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Invited Research Article

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

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ABSTRACT

The damming of the estuaries Brielse Maas, Haringvliet and Grevelingen in the SW Netherlands, distributaries of the rivers Rhine and Meuse, caused large-scale morphodynamic changes in their respective ebb-tidal deltas that continue until today. The strong reduction of the cross-shore tidal flow triggered erosion of the ebb-delta front, the building of a coast-parallel, linear intertidal sand bar at the seaward edge of the delta platform, levelling of bars and infilling of the tidal channels.

The stepwise extension of the port of Rotterdam north of the Haringvliet ebb-tidal delta increasingly sheltered this area from the impact of waves and caused a large supply of sand. This finally led to breaching and erosion of the shore-parallel bar. Moreover, large-scale sedimentation reduced the average depth in this area. The Grevelingen ebb-tidal delta has a more exposed position and a smaller sediment supply and has not reached the stage of bar breaching yet.

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

1. Introduction

Climate change and the associated acceleration of sea-level rise will impact on coasts and estuaries around the world. This will likely cause drastic changes in natural conditions that can trigger large-scale engineering interventions. These interventions, in turn, will alter the morphodynamics of the engineered systems. Large-scale engineering in estuaries in the SW Netherlands between 1950 and 1970 triggered substantial changes in the contiguous coastal zone in the following decades. Analysis of these changes provides an overview of the impacts that future interventions can cause.

The estuaries in the SW Netherlands, a series of interconnected 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 and subsequent closing of their seaward sides with dams, in order to improve safety against flooding, diminish salt-water intrusion 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 discharge. Watson and Finkl (1990, 1992) present a detailed description of the project. The complete or partial damming of these estuaries triggered a series of large-scale morphological changes in their ebb-tidal deltas that continues until today.

1.1. 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. (Note that the rivers bring only mud to the coast.) The estuaries, with exception of Nieuwe Waterweg, are bounded on their seaward end by ebb-tidal deltas that have coalesced into an extensive

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area of shallow grounds, transected by tidal channels, that is known as the *Voordelta* (English: Fore Delta). Ebb-tidal deltas are formed 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 threshold value for sediment transport 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.

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 west-southwest and a corresponding wave period of 5 s (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 observed. 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).

The bed of the inlets and tidal deltas consists of fine- to medium-grained sand (Terwindt, 1973). Sand was predominantly transported by tidal currents in channels and by waves on the shoals (Terwindt, 1973). Grainsize distributions show an overall fining to the northeast, corroborating the north-easterly net transport of fine sand in the Voordelta.

This paper starts with an account of the evolution of the mouths of the Brielse Maas, Haringvliet and Grevelingen estuaries since the nineteenth century. Large-scale engineering works such as channel construction, land reclamation and damming and their impacts have changed the geomorphology of this area significantly. The evolution of the contiguous ebb-tidal deltas of all estuaries in the southwest Netherlands is discussed by Elias et al. (2017). In the present paper we will further analyse in detail the morphodynamic changes in the mouths of the estuaries Brielse Maas and Haringvliet, which shared a joined outer delta, and Grevelingen after damming of their inlets. 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. The almost annually surveyed changes in the bathymetry of these ebb-tidal deltas facilitate a detailed analysis of the closure-related morphodynamics. Moreover, the paper aims to summarize more than half a century of morphological

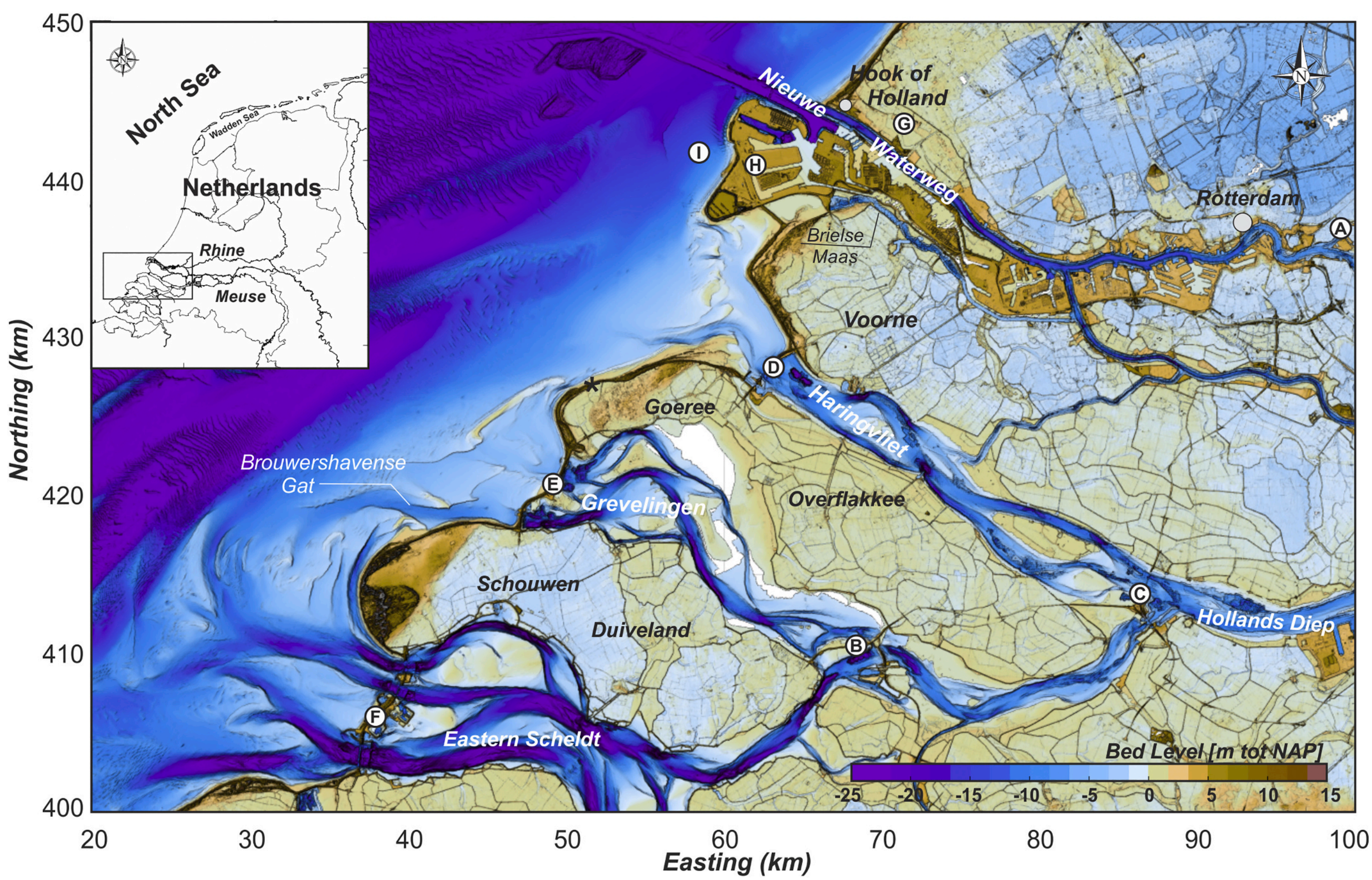

Fig. 1. Overview of the northern part of the Dutch Delta, showing the (now dammed) distributaries of the rivers Rhine and Meuse, the contiguous ebb-tidal deltas known as the *Voordelta*, and the major dams and barriers constructed as part of the Delta Project. A: Hollandse IJssel storm-surge barrier; 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 this holds for all bathymetric maps in this paper.

changes in the mouths and ebb-tidal deltas of the estuaries following damming 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 are 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

2.1. Evolution of the mouth of the rivers Rhine and Meuse since the 16th century

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) and 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 floodplain, 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 (see Kuipers, 1962, for a detailed account and series of maps), 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 the spit De Beer that was growing from the northern shore to the south narrowed the mouth (Fig. 2).

Haringvliet is a younger distributary of Rhine and Meuse that was formed in the early 13th century south of Voorne (see Elias et al., 2017, for details). 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 min earlier than the tide travelling along the 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). As the tidal prism of Haringvliet and

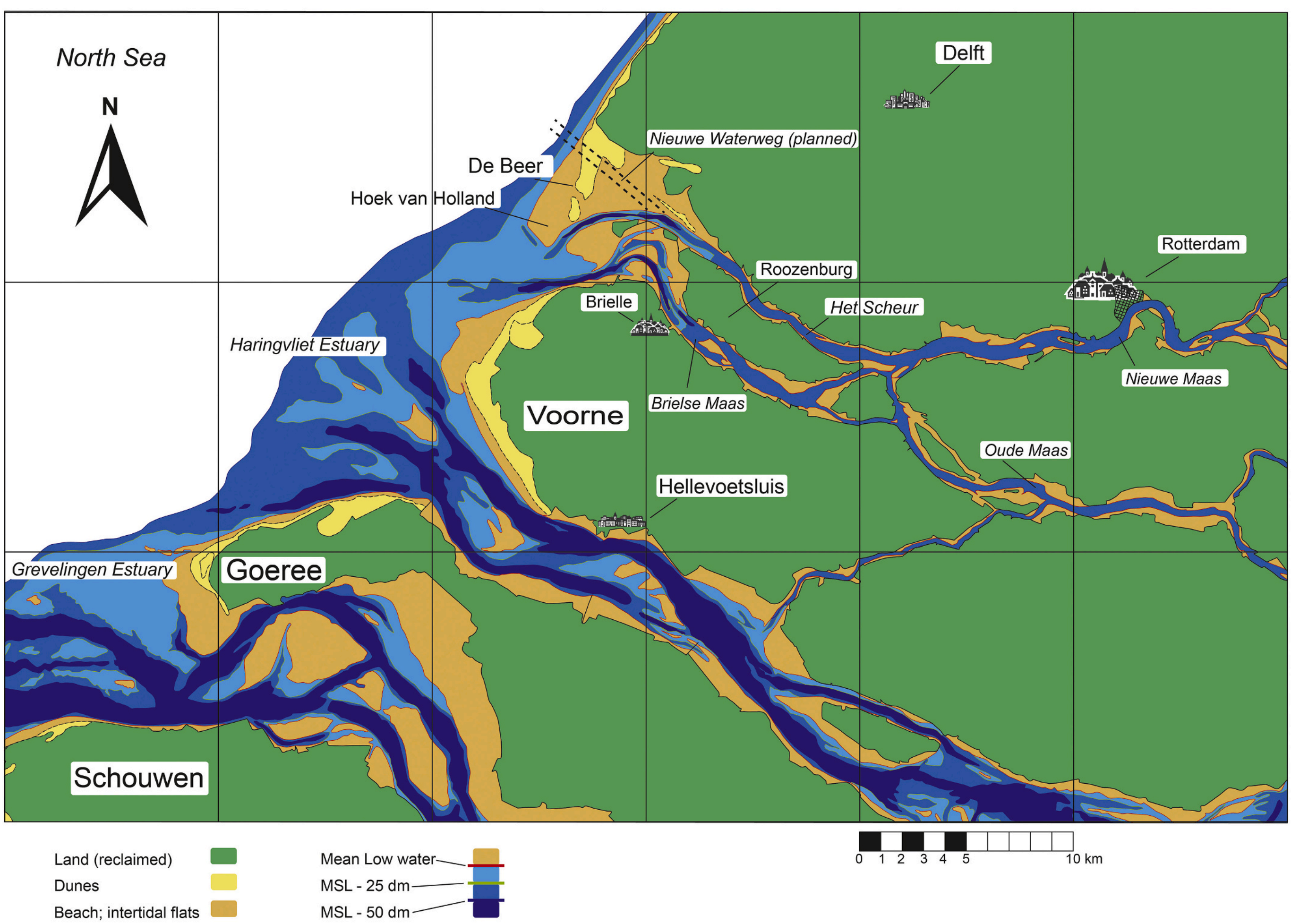

Fig. 2. Topography of the mouths of the distributaries of the rivers Rhine and Meuse around 1850. It shows the location of the channels Het Scheur and Oude Maas and the planned location for the Nieuwe Waterweg, to be cut through the spit De Beer/Hoek van Holland (started in 1869). Note that water depths are only indicated for the rivers and ebb-tidal deltas.

Grevelingen decreased, their ebb-tidal deltas started to change.

2.2. The decline of the Brielse Maas estuary - Nieuwe Waterweg takes over

The growth of intertidal flat area and expansion of the island of Rozenburg and the southward growing spit of Hoek van Holland/De Beer illustrate the siltation of Brielse Maas (Fig. 2). This gradually devaluated its relevance as a shipping route to Rotterdam. Between 1866 and 1872 a canal was cut through the spit Hoek van Holland to establish a direct connection between the river and the sea and a shorter and more reliable connection between the North Sea and the port of Rotterdam: Nieuwe Waterweg (Rotterdam Waterway). The connection between the channel Het Scheur and the Brielse Maas was blocked with a dam. As a result of this, Brielse Maas lost its main connection and was reduced to a narrow estuary. The inlet channel reoriented to the northwest and the mouth started to silt up (Van Driel, 1959a). The spit De Beer was literally cut off and turned into a barrier island that subsequently grew together with the island of Rozenburg.

In order to reach the desired navigation depth, the Nieuwe Waterweg has been deepened regularly. Moreover, to reduce dredging costs, the tidal currents in the Waterweg were reinforced by increasing the tidal volume by connecting Nieuwe Waterweg to Oude Maas, the upstream part of the Brielse Maas distributary (De Bruijn, 1949; Fig. 2). 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 through Brielse Maas to the North Sea decreased significantly. The combined effect was an aggravated salinization and siltation of this estuary.

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

Van Driel (1959b) describes the morphodynamics of the mouth of Haringvliet and its outer delta over the period 1821–1957. The estuary comprised two main tidal channels, Rak van Scheelhoek, the main ebb channel, along the shore of Voorne and the flood channel Zuiderdiep along the shore of Goeree, separated by the shoal Plaat van Scheelhoek (Fig. 3). Rak van Scheelhoek had a straight course to the northwest and one or more branches running to the west. Zuiderdiep increased in dimension and migrated 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.

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

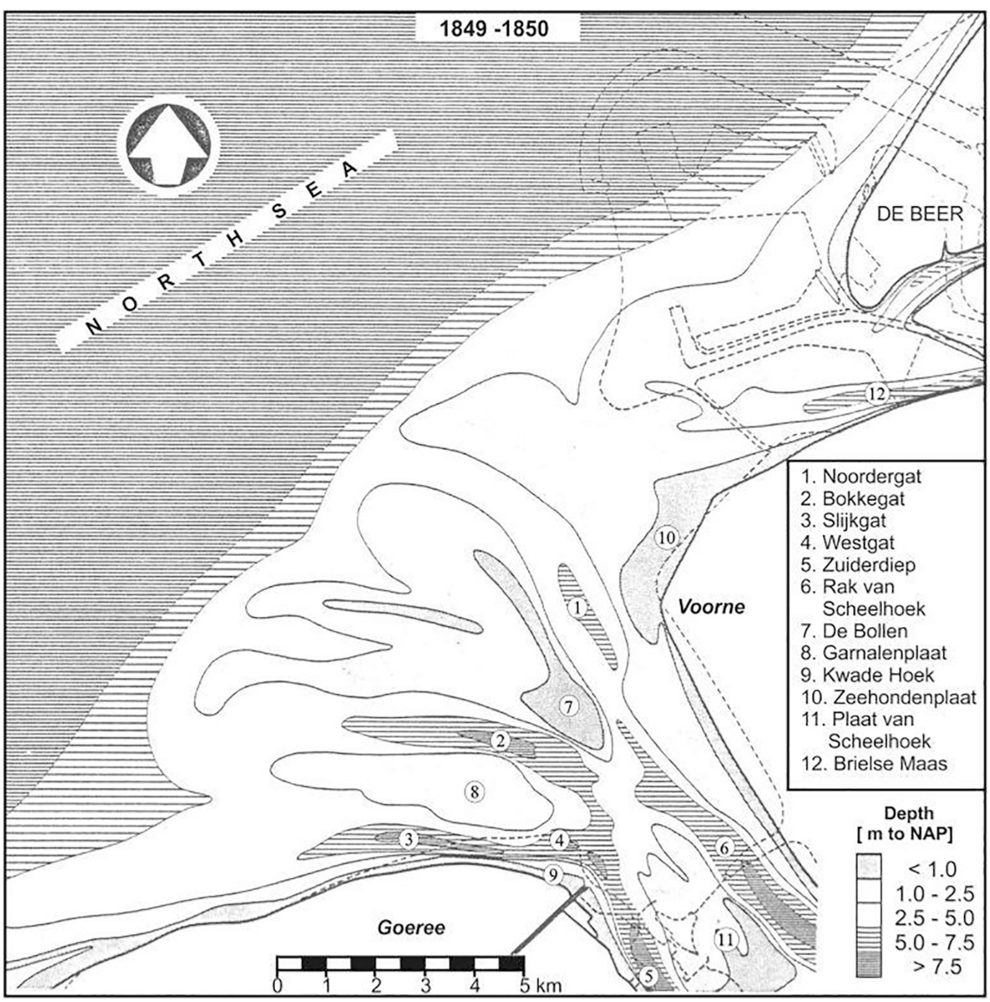

Fig. 3. Morphology of the Haringvliet ebb-tidal delta including the mouth of the Brielse Maas to the north in 1849–1850. Note the spit De Beer that will be cut loose from the mainland of Holland by the digging of the Nieuwe Waterweg in 1869–1871. The contours of both the Haringvliet dam including the sluices and Maasvlakte that was reclaimed between 1964 and 1976 are indicated with dashed lines. Depths are given in meters. (source: Rijkswaterstaat).

migrated towards the inlet.

Accretion of Goeree and erosion of Voorne caused the tidal inlet to shift to the north since 1868. The low-water line near Kwade Hoek (see Fig. 3 for location) prograded over 1 km. Haring (1955) reported scouring of Bokkegat resulting in sediment deposition on its terminal lobe and silting up of the Haringvliet tidal inlet in general over the interval 1872–1933, followed by an increase in sedimentation in the decades thereafter. 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, 1959b).

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

The decline of Brielse Maas triggered a plan to close off this distributary. Shortening of the coastline by damming the smaller estuaries, would reduce the length of sea dikes and hence, the risk of flooding during storm surges (Rijkswaterstaat, 1970b, 1978). Moreover, damming would create a large freshwater storage to counteract the growing detrimental impact of salinization on agriculture in the bordering low-lying polders. In the course of these plans, Brielse Maas was closed off in 1950. 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

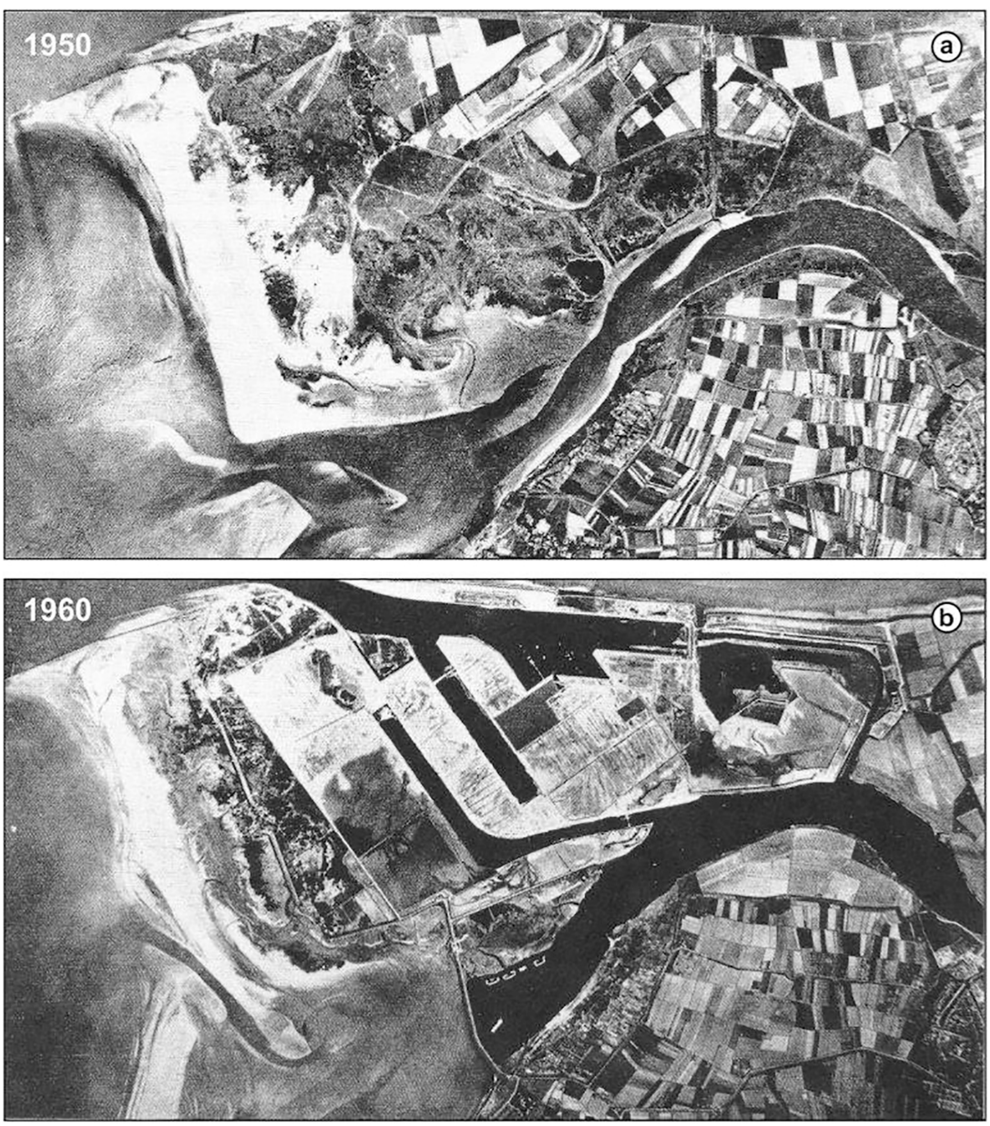

Fig. 4. Aerial photographs of the island Rozenburg before 1950 (top), showing agricultural land and nature reserve De Beer at the coast, and in 1960 (bottom) after construction of the Europoort harbour extension. In the top panel, the course of the blocked and subsequently reclaimed channel Het Scheur can still be recognized (compare with Fig. 2). Moreover, the Brielse Maas estuary is still open. Note that the top side is NorthEast; compare orientation with Fig. 5. (From: Van den Burg, 1989).

discharge of the rivers Rhine and Meuse to the North Sea, and a southern basin consisting of the Grevelingen and the Eastern Scheldt. The Western Scheldt mouth was not included in the project to allow for 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, a storm-surge barrier was constructed (Rijkswaterstaat Deltadienst, 1979).

3.1. Developments in the northern part of the Haringvliet ebb-tidal delta

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; compare Figs. 4 and 5). Wave-driven sand transport to the northeast along the coast of Voorne built a series of prograding spits (Fig. 5). Terwindt (1964) concluded that the damming of 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 gradients of the North Sea tide had become dominant, which caused 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 transformed into a shore-parallel, wave-built bar. These developments heralded the large-scale changes to be expected in the ebb-tidal deltas of Haringvliet and Grevelingen due to the Delta project.

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

Fig. 5. Aerial photograph of the mouth of the Brielse Maas and the shorelines of the islands of Rozenburg and Voorne in 1961. The channels Brielsche Gat and Sluische Gat in the ebb-tidal delta have rotated to an approximate 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).

of the Haringvliet ebb-tidal delta (Fig. 4). 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 (Fig. 6). 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 reclamation (Figs. 6, 7). Moreover, the largest part of Westplaat shoal disappeared when Maasvlakte was built on top of it. This stepwise extension increasingly sheltered the Haringvliet ebb-tidal delta from waves from the north and north-west.

3.2. Damming the estuaries

3.2.1. Haringvliet

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.), the composition and erodibility of the estuarine deposits in the Haringvliet was studied in detail (see Oomkens and Terwindt, 1960; Terwindt et al., 1968; and Terwindt, 1971). Tidal deposits in the Haringvliet mouth consisted of sequences of alternating cm-thick sand and clay layers of up to 20 m thick (Terwindt, 1971).

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. 7, 8). In 1957 a ring-dike was built perpendicular to the estuary axis (see Rijkswaterstaat, 1957, for details). This reduced the cross-sectional area of the estuary with c. 20% 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 sluices, 1 km wide in total, was built. The ring-dike caused scouring of the channels and changes in the current patterns, which established a connection between the flood channel Slijkgat and the ebb channel Rak van Scheelhoek (Rijkswaterstaat, 1964).

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. 8). Subsequently, a new harbour was excavated and the southern shore of the estuary was reconstructed.

After completion of the discharge sluices, the floor of the construction pit was lowered to MSL −15 m and the ring-dike was levelled. In October 1968, the dike was completely removed and the sluices were opened (see Fig. 8). The increase in cross-sectional area caused a decrease in the current velocities in the channels which allowed for the blocking of Noord-Pampus with a sand dam that was completed in early November 1968 (Rijkswaterstaat, 1969). At the same time channels were dredged both landward and seaward of the sluices to direct the discharge. 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 concrete blocks, the discharge through the sluices increased. Finally, in April 1970 Rak van Scheelhoek was completely blocked and the sluices were conveying the tidal currents (Rijkswaterstaat, 1972). In total, a volume of 40 million cubic metres (*mcm*) of sediment had been moved to reconstruct the Haringvliet inlet (Zuiderwijk, 1971).

3.2.2. Grevelingen

In 1965 the first sections of Brouwers dam, the closure dam of the Grevelingen estuary, across the shoals Middelplaat and Kabbelaarsbank were finished (see Fig. 9 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. More or less concurrently, Grevelingen dam (Fig. 1 [B]) at the eastern end of the estuary was finished. Grevelingen dam separated the estuary from the Eastern Scheldt which reduced its 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

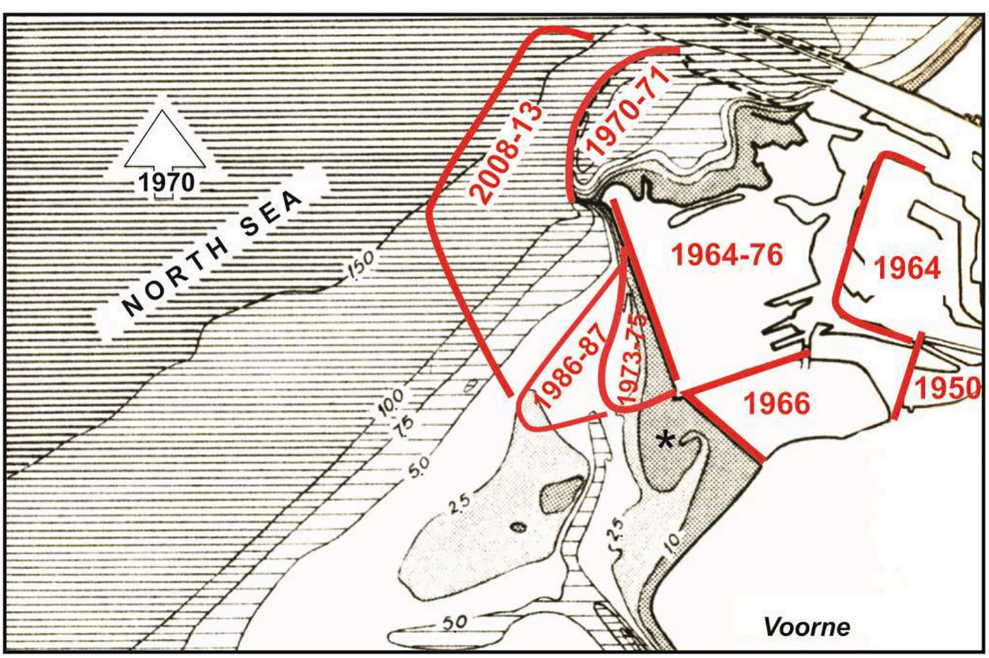

Fig. 6. The westward expansion of the coast of the island Rozenburg between 1960 and 2013, due to the construction of Europoort (1964-1966), Maasvlakte (1964-1976), Slufterdam (1986–1987) and Maasvlakte 2 (2008–2013). The asterisk indicates the remnants of Westplaat shoal.

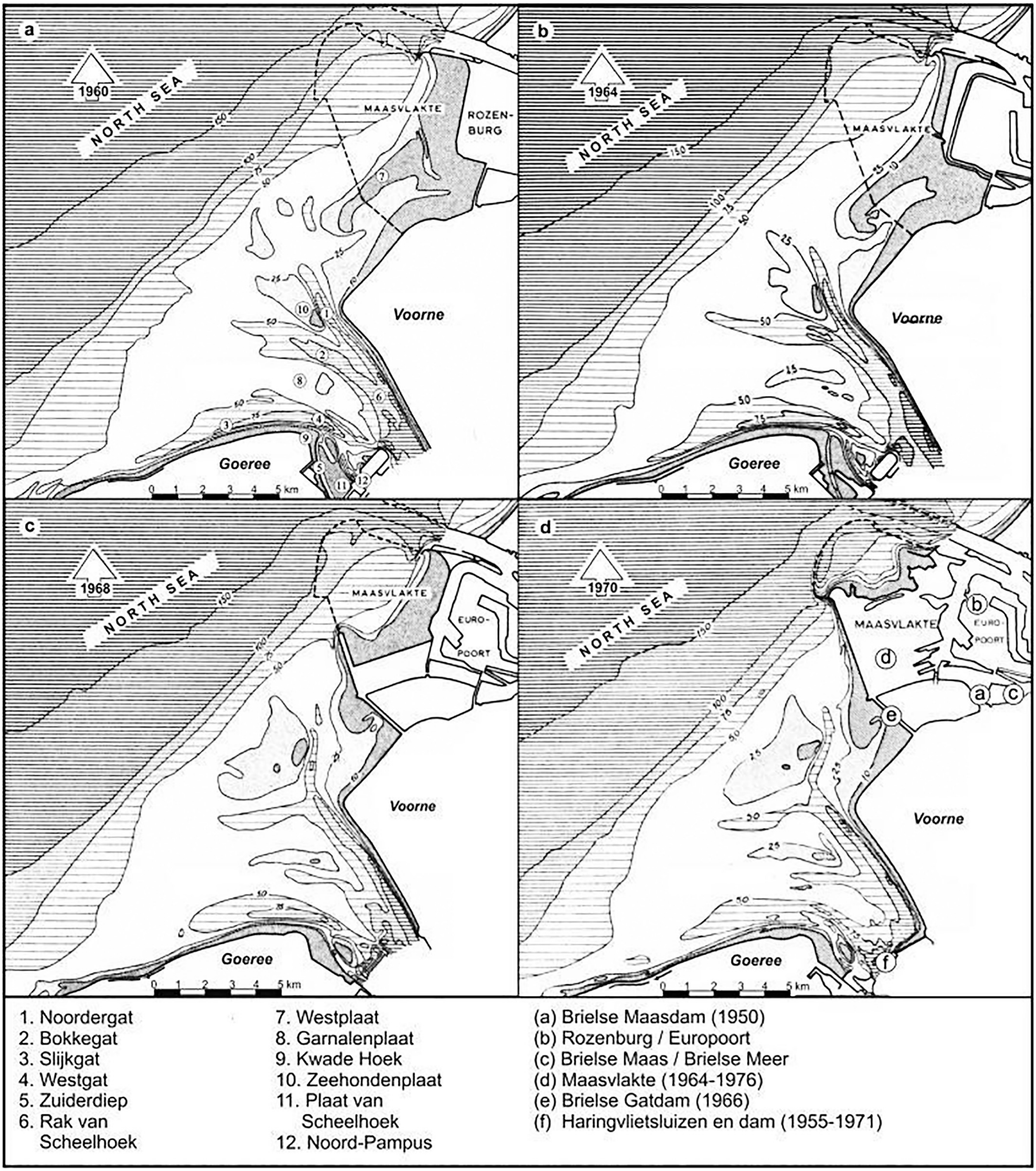

Fig. 7. The changes in the mouth of the Haringvliet and Brielse Maas estuaries between 1960 and 1970. Brielse Maas had been dammed in 1950 and its former ebb-tidal delta had swiftly adapted to the new hydraulic situation. In the Haringvliet ebb-tidal delta the major ebb channel Rak van Scheelhoek is situated along the SW 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 (situation 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 had been removed and in 1970 Rak van Scheelhoek was completely 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 Sections 3.2 and 3.3 for details and explanation). Depths are in meters. (From: Rijkswaterstaat Deltadienst, 1970; appendix).

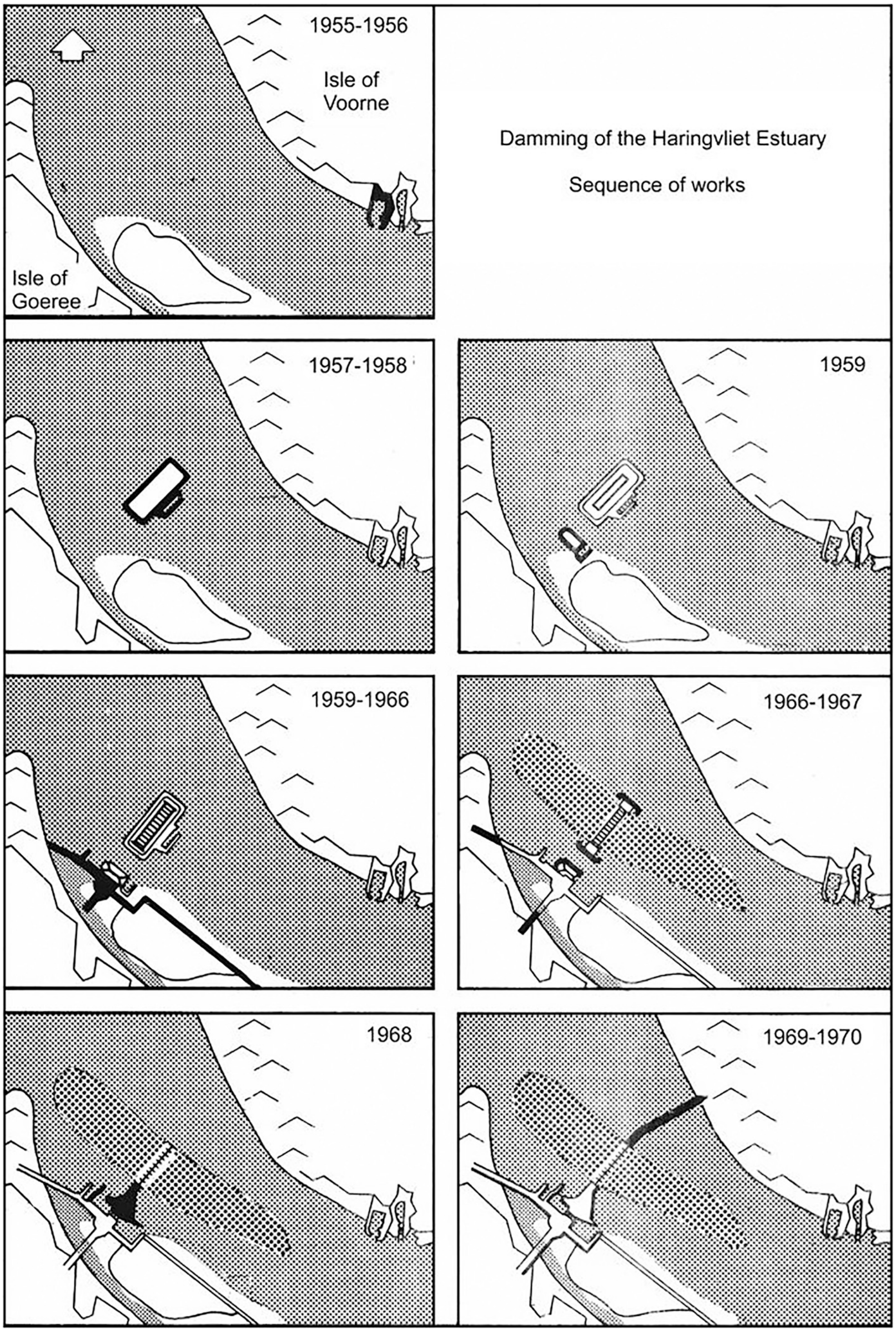

Fig. 8. The sequence of interventions in the mouth of the Haringvliet estuary over the period 1955–1970 leading to its complete damming. This sequence includes building of the ring-dike for the construction pit of the discharge sluices in 1957, reconstruction of the Goeree shore between 1959 and 1966, removal of the ring-dike and dredging of the discharge channels from 1966 to 1968, closure of the Noord-Pampus channel south of the sluices in 1968 and, finally, blocking of the Rak van Scheelhoek channel in 1970. (Source: Rijkswaterstaat).

basin into a saltwater lake.

3.3. Impacts of large-scale engineering on ebb-tidal deltas

This section describes the morphological changes in the ebb-tidal deltas of the Haringvliet and Grevelingen estuaries during and after the construction of the sluices and dams. The analysis is based on changes in the bathymetry of the areas that were surveyed (bi-)annually (Haringvliet) to quadrennially (Grevelingen) between 1957 and 2015. Fig. 9 presents the bathymetries for 1964, 1976, 1992 and 2015.

3.3.1. Haringvliet ebb-tidal delta 1957–1970; impact during construction

Before the construction of the ring-dike in 1957, the Haringvliet tidal inlet at its narrowest point consisted of two north-west running channels, Rak van Scheelhoek in the north and Noord-Pampus in the south (Fig. 7). Noord-Pampus continued seawards as Slijkgat channel, branching off to the west. Rak van Scheelhoek split into the distributaries Bokkegat and Gat van de Hawk. Gat van de Hawk was running north, bounded in the east by Westplaat, part of the Brielse Maas ebb-tidal delta, and in the west by Zeehondenplaat ('Seal shoal'), which separated the channel from Bokkegat. Bokkegat was running to the west, separated from Slijkgat in the south by the shallow shoal Garnalenplaat ('Shrimp shoal').

The construction of the ring-dike 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. Slijkgat gradually lost its connection with Noord-Pampus and linked up with Rak van Scheelhoek north of the construction pit, after which the major tidal channels were concentrated in the northern half of the inlet.

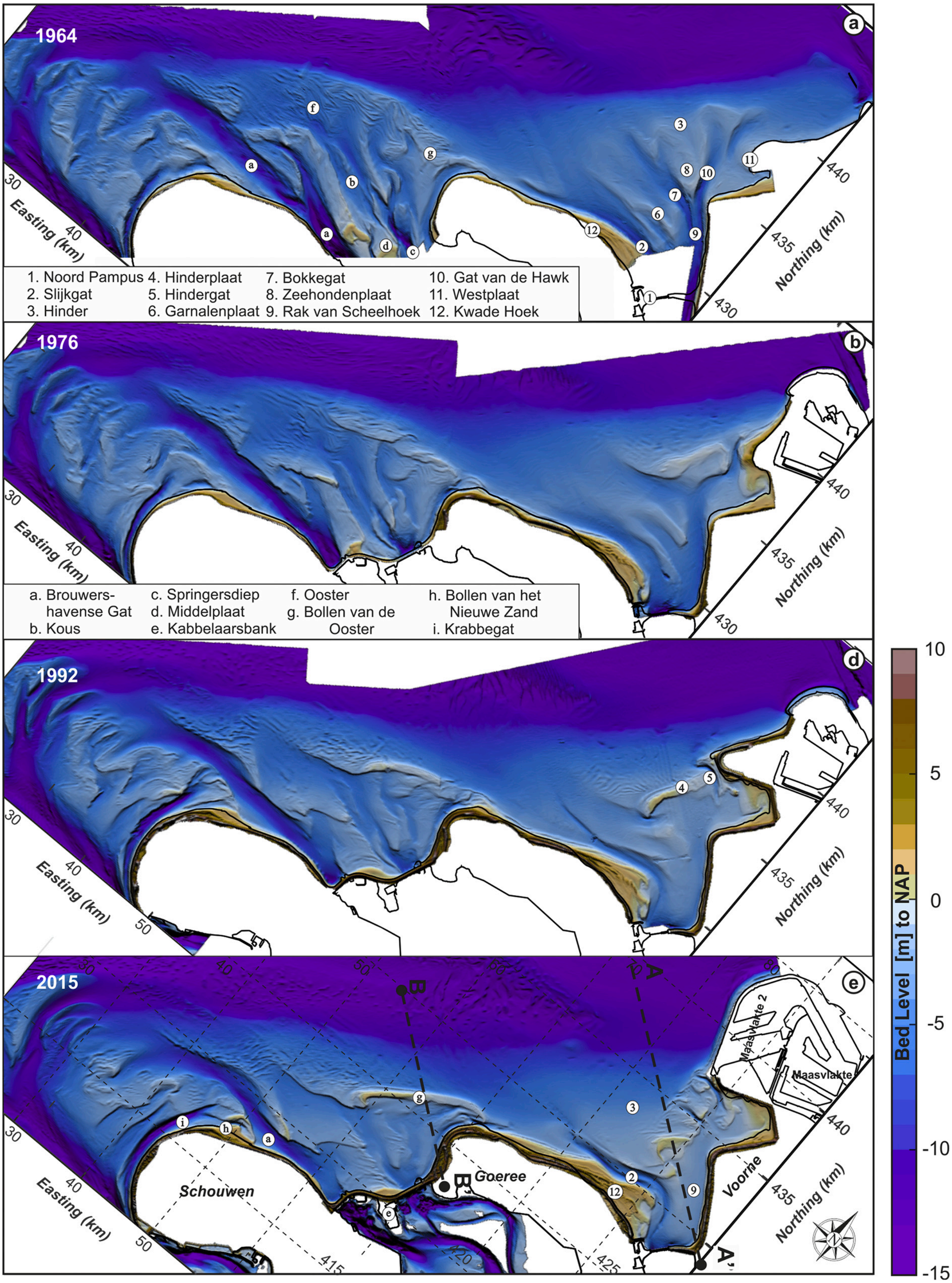

Fig. 9. Bathymetry of the Haringvliet and Grevelingen ebb-tidal deltas before (1964) and after the damming of the estuaries (1976–2015). See Section 3.3 for details on the changes over time. The position of the cross-sections of Fig. 10 are indicated in the 2015 map.

Bokkegat migrated northward and became an ebb-dominated channel. The bifurcation of Rak van Scheelhoek into Gat van de Hawk and Bokkegat had been migrating seaward since 1957. The rate of migration increased between 1965 and 1968 and came to a halt in 1969. Concurrently, both channels had rotated into a shore-parallel orientation (Figs. 7, 9). 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 south of it (Fig. 7). The average depth in the mouth landward of the 10 m depth contour decreased with 0.5 m between 1956 and 1969, which implies deposition of 80 *mcm* of sediment (Rijkswaterstaat, 1970d). During the gradual closure of Rak van Scheelhoek, already several metres of mud settled in the channel on both sides of the growing dam (Rijkswaterstaat, 1970a).

3.3.2. Haringvliet ebb-tidal delta 1970–1986; changes after completion

Following the closure of the remaining part of Haringvliet inlet in 1970, the seaward edge of the ebb-tidal delta eroded and the shore-parallel Hinderplaat grew rapidly in both length and height, see Figs. 9, 10. The elongated, spit-shaped Hinderplaat sheltered the back-barrier area. The decrease in current velocities caused siltation in the channels, with exception of Gat van de Hawk where an increase in discharge caused this channel to scour (Rijkswaterstaat, 1973). In general, shore-parallel tidal currents became more important in the seaward parts of the ebb delta. The other channels filled in with predominantly mud. Piekhaar and Kort (1983) reported a thickness of up to 4.8 m of mud (with less than 10% sand) in Rak van Scheelhoek in 1981. 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. The only remaining tidal channel in Haringvliet ebb-tidal delta is Slijkgat (Fig. 9), the main discharge channel for the sluices and the fairway to the fishing harbour of Stellendam, which needs to be dredged regularly.

A large sediment supply from the SW, fed by erosion of the delta front of Grevelingen ebb-tidal delta and 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. 9 [12]). 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 *mcm* of sand was added, mainly to strengthen the dunes.

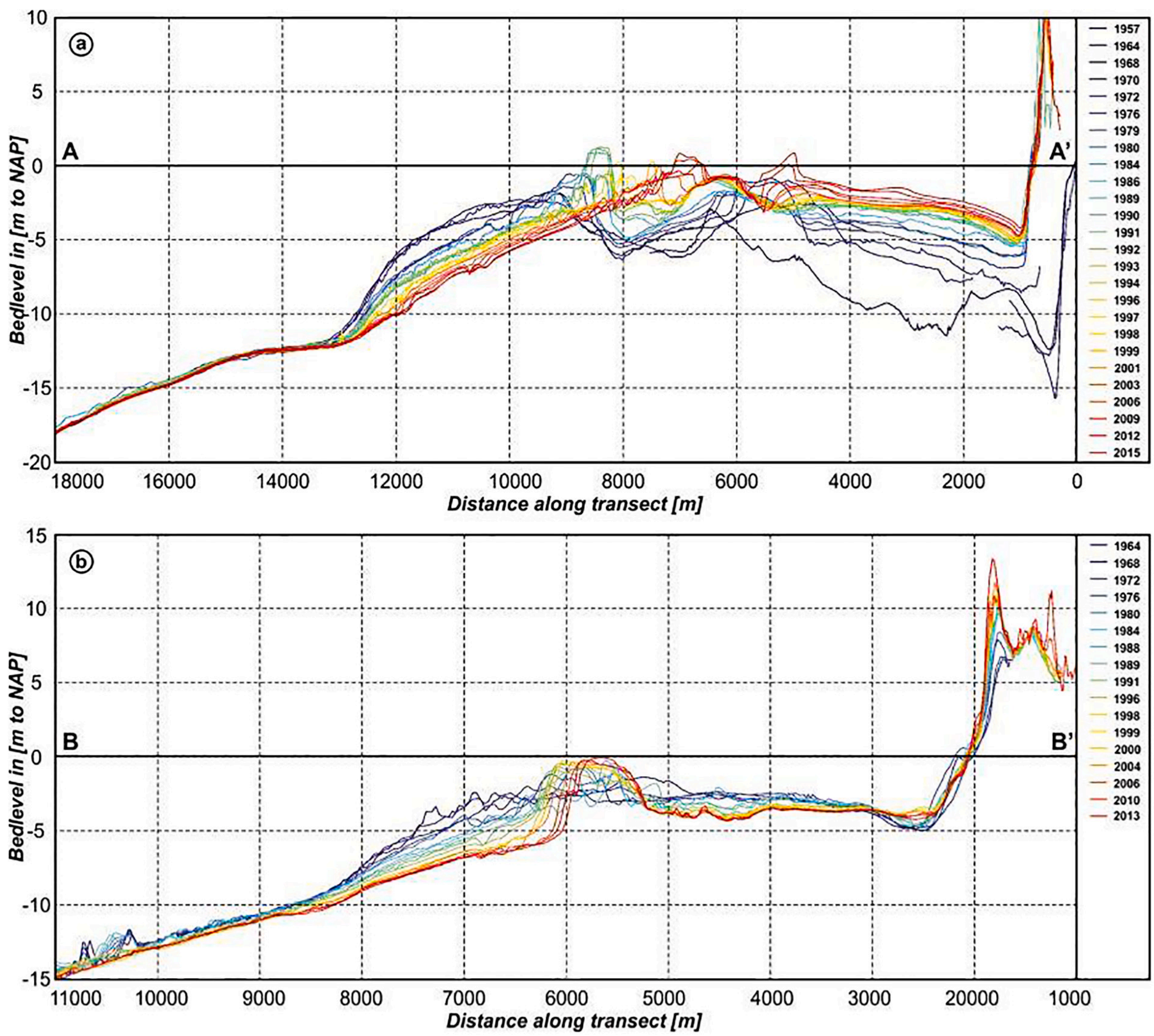

Fig. 10. Development of representative profiles of the ebb-tidal deltas of Haringvliet (AA') and Grevelingen (BB') showing the consequences of the damming of the estuaries. The shoreface of the ebb-tidal deltas is eroded down to NAP -10 to −12 m and (part of) the sand is pushed up in a sand bar on the edge of the delta. The profile of Haringvliet shows the large-scale infilling of the former tidal channel Rak van Scheelhoek. See Fig. 9 for location of the profiles.

3.3.3. Haringvliet ebb-tidal delta since 1986; engineering continued

In 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 (Fig. 6). Since it covered the northern part of Hinderplaat (Figs. 6, 9), the existing channel Gat van de Hawk disappeared and a new channel, Hindergat, had to be dredged through Hinderplaat further south. The NNE-SSW trending sand dam of the Slufter was maintained with sand nourishments, both on its beach and shoreface. Since 1991 over 11 *mcm* of sand was added. Moreover, the dunes at the tip of Voorne were strengthened with 3 *mcm* 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 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 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, the latest seaward extension of Maasvlakte that was built mainly with sand. After completion of its 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. 6, 9), further sheltering the Haringvliet mouth from waves coming from the north and northwest.

The morphology of Haringvliet ebb-tidal delta changed significantly 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 (Fig. 9). The tidal channels continued to fill in. In Van Heteren (2002) reported the mud deposits in Rak van Scheelhoek to be up to 7.5 m thick. The entire ebb-tidal delta was pushed further landward due to wave action.

As the Hinderplaat increased in height and length, it decreased in width. Hindergat, the channel cutting across Hinderplaat in its most northern part, was gradually blocked by a sand spit that grew in front of it (Fig. 9c, 1992). This spit was fed by southwards wave-driven sand transport along the sandy Slufterdam. Numerical model simulations show persistent southward transport along the Slufterdam under winds and waves from northwest to north (Colina Alonso, 2018). From 1992 on, the northern part of Hinderplaat got lower and small channels formed across it. This development was possibly accelerated by an extreme river discharge event in February 1995 (Colina Alonso, 2018). In 1999 a new tidal channel formed south of Hindergat. In the following years Hinderplaat disintegrated and the remaining parts migrated landwards (Fig. 11A), merging with the intertidal shoals (see Fig. 9e, 2015). With the construction of Maasvlakte 2 between 2008 and 2013, the supply of sand from the north was likely sustained if not increased (De Winter, 2014). The occurrence of typical wave-formed phenomena such as flying spits along the NNW-SSE trending southwestern shore of Maasvlakte 2 (Fig. 11D) and recurved spits at its southern end witness continued large-scale wave-driven sand transport to the south.

The surface area of the shoals above NAP-2.2 m increased from 6 km^2 in 2001 to 16 km^2 in 2012 (De Winter, 2014). Since 1967, the average height of the shoals has been fluctuating 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.

Since 1986 Bokkegat channel had been forced to the south and finally got squeezed between the south- and landward extending Hinderplaat and the seaward expanding Garnalenplaat (Fig. 9). Concurrently, a new channel developed further south, through Garnalenplaat. After 2001, Bokkegat filled in and disappeared. Next, the new channel was forced southwestwards and gradually filled by the migrating intertidal shoals. Slijkgat remained the flood channel filling the area

Fig. 11. Arial photographs showing typical phenomena in the ebb-tidal deltas of Haringvliet and Grevelingen. A: small-scale channels and shoals in the Haringvliet tidal delta after breaching of Hinderplaat shoal (November 2005). B: dunes formed on the Brouwersdam by eolian transport of beach sand (March 2008). C: recurved spits at 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).

between the growing shoals and the coast of Voorne and draining the combined tidal and river discharge. Moreover, Slijkgat is a navigation channel and has to be dredged regularly due to the large-scale sediment accretion.

At Kwade Hoek, the north-eastern tip of Goeree, successive generations of spits formed (see Reintjes, 2002, for details). Continued wave-driven sand transport from the southwest created a fan-like spit complex (Fig. 9: 1992–2015; Fig. 11C). A similar development had been observed earlier on at the northern shore of Voorne (see 3.1 and Fig. 5). Moreover, the central part of Goeree, between the most western spit and Flaauwe Werk, accreted rapidly since the mid-1990s (Reintjes, 2002; Figs. 9, 12).

3.3.4. Grevelingen ebb-tidal delta since 1971; impact of damming

Completion of the Brouwers dam reduced the ebb-tidal flow in the ebb delta strongly, leading to onshore reworking of the delta terminal lobe by waves down to MSL −10 m. This landward transport of sand built a longshore bar called Bollen van de Ooster (Van der Spek, 1987; Kohsiek, 1988; see Fig. 10), a development very similar to the formation of Hinderplaat to the north. Part of the eroded sand will have been transported to the northeast, feeding the coast of the island of Goeree and extending the recurved spits at Kwade Hoek (Fig. 9). 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, grew in longshore direction and its south-western tip rotated anti-clockwise. Presently, the bar is still growing in both height and length, especially to the northeast. Waves also eroded

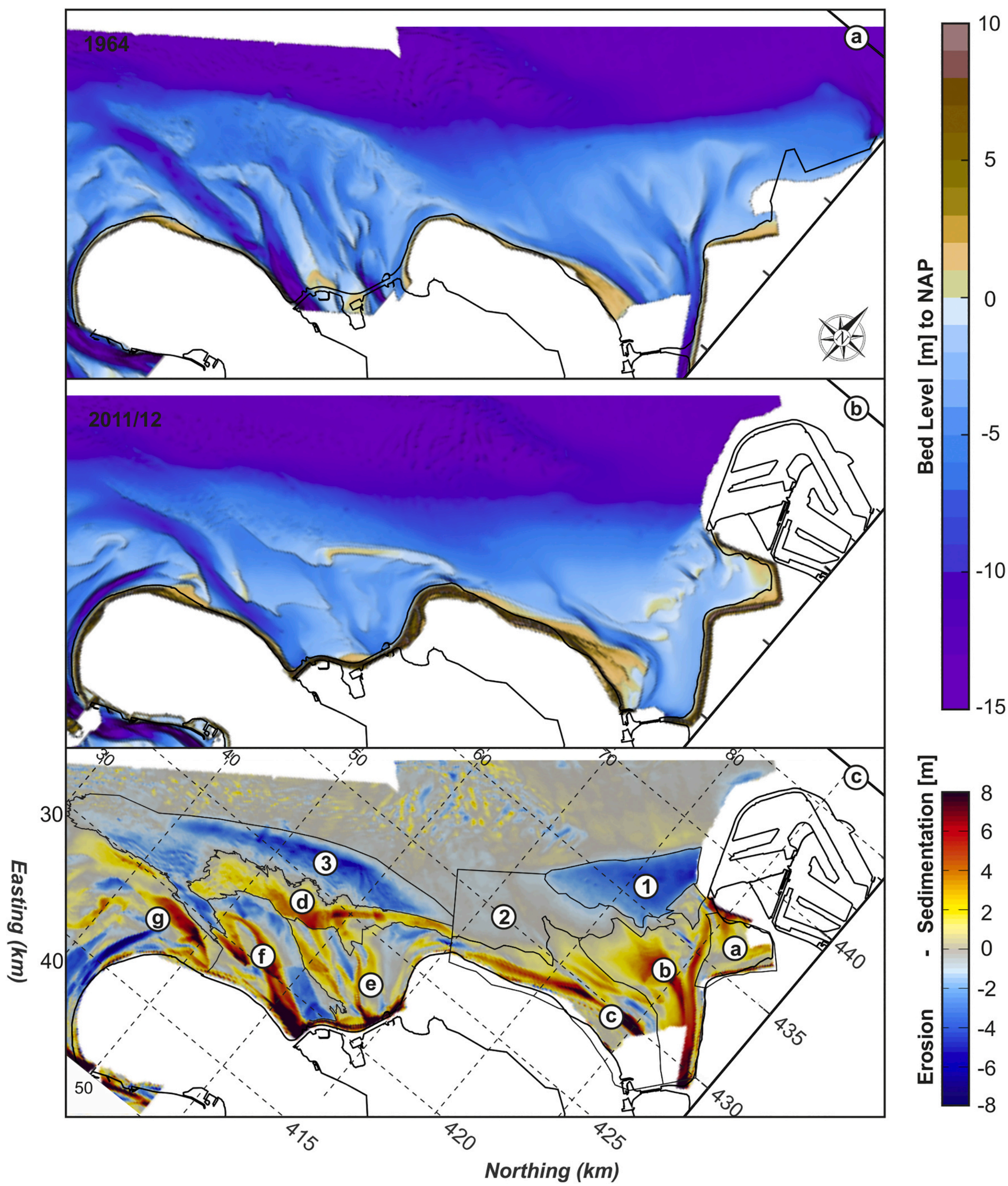

Fig. 12. The bathymetry of the Voordelta in 1968 (a) and 2012 (b). The morphological changes over this interval are illustrated by the sedimentation-erosion patterns in panel (c). Table 1 presents the volume changes of the polygons in panel (c).

Middelplaat shoal directly seawards the dam (Fig. 12) and transported the sand towards it, forming a wide beach. Eolian transport of the beach sand resulted in formation of a natural dune row on top of the seaward side of the dam (Fig. 11B). At the southern boundary of the ebb delta, Krabbengat channel built a terminal lobe, the shoal Bollen van het Nieuwe Zand into Brouwershavense Gat channel (Figs. 9, 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).

4. Summary of morphodynamic changes and conceptual model

Fig. 9 illustrates the large-scale morphological changes in the northern part of the Voordelta. Damming of the estuaries caused erosion of the delta front and building of sand bars along the outer rim of the ebb-tidal deltas (Fig. 10; see Van der Spek, 1987; Kohsiek, 1988; for details). Besides that, with reduction of the shore-normal tidal flow, shore-parallel currents became more dominant which promotes shore-parallel flow through the seaward parts of the channels on the ebb-tidal delta. The large-scale erosion of the seaward parts and sedimentation in the landward parts of the tidal deltas of both Haringvliet and Grevelingen are in line with the changes in the mouth of the Brielse Maas estuary following its damming (as described in Section 3.1). Fig. 12 shows the sedimentation-erosion pattern of the area over the period 1968–2015.

4.1. Sediment volume changes 1964–2010

Elias et al. (2017) reconstructed and analysed the volume changes of the ebb-tidal deltas in detail. Table 1, based on their study, gives the net volume changes for the Haringvliet and Grevelingen ebb-tidal deltas since 1964. Erosion of the seaward part of the Haringvliet ebb-tidal delta amounts to 65 *mcm*. Sedimentation in the landward part of the delta is almost double that volume: 124 *mcm*. This volume includes the extensive mud deposits in the largely inactive channels (note that mud is introduced from outside the system) and supply of sand from the Grevelingen area to its south-west and the land reclamations to its north. The maintenance volume of Slufterdam (11.2 *mcm* between 1991 and 2005) gives an indication of the supply from the north. Beach and shoreface nourishments, predominantly on the island of Voorne since 1980, added an extra 12.4 *mcm* of sediment to the system.

The volume loss of the delta front of the Grevelingen ebb delta is 89 *mcm* (Table 1), which is more than the volume gain of 86 *mcm* in the landward part of this ebb delta. The latter volume includes a significant volume of mud that accreted in the closed-off channel Brouwershavense Gat and an extra 10 *mcm* of sand that was nourished mainly at the western tip of the island of Goeree, what increases the discrepancy between the eroded and deposited volumes. A large part of the missing volume was almost certainly transported to the northeast. Along its southern boundary, the ebb delta has been receiving a substantial supply of 28 *mcm* of sand from the Banjaard shoal (see Fig. 12 and Table 1).

Table 1
Sediment volume changes of selected polygons in the ebb-tidal deltas of Grevelingen and Haringvliet between 1964 and 2011 in million cubic meters. Numbers and letters refer to polygons in Fig. 12 (c). Based on Elias et al. (2017).

Sediment budget ebb-tidal deltas	+84.4
Total erosion tidal-delta front	−153.8
1. shoreface Hinderplaat	−50.0
2. nearshore Goeree	−15.0
3. shoreface Bollen vd Ooster	−88.8
Sedimentation	238.2
a. Brielse Gat	9.6
b. Rak van Scheelhoek, incl. Hinderplaat	64.4
c. Slijkgat & coast Goeree	50.2
d. Bollen van de Ooster	38.2
e. Aardappelenbult	17.6
f. Brouwershavense Gat	30.0
g. Banjaard shoal	28.2

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

Damming of the estuary 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. Despite differences in local conditions and dimensions of the estuary mouths, the developments after intervention are comparable. In the adaptation of the ebb-tidal deltas to the new conditions we can observe distinct stages of development. In each stage the ebb-tidal delta is further reduced in size.

4.2.1. Phase 1: Open inlet - dynamic equilibrium (Fig. 13, upper left panel)

Before intervention, a dynamic equilibrium existed between ebb-tidal currents that bring sand seawards to form shoals and waves breaking on these shoals and bringing the sand landwards again. Dynamic equilibrium implies that the large-scale morphology of the area is in balance with the forming physical processes. Small-scale dynamics such as, e.g., wave-driven bar migration, occur.

4.2.2. Phase 2: closed inlet - distorted state (Fig. 13, upper right panel)

Damming of estuaries causes a large reduction in tidal prism and an attendant decrease in ebb discharge. These changes reduce the seaward transport of sand in the major channels, thereby increasing landward sand transport by waves, both cross-shore and alongshore. Especially the wave-driven cross-shore transport results in erosion of the delta front and formation of (shore-parallel) intertidal sand bars. (Inter)tidal bars in the sheltered inner part of the ebb-tidal delta lose height. The landward parts of the tidal channels fill in, predominantly with mud. The seaward parts of the channels adapt to shore-parallel tidal flow.

4.2.3. Phase 3: infilling basin (Fig. 13, lower left panel)

The changing ebb-tidal delta can be considered a new, much smaller tidal basin, sheltered by the shore-parallel bar. The morphology of this new basin is not yet in equilibrium with the largely reduced tidal prism 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. The tidal exchange is too limited to sustain the former channel-and-shoal topography which results in gradual levelling of the relief. Waves rework the shoals and island beaches, the sediment is deposited in the remaining channels. Over time, as the landward retreat of the delta front slows down, the shore-parallel bar will lose height, be breached and finally merge with the shallow shoals. It is expected that the sedimentation in the former ebb delta will continue until eventually the reworked ebb-delta deposits, potentially increased by an additional influx of sediments from neighbouring areas, fill the basin completely, merging it with the coast and thereby extending the coastal plain.

The pace of the developments in the infilling stage depends on local conditions. For instance, the Haringvliet ebb-tidal delta filled in rapidly due to a large supply of sediment, sand from the southwest and from the north and mud predominantly from the river, and sheltered conditions provided by the extension of the Port of Rotterdam. The Grevelingen ebb-tidal delta, by contrast, evolves much slower. Here, large-scale sediment supply is lacking and wave-driven sand transport along the delta front causes a net loss to the northeast, to the coast of Goeree and beyond. Moreover, this area is impacted by North Sea waves from all directions and north-south tidal currents in its seaward part. Hence, the dominating development is reworking followed by landward transport of sand.

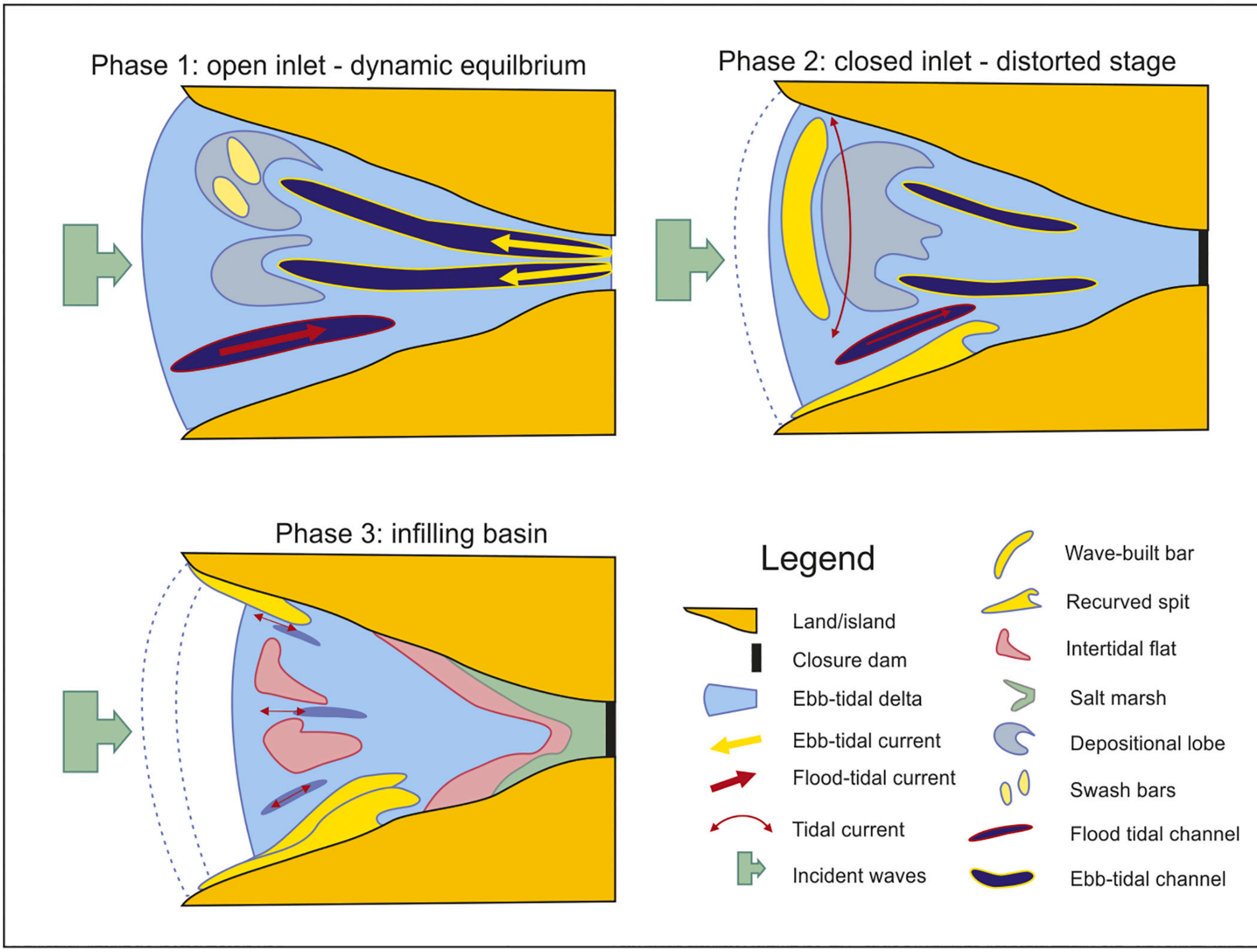

Fig. 13. Conceptual model for ebb-tidal delta evolution after a significant reduction in cross-shore flow, based on the evolution of the Haringvliet and Grevelingen ebb-tidal deltas between 1964 and 2015.

4.3. Applicability of the model

This conceptual model describes in general the morphodynamic evolution of ebb-tidal deltas that can be expected after a significant reduction of the tidal prism of its tidal inlet or estuary. The scale and pace of these changes will depend on local conditions such as surface area, level of exposure, rate and composition of sediment supply and interaction of cross- and longshore tidal currents. The model gives a first indication of the changes to be expected after interventions in estuary mouths and tidal inlets. In the disrupted state directly following the intervention (Phase 2), temporary phenomena such as the shore-parallel bar dominate the changing morphology. In the longer run, these elements will gradually decrease in size and become part of the new landscape (Phase 3).

Declaration of Competing Interest

The authors state no conflicting interests.

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References

Colina Alonso, A., 2018. Morphodynamics of the Haringvliet ebb-tidal delta. Unravelling the Mechanisms behind its Morphological Evolution. MSc thesis. Delft University of Technology, Faculty of Civil Engineering and Geosciences. https://repository.tudelft.nl/islandora/object/uuid%3Af46c3394-ac26-43b5-9338-21b202703961?collection=education.

Davis, R.A., Hayes, M.O., 1984. What is a wave-dominated coast? Mar. Geol. 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. Neth. J. Geosci. 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. (Ed.), Sediment Dynamics in the Rhine Catchment. Quantification of Fluvial Response to

Climate Change and Human Impact. Utrecht University, pp. 117–171. PhD thesis. 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. In: 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. In: 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 Lawrence to the Gulf of Mexico. Academic Press, New York, pp. 1–27.
Hillen, R., Haan, De, 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. J. Coast. Conserv. 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.
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. J. Sediment. Petrol. 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.
Kuipers, H., 1962. The changing landscape of the island of Rozenburg (Rotterdam Port Area). Geogr. Rev. 52 (3), 362–378.
Meyer, H., 2017. The State of the Delta. In: 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). Geol. Mijnb. 39, 701–710.
Piekhaar, R.S., Kort, M.W., 1983. Haringvliet monding - Sedimentatieonderzoek 1970-1981. In: 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. In: 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. Rijkswaterstaat Deltadienst, The Hague, pp. 37–43.
Rijkswaterstaat, 1962. De morfologische veranderingen in de mond van de Brielsche Maas sedert de afsluiting daarvan. Driemaandelijks Bericht Deltawerken, 20. Rijkswaterstaat Deltadienst, The Hague, pp. 25–33.
Rijkswaterstaat, 1964. De trog bij de bouwput voor de uitwateringssluizen in het Haringvliet. Driemaandelijks Bericht Deltawerken, 28. Rijkswaterstaat Deltadienst, The Hague, pp. 412–420.
Rijkswaterstaat, 1969. Afsluiting van het Noord-Pampus (Haringvlietmond). Driemaandelijks Bericht Deltawerken, 47. Rijkswaterstaat Deltadienst, The Hague, pp. 372–376.
Rijkswaterstaat, 1970a. Loden en meten tijdens de afsluiting van het Rak van Scheelhoek. Driemaandelijks Bericht Deltawerken, 53. Rijkswaterstaat Deltadienst, The Hague, pp. 120–133.
Rijkswaterstaat, 1970b. Voorspel (van het Delta Plan). Driemaandelijks Bericht Deltawerken, 54. Rijkswaterstaat Deltadienst, The Hague, pp. 172–177.
Rijkswaterstaat, 1970c. Het ontwerp van de afdamming van het Haringvliet. Driemaandelijks Bericht Deltawerken, 54. Rijkswaterstaat Deltadienst, The Hague, pp. 179–181.
Rijkswaterstaat, 1970d. De gevolgen van de afsluiting van het Haringvliet voor het mondingsgebied en de aansluitende kust. Driemaandelijks Bericht Deltawerken, 54. Rijkswaterstaat Deltadienst, The Hague, pp. 203–211.
Rijkswaterstaat, 1972. De bodemveranderingen aan weerszijden van de Haringvlietsluizen. Driemaandelijks Bericht Deltawerken, 60. Rijkswaterstaat Deltadienst, The Hague, pp. 517–520.
Rijkswaterstaat, 1973. Veranderingen in de mond van het Haringvliet sedert de afsluiting. Driemaandelijks Bericht Deltawerken, 63. Rijkswaterstaat Deltadienst, The Hague, pp. 146–163.
Rijkswaterstaat, 1978. De oorsprongen van het Deltaplan. Driemaandelijks Bericht Deltawerken, 83. Rijkswaterstaat Deltadienst, The Hague, pp. 114–123.
Rijkswaterstaat, 2013. Kenmerkende Waarden Getijgebied 2011.0. Report Rijkswaterstaat Centrale InformatieVoorziening, Delft.
Rijkswaterstaat Deltadienst, 1979. The storm-surge barrier in the Eastern Scheldt. Geol. Mijnb. 58, 459–462.
Roskam, A.P., 1988. Golfklimaten voor de Nederlandse Kust. In: Report GWAO-88.046, Rijkswaterstaat, Tidal Waters Division, The Hague.
Stouthamer, E., Cohen, K.M., Hoek, W.Z., 2015. De Vorming van het Land. Geologie en Geomorfologie. Perspectief Publishers, Utrecht.
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. Geol. Mijnb. 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. Geol. Mijnb. 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.
Van de Kreeke, J., Haring, J., 1979. Equilibrium flow areas in the Rhine-Meuse delta. Coast. Eng. 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. In: Report ZL 87.0020, Rijkswaterstaat, Deltadienst, Zierikzee.
Van den Burg, G., 1989. De Nieuwe Waterweg – Poort van Europa. De Bataafsche Leeuw, Amsterdam, 144 pp.
Van der Spek, A.J.F., 1987. Inventariserend morfologisch onderzoek Voordelta; Beschrijving van de ontwikkeling van de buitendelta's van Haringvliet en Grevelingen. In: Report GWAO-87.105, Rijkswaterstaat, Tidal Waters Division, Middelburg.
Van Driel, W., 1959a. Bodemveranderingen in de mond van het Brielse Gat en het aangrenzend zeegebied in de periode 1821 tot en met 1950. In: Report K-146. Rijkswaterstaat Deltadienst, Waterloopkundige Afdeling, The Hague.
Van Driel, W., 1959b. Bodemveranderingen in de mond van het Haringvliet en het aangrenzende zeegebied in de periode 1821 tot en met 1957. In: Report K-149. Rijkswaterstaat Deltadienst, Waterloopkundige Afdeling, The Hague.
Van Heteren, S., 2002. Analyse van slibdikte in de monding van het Haringvliet. In: Report NITG 02-200-B. Netherlands Institute 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).
Watson, I., Finkl, C.W., 1990. State of the art in storm-surge protection: the Netherlands Delta project. J. Coast. Res. 6 (3), 739–765.
Watson, I., Finkl, C.W., 1992. Simplified technical summary of the complete Delta Works, including the Eastern Scheldt. J. Coast. Res. 1–56.
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. In: Weg en Waterbouw - Dokumentatiereeks Bouwen en Baggeren, Part 1, pp. 44–50.