estuary in particular. Specifically, we aim to (i) describe the general characteristics of estuarine morphology, (ii) review the current understanding of the physical mechanisms that generate these characteristics and (iii) indicate how these mechanisms apply to the mouth region of the Scheldt estuary.

2 ESTUARINE MORPHOLOGY

The definition of an estuary has been under debate for several years and is still somewhat fogged. For instance, Pritchard (1967) defined an estuary by considering the occurring salinity: i.e. regions “where seawater is measurably diluted with fresh water derived from land drainage” are considered as an estuary. On the other hand, Dalrymple *et al.* (1992), defines an estuary as the marine-influenced portion of a river valley that becomes flooded with seawater when a transgression occurs. This definition was further refined by Dalrymple & Choi (2007) who extend the use of the term estuary by considering all transgressive coastal regions as an estuary.

All in all, estuaries are transitional regions where terrestrial and marine processes interact, which are characterized by transgressive conditions. The latter conditions allow to differ between an estuary and a delta, which also occurs on the transition between rivers and open sea, but can be identified by a progradational character.

Estuarine morphology displays a broad variation of characteristics and features. This large diversity is due to the occurrence and interaction of an extensive number of processes: e.g. physical (tidal action, river discharge, density variations, wind action and waves, etc …), sedimentary (bottom composition, existing resistant layers, sediment availability and input, ...), climatic conditions, etc. … . Moreover, due to the economical services estuaries provide, their morphology is often strongly influenced by anthropogenic measures.

Despite this apparent complexity, Davies (1964) and Hayes (1975) argued that a general conceptual model of the occurring estuarine morphology can be made by considering the local tidal range. In particular, worldwide, along coastal regions with small tidal range T_r (i.e. *micro-tidal* conditions T_r < 2 m), the transitional zone between terrestrial and marine environment is observed to be characterized by the presence of long (5 – 100 km) and linear barrier islands (Hayes, 1979), as depicted in Figure 1. On the other hand, barrier islands are absent in case of *macro-tidal* conditions (T_r > 4 m). In the seaward (marine dominated) part of the estuary, elongated linear sediment deposits are found in the center of the estuary, which are oriented parallel to the tidal currents, see Figure 2. Moreover, along the shore broad intertidal flats commonly occur. For intermediate conditions (*meso-tidal* conditions), i.e., T_r ranges between 2 and 4 meters, it is found that barrier island also occur, but they are shorter and more stunted than those in the case of micro-tidal conditions. Moreover, these islands tend to be dissected by an abundance of tidal inlets. Furthermore, it appears that the individual morphological features within the region are more tidally influenced.

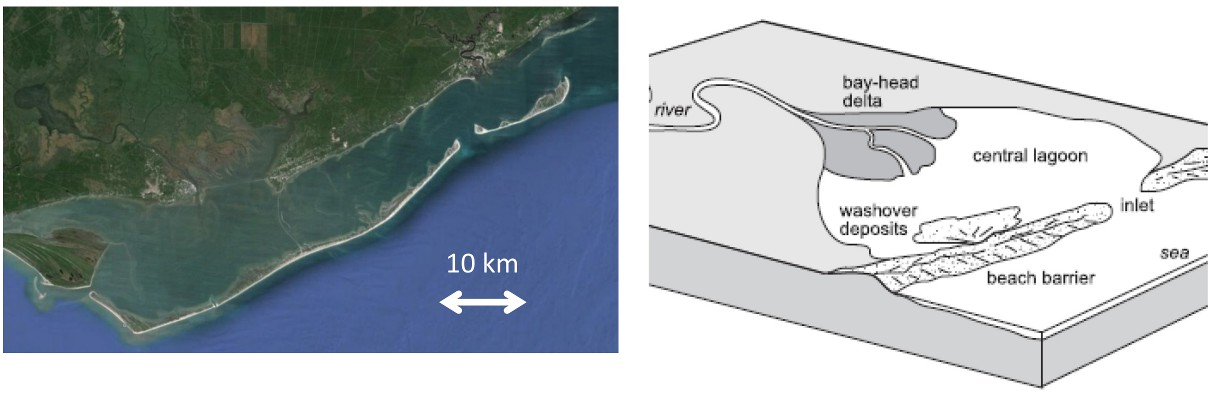


Figure 1 - (left) Top view of the morphology near Crowfordville, Gulf of Mexico (figure adopted from Google Earth), which is characterized by microtidal conditions. (right) Sketch illustrating the conceptual morphological model for a microtidal estuary, figure taken from Nicols (2009).

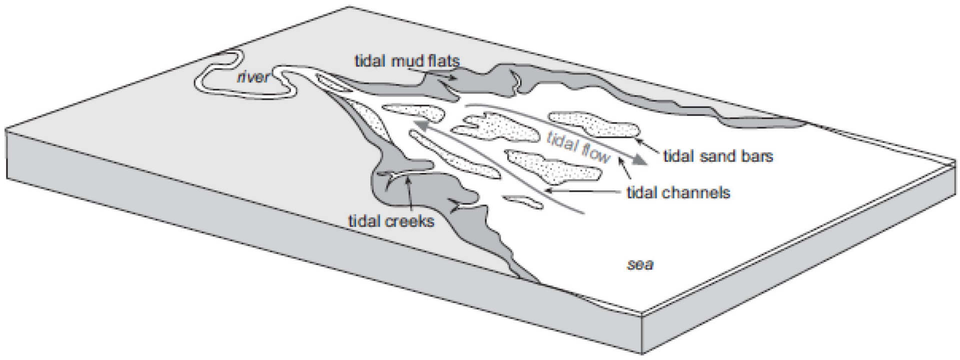


Figure 2 - Sketch of the general features observed in a macro-tidal estuary. Figure taken from Nicols (2009).

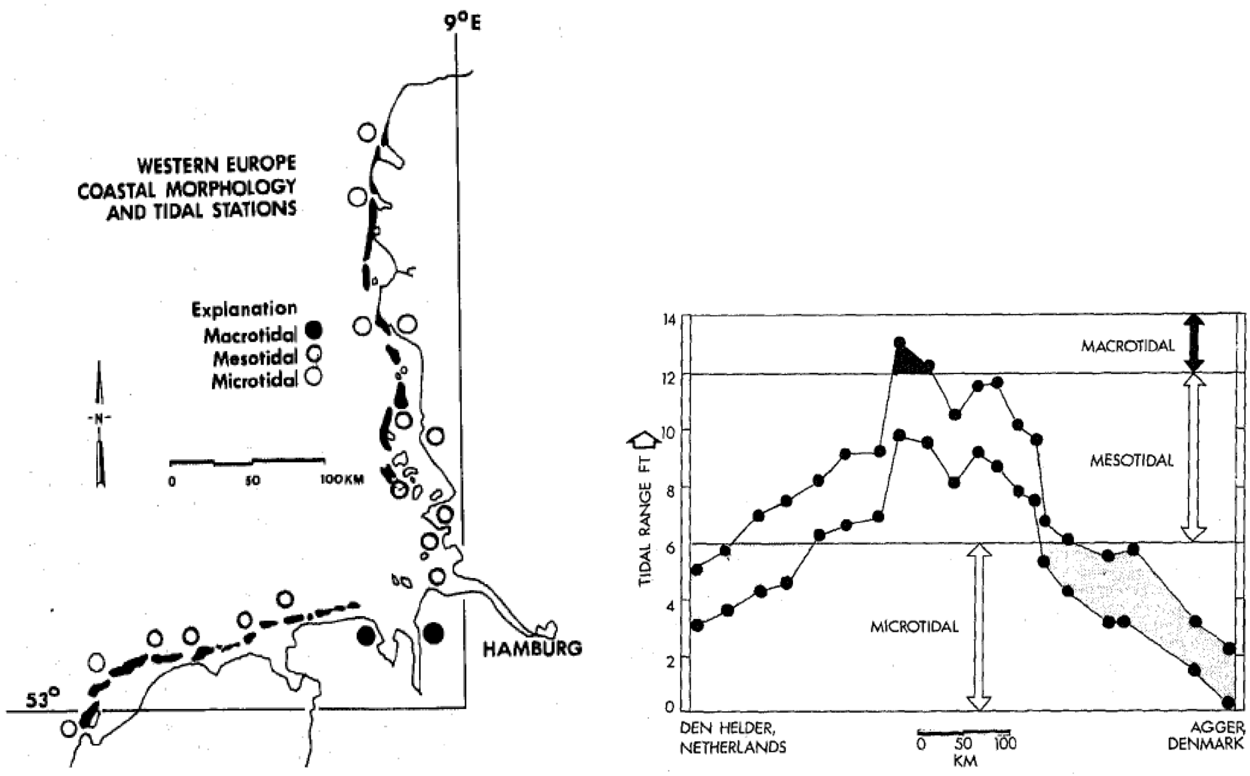


Figure 3 - (left) Morphology and corresponding tidal range occurring along the northern Dutch coast up to the western part of the coast of Denmark. (right) Corresponding observations of the tidal range. Lower line represents mean neap tide, and upper line describes mean spring tide. Figures adopted from Hayes (1975).

Field evidence supporting this general classification and geomorphological model is found for instance by considering the morphology along the northern part of the Dutch coast (Wadden Sea) up to Denmark, as illustrated in Figure 3. In particular, along the Wadden Sea (meso-tidal conditions), stunted barrier islands occur with many inlets and tidal deltas. Towards the mouths of the Elbe and Weser rivers, it is observed that the occurrence of barrier islands decreases, which agrees with the fact that the tidal range increases in this area (macro-tidal conditions). Finally, moving even further up north, along the west coast of northern Denmark, the tidal range becomes very small (~ micro-tidal conditions), and long linear barrier islands are observed, which are dissected only by a few inlets (Hayes, 1975).

By considering also the impact of wave energy, Hayes (1979) refined this classification, which was based only on the locally occurring tidal range. In particular, building upon observations made by Price (1955), Hayes (1979) takes into account that in regions of small waves, a smaller tidal range is necessary to induce a tidally-dominated morphology compared to that along coasts where the wave energy is medium or high. In particular, Hayes (1979) arranged 21 shorelines based on characteristics of the morphology (density of tidal inlets, shape of the barrier islands, presence of tidal sand bars, signatures of overwash sediment deposition) into 5 different classes and compared this classification with the local hydrodynamic conditions (tidal range and wave height). The obtained result is presented in Figure 4. It is apparent that the inclusion of wave energy to classify the occurring conditions is necessary to obtain a correct estimate of the resulting morphology. Indeed, Figure 4 shows that regions where the tidal range is less than 1 m, can be characterized as (low) tidally dominated in case that the wave energy is also small. If the wave energy is high, barrier coasts with wave dominated features can still be found in a region with a tidal range of 1.5 m.

Within an estuary, several individual morphological features can be identified such as tidal channels, intertidal flats, inlets, barrier islands, point bars, elongated tidal sand bars, ebb- and flood tidal deltas, etc. An overview of these features is presented in Figure 5. In particular, Figure 5a presents a schematic view of an estuary with barrier islands separating the open sea from the back barrier lagoon. In this figure a tidal inlet dissects the barrier island and both ebb- and flood tidal deltas occur (figure adopted from Dalrymple & Choi, (2007)). In Figure 5b, similar features as presented in Figure 5a are illustrated, however now with a funnel-shaped estuary (Dalrymple, *et al.*, 1992). Figure 5c sketches channel patterns that occur in a long tidal estuary, while Figure 5d presents a detailed sketch of possible recirculating cells. Figure 5e shows a meandering tidal channel morphology (figures Figure 5c,d,e are taken from Guo (2014) and reference therein). Finally, Figure 5f illustrates a funnel-shaped estuary with elongated tidal sand bars in the mouth region and a meandering channel more landward. Remark the presence of vegetated and unvegetated intertidal flats at the landward borders of the estuary, figure taken from Dalrymple & Choi (2007).

As will be discussed in Section 5, the morphological characteristics of the Scheldt mouth region resembles those of an ebb-tidal delta and elongated tidal sand bars. Therefore, in the following sections, we will discuss these morphological features in-depth. For a description of the other features, we refer among others to Dalrymple and Rhodes (1995), Marani *et al.* (2002), Seminara (2006) and Fagherazz *et al.* (2012).

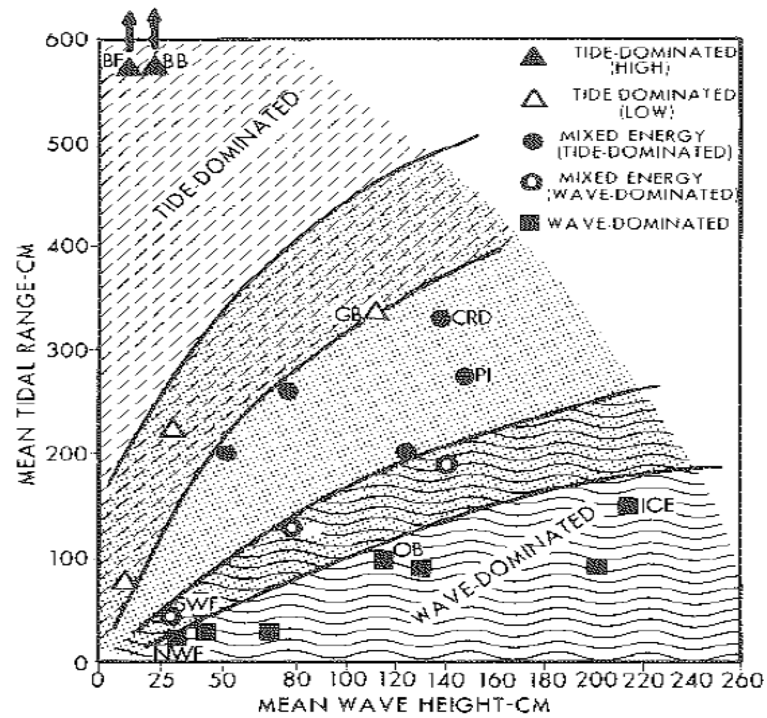


Figure 4 - Comparison of the morphological features of 21 shorelines, with the occurring mean tidal range and mean wave height. Figure taken from Hayes (1979)

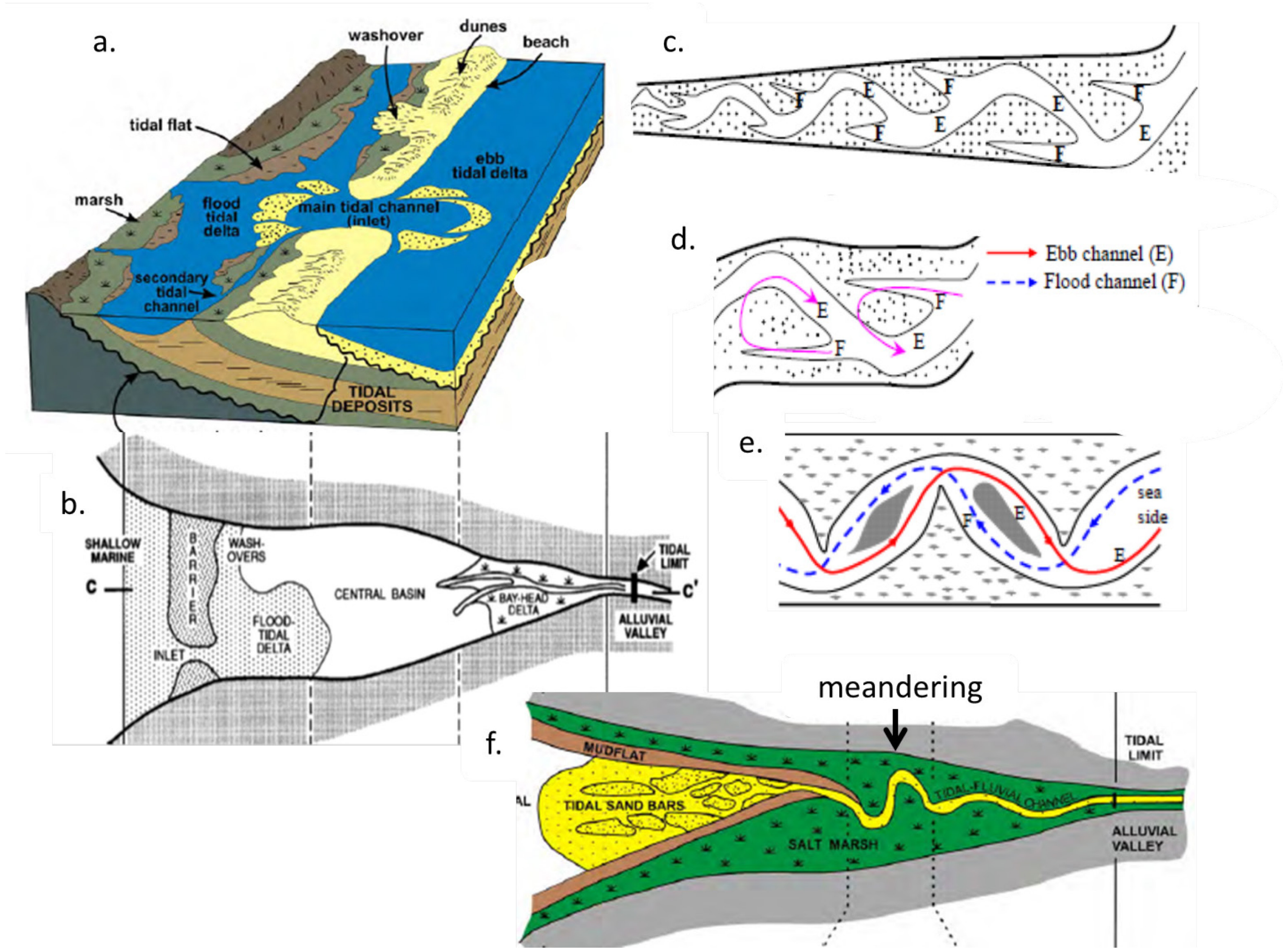


Figure 5 - Overview of the individual morphological features, which can occur within an estuary. (a) Schematic view of an estuary with barrier islands separating the open sea from the back barrier lagoon. A tidal inlet dissects the barrier island and both ebb- and flood tidal deltas occur. (b) Sketch illustrating similar features as present in figure a, however with a funnel-shaped estuary. (c) Channel patterns occurring in a long tidal estuary. (d) Recirculating cells. (e) Sketch of a meandering tidal channel morphology. (f) Funnel-shaped estuary with elongated tidal sand bars in the mouth region and a meandering channel more landward; note the presence of vegetated and unvegetated intertidal flats at the landward borders of the estuary. Figures adopted from Dalrymple & Choi (2007), Dalrymple *et al.* (1992) and Guo (2014).

3 ESTUARINE TIDAL DELTAS

3.1 Morphological characteristics

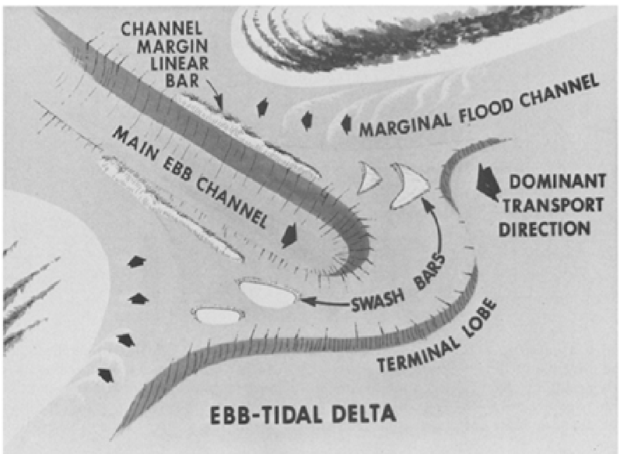
Estuarine tidal deltas are intriguing morphological features, which occur in concert with tidal inlets. The latter are often associated with barrier islands, and can be defined as a narrow channel connecting the open sea with a tidal basin, estuary or lagoon, see Figure 1 and Figure 5a. These inlets are important features as they provide for the exchange of water, sediment and nutrients; and provide a natural shipping lane (e.g. Davis & FitzGerald, 2004). We refer to de Swart & Zimmerman (2009) for a more general description of morphodynamics of tidal inlet systems.

Tidal deltas can occur on both the seaward (ebb-tidal delta) and landward (flood-tidal delta) of a tidal inlet. A first general description of the characteristics of an ebb-tidal delta was given by Hayes (1975), see Figure 6. In particular, ebb-tidal deltas can be identified by a substantial body of sand (terminal lobe) intersected by a large channel in the middle in which the peak ebb currents are larger than the peak flood currents, and two channels at the sides that have larger peak flood than peak ebb currents (Hayes, 1975). The ebb-channel is flanked by channel – margin linear bars. At a smaller scale, swash bars are often present on both sides of the terminal lobe flanking the main ebb channel. These are not static features but often migrate in the direction of dominant sediment transport.

The morphology presented in figure 1 is based on ebb-tidal deltas observed along the east coast of the United States. In particular, at these locations the tidal wave propagates mainly in the cross-shore direction, such that tide-induced longshore currents are relatively small. Ebb-tidal deltas are observed at many places in the world. Some examples: Arcachon basin (Cayocca, 2001), North and south Carolina coast (Fitzgerald, 1984), New Zealand (Hicks and Hume, 1996), Gulf of Mexico (Hayes, 1975), and many more.

Flood-tidal deltas, on the other hand, occur on the landward side of a tidal inlet and are composed of several features, such as (a) a flood ramp and (b) bifurcating flood channels on the seaward side of the delta. Both are dominated by flood currents and often flood-oriented sand waves occur within these regions. Furthermore, within a flood-tidal delta, commonly, (c) ebb shields, (d) ebb spits and (e) spillover lobes can be found on the landward side, which contain an abundance of ebb-oriented bedforms, see Figure 6.

In tide-dominated inlet systems, ebb-tidal deltas are extensive while the flood-tidal deltas are only little developed. On the other hand, for wave-dominated locations, the morphology near an inlet is expected to be opposite: small to absent ebb-tidal delta´s and larger flood-tidal delta´s. Finally, when waves and tides provide a comparable energetic input, the ebb-tidal delta can be expected to be well-developed (e.g. Nahon *et al.*, 2012).



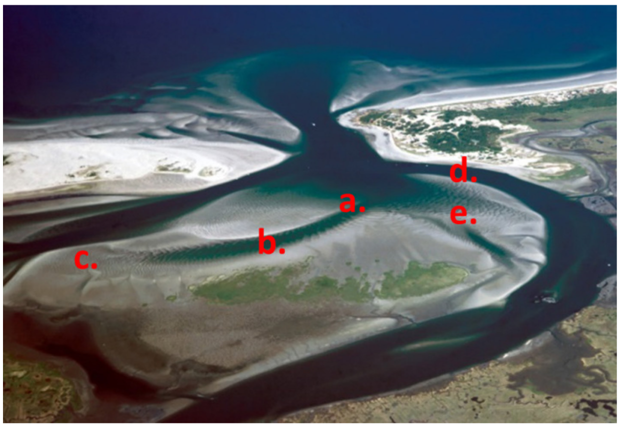


Figure 6 - (left) Sketch of the main components of an ebb-tidal delta. Figure adopted from Hayes (1975). (right) Picture illustrating a flood-tidal delta occuring at the Essex inlet, Massachusetts and the various morphological features (see text). Figure adjusted from a picture from http://www.oberlin.edu.

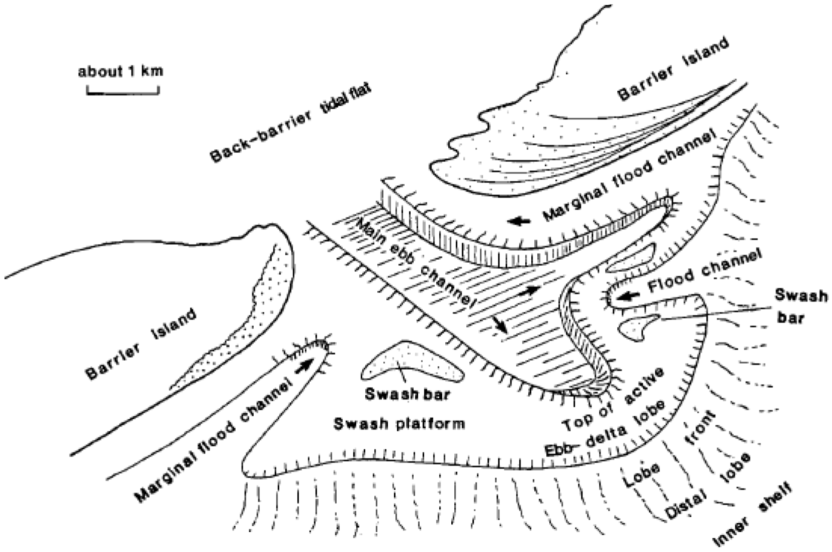


Figure 7 - Generalized sketch of the morphology of an ebb-tidal delta based on the bathymetry occurring at Texel Inlet, Terschellingen and Ameland Inlet (The Netherlands). Figure adopted from Sha (1990).

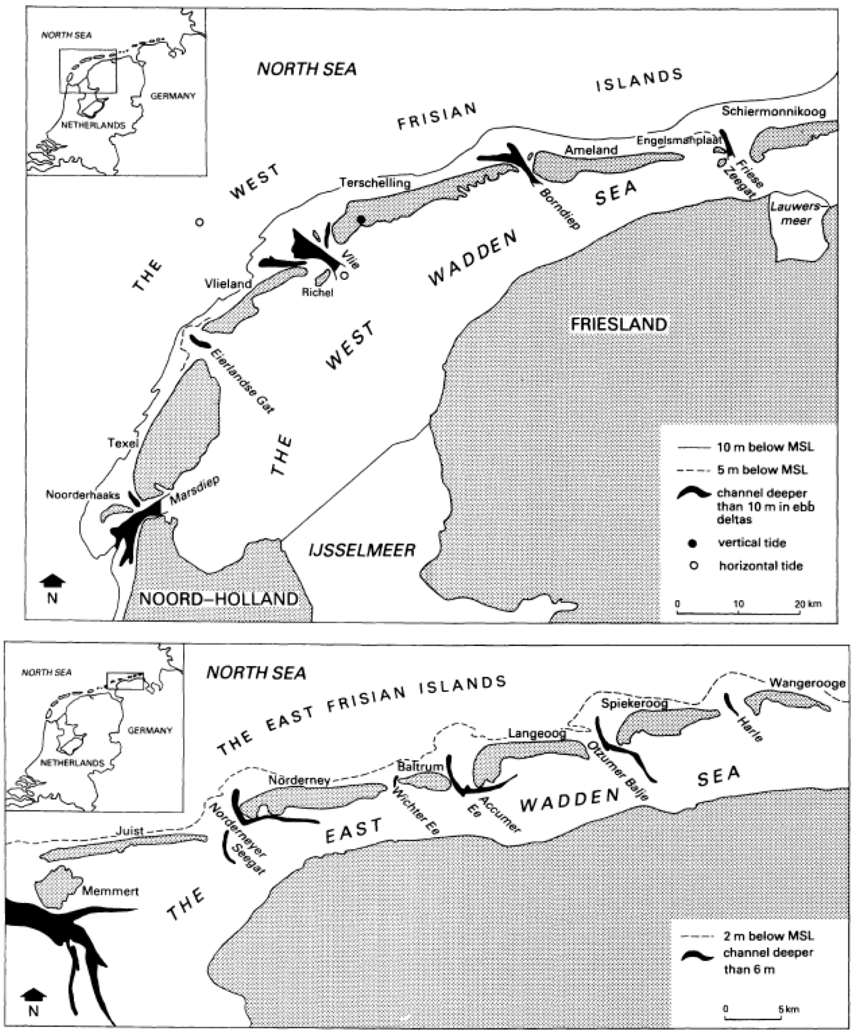


Figure 8 - Variation of the geomorphology of the ebb-tidal deltas occurring along (top) the West Frisian Islands and (down) the East Frisian Islands. The black areas denote channels deeper than 6 m. Note the shift in orientation of main ebb-channel moving from West to East. Figure adopted from Sha & Van den Berg (1993).

The classical picture discussed above and introduced by Hayes (1975) was adapted for the Dutch Wadden Sea inlet by Sha (1989, 1990) and Sha & Van den Berg (1993). In particular, in contrast to the general morphological picture introduced by Hayes (1975), the main ebb channel along the tidal inlets at the Dutch Wadden Sea has an oblique orientation with respect to a hypothetical shore-normal axis through the inlet. Similarly, the sand body of the ebb-tidal delta is also asymmetric, see Figure 7. Moreover, as illustrated in Figure 8, remarkable differences exist in the orientation of the channels and shoals along the coast from the South-West Netherlands to the German Bight. In particular, the features of the ebb-tidal deltas along the western Wadden Islands are oriented more towards the left (when viewing from the inlet in seaward direction); while the systems more to the East, reveal an orientation to the right. Hence, it appears that, depending on the local conditions, the ebb-tidal delta morphology can be characterized by symmetric or asymmetric features.

Finally, field observation indicate that there is an almost linear relation between the ebb-tidal sand volume (ESV) and the tidal prism (TP); e.g. Walton & Adams (1976) and Sha (1989). The former (ESV) is defined as the positive sediment volume (sediment surplus) of the mouth region with respect to a reference bathymetry outside the region influenced by the tidal inlet (e.g. the region at the middle of the adjacent barrier island), while the tidal prism is the difference between the maximum and the minimum volume of water in a tidal basin during a tidal cycle. In particular for Dutch Wadden Sea, the following relation is found to hold:

$$ESV^* = 65.7 * 10^{-3} * (TP^*)^{1.23},$$

where *ESV** and *TP** denote the ebb-tidal sand volume and the tidal prism made dimensionless. Similar relationships have been found for systems elsewhere. They all confirm the slightly faster than linear increase in sediment volume as a function of tidal prism. On the other hand, recently, Ridderinkhof *et al.* (2014) did not find a unique relationship between tidal prism and the sand volume of the ebb-tidal delta as discussed in the next Section.

Various other empirical relationships for different parameters within an ebb-tidal delta exist, for example for shoal area as a function of tidal range and tidal prism. It is not clear whether these relations are applicable for Western Scheldt, therefore we do not elaborate on these relations in the present report.

3.2 Mechanisms controlling the morphological characteristics of ebb-tidal deltas

Using an idealized 2D morphodyamic model that considers only cross-shore tidal currents, Van der Vegt *et al.* (2006) illustrate that the morphology of a symmetric ebb-tidal delta results from the distinct characteristics of the flow field at the seaward side of the inlet during the flood and ebb phase, seeFigure 9. In particular, during ebb phase, the flow field echoes a jet flow pattern while a more radial inflow pattern occurs during the flood phase. This difference in hydrodynamic characteristics results in a residual flow pattern characterized by two eddies, which induce sedimentation/erosion patterns such that an ebb-tidal delta forms, see Figure 10.

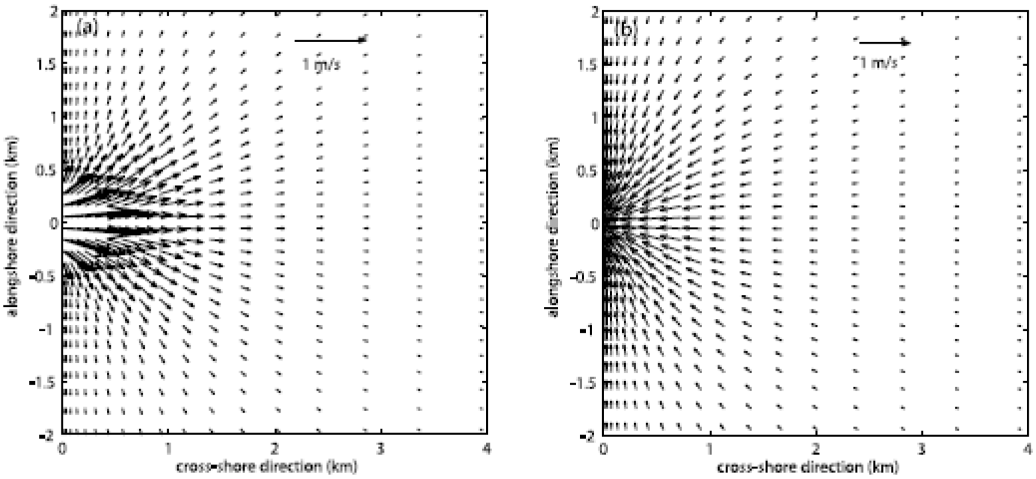


Figure 9 - Flow field seaward of the tidal inlet at the instant the flow velocity is maximum in the ebb phase (left figure) and the flood phase (right figure). Figures taken from Van der Vegt *et al.* (2006).

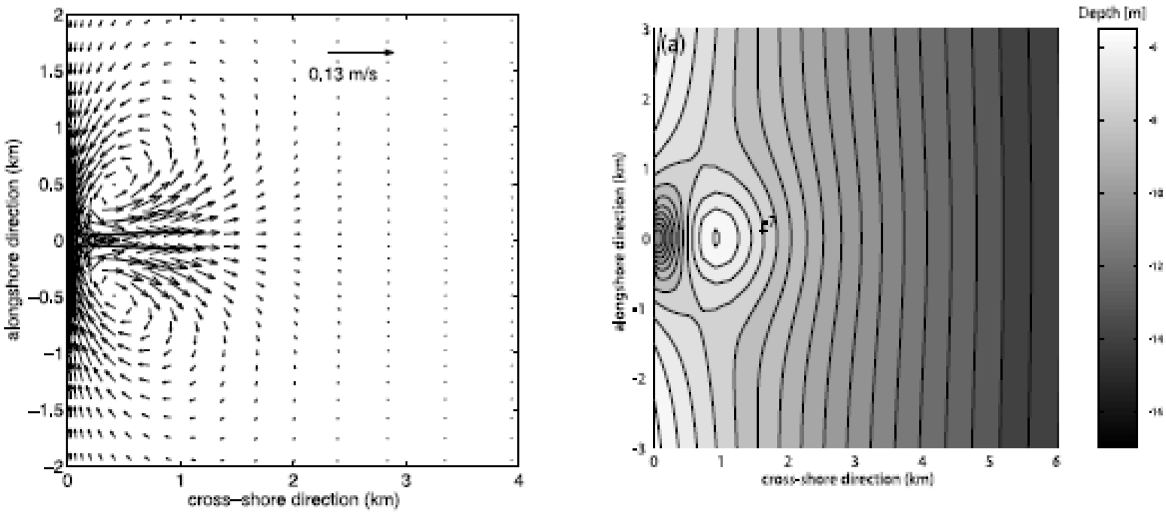


Figure 10 - (left) Residual (tidally averaged) flow pattern seaward of a tidal inlet. (right) Modelled equilibrium morphology, seaward of a tidal inlet. Figures taken from Van der Vegt *et al.* (2006). Please note that the horizontal and vertical axes are not equally scaled.

As discussed above, next to symmetric ebb-tidal deltas, also asymmetric deltas are present of which the orientation can shift for distinct local conditions, see Figure 8. Van den Berg (1987) coined that the orientation of the flood- and ebb- channels is strongly affected by the phase-difference between the tidal wave at sea, and the tidal wave in the inlet. For instance, if maximum flood occurs simultaneously with high water level (see Figure 11, situation I), together with a propagation tidal wave, the main ebb-channel will be concentrated on the left side of the channel; i.e. the side towards which the tidal wave is propagating during ebb. This situation is characteristic for the tidal inlets occurring at the Wadden Sea. On the other hand, Van den Berg (1987) discusses that for the Scheldt mouth area it occurs that the phase difference between the tidal wave at sea and that in the inlet is such that it does not lead to a preferential ebb-channel orientation. In particular, since the along-shore component of the horizontal tidal wave at open sea has a phase difference of approximately 3 hours with the flow velocity in the inlet (see Figure 12). As indicated by Figure 11, situation II, this does not induce a preferential location and orientation of the channel system.

Hence, forcing the system with alongshore tidal currents results in a possible mechanisms for asymmetric ebb-tidal deltas. In that case the asymmetry depends on the relative phase difference between cross-shore and shore-parallel currents. When the relative phase difference is equal to 90 degrees, a symmetric delta can arise. These hydrodynamic conditions occur along the deltas in the south west of the Netherlands. Therefore, based on this schematic representation of the morphodynamics, van den Berg (1987) coins that the channel locations in the Scheldt estuary mouth are induced by wave-current induced effects.

Recently, based on morphodynamic modelling experiments using Delft3D, Ridderinkhof *et al.* (2014) has related this phasing of cross-shore and shore-parallel currents to the length of the tidal basin landward of the inlet. In particular, Ridderinkhof *et al.* (2014) show that, considering tidal conditions representative for the Wadden Sea, together with long basin lengths, the phase difference tends to 90 degrees, while for shore systems it tends to zero degrees. Based on this observation, an insightful explanation is provided of the shift in orientation of the ebb-tidal delta of the Texel and Vlie inlet after closure of the Zuiderzee in 1932. This closure resulted in a 70 km reduction in basin length and resulted in a shift of the ebb-delta from being symmetric to more asymmetric orientation. In addition, the results presented by Ridderinkhof *et al.* (2014) suggest that the net tide-induced sediment transport can change from exporting to importing when the basin length is altered. This might explain the apparent strong reduction in ebb-tidal sand volume of these deltas. In addition, these results suggest that there is no unique relationship between ebb-tidal sand volume and tidal prism, contrasting the field evidence discussed above (Walton & Adams, 1976).

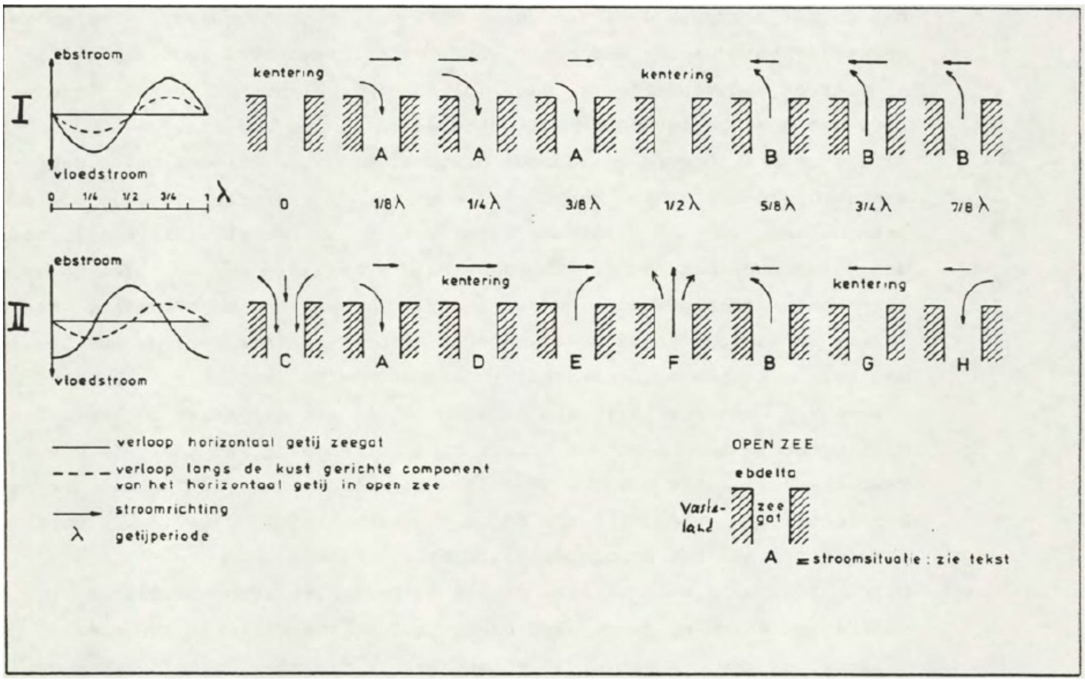


Figure 11 - Sketch of the impact of phase-difference between tidal wave propagation along the coast and the characteristics of the tidal wave in the inlet. Figure taken from Van den Berg (1987).

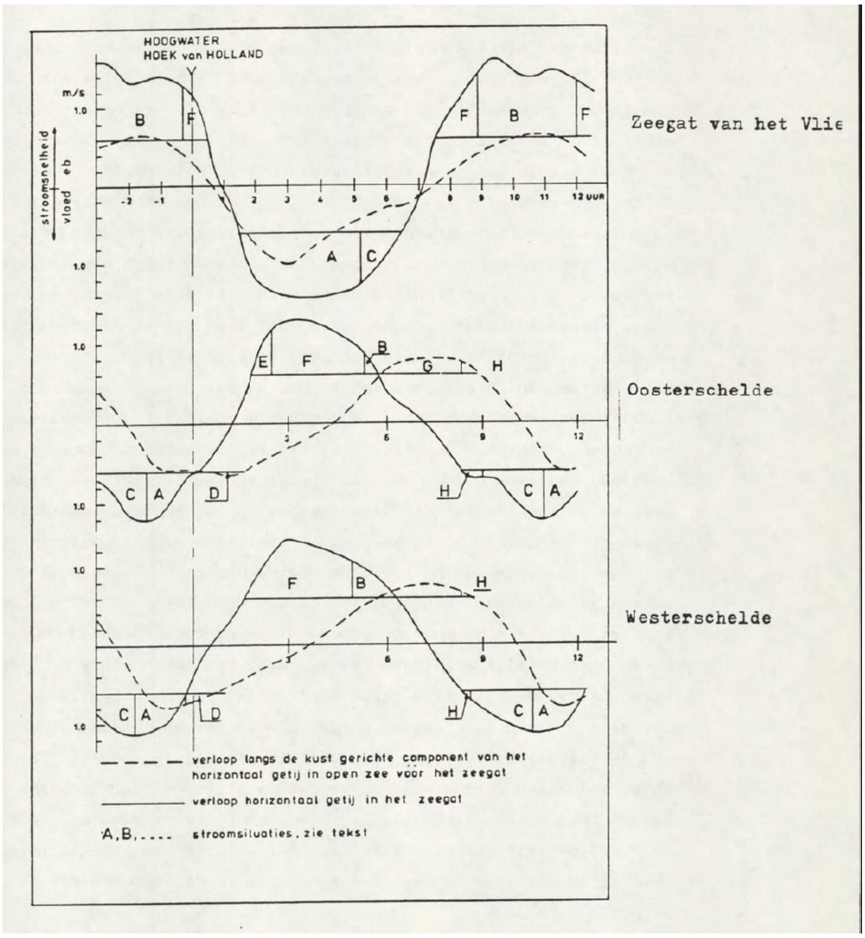


Figure 12 - Evolution of the magnitude of the along-shore component (solid line) of tidal velocity in open sea, and flow velocity in the tidal inlet (dashed lines) at (above) Zeegat van Vliet (conditions representative for the Wadden Sea) and at (middle and lower) the Eastern and Western Scheldt. Figure adopted from Van den Berg (1987).

The role of waves is found to be threefold. On the one hand, wave-induced longshore sediment transport tends to steer the delta in the direction of the generated longshore drift. Furthermore, waves are assumed to push the ebb-tidal delta landward. In particular, as also discussed above (Hayes, 1975), systems with relatively weak waves tend to have an ebb-tidal delta that protrudes further into sea than systems more influenced by waves. In addition, Eelkema *et al.* (2013) describes that the impact of waves on the morphology, in general, leads to a redistribution of sediment in the shallower region into the channels. Finally, it is worth to mention that the general relations derived from field observation as described above (e.g. the conceptual models introduced by Hayes (1979)) were compared with the outcome of a process based model by Nahon *et al.* (2012). This comparison showed that overall the general empirical relations are respected. For instance, it is found that the inlet channel width and depth increase with the tidal range and decreases with wave height. Moreover, the ebb sand banks are found to increase significantly with tidal range and extend further offshore. On the other hand, it is also found that flood sand banks grow with larger tidal range, which is in contrast to the simplified overall classification introduced by Hayes (1979). Furthermore, Nahon et al. (2012) find that the tidal prism also impacts the resulting morphology, which is not taken into account in the classification of Hayes (1979). Even though, as pointed out above, it is unveiled that there is no unique relationship between tidal prism and sand volume in the case the tidal characteristics along the coast lead to phase differences between the cross-shore and along-shore currents (Ridderinkhof et al., 2014).

3.3 Impact of anthropogenic measures on the morphology of ebb-tidal deltas

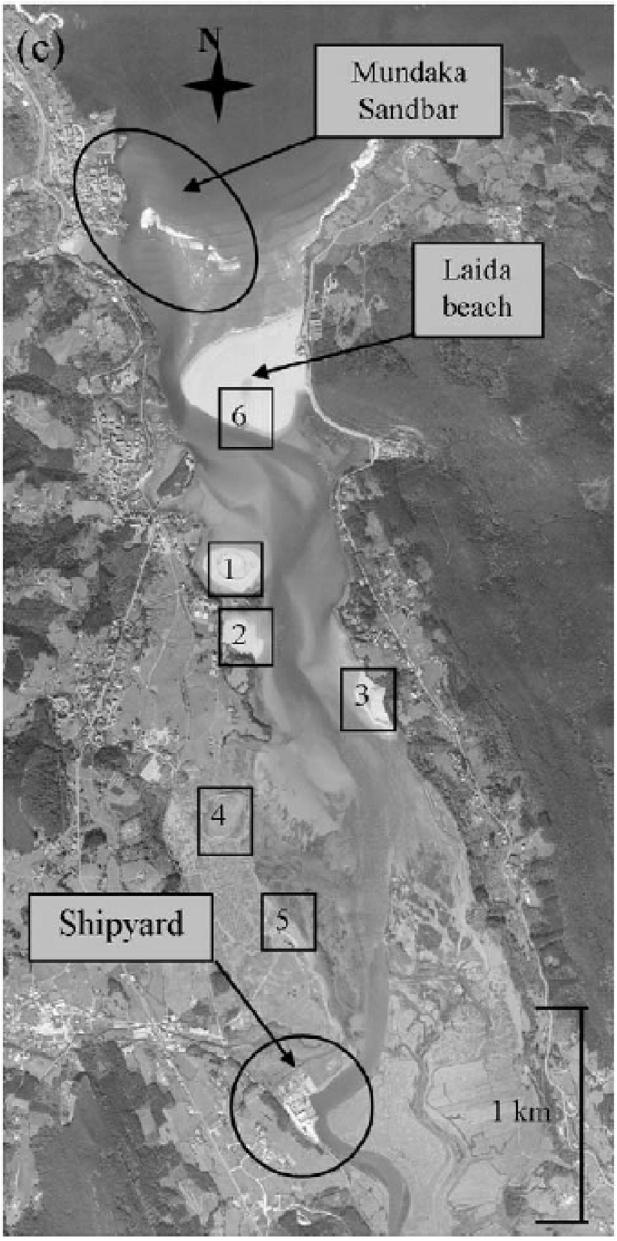


Figure 13 - Top view of the Oka estuary.
Figure taken from Liria *et al.* (2009).

Liria *et al.* (2009) describes the impact of anthropogenic measures on the morphology (and related wave surfing conditions) of an ebb-tidal delta occurring at the mouth of the Oka Estuary in the North of Spain.

The Oka estuary is 12 km long and characterized by meso- to macrotidal conditions (tidal ranges between 1.5 m and 4.5 m), a mean tidal prism of 5 10^6 m^3, and a mean river discharge of 0.59 m^3s^{-1}. This leads to intense current velocities in the main channel: maximum of 0.8 m/s (0.4 m/s) for spring (neap) conditions during the ebb phase; while over the remainder of the area they are less strong. The wave climate at this location displays a broad variation during the year, with mild conditions during summer (significant wave height H_s = 1.5 m), while during winter wave heights are larger than 2 m over more than 50% of the time and H_s = 2.5 m. As such, under summer wave conditions, tidal currents are dominant for the sediment transport patterns; while during winter, and especially during storms, wave action controls the majority of the sediment transport.

Within the estuary mouth, an extensive shallow area is present (denoted as *Mundaka Sandbar*) which is partly connected with a submerged sandy region (*Laida beach*).

The impact of a substantial beach nourishment (240 103 m3) on the southern part of the Laida Beach on the morphology of the outer shallow region is described by Liria et al. (2009). In particular, after the replenishment, it was observed that about 70% of the nourished sediment was eroded from the beach within two years and partly deposited into the main channel (see Figure 14). As a consequence, the location of the main channel was significantly altered eastwards, changing, in turn the overall characteristics of the ebb-tidal delta such as the obliquity with respect to the incoming waves and the bathymetric gradient. This morphological evolution posed severe navigational risks, but affected also strongly the surfing conditions which are renowned at this location. Current field observations indicate, however, that the natural shape of the sandbar, and the channel is gradually recovering.

These observations thus illustrate that measures taken within an estuarine system can have significant non-local effects. Moreover, for this particular setting and measure, it is found that the occurring wave and tidal conditions appear to be able to drive the morphology again towards the bathymetry present before the measure.

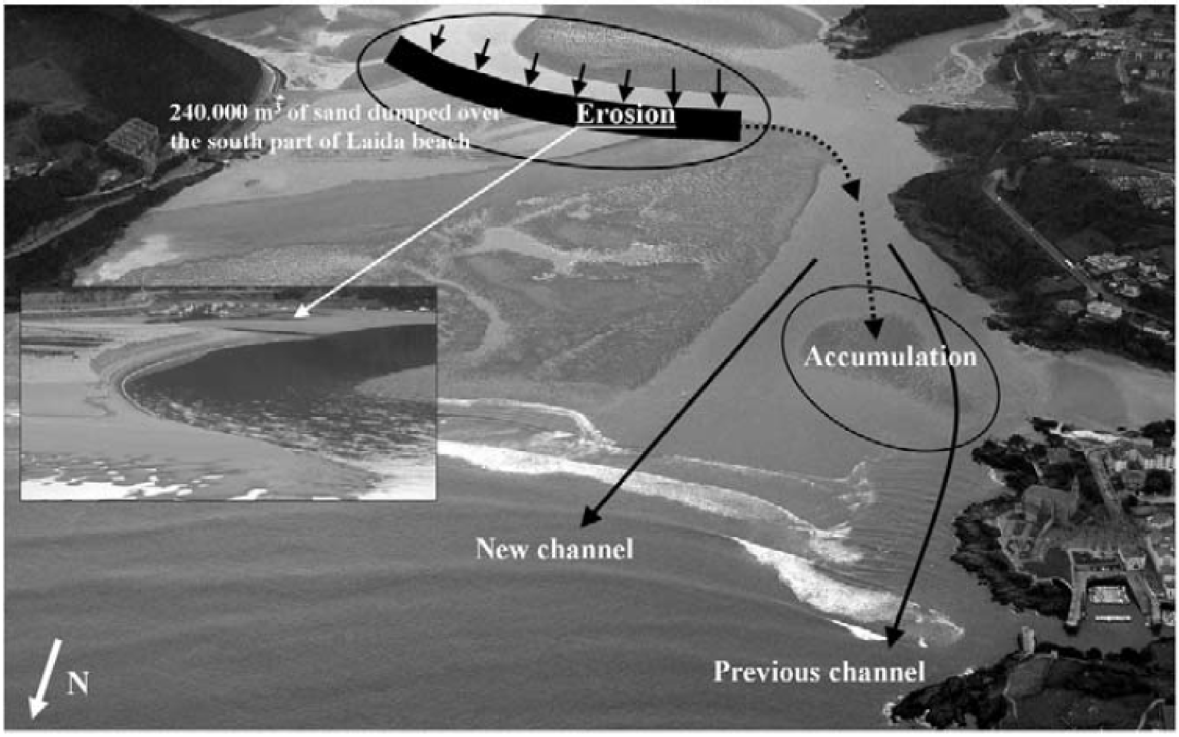


Figure 14 - Bathymetrical variations in the Oka estuary induced by the anthropogenic measures as described in the main text.
Figure taken from Liria et al. (2009).

Dallas and Barnard (2009) present an analysis of four historic bathymetric surveys which reveal large changes to the morphology of the San Francisco Bay and the occuring ebb-tidal delta at the mouth of the San Francisco Bay. These observations show that over 150 years, the ebb-tidal delta has substantially contracted radially; i.e. the crest of the delta migrated approximately 1 km landward within this period. This evolution corresponds to a volume loss of about $100 \pm 65 \times 10^6 m^3$. Dallas and Barnard (2009) hypothesize that this retreat is related to a decrease in sediment supply within San Francisco Bay coastal system induced by dredging and mining of sediment, and the damming of rivers that drain into the bay. In particular, it is found that approximately $130 \times 10^6 m^3$ of sediment has been permanently removed by anthropogenic measures. Even though, Dallas and Barnard (2009) only coin the relation between the retreat of the delta and anthropogenic activities, it is clear that sediment management decisions can have severe non-local effects.

Other manuscripts describing the impact of anthropogenic measures on the morphology of ebb-tidal deltas are presented by Cleary and FitzGerald (2003) and Healy *et al.* (1996). The former discusses the evolution of the morphology of a flood-tidal delta after the completion of a significant dredging campaign, Tauranga Harbour New Zealand, while Cleary & FitzGerald (2003) present the morphological changes that occur at Mason inlet in response to anthropogenic measures and natural sedimentation processes.

4 ELONGATED TIDAL SAND BARS

Elongated tidal sand bars are large scale sediment deposits which, generally speaking, occur in the mouth region of a broadmouthed and funnel-shaped tidally dominated estuary; i.e. typically speeds > 0.75 m s^{-1} (Dalrymple and Rhodes, 1995). The organization and size of these bars can vary from estuary to estuary, however, these bedforms can be identified as long linear features, which are oriented quasi parallel with the tidal currents. Typically, the bars are oriented at a small angle with the dominant direction of the tidal currents. As indicated by Figure 15, the entire estuary bathymetry can be composed of a chain of individual bars which are dissected by channels called swatchways. Individual elongated bars are generally 1 – 15 km long, whereas the entire chain can extend to 40 km in length (Dalrymple and Rhodes, 1995). The widths of the bars are between 0.2 and 4 km, with typical length-width ratios larger than 3 and sometimes even larger than 10. Moreover, it is observed that narrower bars occur at locations where the local depth is larger. The amplitude of the bar (i.e., half of the height between the crest of the bar and its neighbouring trough) can reach up to 10 m, and the wavelength of the bed form pattern is smaller than the width of the estuary; i.e. multiple bars occur within one cross channel section of the estuary.

To the authors´ present knowledge, the mechanisms and conditions controlling the generation and evolution of these bed forms is not conclusively described. One hypothesis (Dalrymple and Rhodes, 1995) considers that these bed form patterns are generated by a mechanisms similar to the formation of tidal sand ridges on the continental shelf (e.g. Huthnance, 1982 and Calvete *et al.*, 2001). However, as pointed out by Dalrymple and Rhodes (1995), this mechanism only cannot fully account for the occuring morphological characteristics such as the presence of swatchways.

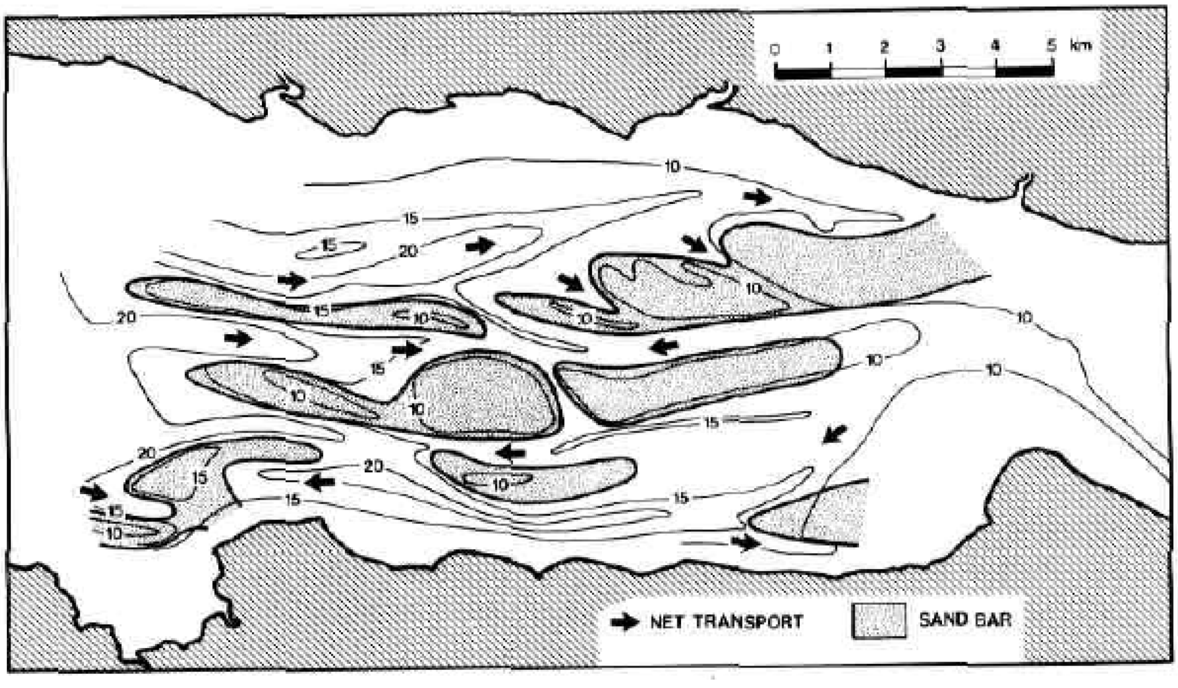


Figure 15 - Elongated tidal sand bars observed in the Cobequid Bay, Bay of Fundy. Figure taken from Dalrymple and Rhodes (1995).

5 MORPHOLOGY OF THE SCHELDT ESTUARY MOUTH

5.1 General characteristics

The bathymetry of the Scheldt mouth is characterized by a sequence of banks with adjacent channels and shallow platforms. The main channels are Oostgat, which occurs near the coast of Walcheren, and Wielingen, an ebb-dominated channel at the southern part of the delta (respectively indicated by #1 and #2 in Figure 16). In-between these two main channels, an extensive shallower region occurs, which is composed out of a sequence of banks and secondary channels. In particular, the channel Oostgat is flanked by a local sand bank, Bankje van Zoutelande (# 5) with, presently, a North-West to South-East orientation. In the direction of the inlet, Oostgat flows into the channel denoted as Sardijnengeul (# 4), which has flood-dominant characteristics. West of Bankje van Zoutelande, the channel Deurloo East (# 9) is situated, which is connected to the open sea by the channel of the Rassen. West of Deurloo East, a series of banks occurs with an approximately North-West to South-East orientation; i.e. Nolleplaat (# 7), Elleboog (# 6) and Rassen (# 8). On the southern part of the mouth region, the Wielingen is flanked by a shallow platform (region of approximately 5x15km, with a depth less than 5m): the Vlakte van de Raan (# 3). This shallow platform is separated from the previously mentioned banks, by the channel Deurloo West (# 10) and the channel of the Walvisstaart, which occurs west of Nolleplaat. South of the Wielingen a shallow bank is present (the Paardenmarkt), which is separated from the coast by an ebb-channel (the Appelzak; not shown in Figure 16).

The bathymetry of the mouth area thus echoes the characteristics of several morphological features. On the one hand, the shallower region comprising the Vlakte van de Raan up to Bankje van Zoutelande flanked by the Wielingen and Oostgat echoes the characteristics of an ebb-tidal delta; while the sequence of banks and channels in the northern part of the mouth region suggests the presence of elongated tidal sand bars.

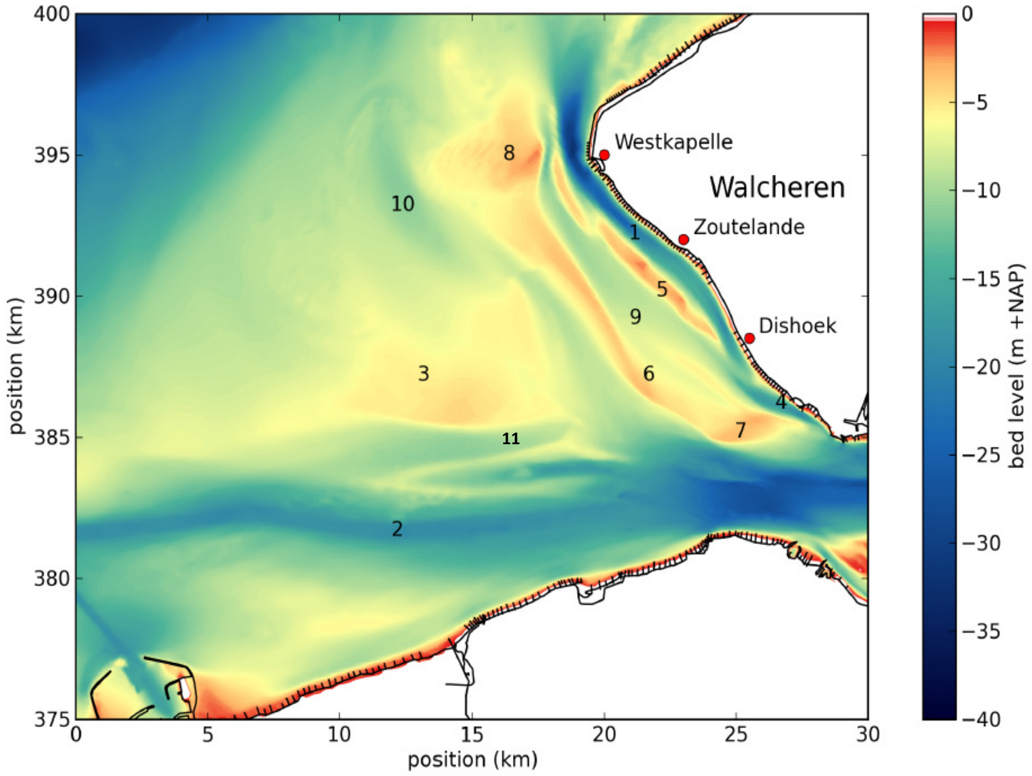


Figure 16 - Bathymetry of the Scheldt mouth region based on surveys performed in 2011. Several regions are indicated in the figure: (1) Oostgat, (2) Wielingen, (3) Vlakte van de Raan, (4) Sardijngeul, (5) Bankje van Zoutelande, (6) Elleboog, (7) Nolleplaat, (8) Rassen, (9) Deurloo Oost, (10) Deurloo West and (11) the channel of the Walvisstaart. Figure taken adopted from Damen (2014).

The mouth region and estuary are subject to *macro-tidal* conditions with a tidal range between 3.5 and 5 m. The tidal wave in this region propagates in the North-East direction along the Belgian and Dutch coast. As such, a phase-difference occurs between the tidal wave characteristics at distinct points within the mouth. For instance, as pointed out by de Looff and Verhagen (1986), high water occurs one hour later at Vlissingen than at Cadzand. Moreover, tidal range difference occur within the region; e.g. the tidal amplitude is smaller at Westkapelle than at Vlissingen which leads to a higher mean free surface elevation at Vlissingen than at Westkapelle during high water; and vice versa during low water (Walstra, 2005). Combined with the interaction of the cross-shore component of the tidal wave, due to the filling and emptying of the estuary; the interpretation of the resulting flow field is not straightforward.

In the mouth area the dominant wind direction is from the southwest with an average wind velocity of approximately 5 m/s (Figure 17a). Wave directions are mainly from the southwest and northwest (Figure 17b). Generally, the waves break on the beach of Walcheren (Figure 16), but during large storms from the southwest the waves can break on the 'Bankje van Zoutelande'. The waves stir up sediment locally, thereby increasing the sediment concentration. Additionally, the flow caused by the breaking waves induces a sediment transport to the south of around 0.2 Mm3/year in the breaker zone (Steijn & Van der Spek, 2005; Walstra, 2005). Considering the large tidal range at the mouth of the Scheldt estuary (~ 4 m), the location can be considered as a tidally dominated, even though the mean wave height is significant.

The sediment in the downstream part of the Scheldt estuary mainly consists of sand with less than 10% mud in the channels and on the shoals (Bolle, 2006). Relatively fine sand is found in the estuary. The median diameter d_{50} ranges between 0.15 mm and 0.3 mm. In the mouth area, however, the sediment composition is very heterogeneous (Du Four *et al.*, 2007; see also Figure 18). The shoal area, Vlakte van de Raan, is characterized by fine sands, while coarse sand is found in the Wielingen. On the other hand, clay is found in the area surrounding Zeebrugge. Furthermore, several resistant bottom layers of stiff clay occur in the mouth area, particularly north of the coast of Zeeuws-Vlaanderen and south of the coast of Walcheren (van der Slikke, 1999). These layers make e.g. the north- and westward migration of the Wielingen difficult. Sediment concentrations in the delta are relatively high. Terwindt (1967) reported sediment concentrations of 200 mg/liter on average. Similar sediment concentrations were found from recent observations by Plancke et al. (2014).

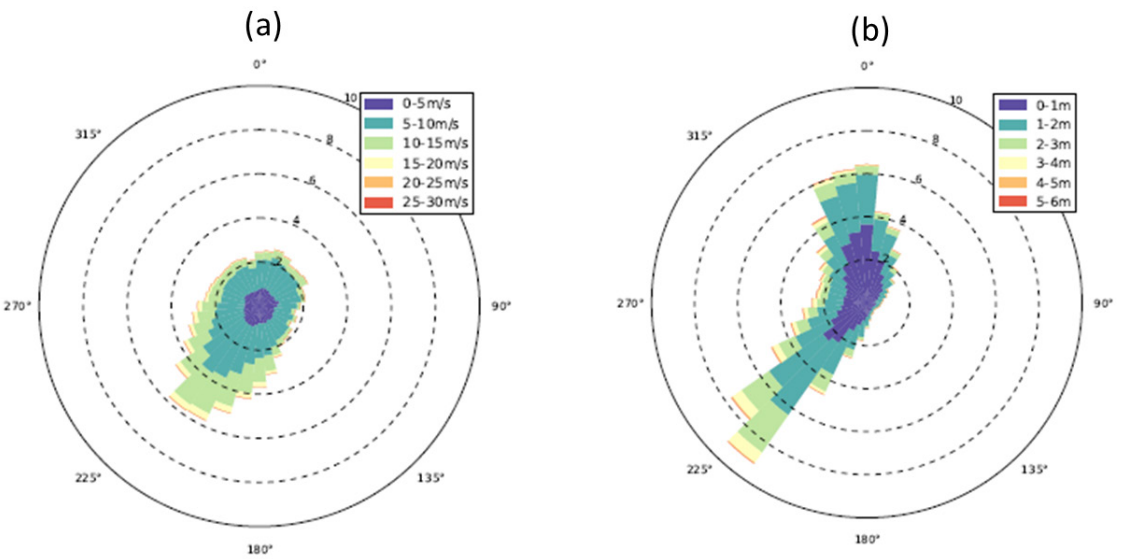


Figure 17 - (a) Measured wind directions and velocities. The radial values are the percentages of occurrence. (b) As in (a) but for the wave directions and heights. Figures adopted from Damen (2014).

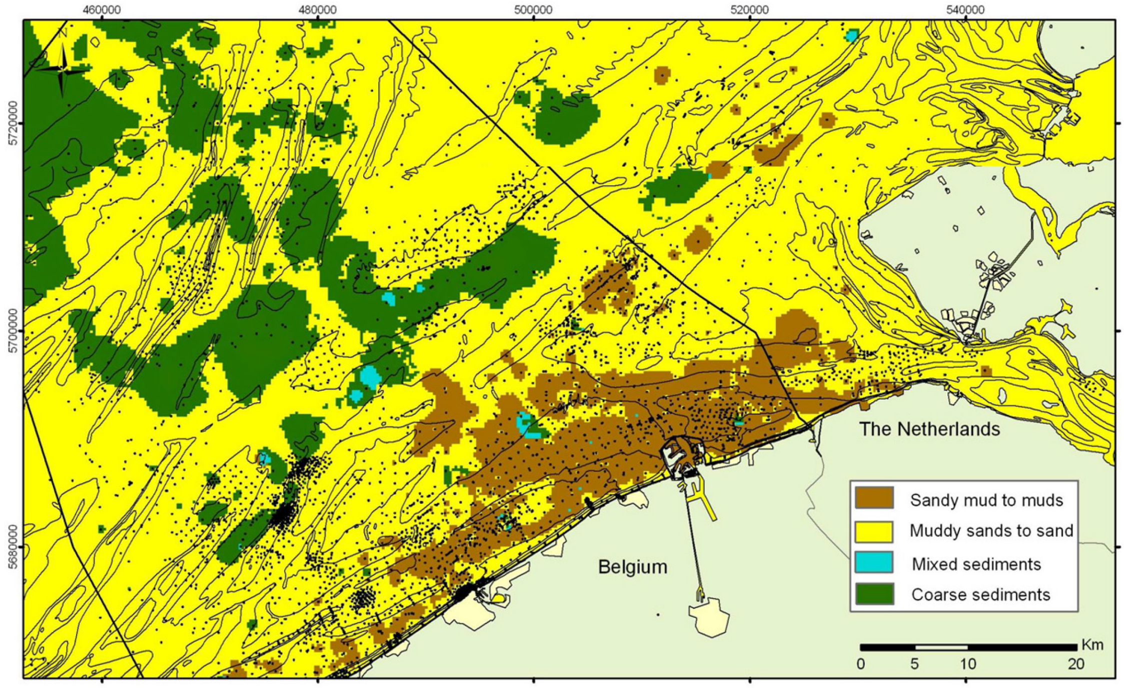


Figure 18 - Map of the bed composition in the study area. Figure adopted from Van Lancker & van Heeteren (2014).

5.2 Historical evolution of the morphology

The historical evolution of the morphology of the mouth area is described in this section. This description is based on the study by van Enckevort (1996) on morphological changes in the Scheldt mouth region since 1800.

The first reasonable map of the mouth region of the Scheldt estuary was made by Beautemps-Beaupré between 1804-1805. Thereafter, a bathymetry survey was conducted each 15 - 20 years by the Dutch Navy. Since 1960, RWS executes baythymetrical surveys almost each two years. In the following, we first discuss the morphological evolution until 1978. After that, morphological changes over the last 60 years are described.

5.2.1 Morphological evolution between 1800 and 1978

Figure 19 illustrates the morphological evolution of the Scheldt mouth between 1800 and 1970 by showing bathymetric maps at four time periods (1823, 1863, 1932, 1978). In the Appendix, all available bathymetric maps before 1970 are presented. Even though the accuracy of these bathymetric data can be disputed, several morphological trends can be observed:

i. The location of *Oostgat* appears to be stable, together with *Bankje van Zoutelande.* Even though the latter at some point connected with the platform *the Rassen*, after which it was dissected again by the *channel of the Rassen*.

ii. The ebb-channel *Wielingen* extended largely in Northern direction. In particular, two centuries ago, two channels (*the Spleet* and *the Wielingen)* existed near the coast of Zeeuws Vlaanderen, separated by the platforms *the Walvisstaart* and *the Zeeuwse Hompels*. Gradually, these platforms eroded or migrated such that the *Wielingen* and the *Spleet* merged into one large ebb-dominated channel (see also Van der Spek, 1997).

iii. Initially, the platform *the Walvisstaart* had a West-East orientation. Then, the platform migrated north (especially the western tip), connecting the *Walvisstaart* with the *Vlakte van de Raan*. Remarkably, since the beginning of the 20th century, a channel was formed in the south of the *Walvisstaart* with NNW – SSE orientation, cutting through the connection between the *Walvisstaart* and the *Vlakte van de Raan*.

iv. In 1823, the *Vlakte van de Raan* consisted of an elongated platform with East – West orientation, which was connected with the *Elleboog* and in a later stadium with the *Walvisstaart*. The formation of the channel of the *Walvisstaart*, however, challenges this connection.

v. Over two centuries, the *Deurloo* experienced significant morphological changes. The channel was first elongated over the entire mouth region and characterized by a West – East orientation. Similarly to the formation of an channel through the *Walvisstaart*, also through the *Deurloo* and the *Rassen* a channel formed in NNE – SSW direction. The latter eventually forms the *channel of the Rassen* which was already mentioned above. Due to the connection between *the Rassen* and the *vlakte van de Raan*, the orientation of the channel strongly rotated from West – East into NNE – SSW direction.

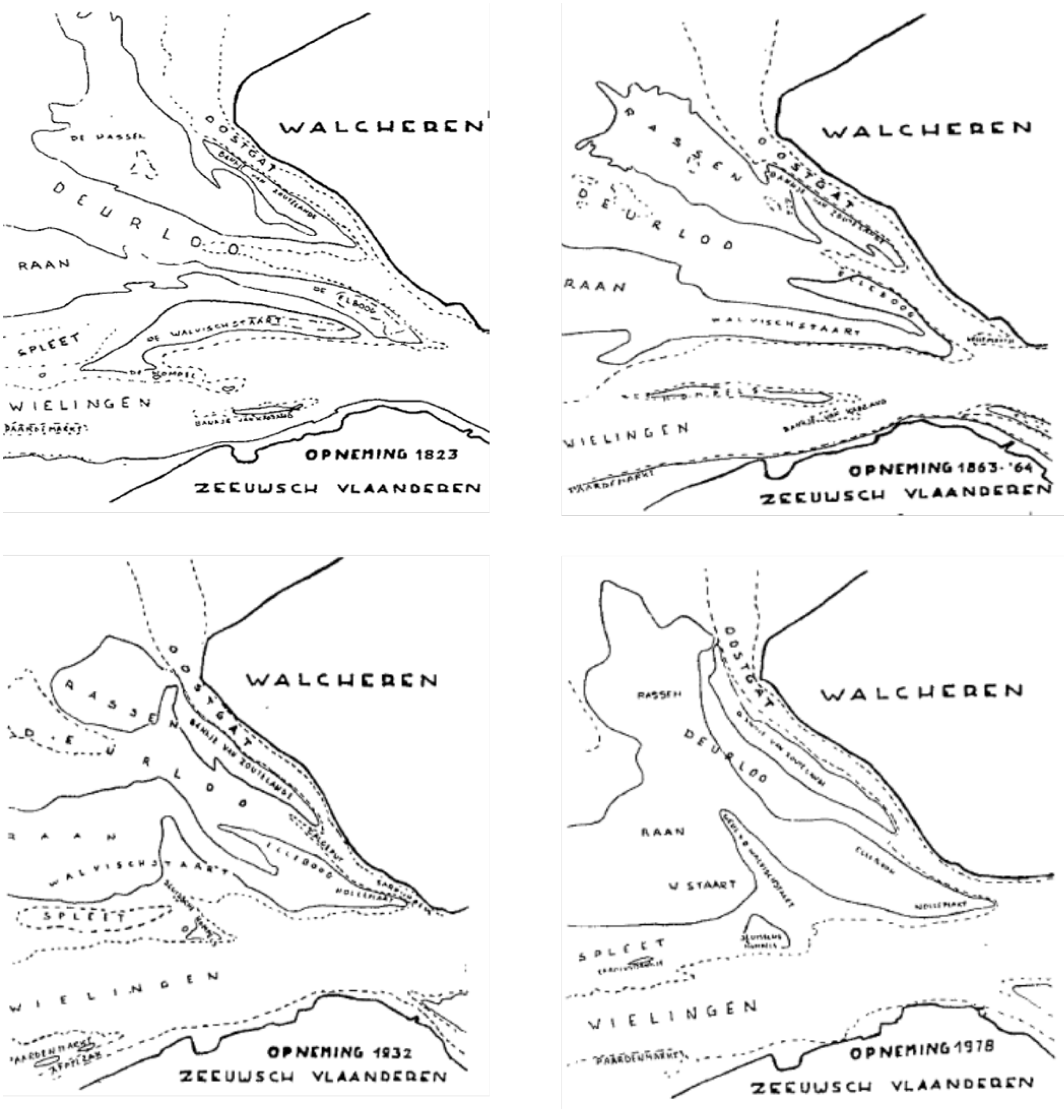


Figure 19 - Morphological evolution of the mouth region of the Scheldt estuary illustrated by means of bathymetrical data at four points in time (1823, 1863, 1932, 1978).

In summary, the morphological changes since 1800 within the region concern the rotation of the orientation of the channel-platform sequence in the central part of the mouth area (*Deurloo*, *Walvisstaart*, *Vlakte van de Raan, Elleboog*) from West - East to NNW – SSE direction. On the other hand, the orientation and location of the channel and bank (*Oostgat*, *Bankje van Zoutelande*) near the coast of Walcheren were relatively stable; while near the coast of Zeeuws Vlaanderen, the *Wielingen* extensively widened by the erosion of the *Sluise Hompels*, lumping the *Wielingen* with the channel *the Spleet*.

5.2.2 Morphological evolution after 1970

After 1970, more frequent bathymetric surveys were conducted of the entire region (approximately each 2 years). It is found that the location and depth of the *Wielingen* remains approximately stable, except that the western part of the *Wielingen* and the *Scheur* deepened; even though this is chiefly related to dredging activities, as discussed below.

In the central part of the mouth region, the main observation is the further development of the channel of the *Walvisstaart*. In particular, the channel extends in the north direction, eventually making the connection with the western part of the *Deurloo* channel, see Figure 16 (#10). The platform the *Rassen* is now connected to *Elleboog* by an elongated sand bank with NNE – SSW orientation.

Finally, *Oostgat*, *Bankje van Zoutelande* and *Sardijnengeul* appear to be characterized by a stable location and orientation. However, it is observed that the channel *Oostgat* migrates in the landward direction, approximately 0,2 m per year between Westkapelle and Zoutelande (Tonnon & Van der Werf, 2014), causing a persistent erosional trend of coast of Walcheren (~ 0,4 – 1,0 m/yr according to van der Slikke, 1999 and references therein). Furthermore, overall, banks and channels in the northern part of the mouth area are observed to migrate in the East direction (van der Slikke, 1999).

All in all, the most striking morphological changes observed in the mouth region concern the increase in width and depth of the *Wielingen*, the deposition of sediment in the *Deurloo* and the rotation of the sequence of banks and channels towards a NNW – SSE direction in the central and northern part of the mouth region.

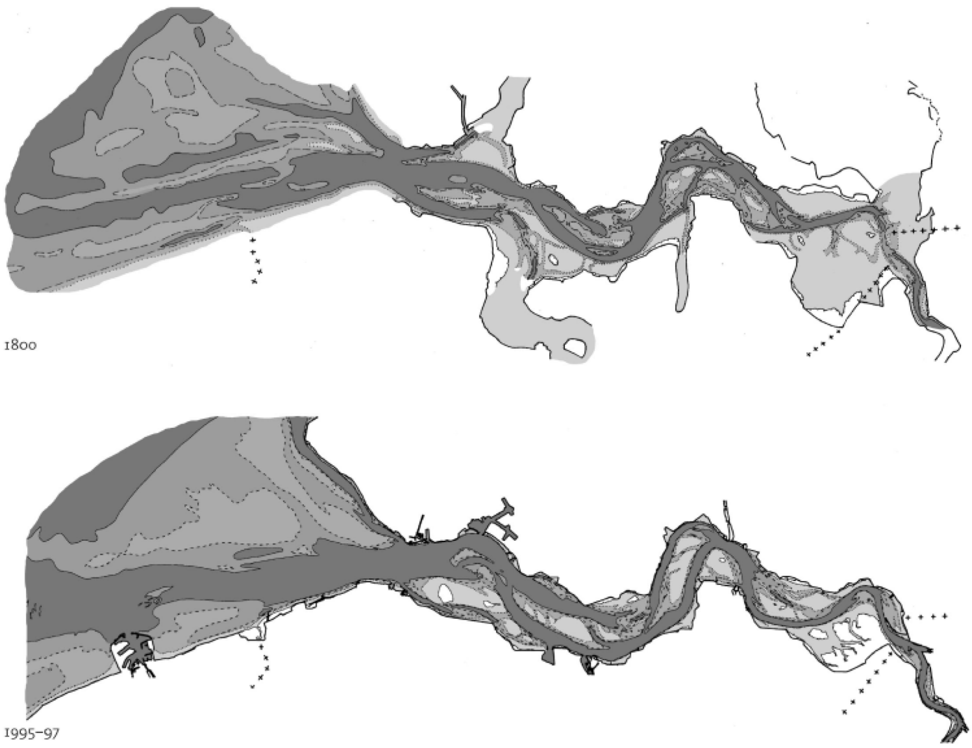


Figure 20 - Evolution of the morphology in the Scheldt estuary and in mouth region. Figure adopted from Peeters (2006).

On the southern part of the mouth region, it is observed that the *Appelzak* changed from a flood-dominated channel into an ebb-dominated channel after the seaward extension of the harbor of Zeebrugge (van der Slikke, 1999).

Elias and Van der Spek (in preparation) present an analysis of the sediment balance in the Scheldt mouth region between 1964 and 2013. They found that the mouth area experienced a net sand loss of ~ 84 million m^3 during this period (not corrected for volume changes due to dredging and dumping activities). The eastern part of the mouth area near the entrance of the estuary, however, gained a net sand volume of ~ 30 million m^3. This sand gain is consistent with recent studies on sand balance in the western Scheldt (Taal et al. 2013; IMDC, 2013), which concluded that the Western Scheldt loses sand to the mouth area.

5.2.3 Variations in external conditions

As discussed by Peters (2006) and coined by Svasek (1995), the morphological evolution within the mouth region is correlated with the natural and anthropogenic changes in the bathymetry and the geometry in the Scheldt estuary, and specifically the region West of Terneuzen. In particular, the channel/shoal and meandering pattern to the East of the narrow inlet between Vlissingen and Breskens (indicated as V and B on Figure 21) is very dynamic and has varied significantly in this period. Partly, these variations can be attributed to the natural and anthropogenic embankment of the tidal basins near Terneuzen (*Braakman*) and the bend of *Honte*; or the construction of the *Kreekrak* and especially the dam of *Sloe* (1871, east of Vlissingen), which separates the eastern Scheldt from the western Scheldt. In any case, these changes influence the direction of the flow- and ebb tidal current going out of the inlet with potential impacts on the morphology of the mouth region.

To which extent these external changes affect the morphology in the mouth area is related with these external changes is currently unknown. Nevertheless, it is clear that the evolution of the bathymetry in the mouth area is coupled with bathymetrical changes in the estuary, but also to changes in hydrodynamic conditions, sediment composition, etc .. .

On the other hand, van den Berg (1987) argued that the rotation of the channels and platforms in the central mouth area towards the North-East is induced by a historical increase of tidal amplitude in the coastal area.

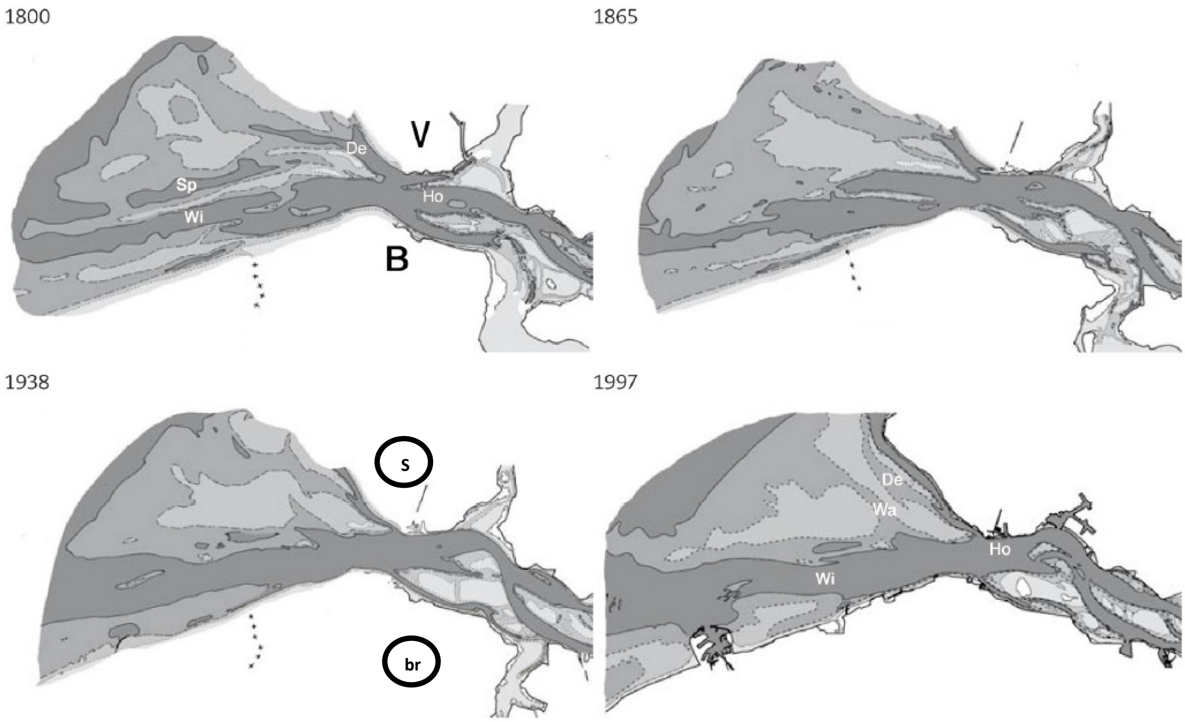


Figure 21 - Evolution of the morphology West of Terneuzen during the past two centuries. Figure adopted from Peeters (2006). V and B, denote the cities of Vlissingen and Breskens, respectively; while s and br represent the approximate location of the *Dam of Sloe* and *Braakman*, respectively.

5.2.3.1 Dredging and relocation

The mouth region is significantly influenced by anthropogenic interventions. Starting from 1960, dredging works occurred in *Scheur* near Ostend. Initially, these volumes were only marginal, however, after 1968 the amount of dredged volume became substantial when the dredging of *Pas van ´t Zand* started in addition to the dredging works related to *Scheur*. Figure 23 provides an overview of the annual volumes of dredged material for each shipping lane. The dredging works aim to keep the central part of the channel at a certain depth, however, also the banks of the channel deepens.

Dredged material is merely dumped at dumping sites Br&W S1, S2, and Zeebrugge East, see Figure 22. Minor disposals also take place at Br&W Nieuwport and Ostend. Br&W S3 and R4 in Figure 22 are closed since 2004 (Lauwaert et al, 2014). Figure 23 gives an overview of the total dredging efforts up till 1992 (Mol, 1995). Table 1 gives the reported dumping quantities at the different dumping sites from 1991 till 2011 (Lauwaert et al., 2011). Occasionally, dredged material is reused for beneficial purposes. Between 1973 till 1977, dredged material from Scheur was dumped in Appelzak to encounter for further erosion of this gully (Trouw et al. 2015, no volumes reported). Since 2007, material dredged from the Navigation channel to the port of Blankenberge is regularly re-used for shoreface and beach nourishments on the nearby beaches, see also Table 2.

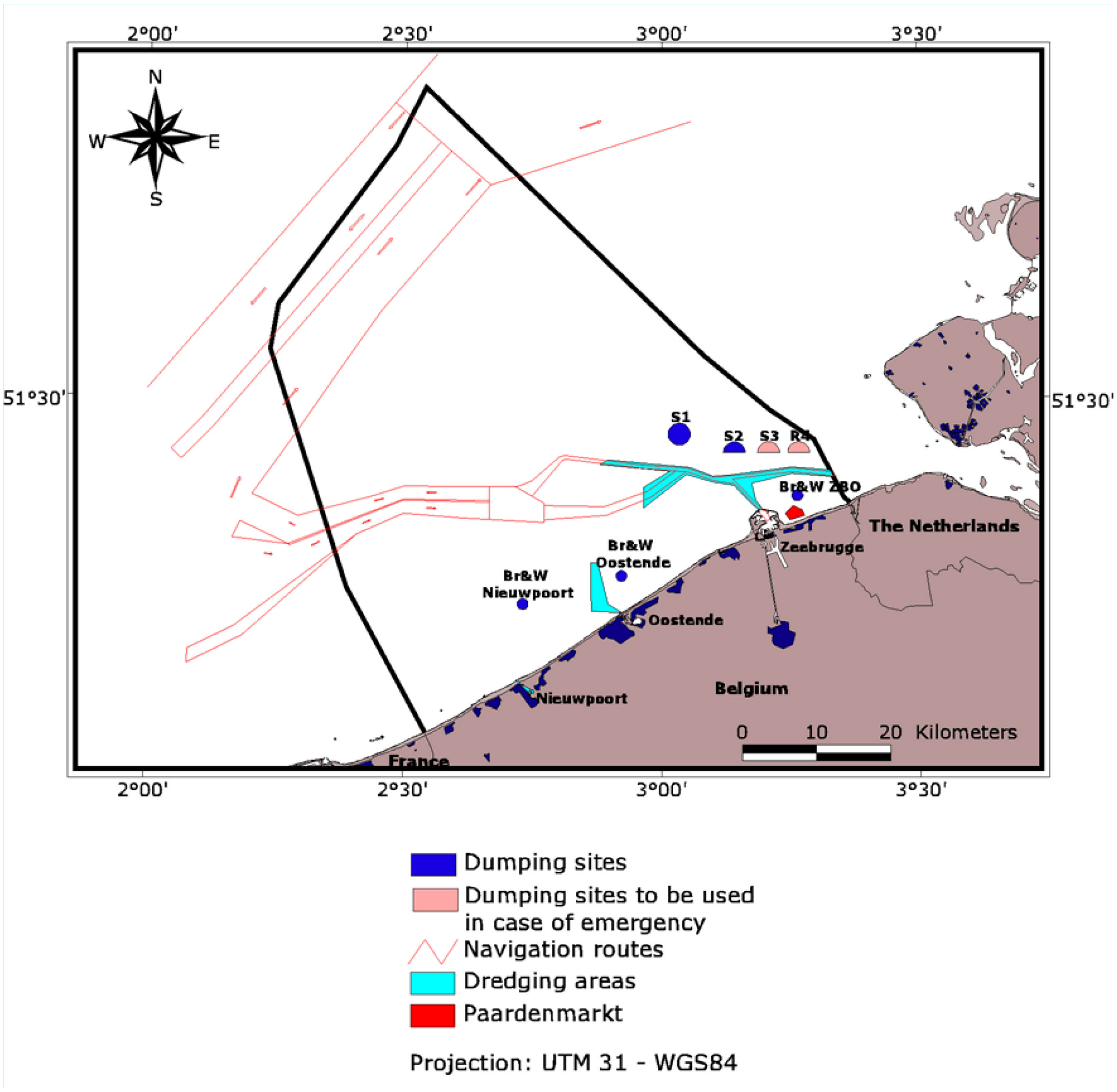


Figure 22 - Dredging and dumping sites (source: www.mumm.ac.be)

Finally, based on numerical computations, Svasek (1997) argued that the dredging of the *Wielingen* increased the propagation speed of the tidal wave such that high water levels at Vlissingen should occur 25 s/10 yr earlier. Observations indeed show that since 1971/1972 high water occurs approximately 2 minutes earlier. On the other hand, the impact on the magnitude of the flow velocity, for instance in *Oostgat*, is still unclear (see van der Slikke, 1999; Arends and Van Maldegem 1999).

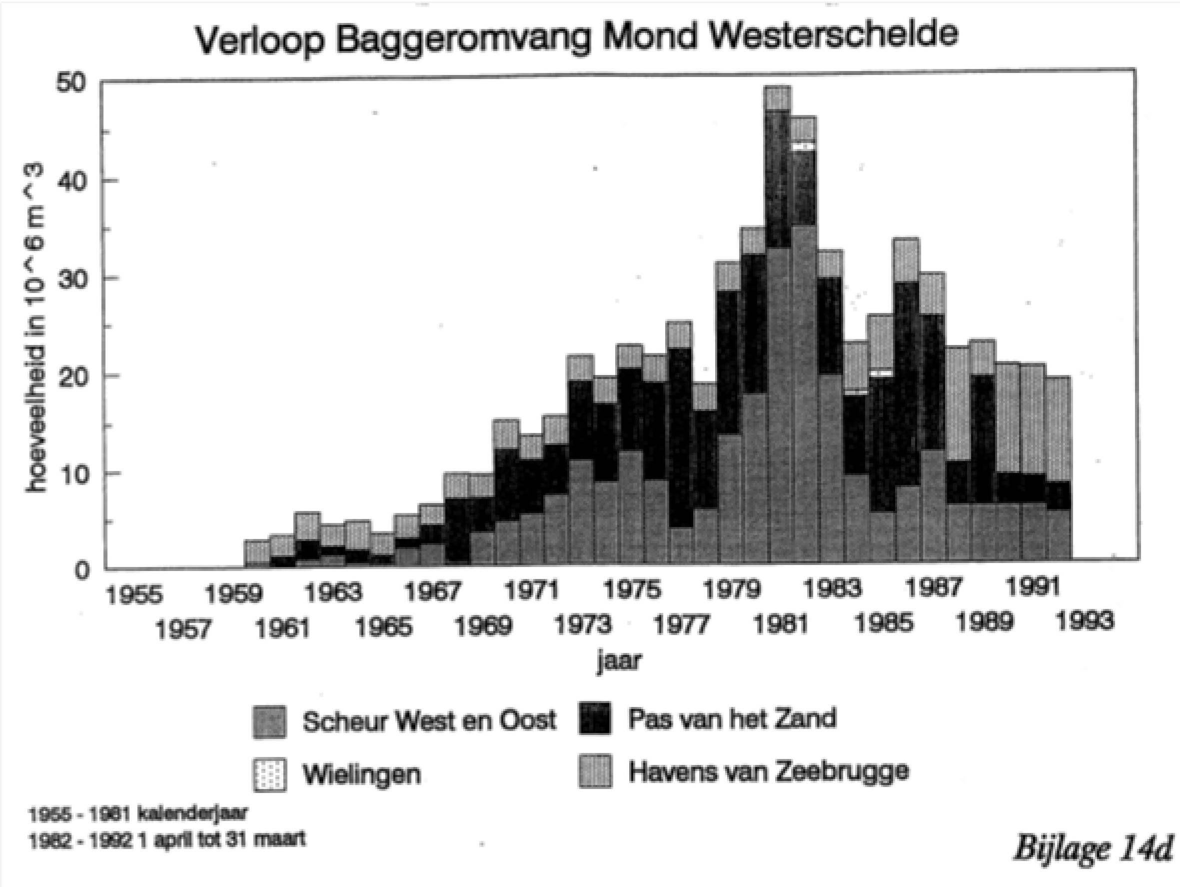


Figure 23 - Histogram of the volumes of sediment dredged from the various shipping channels. Figure taken from Mol (1995).

Table 1 - Quantities of dumped dredging material since 1991 (Lauwaert et al, 2011)

Quantities dumped in wet tonnes(*)								
period	**Br&W S1**	**Br&W S2**	**Br&W Zee-brugge Oost**	**Br&W Oostende**	**Nieuw-poort**	**Br&W R4 (**)**	**Br&W S3 (**)**	**Total**
April 1991 - March 1992	14,176,222	7,426,064	10,625,173	4,416,386				36,643,845
April 1992 - March 1993	13,590,355	5,681,086	10,901,837	3,346,165				33,519,443
April 1993 - March 1994	12,617,457	5,500,173	10,952,205	3,614,626				32,684,461
April 1994 - March 1995	15,705,346	2,724,157	8,592,891	3,286,965				30,309,359
April 1995 - March 1996	14,308,502	2,626,731	8,432,349	4,165,995				29,533,577
April 1996 - March 1997	14,496,128	1,653,382	7,609,627	2,763,054				26,522,191

Quantities dumped in tonnes dry matter (*)								
maintenance								
capital								
period	**Br&W S1**	**Br&W S2**	**Br&W Zee-brugge Oost**	**Br&W Oostende**	**Nieuw-poort**	**Br&W R4**	**Br&W S3**	**Total**
April 1997 - March 1998	6,045,581	1,563,485	6,593,905	745,147				14,948,118
April 1998 - March 1999	7,455,619	482,108	2,976,919	467,107				11,381,753
April 1999 - March 2000	2,885,801	89,556	3,189,077	591,605				6,756,039
	6,187,601	41,583						6,229,184
April 2000 - March 2001	1,684,517	784,343	4,971,782	559,332		310,670	51,150	8,361,794
	3,873,444	614,657						4,488,101
April 2001 - March 2002	2,031,147	329,798	2,623,069	565,938				5,549,952
	2,527,392							2,527,392
April 2002 - March 2003	3,314,115	858,607	2,311,650	491,217	289,949			7,265,538
	2,413,760	208,885	1,369,939					3,992,584
April 2003 – March 2004	5,246306	716,427	3,126,392	646,276	142,420			9,877,821
	829,486	24,896	447,219					1,301,601
April 2004 – March 2005	1,826,561	1,826,033	3,003,397	464,307	71,928			7,192,226
April 2005 – March 2006	3,017,123	1,234,640	2,973,545	599,905				7,890,077
April 2006 – March 2007	3,791,724	505,644	2,394,828	819,665	178,269			7,690,130
	7,930,966	90,673	401,944					8,423,583
April 2007 – March 2008	5,769,680	1,266,266	2,361,012	428,839	201,581			10,027,378
April 2008 – March 2009	4,888,313	59,144	4,603,759	783,545	58,921			10,393,682
	545,907	369,804		335,283				1,250,994
April 2009 – March 2010	5,639,231	2,066,231	4,026,238	182,869	155,716			12,070,285
	1,034,972			476,943				1,511,915
April 2010 – March 2011	3,638,426	2,851,727	2,912,767	629,428	219,399			10,251,747

(*) Before April 1997, the manual "bucket" method was used to evaluate the quantity of dredged material on board a ship. Since April 1997, an automatic measurement device is used which allows directly evaluating the quantity of dry material on board ships. Comparison between both systems is not possible.
(**) Closed for dumping since end 2004

Table 2 - Beneficial re-use of dredged material from the acces channel to Blankenberge

Period Beneficially	used dredged material (m³)
November 2007 – February 2008	69.526
May 2008 – June 2008	18.661
November 2008 – December 2008	30.884
April 2009	9.588
November 2009 – January 2010	21.354
Total	144.013

5.2.3.2 Construction of the port of Zeebrugge

As previously mentioned, the building of the harbor of Zeebrugge, probably, has had a significant impact on the hydrodynamics and morphology in the southern part of the mouth region; i.e. the region east of Zeebrugge up till the border with The Netherlands (van der Slikke, 1999). The first outer harbor of Zeebrugge was constructed between 1896 and 1905, and consisted of a “Claire-voie” to allow for the alongshore sand transport. After the outer harbor protection was changed from piles into a closed wall in 1929, it was observed that the *Appelzak* changed from an flood-dominated channel into an ebb-dominated channel after the extension (van der Slikke, 1999). All in all, after the completion of the extension of the harbor three kilometers in sea (finished in 1986), the hydrodynamic characteristics around the harbor altered leading to erosional trends in the coastline East of Zeebrugge.

6 CONCLUSIONS

A literature review of the morphology of the Scheldt estuary mouth is presented. Considering the general characteristics of bathymetric patterns that occur in estuaries, it is found that the bathymetry of the Scheldt estuary mouth echoes the presence of an ebb-tidal delta together with elongated tidal sand bars. An analysis of the historical evolution of the changes in the bathymetry over the last two centuries shows that the Scheldt mouth area has evolved from a region with multiple channels (Wielingen, Spleet, Deurloo, Oostgat) and shoals with primary East-West orientation (showing the characteristics of elongated tidal sand bars) into a region with two main channels (Wielingen on the southern boundary, and Oostgat on the northern boundary) with in between a large shallow area which resembles an ebb-tidal delta (the Vlakte van de Raan) and a sequence of banks and shoals with NNE-SSW directions.

Several components appear to have had a significant influence on the evolution of the bathymetry:

i. The changes in the geometry of the Western Scheldt estuary, west of Terneuzen.

ii. Historical variations in tidal amplitude.

iii. Dredging and dumping of sediment had a certain impact on the Wielingen, and therefore also altered the entire hydrodynamics of the region. As such, this provides also indirectly an impact on the morphodynamics.

iv. The construction of the outer harbor of Zeebrugge.

Based on the existing literature, the absolute and relative impact of these events is not clear. However, the observed historical variations in the morphology, together with the listed variations in the external conditions provide guidelines to further investigate the morphodynamics of the Scheldt estuary mouth, and eventually enlarge our understanding the physical mechanisms that control the morphology of the region.

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