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# Understanding sediment bypassing processes through analysis of high-frequency observations of Ameland Inlet, the Netherlands

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ABSTRACT

Ameland inlet is centrally located in the chain of West Frisian Islands (the Netherlands). A globally unique dataset of detailed bathymetric charts starting in the early 19th century, and high-resolution digital data since 1986 allows for detailed investigations of the ebb-tidal delta morphodynamics and sediment bypassing over a wide range of scales. The ebb-tidal delta exerts a large influence on the updrift and downdrift shorelines, leading to periodic growth and decay (net erosion) of the updrift (Terschelling) island tip, while sequences of sediment bypassing result in shoal attachment to the downdrift coastline of Ameland. Distinct differences in location, shape and volume of the attachment shoals result from differences in sediment bypassing, which can be driven by morphodynamic interactions at the large scale of the inlet system (O(10 km)), and through interactions that originate at the smallest scale of individual shoal instabilities (O(0.1 km)). Such shoal instabilities would not be considered to affect the ebb-tidal delta and inlet dynamics as a whole, but as we have shown in this paper, they can trigger a new sediment bypassing cycle and result in complete relocation of channels and shoals. These subtle dynamics are difficult, if not impossible, to capture in existing general conceptual models and empirical relationships. These differences are, however, essential for understanding tidal inlet and channel morphodynamics and hence coastal management.

## 1. Introduction and objective

The Wadden Sea (Fig. 1) consists of a series of 33 tidal inlet systems and in total extends over a distance of nearly 500 km along the northern part of the Netherlands (West Frisian Islands), and the North Sea coasts of Germany and Denmark (the East and North Frisian Islands). The Frisian Islands separate the Wadden Sea from the North Sea. Although dissected by several major estuaries, such as Ems, Weser and Elbe, the Wadden Sea is the world's largest uninterrupted system of tidal flats and barrier islands. Over a period of > 7000 years, a wide variety of barrier islands, tidal channels, sand and mud flats, gullies and salt marshes formed under a temperate climate, rising sea level, and, especially during the last centuries, human interventions.

The Wadden Sea is considered to be one of the last large tidal regions where natural forces have free reign without a dominating influence from human activities. Despite this, the study of Elias et al. (2012) points out that natural processes can only reign free within established boundaries. Over the last centuries, multiple large- and small-scale interventions, such as coastal defence works, closure dams, dikes, sea-walls, and land reclamations have reduced and essentially fixed the basin and barrier dimensions in place. The, on the geological scale, observed roll-over mechanisms of landward barrier and coastline retreat (Van Straaten, 1975; Flemming and Davis, 1994; Van der Spek, 1994) can therefore no longer be sustained. So far, despite the large continuous sedimentation in the tidal basins (nearly 600 million $m^3$ since 1935; Elias et al., 2012), the individual inlets were sustained and similar channel-shoal characteristics of the basins retained. This illustrates that the Wadden Sea is resilient to anthropogenic influence, and can still import sediment volumes even larger than those needed to compensate for the present rate of sea-level rise. The realization that at present much of the basin infilling is supplied by the ebb-tidal deltas, that these deltas are limited in size and rapidly reducing in volume, and that increased coastal and barrier-island erosion is to be expected, has renewed scientific interest in studying the Dutch Wadden Sea Inlets. To

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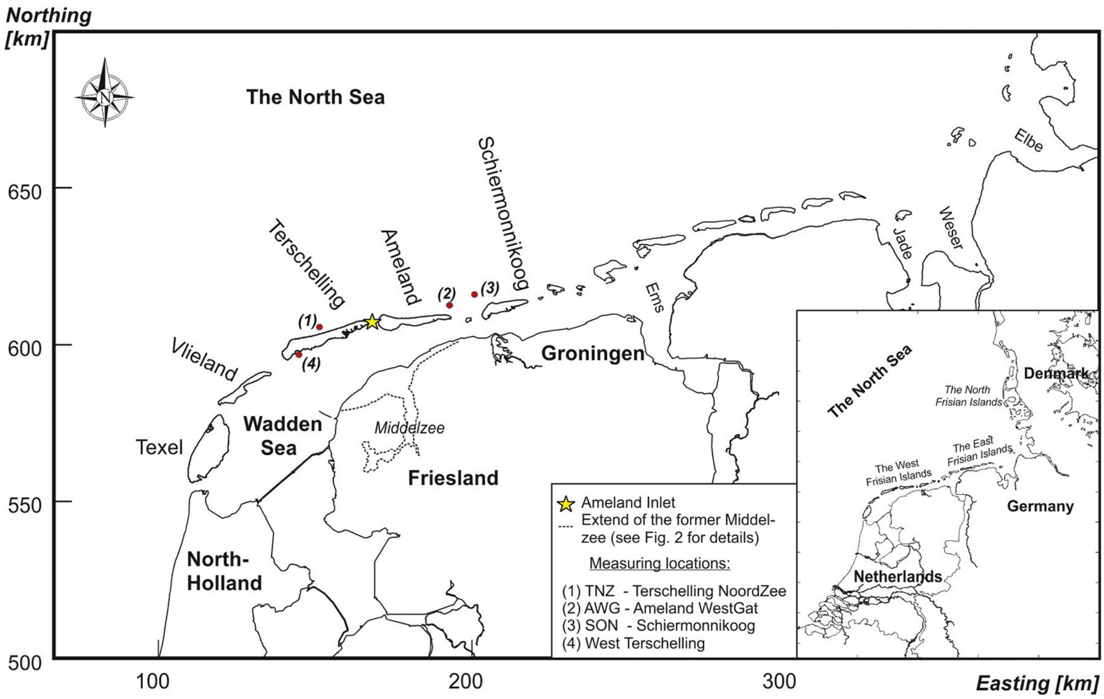


**Fig. 1.** An overview of the location, islands, and inlets that form the West Frisian and the East Frisian Islands.

sustain sufficient sediment availability, repeated beach and shoreface nourishments and potentially ebb-tidal delta nourishments may be used to mitigate shoreline erosion and add to the sediment budget of both islands and basins. However, to successfully apply such nourishments, it is essential that the ebb-tidal delta (morpho)dynamics and particularly the process of sediment bypassing is better understood.

Past studies have resulted in various conceptual models in an attempt to explain the variability in the configuration of inlet shorelines and the distribution of the associated ebb and flood-tidal delta shoals (e.g. Hayes, 1975, 1979; Oertel, 1975; Walton and Adams, 1976; Hubbard et al., 1979; FitzGerald, 1988, 1996; Hayes and FitzGerald, 2013). These studies generally agree on some basic fundamentals. Firstly, the geometry of the back-barrier basin, in combination with tidal range, determines the tidal prism (e.g. Davis and Hayes, 1984) which, in turn, determines the size of the inlet (O'Brien, 1931, 1969; Jarrett, 1976). Secondly, tidal inlets disrupt wave-induced transport of sediment along the coast and, depending on inlet size and forcing regime, large volumes of littoral sand can be stored in the inlet-associated flood- and ebb-tidal deltas (Dean and Walton, 1975; Walton and Adams, 1976). Ebb-tidal deltas not only form large reservoirs of sand but also participate dynamically in exchanges of sand in and around tidal inlets. Oertel (1975) proposed that the distribution of shoals fronting a tidal inlet reflects the relative magnitude of sand transported to the inlet from the adjacent beaches (wave-driven) versus the volume of sand transported seaward by the ebb tidal currents. The configuration of these shoals influences the distribution of wave energy along the adjacent shorelines and controls the sediment bypassing (Luck, 1976; Oertel, 1977; FitzGerald et al., 1984; FitzGerald, 1996). Bruun and Gerritsen (1959) were among the first to recognize the importance of sediment bypassing for the channel-shoal distribution on an ebb delta. They related sediment bypassing to the ratio between longshore sediment transport by waves and tidal inlet currents. For high ratios, wave-induced sand transport along the periphery of the ebb delta dominates. For low ratios, sediment transport through channels and migration of tidal channels and bars prevails. Based on the pioneering work of Bruun and Gerritsen (1959), various other researchers have further elaborated on conceptual models for sediment bypassing (FitzGerald, 1982; FitzGerald et al., 1978, 2000; FitzGerald, 1988), while others question the general applicability of the sediment bypassing concept (Son et al., 2011). Studies by e.g. Oertel (1977), FitzGerald et al. (1984), Israël and Dunsbergen (1999), and Cheung et al. (2007) indicate that sediment bypassing can produce cyclical patterns in barrier island shoreline erosion and deposition. However, a weakness of these studies is the limited temporal resolution of the underlying bathymetric data, and other evidence such as information on the sediment transport pathways is missing. The use of satellite image analysis only partly resolves these issues. The satellite data adds a valuable higher resolution, in both time and space, for the dynamics of inter-tidal and supra-tidal shoals (Ridderinkhof et al., 2016), but the dynamics of the sub-tidal morphology cannot be sufficiently addressed.

In this paper, we use both long-term and high-resolution bathymetric datasets obtained at Ameland Inlet (the Netherlands), to better understand the processes underlying sediment bypassing cycles. Such knowledge is essential to explain, predict, and especially to successfully mitigate associated shoreline erosion. At Ameland Inlet, a clear sediment bypassing event has been observed since 1985 in the form of the attachment, merger and alongshore distribution of the Bornrif shoal. The inlet is well-monitored, resulting in a unique bathymetric dataset containing bathymetric datasets (charts) starting in the early 19th century, and high-resolution, high-frequent digital data over the last decades. Through detailed analysis of (re)constructed bathymetric maps, we can start to unravel and better understand the underlying, intricate ebb-tidal delta dynamics and sediment bypassing processes occurring at this inlet. These processes are responsible for the contrasting present-day behaviour of structural erosion of the eastern island tip (Terschelling) and accretion of the western Ameland coast. Such knowledge is not only essential for future sustainable coastal management of Ameland Inlet but can also provide valuable lessons for similar mixed-energy type inlets.

## 2. Earlier work on sediment bypassing concepts for the East and West Frisian islands

Detailed studies of the morphodynamics of the Frisian barrier islands and inlets started as early as the 1930's (e.g. Van Veen, 1936 and reprint Van Veen et al., 2005; Gaye and Walther, 1935; Beckering

Vinckers, 1943), and have continued since (e.g. Homeier and Kramer, 1957; Bruun and Gerritsen, 1959; Edelman, 1961; Luck, 1976; Nummedal and Penland, 1981; Veenstra, 1982; FitzGerald et al., 1984; Sha, 1989; Flemming and Davis, 1994; Israël and Dunsbergen, 1999; Son et al., 2011, Herrling and Winter, 2014, 2017, 2018; Elias and Van der Spek, 2006, 2017; Elias et al., 2012). Over time, various conceptual models have been formulated and refined in an attempt to explain the variability in the configuration of the barrier islands, inlet shorelines, and distribution of the associated ebb- and flood-tidal delta shoals. FitzGerald et al. (1984) demonstrated that the variability in shape of the East Frisian barriers cannot just be explained by the simple model of wave versus tidal energy as proposed by Oertel (1975), but is primarily related to processes of inlet sediment bypassing, a theory that was initially suggested by Gaye and Walther (1935). FitzGerald et al. (1978) proposed three models to explain inlet sediment bypassing along mixed energy coasts: (1) inlet migration and spit breaching, (2) stable inlet processes, and (3) ebb-tidal delta breaching. These models are based on the relationship between the stability of the inlet throat and the movement of the main ebb channels and have shown to be valid for a wide range of mixed-energy tide-dominated inlets. Further refinements to the sediment bypassing models based on a wide range of tidal inlets were made in the subsequent studies of FitzGerald (1982, 1988) and FitzGerald et al. (2000).

Although the sediment bypassing concept seems generally applicable, studies by e.g. Son et al. (2011), Herrling and Winter (2017, 2018), and Elias and Van der Spek (2006, 2017) all expose that these conceptual models may not always be valid or correct. The studies of Son et al. (2011) and Elias and Van der Spek (2006, 2017) display that bar migration and attachment does not necessarily lead to sediment bypassing. This paradox was explained by Herlling and Winter (2018) by classifying the sediment bypassing process in its three principal mechanisms: (1) flow-bypassing and bar welding, (2) sediment recirculation and (2) ebb-delta periphery bypassing. Through process-based modelling it was shown that the bypassing process may differ depending on the gradation of the sand fraction and the hydrodynamic conditions. At both the Otzum ebb-tidal delta (Son et al., 2011) and Texel inlet (Elias and Van der Spek, 2006, 2017), sediment recirculation dominates over sediment bypassing. The above studies all demonstrate that it is essential to develop a comprehensive understanding of the underlying inlet dynamics and sediment transport processes before generalizing in a conceptual model description. Such understanding cannot be obtained solely by analysing (usually sparsely available) bathymetric data, but must be obtained through applying process-based models (Elias, 2006, Herrling and Winter, 2017, 2018) and/or detailed analysis of field data such as morphological changes, spatial grain-size patterns, and internal sedimentary structures (Son et al., 2011; Elias, 2006, Elias and Van der Spek, 2017). Based on these studies, we may conclude that the existing sediment bypassing concept provides a useful framework to describe channel and shoal formation and migration on the ebb-tidal delta, but it may not describe the (full) process of sediment bypassing.

In a study of the East Frisian Islands, FitzGerald et al. (1984) concluded that most of the ebb deltas along this coast are asymmetrical. The major part of the ebb-tidal delta is situated along the shoreline of the downdrift island due to the predominant eastward wave-driven sediment transport in the region. The degree of asymmetry determines the location where bars move shoreward and attach to the beach, which in turn dictates the sand supply to the barrier shoreline and the shape of the island. It was further concluded that the drumstick barrier model of Hayes and Kana (1976) is only partly applicable. In their model, the bulbous updrift end of the barrier is attributed to a sediment transport reversal caused by waves refracting around the ebb-tidal delta resulting in a broad zone of accumulation. FitzGerald et al. (1984) refined this model by showing that the shape of the front of the bulbous island depends on the location of bar attachment, which is a function of inlet size and ebb-tidal delta configuration. Depending upon where these bars attach to the downdrift shoreline, the barriers can develop different shapes (e.g. drumstick, humpbacked or even downdrift bulbous-shaped). Both studies agree that the downdrift end of a barrier island forms through spit accretion. Although these concepts seem to provide a general explanation of the island shape, they may only be partly applicable in the present-day setting. Both the West and the East Frisian Islands are heavily influenced by human interference. Erosion on the western heads of the Islands is generally prevented through massive groin structures, revetments and seawalls, while island shorelines and dunes are stabilized to counteract breaches and overwash.

Sha (1989) further investigated the asymmetry of the ebb-tidal deltas of the West and the East Frisian Islands and concluded that this asymmetry is not only produced by waves, but also by the interaction of the shore-parallel tidal currents and the tidal currents through the inlet. The latter may limit the applicability of basic conceptual models as proposed by Oertel (1975) to the Frisian Islands. This is especially the case for the larger, tide-dominated West Frisian inlets, where the tidal interaction results in predominantly updrift-directed, asymmetrical, ebb-tidal deltas and main ebb channels, and a main shoal area that lies downdrift (to the north or east) of the main ebb channel.

The sediment bypassing process and related bar attachments are often described as periodic or cyclic events (Oertel, 1977; FitzGerald et al., 1984; Gaudiano and Kana, 2001; Israël and Dunsbergen, 1999; Cheung et al., 2007; Robin et al., 2009; Hein et al., 2016). Based on an analysis of the shoaling behavior on the Wadden Sea ebb-tidal deltas, Ridderinkhof et al. (2016) concludes that the average period between successive shoal attachments correlates to the tidal prism, and has values ranging between 4 and 130 years. A conceptual model for cyclic morphodynamic evolution of Ameland Inlet was presented by Van der Spek and Noorbergen (1992), and further refined by Israël and Dunsbergen (1999). These authors concluded that a cyclic morphodynamic channel-shoal evolution occurs in Ameland Inlet. The observed cycle spans between 50 and 60 years and consists of four distinct stages in evolution in which the inlet configuration changes between one and two main inlet channels. However, the observed continuous (severe) erosion of the eastern island tip of Terschelling (Boschplaat) since 1975 seems to deviate from expected morphodynamic behavior based on this cyclic model concept and has partly motivated the research underlying this paper.

## 3. Study area; Ameland Inlet

### 3.1. General setting

With a tidal range increasing from 1.4 m at Den Helder (Texel Inlet) to 4.4 m near Bremen, and waves with an average significant wave height around 1.4 m, the Frisian Inlets fall in the mixed-energy category (Hayes, 1975; Davis and Hayes, 1984). Characteristic of mixed-energy inlets systems is the presence of large and stable inlets, with barriers typically being short and ‘drumstick’-shaped (Hayes and Kana, 1976). With the variation in tidal range and sizes of their back-barrier basin, some of the smaller inlets, especially along the West Frisian inlets, may have more wave-dominated characteristics, while the larger inlets (such as Ameland Inlet) are more tide-dominated with larger tidal channels and extended ebb-shoal complexes (Sha, 1989).

Ameland Inlet is centrally located in the West Frisian island chain and bordered by the islands Terschelling to the west and Ameland to the east (Fig. 1). The associated Ameland tidal basin has a length of about 30 km and covers an area of 270 $km^2$. Approximately 60% of the basin area consists of intertidal shoals (Eysink, 1993). The present-day location of the Frisian coastline was formed around 1600 CE (Fig. 2). Historically, Ameland Inlet was the outlet of the medieval Middelzee tidal basin, that reached its maximum size around 1000 CE. Infilling with marine sediments and subsequent dike building on these new deposits resulted in the reclamation of the landward part of the basin, decreasing tidal prisms, constriction of the inlet and extension of the

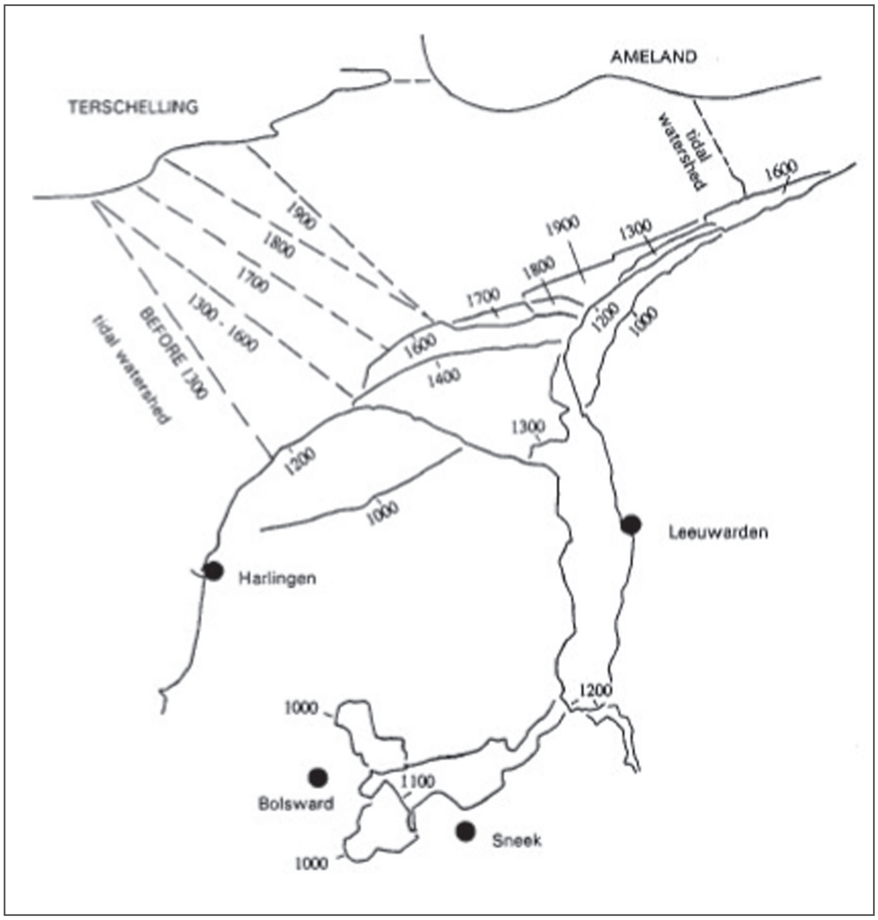


**Fig. 2.** Overview of the dates of construction of dikes and the reclamation of the Middelzee and the adjacent Wadden Sea (from Van der Spek, 1995).

updrift barrier island Terschelling.

The geometry of both the Terschelling and Ameland islands shows the typical drumstick-shape described in the model of Hayes and Kana (1976), having a bulbous updrift side and a long, narrow downdrift end that formed through spit accretion. An eastward littoral drift dominates along the islands as a result of the prevailing winds out of the westerly quadrants. Estimates of the longshore drift vary considerably. Along the Terschelling Island coastline values of 0.5–0.6 to 1.0 million $m^3$/year were reported by Tanczos et al. (2000) and Spanhoff et al. (1997), respectively. Ridderinkhof et al. (2016) estimate the longshore drift rate to range between 0.3 and 0.5 million $m^3$/year along the Terschelling coast and 0.8–1.2 million $m^3$/year along the Ameland coast. Note that in this paper, the terms updrift and downdrift refer to the direction of the longshore drift along the islands, which for the Frisian islands means that downdrift is to the east (i.e. Ameland coast) and updrift to the west of the inlet (i.e. Terschelling coast).

In the basins, we observe a fractal channel pattern (Cleveringa and Oost, 1999). The basins are more or less separated by higher elevation and finer grain size, so-called tidal divides or watersheds. These tidal divides form where the tidal waves traveling through two adjacent inlets meet. Here, sedimentation due to near-zero velocities results in preferred tidal-flat accretion (e.g. Pinkewad in the east and Terschellinger Wad in the west). These tidal divides are often considered to form boundaries that separate inlet systems and are located somewhat eastward of the centre of the barrier islands due to the amplitude differences between the neighboring inlets (Wang et al., 2013) and the prevailing eastward wind direction. Both recent field measurements (Van Weerdenburg, 2019) and the model study of Duran-Matute et al. (2014) show that these tidal divides do not form hydrodynamically closed boundaries, as water and suspended sediment exchange still occurs. Especially during strong wind events, considerable throughflow over the divides and thus between the inlets happens.

### 3.2. A mixed-energy inlet

#### 3.2.1. Tides and tidal prism

Tides and wind-generated waves are the dominant processes governing the morphological development of Ameland Inlet. Major river runoff or fresh-water discharge into the basin is not present, although minor density stratification may occur after fresh-water flushing through the discharge sluices in the Afsluitdijk, especially during strong westerly winds. The semi-diurnal tidal movement is the main driving force behind the water flow through the inlet. Long-term observations of water levels at the station West Terschelling show that the semi-diurnal tide has a dominant $M_2$ constituent with an amplitude of 0.77 m. Distortion of the $M_2$ tide due to shallow water effects results in a significant asymmetry ($M_4$ amplitude is 0.05 m) and faster rise than fall of the tide. A considerable spring-neap variation ($S_2$ amplitude is 0.20 m) introduces an increase of the tidal range to 3 m during spring tide and a drop to about 1.5 m during neap.

The tidal signal represents only part of the measured water levels. Meteorological distortion due to air pressure variations and wind-generated setup or set-down can reach significant heights along the Dutch coast. At station Texel NoordZee (TNZ), setups can exceed 1.5 m during major storm events (see Fig. 1 for location). Setup-gradients can drive complicated residual flow fields over the complex bathymetry of the Wadden Sea, generate shore-parallel velocities and throughflow between adjacent basins (Duran-Matute et al., 2014). In addition, the increased volume of water stored in the Wadden Sea due to the larger setup can considerably enhance the outflow velocities in the inlets

**Table 1**
Overview of measured ebb and flood volumes (converted to mean discharge) in Borndiep based on 13-h measurements (based on data in Israël, 1998).

| Survey year | Dates | Mean discharge ($10^6$ m$^3$) | | |
|---|---|---|---|---|
| | | Flood | Ebb | Total |
| 1937(1) | – | 406 | 431 | -25 |
| 1968–1997(2) | 109 flood tides<br>110 ebb tides | 518 | 494 | 24 |
| 1996(3) | | 448 | 395 | 53 |
| 1999(4) | 26-10-1999 04:00–18:00 | 416 | 454 | −38 |
| 2001(5) | 22-01-2001 05:30–18:30 | 407 | 418 | −11 |

References: (1) Beckering Vinckers (1943), (2) Studiedienst Hoorn (1973), (3) Hut (1996), (4) De Visser (1999), and (5) Briek et al. (2003), Barsingerhom et al. (2003)

following the storm events, thereby affecting channel dimensions, the ebb-tidal delta development and adjacent beaches (Koch and Niemeyer, 1978; Krögel, 1995; Elias and Van der Spek, 2006). Measurements of the mean sea level over the last 150 years reveal an increase of around 0.20 m at the nearby tide gauge of West Terschelling.

The tidal motion drives a significant flow through the inlet gorge. Measurements of the discharge have been taken frequently in transects across the inlet gorge by roving 13-h ship measurements (see Table 1 for an overview based on Israël, 1998). All discharges were recalculated to a representative mean tide using a coherent method (Van Sijp, 1989). The oldest available measurement (1937) has a value similar to the 2001 measurement (Briek et al., 2003). Table 1 shows that, on average, ebb- and flood volumes through the inlet are c. 400–500 million m$^3$. The two most recent measurements have small ebb residuals that are < 10% of the gross ebb and flood volumes. The observed peak ebb and flood-tidal velocities are around 1 m/s in the central Borndiep channel.

*3.2.2. Wind and waves.* Wind measurements obtained at the nearby AWG station (see Fig. 1 for location) display a mean wind velocity of 4.9 m/s from a south-southwesterly direction (200°). Long-term wave measurements are collected at the nearby station Schiermonikoog (SON); see Fig. 1 for location. Analysis of the measurements over the period 1979–2016, and summarized in the wave rose presented in Fig. 3, reveals that the wave climate is mild. Typically, significant wave heights are below 2 m (83% of the record), and only during severe storms can wind-generated significant wave heights occasionally reach values between 4.5 and 9.1 m (< 1% of the record). The mean significant wave height is 1.37 m with a corresponding peak wave period of 7.2 s.

The dominant wind and wave directions differ considerably. The largest and most frequent winds occur from the southwest, a direction hardly present in the wave record due to the sheltering of the mainland and the barrier islands. Roughly 33% of the wave directions lie between west-southwest and north-northwest (235° – 305°). Most waves (62%) are from directions between north-northwest and east (305° – 90°). The remaining 4% are offshore directed and do not significantly contribute to sediment transport. Wave periods ($T_{1/3}$) typically vary between 3 and 6 s for lower wave conditions (89% of the measurements). For typical storm waves ($H_{sig}$ = 2–3 m) a mean wave period of 6.0 s occurs, increasing to 7.6 s for severe storms ($H_{sig}$ > 4 m). Contributions of swell are minor. Wave periods over 9 s are only measured occasionally (0.1% of the record). The short-wave periods indicate that the wave climate is dominated by wind waves generated in the North Sea basin.

### *3.2.3. Channels and shoals of the ebb-tidal delta*

Fig. 4 provides a detailed overview of the main channels and shoals that form the present-day Ameland Inlet. In the inlet gorge, between the islands of Terschelling and Ameland, a deep main ebb-channel exists

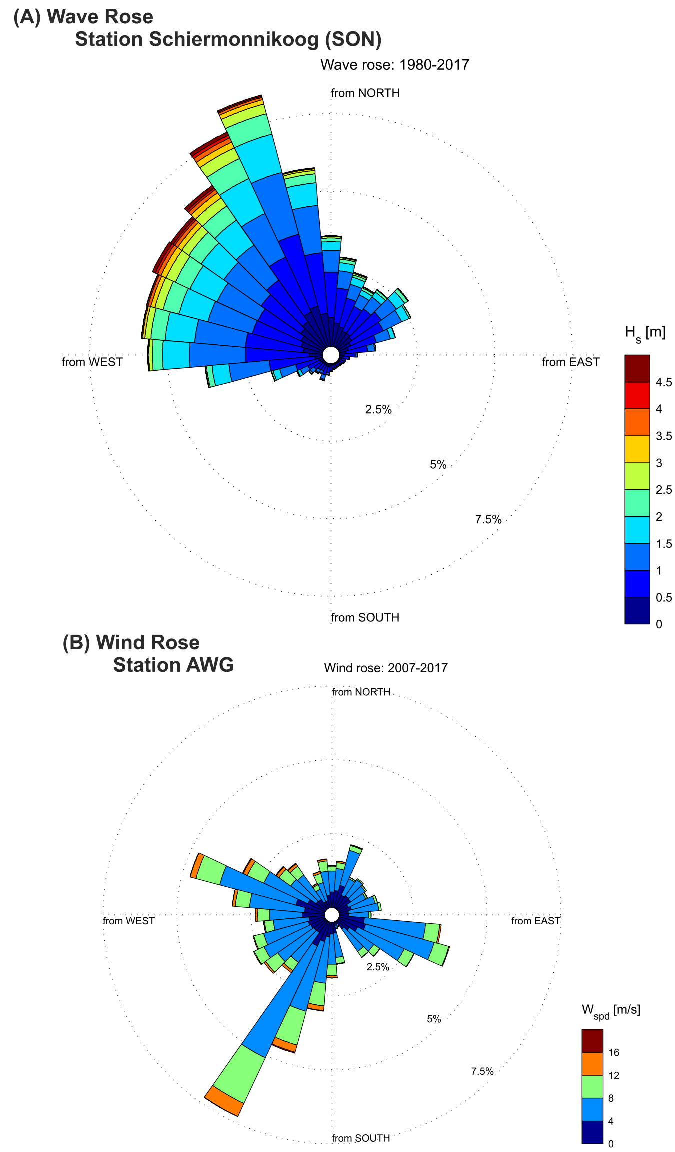


**Fig. 3.** (A) Wave rose for station SON, and (B) wind rose for station AWG, see Fig. 1 for locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

along the west coast of Ameland (Borndiep, see Fig. 4 [1]). The deepest parts of the channel exceed 25 m in depth. In the basin, Borndiep connects to Dantziggat [2] that curves eastward into the basin towards the tidal divide of Ameland (Pinke Wad). To the west, separated by the shoal Zeehondenplaat [16], a smaller channel system is formed by Oosterom [3] and Boschgat [4], both curving southward towards the tidal divide of Terschelling (Terschellinger Wad). In the present bathymetry, Boschgat connects to the ebb-tidal delta and the Westgat flood channel [6] through a series of smaller channels. In past decades, Westgat formed a pronounced (ebb) channel, but in the recent bathymetry, this channel is distorted by an ebb-chute and sill near its connection to Borndiep.

The main channel on the ebb-tidal delta is called Akkepollegat [7]. Akkepollegat had a pronounced seaward outflow in the past, but recently two ebb-chutes [9,10] have formed along its western margin. The most seaward, oldest, ebb-chute [9] formed a noticeable ebb-shield that now covers most of the shoal area known as Kofmansbult [11]. Eastward migration of this shoal has distorted the outflow of Akkepollegat and rotated the channel eastwards [7].

The main shoal area on the ebb-tidal delta lies eastward of

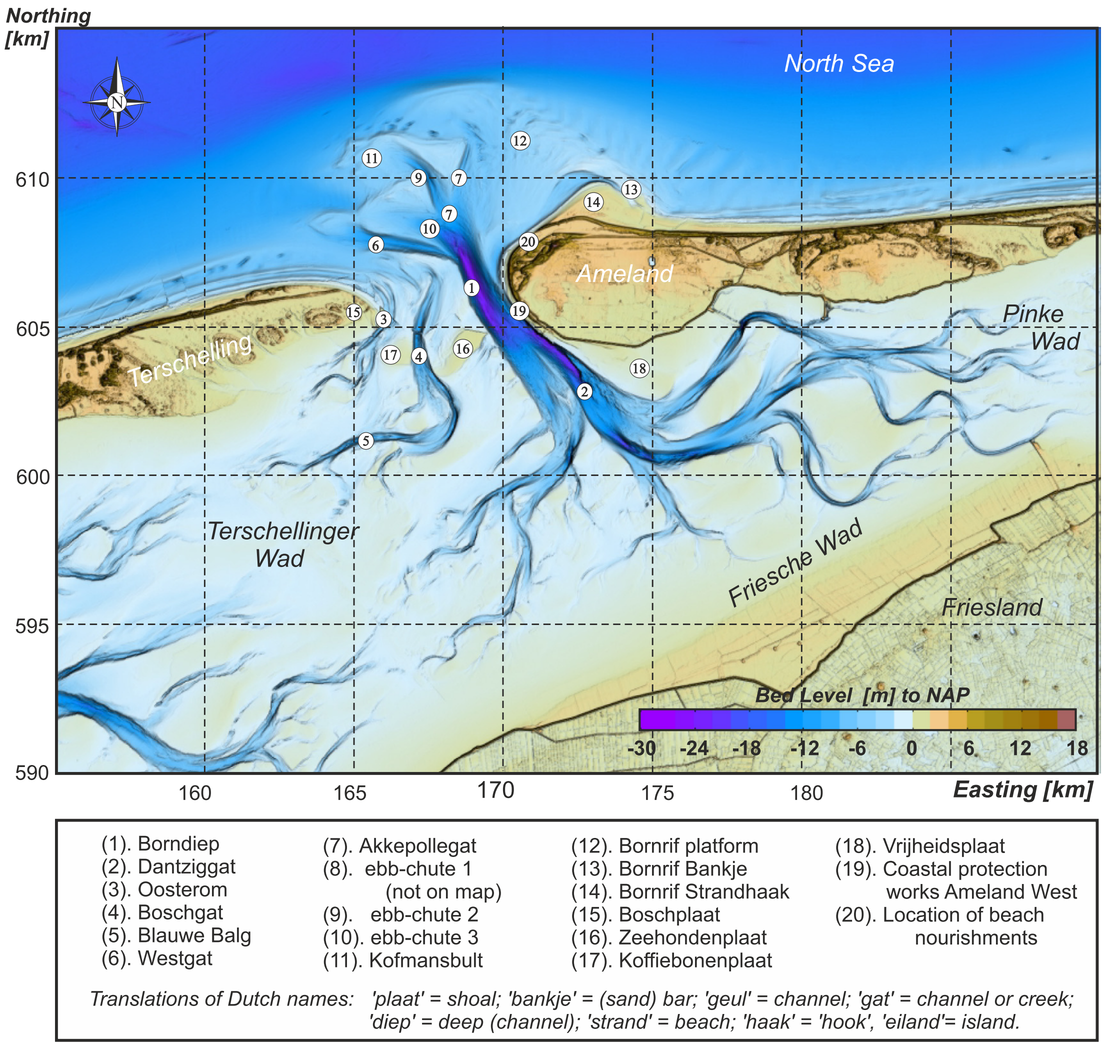


**Fig. 4.** Overview of the channels and shoals that form the present-day Ameland Inlet compiled from 2018 measurements of the ebb-tidal delta and coast, and 2017 measurements of the basin.

Akkepollegat, which is downdrift in relation to the littoral drift. This large shoal area or swash platform is named Bornrif [12]. The remnants of the shoal Bornrif Bankje [13] are still visible. This shoal had formed and migrated as a narrow swash bar, along the seaward margin of the ebb-tidal delta towards the coast. Along the coastline of Ameland, the remains of the Bornrif Strandhaak [14], a former ebb-delta shoal that attached to the coastline around 1985, are still clearly noticeable. This natural mega-nourishment resembles the "Zandmotor" (Stive et al., 2013) both in dimension and layout, and has supplied the (downdrift) coastline of Ameland with sand over the past decades (Fig. 5). Just to the west of this location, repeated nourishments [20] and extensive shore protection works are needed [19] to maintain the coastline.

While shoal attachments built out the coastline of Ameland, the opposite was observed along the coastline of Terschelling. The easternmost tip of this island, Boschplaat [15], has retreated over 1.5 km since 1975 (Fig. 6).

Despite large coastline changes the volume of the Ameland ebb-tidal delta remained relatively stable between 1935 and 2005. Elias et al. (2012) estimate that a small net increase of 34 million $m^3$/year (0.5 million $m^3$/year) has occurred since 1935, although over the time frame 1990–2015 the ebb-tidal delta lost 6 million $m^3$ (−0.4 million $m^3$/year).

### 3.2.4. Grain size distribution

The surface sediment of the Ameland ebb-tidal delta is largely composed of fine sand (126–250 μm); the same is true for much of the basin immediately inland and area immediately offshore. The seabed of the main channel (Borndiep) and the Boschplaat region largely consist of medium sand (250–500 μm). Mud content (< 63 μm) is highest in intertidal areas at the rear of the basin and along tidal watersheds. Fine sediment observed in the main channel can be explained by consolidated clay boulders or clay found on the seabed there, possibly a lag deposit, transported there after erosion from other locations.

## 4. Bathymetric measurements and observations

Ameland Inlet has a long history of bathymetric surveying. The first crude map was probably drawn in 1558, followed by a series of maps and charts that increase in detail with time (Fig. 7). The old maps do not provide a detailed chart of the inlet configuration but do show the main channel(s) and shoals. These rough sketches already illustrate many of the inlet characteristics that are still present today. A large main ebb-channel (Borndiep) is located between the islands. On the ebb-tidal delta, the orientation of the distal part of the channel shows distinct changes in orientation. A relative straight channel with a north-northwesterly direction is present in 1585 and 1723 (Fig. 7 A, D), the outflow has a distinct westerly (updrift) orientation between 1623 and the end of the 17th century, and in the map of 1798 (Fig. 7 B, C, F). Similarly to today, the Bornrif is present as the main shoal area, located downdrift of the main ebb-channel. Periodic shoal attachments occur as

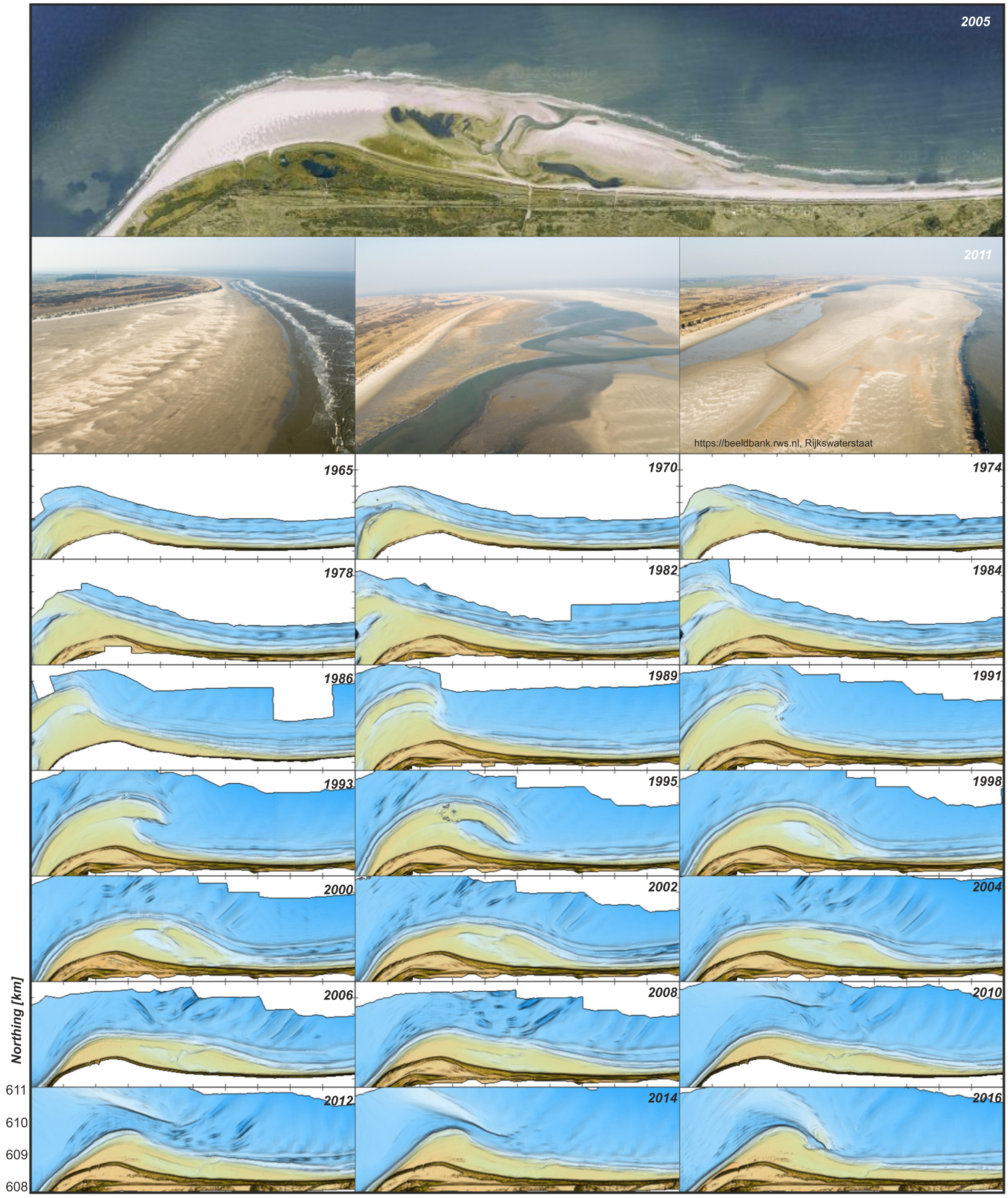


**Fig. 5.** An impression of the Bornrif Strandhaak in 2005/2011 (photographs on top), and formation and evolution of the Bornrif Strandhaak based on annual shoreline surveys called JarKus measurements (from Jaarlijkse Kustmetingen) over the time-frame 1965–2016.

large sand volumes overwhelm the flood channel and merge with the northwestern tip of Ameland. Such attachment occurred around 1623 (Fig. 7B), and just prior to 1798 (Fig. 7F). In the subsequent years, the attached shoal migrates along the coast and a north-eastward directed channel develops along the coast (Fig. 7 C, D). In the inlet gorge, periods with one or two channel configurations alternate. A distinct single main channel, Borndiep, is present in 1723 and 1798 (Fig. 7D-F). An additional second channel along the coast of Terschelling is observed between 1585 and the end of the 17th century (Fig. 7A-C) and in the second half of the 18th century (Fig. 7E). The two channels are separated by a large shoal area.

Between 1798 and 1958 the inlet was surveyed by the Hydrographic Service of the Royal Netherlands Navy and the results were published as nautical charts. The degree of accuracy of the older maps is not exactly known, but, as the primary purpose of these maps was navigation, they are expected to display the distribution of the major channels and

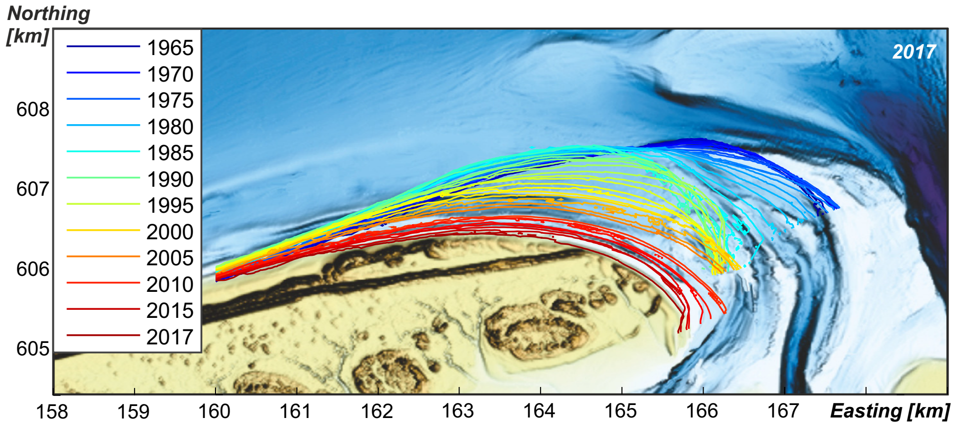


**Fig. 6.** Details of the coastline erosion of Boschplaat; lines indicate the position of the 0 m NAP contour over the 1965–2017 timeframe and are derived from the JarKus dataset. Underlying bathymetry is based on 2017 Vaklodingen.

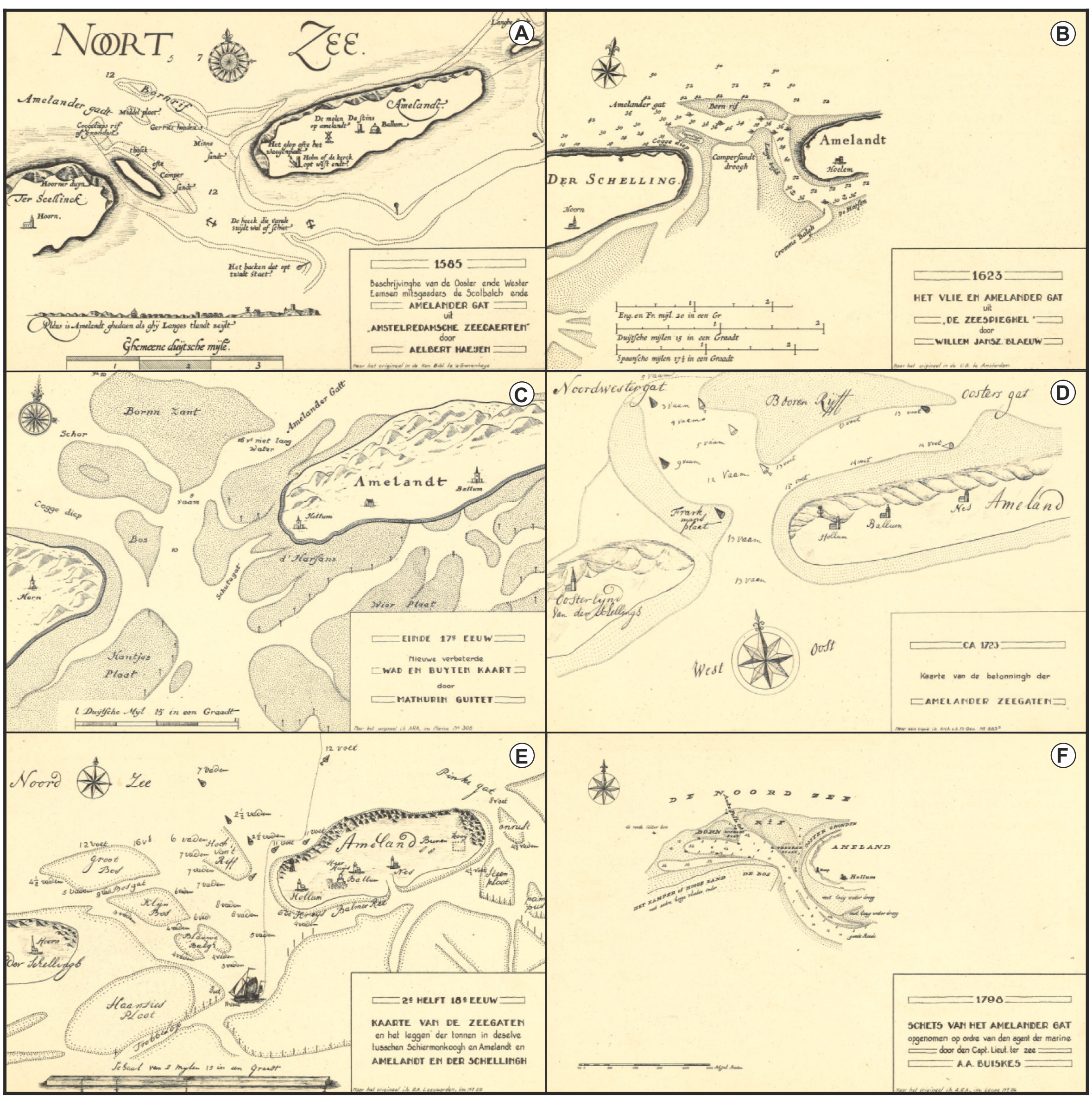


**Fig. 7.** Compilation of bathymetric charts of Ameland Inlet for the years (A) 1585, (B). 1623, (C). end of the 17th century, (D) 1723, (E) second half of the 18th century and (F) 1798.

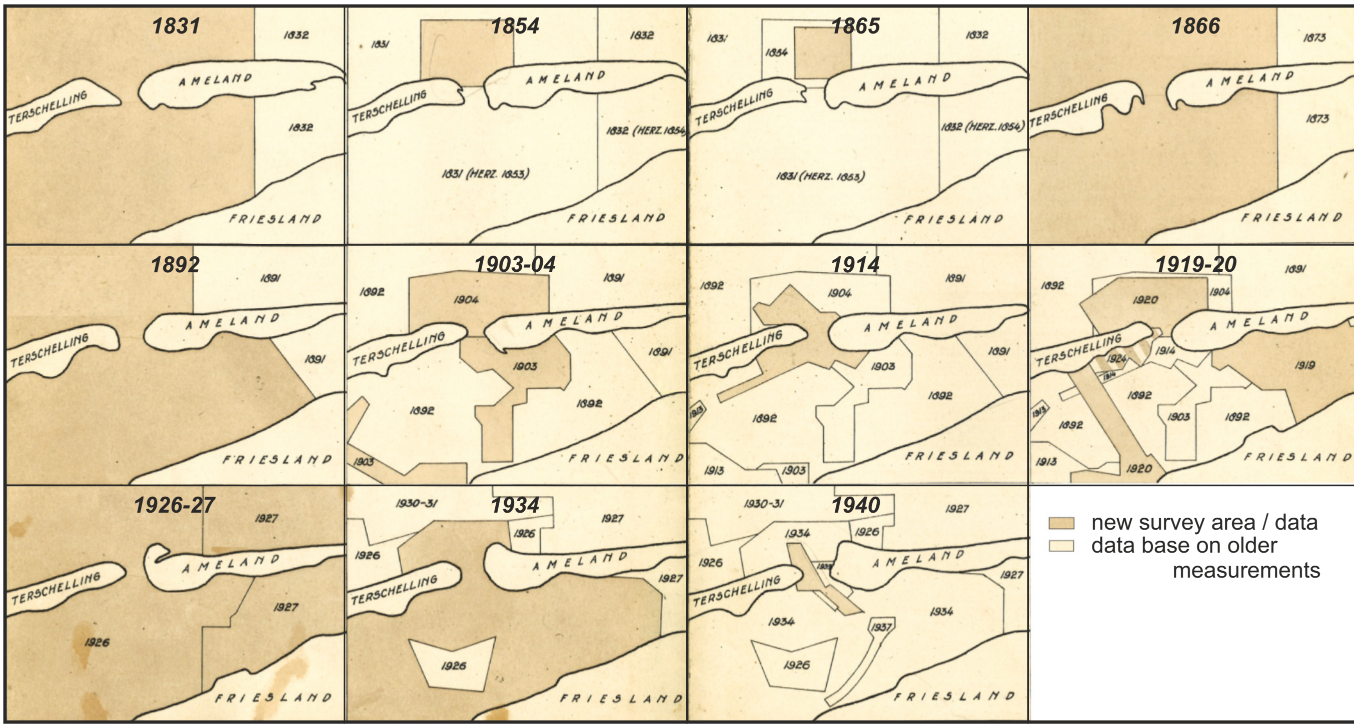


**Fig. 8.** Overview of survey areas for the bathymetric charts taken between 1831 and 1940.

shoals correctly. In this study, we have used the charts taken between 1831 and 1985 (Figs. 8–10) and supplemented these with recent digital renderings based on the Rijkswaterstaat Vaklodingen dataset (1989–2017, Fig. 11). The charts over the 1831–1940 timeframe are of sufficiently high resolution to be directly used in the analysis (Fig. 9). For the 1950–1985 timeframe, we used the digitized contour lines to reconstruct the charts (Fig. 10, see Verhoeff, 2018, for details).

Beckering Vinckers (1943) provides an extensive review of the maps produced between 1831 and 1940 (Fig. 9) and points out that not all charts are based on unique measurements (see Fig.8). This explains some of the stability, or sudden large changes, between subsequent maps. For example, the maps of 1854 and 1865 are largely based on the 1831 map with only new survey data at the centre of the ebb-tidal delta. Between 1903 and 1919 only limited measurements were made in the basin.

Since 1958 data have been collected by Rijkswaterstaat, part of the Ministry of Public works and Infrastructure. Up to 1985, these data were stored as paper charts, although some of the underlying analog data used to construct the charts were digitized in 1991–1992 (De Boer et al., 1991a, 1991b; Rakhorst et al., 1993). Since 1986 all bathymetrical surveys are stored digitally following a strict protocol. The digital maps are based on regularly collected data, in approximately 3-year intervals for the ebb-tidal delta and 6-year intervals for the basin (Dillingh, 1990). Each inlet system is measured with approximately 200 m transect spacing using a single-beam echo-sounder. Following quality checking for measurement errors, data are reduced to 1 m transect resolution, combined with nearshore coastline measurements and lidar data for the tidal flats in the basin, and interpolated to 20 × 20 m grids. The grids are then stored digitally as 10 × 12.5 km blocks called Vaklodingen (De Kruif, 2001). Additional, yearly datasets are available for the interval 2007–2010. These data were obtained by Rijkswaterstaat in the framework of the SBW-Waddenzee project (Zijderveld and Peters, 2006), but processed and saved in a format similar to the Vaklodingen. Half-yearly bathymetric surveys of the ebb-tidal delta started in 2016 and will be continued until the end of 2019 in the KustGenese 2 project. The 2016 and 2017 maps from this series have been added to the dataset. See Fig. 11 for a compilation of recent maps.

In this study, each of the 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. Even for the digitally available data, it is difficult to estimate their accuracy. Through time, multiple changes in survey techniques and instruments, positioning systems, and variations in correction and registration methods have occurred. Perluka et al. (2006) provide an analysis of the present-day survey accuracy in the Wadden Sea. These authors estimate the vertical accuracy of measured (raw) wet data at 0.11 m and 0.40 m for the final interpolated data. Similar error estimates for the Western Scheldt estuary show inaccuracies of 0.19–0.23 m for flat channel slopes and intertidal areas. Errors along the channel slopes are larger (up to 0.39 m) because of the steep gradients in bathymetry there.

## 5. Analysis of the morphodynamic changes

The objective of this study is to better understand the sedimentation and erosion along the island coasts of tidal inlets. In our analysis, we firstly focus on the inlet gorge, as the position of the main inlet channel directly determines the evolution of the adjacent island tips, and small rotational changes impact sediment bypassing on the ebb-tidal delta. Secondly, we discuss the (changes in) sediment bypassing mechanism which determines the sediment delivery to the adjacent (downdrift) barrier island coast. Thirdly, we analyse the coastline evolution of the updrift (Terschelling) and downdrift (Ameland) barrier island tips to better understand the observed sedimentation-erosion cycles. The numbers indicated by [..] refer to the numbers in Figs. 9, 10 and 11; see Fig. 10 for legend. Note that as channels and shoals form, migrate, disappear and reappear, the naming of the channels and shoals was not always consistent through time.

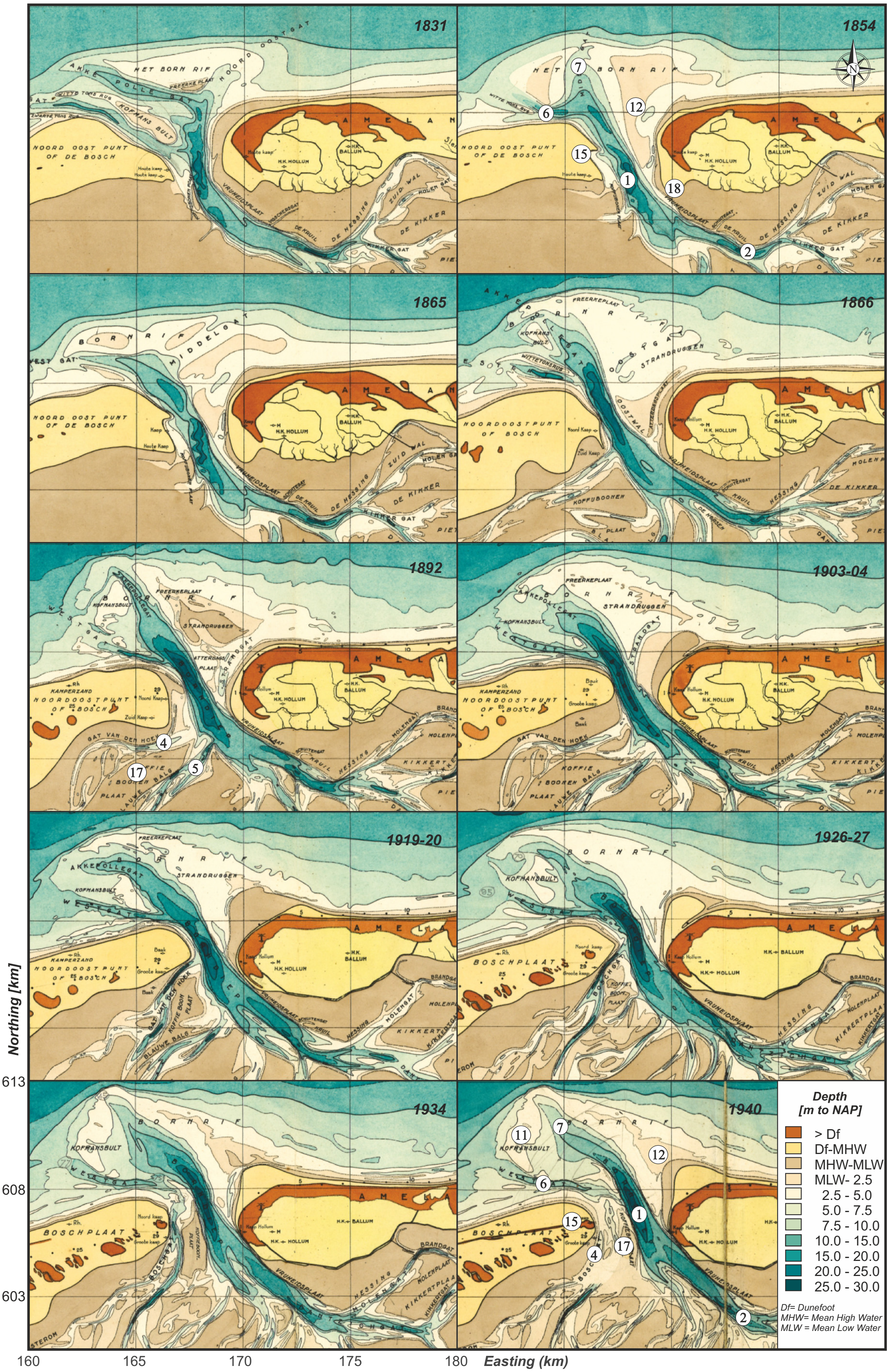


**Fig. 9.** Bathymetric charts of Ameland Inlet for the period 1831–1940. See Beckering Vinckers (1943) for a detailed description of the charts.

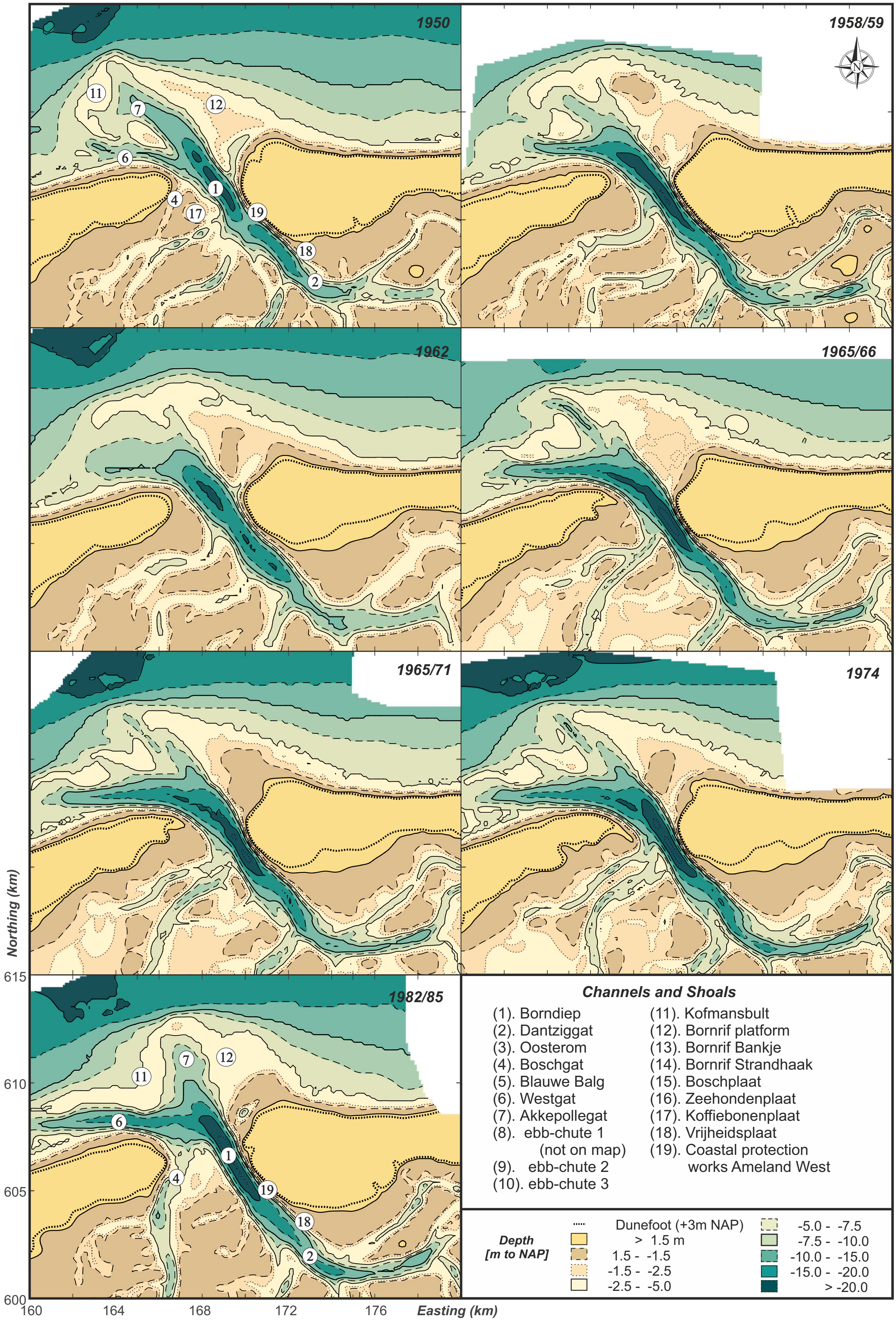


**Fig. 10.** Bathymetric charts of Ameland Inlet for the period 1950–1982/85. Based on digitized contour lines of the bathymetric charts (Verhoeff, 2018).

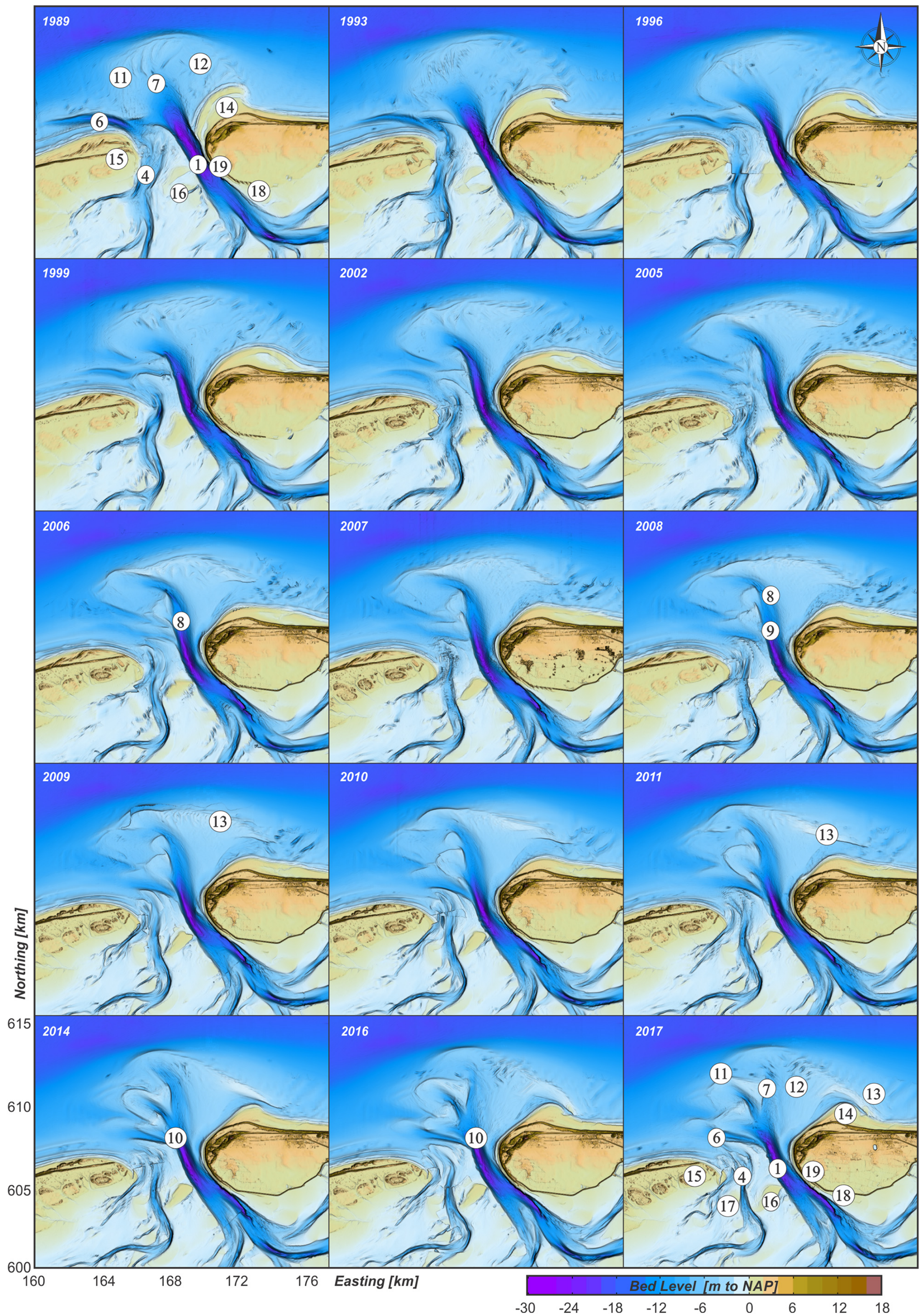


**Fig. 11.** Complete DEMs of the ebb-tidal delta based on measurements over the time-frame 1989–2017.

### 5.1. Inlet gorge

In 1854, the central part of inlet channel Borndiep [1] had a north-northwesterly direction and was located on the western side of the inlet gorge, along the island tip of Terschelling (Boschplaat [15]). The Bornrif platform [12] extended far into the basin, and a shallow shoal area separated the channel from the western tip of the island of Ameland and connected to the Vrijheidsplaat [18]. This latter shoal at the southwest tip of Ameland was well developed. In the basin, Borndiep curved eastward and split into several outflow channels, e.g. Dantziggat [2], Molengat and Kromme Balg which all extended to the east into Pinke Wad. The western part of the basin, towards Terschellinger Wad, drains through several small tributaries that connect perpendicular to the southern margin of Borndiep.

Between 1854 and 1920 the basinward part of Borndiep rotated and migrated towards the (south)western tip of Ameland (Fig. 9). These changes in the orientation of Borndiep probably result from the long-term alterations due to infilling of the Middelzee tidal basin (Van der Spek, 1995). The present-day shoreline was created around 1600 CE (Fig. 2), but the change in basin geometry brought large-scale alterations of the channel pattern in the remaining basin. As the basin changed from a hydrodynamically long basin to a short basin in which the tidal channels were re-directed to the east, the Ameland tidal divide (Pinkewad, Fig. 4) started to migrate towards the east. This migration is in the order of several kilometres since 1830. Up to 1926 this migration primarily impacted the basin, but since 1926 the migration of Borndiep in the inlet gorge started to scour the western tip of the island (Fig. 12C, D), making extensive shore protection works necessary. Already in 1947, the first stone revetments and slag stone armour layers were placed (see Fig. 4 [19] for approximate location). Additional groins and an alongshore stone revetment on the inner channel slope were placed in 1979 and further expanded in 1994. These constructions have kept the channel in place, but frequent maintenance and additional nourishments at the northwest facing beaches are still needed (see Fig. 4 [20]). Nine nourishments, with sediment from offshore sources, have been placed at this location since 1979 that in total added nearly 4.5 million $m^3$ of sand to the system. The Borndiep has retained its downdrift position, attached to the western tip of Ameland, until today.

The transition of the main ebb-channel from the updrift (Terschelling side) to the downdrift (Ameland) side of the inlet altered the outflow onto the ebb-tidal delta, but it also allowed for the formation of a two-channel system in the inlet gorge. Up to 1920, two smaller channel systems, Boschgat (in the older maps called Gat van de Hoek) [4] and Blauwe Balg [5], separated by the shoal Koffiebonenplaat, fill and drain the western part of the basin south of Terschelling and debouch into Borndiep. Based on limited surveys,

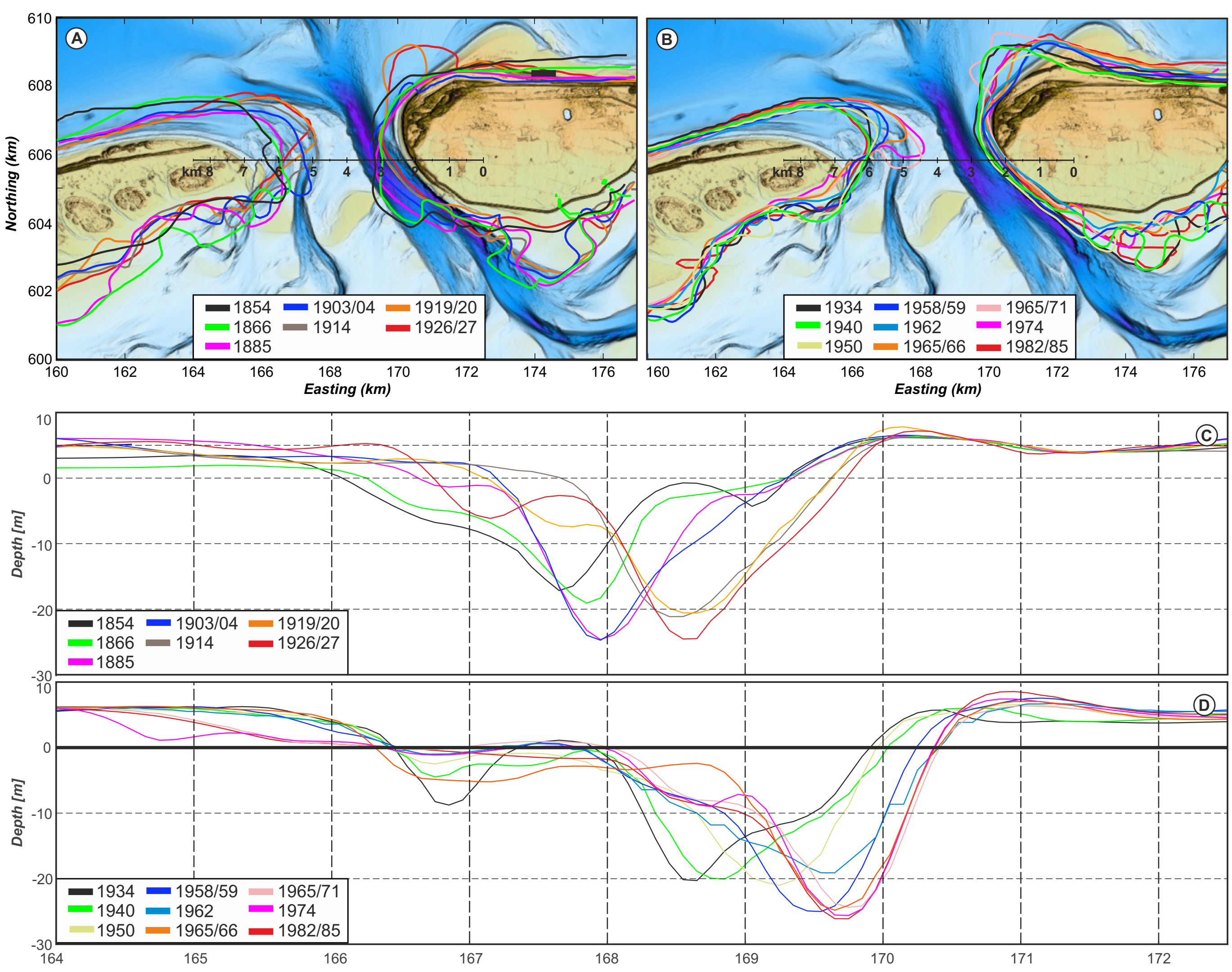


Fig. 12. Coastline position of the islands Terschelling and Ameland based on digitized charts over the time-frame (A) 1854–1926/27 and (B) 1934–1982/1985. (C-D) Cross-sections illustrating the depths of the inlet gorge; scale bar in figs. A and B provides the location of the transect.

these channels appeared to be reasonably stable in position from 1831 to 1914. Between 1914 and 1934, Blauwe Balg [5] migrated northward, eroding the width of Koffiebonenplaat [17]. The Koffiebonenplaat showed a similar northward migration, constraining the dimensions of Boschgat and pushing the channel towards Boschplaat. Boschgat was retained as it had connected to the southern part of Blauwe Balg. This may have increased its drainage area and current velocities considerably. By 1934, Boschgat had breached the Boschplaat and connected directly to the Westgat channel on the ebb-tidal delta. Temporarily, a two-channel system existed in the inlet gorge, with a deep Borndiep and a shallow Boschgat separated by the now elongated, narrow shoal Koffiebonenplaat. This secondary channel is small compared to the primary Borndiep channel, but it must have reduced the Borndiep outflows to some extent since the Borndiep temporarily decreased in depth (Fig. 12C, D) and Westgat increased in size, as it now partly drained the western portion of the basin. This two-channel configuration was only short-lived. A vast amount of sediment had accumulated in Koffiebonenplaat, the shoal between the Boschgat and Blauwe Balg. Landward, towards Boschplaat, shoal migration constricted the flow in Boschgat (1940–1962), and by 1962 attachment of the shoal added a large sediment volume to the southern side of Boschplaat. The redevelopment of Blauwe Balg just south of the Koffiebonenplaat, taking over part of the drainage area of Boschgat, may have contributed to these developments.

By 1974, Boschplaat had grown in length and formed a long but relatively narrow and low spit with a maximum extension into the inlet gorge (Figs. 10 and 12B,D). This spit was breached again between 1974 and 1982, and a clear connection between Boschgat and Westgat is visible in the bathymetries of 1985 through 1999. After 1999 a distinct channel no longer existed, and a shallow platform of roughly NAP -5 m mean depth and dissected by smaller, highly mobile channels, had formed.

### 5.2. Ebb-tidal delta dynamics

#### 5.2.1. "Outer channel shifting"; 1854–1926

Between 1854 and 1926, the general configuration of the ebb-tidal deltas showed similar features and characteristics (Fig. 9). On the ebb-tidal delta, the main shoal area (Bornrif) was located to the east (downdrift) of the main ebb-channel. The main ebb-channel remained centrally located with a northwestward orientation in the vicinity of the inlet, but the distal part (Akkepollegat) periodically switched orientation. Persistent, secondary flood channels occurred along the coastlines of Terschelling (Boschplaat) and along the coast of Ameland (Noordoostgat/Strandgat). Between 1892 and 1903, we observe a shoal attachment to the coast of Ameland. The sediment bypassing processes underlying this shoal attachment consists of two stages.

Stage 1: Sediment delivery from the updrift to the downdrift shoal.

The first stage of the bypassing process follows the conceptual model of 'outer channel shifting" as described in FitzGerald et al. (2000). The inlet retains a stable inlet-throat position with a stable northwesterly outflow onto the ebb-tidal delta, but the distal part of the channel (Akkepollegat [7]) migrates downdrift from a westerly to a northeasterly location. This migration results from sediment accumulation on the updrift side of the channel. The shoal Kofmansbult [11] periodically develops between the ebb channel (Akkepollegat) and the flood-channel (Westgat), grows in size and migrates seaward. Under the influence of the prevailing easterly directed wave-driven transport, the shoal migrates eastward, constricting and deflecting flow in the Akkepollegat (1866–1903 and 1914–1958). Flow in Akkepollegat is initially hydraulically efficient as it directly aligns with the orientation of Borndiep, but becomes increasingly inefficient as it rotates to a northerly or northeasterly direction and is finally abandoned. A new, more efficient channel with a westerly outflow formed south of the main shoal area, and the cycle restarts.

Stage 2: Downdrift shoal formation and attachment.

The volume of the downdrift shoal platform (Bornrif [12]) increases when the updrift shoal (Kofmansbult [11]) merges with it (see 1865, 1903–1904). As sediments accumulate on the downdrift platform, it may take several shoal bypassing cycles before sufficient sediment is available, shallow bars start to form, which are then pushed towards the coast by waves breaking on the platform. As these shoals approach the coast of Ameland, flow is constricted and a narrow channel is formed between the advancing shoal and the barrier island (Noordoostgat or Strandgat). This channel temporarily causes coastal erosion but also stalls the migration of the shoal. The initial landward migration of the shoals over the platform occurs rapidly, but final attachment may take several additional years to complete.

#### 5.2.2. "Main ebb-channel switching"; 1926–2017

After 1926, the morphodynamic behavior of the ebb-tidal delta fundamentally changed. From a regime dominated by outer channel shifting, as described in Section 5.2.1., the morphodynamic behavior changed into what can be described as "main ebb-channel switching". In principle, the two main channels in the ebb-tidal delta, Akkepollegat [7] and Westgat [6], remain in place, but they alternately grow and decay as their ebb discharge increases and subsequently decreases.

Up to 1950, Westgat was a secondary channel, aligned along Boschplaat with a west-northwesterly orientation (Figs. 9, 10). The absence of an ebb-shield facing the channel and the presence of a sill separating Westgat from Borndiep indicate that Westgat was flood-dominated. Borndiep was the main ebb-channel, connecting directly to Akkepollegat. The majority of the transported sediment was deposited on the seaward margin of the ebb-tidal delta. Between 1958 and 1985, the distinctly westward oriented Westgat continued to increase in size and depth (Fig. 10). The sill separating the Westgat from Borndiep disappeared, and it is plausible that Westgat channel temporarily took over from Akkepollegat as the main ebb outflow from Borndiep [1]. The outflow of Akkepollegat was filled in with sediment, among others from the reworked delta front, and formed a large, continuous bar connecting the updrift and downdrift ebb-delta platforms. Large volumes of sediment were also deposited along the seaward (northern) edge of Westgat, building out the ebb-tidal delta close to the coast of Terschelling, in an updrift direction. By 1982 a large ebb-shield and linear shoal had formed along the seaward margin of Westgat. This elongate shoal sheltered the adjacent Terschelling coast from wave energy during storm events, which promoted the spit growth of Boschplaat. By 1974 a long narrow spit had formed extending well into the inlet (Fig. 10).

Westgat retained its size and position until 1985 but started to lose connection to Borndiep by 1989 (Fig. 11). At that time Koffiebonenplaat migrated towards the inlet and extended to the north between Boschgat and Borndiep, forming a shallow sill between the two channels. Temporarily, Westgat and Boschgat connected directly. The constricted flow in Westgat enabled Akkepollegat to redevelop as the main outflow of Borndiep. Between 1989 and 2009 Westgat again changed from an ebb-dominant channel to a flood-dominant channel. It is probable that the reduction of Westgat has increased the dominance of Borndiep-Akkepollegat. As a result, major shoal development has taken place seaward of Westgat on the shoal area Kofmansbult.

The initiation of a new bypassing cycle can be observed in detail in the recent bathymetries that were surveyed near-yearly between 2005 and 2017 (Fig. 11). As Westgat lost its connection to Borndiep (around 1989), Akkepollegat started to redevelop. To the North of Koffiebonenplaat [17], a linear bar developed between Boschgat and Borndiep (see 1989 onwards). This shoal extended seaward, bounding the Akkepollegat channel and causing current velocities to increase, and the channel extended further seaward. At its tip, Akkepollegat remained deflected westward due to the large Bornrif shoal and the preferential hydraulic gradient (Sha, 1989). With a seaward extension of the channel and linear bar, small instabilities developed, triggering the formation of a series of initially small ebb-chutes and ebb-shields (2006, 2008, 2014). A first ebb-chute formed between 2005 and 2006 as a small channel emerged just north of Westgat (Fig. 11, 2006 [8]). As this channel grew, it pushed sediments seaward, forming a small ebb-shield onto the Kofmansbult shoal. By 2008 a second ebb-chute and shield [9] had formed that overwhelmed the first system. The ebb-shield development on the Kofmansbult continued to dominate the morphodynamic changes of the central-downdrift ebb-delta platform. By 2011, the ebb-shield covered the major part of the Kofmansbult. As a result, most of the Akkepollegat [7] now had a northward outflow direction. It is probable that the ebb-delta deposits in front of the channel were transported to the east because a large shallow shoal (Bornrif Bankje [13]) continued to grow along the northeastern margin of the ebb-delta shoal.

Sandwiched between Westgat and the second ebb-chute, a new (third) ebb-chute [10] started to form in 2014. This new ebb-chute quickly grew in size and expanded to the (north)west. A pronounced ebb-shield grew that pushed forward, rotated clockwise, and as a large shoal area formed along its northern edge, constricted flow in Akkepollegat even further. The latter channel increasingly reduced in size and was deflected downdrift, to the east. As a result, the entire downdrift ebb-delta platform (Bornrif) migrated shoreward. Based on the observed channel relocations in the past, it is anticipated that a new, hydraulically more efficient, channel with an updrift orientation will form south of the shoals. The first indications of the growth of such a channel are present in the 2017 bathymetry as a new ebb-chute develops just north of Westgat [6]. This ebb-chute may eventually connect to or merge with Westgat, thereby forming a new main channel.

### 5.3. Barrier islands

#### 5.3.1. Outbuilding and retreat of Boschplaat

In response to the changes in the inlet gorge and ebb-tidal delta, the adjacent coastline of Terschelling showed periods of growth and retreat. Fig. 12A, B summarizes the coastline changes through digitized contour lines obtained from the 1854–1985 bathymetric charts (Figs. 9, 10). The more recent (1965–2017) evolution of Boschplaat is illustrated in Fig. 6 by visualization of the 0 m NAP contour from the yearly coastal measurements (JarKus) datasets. Especially the older charts (1831–1892) show lesser detail compared to the more recent measurements and are not expected to be 100% accurate, but they do allow a qualitative description of the observed changes.

Between 1854 and 1927, Boschplaat reformed from a wide beach platform into a narrower, but longer shape. A general retreat of the Terschelling coastline is especially noticeable between 1854 and 1892. Since 1892 the coastline remained in approximately the same position. Between 1854 and 1926/27, the tip of Boschplaat continued to build out into the inlet gorge. The formation of a channel breaching Boschplaat (see the previous section) caused a sudden, over > 1 km, retreat of the island tip between 1926/27 and 1934. Subsequently, the coastline then remained in approximately the same position till 1940, before starting to build out again. An important factor that contributed to the stability of Boschplaat, was the construction of a sand dike (between 1932 and 1936) to stimulate sand accretion (see the distinct line running over the island tip in the year 1940, Fig. 9). Besides promoting accretion by capturing wind-blown sediments, this dike has impacted the inlet dynamics because storm surges could no longer flood and easily breach the shoal. The sand dike redirects all flow towards the inlet, increasing the scouring of the inlet during storm events. Since 1934 we observe a continuous deepening of Borndiep.

Besides the sand dike, several other factors contributed to the continuous growth of Boschplaat between 1940 and 1974. Part of the spit deposits were the remnants of the Koffiebonenplaat that had closed Boschgat and attached on the basin side of the spit between 1962 and 1965. Also, wave-sheltering by newly formed shoals on the ebb-tidal delta along Westgat must have contributed to the spit growth. By 1974, Boschplaat had formed a long narrow spit which protruded well into the inlet. However, structural erosion of Boschplaat has been observed ever since (Fig. 6). The tip of Boschplaat was breached again between 1974 and 1982 and a shallow subtidal area (roughly 5 m deep), without pronounced tidal channels, developed separating Boschplaat and Borndiep. The formation of a distinct, deep connection between the Boschgat and Westgat channels introduced large tidal flow velocities around, and erosion of, the tip of the Boschplaat between 1989 and 1999. After 1999, the channel connecting Boschgat and Westgat broke up and a shallow platform (still about 5 m deep) dissected by several smaller channels was formed. Despite the reduction in channel depth, the erosion of Boschplaat continued, which is mostly related to the changes on the adjacent ebb-tidal delta. As the Westgat channel [6] reduced in importance, the extensive shoal deposits along its northern, seaward margin could no longer be maintained. These shoals quickly reduced in height and size (1999–2005), and a relatively deep area developed between the Kofmansbult and Boschplaat (2005–2016). As a result, waves could propagate far into the inlet. The increased wave energy and wave activity resulted in net eastward sediment transport from the tip of Boschplaat, over the shallow platform and into Borndiep (Elias, 2017). This sediment transport is probably a major contributor to the continued structural erosion of the Boschplaat. In the most recent bathymetries (2016–2017) we may observe a reversal of this process as the shoals north of Westgat appear to regrow again.

#### 5.3.2. Periodic shoal attachments to the north-west coast of Ameland

In contrast to the eroding southern, basin side of west Ameland, it's North-Sea side shows net coastline accretion. This accretion is at least partly related to three separate shoal attachments. The first measured shoal attachment occurred between 1892 and 1903 (Fig. 9). The origins of the shoal can be traced back to 1831–1854. As Akkepollegat migrated to the east, a large shallow shoal area (Strandruggen) developed on Bornrif. This shallow area extended well into the inlet and had broken into two parts by 1865. The landward part developed as an elongated shoal along the coast and attached to the coast between 1892 and 1902. The mean low water line (MLW) locally migrated a kilometer seaward. The attached shoal formed a large bulbous outcrop that was still visible in 1982 as the second shoal attachment (Bornrif Strandhaak) was about to occur. The attachment of the Bornrif Strandhaak is well documented by the yearly shoreline measurements from the JarKus database (see Fig. 5). Unfortunately, a lack of detail in the depth contours on Bornrif does not allow tracing back the origin of the Bornrif Strandhaak shoal as it formed. The JarKus profiles indicate the presence of a nearshore shoal around 1970. Between 1970 and 1986 this shoal grows in height and finally attaches to the Ameland coast, towards Borndiep. A large recurved spit developed. This shoal is known as the Bornrif Strandhaak (the translation of the Dutch name Strandhaak is 'beach hook'). After the tip of the Strandhaak attached to the shore, the coastline migrated seaward by 1.5 km, followed by a retreat of over 500 m as the deposits were subsequently eroded and predominantly transported downdrift, feeding the adjacent coast of Ameland. Behind the spit, an enclosed lagoon formed. Large-scale erosion was observed at the tip of the spit, as the filling and draining of the lagoon developed a small-scale inlet channel, which eroded into the beaches and dunes. This erosion is still clearly visible in the top panel of Fig. 5. A third shoal attachment occurred in 2017 as the Bornrif Bankje (Fig. 11, [13]) attached to the coastline at the tip of the Bornrif Strandhaak. In contrast to the previous two attachments that occurred on the north-western tip of Ameland near Borndiep, this recent attachment occurred more downdrift at the ebb-delta margin. The origin of Bornrif Bankje can be traced back to the 1989–1999 timeframe. During this interval, the northern ebb-delta front showed a large outbuilding and increase in shoal height at the seaward end of Akkepollegat. This outbuilding

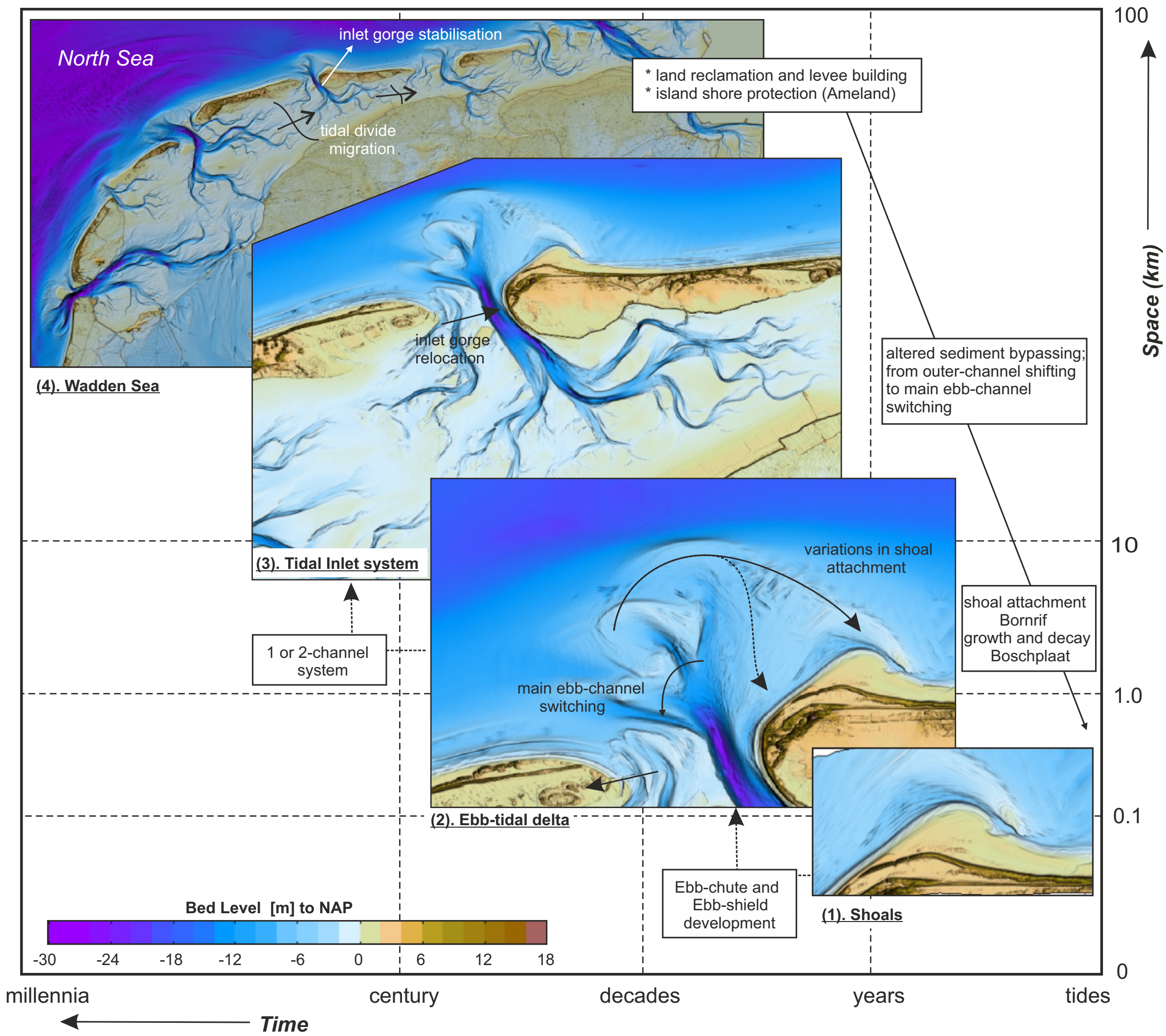


**Fig. 13.** A cascade of scales and relevant processes to describing the change in inlet dynamics over various scales for Ameland Inlet.

continued until 2011. Wave-breaking on this shallow shoal area probably resulted in downdrift sand transport along the ebb-tidal delta margin, and Bornrif Bankje slowly started to emerge on the north-east side of the ebb-tidal delta (2008–2010). The shoal continued to migrate eastward and landward (2011–2014), and by 2014 only a small channel remained separating the Bornrif Strandhaak and Bornrif Bankje. The map of 2017 shows that the tip of Bornrif Bankje finally attached to the Ameland coastline, just downdrift of the Strandhaak.

### 5.4. Summary of the observed morphodynamic changes

The bathymetric maps reveal that large scale alterations of the ebb-tidal delta channels and shoals occured, and several sequences of sediment bypassing were identified. As a result, periodic growth and decay of the updrift island tip of Terschelling (Boschplaat), and shoal attachments to the downdrift Ameland coast, took place. Growth of the Boschplaat has been observed due to: (1) spit accretion (prior to 1926), (2) shoal attachment and subsequent spit extension, and (3) periods of westward ebb-tidal delta expansion and subsequent wave sheltering along the coast. Erosion of the Boschplaat occurs as a continuous Westgat – Boschgat channel forms after breaching of the Boschplaat. Structural erosion is also observed as Akkepollegat develops as the main ebb-channel and the southwestern part of the ebb-tidal delta is sediment starved and relative deep. This allows higher waves to penetrate the inlet and reach the Boschplaat.

Shoal attachments to the Ameland coast show distinct differences in location, shape and volume. The first two shoal attachments occurred near the western tip of Ameland. At this stage, the ebb-tidal delta was well-developed and episodically smaller bypassing events (outer channel shifting) took place adding sediment from the updrift to the downdrift shoal. Landward wave-driven sediment transport forms shoals that eventually attach to the coast. The third shoal attachment occurred farther downdrift, at the margin of the ebb-tidal delta. This difference is attributed to a change in shoal formation and shape at the ebb-tidal delta front. Sediment delivery by the main ebb-channel resulted in a narrow, steep and shallow ebb-delta margin front. Wave-breaking now focusses in this zone and a narrow band of maximum sediment transport occurs over the ebb-tidal delta front. Eventually, a large shoal forms that migrates along the ebb-delta margin to the coast.

## 6. Discussion

Israël and Dunsbergen (1999) and Cheung et al. (2007) conclude that sediment bypassing cycles at Ameland Inlet have a periodicity of 50 to 60 years in connection with the migration of a flood delta channel and the modulation of the two ebb delta channels. Based on the analysis presented in this study, we conclude that such cyclic predictability is limited, as the observed periods of growth and decay so far result from unique sets of ebb-tidal delta configurations, and the underlying sediment bypassing processes may differ fundamentally. In addition, our analysis shows that both large-scale and small-scale morphodynamic interactions can alter or initiate the sediment bypassing process. Understanding of the processes underlying sediment bypassing cycles on the dissimilar time- and special scales is essential to explain, predict, and especially to successfully mitigate associated shoreline erosion but has not received much attention so far. Ameland's availability of detailed bathymetric datasets (charts) starting in the early 19th century, and high-resolution (in time and space) digital data being available since 1986, provides a globally unique dataset, which allows detailed investigations of the ebb-tidal delta morphodynamics over a wide range of scales.

To structure, summarize and thereby better understand the observed morphological developments, we adopt the morphodynamic scale-cascade as proposed by De Vriend (1991). The principle behind this scale-cascade is simple. As stated by De Vriend: “The phenomena of interest are expected to be related to aspects of the underlying physical processes on similar space and time scales. The variation of inputs and processes on much smaller scales are only relevant as far as there are residual effects, whereas variations on much larger scales can be considered as concerning the extrinsic conditions”. For Ameland, we can construct a scale-cascade model (Fig. 13) consisting of four levels of aggregation, starting on the level of (1) individual shoals, (2) the ebb-tidal delta, (3) the inlet system and (4) the Wadden Sea as a whole. Based on the analysis presented in this study, we can conclude that ebb-tidal delta scale changes (level 2) can be driven by morphodynamic interactions resulting from the larger scales of the inlet (level 3) and the Wadden Sea (level 4), and through interactions that originate on the smallest scale of individual shoals (level 1).

The principle of large- to small-scale interaction in tidal inlets is well described by the conceptual models of e.g. Dean (1988) and Stive and Wang (2003). The barrier islands, ebb-tidal delta, inlet gorge, and basin all form part of the same sand-sharing system, and strive to maintain a balance or (dynamic) equilibrium state between these elements. A distortion in one of the elements, either natural or anthropogenic, imposes sediment exchange between the elements until a new equilibrium state is attained. This new equilibrium state imposes different extrinsic conditions on the smaller-scale processes. A large-scale geomorphic transition in the morphodynamic behaviour of Ameland inlet was first visible around 1926 as the main channel in the inlet gorge shifted to the east, from an updrift to a downdrift location. This shift is related to the eastward migration of the tidal divides in the basin (Van der Spek, 1995; De Boer et al., 1991a, 1991b; FitzGerald et al., 1984), which had been ongoing since 1600 CE as a result of land reclamation and levee building. In a natural, non-engineered system, systematic migration of the channels in the basin would induce a similar movement of the tidal inlet and ebb-tidal delta and hence migration of the barrier islands. However, at Ameland, as Borndiep migrated eastward, intensive shore-protection works were constructed that stabilized the inlet channel in that position ever since. The shift in inlet channel position and the stabilization of the channel must have changed the ebb-tidal delta dynamics pre- and post-1926. The observed differences in morphodynamic changes and sediment bypassing pre- and post-1926 support this hypothesis. The sediment bypassing mechanism changed from “outer channel shifting” to “main ebb-channel switching”. Both sediment bypassing mechanisms eventually produce bypassing shoals, but the location of shoal attachment to Ameland may differ.

The recent measurements show that (changes in) sediment bypassing can also be initiated through interactions originating from the smallest scale levels. High-resolution observations taken between 2005 and 2017 illustrate the initiation of a new sediment bypassing cycle originating from an initial small-scale distortion or shoal instability in the central part of the ebb-tidal delta. Five stages of development can be identified:

(1). Sediment accumulation along the (central) main channel: Abundant sediment delivered from the updrift coast and through erosion of the western margin of the ebb-tidal delta, is transported into the inlet, and eventually accumulates in an elongate bar flanking the main ebb-delta channel (Fig. 11, 2005).
(2). Morphodynamic instabilities form on this elongate bar: These instabilities result in small ebb-chute like features (Fig. 11, 2005–2006, [8]).
(3). Ebb-chute and shield formation of the shoal instabilities: The instabilities rapidly grow and expand into (multiple) ebb-chute and shield systems (Fig. 11, 2006–1014, [8,9,10]), which start to dictate the ebb-shoal morphology.
(4). Channel – shoal interactions: As the ebb-shield grows in height and size, wave-dominant transports become increasingly important. As a result, the ebb-chute and shield systems migrate downdrift (to the east) and thereby constrain the flow in the former main channel Akkepollegat, (Fig. 11, 2014–2017, [7]). The recent 2017 bathymetries show a near-abandoned main ebb channel (Akkepollegat) and initial growth of a new channel to the south of it (at the Westgat location). This suggests that another channel switch is imminent (step 5).
(5). Main channel relocation and downdrift shoal attachment: As the main channel becomes hydraulically inefficient, a new channel will form updrift (to the south) of the main shoals. Downdrift and landward sediment transport contributes to sediment accumulation on the Bornrif shoal, eventually leading to shoal formation and attachment. Thereby the sediment bypassing cycle is complete.

The relocation of the main ebb-channel to a more westward position would also affect the flood- dominant channel (Westgat) that is located here. A new flood-dominant channel may form to the west, connecting Boschgat and its drainage area directly to the open sea. Such changes would restore the two-channel system, significantly impact the sediment circulation in the basin, and thereby introduce tidal-inlet scale effects.

The scale-cascade model (Fig. 13) is useful to structure and help understand the observed changes. However, the results of our analysis also show that a clear separation of scales may not exist. Complete relocation of ebb-tidal delta scale channels and shoals can be caused by morphodynamic interactions steered by large scale effects, which may arguably be described as a change in extrinsic condition. However, ebb-delta scale changes can also be initiated through interactions that originate on the smallest scale of individual shoals. Local morphodynamic interactions, originating from a distortion on the smallest scale, can change the configuration of the ebb-tidal delta shoals, and fundamentally alter the state of the ebb-tidal delta from tide- to wave-dominated. Similarly, Harrison et al. (2017) suggest that non-seasonal transitions observed in ebb-tidal delta bathymetry may be the result of morphodynamic “tipping points” being reached: system-wide behaviour that emerges from processes and interactions at smaller scales. Such small-scale changes would generally not be considered to affect the ebb-tidal delta and inlet dynamics as a whole, and their subtle dynamics are difficult, if not impossible, to capture in the general conceptual models and empirical relationships. The notion that initial small-scale distortions can trigger complete ebb-tidal delta relocation also has important consequences in the way we approach process-based numerical modelling of these systems. Over the last decade, good progress has been made with process-based modelling of tidal inlets and ebb-tidal deltas (e.g. Hibma, 2004; De Fockert, 2008; Lesser, 2009; Dastgheib, 2012). For a major part, this progress is related to techniques to efficiently accelerate the morphological predictions (Lesser, 2009; Roelvink, 2006). Separation of scales is a critical aspect underlying these acceleration techniques. We need to critically rethink which processes are noise, an extrinsic condition, or an essential component to include. Subgrid approaches to morphodynamic modelling may provide a solution for bridging the gap in spatial scales (e.g. Volp et al., 2016).

As stated by Son et al. (2011), “the sediment bypassing concept appears to be widely applied, but sound justification or verification is often not allowed as bathymetric maps and data are not adequate". The findings of this study confirm this statement, as the abundant data from Ameland allows us to identify very different processes and mechanisms that underlie the shoal attachments to the coast of Ameland. Conceptual sediment bypassing models provide a good initial framework to help to hypothesise on the governing sediment bypassing processes. However, these hypotheses need to be carefully tested and confirmed. Also, in this study, we have to a certain extent misused the description "sediment bypassing" as, firstly, we did not resolve the complete sediment bypassing process, but primarily focussed on the flow-bypassing and bar welding mechanisms. The presence of smaller scale swash bars (the so-called saw-tooth bars) that appear along the north-eastern side of the ebb-tidal delta (see. Figs. 4, 11) and the Bornrif (see Fig. 6) are indications that a secondary active sediment bypassing pathway exists along the ebb-delta periphery. Secondly, we do not prove that sediments actively propagate from the updrift to the downdrift coast. Our analysis provides us with a detailed view of the formation, growth and migration of shoal (instabilities) on the ebb-tidal delta, but the source of these sediments is not determined. Sediments are available through littoral drift along the updrift island coast, island tip erosion, sediment reworking from the ebb-tidal delta shoals, and potentially sediment delivery from the basin. These missing components can only be resolved through detailed field measurements of sediment characteristics and/or process-based modelling.

## 7. Concluding remarks

(1). At Ameland inlet, a globally unique data-set of long-term bathymetric charts and high-resolution (in time and space) digital data allows for detailed investigations of the ebb-tidal delta morphodynamics over a wide range of scales.

(2). A geomorphic transition in morphodynamics occurred around 1926, as the main ebb-channel has migrated from an updrift to a downdrift position in the inlet gorge. The change in channel position and stability fundamentally changed the ebb-tidal delta dynamics and sediment bypassing behaviour. The sediment bypassing process changed from outer channel shifting to main ebb-channel switching.

(3). The large influence of the ebb-tidal delta dynamics on the shoreline response of the updrift and downdrift sides of the inlet is clearly identified. Periodic growth and decay (net erosion) of the island tip of the updrift island –Terschelling- occurs, while sequences of sediment bypassing result in shoal attachment to the downdrift coastline of Ameland. No clear evidence exists that a long-term morphodynamic cycle occurs on the scale of Ameland Inlet. Instead, morphodynamic changes start with the accumulation of sediment in various places until tipping points are reached. The mechanisms pushing the ebb-tidal delta towards these tipping points are repetitive. These accumulations tend to repeat in similar areas but are never exactly the same, so we never get a true cycle.

(4). Shoal instabilities are initially small morphodynamic changes and would not be considered to affect the ebb-tidal delta and inlet dynamics as a whole, but as we have shown in this paper, they can trigger a new sediment bypassing cycle and result in complete relocation of ebb-tidal delta scale channels and shoals. Such subtle dynamics are difficult, if not impossible, to capture in the general conceptual models and empirical relationships. These differences are, however, essential for understanding tidal inlet and channel morphodynamics, and hence coastal management.

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Open access to the Vaklodingen is provided by Deltares at:
https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/vaklodingen/

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