Half a century of morphological change in the Haringvliet and Grevelingen ebb-tidal deltas (SW Netherlands) - Impacts of large-scale engineering 1964-2015

Ad J.F. van der Spek[1,2]; Edwin P.L. Elias[3]

[1]Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands; ad.vanderspek@deltares.nl

[2]Faculty of Geosciences, Utrecht University, P.O. Box 80115, 3508 TC Utrecht

[3]Deltares USA, 8070 Georgia Ave, Silver Spring, MD 20910, U.S.A.; edwin.elias@deltares-usa.us

Abstract

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. The complete or partial damming of these estuaries in the nineteensixties had an enormous impact on their ebb-tidal deltas. The strong reduction of the cross-shore tidal flow triggered a series of morphological changes that includes erosion of the ebb delta front, the building of a coast-parallel, linear intertidal sand bar at the seaward edge of the delta platform and infilling of the tidal channels.

The continuous extension of the port of Rotterdam in the northern part of the Haringvliet ebb-tidal delta increasingly sheltered the latter from the impact of waves from the northwest and north. This led to breaching and erosion of the shore-parallel bar. Moreover, large-scale sedimentation diminished the average depth in this area. The Grevelingen ebb-tidal delta has a more exposed position and has not reached this stage of bar breaching yet.

The observed development of the ebb-tidal deltas caused by restriction or even blocking of the tidal flow in the associated estuary or tidal inlet is summarized in a conceptual model. This model can help to assess the impact of interventions in other systems, for instance to mitigate the impacts of sea-level rise.

Key words:

coastal morphodynamics; long-term coastal evolution; ebb-tidal delta; Brielse Maas; sediment budget; conceptual model

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. The Delta Project included separation of these estuaries with dams and subsequent damming of their seaward sides, in order to improve safety against flooding and to create freshwater resources for agriculture (see Fig. 1). Currently, the rivers Rhine and Meuse debouch into the North Sea through Nieuwe Waterweg and discharge sluices in the Haringvliet dam. These sluices will open to drain excess river water and regulate a stable freshwater flow out of the Nieuwe Waterweg. This is necessary to prevent saltwater intrusion that threatens the extensive horticulture gardens in the adjacent areas. Watson and Finkl (1990, 1992) presented a detailed explanation of the project. The complete or partial damming of these estuaries had an enormous impact on their ebb-tidal deltas: the strong reduction of the cross-shore tidal flow triggered a series of morphological changes that continues until today.

1.1 Ebb-tidal delta morphodynamics

Ebb-tidal deltas are found at the seaward side of tidal inlets where the sediment-laden ebb current leaves the narrow, constricting tidal inlet and enters the open sea. Here, the tidal flow segregates, current velocities drop below the sediment transport threshold value and the sand is deposited, forming a shallow shoal called *terminal lobe*. This development is counteracted by waves that impact on these shoals and tend to move the sand landwards, back to the inlet and to the bounding shorelines. Consequently, the balance of wave versus tidal energy determines the morphology of an ebb-tidal delta. Wave-dominated ebb-tidal deltas are comparatively small and pushed close to the inlet throat, whereas tide-dominated ebb-tidal deltas extend offshore (see e.g. Hayes, 1975, 1979; Oertel, 1975; Hubbard et al., 1979). Elias et al. (2017) provide an extensive summary of the relevant literature, both on ebb-tidal delta morphodynamics and studies of ebb-tidal delta evolution in the SW Netherlands.

1.2 Study Area

The coast of the SW Netherlands is dissected by six (former) estuaries, from north to south Nieuwe Waterweg, Brielse Maas, Haringvliet, Grevelingen, Eastern Scheldt and Western Scheldt, see Fig. 1. All are distributaries of the combined rivers Rhine and Meuse, with exception of Western Scheldt which is the lower course of the river Scheldt. Nieuwe Waterweg is a man-made outlet connecting Rhine and Meuse to the North Sea. The estuaries, with exception of Nieuwe Waterweg, are bounded on their seaward end by ebb-tidal deltas that have coalesced into an extensive area of shallow grounds, that is transected by tidal channels, known as the *Voordelta* (English: Fore Delta). The bed of the inlets and tidal deltas consists of fine- to medium-grained sand (Terwindt, 1973). Since construction of the closure dams, large volumes of mud have accumulated in closed-off channels in the outer deltas (Piekhaar and Kort, 1983; Van den Berg, 1987).

The tide at the west coast of The Netherlands is semi-diurnal and propagates in northward direction along to the coast. The mean tidal range decreases from 2.50 m in the Grevelingen ebb-tidal delta to 1.75 m at Hoek van Holland at the mouth of Nieuwe Waterweg (Rijkswaterstaat, 2013). The wave climate in the Voordelta consists mainly of wind waves with a mean significant wave height of 1.3 m from the westsouthwest and a corresponding wave period of 5 seconds (Roskam, 1988; Wijnberg, 1995). During storms, wind-generated waves occasionally reach heights of over 6 m and additional surges of over 2 m have been measured. In general, following the classification of Davis and Hayes (1984), the inlets would qualify as ranging from mixed-energy wave-dominated in the north to mixed-energy tide-dominated in the south. However, the inlets show tide-dominated morphological characteristics such as an extended ebb-tidal delta and deep channels which is caused by the large tidal prisms and relatively low wave energy. Around 1959, Nieuwe Waterweg and Haringvliet had ebb volumes of 102 and 295 million m^3 under average tide conditions, which included river volumes of 35 and 60 million m^3, respectively (Van de Kreeke and Haring, 1979).

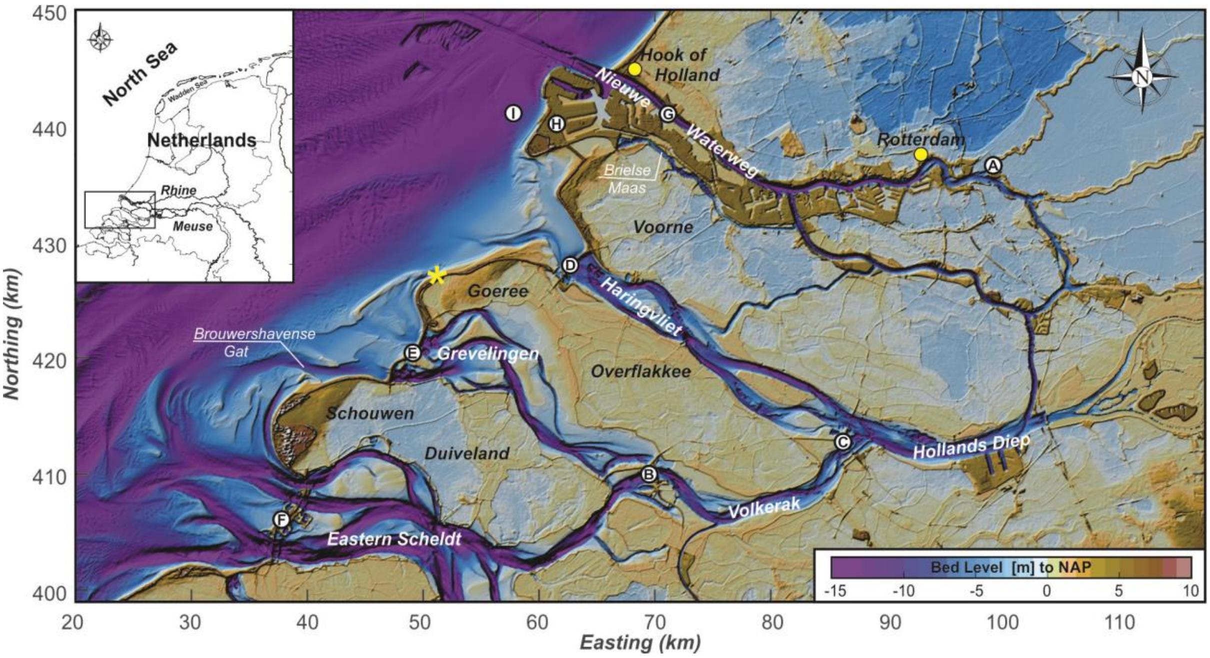

*Fig. 1. Overview of the northern part of the Dutch Delta, showing the (now dammed) distributaries of the rivers Rhine and Meuse, the contiguous ebb-tidal deltas known as the Voordelta, and the major dams and barriers constructed as part of the Delta Project. A: Hollandse IJssel storm-surge barrier; B: Grevelingen dam; C: Volkerak dam; D: Haringvliet dam and sluices; E: Brouwers dam; F: Eastern Scheldt storm-surge barrier; G: Nieuwe Waterweg storm-surge barrier; H: Maasvlakte; I: location of Maasvlakte 2; *: Flaauwe Werk. 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.*

Terwindt (1973) concluded a predominantly shore-perpendicular sand transport by tidal currents in the channels and predominant wave-driven transport to the northeast on the shoals in the Voordelta. Grainsize distributions show an overall fining to the northeast, corroborating north-easterly net transport of fine sand in the Voordelta. Finally, the grain-size survey by Terwindt revealed mixing of fine ebb delta sand and coarse North Sea sand offshore Haringvliet.

This paper starts with an account of the evolution of the mouths of the Brielse Maas, Haringvliet and Grevelingen estuaries since the ninteenth century. The evolution of the contiguous ebb-tidal deltas of all estuaries in the southwest Netherlands is discussed by Elias et al. (2017). The impacts of large-scale engineering works such as channel construction, damming and land reclamation, that already started in the late nineteenth century, have changed the geomorphology of this area significantly. In the present paper we will further analyse the morphodynamic changes in the mouths of the Brielse Maas and Haringvliet estuaries, which share a joined outer delta, and the Grevelingen ebb delta to their south in detail. This 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 1964-2015. Moreover, the paper aims to summarize more than half a century of morphological changes in the mouths and ebb-tidal deltas of the estuaries following the damming of estuaries in a conceptual model that illustrates the general impact of (almost) complete reduction of the shore-normal tidal flow. The anticipated future climate change and resulting accelerated rise in mean sea level, will likely trigger large-scale interventions in estuaries and tidal basins around the world. This conceptual model will help to assess and understand the impact of such interventions.

Note that in this paper we will use Dutch names for tidal channels, shoals, etc. The majority of these names is ending on words that are easily recognized and translated: ‘plaat’ = shoal; ‘bol’ = (sand) bar; ‘geul’ = channel; ‘gat’ = channel or creek; ‘diep’ = deep (channel).

2. Long-term evolution of the Brielse Maas, Haringvliet and Grevelingen estuaries

The outer part of the mouth of the Haringvliet estuary included the smaller ebb-tidal delta of the Brielse Maas estuary, a declining distributary of the combined rivers Rhine and Meuse. Both estuaries are separated by the diamond-shaped island of Voorne (Fig. 1). They have evolved in their own way. Brielse Maas was the remainder of the once wide mouth of the rivers Rhine and Meuse, which had been the major shipping route to the city and port of Rotterdam since medieval times. Nautical charts indicate that this mouth has been silting up since the 16th century (Hofland, 1986a, 1986b). Deforestation along the upper reaches of the Rhine caused an increase in sediment load of the river (Stouthamer et al., 2015, p. 289; Erkens and Cohen, 2009). In addition, natural levee formation and the raising of embankments along the river prevented these sediments from being deposited in the alluvial plain, leading to transport further downstream to the estuaries (see, e.g., Pierik et al., 2017). Over time, sedimentation followed by impoldering along the northern shore and expansion of tidal flats in the central part of the estuary (which were subsequently diked in and formed the island of Rozenburg) greatly reduced the extent of the original estuary and, with that, room for deposition of sediment, which accelerated the silting up (Meyer, 2017; p. 75). Moreover, the formation of a spit that was growing from the northern shore to the south narrowed the mouth and forced the main navigation channel south, towards the island of Voorne (Figs. 2-4).

Haringvliet is a younger distributary of Rhine and Meuse that was formed in the early 13th century south of Voorne. In the mid-19th century, the Haringvliet estuary was connected on its landward end to Grevelingen and Eastern Scheldt by the Volkerak channel (Fig. 1). The tidal wave travelled through these estuaries and channel to the northeast, arriving at Hollands Diep, the inland part of Haringvliet, about 40 minutes earlier than 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, 1987). Part of this sediment was exported to and deposited on the ebb-tidal delta. As the tidal prism of Haringvliet and Grevelingen decreased, their ebb-tidal deltas started to deteriorate.

Fig. 2. Historic chart ‘Het Eylandt West-Voorn of GOEDEREEDE met de Dieptens en Droogtens Ronds-omme, tot aan Den Hoek van HOLLANDT, etc.’ (The island of West-Voorn or Goeree with its surrounding channels and shoals up to Hook of Holland, etc.), showing the mouths of Rhine-Meuse distributaries Haringvliet (south) and De Maas (north). This map was compiled by surveyor Nicholaas Cruquius from his soundings in 1729 (southern part) and 1731 and 1732 (northern part) and published in 1733. Goeree is still an island that was not yet connected to Flakkee to its southeast. The mouth of the Meuse is restricted by the spit De Beer that was stretching southwards from Hook of Holland and had forced the channels in the mouth to the south, against the shore of the island of Voorne. Moreover, Cruquius indicated the shoreline positions of Holland and Voorne in the 17th century, showing the shoreline erosion since.

Fig. 3. De Maas, the former mouth of the rivers Rhine and Meuse, around 1850 A.D. The estuary has been split in separate channels, Het Scheur in the northern part and De Nieuwe Maas in the south, by the formation of the island of Roozenburg. Comparison with the situation in the mid-18th century (Fig. 2) shows continued siltation of this area which is indicated by expansion of the reclamations. (based on: Grote Historische Atlas van Nederland 1:50 000, vol. I West-Nederland 1839-1859. Wolters-Noordhoff Atlasproducties, Groningen, 1990).

2.1 The shipping route to Rotterdam – morphodynamics of the estuaries

Siltation of Brielse Maas, indicated by the growth of intertidal flat area and expansion of the island of Rozenburg, in combination with the southward growing spit of Hoek van Holland/De Beer devaluated its importance as a shipping route to Rotterdam (Figs. 2-4). Therefore, an increasing number of ships had to take alternative, longer routes following the other estuaries to reach the port. Already in 1734 the surveyor Cruquius suggested to cut a new channel through the 'panhandle' at Hook of Holland, in order to create a new opening for the river to the North Sea and, concurrently, improve the access to the port of Rotterdam (Meyer, 2017; p. 79; Hoving and De Kraker, 2013). In 1830 a new shipping route was opened by connecting the Haringvliet to Rotterdam by means of a canal dug through the island of Voorne (Figs. 3, 4). However, the rapid increase in dimensions of commercial vessels rendered the canal that included locks at both ends, obsolete within decades (Figs. 3, 4). Finally, between 1866 and 1872 a canal was cut through the spit Hoek van Holland and the connection between the channel Het Scheur and the Brielse Maas was blocked with a dam (see Fig. 4). This established a shorter and more reliable connection between the North Sea and the port of Rotterdam: the Nieuwe Waterweg (Rotterdam Waterway). As a result of this, Brielse Maas had lost its main connection and was reduced to a narrow estuary and the spit De Beer was literally cut off and turned into a barrier island that later on grew together with the island of Rozenburg.

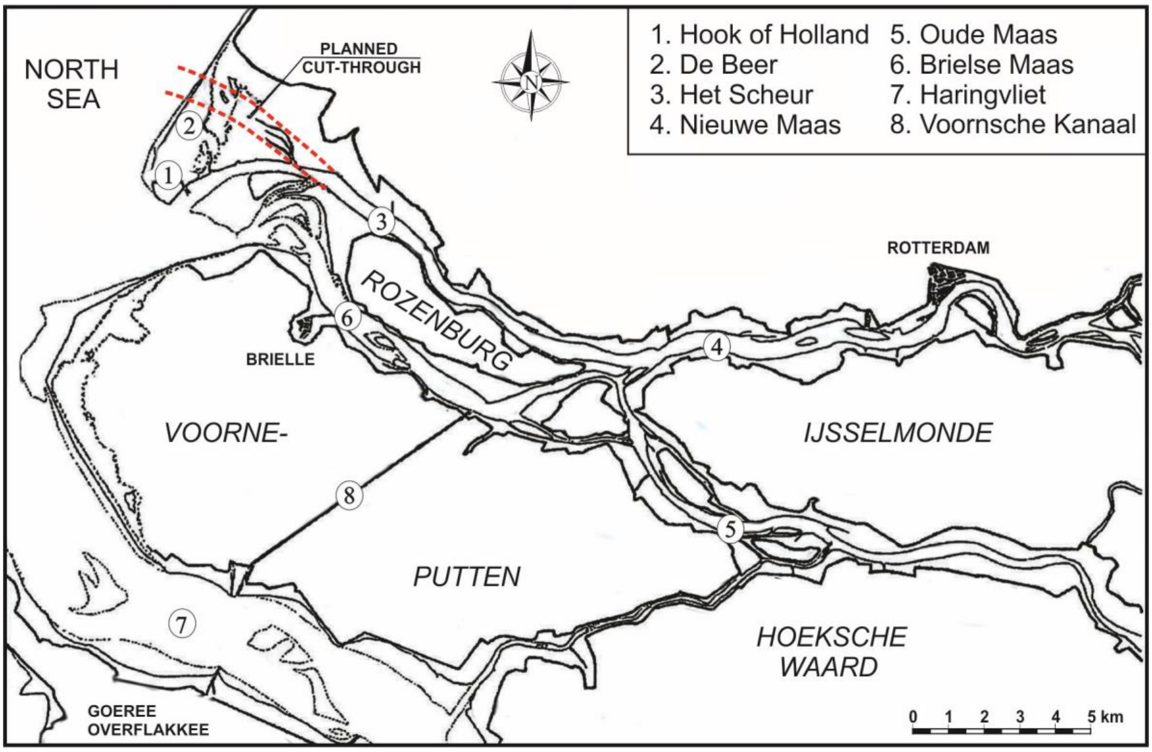

Fig. 4. Topography of the mouth of the Rhine-Meuse around 1850. It shows the location of the channels Het Scheur and Oude Maas, the shipping canal through Voorne (Voornsche Kanaal, finished 1830) and the planned location for the Nieuwe Waterweg, to be digged through the spit De Beer/Hoek van Holland (started in 1869). The topography is comparable with the map of Fig. 3. (After: De Bruijn, 1949).

In order to reach the desired navigation depth the Waterweg has been deepened regularly (see Van den Burg, 1989, for details). Moreover, to reduce dredging costs, the tidal currents in the Waterweg were reinforced through increasing the tidal volume by connecting Nieuwe Waterweg to Oude Maas, the upstream part of the Brielse Maas distributary (De Bruijn, 1949; Fig. 4). Tidal currents were further increased by the expansion of the port of Rotterdam and the increase in dock area. However, with the growth of the tidal volume of Nieuwe Waterweg, 25% over the period 1914-1934 (De Bruijn, 1949), that of Brielse Maas declined, which resulted in weakening of the tidal flow. On top of that, the volume of river water routed along Brielse Maas to the North Sea decreased significantly. The combined effect was an aggravated salinization and siltation of this estuary.

2.2 Shortening the coastline – improving flood defence

The salinization and siltation of Brielse Maas triggered a plan to close off this distributary. Already in the 1930s the safety against flooding of the Delta area was studied. The general idea was to shorten the coastline by damming the smaller estuaries, in order to reduce the length of sea dikes and hence, the risk of flooding during storm surges (Rijkswaterstaat, 1970b, 1978). Additionally, increasing salt water intrusion in the estuaries caused serious problems for agriculture and cattle raising in the bordering low-lying polders. In the course of these plans, Brielse Maas was closed off in 1950, to create a large freshwater storage. A plan for the other estuaries was still under study when the 1953 storm surge hit. Following this disaster, the Delta Project was quickly adopted by Dutch Parliament, it included closing off the Haringvliet estuary, with both a dam and discharge sluices and complete damming of the Grevelingen and the Eastern Scheldt. The dams would reduce the length of dikes exposed to the sea by 700 km. The general idea of the Delta Project was to separate the Delta area into two subsystems: a northern basin consisting of Haringvliet and Nieuwe Waterweg and their connecting channels that had to convey the discharge of the rivers Rhine and Meuse to the North Sea and a southern basin consisting of the Grevelingen and the Eastern Scheldt and its northern tributary Mastgat-Zijpe-Krammer-Volkerak, that would be dammed in a later stage. This was accomplished by building a dam in the Volkerak that kept the tide from penetrating northeastwards into the lower course of the rivers (Fig. 1 [C]). The Grevelingen had to be disconnected from the Eastern Scheldt system in an early stage to facilitate the building of the Volkerak dam. The Western Scheldt mouth was not included in the project to allow unhindered shipping to the port of Antwerp. Plans for complete damming of the Eastern Scheldt were eventually abandoned to preserve the valuable inshore tidal ecosystem. Instead, the Eastern Scheldt storm-surge barrier was constructed (Rijkswaterstaat Deltadienst, 1979).

2.3 Bathymetric changes in the Haringvliet ebb-tidal delta 1821-1957

Van Driel (1959) describes the morphodynamics of the mouth of Haringvliet and its outer delta over the period 1821-1957. The estuary consisted of two main tidal channels, Rak van Scheelhoek along the shore of Voorne in the north and Zuiderdiep along the shore of Goeree in the south, separated by the shoal Plaat van Scheelhoek (Fig. 5). Rak van Scheelhoek was the main ebb channel, it had a straight course to the northwest and one or more branches running to the west. Over this period, it showed four cycles of shallowing and migration to the island of Voorne in the north, followed by a rapid breakthrough to the south and connection to a channel in the centre of the inlet. The most recent shift was in 1932. The flood channel Zuiderdiep increased in dimension and moved to the south, eroding the shore of Goeree until 1857. From then on, Zuiderdiep gradually lost its importance and since 1915 the flood tide followed Noord-Pampus channel, north of the shoal Plaat van Scheelhoek.

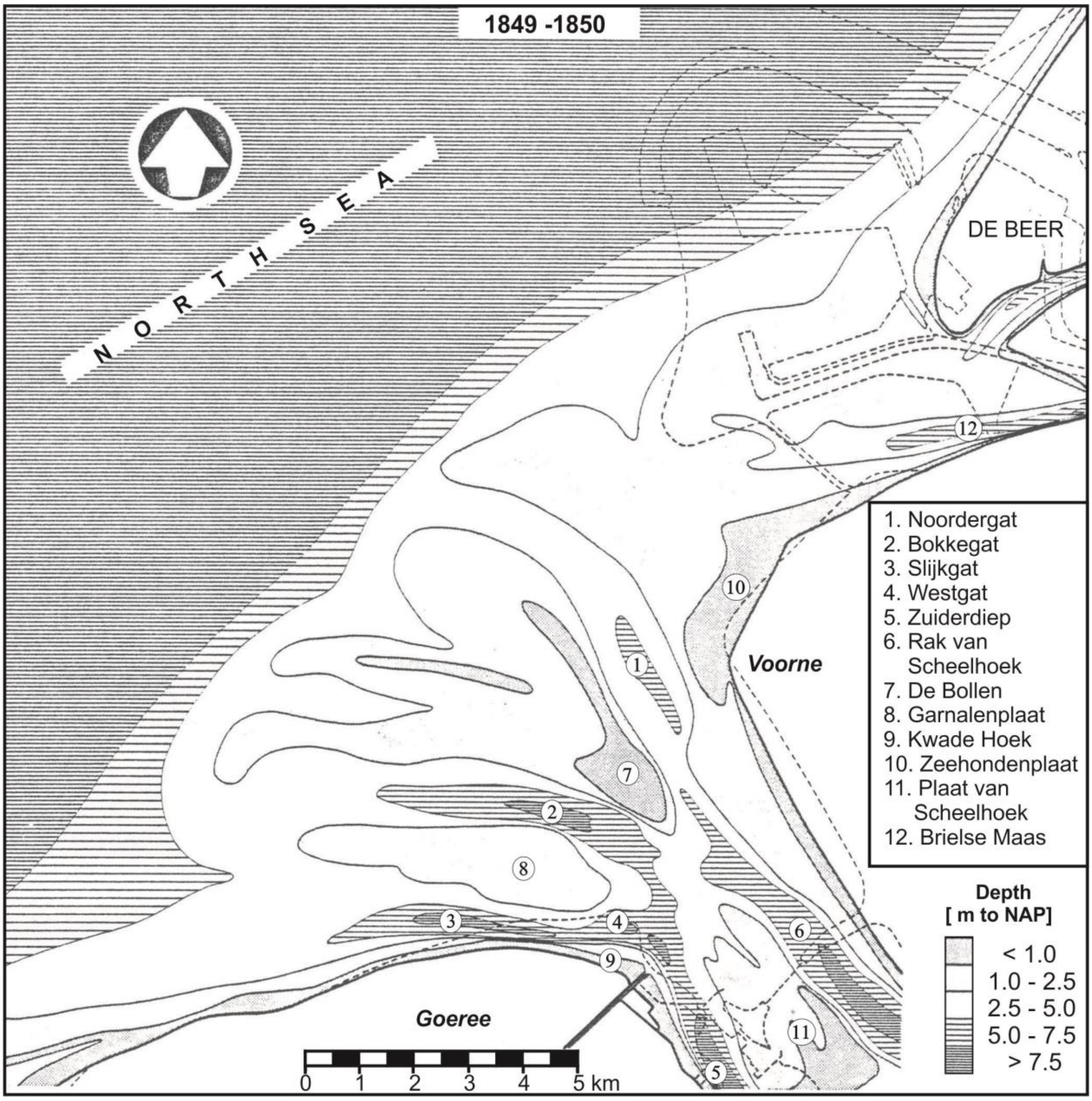

Fig. 5. Morphology of the Haringvliet ebb-tidal delta including the mouth of the Brielse Maas to the north in 1849-1850. Note the spit De Beer that will be cut loose from the mainland of Holland by the digging of the Nieuwe Waterweg in 1869-1871. The contours of both the Haringvliet dam including the sluices and Maasvlakte that was reclaimed between 1964 and 1976 are indicated with dashed lines. Depths are given in m's. (source: Rijkswaterstaat).

The successive westward running branches of Rak van Scheelhoek, called Bokkegat, migrated northwards through the inlet, thereby pushing the shoals in the northern part of the ebb-tidal delta seaward. Shoals bordering the main flood channel in the southern part of the delta migrated towards the inlet.

The shoreline of Voorne accreted until 1868 and then started to erode. The shoreline of Goeree was more or less stable until 1868 and subsequently accreted as the main channel in the southern part of the delta migrated to the north. The low-water line near Kwade Hoek (compare Figs. 5, 6) prograded over 1 km. The tidal inlet as a whole shifted to the north since its total width remained approximately constant. Haring (1955) reported scouring of Bokkegat resulting in sediment deposition on its terminal lobe and silting up of the Zeegat van Goeree (Goeree tidal inlet; which is the Haringvliet mouth) in general over the interval 1872-1933, followed by an increase in sedimentation in the decades to come. Simultaneously, the estuary itself also silted up. The sediment volume of the inner part of the ebb-tidal delta has been increasing since the start of the 20th century, whereas the delta front was eroding. The ebb-tidal delta as a whole has been shifting landward (Van Driel, 1959).

2.4 Bathymetric changes in the Grevelingen ebb-tidal delta 1872-1952

The mouth of the Grevelingen estuary comprised two major tidal channels, the main channel Brouwershavense Gat was situated in the southern part along the coast of Schouwen (Fig. 1). The Grevelingen estuary and its ebb delta showed minor silting up since 1872 whereas the Eastern Scheldt and its northeast running branches eroded strongly (Haring, 1955), due to the aforementioned increase in tidal flow. This captured part of the discharge of Grevelingen which caused a reduction in cross-sectional area of the inlet channels, they became narrower and deeper (Haring, 1978), and expansion of the intertidal shoals. With the reduction in tidal prism, the extent of the ebb-tidal delta will have diminished too. Sedimentation in the ebb-tidal delta increased sharply after 1933 (Haring, 1955).

3. Engineering and morphodynamic changes since c. 1950

3.1 Development of the northern part of the Haringvliet ebb-tidal delta

The Haringvliet ebb-tidal delta included the ebb-tidal delta of the comparatively small Brielse Maas estuary to the north. The Brielse Maas estuary was dammed in 1950. Later on, this area was changed completely due to the expansion of the port of Rotterdam directly north of it.

3.1.1. Closing off Brielse Maas

The damming of the Brielse Maas estuary in June 1950 caused drastic changes in the morphology of its ebb-tidal delta. Within 10 years the channels had filled in with mud and their orientation had changed from east-west to north-south. The shoal Westplaat rapidly increased in height and surface area, rotated parallel to the shoreline and migrated landward (Rijkswaterstaat, 1962; Terwindt, 1964; see Fig. 6: 1960, 1964; Fig. 7). Sand transport to the northeast along the coast of Voorne resulted in the formation of a series of prograding spits (Fig. 7). Terwindt (1964) concluded that the damming of the Brielse Maas resulted in infilling of the tidal channels due to low current velocities caused by the loss of discharge since the tidal prism was greatly reduced. Moreover, the north-south water-level gradient had become dominant, which caused the reorientation of the tidal channels. Wave-driven erosion of the delta front was no longer compensated by sand transported by the ebb tide. Consequently, the ebb-tidal delta became smaller and Westplaat shoal expanded to a shore-parallel, wave-built bar. These developments indicated the changes in the ebb-tidal deltas of Haringvliet and Grevelingen that were to be expected after blocking of the estuaries.

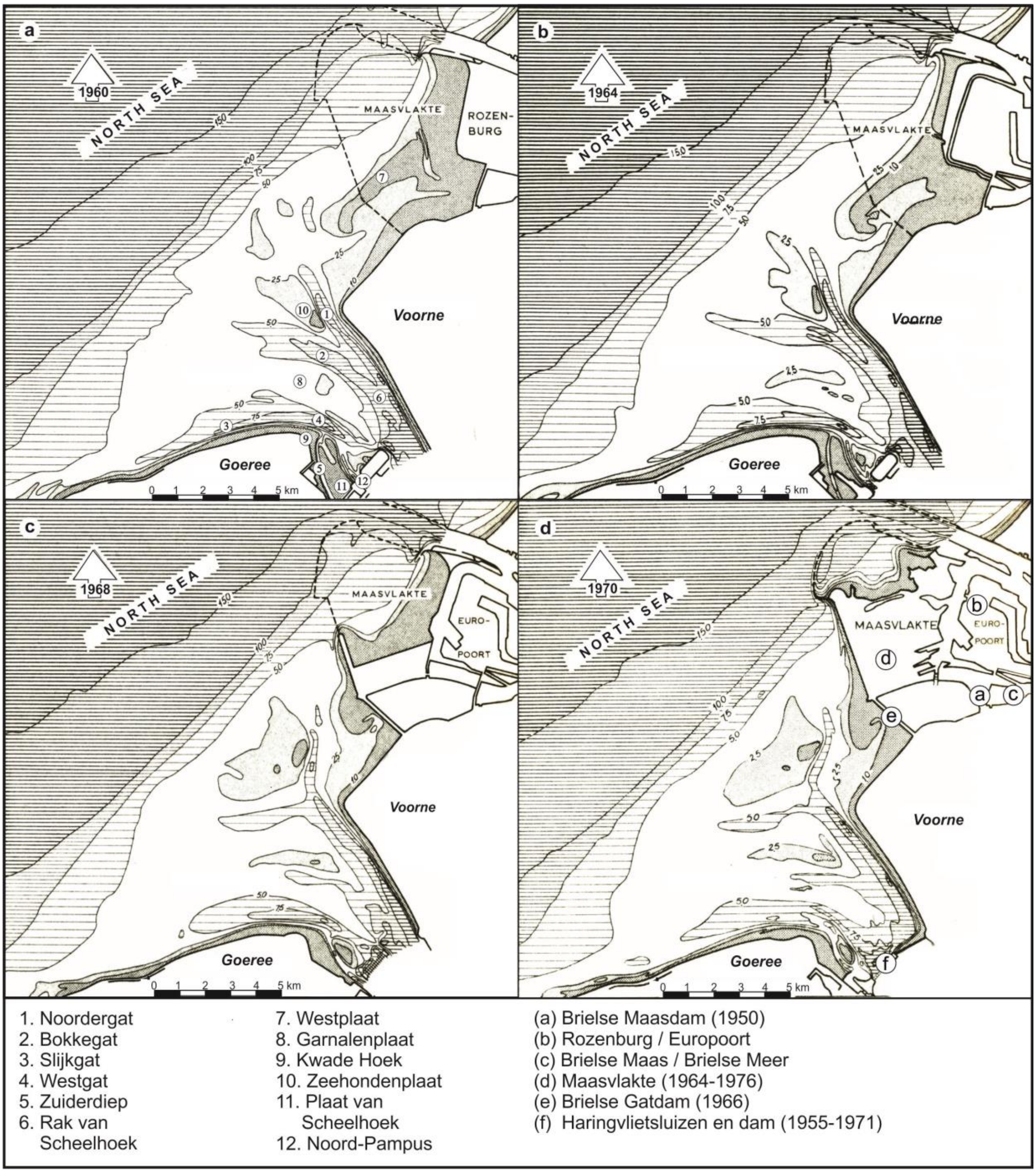

Fig. 6. The changes in the mouth of the Haringvliet and Brielse Maas estuaries between 1960 and 1970. Brielse Maas had been dammed in 1950 and its former ebb-tidal delta had swiftly adapted to the new hydraulic situation. In the Haringvliet ebb-tidal delta the major ebb channel Rak van Scheelhoek is situated along the shore of the island of Voorne. The ring-dike of the construction pit for the discharge sluices is situated in the middle part of the estuary (1960, 1964). Directly south of it runs the channel Noord-Pampus which connects to the channel Slijkgat along the shore of the island of Goeree. In 1968 the ring-dike has been removed and in 1970 Rak van Scheelhoek has been dammed. In the northern part of the ebb-tidal delta, the construction of Europoort and Maasvlakte extended the island of Rozenburg seaward. The maps show the changes in the channel and shoal pattern caused by the interventions (see text for details and explanation). Depths are indicated in m's. (From: Rijkswaterstaat Deltadienst, 1970; appendix).

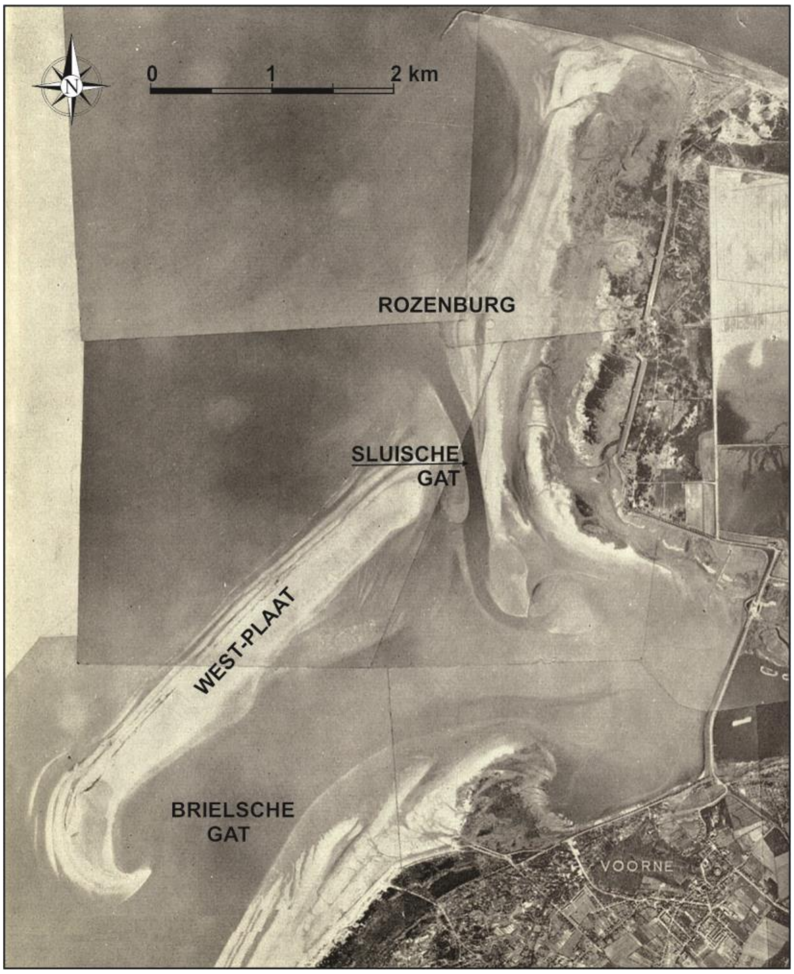

Fig. 7. Aerial photograph of the mouth of the Brielse Maas and the shoreline of the island of Rozenburg in 1961. The channels Brielsche Gat and Sluische Gat in the ebb-tidal delta have rotated to a more or less north-south orientation. The shoal Westplaat has grown in surface area, has migrated shorewards and shows recurved spits at its southern tip. In front of the island of Voorne (bottom of picture), a fan-like spit complex has formed. (From: Terwindt, 1964).

3.1.2. Extending the coast of Rozenburg

After the closure of Brielse Maas in 1950, westward expansion of the port of Rotterdam further changed the morphology of the northern part of the ebb-tidal delta. The construction of, respectively, Europoort (1964-1966), Maasvlakte (1964-1976), Slufterdam (1986-1987) and Maasvlakte 2 (2008-2013) shifted the shoreline of the island Rozenburg 8 km seaward and covered the northern part of the ebb-tidal delta (Figs. 6, 8, 9). In 1966 the remaining mouth of the Brielse Maas estuary was restricted further with the Brielse Gat dam, 3.8 km seaward of the 1950 dam, as part of the Maasvlakte port extension (Figs. 6d, 9). Moreover, the largest part of Westplaat shoal disappeared when the Maasvlakte was built on top of it. This stepwise reclamation increasingly sheltered the Haringvliet ebb-tidal delta from north-westerly waves, which will have influenced its development significantly.

Fig. 8. Aerial photographs of the island Rozenburg before 1950 (top), showing agricultural land and nature reserve De Beer at the coast, and in 1960 (bottom) after construction of the Europoort harbour extension. In the top panel, the course of the blocked and subsequently reclaimed channel Het Scheur can still be recognized (compare with Fig. 4). (From: Van den Burg, 1989).

3.2 Damming the Haringvliet estuary

Since the beds of the mouths of the estuaries in the SW Netherlands are composed of unconsolidated sediments and the tidal currents are capable of transporting large volumes of sand and mud, engineering in tidal inlets should be based on the principle of maintaining the cross-sectional area of the inlet during construction as long as possible to avoid excessive scouring of the tidal channels (Rijkswaterstaat, 1970c). Hence, construction should start in the shallow shoal areas. Moreover, since the construction and damming of an estuary mouth implies large-scale sediment displacement, both mechanical (sand extraction) and by natural processes (channel migration, scour of the bed, etc.), information on the composition and erodibility of the estuarine deposits is essential

(Rijkswaterstaat, 1966). Oomkens and Terwindt (1960) described the sediment sequences that were excavated in the construction pit of the discharge sluices (see below), along with information on tidal currents and sediment transport near the location of the pit. Terwindt (1971) presented different types of litho-facies that were produced under varying tidal current strength, based on the study of these excavations and cored borings. In the Haringvliet estuary he found sequences of alternating cm-thick sand and clay layers of up to 20 m thick. Unique in-situ flume experiments on the natural estuary bed at the bottom of the excavation pits showed that the erosion resistance of sand-clay alternations is in the same order of magnitude as clay layers (Terwindt et al., 1968).

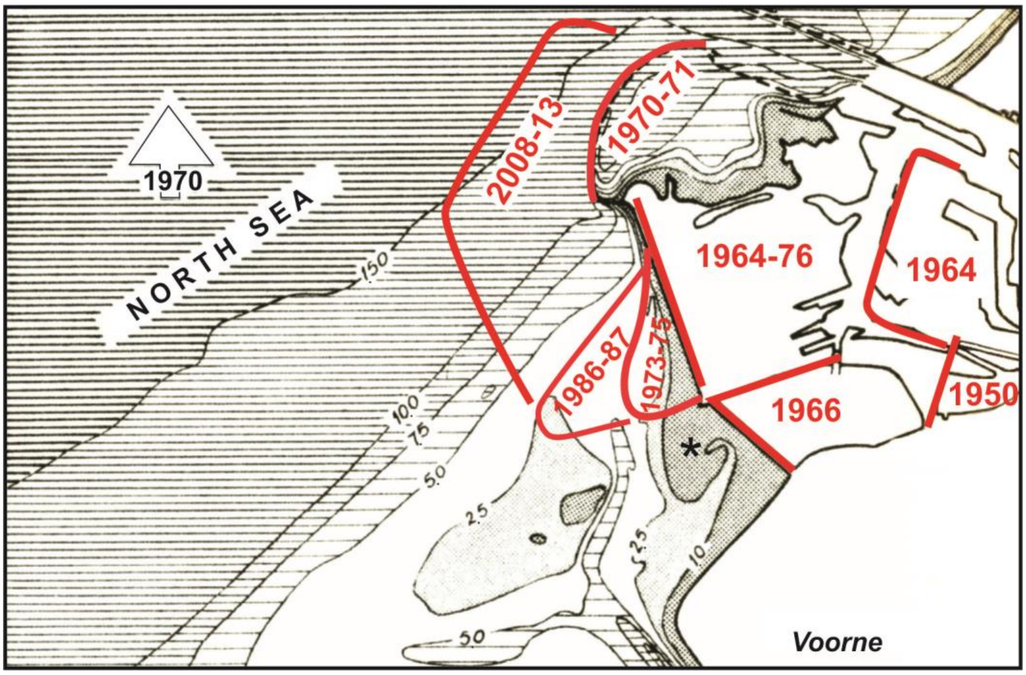

Fig. 9. The westward expansion of the coast of the island Rozenburg between 1960 and 2013, due to the construction of Europoort (1964-1966), Maasvlakte (1964-1976), Slufterdam (1986-1987) and Maasvlakte 2 (2008-2013). The asterisk indicates the remnants of the Westplaat.

Accordingly, the construction of the discharge sluices in the Haringvliet mouth which preceded the actual closure, was planned on the shoal between the main channels Rak van Scheelhoek and Noord-Pampus (Figs. 6, 10). In 1957 a ring-dike that measured 560 m parallel to the estuary axis and 1400 m perpendicular to it, was built (see Rijkswaterstaat, 1957, for details). This reduced the cross-sectional area of the estuary with c. 20% from 19 500 m^2 to 15 700 m^2 and caused a 25% increase in maximum current velocities (Rijkswaterstaat, 1970a, 1970c). After completion of the dike, the enclosed area was pumped dry and a series of 17 sluices, each 56.5 m wide and taking up 1 km in total, was built. The ring-dike caused changes in the current patterns and a 22 m-deep scour pit formed at the NE side of it. This pit established a connection between the flood channel Slijkgat and the ebb channel Rak van Scheelhoek (Rijkswaterstaat, 1964). The scouring of the channels increased the cross-sectional area to 17 700 m^2 (Rijkswaterstaat, 1970a).

A second ring-dike for the construction of shipping locks (that would connect the estuary to the North Sea after completion of the dam) was built at the NW tip of the shoal Plaat van Scheelhoek in

1959 (Fig. 10). Subsequently, the southern shore of the estuary was reconstructed: a new harbour was excavated in Plaat van Scheelhoek to replace the fishing harbours of Goedereede and Stellendam that would lose their connection to the North Sea (Rijkswaterstaat, 1961), the silted channel Zuiderdiep was closed off in October 1965, a drainage channel for NW Goeree was dug and the dunes in NW Goeree were reinforced.

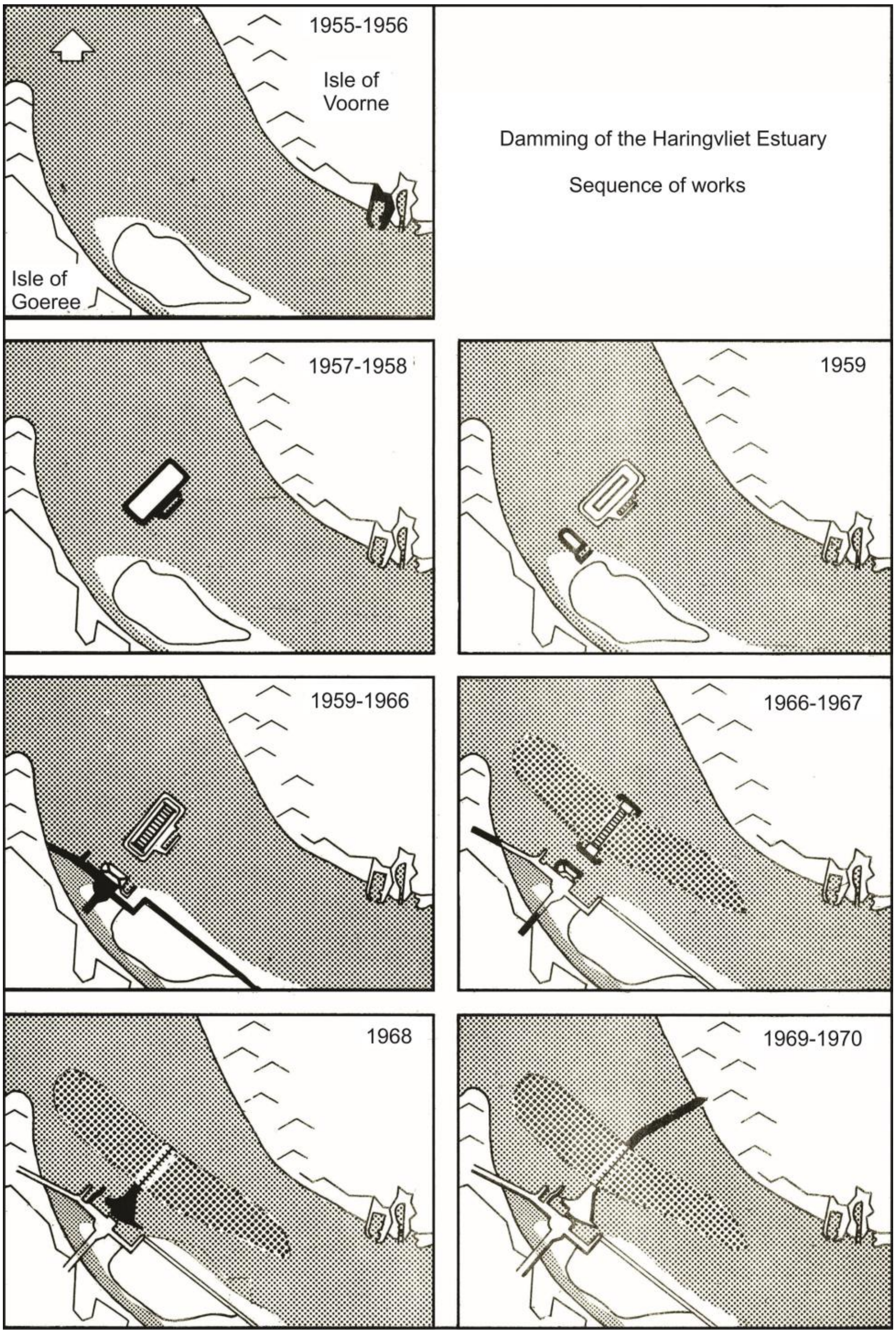

Fig. 10. The sequence of interventions in the mouth of the Haringvliet estuary over the period 1955-1970 leading to its complete damming. This sequence includes building of the ring-dike for the construction pit of the discharge sluices in 1957, reconstruction of the Goeree shore between 1959 and 1966, removal of the ring-dike and dredging of the discharge channels from 1966 to 1968, closure of the Noord-Pampus channel in 1968 and, finally, blocking of the Rak van Scheelhoek channel in 1970. (Source: Rijkswaterstaat).

After completion of the discharge sluices, the floor of the construction pit was lowered to MSL -15 m and from June 1967 on the ring-dike was levelled. At the first of October 1968 this dike was completely removed and the sluices were opened (see Fig. 10). This increased the cross-sectional area of the estuary to 21 300 m^2 (Rijkswaterstaat, 1970a) which is actually larger than at the start of the construction. This was due to the fact that the sills of the sluices were lower than the top of the original shoal and the scouring of the channels on both sides of the pit (Rijkswaterstaat, 1972). The increase in cross-sectional area caused a decrease in the current velocities in the channels Noord-Pampus and Rak van Scheelhoek. This allowed for construction of a sand dam blocking Noord-Pampus that was completed in early November 1968 (Rijkswaterstaat, 1969). At the same time channels were dredged both landward and seaward of the sluices; since the sluices were built on top of a shoal the discharge should not be obstructed by remaining shallow parts after complete damming of the estuary. In this stage, about 35% of the maximum ebb- and flood discharges was passing through the sluices. With the gradual horizontal infilling of the last tidal channel Rak van Scheelhoek with 93,000 concrete blocks each measuring 1 m^3 that were dumped in the channel using a funicular railway (Zuiderwijk, 1971), the discharge through the sluices increased. Finally, in April 1970 the channel was completely blocked and the sluices were conveying the tidal currents (Rijkswaterstaat, 1972).

The discharge regulation by the sluices started at November 2, 1970. In total, a volume of 40 million m^3 of sediment had been moved to reconstruct the Haringvliet inlet (Zuiderwijk, 1971).

3.3 Damming the Grevelingen estuary

In 1965 the first sections of the closure dam Brouwersdam of the Grevelingen estuary across the shoals Middelplaat and Kabbelaarsbank were finished (see Fig. 11 for locations). They blocked the smaller tidal channels in the inlet. This caused scouring of the remaining main channels Brouwershavense Gat in the south and Springersdiep/Kous in the north of the inlet because of the reduction in total cross-section. More or less concurrently, the Grevelingendam (Fig. 1 [B]) at the eastern end of the estuary (that disconnected Grevelingen and Eastern Scheldt) was finished, which reduced the tidal prism with c. 14% (Haring, 1978). Consequently, the ebb-tidal delta started to adjust. In 1971 the large channels were dammed completely, separating Grevelingen from its ebb-tidal delta and changing the tidal basin into a saltwater lake.

3.4 Impacts of large-scale engineering on the Haringvliet ebb-tidal delta

3.4.1 Impact during construction of Haringvliet dam (1957 - 1970)

Before the construction of the ring-dike in 1957, the Zeegat van Goeree at its narrowest point consisted of two north-west running channels, Rak van Scheelhoek in the north and Noord-Pampus in the south (Fig. 6). Going seawards, Noord-Pampus continued as Slijkgat channel, branching off to the west and hugging the coastline of Goeree. Rak van Scheelhoek split into two distributaries, Bokkegat and Gat van de Hawk. The Gat van de Hawk was running north, bounded in the east by the Westplaat, part of the Brielse Maas ebb-tidal delta, and in the west by the Zeehondenplaat ('Seal shoal'), which separated the channel from the Bokkegat. The Bokkegat was running to the west, its seaward part was flood-dominated, whereas the channel was ebb-dominated near Rak van

Scheelhoek. The shallow shoal between Bokkegat and Slijkgat was named Garnalenplaat ('Shrimp shoal').

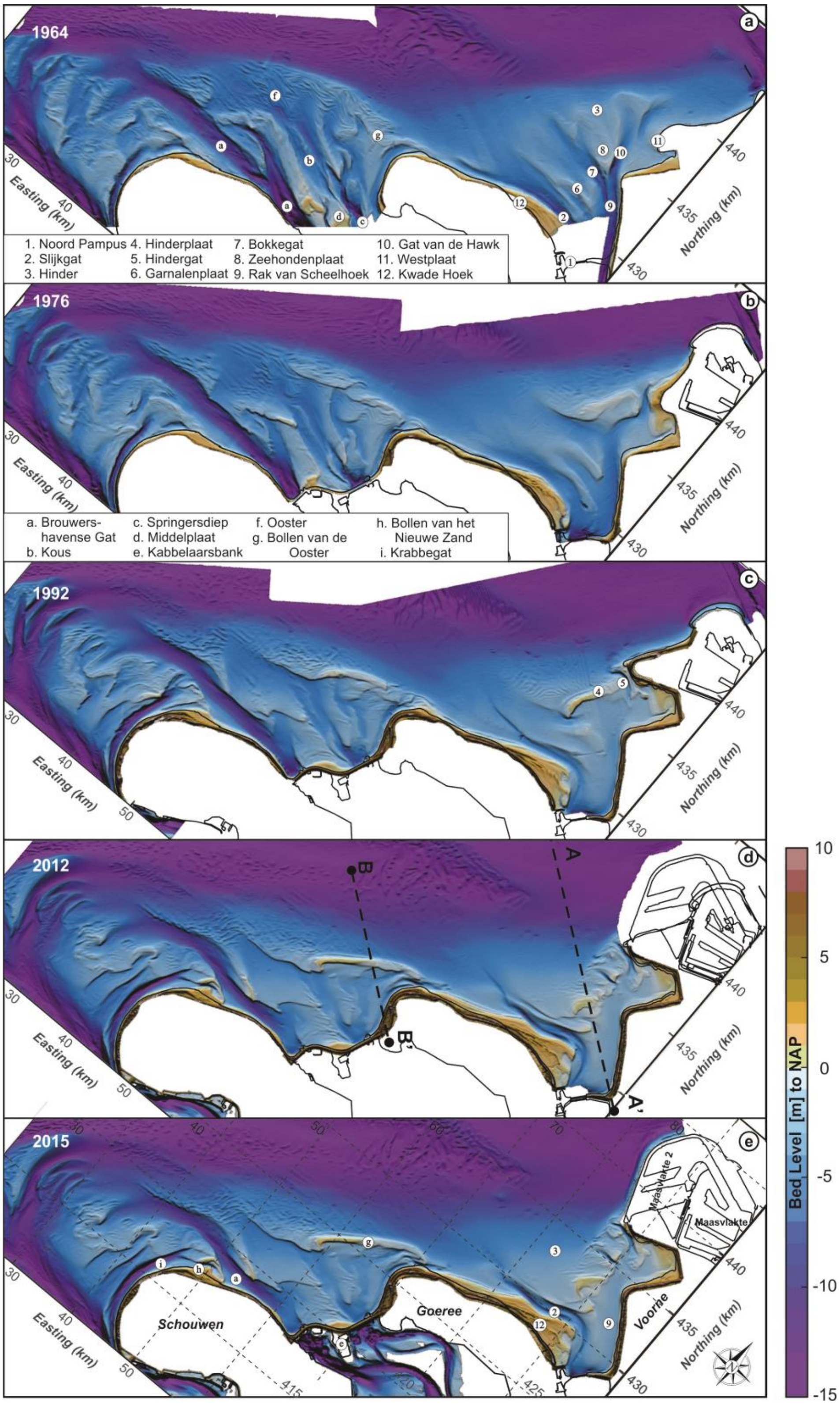

Fig. 11. Bathymetry and topography of the Haringvliet and Grevelingen ebb-tidal deltas before (1964) and after the damming of the estuaries (1976-2015). See text for details on the changes over time. The position of the cross-sections of Fig. 12 are indicated in the 2012 map.

The construction of the coffer-dams on the bed of the Haringvliet estuary from 1956 on and the subsequent reconstruction of the southern bank had reduced the width of the estuary with over 50% by the early 1960s. This caused significant morphological changes in the mouth (Rijkswaterstaat, 1970d). The ring-dike in the central part of the estuary entrance induced changes in the channel pattern. Slijkgat gradually lost its connection with Noord-Pampus and made contact with Rak van Scheelhoek north of the construction pit. Bokkegat migrated northward and became an ebb-dominated channel. The bifurcation of Rak van Scheelhoek into Gat van de Hawk and Bokkegat had migrated seaward since 1957. The rate of migration increased between 1965 and 1968 and came to a halt in 1969. Simultaneously, both channels rotated into a shore-parallel orientation (Figs. 6, 11). Moreover, the orientation of the shoals in the ebb-tidal delta had changed, the shore-normal Zeehondenplaat had turned into the shore-parallel Hinderplaat. Garnalenplaat migrated seaward together with the channel Bokkegat and a new ebb-channel started to form between Garnalenplaat and the connection between Slijkgat and Rak van Scheelhoek (Fig. 6). The average depth in the mouth landward of the -10 m contour decreased with 0.5 m between 1956 and 1969 which implies deposition of 80 million m^3 of sediment (Rijkswaterstaat, 1970d). During the gradual closure of Rak van Scheelhoek, already several m's of mud settled in the channel on both sides of the growing dam (Rijkswaterstaat, 1970a).

3.4.2 Changes after completion 1970 - 1986

Figure 11 illustrates the large-scale morphological changes of the northern part of the Voordelta over the period 1964-2015, which include the response to damming of the estuaries. The effect of damming is a large reduction of the tidal volumes of the inlets that results in a sharp 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 (Fig. 12; 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 adaptations in the ebb-tidal delta morphology and net transport of sediment to the neighbouring, downstream delta. The ebb-tidal deltas of both Haringvliet and Grevelingen show large-scale erosion of their seaward parts and sedimentation in the landward parts (Figs. 11, 12). These developments are in line with the aforementioned changes in the mouth of the Brielse Maas estuary following its damming (as described in 3.1). The almost annually surveyed changes in the bathymetry of these ebb-tidal deltas facilitate a detailed analysis of the closure-related morphodynamics.

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. The elongated, spit-shaped Hinderplaat temporarily created a fairly stable state and sheltered the back-barrier area. The decrease in current velocities caused siltation in the channels, with exception of Gat van de Hawk. The south-north running North Sea tide had started to dominate the current pattern in the seaward part of the mouth after the closure. This increased the discharge of Gat van de Hawk during part of the tidal cycle and caused this channel to scour (Rijkswaterstaat, 1973). The other channels filled in with predominantly mud. Piekhaar and Kort (1983) report a thickness of up to 4.8 m of mud (with less than 10% sand) in Rak van Scheelhoek. The ebb-tidal delta shrunk in surface area and since the elevation of the shoals diminished and the channels filled in, the average depth of the ebb-tidal delta decreased. Figure 13 shows the sedimentation-erosion pattern of the area over the period 1968-2015.

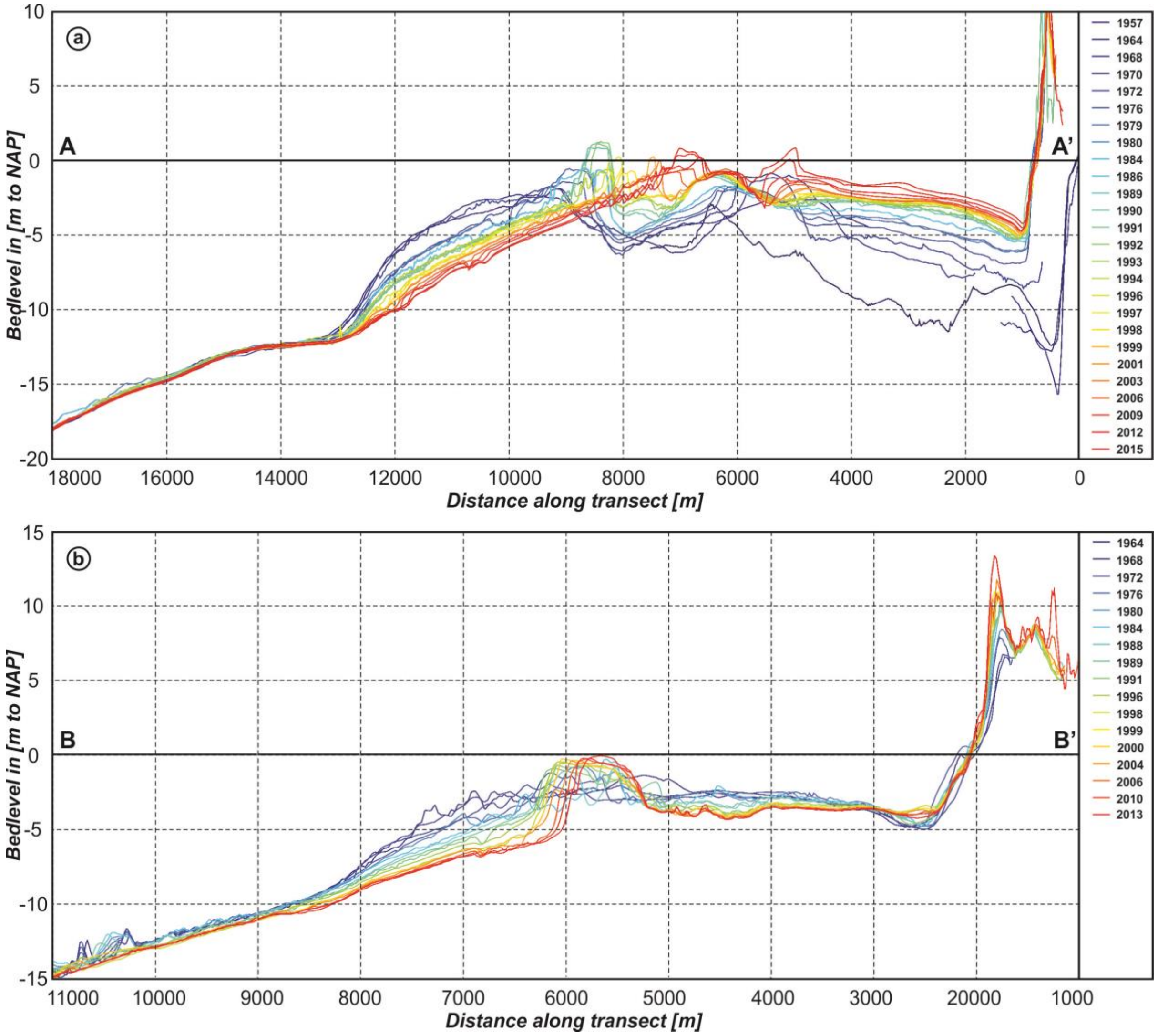

Fig. 12. Development of representative profiles of the ebb-tidal deltas of Haringvliet (AA') and Grevelingen (BB') showing the consequences of the damming of the estuaries. The shoreface of the ebb-tidal deltas is eroded from NAP -10 to -12 m upwards and (part of) the sand is pushed up in a sand bar in the edge of the delta. The profile of Haringvliet shows the large-scale infilling of the former tidal channel rak van Scheelhoek. See Fig. 11 for location of the profiles.

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. 11 [12]).

The only remaining tidal channel in Haringvliet ebb-tidal delta is Slijkgat (Fig. 11), the main discharge channel of the sluices and the fairway to the fishing harbour of Stellendam, which has to be dredged regularly to maintain its minimum depth of NAP-4 m.

The beaches and dunes on the tip of the island Voorne proved vulnerable to erosion and have been nourished and reinforced on a regular basis. Between 1970 and 1986 a total volume of 6.6 million m^3 of sand was added, mainly to strengthen the dunes.

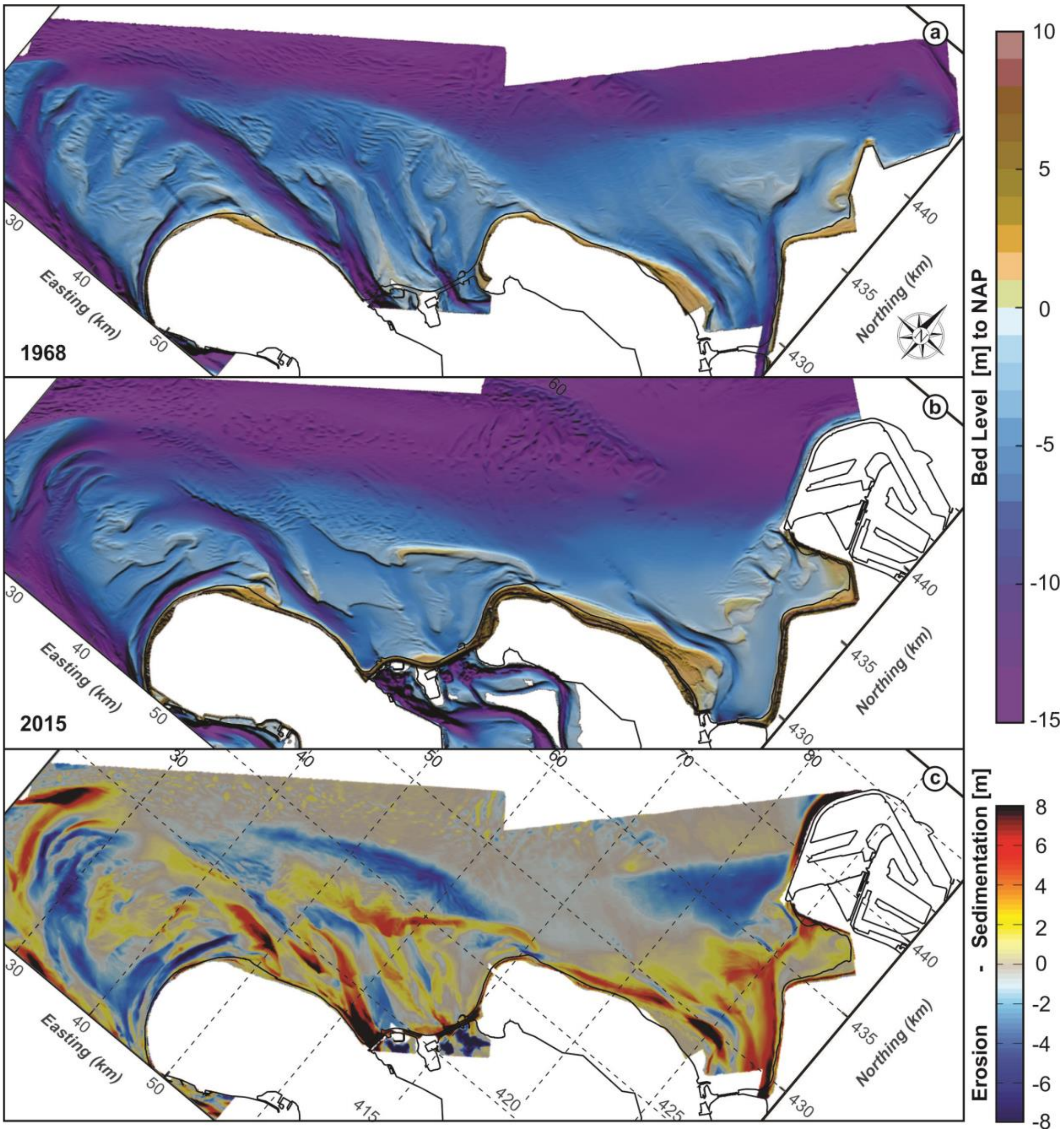

Fig. 13. The bathymetry of the Voordelta for the representative years 1968 (a) and 2015 (b). The morphological changes over this interval are shown by the sedimentation-erosion patterns in panel (c).

3.4.3 Changes since 1986

3.4.3.1. Engineering continued

Between 1986 and 1987 the Slufter, a storage basin for contaminated sediments dredged in the port of Rotterdam, was built as an extension to the Maasvlakte reclamation. It covered the northern part of Hinderplaat (Figs. 9, 11). The existing channel Gat van de Hawk disappeared in this operation and a new channel, Hindergat, was dredged through Hinderplaat further south. The NNE-SSW trending sand dam of the Slufter was maintained with sand nourishments, both on the beach and shoreface. Between 1991 and 2005 nearly 12 million m^3 of sand was added to this dam. Moreover, the dunes at the tip of Voorne were strengthened with 3 million m^3 of sand in 1987 and from 1991 on, the coastlines of Voorne and Goeree were evaluated yearly and, if necessary, nourished with sand as part of the *Dynamic Maintenance* policy (see Hillen and De Haan, 1995, and Hillen and Roelse, 1995).

In the first decade of the 21st century, new large-scale engineering projects were started in the Haringvliet mouth area. The Flaauwe Werk on the northern shore of Goeree and the dunes at the western tip of the island of Voorne were adjusted to the new safety standard for sea defences, the so-called *Weak Links* programme (see Ten Brinke and Bannink, 2004, for background). The sea dike Flaauwe Werk was raised and widened in 2008, and the dunes and beach on the tip of Voorne were, respectively, widened and nourished in 2009-2010. Moreover, in 2008 started the construction of Maasvlakte 2, a seaward extension of Maasvlakte that was built mainly with sand. After completion of the sandy sea defences in early 2012, this newly reclaimed part of the port of Rotterdam protruded further west than the ebb-tidal delta ever had (Figs. 9, 11), further sheltering the Haringvliet mouth from waves coming from the north and northwest.

Slijkgat, the discharge channel in the southern part of the mouth, had been dredged since 1970. A 200 m-wide channel had been maintained at a depth of NAP-4 m to keep the harbour of Stellendam accessible. In 2000 the dredging scheme was adapted to a fairway of 100 m wide and NAP-5 m deep. In 2005 the depth was further increased with 0.5 m (data from De Winter, 2014; p.81-82).

3.4.3.2. Morphological changes since 1986

The erosion of the delta front continued, reducing the extent of the ebb-tidal delta, while the remaining area behind Hinderplaat silted up. The tidal channels continued to fill in. Recent analyses of the mud deposits in Rak van Scheelhoek indicate thicknesses of up to 7.5 m (Van Heteren, 2002). The entire ebb-tidal delta was pushed landward due to wave action. As the Hinderplaat increased in height and length, it decreased in width. Around 1996 this resulted in breaching of the bar and a more dynamic system with (multiple) small inlets was formed (compare Fig. 11, 1992 and 2015). In the present-day situation, Hinderplaat is no longer a distinct bar but has spread out to the east, forming an area of small tidal channels and intertidal shoals (Fig. 14A).

De Winter (2014) describes the growth of the intertidal shoal areas and the coalescence of the shoals into a ‘supershoal’ since 2001. The surface area of the shoals above NAP-2.2 m increased from 6 km^2 in 2001 to 16 km^2 in 2012. The average height of the shoals fluctuates since 1967 between NAP+0.7 m and NAP+0.9 m (local MHW level is NAP+1.24 m). The sedimentation rate in the shoals has increased since 2009. More or less simultaneously with the growth of the ‘supershoal’, a new channel cutting across Hinderplaat developed c. 2 km south of Hindergat (see Fig. 11).

Fig. 14. Arial photographs showing typical phenomena in the ebb-tidal deltas of Haringvliet and Grevelingen. A: small-scale channel and shoals in the Haringvliet tidal delta (Nov 2005). B: dunes formed on the Brouwersdam by eaolian transport of beach sand (March 2008). C: Kwade Hoek at Goeree with Haringvliet sluices in the background (July 1987). D: Recurved spits and flying spits along the western shore of Maasvlakte 2 (July 2013). (Source: https://beeldbank.rws.nl, Rijkswaterstaat / Joop van Houdt)

Since 1986 Bokkegat channel has been squeezed between the south- and landward extending Hinderplaat and the seaward expanding Garnalenplaat (Fig. 11). Simultaneously, a new channel developed through Garnalenplaat, north of and parallel to Slijkgat. The latter became the flood channel filling the area between the growing shoals and the coast of Voorne. After 2001, Bokkegat filled in and disappeared. In 2015, the new channel had been reduced in cross-section.

Reintjes (2002) analysed the spit formation at Kwade Hoek, at the north-eastern tip of Goeree. She identified the formation of 3 successive generations of spits, where the growth of a new spit seaward of an existing one would render the latter inactive due to shielding of wave action and sediment supply. As a result of this, spit formation shifted from east to west with time. Moreover, the southward migration of Slijkgat blocked further extension of the spits or eroded them. This created a fan-like spit complex (Fig. 11: 1992-2015; Fig. 14C). A similar development had been observed earlier on at the northern shore of Voorne (Fig. 7). Moreover, Reintjes established rapid accretion in the area between the most western spit and Flaauwe Werk since the mid-1990s. The growth of this area seems to be coupled to erosion at the eastern tip of Goeree. Transport of sand in Slijkgat channel to the west during high discharges through the sluices, could explain this. Once this area started to grow, it would at least partly block the longshore transport from the west, leading to further growth of this area. Besides that, the overall shallowing of the seaward edge of the ebb-tidal delta could have added to this.

3.5 Impacts of damming on the Grevelingen ebb-tidal delta

With the completion of the Brouwersdam, the tidal flow in the ebb-tidal delta was strongly reduced and, consequently, waves started to erode the ebb-tidal delta shoreface down to MSL -10 m, bulldozing the sand upwards into a longshore bar called Bollen van de Ooster (Van der Spek, 1987; Kohsiek, 1988; see Fig. 12), a development very similar to the observed formation of Hinderplaat in the Haringvliet ebb-tidal delta. Part of the eroded sand will have been transported to the northeast, feeding the coast of the island of Goeree and the extending the recurved spits at Kwade Hoek (Fig. 11). The ebb-tidal delta reduced in surface area, the former shoals were eroded by waves and the channels filled in. Over the years, the sand bar Bollen van de Ooster increased in height and grew in longshore direction. Waves also eroded Middelplaat shoal directly seawards the dam (Fig. 11) and transported the sand towards it, forming a wide beach. Aeolian transport of the beach sand resulted in formation of a dune row on top of the seaward side of the dam (Fig. 14B). At the southern end of the ebb delta, Krabbengat channel built its terminal lobe/shoal Bollen van het Nieuwe Zand into Brouwershavense Gat channel (Fig. 11, 1992-2015) as a result of its increased tidal flow and the decline in current velocities in the latter channel (Vermaas et al., 2015; Elias et al., 2017).

3.6. Sediment budget 1964-2010

Elias et al. (2017) reconstructed and analysed the volume changes of the ebb-tidal deltas in detail, see Fig. 15. Prior to the closure of Rak van Scheelhoek in 1970, that completed the damming of the Haringvliet, the volume of the ebb-tidal delta increased with over 20 million cubic meters (*mcm*). The volume remained constant until 1976 after which it increased rapidly to 57 *mcm* in 1980. Since then the volume has gradually decreased until the pre-1976 volume of 20 *mcm* was reached again in 1999. The sequence of interventions in this area will have caused variations in the volume development over time. For instance, the temporary volume increase between 1989 and 1994 can be linked to the construction of the Slufter (see 3.4.3). Despite the large changes, the net volume change over the period 1968-2010 is small; sediments are mainly redistributed from the offshore landward (Figs. 13, 15). The volume reduction is small since the eroded sediments cannot be transported into the estuary because of the dam. Note that the effect of the construction of Maasvlakte 2 is not (yet) included in this interval. Beach and shoreface nourishments have added an extra 24 *mcm* of sediment to the system, in particular since 1980.

The Grevelingen ebb-delta showed more gradual changes in volume (Fig. 15). After the closure of the Brouwershavense Gat in 1971 the volume of the ebb-tidal delta started to grow. A maximum volume of 37 *mcm* was reached in 1989, whereupon it started to decrease. By 2006, 30 *mcm* of sediment had been eroded (Fig. 15). Part of the eroded volume will have been transported to the northeast, along the coast of Goeree and finally to Kwade Hoek in the Haringvliet delta. In a similar manner sand transport by Krabbengat channel and wave-driven transport along the coast of Schouwen are adding sediment to the southern part of the Grevelingen ebb-tidal delta. Since 1966 an extra 10.4 *mcm* of sand was added to this area, for the greater part before 1980 by nourishing the western tip of the island of Goeree where small tidal channels between coastline and the shoal complex Bollen van de Ooster caused erosion of the island.

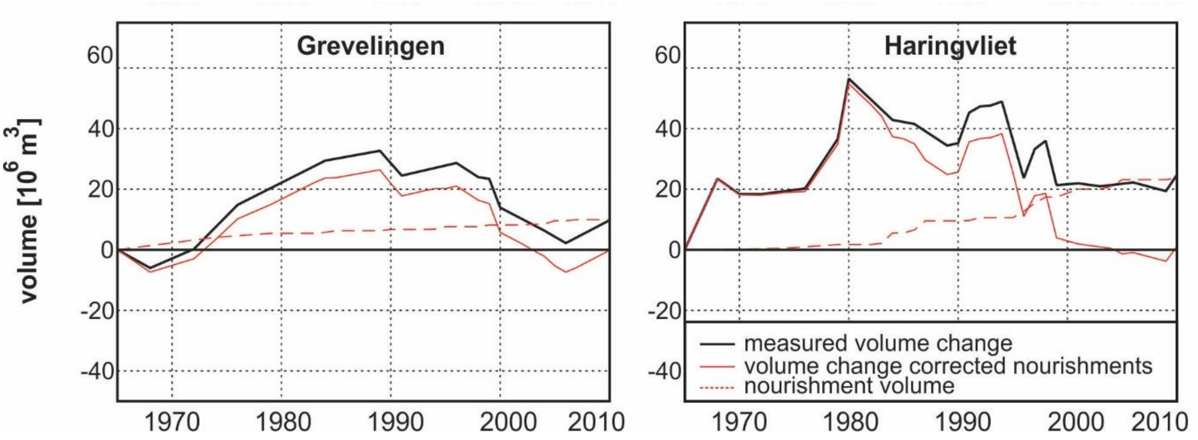

Fig. 15. Cumulative volume changes of the ebb-tidal deltas of Grevelingen and Haringvliet between 1964 and 2010. The red lines represent cumulative nourishment volumes (excluding dune nourishments). From Elias et al. (2017).

4. Summary and conceptual model of the morphologic adaptation of ebb-tidal deltas

4.1 General model for ebb-tidal delta evolution after a significant reduction in cross-shore flow

Damming of the estuaries Brielse Maas and Haringvliet and extensive land reclamation in its northern part, have resulted in large-scale morphodynamic changes in the Haringvliet ebb-tidal delta that continue until today. The same holds for the Grevelingen ebb-tidal delta after damming of this estuary. The wave-driven erosion of the ebb-tidal delta margin resulting in landward retreat and building of shore-parallel bars is the most conspicuous change.

Complete damming of the Brielse Maas and Haringvliet estuaries resulted in strong shoreface erosion and landward sediment transport. Wave action pushed the ebb-delta margin landward and built sand bars while the closed-off channels filled in with sand and mud. This is explained by the reduction of the tidal prism that causes a decrease in sand supply by the ebb current and concurrently relatively increases the impact of wave-driven landward sand transport. Since the closure dams block transport of sediment into the estuaries, the volumes of the ebb-tidal deltas did not decrease with the amount that could be expected from the Walton and Adams (1976) relationship. However, lateral transport of sediment to downdrift parts of the coast, both by the predominat waves from the SW and the shore-parallel tidal flow, will diminish the volume of the eroding ebb delta but at a slower pace. This is illustrated by the transport of sand along the island coast of Goeree that is eroded from the delta front of Grevelingen ebb delta.

The well-monitored changes in the mouth of Haringvliet provide detailed insight into the consequences for an ebb-tidal delta caused by damming of its estuary. In the adaptation of the ebb-tidal deltas to the new conditions caused by damming we observe subsequent stages of development. In each stage the ebb-tidal delta is further reduced in size.

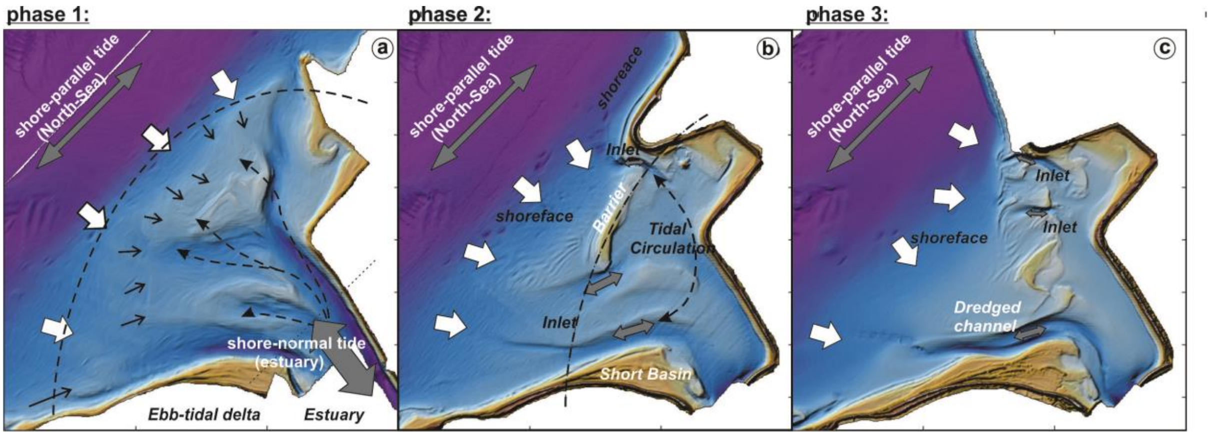

Figure 16; General model for ebb-tidal delta evolution after a significant reduction in cross-shore flow, based on the evolution of the Haringvliet ebb-tidal delta between 1964 and 2015.

Phase 1: Dynamic equilibrium (Fig. 16, left-hand panel)

The North Sea tide (that travels from southwest to northeast along the coast) fills and drains the estuary, what results in strong shore-normal tidal flows. During ebb, sediments are transported from the estuary mouth seaward and deposited where current velocities decrease beyond the sediment transport threshold. Hence, relatively shallow shoals are formed. Waves breaking on these shoals generate a landward sediment transport. The characteristic interaction of offshore and inlet tides in the SW Netherlands results in a radial channel pattern and hence, more or less symmetrical ebb-tidal deltas (see Sha and Van den Berg, 1993, for details). The decrease in tidal range in a northerly direction along the coast causes the main tidal channels to form on the SW side of the deltas. Prior to large-scale human intervention, a dynamic equilibrium must have existed that shaped the individual ebb deltas. Dynamic equilibrium implies that the morphology of the area is in balance with the forming physical processes. These processes included, e.g., channel migration (e.g. by outer bank erosion in meanders) which in cases resulted in channel abandonment and infilling. With a reduction in sand supply by tidal currents, wave action will remodel this part of the ebb delta, often transporting the sand away. Moreover, larger-scale changes, such as gradual changes in tidal prism over time, will have affected the deltas too. However, it is clear that the observed changes since 1965 are dominated by the effects of the damming of the estuaries.

Phase 2: Distorted state (Fig. 16, middle panel)

Complete damming of the Brielse Maas and Haringvliet estuaries resulted in a regime shift, from a mixed-energy to a wave-dominated state. A decrease in tidal prism causes in a decrease in ebb currents and sediment supply and therefore the (unmodified) wave climate moves sand onshore and/or alongshore. This results in strong erosion of the ebb-delta front and sediment deposition in the landward part of the ebb-tidal delta. This abundant supply of sediment builds a long and narrow, predominantly intertidal, coast-parallel sand bar. The bar shelters the landward part of the ebb-tidal delta from open sea conditions. Only the channels in the southern part and a small short-cut channel in the north exchange flow between these two areas. This sand bar can be considered to act as a coastal barrier, with small tidal inlets to the north and south. The basin is formed by the former ebb-delta channels that provide storage area and, in combination with throughflow between the two inlets, a secondary circulation develops. The shoals in between the channels are losing height since they are no longer maintained by tidal currents. The system has evolved from an ebb-tidal delta into a small-scale tidal inlet-basin system.

Phase 3: Breaching and formation of a coastal plain (Fig. 16, right-hand panel)

The newly developed tidal basin has a much smaller tidal prism and shore-normal flows are much weaker than prior to damming. A (dynamic) equilibrium between tidal- and wave-driven sediment transports is therefore not reached and the delta front and bar/barrier continue to erode. The sheltered back-barrier with still relatively deep channels provides accommodation space which promotes deposition of both sand and mud and fills in rapidly, reducing the tidal circulation. In the Haringvliet ebb delta the low, narrow barrier was finally breached, forming multiple, smaller-scale inlets. Such inlets can only be sustained by sufficient tidal flow to keep them open. In this case their individual tidal prisms are very limited. Therefore these inlets are likely to be closed by wave action and re-form due to new breaches during storm events. With each step the new basin is reduced in size. It is expected that this process will continue until eventually the reworked ebb-delta deposits, and possibly an additional influx of sediments from neighbouring areas, fill the basin completely, merging it with the coast and thereby extending the coastal plain.

4.2 Discussion of morphological changes

The collapse of the ebb-tidal deltas due to decreasing tidal prisms is in accordance with the relationship between these two variables that is described by Walton and Adams (1976), although the volume of the ebb-tidal deltas did not decrease significantly since the eroded sand could not be transported into the estuary because of the dam. However, sediment transport to downdrift neighbouring shorelines and ebb-tidal deltas slowly diminished these volumes. Compaction of the thick mud layers that have been deposited in the cut-off tidal channels, possibly contributed to the gradual loss of sediment volume in the ebb-tidal deltas.

Despite an abundant supply of sediment from the ebb-delta front and the presence of a large barrier, the sheltered coastline of Voorne is still subject to erosion. The tidal exchange in the new basin is too limited to sustain the former channel-and-shoal topography which results in gradual levelling of the relief. Moreover, the local wave climate behind this barrier is too weak to build up the beaches again. As a result, sediment is eroded from these shoals and also the adjacent beaches and deposited in the remaining channels. This sediment deficit is expected to persist until the basin is fully filled (or the barrier merges with the coastline). The rapid infilling of the remaining Haringvliet basin is partly due to mud deposition that is enhanced by the outflow of freshwater and suspended mud through the sluices. As a result, the remaining main ebb channel can only be maintained by dredging. The most southern part of the ebb-tidal delta is dominated by the progradation of the shore of Goeree island that is fed both by the erosion of the Grevelingen outer delta and nourishments in this area (see e.g. Reintjes, 2002). It goes without doubt that the successive reclamation of Maasvlakte, Slufter and Maasvlakte 2 in the northern part of the Haringvliet ebb-tidal delta has influenced the development of this area. This step-by-step seaward extension of the shoreline of the island of Rozenburg will have increasingly sheltered the part of the ebb-tidal delta directly south of it from waves from the northwest (Tönis et al., 2002). Moreover, the sand eroded from the shoreline of the reclamations and transported south by waves, will have contributed considerably to the infilling of this part of the area. Reintjes (2002; p. 46) suggested that the growth of a spit in front of Hindergat, fed by southward sand transport along the Slufterdam from 1991 on, gradually blocked the inflow of tidal currents. The inflow was probably taken over by the small channels across Hinderplaat. De Winter (2014) suggests that the increased sedimentation rate between 2009 and 2012 is related to the construction of Maasvlakte 2 during this interval. The occurrence of typical wave-formed phenomena such as flying spits along the NNW-SSE trending SW shore of Maasvlakte 2 (Fig. 14D) and recurved spits at its southern end suggests continued large-scale wave-driven sand transport to the south.

At the Grevelingen ebb-tidal delta, the bar/barrier is currently still present and even growing in longshore direction, which is characteristic for the distorted state (Phase 2) of the above described general model. The slower adaptation time scale of this system may be explained by the difference in size, and the absence of large-scale interventions (such as the building of Maasvlakte and Maasvlakte 2) that must have influenced Haringvliet. Especially the sheltering effect of these land reclamations is missing in the Grevelingen ebb-tidal delta. Moreover, the infilling of the area landward of the barrier is much slower since large-scale supply of suspended mud by discharged river water and large-scale wave-driven sand transport along the shores of the bounding islands are lacking here. Also, tidal flow in south-north direction is sustained in the Grevelingen ebb-tidal delta, which delays (or even precludes) the breaching of the shore-parallel bar.

5. Concluding remarks

Damming of the estuaries Brielse Maas, Haringvliet and Grevelingen and large-scale harbour construction and land reclamation 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 1964 to 2010 are small; an annual increase of 0.1 to 0.2 *mcm* in the Haringvliet and Grevelingen ebb-tidal deltas. The strong reduction in tidal volume resulted in a decrease in surface area of the ebb-tidal deltas but not in the total volume. Since transport into the estuaries is blocked by the dams, sediment can only be transported laterally, to adjacent tidal deltas.

The morphodynamic changes observed are related to the scale of the intervention. Complete damming of estuaries results in a regime shift, from a balance of tidal and wave-energy to wave-dominated conditions. At all inlets, a long but narrow, coast-parallel, sub- to intertidal sand bar developed as sand was reworked by waves on the former ebb-delta margin and pushed landward. This bar temporarily sheltered the area behind it and thereby enhanced sedimentation. Destruction of the barrier at the Haringvliet delta by breaching led to the development of several small, highly dynamic inlets. It is expected that frequent formation and closure of these small inlets will continue until eventually the basin is completely filled, after which the area can merge with the coast and extend the coastal plain. The changes in the Grevelingen ebb-tidal delta haven’t reached this state yet. This is probably due to the more exposed position of the Grevelingen ebb-tidal delta and a much smaller supply of both sand and fine-grained sediment.

Summary in a conceptual model of the observed adaptations of the ebb-tidal deltas to restriction or even blocking of the tidal flow in the associated estuary or tidal inlet, might help to assess the impact of such an intervention in other systems. However, it is the local balance of wave climate and tidal currents, and the changes therein, that will finally determine the morphodynamic changes and the rate at which they will occur.

Acknowledgements

This work was supported by the *KPP Beheer en Onderhoud Kust* research programme (project numbers 1206171; 1207724; 1209381; 1220040 and 1230043). This programme includes in-depth data analysis to understand the evolution of the Dutch coast as a basis for effective coastal management in the Netherlands and is executed by both Rijkswaterstaat and Deltares. Many thanks to Marian Lazar and Quirijn Lodder (Rijkswaterstaat Traffic- and Watermanagement) for the pleasant co-operation and permission to publish these results.

References

Davis, R.A., Hayes, M.O., 1984. What is a wave-dominated coast? Marine Geology 60, 313-329.

De Bruijn, M., 1949. De afdamming van de Brielsche Maas. De Ingenieur 61 (36), Bouw- en Waterbouwkunde 10, B113-B126.

De Winter, W., 2014. Morphological development of the Haringvliet ebb tidal delta since 1970. A study based on the morphological development of individual morphological units. MSc report, Utrecht University, Faculty of Geosciences.

Elias, E.P.L., Van der Spek, A.J.F., Lazar, M., 2017. The 'Voordelta', the contiguous ebb-tidal deltas in the SW Netherlands; Large-scale morphological changes and sediment budget 1965-2013; Impacts of large-scale engineering. Netherlands Journal of Geosciences 96 (3), 233-259. On-line version (2016): https://doi.org/10.1017/njg.2016.37.

Erkens, G., Cohen, K.M., 2009. Quantification of intra-Holocene sedimentation in the Rhine-Meuse delta: A record of variable sediment delivery. In: Erkens, G., Sediment Dynamics in the Rhine Catchment. Quantification of Fluvial Reponse to Climate Change and Human Impact. PhD thesis Utrecht University, pp. 117-171. https://dspace.library.uu.nl/handle/1874/36680

Haring, J., 1955. Zandbalansen van de zuidwestelijke wateren van Nederland over de perioden 1872-1933 en 1933-1952. Report nr. 3, Rijkswaterstaat, Benedenrivieren Directorate, Study Department, The Hague.

Haring, J., 1978. De geschiedenis van de ontwikkeling van de waterbeweging en van het profiel van de getijwateren en zeegaten van het zuidelijk deltabekken en van het hierbij aansluitende gebied voor de kust gedurende de perioden 1872-1933-1952-1968-1974. Report K77M031E, Rijkswaterstaat, Deltadienst, The Hague.

Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Cronin, L.E. (Ed.), Estuarine Research, Vol. 2. Academic Press, New York, pp. 3-22.

Hayes, M.O., 1979. Barrier Island morphology as a function of tidal and wave regime. In: Leatherman, S.P. (Ed.), Barrier Islands: From the Gulf of St Lawerence to the Gulf of Mexico. Academic Press, New York, pp. 1-27.

Hillen, R., De Haan, Tj., 1995. Development and implementation of the coastal defence policy for the Netherlands. In: Hillen, R., Verhagen, H.J. (Eds.), Coastlines of the Southern North Sea. ASCE, New York, pp. 188-201.

Hillen, R., Roelse, P., 1995. Dynamic preservation of the coastline in the Netherlands. Journal of Coastal Conservation 1, 17-28.

Hofland, T.H., 1986a. De historisch-geografische informatie. In: Maarleveld, Th.J. (Ed.), Vooronderzoek Archeologie. Rapport van de werkgroep Archeologisch Onderzoek in het kader van de voorbereiding/uitvoering van de aanleg van de Grootschalige Locatie voor berging van baggerspecie uit het benedenrivierengebied. Gemeente Rotterdam, Rijkswaterstaat, Openbaar lichaam Rijnmond, pp. 29-61.

Hofland, T.H., 1986b. De bevaarbaarheid van de Maasmond sedert de 16e eeuw. Toegepast historisch-geografisch onderzoek onder de waterspiegel. Historisch Geografisch Tijdschrift 4 (3), 84-89.

Hoving, J., De Kraker, A., 2013. Cruquius' aanpak van het Goereese Gat. De casus van de verzanding van het Goereese Gat en de veiligheid van Goeree getoetst tijdens de achttiende eeuw. Tijdschrift voor Waterstaatsgeschiedenis 22 (1), 57-68. (web version 2016)

Hubbard, D.K., Oertel, G., Nummedal, D., 1979. The role of waves and tidal currents in the development of tidal-inlet sedimentary structures and sand body geometry: examples from North Carolina, South Carolina and Georgia. Journal of Sedimentary Petrology 49 (4), 1073-1092.

Kohsiek, L.H.M., 1988. Reworking of former ebb-tidal deltas into large longshore bars following the artificial closure of tidal inlets in the southwest of the Netherlands. In: De Boer, P.L., Van Gelder, A., Nio, S.D. (Eds.), Tide Influenced Sedimentary Environments and Facies. D. Reidel Publishing Cie, Dordrecht, pp. 113-122.

Meyer, H., 2017. The State of the Delta. Engineering, Urban Development and Nation Building in the Netherlands. Vantilt Publishers, Nijmegen.

Oertel, G.F., 1975. Ebb-tidal deltas of Georgia Estuaries. In: Cronin, L.E. (Ed.), Estuarine Research, Vol. 2. Academic Press, New York, pp. 267-276.

Oomkens, E., Terwindt, J.H.J., 1960. Inshore estuarine sediments in the Haringvliet (Netherlands). Geologie en Mijnbouw 39, 701-710.

Piekhaar, R.S., Kort, M.W., 1983. Haringvliet monding - Sedimentatieonderzoek 1970-1981. Report WWKZ-83.S001, Rijkswaterstaat Deltadienst, The Hague.

Pierik, H.J., Stouthamer, E., Cohen, K.M., 2017. Natural levee evolution in the Rhine-Meuse delta, the Netherlands, during the first millennium CE. Geomorphology 295, 215-234.

Reintjes, C.M., 2002. Morfologische ontwikkeling van de Kwade Hoek en het omringend kustgebied in de Haringvlietmond. Report NITG 02-069-C, Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, Utrecht.

Rijkswaterstaat, 1957. De afsluiting van het Haringvliet. Driemaandelijks Bericht Deltawerken 2, 37-43. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1961. De aanleg van de havens ten zuiden van de uitwateringssluis in het Haringvliet. Driemaandelijks Bericht Deltawerken 18, 12-14. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1962. De morfologische veranderingen in de mond van de Brielsche Maas sedert de afsluiting daarvan. Driemaandelijks Bericht Deltawerken 20, 25-33. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1964. De trog bij de bouwput voor de uitwateringssluizen in het Haringvliet. Driemaandelijks Bericht Deltawerken 28, 412-420. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1966. De erosiegevoeligheid van bepaalde grondsoorten in de zeegaten. Driemaandelijks Bericht Deltawerken 37, 369-372. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1969. Afsluiting van het Noord-Pampus (Haringvlietmond). Driemaandelijks Bericht Deltawerken 47, 372-376. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1970a. Loden en meten tijdens de afsluiting van het Rak van Scheelhoek. Driemaandelijks Bericht Deltawerken 53, 120-133. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1970b. Voorspel (van het Delta Plan). Driemaandelijks Bericht Deltawerken 54, 172-177. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1970c. Het ontwerp van de afdamming van het Haringvliet. Driemaandelijks Bericht Deltawerken 54, 179-181. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1970d. De gevolgen van de afsluiting van het Haringvliet voor het mondingsgebied en de aansluitende kust. Driemaandelijks Bericht Deltawerken 54, 203-211. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1972. De bodemveranderingen aan weerszijden van de Haringvlietsluizen. Driemaandelijks Bericht Deltawerken 60, 517-520. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1973. Veranderingen in de mond van het Haringvliet sedert de afsluiting. Driemaandelijks Bericht Deltawerken 63, 146-163. Rijkswaterstaat Deltadienst, The Hague.

Rijkswaterstaat, 1978. De oorsprongen van het Deltaplan. Driemaandelijks Bericht Deltawerken 83, 114-123.

Rijkswaterstaat, 2013. Kenmerkende Waarden Getijgebied 2011.0. Report Rijkswaterstaat Centrale InformatieVoorziening, Delft.

Rijkswaterstaat Deltadienst, 1970. De ontwikkeling in het mondingsgebied van het Haringvliet na de afsluiting. Report W-70.108, Rijkswaterstaat Deltadienst, Waterloopkundige Afdeling.

Rijkswaterstaat Deltadienst, 1979. The storm-surge barrier in the Eastern Scheldt. Geologie en Mijnbouw 58, 459-462.

Roskam, A.P., 1988. Golfklimaten voor de Nederlandse Kust. Report GWAO-88.046, Rijkswaterstaat, Tidal Waters Division, The Hague.

Sha, L.P., Van den Berg., J.H., 1993. Variation in ebb-tidal delta geometry along the coast of the Netherlands and the German Bight. Journal of Coastal Research 9, 730-746.

Stouthamer, E., Cohen, K.M., Hoek, W.Z., 2015. De Vorming van het Land. Geologie en Geomorfologie. Perspectief Publishers, Utrecht.

Ten Brinke, W.B.M., Bannink, B.A., 2004. Dutch dikes and risk hikes. A thematic policy evaluation of risks of flooding in the Netherlands. Report 5007799002, Rijksinsituut voor Volksgezondheid en Milieu RIVM, Bilthoven.

Terwindt, J.H.J., 1964. De veranderingen in de mond van het Brielse Gat als gevolg van de afdamming. Tijdschrift Koninklijk Nederlands Aardrijkskundig Genootschap 81, 329-334.

Terwindt, J.H.J., 1971. Litho-facies of inshore estuarine and tidal-inlet deposits. Geologie en Mijnbouw 50 (3), 515-526.

Terwindt, J.H.J., 1973. Sand movement in the in- and offshore tidal area of the SW part of the Netherlands. Geologie en Mijnbouw 52 (2), 69-77.

Terwindt, J.H.J., Breusers, H.N.C., Svasek, J.N., 1968. Experimental investigation on the erosion-sensitivity of a sand-clay lamination. Sedimentology 11, 105-114.

Tönis, I., Stam, J.M.T., Van de Graaff, J., 2002. Morphological changes of the Haringvliet estuary after closure in 1970. Coastal Egineering 44, 191-203.

Van de Kreeke, J., Haring, J., 1979. Equilibrium flow areas in the Rhine-Meuse delta. Coastal Engineering 3, 97-111.

Van den Berg, J.H., 1986. Aspects of Sediment- and Morphodynamics of Subtidal Deposits of the Eastern Scheldt (the Netherlands). PhD thesis, Utrecht University. Also published as: Rijkswaterstaat Communications No. 43. Rijkswaterstaat, The Hague.

Van den Berg, J.H., 1987. Toelichting bij de isallobatenkaart Voordelta 1975-1984. Report ZL 87.0020, Rijkswaterstaat, Deltadienst, Zierikzee.

Van den Burg, G., 1989. De Nieuwe Waterweg - Poort van Europa. De Bataafsche Leeuw, Amsterdam.

Van der Spek, A.J.F., 1987. Inventariserend morfologisch onderzoek Voordelta; Beschrijving van de ontwikkeling van de buitendelta’s van Haringvliet en Grevelingen. Report GWAO-87.105, Rijkswaterstaat, Tidal Waters Division, Middelburg.

Van Driel, W., 1959. Bodemveranderingen in de mond van het Haringvliet en het aangrenzende zeegebied in de periode 1821 t/m 1957. Report K-149, Rijkswaterstaat Deltadienst, Waterloopkundige Afdeling, The Hague.

Van Heteren, S., 2002. Analyse van slibdikte in de monding van het Haringvliet. Report NITG 02-200-B, Netherlands Insitute of Applied Geoscience TNO - *National Geological Survey.*

Vermaas, T., Elias, E., Van der Spek, A., 2015. Relocating Krabbengat channel; A tale of two developments. In: Wang, P., Rosati, J.D., Cheng, J. (Eds.), The Proceedings of the Coastal Sediments 2015, San Diego, CA, 11-14 May, 2015. CD-ROM.

Walton, T.L., Adams, W.D., 1976. Capacity of inlet outer bars to store sand. In: Coastal Engineering 1976, Proceedings of 15th Int. Conference on Coastal Engineering, Honolulu, Hawaii, July 11-17, 1976, pp. 1919-1937.

Watson, I., Finkl, C.W., 1990. State of the art in storm-surge protection: the Netherlands Delta project. Journal of Coastal Research 6 (3), 739-765.

Watson, I., Finkl, C.W., 1992. Simplified technical summary of the complete Delta Works, including the Eastern Scheldt. Journal of Coastal Research, Special Issue 10.

Wijnberg, K.M., 1995. Morphologic Behaviour of a Barred Coast over a Period of Decades. PhD thesis, University Utrecht.

Zuiderwijk, C.A., 1971. ‘Grootgrondverzet’ in het Haringvliet. In: De afsluiting van het Haringvliet. Weg en Waterbouw - Dokumentatiereeks Bouwen en Baggeren, Part 1, 44-50.