# *Dynamic Preservation* of Texel Inlet, the Netherlands. Understanding the interaction of an ebb-tidal delta with its adjacent coast.

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## Abstract

Already in 1990, the Dutch government enacted a new coastal policy, called 'Dynamic Preservation', to fight structural erosion using sand nourishments as its principal source. Over 30 million $m^3$ of sand was placed on the coastlines adjacent to Texel Inlet since 1990, making maintenance of these beaches to the most intensive of the entire Dutch coastal system. High-frequent and detailed observations of both hydrodynamics and morphodynamics of Texel inlet have resulted in a unique dataset of this largest inlet of the Wadden Sea. The availability of these data, in combination with substantial changes in ebb-tidal morphology and volume, provide a unique opportunity to investigate inlet sediment dynamics in a mixed-energy tide-dominated environment, conceptually describe the linkage between the morphodynamic behavior of the ebb-tidal delta with the adjacent coastlines, and evaluate the effects of over 20 years of Dynamic Preservation.

Eighty-five years after closure of a major part of its basin, the morphological developments on the Texel ebb-tidal delta are still dictated by sediment redistribution on the ebb-tidal delta, and sediment exchange between ebb-tidal delta and basin. In the timeframe 1986-2012, over 200 million $m^3$ of sediment was eroded from the ebb-tidal delta and coast. Half of these sediments were redeposited further landward on the ebb-delta, and the remaining half was likely transported into the basin. Sand nourishments applied as part of the Dynamic Preservation strategy have been able to stabilize structural retreat of the inlet adjacent coastlines. Moreover, the abundant supply of sediment may have also compensated for the sediment losses on the larger scale of the southern part of the ebb-tidal delta resulting in a recent stabilization of its volume. This response illustrates the potential benefits of Dynamic Preservation not only for coastline resilience but also on the larger scale of the inlet systems. Such knowledge is essential for future preservation, management and maintenance of inlet systems in the scope of climate change and accelerated sea-level rise.

**Key words:**

coastal morphodynamics; coastal management; ebb-tidal delta; impact of large-scale engineering; the Netherlands; sediment budget; tidal inlet

# 1. Introduction and objective

## Introduction

Systems of barrier islands and associated tidal inlets are found along a major part of the world's coastlines and in a wide variety of geomorphic settings (Glaeser, 1978; Davis & FitzGerald, 2004; Stutz & Pilkey, 2011). Historically, the barrier islands, adjacent coasts, and sheltered back-barrier basin have been attractive for human settlement. In recent times, more and more awareness arose that these inlet systems also form unique landscapes and valuable habitats for numerous marine species and birds, and that coastal development and shoreline protection structures, may have severely impacted or constrained the natural dynamics. How exactly anthropogenic pressure impedes the ability of natural systems to respond to changing forcing, at present or in the future (especially in the scope of climate change), and how to support a sustainable environment for both humans and nature, are essential questions that still need to be answered. Analysis of field data obtained for Texel Inlet (the Netherlands) that illustrates the interaction of Texel inlet with its adjacent coasts, including the effects of decades of coastal maintenance and management, can provide valuable insights to unravel this question.

## Dynamic Preservation

In 1990, the Dutch government enacted a new coastal policy, called '*Dynamic Preservation*', to fight structural erosion occurring along the major part of the Dutch coastline (see e.g. Rijkswaterstaat, 1990; Hillen & de Haan 1993; Hillen & Roelse, 1995; de Ruig, 1998). Through this policy, the coastline is maintained at its 1990 position using sand nourishments as a principal source which allows natural coastal processes to be maintained. Preservation of natural dynamics is especially relevant in complex morphodynamic settings such as found in and around tidal inlets.

Texel inlet forms the transition from the continuous beach-dune coast of Holland to the interrupted barrier-inlet-estuary system of the Wadden Sea: a worldwide recognized maritime conservation area and Unesco Word Heritage site since 2009. Over 30 million $m^3$ of sand was placed on the coastlines adjacent to Texel Inlet since 1990, making maintenance of these beaches to the most intensive of the entire Dutch coastal system (e.g., Mulder, 2000; Roelse, 2002; Hoogervoorst, 2005). It is generally assumed, that the major part of these sand losses results from the sediment transport into the basin (Stive & Eysink, 1989; Louters & Gerritsen, 1994), but how the sand exchange between coast, ebb-tidal delta, inlet and basin transpires, and exactly which processes determine this exchange are not fully understood, even though many studies have been conducted in the past (e.g. Beckering Vickers, 1951; Battjes, 1962; Sha, 1989; Sha, 1990; Elias, 2006; Elias & Van der Spek, 2006; Elias et al., 2012).

## Conceptual Models

The basic processes controlling the shape of an ebb-tidal delta are well known (see a recent summary by Hayes & FitzGerald, 2013). In principle, the geometry of the back-barrier basin, in combination with tidal range, determines the tidal prism which, under equilibrium conditions, in turn determines the cross-sectional size of the inlet (Jarrett, 1976; O'Brien, 1931; 1969) and the volume of the ebb-tidal delta (Walton & Adams, 1976). The geometry of barrier islands, the inlet gorge and the ebb-tidal delta facing the inlet are shown to reflect the ratio between wave- versus tidal energy. Conceptual descriptions by e.g. Hayes, (1975, 1979), Oertel (1975) and Hubbard et al., (1979) show that wave-dominated ebb-tidal deltas tend to be pushed closer to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore. The inlet morphology is also influenced by other variables such as geological parameters (coastal physiography, regional stratigraphy, bedrock outcrops), basin geometry, and processes such as sediment supply, river discharge and sea-level changes (Davis & Hayes, 1984, FitzGerald, 1996). Elias & van der Spek (2006) showed the importance of anthropogenically induced change that dominated the recent history of Texel Inlet. For the configuration of the adjacent coastlines, the sediment delivery through longshore drift, and sediment bypassing on the ebb-tidal delta play an important role (Bruun & Gerritsen, 1960; Hayes, 1979, FitzGerald et al., 1984).

Conceptual models and empirical relationships have significantly contributed to an improved understanding of inlet behavior and evolution on higher levels of aggregation. However, their major shortcoming is that they often lack descriptions of the underlying physics. These physics are essential if one aims to understand changes on smaller scales, where human intervention may influence the behavior such that it cannot be accurately described by existing concepts and equilibrium relations.

### Objective

The processes controlling the sediment exchange between the Texel tidal inlet and the adjacent North-Holland and Texel coasts are insufficiently understood, despite the importance of the inlet in the Dutch coastal system and sand budget. The specific research goals of this study are:

(1) to improve the understanding of the sediment dynamics of Texel Inlet and its influence on the adjacent coast. Such knowledge is not only essential for future sustainable coastal management of Texel inlet but can also teach valuable lessons for many of the worlds inhabited inlet systems that are under erosional threat;

(2) to derive and explain the main transport patterns and mechanisms, and their relation to coastline management strategies (nourishments) applied, and

(3) to disclose the data of the evolution of Texel inlet to the international community since datasets comprising both frequent observations of anthropogenically-induced morphodynamic change, and the responses of the system to a wide variety of coastline protection measures, are scarce.

To achieve these goals, we analyze recent measurement of hydrodynamics and morphodynamics. An extensive record of well-monitored human interventions (e.g. nourishments) in addition to intensive monitoring of the Texel ebb-tidal delta by Rijkswaterstaat (the water and coastal management authority of The Netherlands), over this interval has created a globally unique dataset. The use of monitoring techniques such as Acoustic Doppler Current Profilers (ADCPs) and MultiBeam EchoSounder surveys, provides background for an in-depth analysis of the underlying physics that determine the morphodynamic changes of the inlet.

## 2. Study Area

### 2.1. General Setting

Texel Inlet is the largest and most westerly located inlet of the Wadden Sea (Fig. 1). The inlet gorge, Marsdiep, is located between the northern tip of North-Holland and the island of Texel. Marsdiep connects to Texelstroom, the main channel in the basin and the channels on the ebb-tidal delta: Molengat, Schulpengat and Nieuwe Schulpengat. Acceleration of flow around the western tip of Helderse Zeewering (zeewering = sea defense) locally increased the channel depths to over 50 meters at the location of Helsdeur (Fig. 1; [5]). The ebb-tidal delta protrudes approximately 10 km seaward and stretches 20 km alongshore, determining the nearfield bathymetry of the adjacent North-Holland coast in the south and the Texel Island coast to the north. The ebb-tidal delta is asymmetrically shaped. The center is formed by Razende Bol, the eastern, supratidal part of the Noorderhaaks swash-platform, which faces the inlet gorge. North of Noorderhaaks a large sub-tidal spit (Noorderlijke Uitlopers van de Noorderhaaks which translates into Northern extension of Noorderhaaks shoal and is further indicated with NUN) extends along the Texel coastline, separated from the island by the Molengat channel. The interaction between Molengat and the Texel coastline plays an important role in the sand losses of the adjacent beaches (Cleveringa, 2001). On the southern part of the ebb-tidal delta, the two main channels Schulpengat and Nieuwe Schulpengat, divided by the channel-margin linear bar Bollen van Kijkduin, extend along the North-Holland coastline. Nieuwe Schulpengat extends in a southward direction, diminishing in depth and curving seaward. The shallow channel Nieuwe Landsdiep is located in between Nieuwe Schulpengat and the North-Holland coastline, causing structural sand losses (Elias & Cleveringa, 2003). At the seaward end of Nieuwe Schulpengat, Franse Bankje forms the channel's terminal lobe. The more seaward positioned Zuiderhaaks can be considered to be the terminal lobe of the channel Schulpengat.

The ebb-tidal delta is primarily composed of sand, with the coarsest sand in the inlet channel and proximal parts of the ebb-delta channels (Sha, 1990, McLaren et al. 1998, and Fig. 2). In the inlet gorge (Mardiep and Breewijd) the average grain size exceeds 300 $\mu$m and locally sediments exceed 400 $\mu$m. In Schulpengat and Nieuwe Schulpengat, average grain sizes vary between 200 and 300 $\mu$m. Generally, in a seaward direction, the average grain size decreases to values between 180 and 240 $\mu$m on the shoals (Zuiderhaaks and NUN). The central part of Noorderhaaks is slightly coarser with values between 200 and 300 $\mu$m. In Nieuwe Schulpengat, outcropping Pleistocene clay and peat layers cause alongshore and temporal variations in the migration rates and cross-sectional geometry of the channel (van der Spek & van Heteren, 2004).

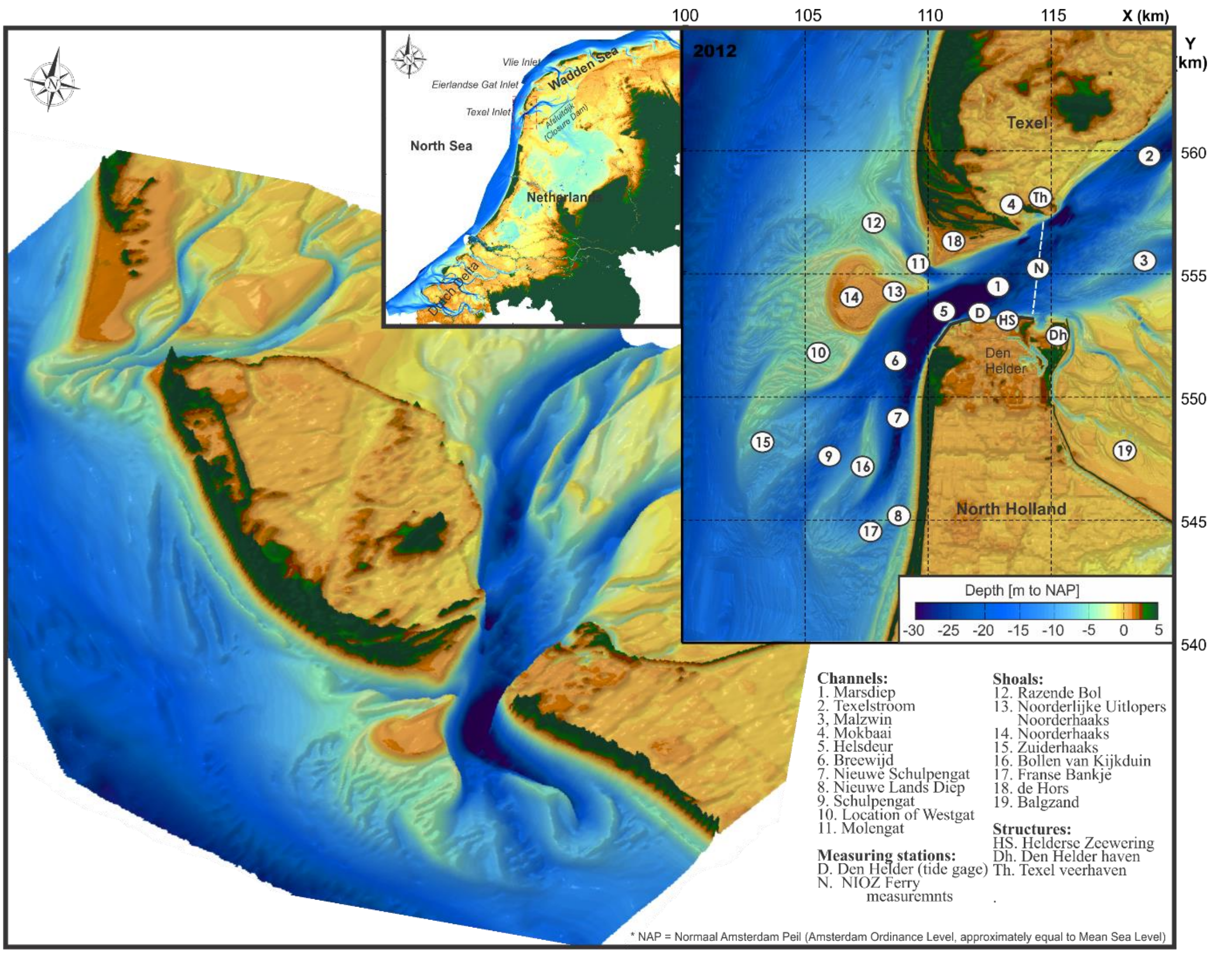


***Figure 1:*** *Location plot of the western part of the Wadden Sea coast including details of the main channels and shoals forming the Texel inlet and its ebb-tidal delta (based on 2012 measurements).*

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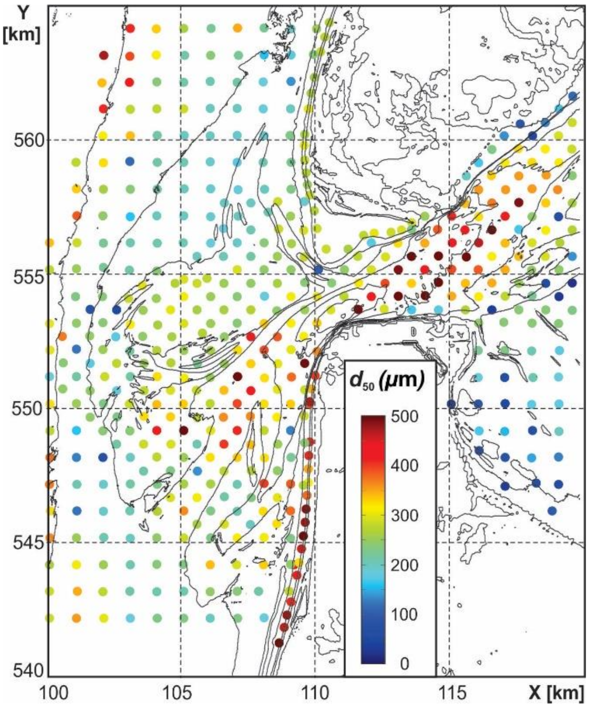


***Figure 2:*** *Grain size diameters on Texel ebb-tidal delta. Depth contours indicate the 1992 bathymetry (see Mc. Laren et al. 1998 for details on measurements).*

## 2.2. A mixed-Energy inlet

Tides and wind-generated waves are the dominant (natural) processes governing the morphological development of Texel Inlet. Following the classification of Davis and Hayes (1984) the inlet qualifies as mixed-energy wave-dominated, even under spring-tide conditions. However, the morphology of the inlet shows tide-dominated characteristics such as a large ebb-tidal delta. This is caused by the large tidal volume and associated strong currents in the inlet, and the relatively low wave energy.

In the inlet gorge Marsdiep, the semi-diurnal tide has a mean tidal range of nearly 1.4 m which increases to 2.0 m during spring tide and drops to about 1.0 m during neap. On average ebb- and flood volumes through the inlet are c. 1 billion $m^3$, with peak ebb- and flood-tidal velocities ranging between 1 and 2 m/s (Postma, 1954; Ridderinkhof et al. 2002; Buijsman & Ridderinkhof, 2007a). The tidal signal only partly represents the measured water levels. Meteorological distortion due to air pressure and wind-generated set-up or set-down can reach significant heights along the Dutch coast. At the Den Helder tidal station, set-ups of nearly 2 m are measured sporadically during major storm events. In the Wadden Sea, with its complex bathymetry, set-up-gradients can drive complicated residual flow fields, generate shore-parallel velocities and throughflow between adjacent basins (Duran-Matute et al., 2014). In addition, the volume of water stored in the Wadden Sea due to the larger set-up can considerably enlarge the outflow velocities in the inlets following the storm events, thereby affecting channel dimensions, the ebb-tidal delta development and adjacent beaches (Elias, 2006).

Supply of fresh water into the western Wadden Sea is limited. No direct river runoff occurs into the Texel basin, but periodically fresh-water from the IJsselmeer is drained into the basin through sluices in the closure dam “Afsluitdijk” near Den Oever and Kornwerderzand. The yearly averaged release of 450 $m^3$/s is minor relative to the tidal fluxes through the inlets, however, significant seasonal variations occur. During dry periods (summer), discharges can reduce to zero and in periods of high rainfall (autumn and spring) discharges can exceed 1500 $m^3$/s. Observations by Zimmerman (1976) indicate that the bulk of the fresh-water discharged through the Den Oever sluices leaves the Wadden Sea via Marsdiep, and surface salinity values below 20 ppt. are occasionally observed in Marsdiep during and after periods of major fresh-water discharge. The resulting density gradients may be important for the sediment exchange through the inlets (Buijsman & Ridderinkhof, 2008c; Burchard et al., 2008; Elias & Stive, 2006).

Wind measurements taken at the nearby Texelhors station (Fig. 3A) show a mean wind velocity of 7.1 m/s from a south-southwesterly direction (196°). Limited knowledge is present on the importance of the wind and wind-driven flow in the inlet domain, but with a predominant landward direction, wind is likely to enhance tidal flow and sediment import into the basin. Inside the basin, we can expect the wind to be important for mixing and estuarine circulations, and in shallow areas wind is effective in generating large currents and tidal flat degeneration by locally generated waves. The eastward migration of the tidal divides in the Wadden Sea may for a major part be related to the prevailing wind direction (FitzGerald et al., 1984; Van Veen et al., 2005).

Representative measurements of the nearshore wave climate are taken at the nearby Eierlandse Gat wave buoy located in the open sea 30 km to the north of Texel inlet in a water depth of 26 m (X-km: 106514, Y-km: 587985). Analysis of the measurements over the period 1980-2016 and summarized in the wave rose presented in Fig. 3B reveals that the wave climate is dominated by wind-generated waves in the North Sea basin. The wave climate is fairly mild. Typically waves are below 3 m (95% of the record), only during severe storms wind-generated significant wave heights can occasionally reach heights between 4.5 and 8.1 m (less than 1 % of the record). Most frequently wave directions (81%) lie between southwest (32%) and north (49%) with mean significant wave heights of 1.44 and 1.48 m respectively. Waves from the easterly direction (0°-360°) are smaller due to the sheltering by the mainland (offshore directed) and occur less frequently. Wave periods ($T_{1/3}$) generally vary between 3 to 5 seconds for low wave conditions (95 % of the measurements). For typical storm waves ($H_{sig}$= 2-3 m) a mean wave period of 5.5 s occurs increasing to 6.5 s for severe storms ($H_{sig}$ > 3m). Contributions of swell are minor. Wave periods over 9 seconds are only measured occasionally (< 1% of the record).

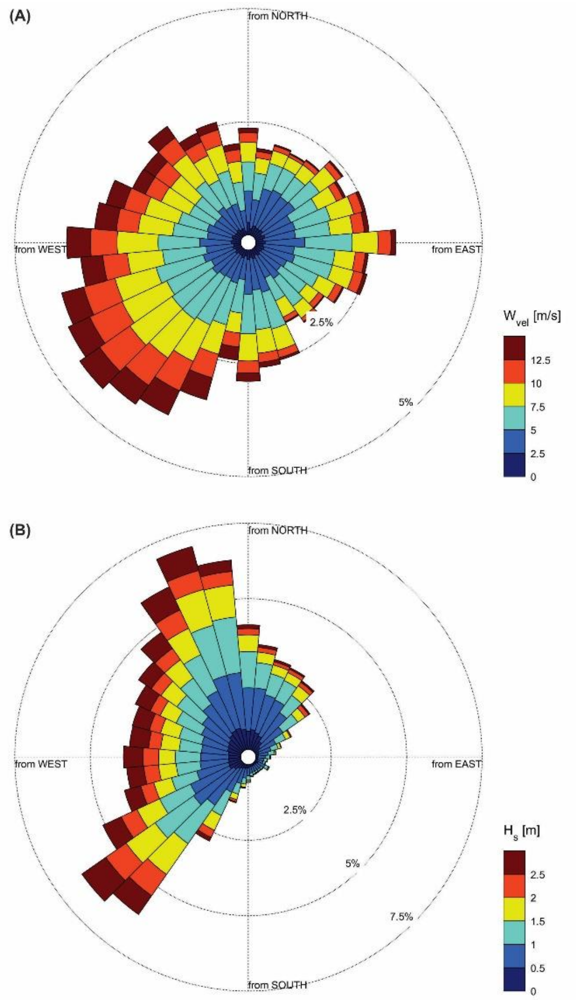


***Figure 3 (A):*** *Wind rose for measurements of wind velocity and direction at station Texelhors (1980-2016), and* ***(B)*** *wave rose based on measurements of significant wave height (Hsig)and direction at the Eierlandse Gat wave buoy (1980-2016).*

## 2.4. History of the Ebb-tidal delta

The present day Wadden Sea was shaped over a period of over 7000 years. A wide variety of barrier islands, channels, sand and mud flats, gullies and salt marshes formed under a temperate climate, rising sea-level (Eisma & Wolff, 1980; Vos et al., 2011), and, in particular during the last century, human interventions (Oost & de Boer, 1994; Schoorl, H. 1999; Elias & van der Spek, 2006; Elias et al. 2012). Regular bathymetric observations of Texel Inlet's ebb-tidal delta have been conducted since the 16th century, and digitally available recordings are present since 1925 (De Kruif, 2001). Analysis of these long records can yield valuable insights in the sediment budget of Texel Inlet, and improve insight into inlet-coast dynamics in general (see e.g., Sha, 1989a; 1989b; 1990; for examples). Elias & Van der Spek (2006) demonstrated the importance of the construction of extensive coastal defense works on the southern shore of the inlet in 1750 A.D (predecessors of Helderse Zeewering), and the damming of the Zuiderzee completed in 1932 A.D.

Prior to construction of the Helderse Zeewering, the ebb-tidal delta showed a downdrift asymmetry. Periodic shoal breaching and downdrift channel relocation were the dominant mechanisms for sediment bypassing (Joustra, 1973; Sha, 1990; Van Heteren et al., 2006). Although other factors may have played a role, after the construction of the coastal defense works, a stable ebb-tidal delta with a westward stretching main ebb-channel and large downdrift shoal area, Noorderhaaks, developed over a period of c. 60 years (see Fig. 4, 1926 for a representative bathymetry for this stable state).

Damming of the Zuiderzee, separating the major part of the back-barrier basin, distorted this stable state. The closure dam Afsluitdijk, completed in 1932, reduced the Texel and Vlie basins from over 4000 km$^2$ to roughly 1400 km$^2$. The change in tidal characteristics from a propagating to a standing tidal wave, and greater tidal wave reflection at the closure dam drastically increased the tidal range from approximately 1.15 to 1.4 m at Den Helder tidal station and the tidal prism through Texel inlet enlarged by 26% (Elias et al., 2003; Rietveld, 1962; Thijsse, 1972).

The large changes in basin hydrodynamics and geometry resulted in pronounced changes in the morphodynamic evolution of the remaining basin. These changes have been intensively investigated and are well documented (see Berger et al., 1987; Oost & de Boer, 1994, Elias et al., 2003; Elias et al., 2012). On the ebb-tidal delta, over a period of c. 40 years the main channel switched to a southward direction and developed into two separate channels: Schulpengat and Nieuwe Schulpengat (Fig. 4, 1948 and 1971). These channels reached a maximum length in approximately 60 years and have remained stable in position since (Elias et al., 2003; Elias & Van der Spek, 2006). In the meantime, the ebb-tidal delta showed a southward and northward growth. In the southern part, sediment supplied by the main tidal channels extended the ebb-delta front (Zuiderhaaks), while wave-driven transports contributed to landward- and northward-directed redistribution of sand from the abandoned ebb-delta front (western margin of Noorderhaaks) in the northern part (Fig. 4). This northward transport contributes to the elongate outbuilding of the ebb-tidal delta along the Texel coastline (Elias et al., 2003; Sha, 1989b).

The re-orientation of the main channels and shoals has had large consequences for coastal maintenance; between 1935 and 2005 nearly 300 million m$^3$ (*mcm*) of sand was eroded from the Texel ebb-tidal delta and adjacent coastlines contributing to the over 450 *mcm* of sediments that were deposited in the Western Wadden Sea (Elias et al. 2012). Major deposition of predominantly fine-grained sediments was observed in the cut-off channels near the closure dam and on the shoals along the Frisian coast (Berger et al., 1987; Eisma & Wolff, 1980). The large morphodynamic changes of the ebb-tidal delta must have contributed to the observed erosion of the coastlines. And even today, large nourishment volumes are needed to maintain the coastline position.

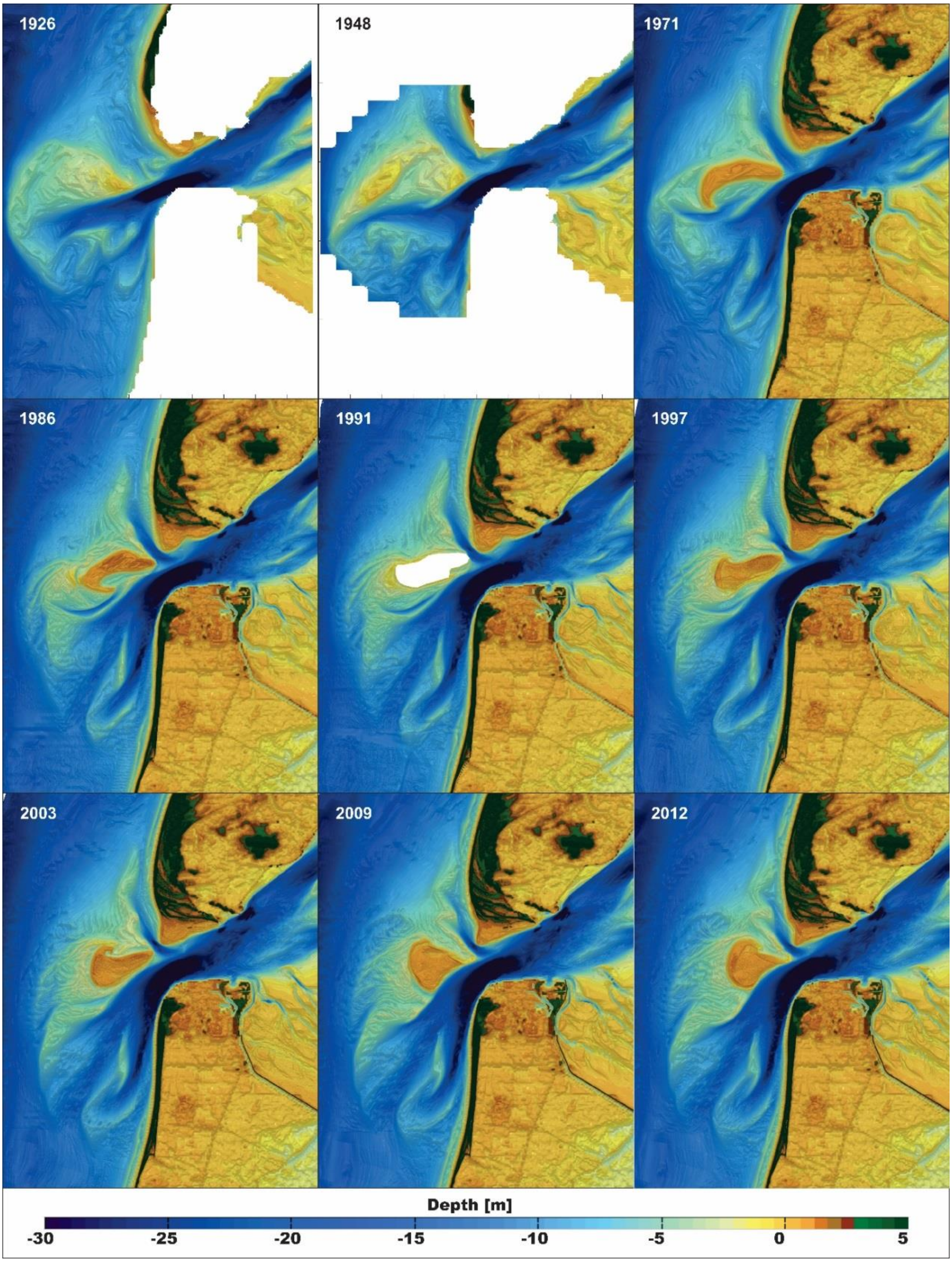


***Figure 4:*** *Representative maps for the 1926-2012 time-frame illustrating the morphodynamic adjustment of the ebb-tidal delta to the effects of closure of the Zuiderzee (completed in 1932).*

## 2.5. Development of the coastlines and shoreline protection measures.

A long history of protection measures along the shorelines adjacent to the Texel inlet exists. In the early 17th century A.D., the first defensive works such as wooden groins and underwater willow mattresses were placed on the southern embankment of Marsdiep to retard the erosion at the tip of North-Holland. Nevertheless, it was not until the 18th century before the continuous scouring was permanently halted by the construction of stone revetments, predecessors of what is now known as Helderse Zeewering (zeewering = sea defense); see Elias & Van der Spek (2006) for details. In the 1800's the first groins were also placed along the North Sea coastline south of the inlet, and by 1930 the entire coastline between the Helderse Zeewering and the Hondsbosche and Pettemer Zeewering, 20 km south of the inlet, was completely protected by 69 stone groins (Fig. 5). Both Rakhorst (1984) and Verhagen & van Rossum (1990) conclude that these groins have not been able to eliminate the coastal erosion. Only the groins that attach to the Helderse Zeewering have been able to maintain the coastline position at this place.

Along the southwest coast of Texel, 22 groins were constructed between 1959 and 1987 (Fig. 5). Similarly to the North-Holland coast, these groins reduced but did not stop the ongoing retreat. An analysis by Rakhorst (1984) reveals that the retreat reduced from 6-16 m/year prior to 1984 to 0-6 m/year since. Rakhorst concluded that groins are particularly successful in blocking the longshore transports in the surf zone, which reduces the associated erosion. However, the groin fields do not (drastically) influence the cross-shore transports that move sediments from the coast seaward. If a significant longshore transport capacity exits outside the groin field, these deposits can still be transported alongshore and result in continued coastal erosion, which explains why periodic nourishments are needed to maintain the adjacent coastline. In addition, increased erosion downdrift of the groin field may occur due to reduced sediment supply (e.g. Fleming, 1990; Kraus et al. 1994, Basco & Pope, 2004, Van Rijn, 2011).

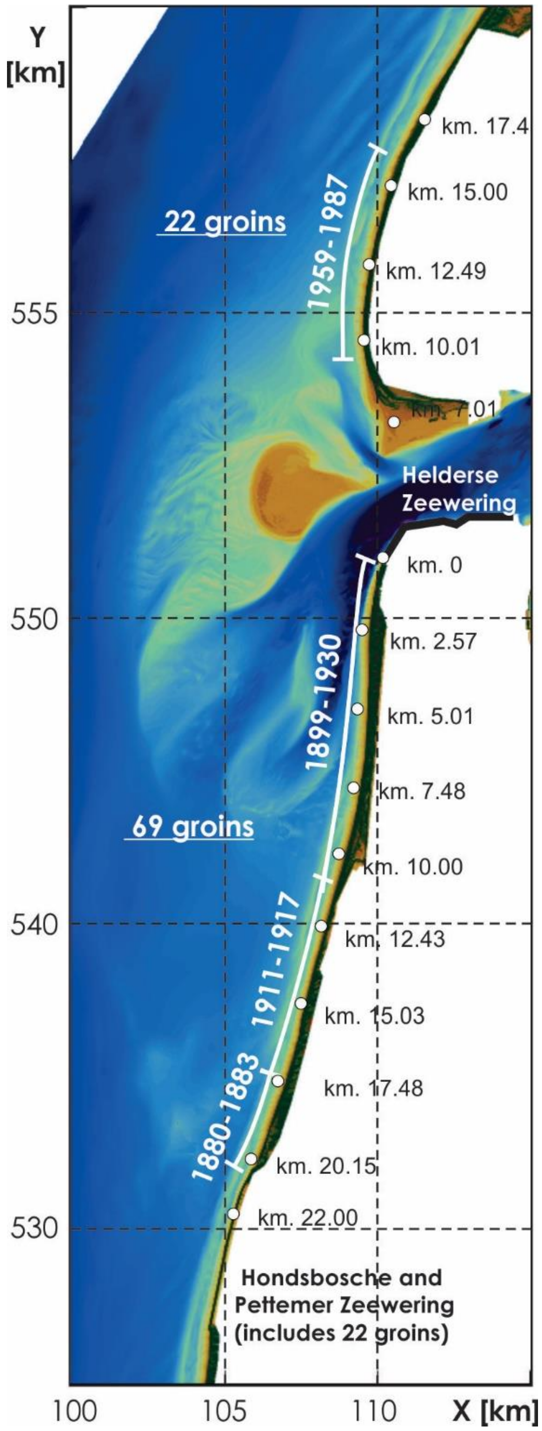


***Figure 5:*** *Overview of locations of groins along the Texel and North-Holland coastlines (source Verhagen & van Rossum, 1990).*

A large increase in nourishment volumes has been observed since 1990 when the national *Dynamic Preservation* policy was enacted. In the southwestern part of Texel Island almost 9 *mcm* of sand was nourished between 1993 and 2012 (see Table 1 for an overview). Most of these nourishments were placed directly on the beach. Only in 2007, a large, 2 *mcm* shoreface nourishment was placed.

Along the North-Holland coast mitigation of the coastline retreat has resulted in the placement of over 38 *mcm* of sand in the period 1978-2012 between the two sea defenses. Most of these nourishments, with a total sand volume of 27.5 *mcm*, were placed in the direct vicinity of the inlet (Fig. 1, Y-km. 540-552.5), making the maintenance of this stretch of shoreline one of the most intensive of the entire Dutch coastal system (Hoogervoorst, 2005; Mulder, 2000; Roelse, 2002).

Recently (2014-2015), the Hondsbossche and Pettemer sea defense has been reinforced with c. 35 *mcm* of sand. It will be interesting to analyze if and how the placement of this large amount of sand directly updrift of the ebb-tidal delta will influence the future morphodynamic developments. However, at present measurement records are too short to perform an analysis.

***Table 1:*** *Overview of the nourishments placed along the coastlines of North-Holland and Southwest Texel (km indication is distance to the inlet, see Fig. 5).*

| North-Holland (km. 0 – km. 20) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Type** (1) | **Year** | **Km. Start** | **Km. End** | **Volume (*mcm*)** | | **Type** (1) | **Year** | **Km. Start** | **Km. End** | **Volume (*mcm*)** |
| 1 | D | 1976 | 12.98 | 13.75 | 0.34 | 14 | B | 2003 | 1.50 | 5.88 | 1.31 |
| 2 | D | 1979 | 11.15 | 12.80 | 0.47 | 15 | SF | 2003 | 9.13 | 9.43 | 0.01 |
| 3 | B | 1986 | 10.83 | 13.73 | 1.24 | 16 | SF | 2003 | 10.00 | 16.00 | 2.32 |
| 4 | D | 1986 | 11.75 | 12.05 | 0.08 | 17 | B | 2003 | 11.10 | 13.75 | 0.44 |
| 5 | B | 1991 | 11.00 | 14.00 | 0.54 | 18 | B | 2004 | 11.10 | 13.74 | 0.26 |
| 6 | B | 1992 | 1.00 | 7.50 | 0.62 | 19 | SF | 2006 | 10.00 | 15.20 | 1.65 |
| 7 | B | 1993 | 3.28 | 5.68 | 0.28 | 20 | CS | 2007 | 0.00 | 2.00 | 1.78 |
| 8 | B | 1996 | 1.50 | 7.50 | 0.40 | 21 | B | 2007 | 1.50 | 5.90 | 1.35 |
| 9 | B | 1996 | 10.01 | 14.10 | 0.46 | 22 | SF | 2007 | 2.00 | 7.10 | 3.24 |
| 10 | B | 1999 | 3.95 | 6.28 | 0.29 | 23 | SF | 2009 | 7.00 | 10.00 | 1.30 |
| 11 | B | 1999 | 13.20 | 14.00 | 0.14 | 24 | B | 2011 | 3.08 | 6.28 | 0.65 |
| 12 | B | 2001 | 1.50 | 5.68 | 1.29 | 25 | CS | 2013 | 0.20 | 2.30 | 3.50 |
| 13 | SF | 2001 | 11.08 | 14.01 | 1.50 | 26 | SF | 2013 | 10.00 | 14.21 | 2.00 |
| ***Total*** | | | | | | | | | | | ***27.46*** |
| **Southwest Texel (km. 0 – km. 18)** | | | | | | | | | | | |
| | **Type** (1) | **Year** | **Km. Start** | **Km. End** | **Volume (*mcm*)** | | **Type** (1) | **Year** | **Km. Start** | **Km. End** | **Volume (*mcm*)** |
| 1 | B | 1993 | 12.10 | 18.13 | 2.25 | 6 | B | 2003 | 9.00 | 11.48 | 0.97 |
| 2 | B | 1994 | 9.30 | 12.10 | 0.76 | 7 | B | 2005 | 8.80 | 10.63 | 0.30 |
| 3 | B | 1997 | 10.38 | 11.43 | 0.34 | 8 | SF | 2007 | 9.00 | 13.50 | 2.00 |
| 4 | B | 2000 | 10.01 | 11.90 | 0.36 | 9 | B | 2009 | 9.00 | 10.70 | 0.40 |
| 5 | B | 2000 | 12.98 | 16.44 | 0.70 | 10 | B | 2012 | 9.00 | 12.00 | 0.75 |
| ***Total*** | | | | | | | | | | | ***8.83*** |

*(1) B= Beach, D = Dune, SF= Shoreface, CS = Channel Slope Nourishment.*

# 3. Analysis of detailed measurements

Improved insight into the processes underlying the observed morphodynamic changes can be obtained from analysis of measurements that were obtained recently, since 1986, with modern techniques. Flow is analyzed using high-frequent ADCP observations in the inlet gorge and main channels on the ebb-tidal delta (section 3.1). Wave measurements are analyzed in section 3.2 based on the data of the nearby Eierlandse Gat station. The analysis of bathymetric changes, using echo-sounding based surveys over the period 1986-2012 in 3-year intervals, and bedform analysis of multi-beam survey data of seafloor bathymetry, complemented with bathymetric data from seismic surveys, provides insight into the dominant sediment transport directions in parts of the ebb-tidal delta (3.3).

## 3.1. Hydrodynamics - flows

### 3.1.1. NIOZ-ferry measurements in the inlet gorge

In 1998 the Royal Netherlands Institute for Sea Research (*NIOZ*) started a long-term high-frequent measuring campaign using a 1.5 MHz ADCP attached to the hull of the ferry from Den Helder to Texel island. During day-time, the ferry (MV Schulpengat and since 2005 MV Dokter Wagemaker) sails the 4.5 km wide Marsdiep every 30 minutes (see Fig. 6B, *NIOZ* for the location of transect and residual flow distribution over the transect). The raw data are transmitted to *NIOZ* and processed. Buijsman & Ridderinkhof (2007a) analyzed the data over the time frame 1998-2002 and reported that the amplitude of water transport through Marsdiep ranges between 50.000 and 90.000 $m^3/s$. Nearly 98% of the variance in the water transport is explained by tides with the $M_2$ (water level amplitude of 0.66 m and horizontal amplitude of 65.750 $m^3/s$), $S_2$ (~27% of $M_2$) and $N_2$ (~15% of $M_2$) being the dominant components. The mean tidal prism amounts to 940 million $m^3$ with ebb volumes between 709-1300 million $m^3$ and a smaller flood volume of 579-1179 million $m^3$. The residual flow through the inlet of around $130x10^6$ $m^3$/tide (~ 3000 $m^3/s$) is seaward directed as a result of the exchange of water with the adjacent Vlie inlet. Based on analytical model results, the earlier work of Ridderinkhof (1988) concluded that this throughflow is related to the tidal amplitude difference between both inlets. However, based on the ferry observations, Buijsman & Ridderinkhof (2007b) suggest that the transport from the Vlie to the Marsdiep is predominantly forced by the local wind stress and to a lesser extent by the tidal stresses between the two inlets. This latter observation is confirmed by the recent studies of Nauw et al. (2014) and Duran-Matute et. al. (2014). Nauw et al. (2014) indicate that the residual volume transport displayed an inter-annual change from export in 2003–2004 to import in 2004–2005. This variation is explained by significant differences in the meteorological forcing conditions of the along-shore current, indicating that the wind-stress forcing dominates over the tidal gradients. A similar conclusion was reached in the numerical model study of Duran-Matute et al. (2014). This study also indicated that for typical conditions the outflow of 600–700 $m^3/s$ through Texel inlet, balancing the inflow of 600–700 $m^3/s$ at Vlie inlet, a 450 $m^3/s$ inflow through the discharge sluices in the Afsluitdijk and net outflow of 100–200 $m^3/s$ through the Eierlandse Gat and over the Terschelling watershed, is much smaller than the values given by Buijsman & Ridderinkhof (2007a).

Detailed analysis of the depth-averaged velocities shows that velocities are more equally distributed across the inlet during flood than during ebb. During ebb, the largest velocities occur along the Texel coastline. As a result, a small flood dominant tidal residual flow is observed along the North-Holland coastline, and a larger ebb-dominant flow dominates the Texel coastline (see Fig. 6B NIOZ transect). Similar flow distributions were observed in the numerical model studies of Elias et al. (2004) and Duran-Matute et al. (2014).

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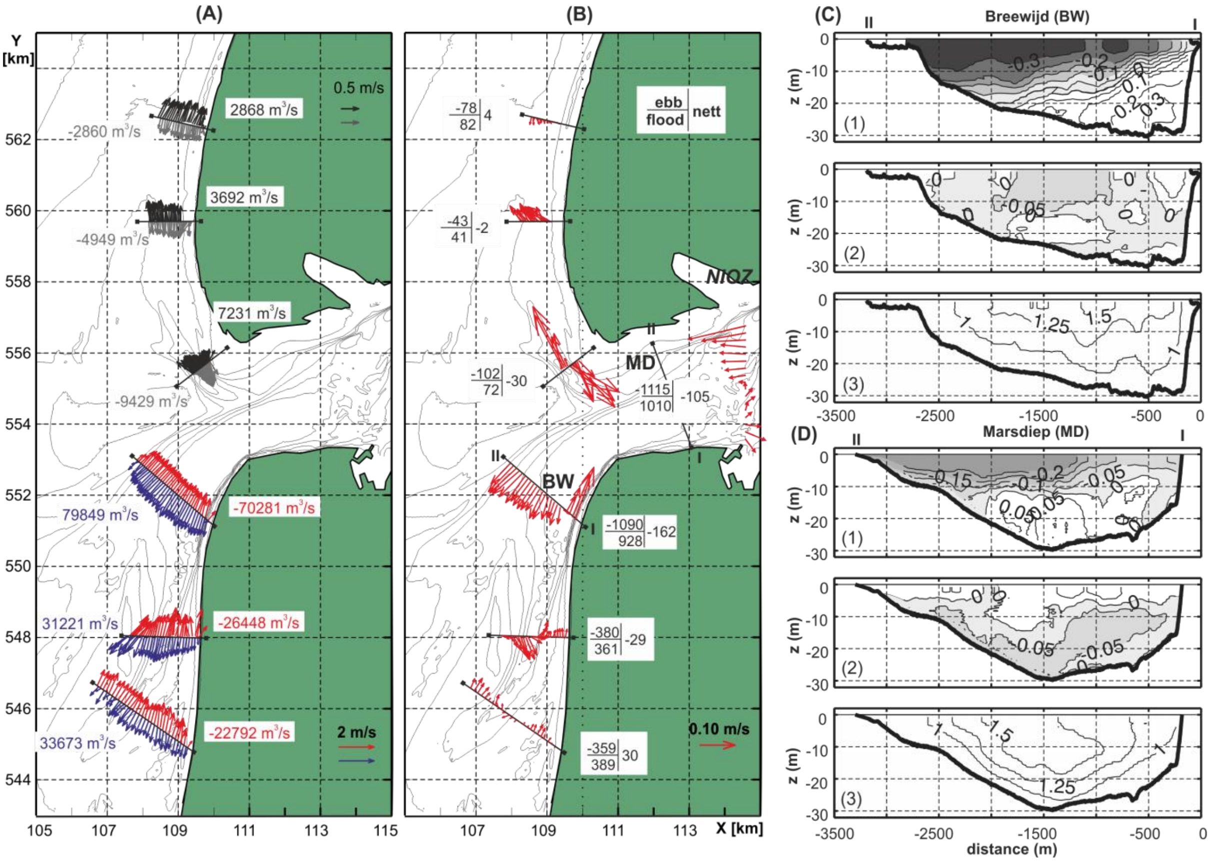


***Figure 6 (A):*** *Overview of measured depth-averaged peak-ebb and peak-flood velocity vectors in Molengat and (Nieuwe) Schulpengat. Numbers indicated transect-averaged maximum ebb- and flood discharges in m3/s. (B). Residual velocity vectors and residual discharge (negative numbers indicate ebb dominance, positive numbers are flood dominant). The residual velocity vectors near Den Helder are based on NIOZ ferry measurements for the year 1999 (Ridderinkhof et al., 2002). Left panels show harmonically analyzed flow measurements in (C) Breewijd and (D) Marsdiep for residual flow in (1) along-channel and (2) across channel direction, and (3) amplitudes of the M2 velocity component.*

### 3.1.2. Roving ADCP transects on the ebb-tidal delta

Flow and velocity estimates in the main channels of the ebb-tidal delta (Marsdiep, Molengat, Breewijd and Nieuwe Schulpengat) were obtained from three 13-hour ADCP campaigns, conducted between 2001 and 2004 by Rijkswaterstaat (Blok & Mol, 2001; Rab, 2004a,b). The raw data were thoroughly analyzed by Rijkswaterstaat to remove systematic errors and erroneous data. During each campaign multiple transects were run obliquely to the channel axes and continuously over a tidal cycle, resulting in 10 three-dimensional flow field distributions of the main ebb-tidal delta channels and inlet gorge (Fig. 6A, B). Although these datasets do not provide long-term time-series, they do allow for an estimate of the discharge patterns and velocity distributions over the individual channels of the ebb-tidal delta.

Flood enters the inlet mainly through Schulpengat (50%) and Nieuwe Schulpengat (40%). Discharges through Molengat are minor (10%). Vice versa, during ebb the majority of the flow is directed from Marsdiep towards the southern part of the ebb-tidal delta (90%). Both Molengat and Nieuwe Schulpengat show a similar distribution of larger flood-dominant flow along the landward side of the channel, and smaller ebb dominant flow along the seaward side, onto the ebb-tidal delta. The distinct separation of flood and ebb flow is plausibly related to the phase lag between the horizontal and vertical tide, and the strong curvature of the coast around the tip of Helderse Zeewering. As a result of this phase lag, ebb-flow still dominates the central part of the channel as flood starts. Seeking the path of least hydraulic resistance, flood, therefore, enters along the Holland coast. Contraction of flood flow around the tip of Helderse Zeewering accelerates the velocities into the inlet. Conversely, the ebb flow originating from the Texelstroom is directed seaward, along with the Texel coastline and Noorderhaaks due to the inertia of flow. For more details see Elias (2006; chapter 5 pages 129-136).

### 3.1.3. Importance of estuarine circulation during high-discharge events

The importance of vertical salinity stratification in the inlet gorge Marsdiep was shown in the studies of Buijsman & Ridderinkhof (2008) and De Vries et al. (2014, 2015). An indication of the large influence of estuarine circulations on the ebb-tidal delta flows may be obtained from the spring 2001 measurements (Blok & Mol, 2001; Elias & Stive, 2006). During this campaign, roving ADCP measurements were performed simultaneously in the main channels. Prior to and during the measurements wind and waves were absent and the freshwater discharge through the drainage sluices in Den Oever and Kornwerderzand was significant with the monthly-mean discharges prior to the measurements exceeding 900 $m^3/s$. In Marsdiep surface salinity values of 24 ppt. and 26 ppt. were observed.

The ADCP flow data was harmonically analyzed to determine the main tidal current amplitudes and residual velocities in along-channel and across-channel direction for the transects Breewijd and Marsdiep (indicated as *BW* and *MD* in Fig. 6B). In Breewijd (Fig. 6C) the axial residual flow velocities dominate over the transverse velocities. Axial residual flood flow in excess of 0.3 m/s is observed along the North-Holland coastline in the deeper part of Breewijd, while along the Noorderhaaks equally strong residual ebb velocities are directed onto the ebb-tidal delta. These residual velocities plausibly result from a combination of density gradients, the bed-topography and the presence of Helderse Zeewering with a distinct sharp bend of the western tip. Ebb-flow of lower salinity is directed from Texelstroom into Marsdiep and onto the ebb-tidal delta. The inertia of flow results in a southwesterly outflow that is largest along the margins of Noorderhaaks. As flood starts to enter the inlet, due to the time-velocity asymmetry, a still relative strong ebb current dominates the central parts of Marsdiep. Flood-flow of higher salinity dominates near the channel bed along the North-Holland coast. Convergence of flow at the tip of Helderse Zeewering results in strong flood velocities along this part of the North-Holland coastline. This flow segregation is observed during a considerable period of the tidal cycle.

In Marsdiep (Fig. 6D), residual flood magnitudes are considerably smaller, and the axial and transverse velocities in the lower part of the profile (below - 15m) are of equal magnitude. Hence, ebb and flood follow similar paths due to the confinement of the flow in the inlet gorge. As in Breewijd, the upper-layers in Marsdiep are dominated by a large ebb-residual flow and a strong vertical shear is observed. The significant differences between patterns and magnitudes of the residual flow and flow amplitude between Breewijd and Marsdiep are an indication of the large influence of the curvature of Helderse Zeewering.

The velocity amplitude of the semidiurnal component in Marsdiep exceeds the amplitude in Breewijd. Acceleration of flow in the inlet gorge is related to a Bernoulli-type acceleration of flow due to constriction of streamlines in the narrow inlet gorge and the strong channel curvature inducing centrifugal acceleration and secondary flow phenomena at the tip of Helderse Zeewering. The amplitude growth is not limited to the $M_2$ but also the $M_4$ and $M_6$ amplitudes (not shown) increase towards Marsdiep. Generation of $M_4$ is generally related to non-linearity in advection, continuity and bottom friction. These nonlinearities seem to result from the transition from the wider ebb-delta to the narrow inlet gorge, that transfers energy from $M_2$ to the $M_4$ and $M_6$ (Blanton et al., 2002).

## 3.2. Waves

Waves are an important factor for sand transport on the ebb-tidal delta. The gross ebb-tidal delta volume might be related to tides or tidal prism (e.g., Hayes, 1975; Oertel, 1975, Walton & Adams, 1976), but waves redistribute the sediments and contribute to the sediment bypassing mechanism (FitzGerald, 1988). Sediment transports are directly influenced due to radiation stresses generated by wave breaking of obliquely incident waves that generate currents, and due to wave asymmetry. Indirectly, waves enhance bed-shear stresses and stir-up sediment, allowing more sediment into suspension to be transported by the tidal and wind-driven flows.

Wave measurements on the Texel ebb-tidal delta are absent, but to obtain an estimate of the dominant components of the wave climate for sediment transport, we have used the wave data for Eierlandse Gat station over the period 1980 - 2016 (Fig. 2B). A morphological wave height (impact) was determined (Fig. 7) using a power relation between transport and wave height with a value of 2.5; similar to the power law in the CERC formulation (CERC, 1984). The MI illustrates that the total transport is bimodal with large contributions from both the southwesterly and north-northwesterly components (Fig. 7). In total, the net wave-driven transports are likely southward directed due to the dominance of the northerly components.

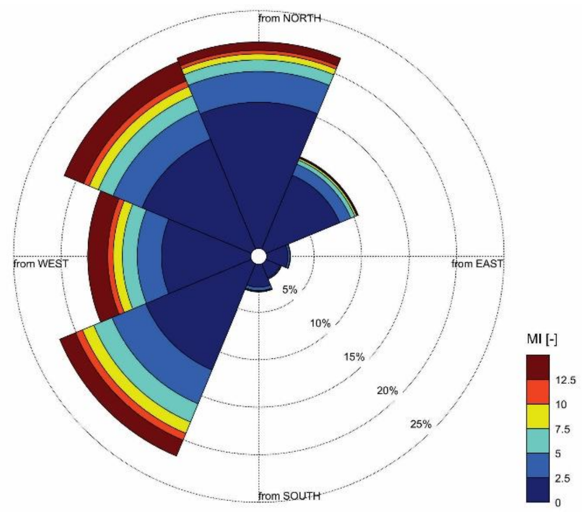



***Figure 7:*** *Estimated Morphological Impact (MI) relative to direction based on data for the wave climate of station Eierlandse Gat over the time frame 1980-2016.*

Although local measurements of the wave-climate in the ebb-tidal delta are absent, inlet systems have shown the effectiveness of ebb-tidal deltas in modifying the near-shore wave climate and reducing the wave energy on the adjacent coastlines (e.g. Hine, 1975; FitzGerald, 1988; Van Rijn, 1997; Elias & Hansen, 2013). The shallow ebb-tidal delta shoals provide a natural breakwater for the adjacent shorelines and effectively prohibit wave propagation from the

North-Sea into the basin. Refraction on the large shoal areas, wave breaking on the shoals especially during the high wave-energy events with large morphodynamic impact, and wave blocking by the supra-tidal shoal areas can largely modify and distort the nearshore wave climate. At Texel Inlet, it is expected that the larger refraction and wave sheltering of the waves from the north results in a net northward directed transport along the North-Holland coastline, and vice versa, the larger reduction of southerly waves enhances the net southward directed transport along the Texel coastline. Thus, on either side of the inlet wave-driven transports are directed towards the inlet. Van Rijn (1997) estimates the northward littoral drift along the North-Holland coastline to range between 0.1 - 0.5 mcm/year.

## 3.3. Sediment Transports and Morphodynamic changes.

### 3.3.1. Introduction and Available data

Direct measurements of sediment transport in Texel Inlet are not available. In this section, we aim to improve our understanding of the dominant sediment transport patterns and rates by analysis of bedforms (section 3.3.2), channel-shoal patterns (3.3.3) and sedimentation and erosion patterns (3.3.4).

The analysis of bedforms is based on a series of detailed multi-beam echo-soundings collected between 2002 and 2004 at several locations in the ebb-tidal delta (see Figs. 8 and 9). These detailed maps allow for the identification of the individual bedform characteristics such as height and asymmetry. Various studies point to the link between bedform morphology, viz. size and orientation, and tidal dominance and flow magnitude. Assuming that the bedforms are still active and governed by present-day hydrodynamic conditions, the bedform distribution, arrangement, and morphology provide information about the locally dominant bottom currents and sediment transports (Boothroyd & Hubbard, 1975; Hine, 1975; Boothroyd, 1985; Ashley, 1990; Lobo et al., 2000).

The analysis of bathymetric changes and construction of a detailed sediment budget are based on a series of bathymetric datasets, starting from 1986 that are digitally available from the Donar database at Rijkswaterstaat. The maps are based on data collected frequently, in approximately 3-year intervals for the ebb-tidal delta and 6-year intervals for the basin. Following quality checking for measurement errors, data are combined with nearshore coastline measurements, interpolated to 20x20 m grids and stored digitally as 10x12 .5 km blocks called *Vaklodingen* (De Kruif, 2001). Each of these maps was visually inspected and clear data outliers or missing (individual) data points were corrected. Maps with missing data along the island shores have been completed using *JarKus* survey data (JarKus, from Jaarlijkse Kustmetingen, Annual Shoreline Surveys) or linear interpolation between the nearest available data points. Example Digital Elevation Models (DEMs) based on these measurements are presented in Figures 1 and 4.

It must be noted that changes in survey techniques and instruments, positioning systems, and variations in correction and registration methods over time make it difficult to estimate the exact accuracy of the measurements and therefore the DEMs. Wiegmann et al. (2005) and Perluka et al. (2006) estimate the vertical accuracy of Vaklodingen data to range between 0.11 - 0.40 m.

### 3.3.2. Bed form analysis.

#### *Nieuwe Schulpengat and Nieuwe Landsdiep*

Visualization of the 2002 high-resolution survey reveals a wide variety in size and orientation of bed forms covering the bed of the Schulpengat and Nieuwe Schulpengat channels (Fig. 8). The largest sand waves, up to 4.25 m in height and having wavelengths of over 200 m, are observed in the deeper parts of Nieuwe Schulpengat (below -20 m) where the highest near-bed tidal current velocities occur. Sand waves in the northern part of the channel predominantly show three-dimensional cuspate crest lines.

Only slipface orientations of the large-scale bedforms, classified as sandwaves and large mega ripples or dunes having wave lengths of over 50 m and wave heights over 0.5 m, have been determined from bathymetric cross-sections of the bedforms taken perpendicular to the crest (indicated by the arrows in Fig. 8A). These large bedforms have long response times and their size and shape hardly change when imposed to high-frequency variations in shear stresses such as e.g., caused by waves and spring/neap cycles in tidal current velocities. For that reason, they provide indications of the long-term (averaged over periods of several days to months) dominant transport directions (Ashley, 1990; Boothroyd & Hubbard, 1975). The slip-face asymmetries point toward a predominantly flood-orientated transport (i.e. to the north). In southward direction, where the depth of Nieuwe Schulpengat decreases and tidal flow velocities diminish, the dominant sand waves are smaller in height (maximum of 2 m) and length (up to 100 m), and have a more two-dimensional setting with relatively straight crestlines. Similar sand waves are also observed in the shallow region along the coastline and in Nieuwe Landsdiep, where the dominant slip-face orientations suggest a net northward sand transport (Fig. 8A). In the distal part of Nieuwe Schulpengat, where the channel ends in the spillover lobe, sand waves are smaller in height, ranging between 0.5 and 2.0 m and having wave lengths between 50 to 110 m. In contrast to the nearshore area, the slip-face orientations of the dominant sand waves indicate that transports are ebb-dominant. A prominent feature is the steep inner channel slope of Nieuwe Schulpengat roughly located at the -15m contour (Fig. 8B), which may result from the presence of erosion-resistant Eemian clay deposits (Van der Spek & Van Heteren, 2004)

### *Marsdiep and Texelstroom*

Additional MBES data are available in a 500 m wide stretch along the Helderse Zeewering, that were collected yearly for monitoring of the state of the toe of the sea defense during autumn and spring since 1999. Consistent bedforms viz., mega ripples and sand waves (dunes) having maximum wave heights of nearly 4.50 m and lengths over 190 m occur in east-west direction along Helderse Zeewering, east of Helsdeur (Fig. 9A). During spring time, bedform heights range between 0.9 and 4.5 m. The average height is 2.6 m with an average length of 90 m. The bedforms are distinctively flood dominant having mean slipface ratios (defined as length of the flood slope/length of the ebb-slope) of 2. During autumn most of the bedforms are over 3 m in height with a maximum of 4.5 m. A slipface ratio of 2.5 indicates an even more flood dominant character of the bedform field. Average wave lengths of 145 m exceed the 90 m spring average. Annual sand-wave migration rates range between 40 and 60 m in an eastward direction. These larger bedforms and migration rates may reflect the seasonality in the wave forcing conditions as typically during autumn large wind and waves (and associated sediment transports) are observed. Similar rates of eastward migration are observed in the NIOZ ferry data (Buijsman & Ridderinkhof, 2008a, b). Their study shows that in the southern half of the inlet, the sand waves are of the progressive type with mean heights of 3 m and lengths of 190 m. In the northern half, the sand waves are asymmetrical-trochoidal with area-mean heights of 2 m and lengths of about 165 m. These authors also point out the seasonal variability in height and migration of the sand waves in the northern half of the inlet. The sand-wave heights are about 0.5 m higher in fall than in spring and the migration rates are about 30 m.y-1 higher in winter than in summer. A shallow seismic profile, by the Geological Survey of The Netherlands (Fig. 9B), confirms the presence of eastward-oriented dunes in Marsdiep. Travelling from west to east, from Helsdeur to Texelstroom, we subsequently observe: no ripples near Helsdeur, predominantly symmetric bedforms in area II-III, large flood-oriented bedforms in area III-IV (see insert 5), no clearly defined bedforms in area IV-V, symmetric bedforms in area V-VI, and large flood-oriented bedforms in area VI-VIII.

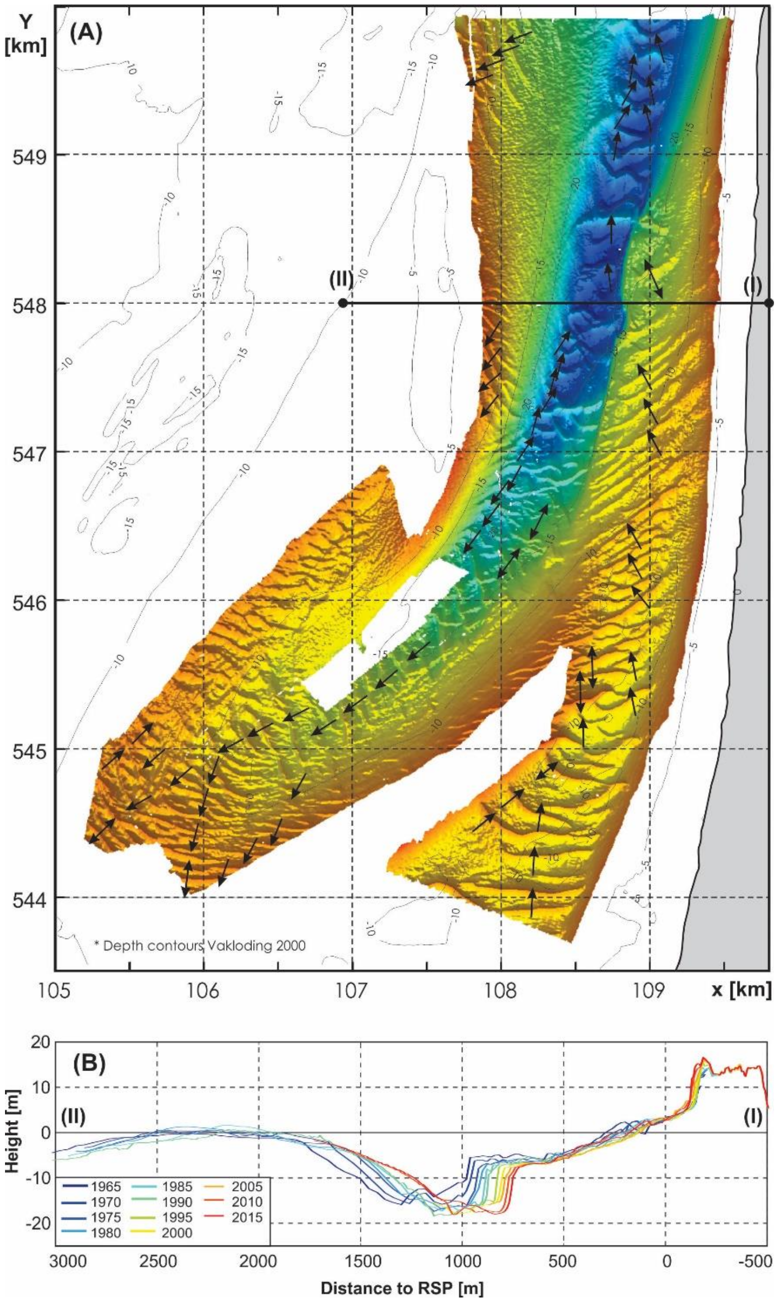



***Figure 8 (A):*** *High-resolution (multi-beam) map of approximately 11 km2 of seafloor bathymetry covering the major part of the Nieuwe Schulpengat and Nieuwe Lands Diep channels (see Rab, 2003, for details). Arrows indicate slip-face orientations of the larger-scale bedforms.* ***(B)*** *Development of cross-section I-II in the time frame 1965-2015.*

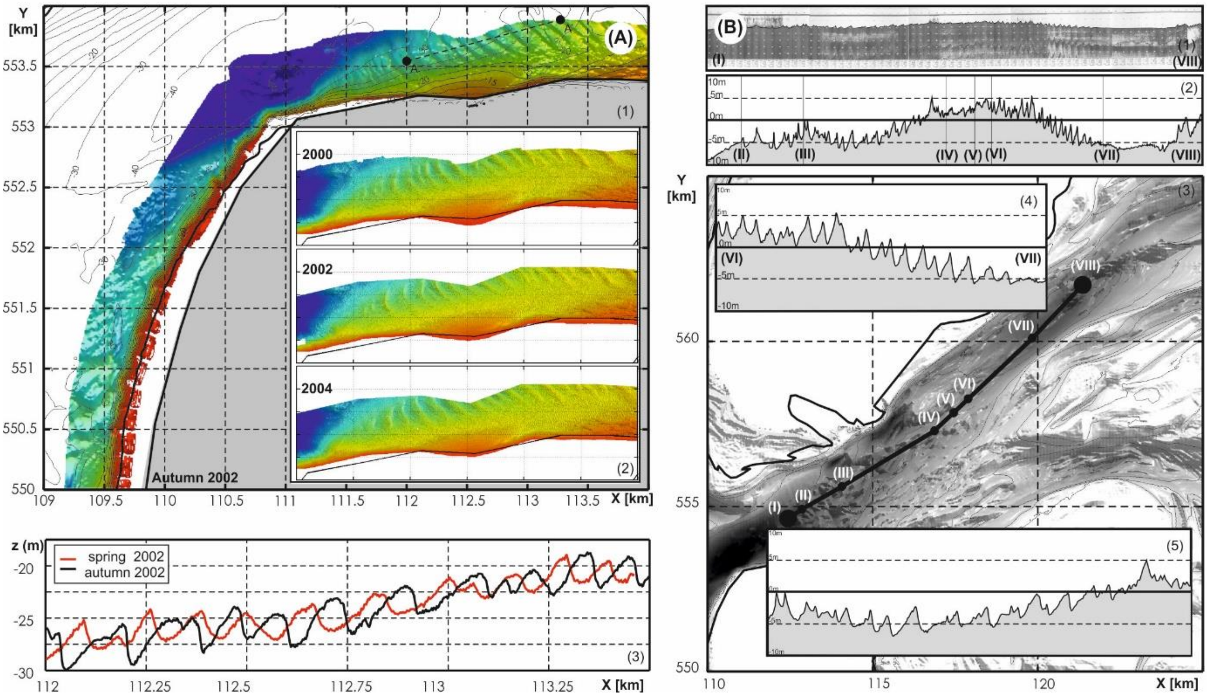


***Figure 9 (A):*** (1) High-resolution multi-beam map of the bedforms present along the Helderse Zeewering (autumn 2002). (2) Details of multi-beam data collected along the northern part of Helsdeur in the spring of 2000, 2002 and 2004. (3) Example of annual bedform variability and migration in transect A-A' by plotting the data taken during spring and autumn of 2002.

**(B):** Shallow seismic cross-section showing bedforms in Marsdiep and Texelstroom: (1) recorded data profile (I)-(VIII) see (3) for location, (2) digitized and rescaled (in the vertical) profile of the bed surface, (3) location plot of measured transects underlying DEM is based on 1997 measurements. Details of the flood-oriented bedforms are shown in insets (4) Texelstroom (transect VI-VII) And (5) Marsdiep (transect III-IV).

### 3.3.3. Channel and shoal distributions on the ebb-tidal delta

In addition to the analyses of smaller-scale bedforms, also the distribution, evolution, shape and size of typical, large-scale ebb-tidal delta elements, such as ebb and flood channels, channel-margin linear bars, terminal lobes and swash-bar patterns can provide useful insights in sediment transport patterns (see e.g. Hayes, 1975; Hine, 1975; Hubbard et al., 1979; Boothroyd, 1985; Sha, 1989b; FitzGerald, 1996).

Partitioning of tide-generated flow, dominating in the major channels, and wave-driven flow prevailing over the shallow platforms is characteristic for ebb-tidal deltas (Hine, 1975). The asymmetrical shape of the ebb-tidal delta, the larger-scale bedforms, and bathymetric features, and the updrift-oriented main ebb channels point to the presence of such partitioning in the Texel ebb-tidal delta (Fig. 4).

A distinction can be made in a shallow, wave-dominated northern and a deeper tide-dominated southern sub-domain, divided by the supratidal Noorderhaaks shoal (Elias et al., 2003). The largest changes in geometric shape are observed in this supratidal area as Noorderhaaks reformed from a concave spit with its apex pointed southward to a more northward dipping configuration (Fig. 4, 1926-1991 versus 1991-2012). This distinct change likely results from the bimodal wave-climate with dominant contributions from both the southerly and northerly directions. As the ebb-delta front eroded and adjusted, the morphological response indicates that wave transformations (sheltering and refraction) resulted in the net sediment transport reversing from southward to northward around 1991. During this landward displacement of the ebb-delta front, the shoal area above MSL increased from about 4.5 $km^2$ in 1986 to over 6 $km^2$ in 2012. A large number of landward migrating saw-tooth bars along the northern margin of the supratidal Noorderhaaks and the northward spit formation at the western tip of this shoal (Fig. 4, 1971 - 2012) indicate that the morphologic developments here are dictated by landward and northward directed transport.

While the seaward side of Noorderhaaks shows large changes, the landward part (Onrust) remained remarkably stable in position over the period 1991-2003. Here, the large flow velocities through Molengat effectively redistribute the landward sediment transports from Noorderhaaks, northward and southward. These transports prohibit the NUN to rapidly migrate landward due to the onshore wave-driven transports. The stability of the shoal and spit indicate that near the inlet a balance between along-channel, tide-dominated transports and landward wave-driven transports exists. This stability is clearly present till 2003, but large changes in the eastern tip of Noorderhaaks and adjacent Molengat channel occur since (Fig. 10A). Between Noorderhaaks and Molengat a new flood channel emerges that pushes the tip of Noorderhaaks to the south. As a result, the width of the channel between Noorderhaaks and De Hors increases, a clear shift from the deepening and landward migrating trend observed since the 1950's (Fig. 10B).

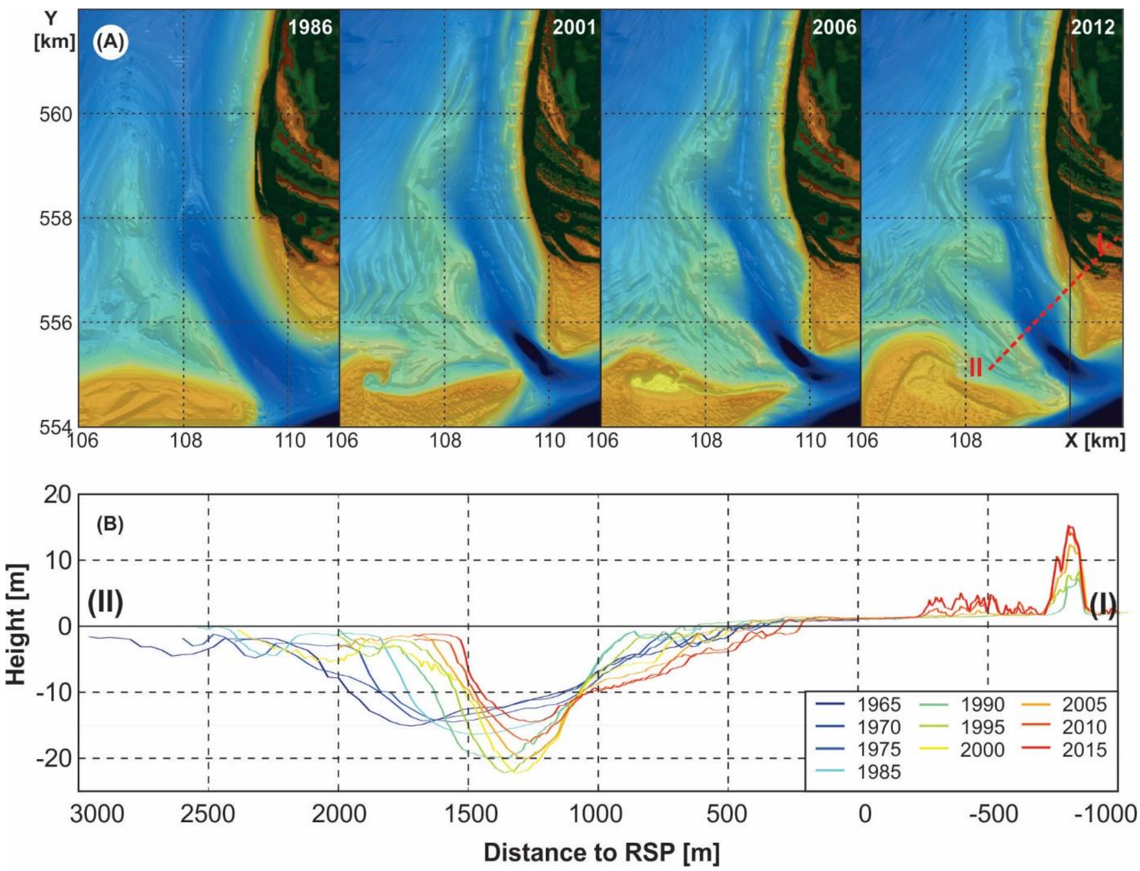
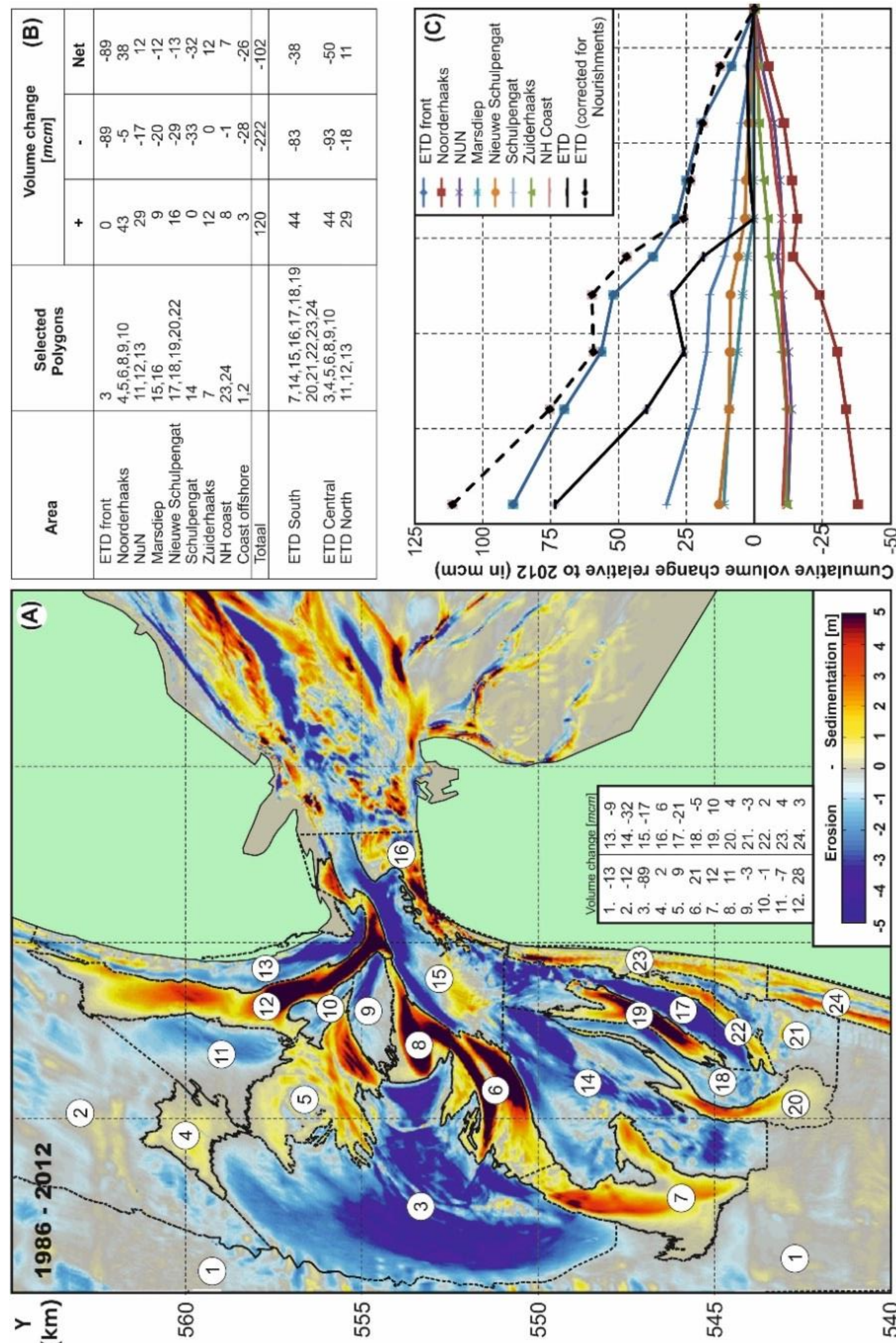



***Figure 10 (A):*** *Details of the morphodynamic changes on the NUN based on Vaklodingen for 1986, 2001, 2006 and 2012 (left to right), and (B) the development of Jarkus profile 704 (see 2012 for location) over the time frames 1965-2015.*

This distorted state has large implications for the nearshore and beach of the island of Texel. Prior to 2006, the channel was deep and narrow, with steep embankments (Fig. 10B). Since 2006 the channel reduces in depth, and the steep channel slopes cannot be maintained. As a result, locally, strong coastal (shoreline) erosion is observed as the channel reduces in slope; the upper part of the profile extends landward due to ongoing wave-driven erosion. By this time the northern tip of the spit has (nearly) merged with the coastline (Fig. 10A, 2006, 2012).

In the southern sub-domain large tidal channels prevail (Fig. 4). Flow acceleration around the tip of Helderse Zeewering has scoured a deep hole called Helsdeur with depths over 50 m locally. The occurrence of the shoals Bollen van Kijkduin and Franse Bankje respectively along and at the seaward end of the Nieuwe Schulpengat point to the ebb-dominant character of this channel. Despite the size of the channel, and hence large current velocities and sediment transport capacity, both the Bollen van Kijkduin and Franse Bankje remained remarkably stable in shape and position since 1986. The presence of the large tidal channel Nieuwe Schulpengat directly adjacent to the North-Holland coastline results in large-scale coastal erosion. In the period 1976-2013, nearly 27.5 *mcm* was nourished on the beaches (see Table 1).

The western (seaward) margins of Noorderhaaks and Zuiderhaaks exhibit a contrasting behavior. The margin of Noorderhaaks is mildly sloped, covered by multiple bar systems (Figure 4) and shows a landward retreat. Such development is similar to the landward retreat of the large ebb-tidal deltas in the southern part of the Netherlands after damming of the Grevelingen and Haringvliet estuaries (Aarninkhof & van Kessel, 1999; Elias et al., 2016). On the broad sub-tidal swash-platforms along the western and northern margins of Noorderhaaks, the northward spit developments, the ripples and smaller scale bedforms, and a large number of saw-tooth bars separated by runnels along the northern side of the supra-tidal Noorderhaaks shoal all testify to the wave-dominated character of this area. In contrast to the landward retreat of Noorderhaaks, the seaward margin of Zuiderhaaks strongly developed over the last years into a remarkable straight and steep southward-directed slope (Fig. 4). This southward outbuilding of Zuiderhaaks is an indication of ebb-directed sediment transport through Schulpengat and deposition on its terminal lobe.




| Area | Selected Polygons | Volume change [mcm] + | - | Net |
|---|---|---|---|---|
| ETD front | 3 | 0 | -89 | -89 |
| Noorderhaaks | 4,5,6,8,9,10 | 43 | -5 | 38 |
| NuN | 11,12,13 | 29 | -17 | 12 |
| Marsdiep | 15,16 | 9 | -20 | -12 |
| Nieuwe Schulpengat | 17,18,19,20,22 | 16 | -29 | -13 |
| Schulpengat | 14 | 0 | -33 | -32 |
| Zuiderhaaks | 7 | 12 | 0 | 12 |
| NH coast | 23,24 | 8 | -1 | 7 |
| Coast offshore | 1,2 | 3 | -28 | -26 |
| Totaal | | 120 | -222 | -102 |
| ETD South | 7,14,15,16,17,18,19,20,21,22,23,24 | 44 | -83 | -38 |
| ETD Central | 3,4,5,6,8,9,10 | 44 | -93 | -50 |
| ETD North | 11,12,13 | 29 | -18 | 11 |

***Figure 11 (A):*** *Observed sedimentation-erosion patterns and volume changes over the time period 1986-2012. (B): Table provides the volume changes for selected parts of the ETD. (C) Volume development of these elements through time (1986-2012).*

### 3.3.4. Sedimentation-erosion patterns (1986 - 2012)

Estimates of net transport rates on the Texel ebb-tidal delta are obtained by quantitative analysis of sedimentation-erosion patterns derived by subtraction of the 1986 bathymetry from the 2012 bathymetry (Fig. 11).

The interaction of tidal, the wind- and wave-driven flow with the compound ebb-tidal delta bathymetry produces a complex pattern of mutually linked sedimentation-erosion areas (Fig. 11A). The relative stability of the channel and shoal patterns since 1986 is remarkable given the large volume changes over the entire ebb-tidal delta, with a gross volume change of over 300 *mcm* and a 76 *mcm* (this excludes the 26 *mcm* of net change of the adjacent shoreface). The largest erosion is observed on the northern part of the delta front, at the seaward margin of Noorderhaaks, due to a redistribution of sediment in a landward direction (-89 *mcm* [3], see Fig. 11A for numbering). Flow acceleration due to contraction of the open-sea tides around the ebb-delta bathymetry, and wave-related transports such as wave-asymmetry and wave breaking contribute to these transports, resulting in e.g. accretion of the Noorderhaaks (38 *mcm*), Zuiderhaaks (12 *mcm*), and spit formation at the north-western margin of Noorderhaaks (9 *mcm* [5]) and NUN spit (28 *mcm* [12]). Landward migration of the NUN spit and associated landward displacement of the Molengat channel induces significant erosion of the adjacent Texel coastline. Since 1986 over -9 *mcm* [13] was eroded from the near-shore area despite 9 *mcm* of nourishments that have taken place at the southwest corner of Texel Island.

South of Noorderhaaks, the morphodynamic developments are tide-dominated due to the presence of the large tidal channels Schulpengat, Nieuwe Schulpengat and the small channel Nieuwe Landsdiep. The main developments are: (1) an increasing depth of the channels Nieuwe Schulpengat (-21 *mcm* [17]), Schulpengat (-49 *mcm* [14, 15]), and (2) a seaward and southward outbuilding of the shoals Zuiderhaaks (12 *mcm* [7]) and Franse Bankje, (6 *mcm* [20,22]). The alternating patterns of sedimentation and erosion in the distal part of Nieuwe Schulpengat, Bollen van Kijkduin, and Franse Bankje relate to a small anti-cyclonic rotation and migration of the channel. The total 44 *mcm* sediment accumulation on the shoals is small compared to the large erosion of the main channels 83 *mcm*.

Time series of the volume development derived for all available DEMs over the 1986-2012 interval, show a net sediment loss for the Nieuwe Schulpengat (NSG), Marsdiep (MD), Schulpengat (SG) and ebb-tidal delta front (ETD), while the Noorderhaaks (NH), North-Holland (NH) coast, Zuiderhaaks (ZH) and NUN show an increase in volume (Fig. 11C). Not corrected for nourishments a distinct shift in trend can be observed around 2001 from a 5 *mcm*/year erosion to a near-stable volume. The most pronounced difference occurs in the southern portion of the ebb-tidal delta. Here the channels Schulpengat and Nieuwe Schulpengat are remarkable stable in volume. A clear trend of deepening can no longer be observed. Only local erosion of Nieuwe Schulpengat takes place, due to the landward channel migration under the influence of Bollen van Kijkduin. Part of this stabilization may be explained by the recent large-scale nourishments that result in the pronounced increase in volume along the North-Holland coast.

## 4. Synthesis; Understanding the observed morphodynamic changes and underlying processes

In this paper, we focused on the timeframe 1986-2012, a period in which the re-orientation of the main channels on the ebb-tidal delta was already completed, and the general distribution of the channels and shoals remained more or less similar, but still large volumetric changes have taken place. Based on the observed bed level changes, we can subdivide the ebb-tidal delta into 4 areas with distinct morphodynamic behavior (Fig. 12B).

The sediment budget of the ebb-tidal delta reveals that over 200 *mcm* of sediment was eroded here and from the coast. Roughly half of the sediment was redeposited landward on the ebb-delta and the other remaining half was likely transported into the basin as the sediment volumes in the western Wadden Sea increased (see Elias et al., 2012). Excluding sediment loss from the adjacent offshore coast (areas 1 and 2 in Figure 11), but including the addition of sand through nourishments, import rates are estimated at 5.3 *mcm* per year. An explanation for these high import rates can be found in both the flow measurements and the dominant channel and shoal features as summarized in Figure 12B. Although distinct flood channels cannot be observed along the North-Holland coast, both the dominant flow directions and the slip-face asymmetries of the prevailing bedforms point to a distinct segregation in ebb-dominant flow and sediment transports along Noorderhaaks and flood-dominance along the coastlines of North-Holland and Texel, into Marsdiep and the basin. Flow acceleration around the tip of Helderse Zeewering, resulting in a zone of strong flow convergence and related transport gradients, effectively transporting sediment from the coast into the main inlet circulation, is likely a major contributor to the coastal erosion. During flood, sediments are transported into the basin, which continues to act as a sink for sediment. During ebb part of these deposits are transported back onto the ebb-tidal delta, where they contribute to the outbuilding of Zuiderhaaks (area 3 in Figure 12B), and eventually feed back onto the Noorderhaaks ebb-delta front (area 2). As the Noorderhaaks ebb-delta front eroded, a wide shallow platform emerged that shelters the supra-tidal Noorderhaaks shoal from storms. Sediment recirculation and wave sheltering are two likely reasons why the Noorderhaaks is still present eighty-five years after closure. The presence of the large tidal channel (Breewijd, Nieuwe Schulpengat), steep embankments and dominant ebb-transport along the margin of Noorderhaaks render it likely that hardly any sediments are transported back onto the coast. Increased, near-bed flow in the flood direction because of estuarine circulation during and after high-discharge events, and wave-driven transports along the adjacent coast may significantly enhance sediment imports.

Northward transports contribute to the formation of the spit NUN (area 1). Although this spit is the most obvious developing feature, the sediment budget reveals that net changes are small. The formation of this spit has had large consequences for the adjacent coast. As the sediments deposit in the spit and recirculate back into the inlet, sediment by-passing from the ebb-tidal delta onto the coast is likely to be limited, contributing to the structural sand deficit of the entire Texel coastline. The losses in the coastal section facing the ebb-tidal delta are further enlarged by the landward movement of both spit and adjacent Molengat channel. Recent deviations in the morphodynamic behavior indicate that spit attachment and breaching will occur in the near future, a first indication of the restoration of the sediment bypassing cycle.

In area 4, the interaction of the Nieuwe Schulpengat with the shoal Bollen van Kijkduin and its ebb-shield Franse Bankje dominates the developments. Since 2001, deepening of the channels in this part of the ebb-tidal delta is no longer observed and the total volume of this part of the ebb-delta stabilized. This recent stabilization may partly have been attributed to the massive nourishments (1.3 *mcm*/yearly) that have taken place along the North-Holland coastline. It appears that these nourishments were not only successful in stabilizing the coastline position, but the abundant supply of sediment may have also compensated for the sediment losses on the larger scale of the Schulpengat and Nieuwe Schulpengat subsystems.

## 5. Discussion

Historically, coastal management in the Netherlands and along Texel Inlet was restricted to flood-hazard and coastal-erosion prevention and mitigation. The construction of Helderse Zeewering and the Afsluitdijk are clear examples. These interventions caused long-term changes in the inlet system. Elias et al. (2012) estimated that over 450 *mcm* of sediment accumulated in the Western Wadden Sea between 1933 and 2005 to partly fulfill the sediment demand in the basin. Nearly 300 *mcm* of these sediments were delivered by the Texel ebb-tidal delta and adjacent coasts despite the increase in the tidal prism. The analysis presented in this study shows that even 85 years since closure the morphodynamic changes are still dictated by this adaptation.

Twenty-five years of data on "*Dynamic Preservation*" proves that sand nourishments are well capable of keeping the coastlines adjacent to the Texel inlet in place. Importantly, these nourishments do not significantly alter the characteristics of the ebb-tidal delta. Channel and shoal features in the past, prior to 1990, and at present show similar sizes and shapes. Recent large-scale nourishments may have contributed to a stabilization of the southern part of the ebb-tidal delta, but the data record so far is too short to provide conclusive answers.

In this paper, we particularly aim to better understand the processes driving the sediment loss from the ebb-tidal delta and coast. Based on literature (summarized and analyzed in Elias & Van der Spek, 2006) and the analysis of recent measurements taken between 1986 and 2012, wherein the availability of both detailed measurements of the hydrodynamics and morphodynamics, allows us to analyze the processes behind the observed changes in depth. Four distinct stages of ebb-tidal delta development can be identified (Fig. 12 A1-4). Each of these stages has different implications for the erosion of the adjacent coastlines.

***Stage 1: Prior to Closure of Zuiderzee; A dynamic equilibrium state (Fig. 13A).***

Elias & Van der Spek (2006) show that prior to closure of the Zuiderzee a stable ebb-tidal delta had formed with a westward stretching main ebb-channel, and marginal flood channels along both of the adjacent coasts of Texel and North-Holland. With the exception of the south-western tip of Texel, both coastlines experienced severe erosion. Such erosion can be explained by common inlet processes. The conceptual model of Oertel (1988) explains the formation of an ebb-dominated, main central channel, and marginal flood channels to the side. At an idealized inlet, a (free) jet outflow forms on the seaward side of the inlet during the ebbing tide and material eroded from the inlet gorge is deposited on the bed below the far field of the jet were flow segregates and velocities drop beyond the sediment entrainment threshold. During flood, the return flow towards the inlet is uniformly distributed in a convergent flow towards the inlet and since the velocity field is distributed over a broad arc, the flood velocities that correspond to the near-field of the ebb-jet are lower than during ebb. The residual velocity field is, therefore, ebb-dominant in the axial part of the near-field and flood-dominant in the lateral parts. At Texel inlet separation between ebb and flood channels is further enhanced by the phase difference between the horizontal and vertical tide. Postma (1967) already recognized the importance of these flood channels for transporting sediments back into the basin, introducing erosion of the coastlines.

Alongshore gradients in sediment transports arise from the tidal flow acceleration towards the inlet during the flooding tide, but also waves play an important role. Firstly, wave breaking on the ebb-tidal delta shoals reduces the nearshore wave energy, but also introduces large variations in wave height. This can result in areas of flow divergence and hot-spot erosion (Elias & Hansen, 2013). Secondly, wave sheltering by the ebb-tidal delta alters the nearshore wave climate from bimodal to distinctively unidirectional along both the updrift and downdrift coastlines, which drives a net transport towards the inlet on both sides. Thirdly, the wave-driven cross-shore transports are likely to play an important role. During storm events, a large volume of sediment can be moved from the intertidal area into the (shallow) nearshore. Along an uninterrupted beach, during calm conditions, these sediments move landward and the beach recovers. If longshore gradients exist, for example, due to the presence of large tidal channels, the sediments are transported away before beach recovery can take place. This process is likely to play a dominant role in coastline erosion adjacent to inlets.

Even prior to Closure of the Zuiderzee the coastlines of Texel and Holland were eroding. The basins of the Wadden Sea required sediments to compensate for the effects of e.g., sea-level rise and land subsidence (Stive & Wang, 2003), and supply of sediment to the system true littoral drift was insufficient to compensate for these losses. The inlet downdrift coastlines can only remain stable if sediment supply from the ebb-tidal delta, in the form of sediment bypassing, is sufficient to counterbalance the structural sediment losses into the inlet. At Texel inlet, shoal bypassing occurs on the large swash platform that formed downdrift of the main channel. Periodic shoal merging with the Texel coastline exceeded the structural erosion rates and contributed to the southward outbuilding of the south-westerly tip op Texel Island (van Heteren et al., 2006). This supply fed by bypassing is not sufficient to counterbalance the structural retreat of the central part of the island, that for the most part is related to the convex shape of the coastline. The construction of stone jetties was able to reduce but not completely eliminate the erosion (Rakhorst, 1984).

***Stage 2: 1932- 1975 Adaptation to Closure of the Zuiderzee (Fig. 13B).***

Morphological changes in roughly the first 40 years since the closure were dominated by the rotation and scouring of large tidal channels and landward retreat of the Noorderhaaks ebb-shoal (Elias et al. 2003; Elias & van der Spek, 2006). The distinct southward reorientation of the main channels was ascribed to the process of back-barrier steering (= the sum of all possible constraints that might influence the outflow onto the ebb-tidal delta, viz. tidal prism, oblique basin-channel orientation, composition of the subsurface and phase-difference between ocean and inlet tides) as the changed hydrodynamics in the basin force the main channels to rotated southward. The large tidal prisms and velocities, with large erosive capacity, are well capable of scouring deep channels into the underlying Pleistocene semi-consolidated layers which contribute to the (future) stability of these channels. The scouring of these channels directly influenced the coast and formation of steep embankments and coastal retreat was observed.

***Stage 3: 1975 -2001 Equilibrium-Erosional state (Fig. 13C).***

Between 1975 and 2001 the system showed behavior that we can best describe as an “equilibrium-erosional state”. In this equilibrium-erosional state, the re-orientation of the main channels on the ebb-tidal delta was already completed, and the general distribution of the channels and shoals remained similar. Morphological adjustments of the local channels and shoals now dominate the developments. Most prominent are the large sediment losses of the Noorderhaaks shoal. At this stage, Noorderhaaks can be considered as an abundant source of sediment originating from the pre-closure situation where it was formed as a balance between sediment supply by the ebb-tidal currents through Westgat and landward displacement driven by waves. After abandonment by the main channels, this area became wave-dominated and the deposits could not maintain their form and shape. As among others Hayes, (1975, 1979), Oertel (1975) and Hubbard et al., (1979) already indicated: the geometry of the ebb-tidal delta reflects the ratio of wave- versus tidal energy. Wave-dominated ebb-tidal deltas are pushed close to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore. Such concepts not only apply for the ebb-tidal delta as a whole, but also for its main elements. For Noorderhaaks, updrift channel rotation resulted in a loss of sediment supply. Sediment redistribution by particularly the waves cannot be compensated by the reduced sediment supply and the shoal is pushed landward. The detailed observations of flow and morphodynamic change over the timeframe 1986-2012 (see synthesis presented in Chapter 4) help explain the processes behind the observed developments.

Coastal erosion mechanisms as described in stage 1 are also present during this stage. Very limited sediment bypassing and beach recovery is expected to occur (see e.g Elias & Van der Spek, 2006), making maintenance of the adjacent coastal stretches the most intensive of the entire Dutch coastal system (Roelse, 2002; Cleveringa et al., 2004; Hoogervoorst, 2005).

***Stage 4: Present day stabilization (Fig. 13D)***

A major shift in the morphologic development of the ebb-tidal delta is observed around 2001 as sediment import into the basin (estimated from the sediment budget of the ebb-tidal delta) reduces from 5,3 *mcm*/yearly prior to 2001 to 2 *mcm*/year since. This reduction is for a major part related to a stabilization of the morphology in the southern part of the ebb-tidal delta (Figure 12 A4, area 1). Only locally, were channel-shoal interactions are dominant, erosion of Nieuwe Schulpengat and adjacent coastline continues. The southward and landward movement of Bollen van Kijkduin, confines flow through Nieuwe Schulpengat and induces a small southward displacement, scour and clock-wise rotation of Nieuwe Schulpengat, landward migration of the adjacent Franse Bankje shoal and localized coastline erosion. While the southern part of the ebb-tidal delta stabilized, in the northern subdomain the former balance between Molengat and NUN spit is distorted allowing the tip of the spit to merge with the island tip. The spit itself has not been breached but two ebb-chutes have formed. It can be expected that a new main channel will form through the spit allowing the remainder to merge with the Texel coastline. This will restore the shoal bypassing mechanism and provides an additional source of sediment to the coastline sediment budget (Figure 12 A4, area 2). Despite these significant changes in behavior in both the northern and southern part of the ebb-tidal delta, the erosion of the central ebb-tidal delta front continues at a constant rate (Figure 12 A4, area 3).

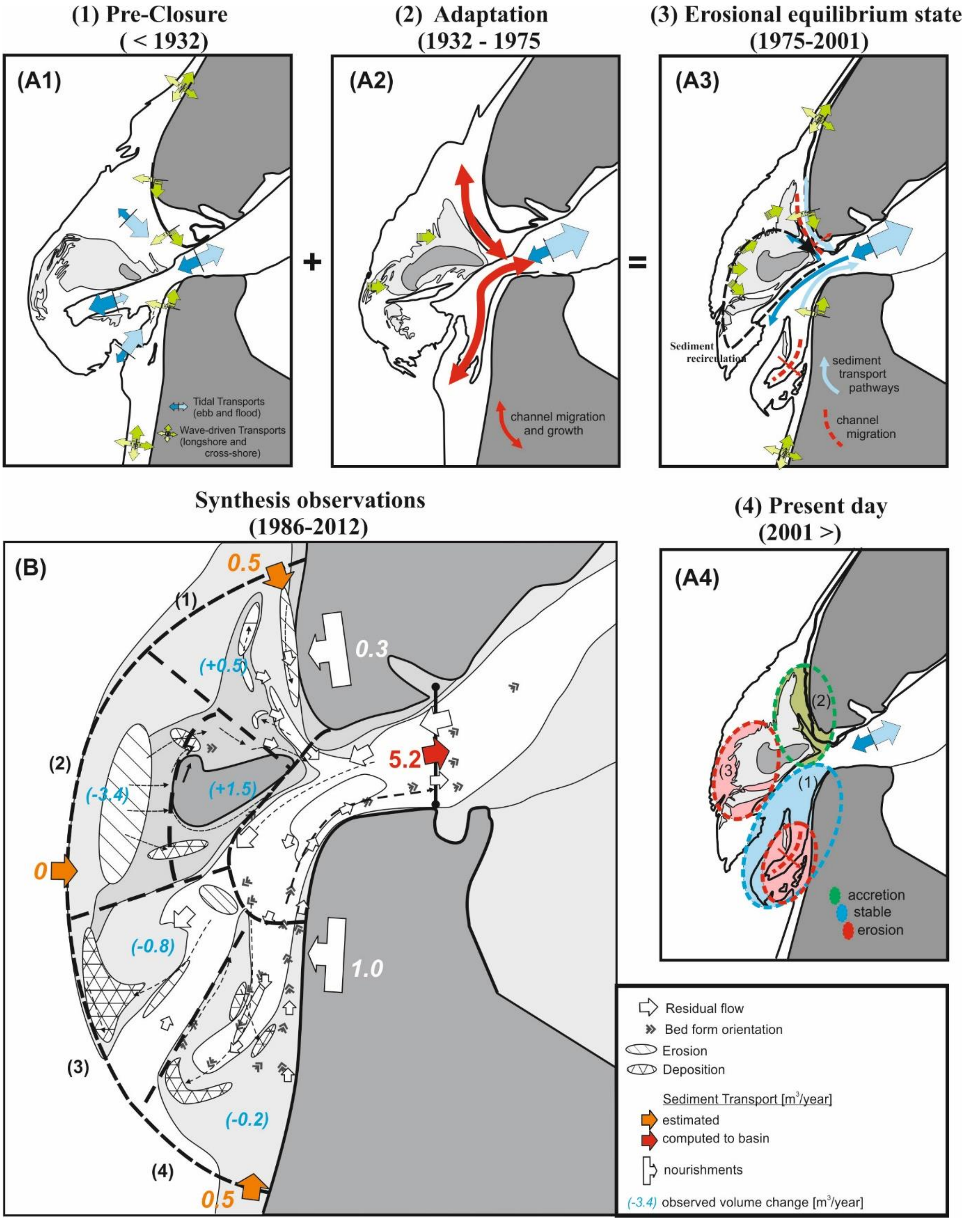



***Figure 12 (A)**: Conceptual visualization of sediment transport mechanisms for 4 different stages of ebb-tidal delta development at Texel inlet (A1) Pre-closure, (A2) Adaptation, (A3) Erosional equilibrium state and (A4) Present day condition. **(B)** Summary of the observed flows, bedform directions and morphodynamic changes over the timeframe 1986-2012.*

## 5. Concluding remarks

(1). High-frequent and detailed observations of both hydrodynamics and morphodynamics of Texel inlet have resulted in a unique dataset of this largest inlet of the Wadden Sea. The availability of these data, in combination with substantial changes in ebb-tidal morphology and volume, provide a unique opportunity to investigate inlet sediment dynamics in a mixed-energy tide-dominated environment. By linking detailed measurements of bathymetric change to direct observations of processes we are able to unravel the various components that have contributed to the supply of sediment to the basin, and conceptually describe how this sediment exchange takes place. Such a conceptual model is a first step in understanding the underlying physical processes responsible for the observed changes in the morphodynamic behavior of the ebb-tidal delta, and its linkage with the adjacent coastlines.

(2). Even nowadays, over eighty-five years after closure, the morphological developments on the ebb-tidal delta are dictated by sediment redistribution on the ebb-tidal delta and by sediment exchange between ebb-tidal delta and basin; sediment is eroded from the ebb-tidal delta (including its adjacent shorelines) and deposited in the basin. In the timeframe 1986-2012, over 200 *mcm* of sediment was eroded from the ebb-tidal delta and coast. Roughly half of these sediments were redeposited more landward in the ebb-delta and the remaining half was likely transported into the basin. The sediment budget also reveals that on average a sediment import of 5.3 *mcm* between 1986-2012 prevailed. Nett sediment losses from the ebb-tidal delta however reduced from 5,0 *mcm*/yearly prior to 2001 to near-zero since.

(3). Coastal retreat along the North-Holland coastline can be attributed to the presence of large tidal channels, with a large sediment transport capacity, in close vicinity to the coast. Flow acceleration towards the inlet, velocity asymmetry of the tidal currents, wave sheltering by the ebb-tidal delta and salinity stratification all contribute to the transport gradients. Locally, channel rotation and related landward migration of the main channel Nieuwe Schulpengat induce additional losses.

(4) Coastal retreat along the Texel coastline partly results from spit formation on the ebb-tidal delta. Spit and channel migration have induced large sediment losses from the adjacent Texel coastline and prohibit sediment bypassing from the ebb-tidal delta to the downdrift shoreline. A merger of the spit with the shoreface of the island in the near future will restore the feeding shoal bypassing mechanism.

(5). Sand nourishments applied for *Dynamic Preservation* of the coastline are shown to be effective in maintaining the coastline position. These nourishments not only increase coastal resilience but may also benefit the entire inlet system. Although the interval covered by the available datasets is too short to provide a conclusive answer, the recent stabilization of the ebb-tidal delta losses may at least partly be attributed to the massive nourishments that have taken place along the North-Holland coastline.

## Acknowledgements

The result of projects 1207724, 1209381 KPP Beheer en Onderhoud Kust; data analysis to understand the evolution of Dutch coast which is the basis for effective coastal management in The Netherlands. Quirijn Lodder and Marian Lazar (both Rijkswaterstaat Traffic- and Water management) are thanked for pleasant co-operation and advice.

# References


Aarninkhof, S. G. J. & T. van Kessel, T., 1999. Data analyze Voordelta. Grootschalige morfologische veranderingen 1960-1996. Report, WL Delft Hydraulics / Deltares (Delft): 77pp.

Ashley, G. M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. SEPM bedforms and bedding research. Journal of Sedimentary Petrology, 60(1): 16-172.

Battjes, J. A., 1962. Studie Zeegat van Texel. Report (in Dutch). Delft University of Technology (Delft). MSc. report.

Basco, D.R., Pope, J., 2004. Groin Functional Design Guidance from the Coastal Engineering Manual, Journal of Coastal Research, SI 33: 121-130.

Beckering Vickers, J. A., 1951. Nota betreffende het Zeegat van Texel en de aangrenzende oevers. Report 51.1 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, Studiedienst Hoorn (Hoorn).

Berger, G. W., D. Eisma & van Bennekom, A. J., 1987. $^{210}$Pb-derived sedimentation rate in the Vlieter, a recently filled-in channel in the Wadden Sea., Netherlands Journal of Sea Research, 21 (4): 287-294.

Blanton, J. O., Lin, G. & Elston, S.A., 2002. Tidal current asymmetry in shallow estuaries and tidal creeks. Continental Shelf Research, 22: 1731-1743.

Blok, M. & Mol, J.W., 2001. Debietmeting zeegat van Texel. Report (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, Directie Noord-Holland, Informatiedienst Water (IJmuiden).

Boothroyd, J. C., 1985. Tidal inlets and tidal deltas, Coastal Sedimentary Environments: 445-532.

Boothroyd, J. C. & Hubbard, D. K., 1975. Genesis of bedforms in meso-tidal estuaries. In: Cronin, L.E., (*ed.*) Geology and Engineering, Academic Press (New York): 217-234.

Bruun, P. & Gerritsen, F., 1960. Stability of tidal inlets, North-Holland Publishing (Amsterdam): 123 pp.

Buijsman, M. C. & Ridderinkhof, H. 2007a. Long-term ferry-ADCP observations of tidal currents in the Marsdiep inlet. Journal of Sea Research, 57 (4): 237-256.

Buijsman, M.C. & Ridderinkhof, H., 2007b. Water transport at subtidal frequencies in the Marsdiep inlet. Journal of Sea Research, 58 (4): 255-268.

Buijsman, M. C. & Ridderinkhof, H., 2008a. Long-term evolution of sand waves in the Marsdiep inlet. I: High-resolution observations. Continental Shelf Research, 28 (9): 1190-1201.

Buijsman, M. C. & Ridderinkhof, H., 2008b. Long-term evolution of sand waves in the Marsdiep inlet. II: Relation to hydrodynamics. Continental Shelf Research, 28 (9): 1202-1215.

Buijsman, M. C, & Ridderinkhof, H., 2008c. Variability of secondary currents in a weakly stratified tidal inlet with low curvature, Continental Shelf Research, 28 (14), 1711-1723.

Burchard, H., Flöser, G., Staneva, J.V., Badewien, T.H. & Riethmüller, R., 2008. Impact of density gradients on net sediment transport into the Wadden Sea. Journal of Physical Oceanography 38: 566-587.

Cleveringa, J., 2001. Zand voor zuidwest Texel. Technisch advies RIKZ over vier mogelijke ingrepen in het Zeegat van Texel. Report RIKZ/OS/2001/031 (in Dutch). National Institute for Coastal and Marine Management RIKZ, (The Hague): 59 pp.

Cleveringa, J., Mulder, S. & Oost, A.P., 2004. Kustverdediging van de koppen van de Waddeneilanden. De dynamiek van de kust nabij buitendelta's en passende maatregelen voor kustbeheer. Report RIZK/2004.017 (in Dutch). Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (The Hague): 69 pp.

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

Davis Jr., R.A. & FitzGerald, D.M., 2004. Beaches and Coasts. Blackwell Publishing, Oxford: 419 pp.

De Kruif, A.C., 2001. Bodemdieptegegevens van het Nederlandse kustsysteem; Beschikbare digitale data en een overzicht van aanvullende analoge data. Report RIKZ/2001.041 (in Dutch). Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ, (The Hague): 34 pp.

De Ruig, J.H.M., 1998. Coastline management in The Netherlands: human use versus natural dynamics. Journal of Coastal Conservation, 4 (2): 127-134.

De Vries, J.J., Nauw, J.J., Ridderinkhof, J. & van Aken, H.M., 2014. An exploratory study of the variability of currents and density in the Marsdiep. Continental Shelf Research, 84: 70–83.

De Vries, J.J., Ridderinkhof, J. Maas, L.R.M. & van Aken, H.M., 2014. Intra- and inter-tidal variability of the vertical current structure in the Marsdiep basin. Continental Shelf Research, 93: 39–57.

Duran-Matute M, Gerkema T, de Boer G.J., Nauw J.J., Gräwe U, 2014. Residual circulation and freshwater transport in the Dutch Wadden Sea: a numerical modelling study. Ocean Sciences, 10(4): 611–632.

Eisma, D. & Wolff, W. J., 1980. The development of the western most part of the Wadden Sea in historical times. *In:* Dijkema, K.S., Reineck, H.E. & Wolff, W.J. (*eds.*), Geomorphology of the Wadden Area. Report 1. Wadden Sea Working Group (Leiden): 95-103.

Elias, E.P.L., 2006. Morphodynamics of Texel Inlet. Ph.D. Thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences (Delft): 261 pp.

Elias, E. P. L. & Cleveringa, J., 2003. Morfologische analyse van de ontwikkeling van het Nieuwe Schulpengat en de aangrenzende kust. Report RIKZ-2003.040 (in Dutch), National Institute for Coastal and Marine Management RIKZ (The Hague): 61 pp.

Elias, E.P.L. & Hansen, J.E. 2013. Understanding processes controlling sediment transports at the mouth of a highly energetic inlet system (San Francisco Bay, CA). Marine Geology 345: 207–220.

Elias, E.P.L. & Stive, M.J.F., 2006. The effect of stratification on the residual flow in a mixed-energy tide-dominated inlet. *In:* A Sanchez-Arcilla (Ed.), Coastal Dynamics 2005: proceedings of the 5th international conference (pp. 1-13). Reston, USA: ASCE.

Elias, E.P.L., Stive, M.J.F., Bonekamp, J.G. & Cleveringa, J., 2003. Tidal inlet dynamics in response to human intervention. Coastal Engineering Journal 45(4): 629-658.

Elias, E.P.L., Stive, M.J.F. & Roelvink, J.A., 2004. Impact of Back-Barrier Changes on Ebb-Tidal Delta Evolution. Journal of Coastal Research, SI (42): 460-476.

Elias, E.P.L. & Van der Spek, A.J.F., 2006. Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). Marine Geology, 225: 5-21.

Elias, E.P.L., Van der Spek, A.J.F. & Lazar, M., 2016. '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 - Geologie en Mijnbouw: 1–27.

Elias, E.P.L., Van der Spek, A.J.F, Wang, Z.B. & de Ronde, J., 2012. Morphodynamic development and sediment budget of the Dutch Wadden Sea over the last century. Netherlands Journal of Geosciences - Geologie en Mijnbouw, 91 (3): 293-310.

FitzGerald, D.M., 1988. Shoreline erosional-depositional processes associated with tidal inlets. In: Aubrey, D., Weishar, L. (*eds.*). Hydrodynamics and Sediment Dynamics of Tidal Inlets, Lecture Notes on Coastal and Estuarine Studies, 29, Springer (New York): 186-225.

FitzGerald, D.M., 1996. Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. In: Mehta, A.J. (*ed.*). Understanding Physical Processes at Tidal Inlets Based on Contributions by Panel on Scoping Field and Laboratory Investigations in Coastal Inlet Research. Journal of Coastal Research, SI. 23: 47–71.

FitzGerald, D.M., Penland, S. & Nummedal, D. 1984. Control of barrier island shape by inlet sediment bypassing: East Frisian Islands, West Germany. Marine Geology, 60: 355-376.

Fleming, C.A., 1990. Guides on the Uses of Groynes in Coastal Engineering, Construction Industry Research and Information Association (CIRIA) (London, England), Report 0305-408X: 114 p.

Glaeser, D. J., 1978. Global distribution of barrier islands in terms of tectonic setting, Journal of Geology, 86(3): 283-297.

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): 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): 1-27.

Hayes, M.O. & FitzGerald, D.M., 2013. Origin, Evolution, and Classification of Tidal Inlets. *In:* Kana, T.; Michel, J. & Voulgaris, G. (*eds.*). Proceedings, Symposium in Applied Coastal Geomorphology to Honor Miles O. Hayes, Journal of Coastal Research, SI. 69: 14–33.

Hillen, R. & De Haan, Tj.,1993. Development and implementation of the coastal defense policy for the Netherlands. *In:* Hillen, R. & Verhagen, H.J. (*eds.*) Coastlines of the southern North Sea, American Society of Civil Engineers (New York, NY): 118-201.

Hillen, R. & Roelse, P., 1995. Dynamic Preservation of the Coastline in the Netherlands. Journal of Coastal Conservation, Vol. 1, No. 1: 17-28

Hine, A. C. (Ed.), 1975. Bedform distribution and migration patterns on tidal deltas in the Chatham Harbor Estuary, Cape Cod, Massachusetts, Academic Press (New York): 235-253.

Hoogervoorst, R.D.N., 2005. Inventarisatie Bagger-, Stort- en Zandwingegevens binnen de -20 m NAP ten behoeve van een Zandbalans van het Nederlands Kustsysteem. Report RIKZ/KW/2005.103W (in Dutch). Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (The Hague): 59 pp.

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.

Jarrett, J.T., 1976. Tidal prism – inlet area relationships. General Investigation of Tidal Inlets, Report no. 3, Coastal Engineering Research Center, US Army Corps of Engineers (Washington DC): 32 pp.

Joustra, D. S., 1973. Geulbeweging in de buitendelta's van de Waddenzee (in Dutch). Rep. W.W.K. 71-14 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (The Hague).

Kraus, N.C., Hanson, H., Blomgren, S.H., 1994. Modern Functional Design of Groin Systems. Proceedings 24th International Conference on Coastal Engineering, ASCE, Kobe, Japan: 1327-1342.

Lobo, F. J., Hernandez-Molina, F. J., Somoza L., Rodero, J. & Maldonando, B., 2000. Patterns of bottom current flow deduced from dune asymmetries over the Gulf of Cadiz shelf (southwest Spain). Marine Geology, 164: 91-117.

Louters, T. & Gerritsen, F., 1994. The Riddle of the Sands. A Tidal System's Answer to a Rising Sea Level. Report RIKZ-94.040. Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (The Hague): 69 pp.

McLaren, P., Steyaert, F. & Powys, R., 1998. Sediment transport studies in the Tidal Basins of the Dutch Wadenzee, Senckenbergiana martima, 29 (1/6): 53-61.

Mulder, J.P.M., 2000. Zandverliezen in het Nederlandse kustsysteem. Advies voor Dynamische Handhaven in de 21e eeuw. Report RIKZ/2000.36 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (The Hague): 55 pp.

Nauw, JJ, Merckelbach, LM, Ridderinkhof, H, van Aken, HM, 2014. Long-term ferry observations of the suspended sediment fluxes through the Marsdiep inlet using acoustic Doppler current profilers. Journal of Sea Research, 87, 17-29.

O'Brien, M. P., 1931. Estuary tidal prisms related to entrance areas, Civil Engineering, 1: 738-739.

O'Brien, M. P., 1969. Equilibrium flow areas of inlets and sandy coasts, Journal of Waterways, Harbors, and Coastal Engineering, 95: 43-55.

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

Oertel, G. F., 1988. Processes of sediment exchange between tidal inlets, ebb deltas and barrier islands, Springer-Verlag (New York): 297-318.

Oost, A.P. & De Boer, P.L., 1994. Sedimentology and development of barrier islands, ebb-tidal deltas, inlets and back-barrier areas of the Dutch Wadden Sea. Senckenbergiana Maritima 24: 65-115.

Perluka, R., Wiegmann, E.B., Jordans, R.W.L. & Swart, L.M.T., 2006. Opnametechnieken Waddenzee. Report AGI-2006-GPMP-004, Rijkswaterstaat, Adviesdienst Geo Informatie en ICT (Delft): 47 pp. (in Dutch)

Postma, H., 1954. Hydrography of the Dutch Wadden Sea. Archives Néerlandaises de Zoologie 10: 405-511.

Postma, H., 1967. Sediment transport and sedimentation in the estuarine environment. *In:* Estuaries, Lauff, G. H., (*ed.*), American Association for Advancement of Science (Washington DC): 158-179.

Rab, M., 2004a. Stroommeting Nieuwe Schulpengat. Report ANI-05.05 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, directie Noord-Holland, Informatie dienst Water (IJmuiden): 33 pp.

Rab, M., 2004b. Stroommeting Molengat, September 2003. Report ANI-04.02 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, directie Noord-Holland, Informatie dienst Water (IJmuiden): 34 pp.

Rakhorst, H.D., 1984. Werking strandhoofden Noord-Holland, Texel, Vlieland, , Nota WWKZ-84.H007 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, adviesdienst Hoorn (Hoorn): 31 pp.

Ridderinkhof, H., Van Haren, H., Eijgenraam, F. & Hillebrand, T., 2002. Ferry observations on temperature, salinity and currents in the Marsdiep tidal inlet between the North Sea and Wadden Sea. *In:* Flemming, N.C., Vallerga, S., Pinardi, N., Behrens, H.W.A., Manzella, G., Prandle, D. & Stel, J.H. (*eds.*), Proceedings of the second international conference on EUROGOOS, Operational Oceanography: Implementation at the European and Regional Scales. Elsevier Oceanography Series, vol. 66: pp. 139–148.

Rietveld, C.F.W., 1962. The natural development of the Wadden Sea after the enclosure of the Zuider Sea. Proceedings 8th International Conference on Coastal Engineering, ASCE, Mexico City, Mexico: 765-781. Conference proceedings.

Rijkswaterstaat, 1990. A new coastal defense policy for the Netherlands. Rijkswaterstaat, Tidal Waters Division (The Hague): 100 pp.

Roelse, P., 2002. Water en Zand in Balans. Evaluatie Zandsuppleties na 1990; Een Morfologische Beschouwing. Report RIKZ/2002.003 (in Dutch). Ministry of Transport and Public Works, Rijkswaterstaat, National Institute for Coastal and Marine Management RIKZ (Middelburg): 108 pp.

Schoorl, H., 1999. De convexe kustboog Texel-Vlieland-Terschelling: bijdragen tot de kennis van het westelijk Waddengebied en de eilanden Texel, Vlieland en Terschelling: 1. Het westelijk Waddengebied en het eiland Texel tot circa 1550 (in Dutch). Pirola (Schoorl): 187 pp.

Sha, L.P., 1989a. Cyclic morphologic changes of the ebb-tidal delta, Texel Inlet, The Netherlands. Geologie en Mijnbouw, 68, 35-48.

Sha, L. P., 1989b. Variation in ebb-tidal delta morphologies along the west and East Frisian Islands, the Netherlands and Germany. Marine Geology 89: 11-28.

Sha, L.P., 1990. Sedimentological Studies of the Ebb-Tidal Deltas along the West Frisian Islands, the Netherlands. Geologia Ultaiectina, Mededelingen van de Faculteit Aardwetenschappen 64, University Utrecht (Utrecht): 159 pp. Thesis.

CERC, 1984. Shore Protection Manual Volume 1 and 2 (Fourth Edition). Coastal Engineering Research Center (CERC), Department of the Army, Waterways Experiment Station (Vicksburg, USA): 1304 pp.

Stive, M.J.F. & Eysink, W.D., 1989. Voorspelling Ontwikkeling Kustlijn 1990-2090. Fase3. Deelrapport 3.1: Dynamisch Model van het Nederlandse Kustsysteem. Report H825 (in Dutch). Waterloopkundig Laboratorium, Deltares (Delft): 66 pp.

Stive, M.J.F. & Wang, Z.B., 2003. Morphodynamic modeling of tidal basins and coastal inlets. *In:* Lakhan, C. (*ed.*): Advances in Coastal Modelling. Elsevier Oceanography Series 67: 367-392.

Stutz, M.L. & Pilkey, O.H., 2011, Open-ocean barrier islands: Global influence of climatic, oceanographic, and depositional settings. Journal of Coastal Research, 27(2): 207–222.

Thijsse, J.T., 1972. Een Halve Eeuw Zuiderzeewerken 1920-1970 (in Dutch). Tjeenk Willink (Groningen): 469 pp.

Van der Spek, A. J. F. & Van Heteren, S., 2004. Analyse van steekboringen verzameld in het Molengat en het Nieuwe Schulpengat. Report NITG 04-095-C (in Dutch), TNO-NITG (Utrecht): 45 pp.

Van Heteren, S., Oost, A. P., de Boer, P.L., Van der Spek, A. J. F. & Elias, E. P. L., 2006. Island-terminus evolution as a function of changing ebb-tidal delta configuration: Texel, The Netherlands, Marine Geology, 235 (1): 19-23.

Van Rijn, L.C., 1997. Sediment transport and budget of the central coastal zone of Holland. Coastal Engineering 32: 61-90.

Van Rijn, L.C., 2004. Coastal erosion and control, Ocean & Coastal Management, 54(12), 867-887.

Van Veen, J., van der Spek, A.J.F., Stive, M.J.F. & Zitman, T., 2005. Ebb and flood channel systems in the Netherlands tidal waters. Journal of Coastal Research, 21(6): 1107–1120.

Verhagen, H. J. & van Rossum, H., 1990. Strandhoofden en paalrijen: evaluatie van hun werking. Report (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, Dienst Weg- en Waterbouwkunde (The Hague): 40 pp.

Vos, P.C., Weerts, H.J.T., Bazelman, J., Hoogendoorn, B. & Van der Meulen, M.J.M., 2011. Atlas van Nederland in het Holoceen. Bert bakker (Amsterdam): 94 pp.

Walton, T.L. & Adams, W.D., 1976. Capacity of inlet outer bars to store sand. 15th Conference on Coastal Engineering, 11–18 July 1976, Honolulu, Hawaii: 1919–1937. Conference proceedings.

Wiegmann, E.B., Perluka, R., Oude Elberink, S. & Vogelzang, J., 2005. Vaklodingen: De inwintechnieken en hun combinaties. Report AGI-2005-GSMH-012 (in Dutch), Ministry of Transport and Public Works, Rijkswaterstaat, Adviesdienst GeoInformatie (Delft): 47 pp.

Zimmerman, J.T.F., 1976. Mixing and Flushing of Tidal embayments in the western Dutch Wadden Sea. Part 1: Distribution of salinity and calculation of mixing time scales. Netherlands Journal of Sea Research, 10(2): 149-191.