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# THE 'VOORDELTA', THE CONTIGUOUS EBB-TIDAL DELTAS IN THE SW NETHERLANDS; IMPACTS OF LARGE-SCALE ENGINEERING 1965-2013

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**Abstract**

The estuaries in the SW Netherlands, distributaries of the rivers Rhine, Meuse and Scheldt known as the Dutch Delta, have been engineered to a large extent. This impacted the Voordelta, the coalescing system of the ebb-tidal deltas of these estuaries, largely. Complete damming of the three northern estuaries caused a regime shift, from mixed-energy to wave-dominated conditions, and sediments are transported in landward and downdrift direction. This results in large morphodynamic changes, but small net volume changes since the dams block sediment transport into the estuaries. Larger sediment volume losses are observed on the ebb-tidal deltas of the partially closed Eastern Scheldt and still open Western Scheldt estuary. Despite the preservation of the tide in the mouth of the Eastern Scheldt, the north-south running North Sea tidal wave has gained impact on its ebb-tidal delta causing morphological adjustments and erosion of the shoal areas.

**Key words:** coastal morphodynamics, ebb-tidal delta, impact of large-scale engineering, long-term coastal evolution

## 1. Introduction

The estuaries in the SW Netherlands, a series of distributaries of the rivers Rhine, Meuse and Scheldt known as the Dutch Delta, have been engineered to a large extent as part of the Delta Project, a flood protection scheme that was developed and executed after the dramatic storm surge disaster of February 1, 1953. The project included separation of the respective estuaries with dams and subsequent damming of their seaward sides, in order to improve safety against flooding and to create freshwater basins as a resource for agriculture. Moreover, sluices were planned to be built in the Haringvliet dam in order regulate the discharge of the rivers Rhine and Meuse. Only the Western Scheldt would remain an open estuary, since it is the entrance to the port of Antwerp. In the nineteen seventies, after the completion of first projects of the programme, deterioration of the water quality in the closed basins became problematic. This triggered adaptation of the original plans. For instance, the plans for damming of the Eastern Scheldt were abandoned and a storm-surge barrier was built in the inlet, in order to preserve the valuable inshore tidal ecosystem and the successful commercial shellfish culture.

The complete or partial damming of the estuaries had an enormous impact on their contiguous ebb-tidal deltas: the strong reduction of the cross-shore directed tidal flow triggered a series of morphological changes that continues until today. Moreover, large-scale dredging in the Western Scheldt estuary and the shipping lane Wielingen, the southernmost channel of the ebb-tidal delta has changed the hydrodynamics and morphology of its ebb-tidal delta.

This paper gives an overview of half a century of morphological changes, both for the individual ebb-tidal deltas and the Voordelta as a whole. Up till now, the impact of the Delta Project has been described for individual ebb-tidal deltas (see, e.g., Kohsiek, 1988; Louters et al., 1991; Tönis et al., 2002; Eelkema et al., 2012). A first integral analysis for the Voordelta as a whole, addressing the morphodynamic interaction of adjacent ebb-tidal deltas was presented by Elias et al. (2016). Their analysis is based mainly on a digital data base of repeated bathymetric surveys executed by Rijkswaterstaat, the water management authority of The Netherlands, covering the period 1964-2012.

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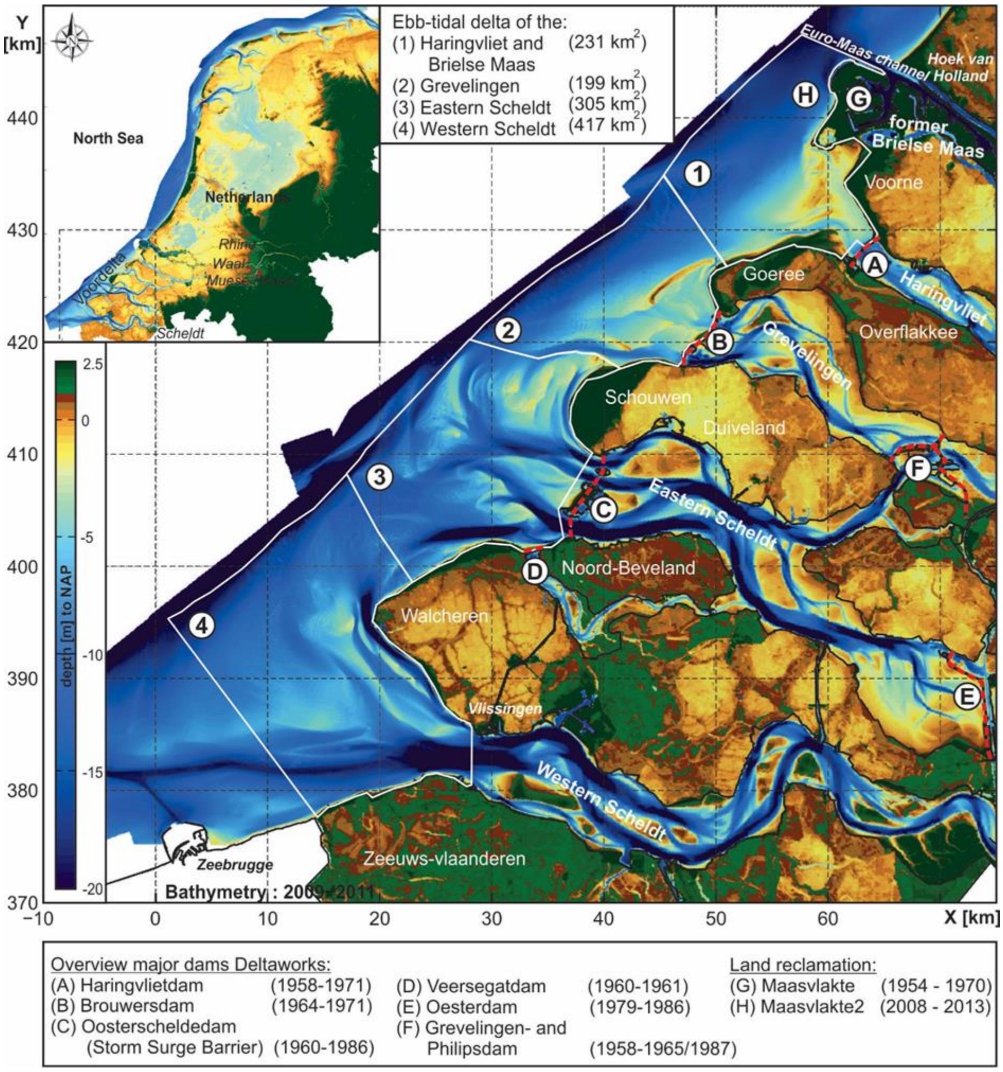


Figure 1. Overview of the estuaries that form the Dutch Delta and their ebb-tidal deltas, collectively known as the *Voordelta*. The dams that were constructed as part of the Delta Project are indicated with red dashed lines. The boundaries of the respective ebb-tidal deltas discussed in this paper, are indicated with white lines. Depths are given in meters relative to NAP (Normaal Amsterdams Peil), the Dutch ordnance datum which is about present-day mean sea level. Note that the latter holds for all bathymetric maps in this paper

### 1.1. *Study Area*

The coast of the SW Netherlands consists of a series of five (former) estuaries, from north to south Brielse Maas, Haringvliet, Grevelingen, Eastern Scheldt and Western Scheldt, see Fig. 1. Brielse Maas, Haringvliet, Grevelingen and Eastern Scheldt are distributaries of the combined rivers Rhine and Meuse, whereas Western Scheldt is the lower course of the river Scheldt. Only Eastern Scheldt and Western Scheldt are still tidal basins, the former by means of a storm-surge barrier. The estuaries are separated by (former) islands that do not show the typical shore-parallel morphologies of barrier islands. Nevertheless, they are bounded on their seaward end by coalescing ebb-tidal deltas. This relatively shallow, up to 10 km wide offshore area stretches from Hoek van Holland in the north to south of Zeebrugge in Belgium (Fig. 1), an alongshore distance of almost 90 km and a total area of 1155 km$^2$, and is known as the *Voordelta* (English: Fore Delta). The average depth increases and the surface area of the shallow shoals decreases when going from north to south. The sediments of the inlets and tidal deltas consists of fine to medium sand (Terwindt, 1973). Sand transport by waves was predominantly to the northeast; moreover grainsize distributions show an overall fining to the northeast, also indicating a north-easterly net transport of fine sand in the Voordelta (Terwindt, 1973). Since construction of the closure dams, significant amounts of mud have been deposited in closed-off channels.

In the Voordelta, waves and tides are the dominant forcing mechanisms. Both vigorous tidal currents and heavy seas, especially during strong winds, create a highly dynamic environment that consists of rapidly shifting, shallow bars and shoals, dissected by both small and large and deep tidal channels. Only the discharge sluices in the Haringvliet dam (maximum capacity 25,000 cubic meter per second) can create (temporary) significant density gradients during periods of peak river discharge that might affect the local morphology. The wave climate consists mainly of wind waves locally generated in the shallow North Sea basin. The mean significant wave height is 1.3 m from the west southwest, with a corresponding mean wave period of 5 seconds. During storms, wind-generated waves occasionally reach heights of over 6 m and additional water-level surges of more than 2 m have been measured. The semi-diurnal tide propagates in northward direction parallel to the coast. The mean tidal range decreases from 3.86 m in Vlissingen (Western Scheldt) to 1.74 m in Hoek van Holland.

### 1.2. *Ebb-tidal delta morphodynamics*

Tidal inlets and their associated tidal deltas make up a major part of the world's barrier coastlines. Ebb-tidal deltas form where the sediment-laden ebb current leaves the comparatively narrow tidal inlet and enters the sea/ocean, and as flow segregates, velocities diminish beyond the sediment transport threshold. Hence, the sand is deposited and a shallow distal shoal called *terminal lobe* is formed. This process is counterbalanced by waves that impact on the shallow shoals and tend to move the sand back to the inlet and bounding shores. Hence, the morphology of the ebb-tidal delta is essentially determined by the relative importance of wave- versus tidal energy. Wave-dominated ebb-tidal deltas are pushed close to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore (see, e.g., Hayes, 1979).

Davis & Hayes (1984) showed that ebb deltas are found in a wide spectrum of wave height-tidal range combinations. Moreover, there is considerable variation in ebb-tidal delta morphology along stretches of coast where tidal and wave conditions hardly vary. They concluded that it is the relative effect of the tidal processes vs. wave processes and not the absolute values that produces the typical ebb-tidal delta geometry and that variation in ebb-tidal delta morphology is better explained by variation in tidal prism (see also Davis, 2013, for a recent discussion).

O'Brien (1931) was the first to establish that the cross-sectional size of an inlet is primarily governed by its tidal prism and also, to some extent the sediment volume supplied by longshore transport. Walton & Adams (1976) determined outer bar volumes and inlet tidal prisms and cross-sectional areas for 44 inlets from highly, moderately and mildly exposed coasts from around the USA and found that the volume of sand stored in the outer bar and shoals correlates strongly with the tidal prism and the cross-sectional area. Moreover, their correlations show that the volume of material that is stored in the outer bar decreases with an increase in wave energy.

### 1.3. *The Voordelta*

In general, following the classification of Davis & Hayes (1984), the inlets of the Voordelta prior to damming would qualify as ranging from mixed-energy wave-dominated in the northern part, to mixed-energy tide-dominated and finally tide-dominated in the Western Scheldt mouth. However, the morphology of the major inlets shows tide-dominated characteristics such as a large ebb-tidal delta and deep channels. These result from large tidal prisms and relatively low wave energy.

By the end of the 19th century, the system of estuarine inlets along the Voordelta area comprised from north to south the Nieuwe Waterweg (Rotterdam Waterway, dug between 1866 and 1872 to make a shorter and more reliable connection between the North Sea and the harbour of Rotterdam); Brielse Maas (a former distributary of the river Meuse); Haringvliet; Grevelingen; Eastern Scheldt; Veerse Gat (a small channel separating the islands of Noord-Beveland and Walcheren); and the Western Scheldt (Fig. 1). Eastern Scheldt, Grevelingen and Haringvliet were connected on their landward ends. The tidal wave travelled through these channels to the northeast, arriving at the Hollandsch Diep about 40 min earlier than

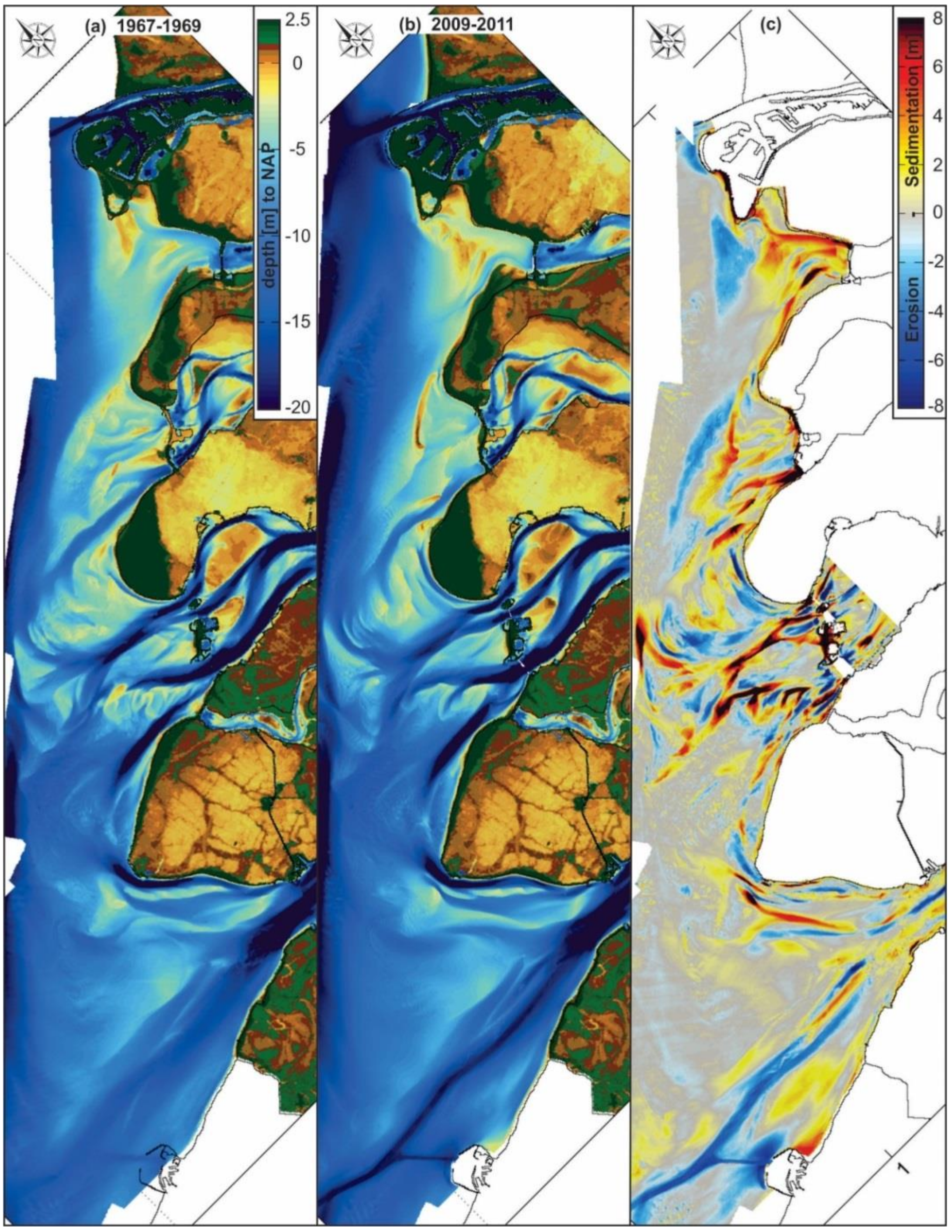


Figure 2. The bathymetry of the Voordelta for the years 1967-1969 and 2009-2011. The morphological changes over this interval are shown by the sedimentation-erosion patterns in panel (c). Note that for Haringvliet the 2009 bathymetry was used, prior to construction of Maasvlakte2

the tide travelling along the Haringvliet estuary. The expansion of the tidal currents in the Eastern Scheldt to the northeast since the 18th century at the expense of the tidal prisms of both Grevelingen and Haringvliet, resulted in an increase of the tidal prism of this estuary and scouring of its tidal channels (Haring, 1978; van den Berg, 1986). Part of this sediment was exported to and deposited on the ebb-tidal delta. With the decrease in tidal prism of Haringvliet and Grevelingen, their ebb-tidal deltas started to deteriorate.

Brielse Maas and the Zeegat van Goeree-Haringvliet shared an ebb-tidal delta that stretched from NW to SW of the island of Voorne. The Grevelingen ebb-tidal delta is situated SW of the island of Goeree. This ebb-tidal delta is not directly connected to the Haringvliet ebb-tidal delta. Sand that is transported from here to the NE moves along the coast of the island of Goeree, presumably as wave-driven longshore transport, and finally ends up in the southern part of Haringvliet ebb-tidal delta, e.g. in the recurved spits of Kwade Hoek (van der Spek, 1987). Grevelingen ebb-tidal delta is bounded in the south by the island of

Schouwen and the Eastern Scheldt ebb-tidal delta west of that island. The Eastern Scheldt ebb-tidal delta stretches as far south as the coast of NW Walcheren. The southern part of the Eastern Scheldt ebb-tidal delta, Domburger Rassen, is relatively deep and forms a gradual transition to the Western Scheldt ebb-tidal delta. The latter runs south to the shallow coastal zone of Flanders. It is relatively deep and has few shallow shoals.

### 1.4. *The Delta Project*

The general idea of the Delta Project was to separate the Delta area in two subsystems: a northern basin consisting of Haringvliet and Nieuwe Waterweg that had to deal with the discharge of the rivers Rhine and Meuse and a southern basin consisting of the Eastern Scheldt and its northern tributary that would be dammed in a later stage. This was accomplished by building a dam in the Volkerak that kept the tide from penetrating north eastwards into the lower course of the rivers . The Grevelingen had to be 'decoupled' from the Eastern Scheldt in an early stage to facilitate the building of the Volkerak dam. The Western Scheldt mouth was not included to allow unhindered shipping to the important harbour of Antwerp, here dikes were heightened and strengthened. Plans for complete damming of the Eastern Scheldt were eventually abandoned to maintain the valuable inshore tidal ecosystem of this former estuary. Instead, the Eastern Scheldt storm-surge barrier was constructed (Rijkswaterstaat Deltadienst, 1979).

## 2. Recent development of the Voordelta - impacts of the Delta Project

The recent development of the Voordelta was studied using a series of bathymetric maps that has been compiled from a variety of data sources, see Elias et al. (2016) for details on data handling and map preparation. Figure 2 illustrates the large-scale morphological changes of the Voordelta over the period 1968-2010, which include the response to the damming of the estuaries. The effect of (partial) damming of the estuaries is a reduction of the tidal volumes of the inlets that results in a decrease in sand supply by the ebb current and, hence, wave-driven sand transport will increase relatively. This results in net sediment transport in landward direction, erosion of the delta front and building of sand bars on the outer rim of the ebb-tidal delta (see Van der Spek, 1987; Kohsiek, 1988; for details). Moreover, with a reduction of the shore-normal tidal flow, shore-parallel currents will became more dominant which will promote shore-parallel flow through the channels on the ebb-tidal delta. This will cause adaptions in the ebb-tidal delta morphology and net transport of sediment to the neighbouring, downstream delta.

### 2.1. *Haringvliet ebb-tidal delta*

The Haringvliet ebb-tidal delta was originally connected to two tidal inlets: the Brielse Maas estuary to the north and the Zeegat van Goeree / Haringvliet inlet to the south. The comparatively small Brielse Maas was dammed in June 1950 which led to drastic changes in the morphology of its ebb-tidal delta: within 10 years the channels had filled in with mud, their orientation had changed from east-west to north-south and the shoals had grown together to one big shoal, the Westplaat (Terwindt, 1964). Later on, this area was changed completely by the expansion of the port of Rotterdam over the northern part of the ebb-tidal delta (Fig. 3). This stepwise land reclamation increasingly sheltered the Haringvliet ebb-tidal delta from north-westerly waves.

Before the start of the Delta Project, the Zeegat van Goeree at its narrowest point consisted of two north-west running, ebb-dominated channels, Rak van Scheelhoek in the north and Noord Pampus in the south (Fig. 3a). Going seawards, Noord Pampus continued as the channel Slijkgat, branching off to the west and following the coastline of Goeree. Rak van Scheelhoek split into two distributaries, Bokkegat and Gat van de Hawk (Fig. 3a). Changes in the orientation of the shoals in the ebb-tidal delta, the shore-normal Zeehondenplaat changed into the shore-parallel Hinderplaat, were observed well before completion of the Haringvliet dam. The construction of the sluice complex and the subsequent (re-)construction of the southern bank diminished the width of the estuary over 50% by the early nineteen sixties. The remaining part of Haringvliet inlet was closed in 1970. In the following years the seaward edge of the ebb-tidal delta eroded and the shore-parallel Hinderplaat grew rapidly in both length and height (a development very similar to the observed formation of the Bollen van de Ooster in the Grevelingen ebb-tidal delta, see Van der Spek, 1987). The long, spit-shaped Hinderplaat temporarily created a fairly stable state and sheltered the back-barrier area, and the channels filled in with predominantly mud. The ebb-tidal delta shrunk in surface area, the elevation of the shoals diminished and the channels filled in, which reduced the average depth of the ebb-tidal delta. As the Hinderplaat increased in height and length, it decreased in width. Around 1996 this resulted in breaching of the spit and a more dynamic system with (multiple) small inlets formed (see Fig. 3b). The entire ebb-tidal delta was pushed landward due to wave action. Prior to 1976 the ebb-delta increased in volume, but despite the large changes since, the net volume change over the total period is small; sediments are mainly redistributed from the offshore landward. Similar to the Grevelingen ebb-tidal delta, the volume reduction is small since the eroded sediments cannot be transported into the estuary because of the dam.

A large sediment supply from the SW, fed by the erosion of the delta front of Grevelingen ebb-tidal delta and the sand nourishments on the coast of the island of Goeree, resulted in accretion of the shoreface and coast of Goeree and expansion of the recurved spits of Kwade Hoek (Fig. 3b). The only remaining tidal channel on Haringvliet ebb-tidal delta is Slijkgat (Fig. 9), the fairway to the fishing harbour of Stellendam which has to be dredged regularly. The rapid infilling of the remaining Haringvliet basin is partly due to mud deposition that is enhanced by the outflow of river discharge through the sluices.

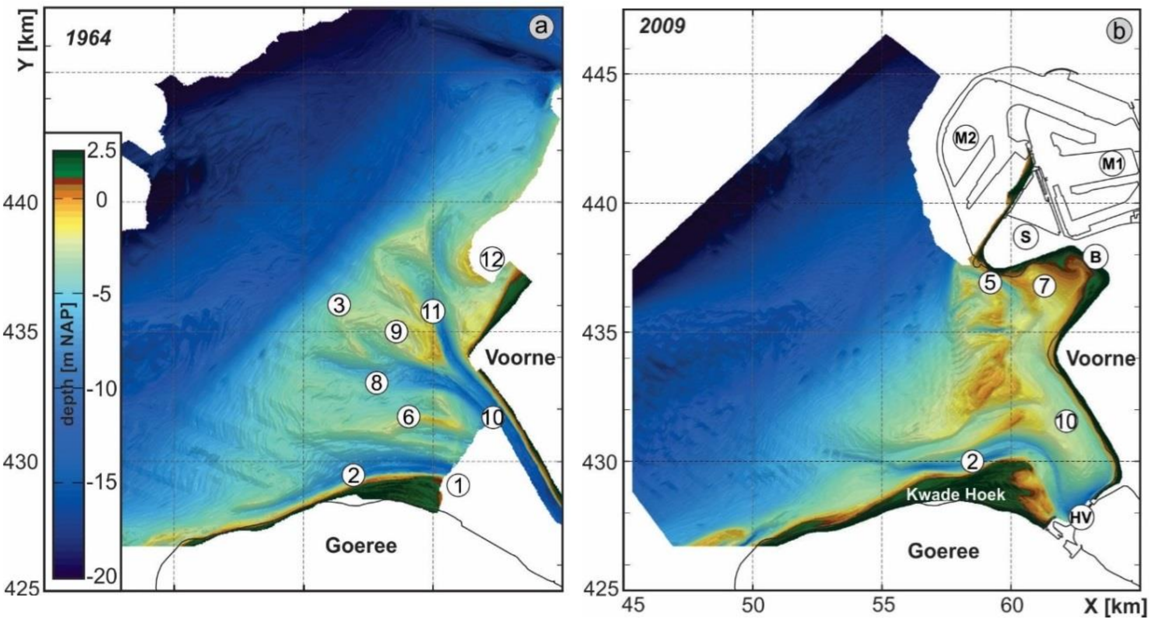


Figure 3. Bathymetry of the Haringvliet ebb-tidal delta for 1965 and 2009. Main *channels* and shoals: (1) *Noord Pampus* (2) *Slijkgat* (3) Hinder (4) Hinderplaat (5) *Hindergat* (6) Garnalenplaat (7) Brielse Gat (8) *Bokkegat* (9) Zeehondenplaat (10) *Rak van Scheelhoek* (11) *Gat van de Hawk* (12) Westplaat

## 2.2. Grevelingen ebb-tidal delta

Before the construction of the Brouwersdam, the Grevelingen ebb-tidal delta comprised the over 30 m deep channel Brouwershavense Gat in the south, bordering the island of Schouwen, and the channel Springersdiep which merged into the channel Kous in the north (Fig. 4). The channels were oriented east-west and separated by the shoals Middelplaat and Kabbelaarsbank. Already between 1933 and 1959, the Grevelingen estuary lost part of its tidal prism to the Eastern Scheldt (as described above). As a result, the cross-sectional area of the tidal channels was reduced, they became narrower and also deeper (Haring, 1978), and the shoals in between the channels expanded. In 1965, the Grevelingen dam (Fig. 1) at the eastern end of the estuary was finished (construction 1958-1965), which decreased the tidal prism with c. 14% (Haring, 1978). During this interval, the construction of the Brouwersdam at the seaward end had started. In 1965 (construction 1962-1965) the first dam sections across the shoals Middelplaat and

Kabbelaarsbank blocked the smaller tidal channels in the inlet. This caused an increase in depth of the remaining larger channels because of the reduced cross-section of the inlet. In 1971 the remaining channels Brouwershavense Gat and Kous were dammed completely, separating Grevelingen from its ebb-tidal delta. The tidal flow in the ebb-tidal delta was strongly reduced and, consequently, waves started to erode the ebb-tidal delta shoreface down to -10 m, 'bulldozing' the sand upwards into a longshore bar called Bollen van de Ooster (Van der Spek, 1987; Kohsiek, 1988) (Figs. 4b, 5). Part of the sand will have been transported to the northeast, along the coast of the island of Goeree and feeding the extension of the recurved spits at Kwade Hoek (Fig. 3; see above). The ebb-tidal delta reduced in surface area, the former shoals were eroded by waves and the channels filled in. Note that despite the reduction in surface area of the ebb-tidal delta, the reduction of its volume is comparatively less than suggested by the Walton & Adams (1976) relationship, since the eroded sediment cannot be transported into the estuary because of the dam. The channel Brouwershavense Gat filled in very rapidly with predominantly mud. The former shoal Middelplaat/Kabbelaarsbank was eroded by the waves since it was no longer maintained by tidal flow. The sand was deposited in front of the closure dam, forming a wide beach, and landward aeolian transport led to the building of an active dune row on the closure dam.

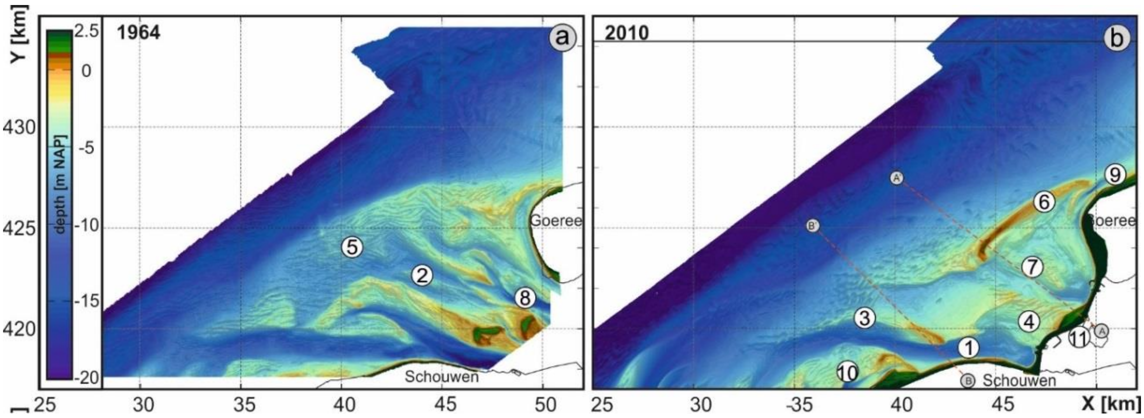

Figure 4. Overview of the bathymetry of the Grevelingen ebb-tidal delta for 1964 and 2010. Main *channels* and shoals: (1) *Brouwershavense Gat* (2) *Kous* (3) Gloeiende Plaat (4) Middelplaat (5) Ooster (6) Bollen van de Ooster (7) Aardappelenbult (8) *Springersdiep* (9) *Schaar* (10) Bollen van het Nieuwe Zand (11) Kabbelaarsbank

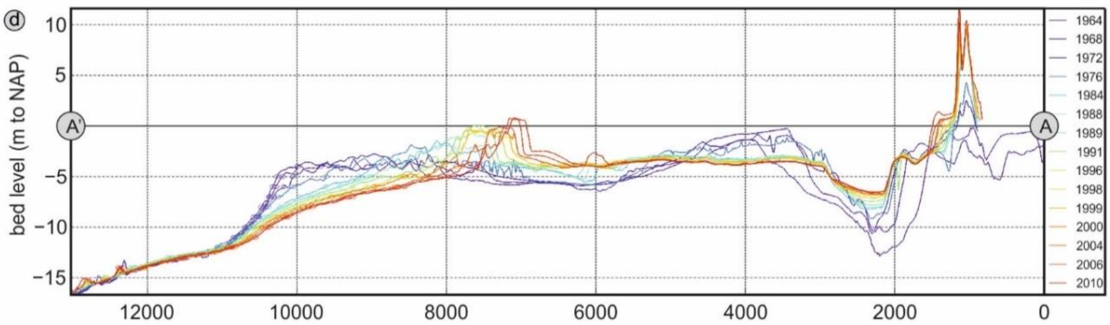

Figure 5. Evolution of a bathymetric transect over the Grevelingen ebb-tidal delta between 1964 and 2010, showing the erosion of the shoreface and the related building of a sand bar (seaward of x 7000), levelling of the channel-shoal relief (between x 7000 and x 2000) and dune formation on the beach (around x 1000). See Fig. 4b for location

Over the years, the sand bar Bollen van de Ooster increased in height and grew in longshore direction (viz. parallel to the ebb-tidal delta front), first to the west-southwest and later on also to the east-northeast (Fig. 4b). At present, the Bollen is still separated from the coast of Goeree by a (relatively shallow) short-cut channel. At the southern part of the ebb-tidal delta a shallow shoal area has been built by the Krabbengat channel, locally forcing the

Brouwershavense Gat channel to the north. The erosion of the seaward front of the ebb-tidal delta continues, as does the sedimentation in the landward part of the ebb-tidal delta. In total there is a small net gain of sediment. Part of this sediment must have been supplied by the eroding Banjaard shoal (see below) and was deposited along its northern edge and along the Schouwen coast (Fig. 4b).

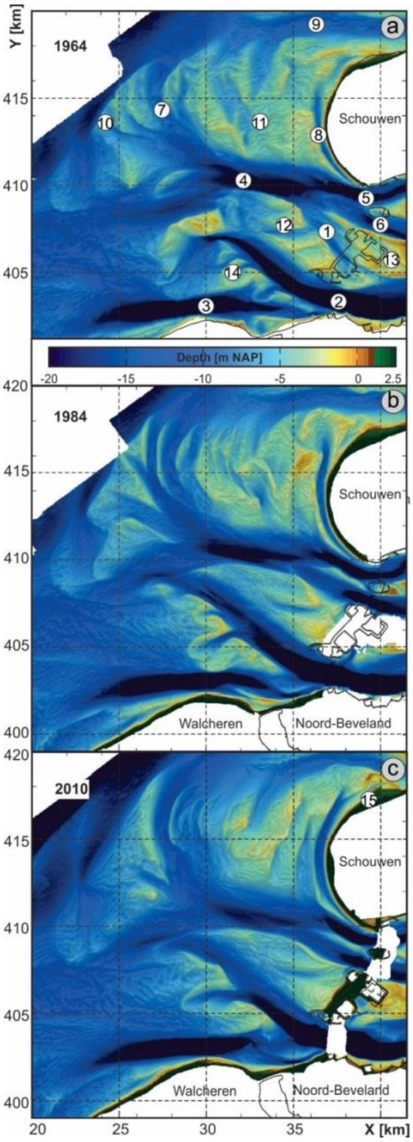


Figure 6. Overview of the bathymetry of the Eastern Scheldt ebb-tidal delta in 1964, 1984 and 2010. The morphological development over the period 1964-1984 differs considerably from the development over the period 1984-2010. Main *channels* and shoals: (1) *Geul* (2) *Roompot* (3) *Roompot Zuid* (4) *Westgat* (5) *Hammen* (6) *Schaar* (7) *Geul van de Banjaard* (8) *Krabbengat* (9) *Brouwershavense Gat* (10, 11) Banjaard (12) Noordland (13) Middelplaat (14) Hompels (15) Bollen van het Nieuwe Zand

## 2.3. *Eastern Scheldt ebb-tidal delta*

The Eastern Scheldt ebb-tidal delta consists of a complex, multiple channel pattern that is bounded to the north by a shallow area, Banjaard. The Banjaard shoal is dissected by smaller channels (Fig. 6). The inlet channels Hammen and Schaar merge seawards into the Westgat which has a southward and a northward outflow. The southern part of the Eastern Scheldt ebb-tidal delta is dominated by the Roompot channel that has a west-running branch, which lies just offshore the NW coast of the island of Walcheren (Roompot Zuid) and a main branch runs to the WNW (Oude Roompot). Small side branches formed a kind of spill-over lobes to the SW, this area is called Hompels.

Prior to the completion of the storm-surge barrier, the sediment volume of the Eastern Scheldt ebb-tidal delta grew due to the increase in tidal prism that was caused by the interventions in the estuary. Van den Berg (1984) and Eelkema et al. (2012) indicate that the volume increase between 1965 and 1984 results from augmented sediment exports caused by the change in hydrodynamics due to the closure dams in the basin (Volkerak dam) and in the Grevelingen. Sedimentation of sand exported out of the estuary on the terminal lobes of the tidal channels expanded the ebb-tidal delta seawards. The tidal flow in the inlet concentrated in the main channels as the smaller channels were blocked by the construction of parts of the barrier, which caused these channels to scour deeper. Significant channel erosion of Westgat and Geul van de Banjaard reduced the volume of the landward Banjaard shoal between 1964 and 1984.

The completion of the storm-surge barrier did not result in major changes in the channel pattern on the ebb-tidal delta, since the tidal currents had largely remained intact. However, the construction of the storm-surge barrier had reduced the active cross-sectional area of the tidal inlet (from 80.000 m2 to 17.900 m2) and the basin area reduced from 452 $km^2$ to 351 $km^2$, which resulted in a c. 28% reduction in tidal volume. Moreover, the sediment export of the estuary was blocked completely by the elevated foundation, large sill beams connecting the pillars of the barrier and the extensive scour pits that developed on both sides of the barrier. With decreased tidal currents and no sediment supply from the estuary, waves started to erode the ebb-delta front. Moreover, since the North Sea tidal currents and tidal range did not change, the eroded sediment was transported predominantly to the north, in the direction of dominant flood tidal currents. The Banjaard, west of the island of Schouwen eroded and the tidal channels cutting through this shoal area re-oriented into a more north-south direction. Krabbengat channel, directly off the western shore of Schouwen, extended to the north and built the flood ramp Bollen van het Nieuwe Zand to the north-northeast (Fig. 6). The erosion of the Banjaard shoal decreased the wave dissipation here, leading to a sustained wave attack on the Schouwen coast (Vermaas et al., 2015).

### 2.4. *Western Scheldt ebb-tidal delta*

The Western Scheldt ebb-tidal delta stretches from the island of Walcheren in the north into Belgian territorial waters in the south. The southern morphological boundary is not distinct since the coastal zone merges into the Flemish Banks, a zone of shallow, shore-parallel sand ridges, separated by deep troughs. The present-day lay-out of the Western Scheldt mouth (Fig. 7), with the largest channel Wielingen in the south and a complex of tidal channels and shoals along the SW coast of Walcheren, came into existence about a century ago. With increasing discharge, the Wielingen enlarged in depth and this contributed to the erosion of the Zeeuws Vlaanderen coastline. The formation of the 2-channel system, also had a major impact on the morphodynamic processes in the northern part of the ebb-tidal delta where the main shoals and the channel Oostgat all rotated or moved landward.

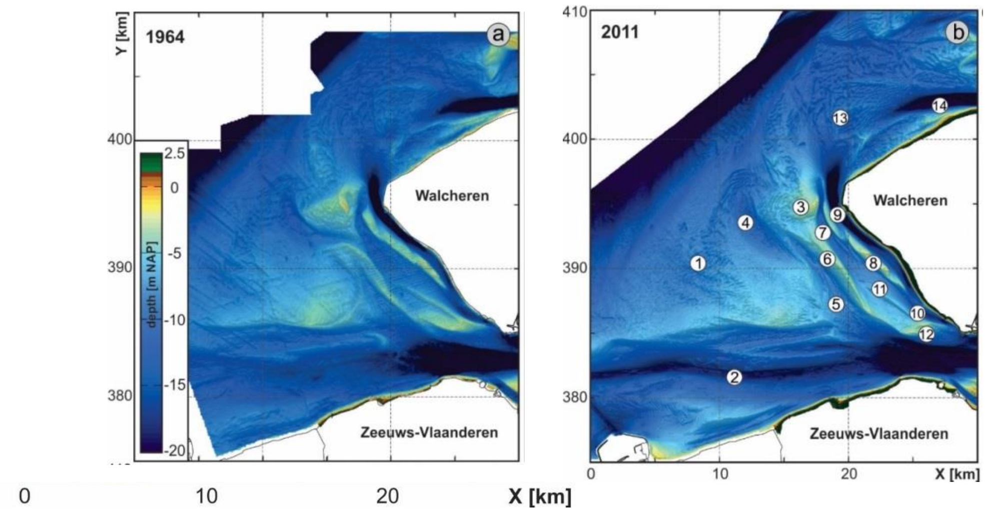


Figure 7. Overview of the bathymetry of the Western Scheldt ebb-tidal delta in 1964 and 2011. Main *channels* and shoals: (1) Vlakte van de Raan (2) *Wielingen* (3) Rassen (4) *Deurloo-West* (5) *Geul van de Walvischstaart* (6) Elleboog (7) *Geul van de Rassen* (8) Bankje van Zoutelande (9) *Oostgat* (10) *Sardijngeul* (11) *Deurloo-Oost* (12) Nolleplaat (13) Domburger Rassen (14) *Roompot Zuid*

This two-channel system has persisted over the past 45 years, despite the partial closure of the Eastern Scheldt and large-scale sediment displacement and extraction in the Western Scheldt estuary. Major changes in ebb-tidal delta morphology between 1964 and 2011 occurred in and along the channels. The Wielingen channel continued to increase in depth, but now for a major part due to, or enhanced by, dredging directly in the channel and in the Western Scheldt estuary. Part of the dredged sediments contributed to the accretion directly north and south of the channel. The increased depth of Wielingen is likely to have influenced the development of the northern part of the ebb-tidal delta. The Vlakte van de Raan, the central part of the ebb-tidal delta situated between Wielingen and the channel-shoal complex offshore SW Walcheren, is eroding, with the delta front slowly migrating landward.

### 2.5. *Volume changes of the ebb-tidal deltas 1965-2010*

Elias et al. (2016) presented a sediment budget over the timeframe 1965-2010 based on the volume changes that can be deduced from the bathymetry changes. The volume changes of the ebb-tidal delta polygons depicted in Fig. 1 (in white lines) are given in Fig. 8. The figure shows that the sediment volume of the Voordelta decreased with 24 million cubic meter (*mcm*) over the period 1965-2010, which is c. 0.5 *mcm*/year. After correction for the volume of sand nourishments along the shorelines of the ebb-tidal deltas of 95 *mcm*, 25 *mcm* of that being extracted from the ebb-tidal deltas themselves, the natural volume change is a loss of 94 *mcm*.

All ebb-deltas show an increase in volume up to approximately 1980 (and 1990 for the Grevelingen). A large volume increase of 45 *mcm* occurred on the Eastern Scheldt ebb-delta between 1965 and 1976. Since 1980, the volume of the ebb-tidal delta has reduced significantly by 77 *mcm* (Fig. 8), which is -2.6 *mcm*/year. The major part of these losses occurred on the Banjaard shoal. Volume changes on the ebb-deltas of the Western Scheldt, Grevelingen and Haringvliet are smaller. Similar to the Eastern Scheldt, the Western Scheldt ebb-tidal delta shows erosion between 1980 and 2010 (-1.2 *mcm*/year), after correcting for the nourishments that have been applied, the erosion rates increase to -2.0 *mcm*/year. Since 1965, the ebb-tidal deltas of Haringvliet and Grevelingen increased in volume, 25 *mcm* and 10 *mcm* respectively, although more recently both inlets showed sediment losses of approximately 1 *mcm*/year.

Further understanding of the observed volume losses and an overview of the sediment fluxes between the respective ebb-tidal deltas can be obtained by constructing a sediment box model that summarizes the sediment budget of the Voordelta, see Elias et al. (2016) and Lazar et al. (2017). Over the period 1965-2010 they observed relative small changes in ebb-delta volumes with a 0.1 and 0.2 *mcm*/year increase in Haringvliet and Grevelingen, and a 1 *mcm*/year volume reduction in the Western Scheldt and Eastern Scheldt ebb-deltas. The model shows that both Haringvliet and Grevelingen are transit areas, the amount of sediment coming in through the southern border is almost similar to that going out through the northern border. Sediment exchange between the Eastern Scheldt and Western Scheldt ebb-tidal deltas reverses in recent years with the Eastern Scheldt delivering sediment to the Western Scheldt. Note that for all time-frames and scenarios, the sediment exchange between the ebb-tidal deltas in most cases is of the same order of magnitude as the net changes and in many cases significantly larger than the net change.

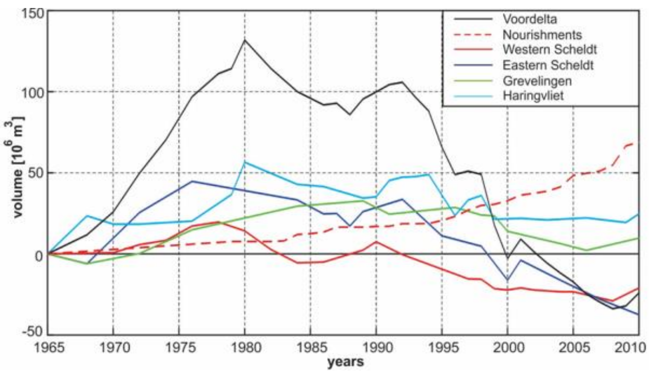


Figure 8. Cumulative sediment volume changes relative to 1965 for the Voordelta as a whole and for the individual ebb-deltas

## 3. Concluding remarks

The Voordelta consists of a series of five contiguous (former) ebb-tidal deltas. (Partial) damming of the estuaries in the course of the Delta Project, and large-scale harbour construction north of the Haringvliet estuary, have resulted in large-scale morphodynamic changes that continue until today. Nevertheless, the net sediment volume changes over the entire period 1965 to 2010 are small; 0.1 to 0.2 *mcm*/year increase in Haringvliet and Grevelingen ebb-tidal deltas, and a 1 *mcm*/year volume reduction of the Western Scheldt and Eastern Scheldt deltas. The sediment volumes that are transported from one ebb-tidal deltas to the next, are in the same order of magnitude or larger than the net changes.

The well-monitored changes in the Voordelta, showing the differences in responses of the ebb-tidal deltas to reductions in tidal volume, provide clear insight in the underlying processes and allow us to refine existing general concepts and models of ebb-tidal delta dynamics. Despite anthropogenic dominance, existing conceptual models and knowledge, based on natural inlets can still explain the observed developments. Reduction of the tidal prism of an inlet will result in a decrease in sand supply by the ebb current and, hence, wave-driven sand transport will increase relatively. This results in erosion of the delta front and net sediment transport in landward and downdrift direction (Grevelingen and Haringvliet). Since the sediment cannot be transported into the estuary because of the dams, the only way to export sediment is lateral transport. Moreover, with a reduction of the shore-normal tidal flow, shore-parallel currents will became more dominant which will promote shore-parallel flow through the channels on the ebb-tidal delta and increase the sediment exchange between the individual delta's. This will cause adaptations in the ebb-tidal delta morphology (Eastern Scheldt). Finally, the decreased tidal flow triggers infilling of the tidal channels, both with sand eroded from the shoals and mud imported from the North Sea.

The observed morphodynamic changes are related to the scale of the intervention. Complete damming of the three northern estuaries Brielse Maas, Haringvliet and Grevelingen resulted in a regime shift from mixed-energy to wave-dominated. At all inlets, a long but narrow, coast-parallel, sub- to intertidal bar developed as sediments were reworked by waves on the former ebb-delta margin and pushed landward. This bar temporarily acts as a coastal barrier, sheltering the area behind and thereby promoting sediment deposition. The closed-off channels have filled in with sediments, both sand and mud. Since the dams block transport of sediment into the estuaries, the volumes of the ebb-tidal deltas did not decrease as would be expected from the Walton & Adams relationship. Coast-parallel sand transport is the only way of volume reduction. A part of the sand eroded from the Grevelingen delta front was transported to and along the coast of Goeree island, towards the Haringvliet ebb-tidal delta. The latter does not have an outlet for sediment since it is blocked in the north by the harbour extensions.

Partial closure of the Eastern Scheldt resulted in a reduced tidal volume, but the tidal flows have been sufficient to maintain the main channels on the ebb-tidal delta. The reduction of the shore-normal tidal flow resulted in dominance of shore-parallel currents on the nearshore Banjaard shoal, promoting scour of the north-south running channels, and erosion of the ebb-delta margin due to wave attack. As a result, the largest sediment losses occur on this ebb-tidal delta (-72 *mcm* since completion of the storm-surge barrier).

Only limited net change was observed in the Western Scheldt ebb-tidal delta in the south. This ebb-tidal delta retained a near identical two-channel configuration with large tidal channels along the southern and northern margin, despite major dredging activities in the estuary (where over 400 *mcm* of sediment was dredged and dumped) and channel deepening in the ebb-tidal delta. Apparently, tide-dominated systems such as the Western Scheldt ebb-tidal delta are robust and resilient to significant anthropogenic change, as long as the balance between tides and waves does not alter significantly.

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