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 the most intensive of the entire Dutch coastal system. Intensive monitoring of the hydrodynamics and morphodynamics of the Texel ebb-tidal delta by Rijkswaterstaat created a globally unique dataset. The use of state-of-the-art monitoring techniques such as Acoustic Doppler Current Profilers (ADCPs) and MultiBeam EchoSounder surveys, provides background for an evaluation of the effects of over 20 years of Dynamic Preservation an in-depth analysis of the underlying physics determining the morphodynamic changes.

Over eighty-five years after closure, the morphological developments on the Texel ebb-tidal delta are still dictated influenced by adaptation through sediment redistribution on the ebb-tidal delta and sediment exchange between ebb-tidal delta and basin. Sediment is eroded from the ebb-tidal delta (including 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 landward on the ebb-delta and the remaining half was likely transported into the basin. The sediment budget reveals that an average a sediment loss from the ebb-tidal delta of 3.0 mcm between 1986-2012, but sediment losses reduces from 5,0 mcm/yearly prior to 2001 to below 2 mcm/year since. 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 stabilization of its volume. This shows that potential benefits of Dynamic Preservation not only for coastline resilience but also on the larger scale of the inlet system. Such knowledge is essential for future preservation, management and maintenance of these systems in the scope of climate change and sea-level rise.

Key words:
coastal morphodynamics; coastal management; ebb-tidal delta; impact of large-scale engineering; the Netherlands; sediment budget;
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. With increasing population density, this has led to extensive coastal development and shoreline protection works. Coastal management, was historically, and often still is, governed by either economic motivations such as ensuring safe navigation and shipping, which often led to the building of harbours and harbour moles, sluices, and establishing shipping lanes, or flood protection and erosion control, resulting in the execution of coastal protection works such as sea walls and dikes, jetties, breakwaters and groins.

In recent times, more and more awareness arose that these inlet systems also form unique habitats for numerous marine species and birds, and that coastal development and shoreline protection structures, has severely impacted or constrained the natural dynamics. How exactly anthropogenic pressure might impede the ability of natural systems to respond, 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 can provide valuable insights to unravel this question.

Dynamic preservation

Already in 1990, the Dutch government enacted a new coastal policy, called ‘Dynamic Preservation’, to fight structural erosion present 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 its principal source. Using sand nourishment allows the natural coastal processes to be maintained. Preservation of natural dynamics is especially important at the tidal inlets such as Texel Inlet. Texel inlet forms the transition from the closed Holland coast to the interrupted barrier-inlet-estuary system of the Wadden Sea: a world recognized maritime conservation area and UNESCO World Heritage 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; Elias & Van der Spek, 2012). It is generally assumed, that the majority of these sand losses results from the sediment losses 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 (Battjes, 1962; Beckering Vickers, 1951; Sha, 1989; Sha,1990; Elias, 2006; Elias et al., 2012).

Conceptual Models

The basic processes controlling the shape of the ebb-tidal delta are well known (see a recent summary by Hayes & FitzGerald, 2003). 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 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 of wave versus tidal energy. Wave-dominated ebb-tidal deltas are pushed close to the inlet throat, while tide-dominated ebb-tidal deltas extend offshore (see, e.g., Hayes, 1975, 1979; Oertel, 1975; Hubbard et al., 1979). Davis & Hayes (1984) and FitzGerald (1996) suggest that wave and tidal processes are useful to describe the gross characteristics of inlet systems, but many additional variables exist. These variables include geological parameters such as coastal physiography, regional stratigraphy (including bedrock outcrops) and

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basin geometry, and processes such as sediment supply, river discharge and sea-level changes. Elias & Van der Spek (2006) showed the importance of anthropogenic induced change that dominated the recent history of Texel Inlet. For the configuration of the adjacent coastlines, the sediment delivery through longshore drift, the pathways and sediment bypassing on the ebb-tidal play an important role (Bruun & Gerritsen, 1959; Hayes, 1979, FitzGerald et al., 1984).

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

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 sand balance. The specific research goals of this study are:

(1) to gain more understanding of acquire more understanding of the sediment dynamics of Texel Inlet and their 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 worlds inhabited inlet systems that are under erosional threat;

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

(3) to disclose these datasets to the international community since datasets comprising both frequent observations of anthropogenic induced morphodynamic change, and the responses of the system to a wide variety of coastline protection measures, are scarce.

To achieve this goal, we analyse recent measurements, taken over the timeframe 1986-2012, of hydrodynamics and morphodynamics. Intensive monitoring of the Texel ebb-tidal delta by Rijkswaterstaat (presently part of the Ministry of Infrastructure and Environment of The Netherlands) over has created a globally unique dataset. The use of state-of-the-art monitoring techniques such as Acoustic Doppler Current Profilers (ADCPs) and MultiBeam EchoSounder surveys, provides background for an in-depth analysis of the underlying physics determining the morphodynamic changes of inlet systems. In addition a well-monitored record of human interventions (e.g. nourishments) is present.
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 port of Den Helder 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 defence) locally increased the channel depths to over 50 meters at the location of Helsdeur. The ebb-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 centre 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) extends along the Texel coastline, separated from the island by the Molengat channel. 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 shoal Bollen van Kijkduin, extend...
along the North-Holland coastline. Nieuwe Schulpengat extends in 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 and 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.

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 prism 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; Buijsman & Ridderinkhof, 2007a; Ridderinkhof et al. 2002). 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-down gradients can drive complicated residual wind-driven flow fields, generate shore-parallel velocities and throughflow between adjacent basins. 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 preceding the storm events, thereby effecting the ebb-tidal delta development and adjacent beaches.

Supply of fresh water in 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 (e.g. summer) discharges can reduce to zero and in periods with high rain fall (e.g. 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 (preceding) periods of major fresh-water discharge. The resulting density gradients may be important for the sediment exchange through the inlets (Buijsman & Ridderinkhof, 2007b; Burchard et al., 2008; Elias 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. Analysis of the long-term time series (1979-2001) reveals that the wave climate is dominated by wind-generated waves in the North Sea basin. Contributions of swell are minor. Most frequently wave directions (~90%) lie between southwest and north. The mean wave height is 1.3 m from the west, with a corresponding significant wave period of 5 seconds. During storms wind-generated significant wave heights can reach heights over 6 m. Wave periods ($T_{1/3}$) vary between 4 to 5 seconds for low wave conditions, and over 10 seconds for the highest waves.

Limited knowledge is present on the importance of wind and wind-driven flow in the inlet domain, but with a predominant landward wind direction wind is likely to enhance tidal flow and sediment import into the basin. Inside the basin we can expect wind to be important for mixing and estuarine circulations, and in shallow areas wind is effective in generating large currents and tidal flat degeneration. 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).

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 balance of Texel Inlet, and improve insight in inlet-coast dynamics in general. Elias & Van der Spek (2006) demonstrated the importance of the construction of extensive coastal defence 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., 2005). After construction of the coastal defence 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 Figure 3, 1926 for a representative bathymetry for this stable state).
Figure 3: Bathymetric changes between 1926 and 2012 illustrating the morphodynamic adjustment of the ebb-tidal delta to the closure of the Zuiderzee completed in 1932.
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 1.1 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 Battjes, 1962; Beckering Vickers, 1951; Sha, 1989; Sha, 1990; Elias, 2006 and 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 (Figure 3, 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. 3). This northward transport contributes to the elongate outbuilding of the ebb-delta along the Texel coastline (Elias et al., 2003; Sha, 1989).

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 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 changes on the ebb-tidal delta must have contributed to the observed erosion of the coastlines, but they cannot directly explain why large nourishment volumes were and still are needed to maintain the coastlines as most of the morphological adjustment (such as the channel relocation) was already completed prior to the execution of the coastline nourishments.

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

A long history of shoreline protection measures on 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 of the updrift embankment was permanently halted by the construction of stone revetments, predecessors of what is now known as Helderse Zeewering (zeewering = sea defence); 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 Seawall and the Hondsbosche and Pettemer Seawall, 20 km south of the inlet, was completely protected by 69 stone groins (Fig. 4). These groins have been able to reduce, but not completely eliminate, the coastal erosion (Rakhorst, 1984; Verhagen and van Rossum, 1990).
Along the southwest coast of Texel 24 groins were constructed between 1959 and 1987 to protect the stretch of coast between km. 9 and 18, just north of the inlet (Fig. 4). 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 surfzone, 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 coastlines.

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 since in the interval 1993-2012. Most of these nourishments (9) were regular beach nourishments, while in 2007 additionally a large 2 mcm foreshore nourishment was placed (see Table 1 for an overview).

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 seawalls. Most of these nourishments, 27.5 mcm, were placed in the direct vicinity of the inlet (km. 0-13), making the maintenance of this stretch of coast to the most intensive of the entire Dutch coastal system (Hoogervorst, 2005; Mulder, 2000; Roelse, 2002).
**Table 1: Overview of the Nourishments placed along the coastlines of North-Holland and Southwest Texel.**

<table>
<thead>
<tr>
<th>North-Holland (km.0 – km. 20)</th>
<th>Type (1)</th>
<th>Year</th>
<th>Km. Start</th>
<th>Km. End</th>
<th>Volume (mcm)</th>
<th>Type (1)</th>
<th>Year</th>
<th>Km. Start</th>
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<td>1976</td>
<td>12.98</td>
<td>13.75</td>
<td>0.34</td>
<td>B</td>
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<td>2003</td>
<td>9.13</td>
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<tr>
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<td>13.73</td>
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<td>FS</td>
<td>2003</td>
<td>10.00</td>
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<td>11.75</td>
<td>12.05</td>
<td>0.08</td>
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(1) B = Beach, D = Dune, FS = Fore-shore, CS = Channel Slope Nourishment.
3. Analysis of detailed measurements

Improved insight in 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 analysed using high-frequent ADCP observations in the inlet gorge and main channels on the ebb-tidal delta (section 3.1). Wave measurements are analysed 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 1986-2000 in 3-year intervals, and bedform analysis of multi-beam survey data of seafloor bathymetry, provide insight in the dominant sediment transport directions in parts of the ebb-tidal delta (3.3).

3.1. Hydrodynamics

3.1.1. NIOZ-ferry measurements in the inlet gorge

In 1998 the Royal Netherlands Institute of 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 (ms Schulpengat and since 2005 ms. Dokter Wagemaker) sails the 4.5 km wide Marsdiep every 30 minutes (see Fig. 5b, NIOZ for location and residual flow distribution over the transect). The raw data are transmitted to NIOZ and processed. Buijsman & Ridderinkhof (2007a) analysed 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 0.66m 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 709-130.000 million m$^3$ and a smaller flood volume of 579-1179 million m$^3$. The residual flow through the inlet of about 130x10$^6$ m$^3$/tide is seaward directed as a result of the exchange of water with the adjacent Vlie inlet.

Detailed analysis of the depth-mean velocities shows that during flood velocities are more equally distributed across the inlet, while during ebb the largest velocities occur along the Texel coastline. As a result, a small flood dominant tidal mean flow is observed along the North-Holland coastline, and a larger ebb-dominant flow dominates along the Texel coastline (see Fig. 5B). Similar flow distributions were observed in the numerical model studies of Elias et al. (2004) and Duran-Matute et al. (2014). The latter study indicates that the exact magnitude of the residual flow is sensitive to the prevailing meteorological conditions. It is indicated that for typical conditions the outflow of 600–700 m$^3$/s through Texel inlet is larger than the values given by Buijsman & Ridderinkhof (2007a), 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.

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 analysed by Rijkswaterstaat to remove systematic errors and erroneous data. During each campaign multiple transects were run obliquely on 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.
A,B). Although these datasets do not provide
long-term time-series, they allow for an
estimate of the discharge patterns and velocity
distributions over the individual channels.

Flood enters the inlet mainly through
Schulpengat (50%) and Nieuwe Schulpengat
(40%). Discharges through Molengat are minor
(10%). Vice versa, during Molengat 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 channel margin
along the Holland coast. Contraction of flood
flow around the tip of Helderse Zeewering
accelerates the velocities into the inlet. While on
the other hand the ebb flow originating from the
Texelstroom is directed seaward from
Texelstroom, along the Texel coastline and
Noorderhaaks due to inertia of flow. For more
details see Elias (2006; chapter 5 pages 129-136).

Figure 5 (A): Overview of measured depth-averaged peak-ebb and flood velocity vectors in Molengat and (Nieuwe)
Schulpengat. Numbers indicated transect-averaged maximum ebb- and flood discharges in m$^3$/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, 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 $M_2$
velocity component.
3.1.3. Importance of estuarine circulation during high-discharge events

An indication of the importance 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, but fresh-water discharge through the discharge sluices in Den Oever and Kornwerderzand was significant with the monthly-mean discharges prior to the measurements exceeding 900 m$^3$/s, resulting in observed surface salinity values of 24 ppt. and 26 ppt. in Marsdiep.

The ADCP flow data was therefore harmonically analysed 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. 5B). In Breewijd 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 (Fig. 5C, upper 3 panels). These residual velocities plausibly result from nonlinearities due to interaction of the tidal flow with the bed-topography interacting with horizontal density gradients. In addition, Coriolis and channel curvature due to the sharp curvature of the western tip of Helderse Zeewering may also influence the flow (see previous section). Ebb-flow of lower salinity is directed from Texelstroom into Marsdiep and onto the ebb-tidal delta. Inertia of flow results in a southwesterly outflow that is largest along the margins of Noorderhaaks. As flood start to enter the inlet, due to the time-velocity asymmetry, still relative large ebb velocities dominate the central parts of Marsdiep. Flood flow of higher salinity dominates in the near-bed region along the North-Holland coast. Convergence of flow at the tip of Helderse Zeewering results in strong flood velocities along the North-Holland coastline. This flow segregation is observed during a considerable period of the tidal cycle.

In Marsdiep 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 (Fig. 5C, bottom 3 panels). 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 and a strong vertical shear is observed. The significant differences between patterns and magnitudes of the residual flow and amplitudes 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 non-linearity's 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, 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), but
waves redistribute the sediments and contribute to the sediment bypassing mechanism (FitzGerald, 1988). Waves contribute directly to the sediment transports 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 flow.

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 sorted the wave data for the nearby Eierlandse Gat station over the period 1979 - 2001 (Fig. 6). A subdivision in six wave height classes and four direction classes between 180° -360° is made. Wave directions between 0° - 180° are generated by offshore directed wind and of negligible height near the Texel Inlet. For each class a representative morphological wave height ($H_{mor}$) is determined using,

$$H_{mor} = \left( \frac{1}{n} \sum_{i=1}^{n} H_{m0}^{(i)} \right)^{1/k} \quad \text{(eq. 1)}$$

where, $n$ represents the total number of observations [-], $H_{m0}$ is the significant wave height [m] and $k$ is the power relation between transport and wave height [-], a value of 2.5 is used. The total Morphological Impact ($MI$) for each class is obtained by multiplying with the probability of occurrence.

Waves from the direction classes between southwest (225°) and north (360°) contribute near-equal to the morphological impact. Due to the non-linear relation between waves and sediment transport, especially the larger wave heights are important. Only 20% of the observations exceed the 2 m wave height, but these waves account for 70% of the morphological impact. At the Eierlandse Gat wave buoy the southward component of the morphological impact exceeds the northward component, which results in a net southward directed wave-driven transport (similar to the observations of Sha, 1989). Note that the littoral drift along the North-Holland coastline is northward, directed towards the inlet (Van Rijn, 1997).

Although measurements of the wave-climate are absent on the ebb-tidal delta, 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 prohibits 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 results in a southward directed transport along the Texel coastline. Thus, on either side of the inlet wave-driven transports are directed towards the inlet.
3.3. Sediment Transports and Morphodynamic changes.

3.3.1. Introduction and Available data

Direct measurements of sediment transports 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 the sedimentation and erosion patterns (3.3.4).

The analysis of bedforms is based on a series of detailed multi-beam echo-soundings taken between 2002 and 2004 at various locations in the ebb-tidal delta (see Figs. 7 and 8). These detailed maps allow for the identification of the individual bedform characteristics such as height and direction. 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 provides information about bottom currents and sediment transports (Boothroyd & Hubbard, 1975; Hine, 1975; Boothroyd, 1985; Ashely, 1990; Lobo et al., 2000).

The analysis of bathymetric changes and construction of a detailed sediment budget are based on a series of datasets, starting from 1986 (example Digital Elevation models based on these measurements are presented in Figures 2 and 3), that are digitally available from the Donar database at Rijkswaterstaat. These maps are 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 a 20x20 m grid 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 = Jaarlijkse Kustmetingen) or linear interpolation between the nearest available data.
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. 7). The largest sand waves, up to 4.25 m in height and having wavelengths over 200 m, are observed in the deeper parts of Nieuwe Schulpengat (below -20 m) where the highest near-bed tidal velocities occur. Sand waves in the northern part of the channel predominantly show three-dimensional cuspate crestlines.

Only slipface orientations of the large-scale bedforms, classified as sandwaves and large megaripples or dunes (Ashely, 1990; Boothroyd & Hubbard, 1975) having wave lengths 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. 7A). These large bedforms have long response times and their size and shape hardly change when imposed to high-frequency processes such as waves and spring/neap cycles. For that reason, they provide indications of the long-term (averaged over periods of several days to months) dominant transport directions. 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. 7A). In the distal part of Nieuwe Schulpengat, where the channel converges with 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. 7B), 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 toe of the sea defense during the 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. 8A). 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 ramp/length of the ebb-ramp) of 2. During autumn most of the bedforms are over 3 m in height with a maximum of 4.5m. 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. Sand-wave migration rates range between 40 and 60 my-1 in an eastward direction.
Figure 7 (A): High-resolution (multi-beam) based map of approximately 11 km$^2$ 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.

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 area-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 my-1 higher in winter than in summer.

A shallow seismic profile, by the Geological Survey of The Netherlands (Fig. 8B), 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 4), no clearly defined bedforms in area IV-V, symmetric bedforms in area V-VI, and large flood-oriented bedforms in area VI-VII.

![Figure 8](image)

**Figure 8 (A):** (1) High-resolution multi-beam based 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.

**Figure 8 (B):** Single beam survey of 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 (4) flood-oriented bedforms in Marsdiep (transect VII-VIII), and Texelstroom (transect VII-VIII).

### 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, larger-scale, ebb-tidal delta elements, such as ebb and flood channels, channel-margin linear bars, terminal lobes and swash-bars patterns can provide useful insights in sediment transport patterns on the ebb-tidal delta (see e.g. Boothroyd, 1985; FitzGerald, 1996; Hayes, 1975; Hine, 1975; Hubbard et al., 1979; Sha, 1989).

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 3).

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). 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. Meanwhile the shoal area above MSL increased from about 4.5 km² in 1986 to over 6 km² in 2012. The 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. 3, 1971 - 2012) indicate that the morphologic developments 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 Noorderlijke Uitlopers van de Noorderhaaks 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 tip of Noorderhaaks and adjacent Molengat channel occur since (Fig. 9). Between Noorderhaaks and Molengat a new flood channel emerges (Fig. 9A). 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. This distorted state has large implications for the nearshore and beach. Prior to 2006 the channel was deep and narrow, with steep embankments (Fig. 9B). 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). By this time the northern tip of the spit (nearly) merged with the coastline (Fig. 9A, 2006, 2012).

In the southern sub-domain large tidal channels prevail (Fig. 3). 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 coastal erosion. In the period 1976-2013 nearly 27.5 mcm was nourished on the beaches.
The western (seaward) margins of Noorderhaaks and Zuiderhaaks exhibit a contrasting behaviour. The margin of Noorderhaaks is mildly sloped, covered by multiple bar systems (Figure 3) 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 and 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 the large number of saw-tooth bars separated by runnels along the northern side of the supra-tidal Noorderhaaks shoal all testify to the wave dominant 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. 3). This southward outbuilding of Zuiderhaaks is an indication of ebb-directed sediment transport through Schulpengat. The absence of an ebb-shield facing Schulpengat is plausibly due the interaction of flood and ebb flow resulting in a net seaward diversion of the sediment transports thereby contributing to the outbuilding of Zuiderhaaks (Elias et al. 2006).

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

Figure 9 (A): Details of the morphodynamic changes on the Noorderlijke Uitlopers van de Noorderhaaks 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.
derived by subtraction of the 1986 bathymetry from the 2012 bathymetry (Fig. 10).

The interaction of tidal, wind- and wave-driven flow with the compound ebb-tidal delta bathymetry produces a complex pattern of mutually linked sedimentation-erosion areas (Fig. 10A). 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 changes over 300 m$^3$ and a 76 m$^3$ net change. 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 landward direction (-89 m$^3$ [3], see Fig. 10A 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 m$^3$), Zuiderhaaks (12 m$^3$), and spit formation at the north-western margin of Noorderhaaks (9 m$^3$ [5]) and Noorderlijke Uitlopers van de Noorderhaaks (28 m$^3$ [12]). Landward migration of the spit and the Molengat channel induces significant erosion along the Texel coastline; since 1986 over -9 m$^3$ [13] was eroded from the near-shore area despite 9 m$^3$ of nourishments that have taken place along the southwest corner of Texel Island.

South of Noorderhaaks, the morphodynamic developments are tide-dominated due to the presence of the tidal channels Schulpengat, Nieuwe Schulpengat and Nieuwe Landsdiep. The total sediment accumulation on the shoals of 44 m$^3$ is small compared to the large erosion of the main channels 83 m$^3$. The main developments are: (1) an increasing depth of the channels Nieuwe Schulpengat (-21 m$^3$ [17]), Schulpengat (-49 m$^3$ [14, 15]), and (2) a seaward and southward outbuilding of the shoals Zuiderhaaks (12 m$^3$ [7]) and Franse Bankje, (6 m$^3$ [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 anticyclonic rotation and migration of the channel.

Time series of the volume development derived for all available DEM’s over the 1986-2012, show a 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 Noorderlijke Uitlopers of the Noorderhaaks (NUN) show an increase in volume (Fig. 10C). Not corrected for nourishments a distinct shift in trend can be observed around 2001 from a 5 m$^3$/year erosion to a near stable volume. The most pronounced difference occurs in the southern portion of the ebb-delta. Here the channels Schulpengat and Nieuwe Schulpengat are remarkable stable in volume. A clear trend of deepening can no longer be observed, and only locally, severe erosion of Nieuwe Schulpengat occurs, 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 similar, but still large volumetric changes have taken place. The sediment budget of the ebb-tidal delta reveals that over 200 mcm of sediment was eroded from the ebb-tidal delta and coast. Roughly half of these sediments were redeposited landward on the ebb-delta and the remaining half was likely transported into the basin as the sediment volumes in the western Wadden Sea increased (see Elias et al., 2012). Including sediment loss from the adjacent coasts and the addition of sand through nourishments Import rates are estimated at 5.2 mcm/year (Fig. 11 B and C). 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 Fig. 11A. Both, the dominant flow directions, as well as 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 towards Texelstroom. 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 of sediment.
During ebb part of these deposits are transported back onto the ebb-tidal delta, where they contribute to the outbuilding of Zuiderhaaks and are fed back onto the Noorderhaaks. 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 (no) sediments are transported back onto the coast. Increased, near-bed, flood-dominant flow during (and preceding) high-discharge events and wave-driven transports along the adjacent coasts can significantly enhance sediment imports.

Based on the observed bed level changes, we can divide the ebb-tidal delta in 4 areas with distinct morphodynamic behaviour (Figure 11A and B). The central part of the ebb-delta (area 2) is formed by the Noorderhaaks shoal. 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 closure, with the main channels switching westward (for details see Elias & Van der Spek, 2006), Noorderhaaks, located conveniently in front of the inlet, is redistributed landwards and into the basin. Even today this process continues to dictate the development of the central part of the ebb-delta.

The eroded Noorderhaaks sediments are transported landward and partly contribute to the formation and stability of the supratidal Noorderhaaks shoal, partly sediments will be transported along its margins into the main channels. With a flood dominant flow in the main channel along the southward margin of Noorderhaaks it is likely that most of the deposits are recirculated back onto the ebb-tidal delta. These sediments contribute to the outbuilding of the southern margin of the ebb-delta (Zuiderhaaks, area 3). It is likely that, with a dominant northward wave-driven transport, sediments from Zuiderhaaks are transported back onto the Noorderhaaks ebb-delta front. As the ebb-delta front eroded, a wide shallow platform emerged that shelters the sub-tidal Noorderhaaks shoal from storms. Sediment recirculation and wave sheltering are two factors are likely reasons why the Noorderhaaks is still present eighty-five years after closure.

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 large

Figure 11 (A): Summary of the observed flows, bedform directions and morphodynamic changes. (B, C). Estimated and computed sediment exchanges in the 4 sub-domains based on the sediment budget between 1986-2012 for the entire ebb-tidal delta and for the individual subdomains.
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 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. Since 2006 the channel reduces in depth, but increases in width. This change in morphodynamic behaviour, will eventually lead to spit attachment and breaching in the near future, is 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 dominate the developments. Since 2001 deepening of the channels in the part of the ebb-tidal delta is no longer observed and the volume of the ebb-delta stabilized. Rotation of the distal part of Nieuwe Schulpengat introduces localized additional erosion of the coastline.

This recent stabilization of the southern part of the ebb-tidal delta 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 stabilising 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.

4. Discussion
Historically coastal management was restricted to flood hazard and coastal erosion prevention and mitigation. The construction of Helderse Zeewering and Closure of 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 2010 to partly fulfil sediment demand in the basin. Nearly 300 mcm were delivered by the Texel ebb-tidal delta and adjacent coasts despite the increase in tidal prism. The analysis presented in this study shows that even 85 years since closure the morphodynamic changes are still dictated by 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 ebb-tidal delta and coast. Based on literature (summarized and analysed in Elias & Van der Spek, 2006) and the analysis of recent measurements taken between 1986-2012, wherein the availability of both detailed measurements of the hydrodynamics and morphodynamics allows us to analyse the processes behind the observed changes in depth. Four distinct stages of ebb-tidal delta development can be identified (Fig. 12). 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. 11 A).

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 coast. With the exception of the southwestern tip of Texel, both coastlines of Texel and North-Holland experienced severe erosion. Such erosion can be explained by common inlet processes. 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 sea-ward side of the inlet during the ebbing tide, and material eroded from the inlet gorge is deposited at the bed below the far field of the jet were flow segregates and velocities drop beyond the sediment fall velocity. 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.

Waves can further enhance the sediment losses adjacent to the inlet. Along the undisturbed coast, the wave climate in the offshore and nearshore is bidirectional, with a slightly larger dominance of the southerly waves over the northerly waves. This drives a small net northward transport estimated to range between 0.1 and 0.5 mcm/year (Van Rijn, 2007). In addition to longshore transports, the cross-shore transports are important for shaping the coastal profile. During storm events large amount of sediments can be moved from the intertidal area into the nearshore. During calm conditions these sediments move landward and the beach recovers. With increasing longshore gradients the sediments accumulated in the offshore are transported away before beach recovery can take place. This process is likely to play a dominant role in coastline erosion adjacent to inlets.  

Alongshore gradients arise from the tidal flow acceleration towards the inlet, but also waves play an important role. 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). Wave sheltering by the ebb-tidal delta results in a nearshore wave climate that is distinctively unidirectional, directed towards the inlet on both sides. Although the gross wave-driven transports are greatly reduced, the resulting net component may enhance sediment import (Stive and Wang, 2003).

Even in an equilibrium state the basins of the Wadden Sea require sediment to compensate for the effects of e.g. sea-level rise and subsidence (Stive and Wang, 2003). The inlet 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 losses into the inlet. At Texel inlet, shoal bypassing occurs on the large swash platform that formed downdrift of the main channel. Periodic shoal merger with the Texel coastline exceeds the structural erosion rates and contributed to the southward outbuilding of the south-westerly tip off Texel Island (van Heteren, 2006). This 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.

**Stage 2: 1932-1975 Adaptation to Closure of the Zuiderzee (Fig. 11 B).**

Morphological change in roughly the first 40 years since the closure were dominated by the scouring of large tidal channels and landward retreat of the Noorderhaaks ebb-shoal (Elias et al. 2003; Elias and van der Spek, 2006). The distinct southward reorientation of the main channels was ascribed to the process of back-barrier steering as the changed hydrodynamics in the basin force the main channels to rotated southward. The large tidal prisms and velocities, with maximum erosive capacity are well capable of scouring deep channels into the underlying 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 were observed.

**Stage 3: 1975-2001 Equilibrium-Erosional state (Fig. 11C).**

Between 1975 and 1986 the system reaches a behaviour that we describe as “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 pronounced 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 and northward displacement driven by waves. After reorientation of the main channels, this area became wave-dominated and the deposits cannot maintain their form and shape. As 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 apply for the ebb-tidal delta, but also for its larger elements. For Noorderhaaks, downdrift channel rotation resulted in a loss of sediment supply and sediment redistribution by particularly the waves cannot be compensated and the shoal is pushed landward. The large tidal channels on either side of the shoal capture these sediments either transporting them into
the basin, that continues to act as a sediment sink, during a flooding tide or back onto the ebb-tidal delta during ebb. Sediment recirculation may explain the longlivety of the Noorderhaaks deposits.

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 to the most intensive of the entire Dutch coastal system (Roelse, 2002; Cleveringa et al., 2004; Hoogervoorst, 2005). Although distinct flood channels cannot be observed along the North-Holland coast, the detailed analysis of flow and bedforms reveals that a distinct segregation in flow over the channels exits. Flow along the coast is flood-dominant and along the Noorderhaaks ebb-dominant. 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.

Along the Texel coast, local coastline changes are dominated by the spit development of the Noorderlijke Uitlopers of the Noorderhaaks and the adjacent Molengat channel. Sediment accumulation in this spit effectively prohibits sediment bypassing in the form of shoals, which contributes to the sand deficit of the Texel coastline. In addition, landward migration of the spit, and the migration and deepening of the adjacent Molengat channel introduces local erosion of the adjacent coast.

**Stage 4: Present day stabilization (Fig. 11D)**

A major shift in 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 over 5,0 mcm/yearly prior to 2001 to 2 mcm/year since. This reduction is for a major part related to a stabilization of the morpodynamic changes in the southern part of the ebb tidal delta (Fig.11D – area 1). Only locally, erosion of Nieuwe Schulpengat were channel-shoal interactions are dominant; 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 local coastline erosion.

This recent stabilization of the southern part of the ebb-tidal delta may partly have been attributed to the massive nourishments (1.3 mcm/yearly) that have taken place along the North-Holland coastline. These nourishments were not only successful in stabilising 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.

While the southern part of the ebb-tidal delta stabilizes, in the northern subdomain (Fig.11D – area 2) the former balance between Molgenat and NuN is distorted allowing the tip of the NUN spit to merge with the island tip. The spit itself has not beached but two ebb-chutes have formed. It is expected that a new main channel will form through the spit allowing the remainder to merge with the Texel coastline. This restores the shoal bypassing mechanism and provides an additional source of sediment to the coastline sediment budget.

Despite these significant changes in behaviour in both the northern and southern part of the ebb-tidal delta, the erosion of the central ebb-tidal delta front continues at a similar rate.
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 in combination with direct measurement of processes we are able to unravel the various components that have contributed to supply of sediment to the basin, and conceptually describe how this sediment exchange takes place. Such conceptual model is a first step in understanding the underlying physical processes responsible for the observed changes in morphodynamic behaviour 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 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 landward on the ebb-delta and the remaining half was likely transported into the basin. The sediment budget of also reveals that on average a sediment import of 3.6 mcm between 1986-2012 prevails, but sediment imports reduces from 5.0 mcm/yearly prior to 2001 to below 2 mcm/year since.

(3). 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 datasets are too short to provide a conclusive answer, the recent stabilization of the ebb-tidal delta losses may partly have been attributed to the massive nourishments that have taken place along the North-Holland coastline.

(4). Coastal retreat along the North-Holland coastline can be attributed to the presence of large tidal channels, with 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 induces additional losses.

(5). Coastal retreat along the Texel coastline partly results from spit formation. Spit and channel migration has induced large sediment losses from the adjacent Texel coastline, and prohibits sediment bypassing from the ebb-tidal delta to the downdrift shoreline to occur. Recent merger of the spit with the foreshore may indicate that shoal bypassing is restored.

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