Marine Geology 453 (2022) 106907

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Research Article

Beach-dune development prior to a shoal attachment: A case study on Texel Island (NL)

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A R T I C L E I N F O

Editor: Edward Anthony

Keywords:
Beach-dune dynamics
Shoal attachment
Coastal dunes
Beach-dune interaction models

A B S T R A C T

Shorelines bordering ebb deltas are often subject to deformation by the approach and attachment of ebb-tidal shoals. Although this is a common behaviour, little attention has been paid to the link between shoal migration and the multi-annual development of the adjacent beach-dune system. This study aims to understand beach-dune systems' behaviour during the approach phase of an ebb-tidal shoal attachment event. Topographic and bathymetric data of the barrier island of Texel (NL) was used to calculate shoreline position, beach and dune volume, dunefoot position, and shoal displacement rates. Two classical beach-dune interaction models were used to understand the observed behaviour: the surfzone-beach-dune model and the sediment budget model. The analysis revealed how a larger bank on the land-facing side of the ebb delta split into two smaller shoals with different morphological behaviours. One of the shoals (S1) moved consistently landwards, recently attaching the shore, whereas the second shoal (S2) is still evolving and presents a milder landward movement than S1. In parallel to the landward movement of S1, the adjacent coastline was subject to erosion, partially counterbalanced by nourishments. However, despite the erosion, dunes are growing in volume, suggesting a net positive transfer of sand from the beach to the dunes. In the surfzone-beach-dune model, regular nourishments positively affect beach state by maintaining sufficient beach size for aeolian sediment transport and reducing shoreline erosion. In the budget model, dune volume growth may occur despite a slightly negative beach budget. Framing Texel in the budget model implies that the beach budget before the start of the approach phase is crucial in defining the behaviour of the dune system during this phase. If the shoal approach significantly reduces the beach budget, the system may cross the budget threshold that dune building is possible. Thus, the dune system may evolve to an erosional state, including dune ridge dissection and blowout development. Hence, nourishments have been essential in keeping the current morphological state during the attachment of the shoal, as they restrict the system from crossing the negative morphological threshold. Thus, without the nourishments, beach erosion driven by the shoal might have led to morphological changes in the dune system that could lead to years of a weakened level of protection until foredune recovery after attachment.

1. Introduction

Beach-dune systems are coastal landforms maintained as the first line of defence against flooding in many countries. Such landforms provide different levels of protection depending on physical characteristics such as dune height, vegetation coverage and grain size (Feagin et al., 2015; van de Graaff, 1986; Sallenger, 2000).

Different from most man-made protection structures, beach-dune systems can be very dynamic. Changes in beach width may reflect on dunefoot position (van Ijzendoorn et al., 2021; Ruessink et al., 2012; Silva et al., 2019) and the potential of sediment transfer towards the dunes (Davidson-Arnott et al., 2005; Delgado-Fernandez, 2010; Short and Hesp, 1982). At the same time, storms may momentarily erode the foredune, leaving the backshore vulnerable to flooding before dune recovery (Hesp, 2002; Houser and Hamilton, 2009). Thus, very dynamic shorelines require detailed attention from coastal managers to ensure desired protection levels amid system dynamics.

As such, beach-dune systems near inlets are particularly challenging. Inlet-driven processes affect the adjacent coastline and, consequently, may influence the beach-dune system (Ambrosio et al., 2020; Elias and

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https://doi.org/10.1016/j.margeo.2022.106907
Received 17 March 2022; Received in revised form 9 September 2022; Accepted 14 September 2022
Available online 24 September 2022
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Van Der Spek, 2006; Fenster and Dolan, 1996; Fitzgerald, 1984; Fitzgerald et al., 1984; Galiforni-Silva et al., 2020; Garel et al., 2014). One notorious process that affects the adjacent beach-dune system is shoal attachment. Shoals are built from sediments transported from the updrift side of the inlet after being reworked within the tidal-inlet system (FitzGerald, 1988; FitzGerald et al., 2000; Herrling and Winter, 2018; Ridderinkhof et al., 2016). Periodically, they detach from the ebb delta and are transported towards the coast, leading to a sudden local input of sediment to the shore (FitzGerald et al., 2000; Herrling and Winter, 2016; Hofstede, 1999). Shoals may vary considerably in size, mostly ranging in the order of 10^2 to 10^3 meters, with volumes upwards of 10^6 m^3 in some cases (Fitzgerald, 1984; FitzGerald, 1988; Gaudiano and Kana, 2001; Kana, 1995). Also, size and onshore migration rates are directly proportional to the inlet size (FitzGerald, 1988).

Shoals are efficient in changing the adjacent shoreline. Shoal bypassing (i.e. sediments that move with the littoral currents around the ebb-tidal delta, forming shoal banks that evolve from the ebb delta, detach from the main lobe and attach to the shoreline downdrift of the tidal inlet) influences the adjacent shoreline through channel compression and temporary erosion of the barrier before attachment of the bypassed sediment mass onto the barrier and consequent shoreline accretion (Gaudiano and Kana, 2001; Héquette et al., 2009; Kana, 1995; McBride et al., 2013) Héquette et al. (2009) analysed the effects of nearshore sand banks and associated channel and discovered that sand banks did not necessarily enhance wave dissipation, but rather constrained tidal flows leading to higher velocities and scouring.

Studies on the effects of shoal behaviour on the coast focus mostly on the effects on the shoreline position (Do et al., 2018; Fenster and Dolan, 1996; Isla, 1997; Robin et al., 2009), without an in-depth analysis on the effects in the foredune. Galiforni-Silva et al. (2020) show, using an idealized model, that after shoal attachment the potential to leave a footprint in the dunes is not only related to the resulting beach width increase but also to the rate at which this beach width decreases afterwards.

Classical beach-dune interaction models may offer a starting point to understanding how shoals may affect dune development at decadal scales. Considering the *surfzone-beach-dune model* (Hesp, 2002; Short and Hesp, 1982), sand supply to the dune is based on the morphodynamic state of the beach. In general, dissipative beaches would have a high potential for aeolian transport resulting from less flow disturbance and higher available fetch distances. In opposite, reflective beaches have a low potential for aeolian transport as the wind accelerates across the beach face and quickly reduces beyond the crest (Ellis and Houser, 2022). In a channel-shoal context, the landward movement of the shoal may lead to changes in the beach characteristics that would affect the potential of sediment transport (e.g. beach width) and, therefore, sand supply to the dunes.

Psuty (2004) presents the *sediment budget model* for a continuum of possible types of foredune evolution as driven by the sediment budget of the beach. The model shows that, in general, a highly positive beach budget leads to low foredunes with multiple ridges, whereas highly negative beach sediment budget leads to washovers and sand sheets (Fig. 1). It also states that the maximum development of the foredune occurs when the beach sediment budget is slightly negative, leading to the formation of a single high foredune. This condition may lead to inland migration of the foredune at similar rates as the shoreline transgression, and is to be expected under sea level rise conditions (Davidson-Arnott, 2010; Davidson-Arnott et al., 2005). Button (2013) extended the conceptual model by including antecedent geology immediately landward of the foredune, such as an ancient coastal dune field. In case of a highly negative beach budget, the foredune may continue to exist as it will cannibalize sediments from the antecedent coastal dune field backing the foredune, allowing the foredune to build and rebuild. For the context of shoals, the approaching and attachment of shoals would affect the beach budget and, therefore, may locally change dune morphology given enough relaxation time.

Previous attempts to link such conceptual models to shoal attachments are sparse, though relations with somewhat similar systems such as welding of sand banks (Anthony et al., 2006; Hequette and Aernouts, 2010), and nearshore bars (Aagaard et al., 2004) exist. Potential reasons include model limitations and the sparse existence of sufficient long time-series on these environments. Davidson-Arnott (2010) argues that these models are, per concept, highly schematic and do not have necessarily universal applicability. For example, the sediment budget

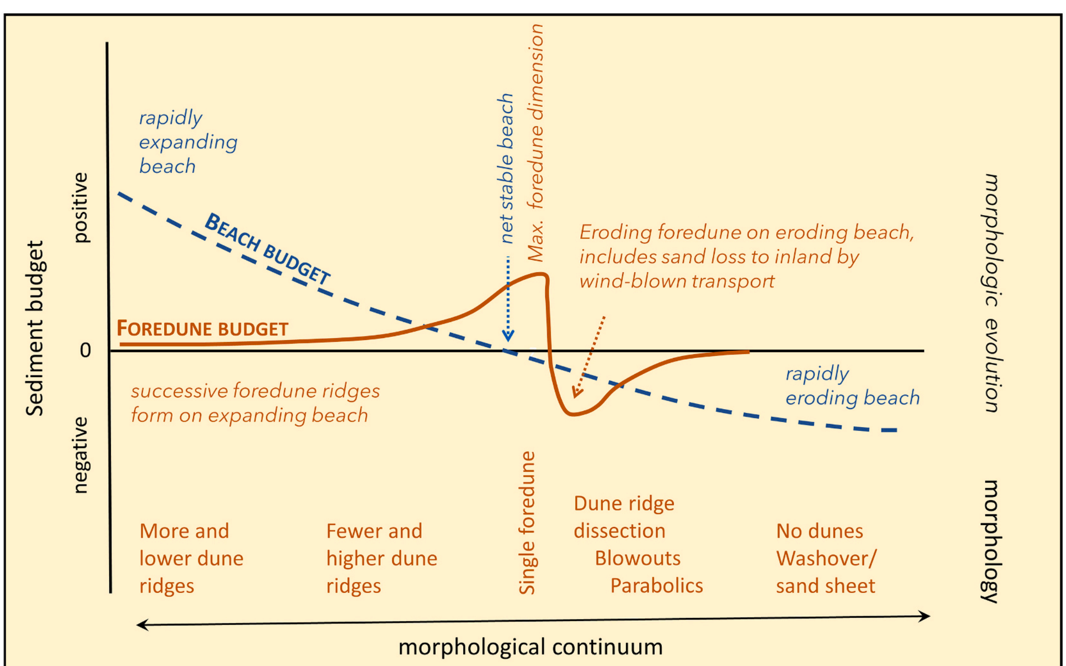

Fig. 1. Conceptual model of the relationship between beach and dune budget, and expected morphology of the beach-dune system, modified after Psuty (2004). Reprinted from Wijnberg et al. (2021).

model is not able to explain large parabolic and transgressive dunefields in environments with high sediment supply and wind energy (Ellis and Houser, 2022) or the presence of blowouts and parabolic dunes on some stable or accreting coasts (Hesp, 2002). Hesp (2002) discusses that a model driven by sediment supply is locally specific, being well established in sediment deficient systems at a century-scale (e.g. Netherlands). However, models driven by wind-wave variability might be better suited for systems where supply is not limited at a century-scale (e.g. Australia). Another limitation is the lack of important variables, such as vegetation on the budget model. The time-scale is also relevant, as any changes in the beach budget need to cross a certain relaxation time before showing any signal at the dunes. Such shortcomings limited previous attempts on linking beach-dune development with shoal attachment processes using classical interaction models.

The Dutch barrier island of Texel offers a unique opportunity to understand how beach-dune systems behave during the attachment of shoals. Historical datasets are available comprising both bathymetric and topographic data for decades. Moreover, a very large shoal (length $> 1 km$) is currently attaching to the shore, offering a unique opportunity to analyse the behaviour of the beach-dune system during the approximation phase of the shoal and, in a latter stage, the effects of the whole cycle.

Therefore, the aim of this study is to develop a conceptual understanding of the behaviour of beach-dune systems during the approach phase of the ebb-tidal shoal attachment. To develop this understanding, we make a morphological analysis of the evolution of an ebb tidal shoal approaching the shore until first attachment and the concurrent changes in beach width and dune volume.

2. The tidal inlet system of SW Texel

Texel is the most westerly barrier island of the Dutch Wadden Sea (Fig. 2). The island has roughly 60 *km* of coastline, of which approximately half consists of sandy beaches bordering the North Sea. To the south-west, Texel island is bordered by the *Marsdiep* inlet. The *Marsdiep* inlet is classified as a mixed-energy inlet, with semidiurnal tides having a mean tidal range of 1.4 *m*, and a spring and a neap tidal range of 2 *m* to 1 *m*, respectively (Elias and van der Spek, 2017). The inlet has a large ebb-tidal delta that protrudes around 10 *km* into the North Sea and 25 *km* alongshore. The ebb-tidal delta is a result of the large tidal volume and strong currents in the inlet, together with relatively low wave energy (Elias and van der Spek, 2017; Van Heteren et al., 2006). The inlet thalweg is about 2.5 *km* wide and 53 *m* deep, bordered in the south by a 17th-century sea-defence structure, and in the north by a sand flat of roughly 3 km^2 (Elias and Van Der Spek, 2006; Van Heteren et al., 2006).

Recent morphological evolution of the ebb-tidal delta has been largely driven by the closure of the *Zuiderzee* (a shallow bay closed off by the construction of a dam in 1932). The closure reduced the drainage area to roughly 712 km^2 and the basin length from 130 *km* to 30*km*, approximately (Elias and Van Der Spek, 2006). Also, tidal prism increased by 26% (Elias and Van Der Spek, 2006). As a result, the morphology of the ebb-tidal delta adapted in a four-stage multi-decadal span (Elias and van der Spek, 2017). The last stage (after 2001) is a stabilisation phase, represented by a reduced overall erosion. During this phase, the large sub-tidal spit north of the ebb-tidal delta (i.e. *Noorderlijke Uitlopers van de Noorderhaaks*, number 5, Fig. 2) started moving landward, evolving towards a shoal attachment process. The attachment of a shoal, which was absent during the multi-decadal adaptation of the ebb-tidal delta, represent the complete re-establishment of the bypassing process. The *Noorderlijke Uitlopers van de Noorderhaaks* (from now on NUN) is the shoal analysed in detail in this manuscript.

To maintain the coastline position of SW Texel, various shoreline management interventions have been implemented to cope with both the structural deficit of sand on the Dutch coast and local dynamics induced by ebb-shoal dynamics. Between 1959 and 1987, 22 groins were constructed and maintained (Elias and van der Spek, 2017). Groins reduced the shoreline retreat by an order of 10 *m/year* but did not stop it completely (Elias and van der Spek, 2017; Rakhorst, 1984). Moreover, Elias and van der Spek (2017) argue that the groin field does not influence cross-shore transports drastically, resulting in a potential continued alongshore transport (and continued erosion) offshore of the groin field. Beach nourishments have also been done in the area since 1986 (Elias, 2006) (Fig. 3). According to Elias and van der Spek (2017), nourishments have been keeping the coastlines adjacent to *Marsdiep* inlet relatively stable. Also, the authors argue that sand nourishments did not significantly alter the characteristics of the ebb-tidal delta. However, the effects on the beach-dune system are still unknown and were outside the scope of Elias and van der Spek (2017).

The state of the beach-dune systems varies along the SW Texel coast.

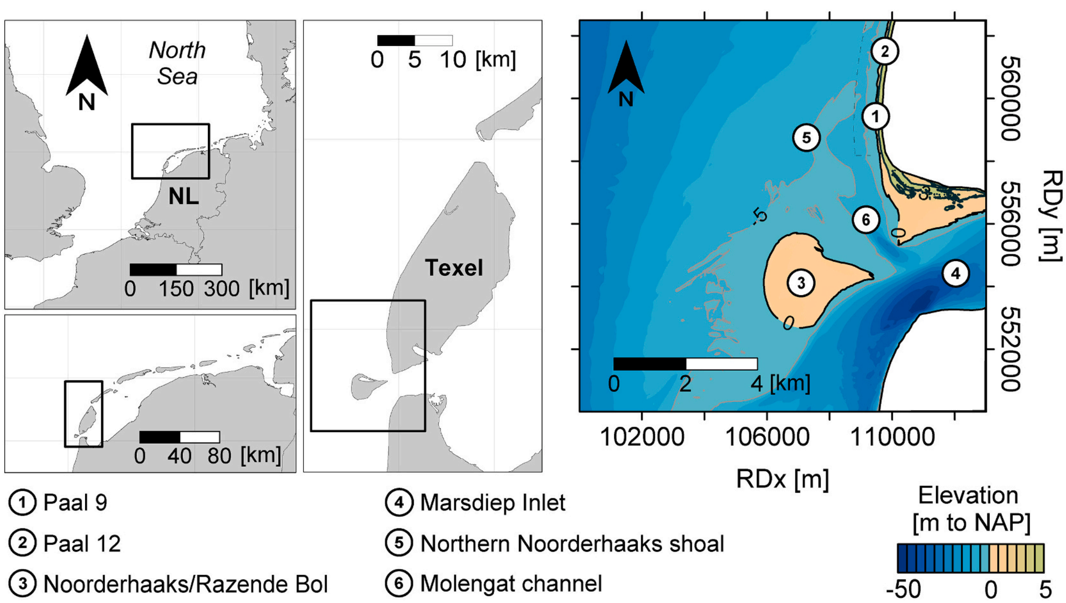

Fig. 2. Study area. Left panels locate the system in a broader geographical context, whereas right colored panel highlights locations around SW Texel that are cited throughout the text. Dashed lines represent the approximate alongshore extent of the groin fields.

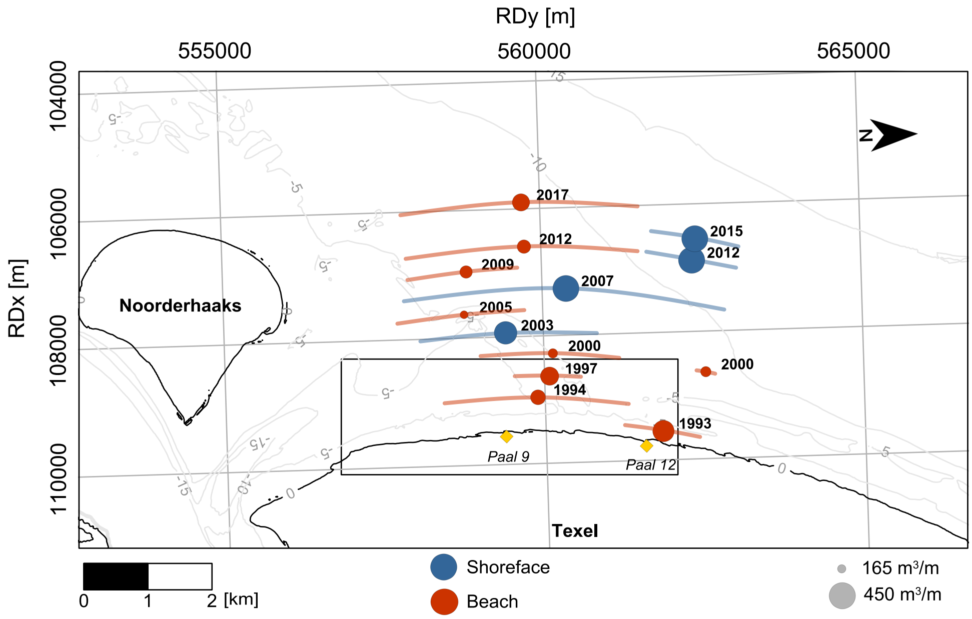

Fig. 3. Alongshore position, type and extent of nourishments done in the SW coast of Texel. The black rectangle roughly represents the area of interest. Cross-shore distance from the coast do not represent actual spatial location of the nourishment.

At the most southern end, a combination of established and incipient dune fields exist on the sand flat bordering the Marsdiep inlet (Silva et al., 2018). Going north, the sand flat transitions into a system formed by established foredunes with incipient trough blowouts and blowouts that reflect past regressive trends in the area (Arens and Wiersma, 1994).

3. Dataset and analysis methodology of multi-annual morphological data

3.1. Data sets

Understanding the effects of a large shoal immediately before the attachment to the beach-dune system requires relatively long monitoring data from both subtidal and subaerial morphology. In this study, we used a combination of bathymetric and topographic datasets routinely collected and maintained by the Dutch government via the Ministry of Infrastructure and Water Management (i.e. *Rijkswaterstaat*). An overview is displayed on Table 1.

The bathymetric data has a resolution of 20 × 20 meters and is available for the years 1971, 1981, 1986 (partially), 1987 (partially), 1991, 1994, 1997, 1999, 2001 (partially), 2003 (partially), 2006, 2009, 2012, 2015, 2016 and 2018. Data from years 1986, 1987, 2001 and 2003 were only partially available, thus combined in the present study for visualisation. Such a combination is reflected on some missing data from the NUN for 1986/1987. Missing subaerial data for 1971 and 1981 reflects on poor interpolation of the shoreline, thus being excluded from quantitative analysis but plotted for qualitative discussion. Between 1991 and 1997, the *Noorderhaaks* was not measured, thus absent in the maps. Vertical accuracy estimates of the bathymetric data range from 0.11 to 0.4 m (Perluka et al., 2006; Wiegmann et al., 2005).

The topographic data, collected annually by airborne coastal LiDAR (Laser Imaging Detection and Ranging), was available from 1997 up to 2017. Vertical accuracy estimate for the LiDAR data is around 0.15 m (Alkemade, 2007). From the topographic data, we also defined 47 cross-shore profiles alongshore to follow variations in shoreline position, beach and dune volume, and foredune position (Fig. 4). Each cross-shore profile is roughly 100 m apart alongshore and follows the azimuth of the dunefoot position estimated from the average of all elevation maps. Some profiles are closer alongshore (e.g. 20 and 21) due to a local change in azimuth.

As is the case for most of the Dutch coast, nourishments and other management interventions are relatively common and should be considered when dealing with multi-year monitoring data. Nourishment datasets are available through *Rijkswaterstaat*. These datasets contained information on the volume of sand, location of deployment and period. Official reports also give estimates for shoreline trends not including direct effects of nourishments. These shoreline trends are based on annual observations of sediment volumes in a predefined control area (bounded by specific elevation contours) which are used to derive a shoreline position (approximately the mean low waterline) and exclude the direct effects of shore nourishment in the control area (Rijkswaterstaat, 2020). When it is not possible to calculate a reliable trend for the period after nourishment with one or two measurements, the trend prior to nourishment is used. Using these shoreline positions, trends are calculated up to a maximum of 10 years. For Texel, those elevation contours are +3 m and − 4.9 m, approximately (Hillen et al., 1991). Trends are available since 1992 and cover the area between profile 1 up to 35, approximately (Fig. 4). It is important to note that, even though direct nourishments are not included in the trend, bias from past nourishments in the area may still appear by affecting the locations of the lower boundary. Detailed information on the methodology can be found on Rijkswaterstaat (2020) and Minneboo (1995).

Table 1
Overview of the datasets. All data is sourced from *Rijkswaterstaat*.

Data	Resolution	Years
Bathymetry	20 × 20 meters	1971, 1981, 1986 (partially), 1987 (partially), 1991, 1994, 1997, 1999, 2001 (partially), 2003 (partially), 2006, 2009, 2012, 2015, 2016 and 2018
Topography	5 × 5 m	From 1997 until 2017
Nourishments	NA	1993, 1994, 1997, 2000, 2003, 2005, 2007, 2009, 2012, 2015 and 2017
Shoreline trends	NA	From 1992 until 2018

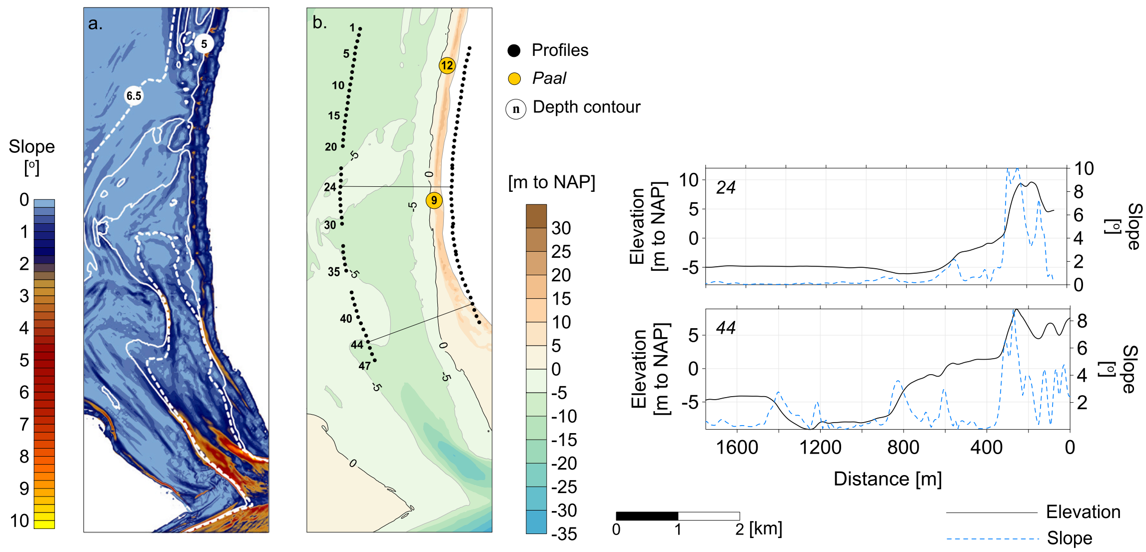

Fig. 4. a. Slope map used for the establishment of the shoal limits. Dashed white line represents the 6.5-m contour, whereas continuous white line represents the 5-m contour. b. Location of the profiles where subaerial information was extracted. Profiles have also been used to locate morphological developments throughout the text. Profiles 24 and 44 were extracted and plotted on the right, for visualisation. Slopes in absolute values.

3.2. Data analysis methods

To quantitatively track the evolution of the shoal, we defined bounding depth contours by a visual interpretation of breaks in slope using a slope map (Fig. 4). Such analysis leads to a contour limit for the shoal that varies somewhere between −5 to −6.5 meters, depending on the year and location. For consistency, we use the −5-m contour as a reference for all calculations.

With the shoal boundaries defined, shoal displacement was analysed through the landward movement of the shoal. Landward movement of the shoal was tracked by changes in the position of its landward border. Four cross-channel profiles (i.e. Prof 15, 20, 25 and 30, Fig. 4) were defined along the shoal, where channel width and depth were tracked throughout time. A rough estimate of time needed to a complete attachment to the shore can be found by extrapolating the observed trends of decreasing channel depth, width, and cross-shore position. This is where the 5-m contour lines bounding the channel have merged, hence channel width equals 0 m, water depth over the channel approached 5 m and channel cross-shore position equals the position of the most landward 5 m depth contour. Considering that the shoal also defines the seaward limit of the channel, boundaries of the channel were defined by the same method and contour used to define the boundaries of the shoal (i.e. -5-m contour on both sides).

After defining characteristics related to the shoal, we looked at the behaviour of the beach-dune system for the period that the shoal was moving landwards. We followed variations in shoreline position, beach and dune volume, and foredune position in the 47 cross-shore profiles.

For the shoreline, apart from the volume-based trends discussed on Section 3.1 (which exclude the direct influence of nourishments), we also extracted the shoreline position for each profile derived from the LiDAR, which accounts for all nourishments in the area. Shoreline position was defined by the location of the 0-m contour. The shoreline derived from the LiDAR data differ from those of the *Rijkswaterstaat* reports. Firstly, years with nourishment are excluded from the latter. Secondly, as the latter is based on the volume of sand in the layer between the $+3\ m$ and $-\ 4.9\ m$ elevation contour, the position of the 0-m contour derived from the LiDAR will to some extent be stabilized by the groins, while the deeper part of the nearshore profile can continue to erode more freely. Throughout the text, the shoreline calculated from the profiles will be referred as “0-m contour”, whereas the ones available from *Rijkswaterstaat* reports will be referred as “volume-based”.

Since 1965, the dunefoot level along the Dutch coast is assumed to be approximately 3 m + NAP (i.e. *Normaal Amsterdams Peil* - in Dutch - is the Dutch reference level, which is close to the mean sea level), an elevation that roughly corresponds to the break in slope between the beach and the foredune (Duarte-Campos et al., 2018; Keijsers et al., 2014; Ruessink and Jeuken, 2002; de Vries et al., 2012). The value is largely empirical and some studies suggest that it is also site-specific within the Dutch coast (Diamantidou et al., 2020; Hoonhout and de Vries, 2017; van Ijzendoorn et al., 2021). van Ijzendoorn et al. (2021) found a linear increase in time of the dunefoot elevation for most of the Dutch coast, which would make the 3-m approximation unrealistic for a time-series analysis. However, the authors did not find a significant trend for the Wadden coast, where Texel is located. Furthermore, Diamantidou et al. (2020) showed that the method used to derive dunefoot (i.e. second derivative) had greater RMSE values for Texel than the 3-m contour with respect to visual observations. Thus, for the present study, we follow the traditional assumption of the 3-m contour as the dunefoot.

Dune volume was calculated as the volume above the 3-m contour and the dunefoot position as the location of the 3-m contour itself. The landward limit for the dune volume calculations was defined by the year with least LiDAR data coverage landward, which results in roughly the backside of the foredune. Such a choice allows for a better visualisation of any potential landward migration of the foredune. As for beach volume, the seaward boundary is the mean low water level, whereas the landward boundary is the dunefoot position. Lower and upper boundaries are the contour levels of both positions.

Cross-correlation analysis was performed to investigate the statistical relation between dune volume against beach volume, shoreline position (0-m contour), and shoreline trends (volume-based). The correlogram was capped at a maximum lag of N/4 and values tested for significance following a two-sided significance test at a 95% confidence interval accounting for large-lag standard errors based on Anderson (1979) and Salas et al. (1988).

4. Results

4.1. Channel-shoal behaviour and nearshore change

The NUN shoal appeared for the first time in the survey of 1971 (Fig. 5), and elongated itself in the northward direction until 1986/1987. The exact date for the start of this elongation is unknown, but a

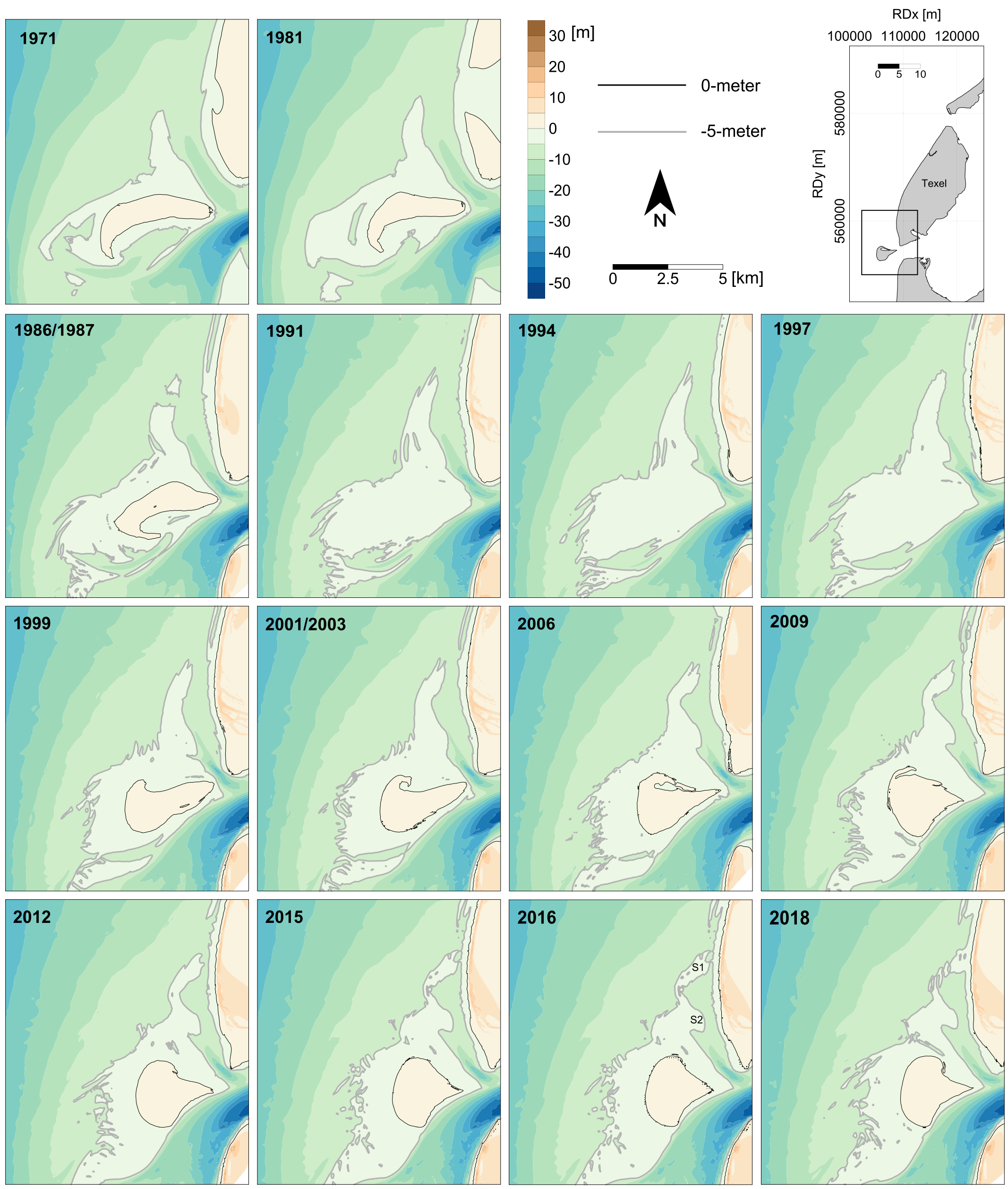

Fig. 5. Bathymetric evolution of the ebb-tidal delta. Years 1986/1987 and 2001/2003 are combined for visualisation. Panel 2016 show shoals S1 and S2.

survey from 1948 did not show clear signs of the shoal. Between 1991 and 1999, NUN essentially moved landward with a displacement of the order of 200–300 *m*, depending on the alongshore position. From 1999, NUN morphologically evolved towards two smaller distinct shoals that we refer to as S1 and S2 (Fig. 6). Both S1 and S2 evolve towards detachment in different locations: one approximately 2 *km* from the northern tip of NUN; and the second in the southern area of the NUN, around 4 *km* south of the northern tip (Figs. 5 and 6). The most recent bathymetry (2018) shows a potential new detachment area in the northeastern border of *Noorderhaaks*.

The two detaching shoals (S1 and S2), each had a distinct morphological evolution. S1 has been moving unevenly towards the coast following a rotation of its tip. S1 starts to rotate clockwise between 1999 and 2016, with a centre of rotation approximately 2 *km* away from the tip (Fig. 5). In 1994, S1 was displaced by 25 degrees clockwise, increasing to 35 degrees in 2006 and 50 degrees in 2016, approximately. In 2016, S1 measured roughly 2.5 *km* in length and 0.6 *km* in width, with the northern tip moving >1 *km* landward from 1994 up to 2016. Between 1999 and 2016, the landward movement lead to sedimentation of up to 4 m (profile d, Fig. 6). The tip attached to the coast between 2016 and 2018.

On the other hand, S2 does not rotate towards the coast and follows a milder landward movement than S1. The reduced landward movement might be related with sufficiently strong currents from the Molengat channel (Fig. 2). Between 1999 and 2016, S2 follows a predominantly northward movement, with a milder landward displacement. S2 also evolves towards a rounded shape, following the erosion in its southern portion. Sedimentation in the channel going with the S2 shoal movement is however larger than for S1, with local gains in bed elevation up to 7 m, approximately (Fig. 6). Elevation change seaward of S2 is mostly small (Transect f., Fig. 6), with exception of the southern seaward portion of S2. Sediment deposited on the landward side of the shoal may have been supplied by either the erosion of the Molengat channel or by the sediment eroded from the southern portion of S2. S2 is also shallower than S1 (Fig. 6).

Between 1991 and 1999, when NUN moves landward as a whole,

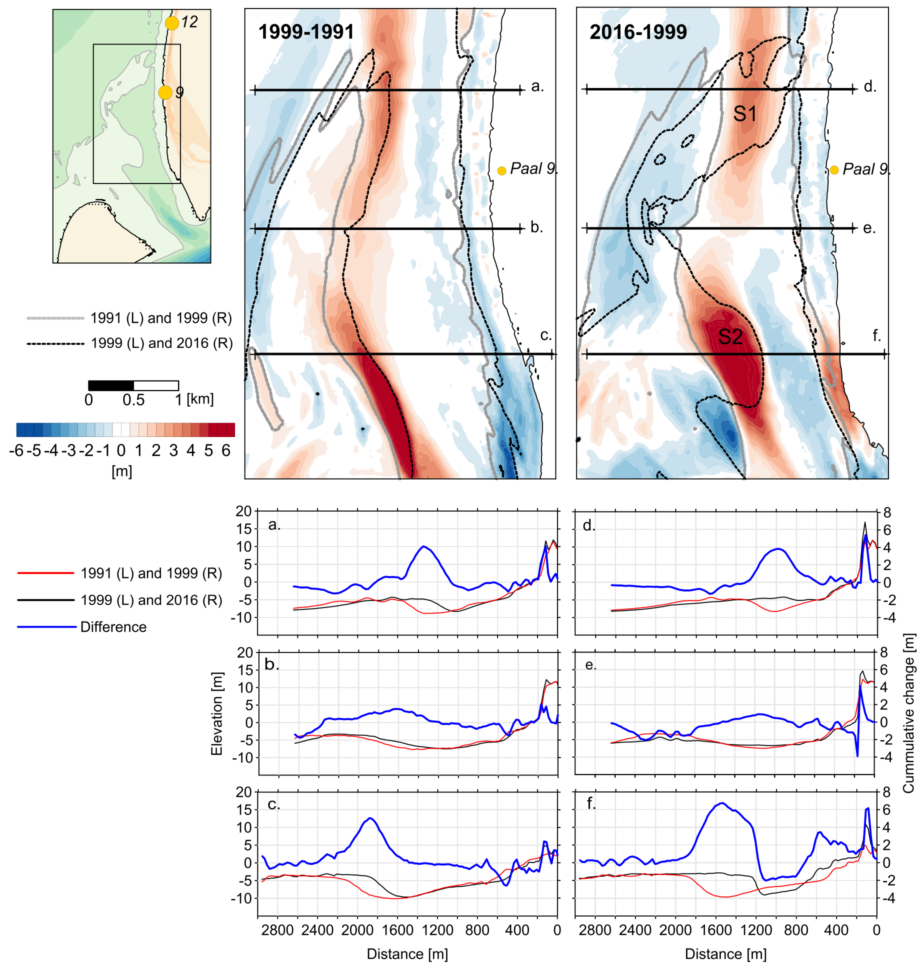

Fig. 6. Difference map highlighting the overall movement trends of the shoal and the shoreline between 1991 and 1999 and 1999–2016. Dashed grey and black lines represent the 5-m contour on the respective early and late survey. Transects (extracted only in this figure to highlight subtidal patterns) show the cross-shore transect at each location, starting from the landward portion. Blue lines represent the elevation change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

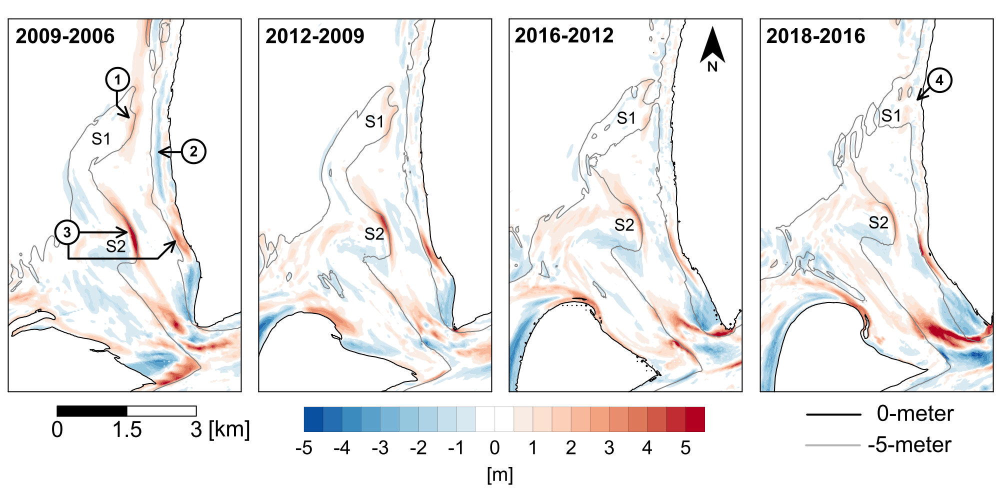

Fig. 7. Difference maps between surveys highlighting specific movements and patterns of the shoal displacement. (1) landward movement of S1; 2) erosion of the subtidal beach around profile 30; 3) the accretion trend on the subtidal beach in front of S2; 4) start of the attachment of S1.

erosion dominates the nearshore zone (Fig. 6). The landward movement and rotation of S1 (1, on Fig. 7) coincide with enhanced erosion of the nearshore between 2006 and 2009 (2 on Fig. 7).

In the most recent survey of 2018, the tip of S1 already entered the nearshore compartment of the shore (4 on Fig. 7), which may be considered the start of the attachment. These lead to an expected full attachment between 2030 and 2050 (Fig. 8).

The present analysis highlights two important shoal-nearshore co-evolution behaviours. The onshore approach of S1, developing at the tip of NUN, co-exists with enhanced nearshore erosion, while the nearshore zone in the proximity of evolving shoal S2 exhibited accretion. In the next session, we analyse the related shoreline change and co-evolution of the beach-dune system.

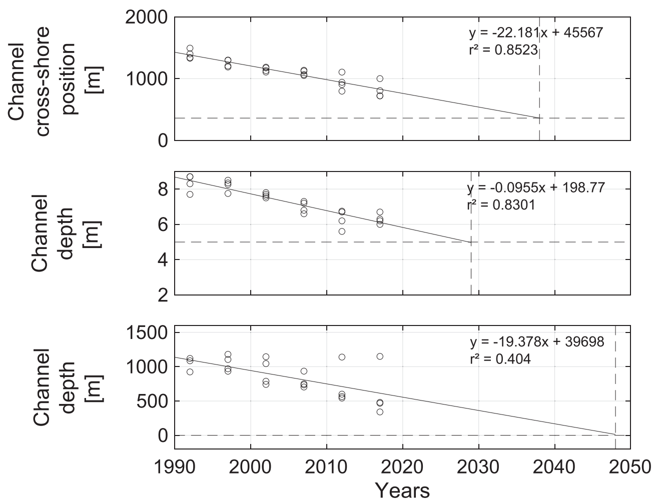

Fig. 8. Trends in the channel cross-shore position, depth and width, where channel depth refers to the water depth over the deepest part of the channel. Profiles used were 15, 20, 25 and 30 from Fig. 4. Dashed lines highlight the point where the shoal is considered attached.

4.2. Beach and shoreline change behaviour

For shoreline position (0-m contour), the most notable change is the strong shoreline progradation between profiles 38–47 (Fig. 9, panels a., b. and d.). This is the same area where nearshore sedimentation occurred in a similar alongshore position to shoal S2, with scaled values showing an increase of up to 250 m (Fig. 9, panel b.). Most of this increase happened between years 2008–2010, though positive changes prevailed after this period (Fig. 9, panel c.)

North of the progradation (between profiles 20–38), mild erosion prevails until the location where S1 has recently attached the shore (Fig. 9, panel b. and d.). However, the strong erosion of the nearshore between 2006 and 2009 is not as pronounced, which can be related to a shoreface nourishment that was placed in the shoreface in 2007. Other progradation years can also be aligned with nourishments, though rapidly followed by erosive years (Fig. 9, panel c.). Patterns found for shoreline position (0-m contour) are similar to patterns found for beach volume (Fig. 10). One exception is the more prominent negative values of the scaled maps between profiles 25–40 (Fig. 10, panel b.), opposite of positive values found in the shoreline map (0-m contour). This means that even though beach volume remained lower than 1997, the shoreline retained a seaward position from 1999 until 2005 (Fig. 9, panel a.).

At the locations where the tip of S1 is attaching (i.e. profiles 15–25), the final shoreline (0-m contour) remained stable or eroded when compared to 1997. This area also shows a persistent shoreline accretion in 1997 between profiles 15–20 (Fig. 9, b). This accretion lines with a beach nourishment in 1997 in the area.

North of the location where the tip of S1 touched the nearshore (i.e. profiles 1–15), the position of the shoreline in 2017 is similar to the position in 1997, despite some small variability in position after 2005 (Fig. 9, b. and c.). In this stretch, shoreline stability is likely related to beach nourishments (Fig. 3).

The picture is slightly different when using the volume-based shoreline position (i.e. data not considering direct nourishment effects from the *Rijkswaterstaat* reports). The shoreline shows a net eroding trend for the full area most of the time (Fig. 11, a.), with average values of 3,9 *m/yr* for the whole area. Values increase significantly after 2010 (7,3 *m/yr*). Spatially, an increase in the erosion magnitude is also observed roughly after 2012 south of profile 20, approximately. The most southern stretch (i.e. between profiles 25–35) is eroding faster than the northern part, with average values of 5,4 and 2,4 *m/yr* (Fig. 12). Note that the accretive years around 2010 are related to problems in the calculations for those years, where parts of the shoal might have been included by mistake (Lodder, Q., personal communication, 2020).

Therefore, trends observed for shoreline change (0-m contour) are mostly similar to those for nearshore change induced by the recent morphological development of NUN, but sometimes trends are masked by nourishments. Volume-based shoreline trends show an erosive trend, specially between 20 and 35 (where several nourishments have been placed), partially induced by the landward movement of S1. For both volume-based and 0-m contour estimates, a general erosive trend exist, though much more pronounced in the former logically due to the nourishments included in the latter.

4.3. Dune behaviour

Despite the erosive trend of the shoreline, dunes generally increase in volume, with some sparse erosion occurrences mostly between profiles 20–35 (Fig. 11, b. and 13, a. b and d.). Between profiles 1–20, dunes exhibit a relatively linear trend in dune growth, exemplified by the well-marked slope in the normalised dune volume plot (Fig. 13, d.). Between profiles 20–38, dune volume growth reduces in recent years, with some profiles even starting to show periods of erosion (e.g. around profile 25 or 35) (Fig. 13, c.). Between profiles 38–47, dune growth increased from 2010 onward. This growth can be related to a distinct seaward shift of

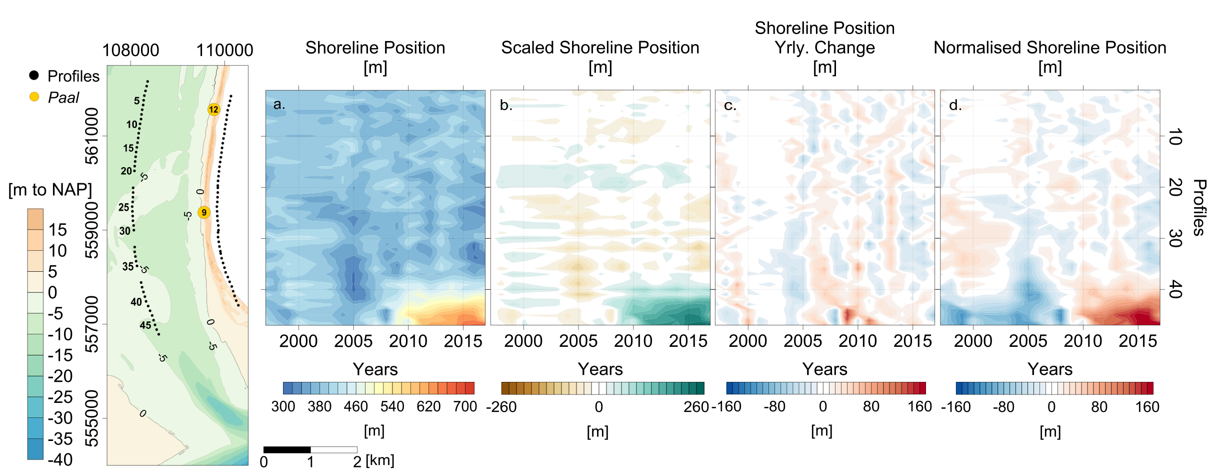

Fig. 9. a. Annual observations for shoreline position (0-m contour) for profiles 1–47 between 1997 and 2017. b. Annual observations for shoreline position (0-m contour) using the position of 1997 as reference. c. Yearly change of shoreline position (0-m contour). d. Shoreline position (0-m contour) normalised by the profile average value. Y-axis represent the alongshore position, whereas X-axis represent time. Left panel used for spatial reference.

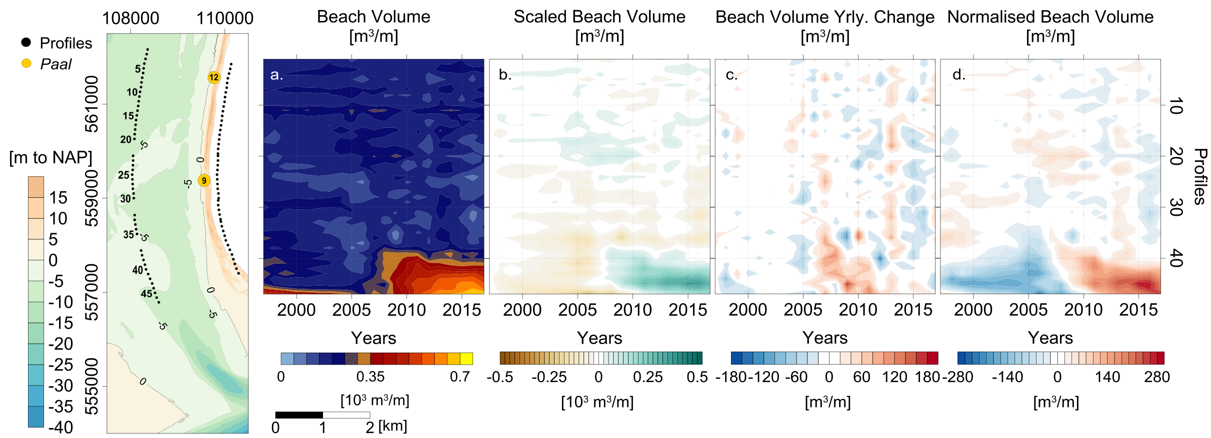

Fig. 10. a. Annual estimates for beach volume for profiles 1–47 between 1997 and 2017. b. Annual estimates for beach volume using the position of 1997 as reference. c. Yearly change of beach volume. d. Beach volume normalised by the profile average value. Y-axis represent the alongshore position, whereas X-axis represent time. Left panel used for spatial reference.

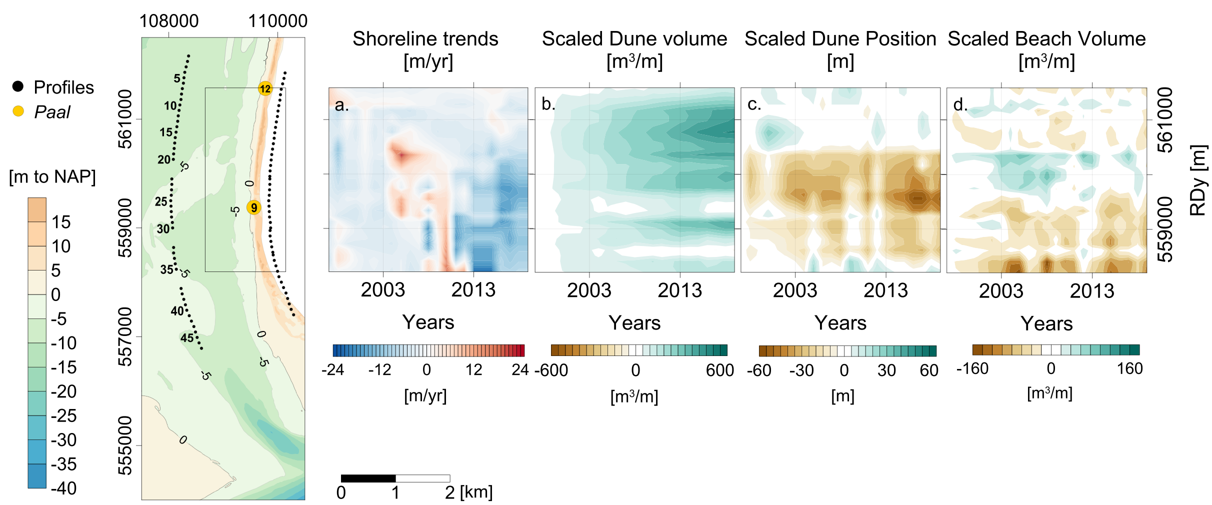

Fig. 11. a. Volume-based shoreline movement trends acquired from *Rijkswaterstaat* for profiles 1–35, approximately, excluding direct influence of nourishments. b. Annual estimates for dune volume using the position of 1997 as reference, based on the topographic data. c. Annual estimates for dunefoot position using the position of 1997 as reference, based on the topographic data. d. Annual estimates for beach volume using the position of 1997 as reference, based on the topographic data. Y-axis represent the alongshore position, whereas X-axis represent time. Left panel used for spatial reference.

the shoreline position, creating a wider beach that would lead to an increase in potential transport and accommodation space for dune progradation. Such a wider beach also increase wave dissipation during storm surge events. Scaled dune volume shows that most dunes have larger volumes than in 1997, with the exception of some profiles around 25 and 35 locations which did not recover from some erosion in 2005 (Fig. 13, b.). Growing dunes generally develop as a single high foredune ridge with steep slopes. A clear exception would be the southern profiles due to the development of a new foredune ridge approximately 300 m in front of the old one (Fig. 14).

Patterns in dunefoot position are closer to patterns in shoreline position than dune volume. Noticeable changes in dunefoot position occurred between 1997 and 1999 (profiles 14–26), 2004–2007 (profiles 22–40), 2009–2012 (profiles 20–38) and 2012–2015 (profiles 7–40) (Fig. 15). All changes are similar: a seaward movement of the dunefoot, followed by a landward retreat. All seaward movements of the dunefoot could be related to nourishment done in the area in 1997, 2007, 2009 and 2012. While some of these patterns are also visible in the shoreline data, seaward movements similar to 1997 are only visible in the dunefoot. Most of the nourishments in the area were subaerial, generally in the form of beach nourishment, so not as a dunefoot nourishment (*'banket'* in Dutch). Nonetheless, it is not possible to separate whether the effect in dunefoot position is a wind-driven process or a bias due to the location where the sand has been placed (i.e. some sand being deployed too close to the dune), with a combination of both being the most likely. Furthermore, the erosion pattern of the dunefoot does not appear as clear in the shoreline, which could be explained by the deposition of eroded sands from the dunefoot in lower parts of the beach and diminishing the signal in the shoreline. Between profiles 38–45, the seaward movement of the dunefoot can be explained by the strong seaward movement of the shoreline, specially the most southern profiles where the resulting beach width increase lead to sufficient space for a new foredune development.

Cross-correlation analysis show that dune volume is generally negatively correlated with beach volume and shoreline trends (volume-based) between profiles 20–38, and positively correlated with the shoreline position (0-m contour) between profiles 1–20 and 40–47. Most significant values are found on Lags 0 to 1, though higher lags (2–5 years) dominate the positive relation between profiles 40–47. The positive correlation between shoreline (0-m contour) and dune volume refer to the areas where a stable or accretive shoreline dominates. Higher lags between profiles 40–47 refer to the sudden increase in the shoreline and

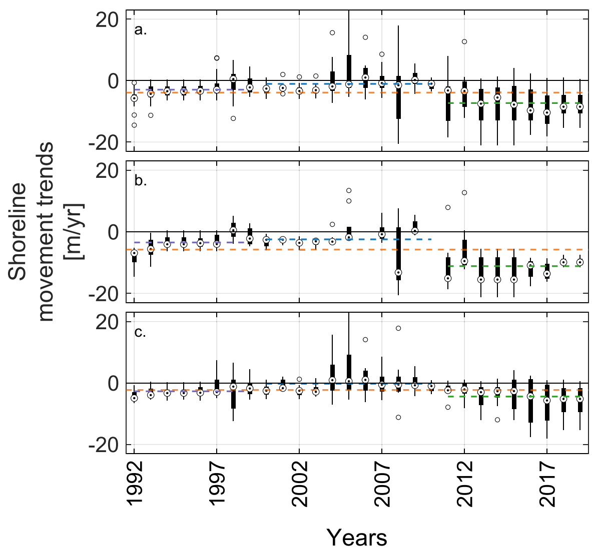

Fig. 12. Shoreline movement trends (volume-based) for SW Texel. Negative values represent erosion, whereas positive values represent accretion. The dataset is also presented in subsets (b. and c.) to highlight the spatial dependency found in the dataset. a. Boxplots using profiles from 1 to 35. b. Boxplots using profiles 25 to 35. c. Boxplots using profiles 1 to 25. Dashed lines represent the mean for different periods of time. Orange line is the mean for the whole period. Purple is the mean between 1992 and 1999, blue is the mean between 2000 and 2010, and green is the mean between 2011 and 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the relaxation time for the new dune development in that region (Fig. 16). The negative correlation between shoreline trend (volume-based) and dune growth refers mostly to the negative trend of shoreline erosion and positive trend of dune growth. Negative relation between beach volume and dune volume is concentrated in the area suffering more with erosion. The lack of correlation in the shoreline for that area suggest that the correlation between beach volume and dune volume is mostly related with changes in volume related to the subtidal zone (i.e channel scouring) that are not well shown in the shoreline (also due to the effects of groins and beach nourishments). This hypothesis was also tested when reducing the upper boundary for beach volume calculations to up to almost 0 m, yielding the same correlation pattern.

Thus, where both the volume-based shoreline position and the 0-m contour shoreline position show an overall erosive trend (in different magnitudes due to the sand nourishment), dunes have mostly still been able to grow in volume, albeit with alongshore varying growth rates.

5. Discussion

Important observations from the previous section are, firstly, the two different shoal-nearshore co-evolutions. The onshore approach of S1, developing at the tip of NUN, goes with nearshore erosion, while the nearshore zone in the proximity of evolving shoal S2 exhibited accretion. Secondly, notwithstanding an erosive shore, the dunes have mostly been able to grow in volume, albeit with alongshore varying growth rates.

5.1. Shoal behaviour and shoreline change

In the literature, shoal attachment and the effect in the adjacent shoreline has been described in three different phases: Detachment, attachment and spreading (Kana et al., 1985). In the first phase, the shoal detaches from the ebb-shield. Wave-breaking on the shoal dominates over ebb-currents, pushing it landwards. As the shoal moves landward, wave refraction will create a convergence zone of longshore drift, leading to the formation of a cuspate spit at the shoreline on the lee side of the shoal. Such a movement may also create erosional arcs adjacent to the attachment location. The last phase is defined by the dispersion of the attached shoal alongshore. The erosion of the shoreline together with the accretion in the lee side during the approximation of the shoal has been described in several articles (Garel et al., 2014; Gaudiano and Kana, 2001; Kana, 1989; Kana et al., 1999; Kana et al., 1985; Traynum and Kaczkwski, 2015).

For the case of Texel, the coastline aligned alongshore with S1 showed signs of increased erosion during the approximation of S1. Since 2006, erosive trends increased in magnitude along the southern stretch of Texel. Between profiles 25–35, erosive processes have been more prominent than between profiles 1–25. The mechanism associated with such an increase has been associated with the landward migration of S1 and, consequently, the channel, which would induce scouring of the shoreline and local erosion (Elias and van der Spek, 2017). In contrast to the above-cited cases, we could not see any cuspate effect in the shoreline during the approximation of S1. One hypothesis is that the formation might have been masked by the nourishments and groins of the area. Another hypothesis is that as the shoal is deeper than shoals in the cited studies, it may be less competent in creating conditions for the bulging of the coastline. Nonetheless, the scaled beach volume (Fig. 11, d.) data show an accretion trend at the lee side of the shoal, surrounded by erosion, which might confirm the idea that convergent gradients in

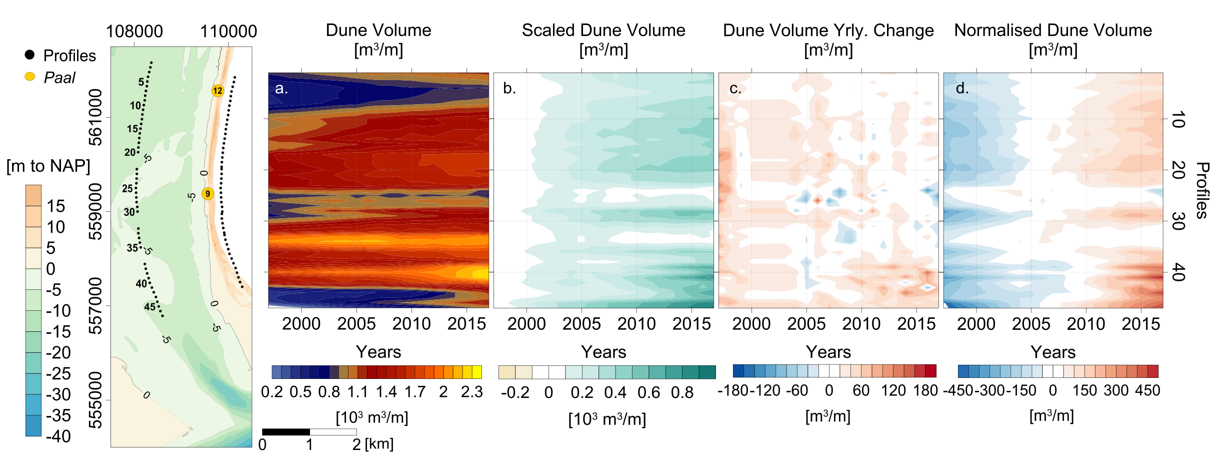

Fig. 13. a. Annual estimates for dune volume for profiles 1–47 between 1997 and 2017. b. Annual estimates for dune volume using 1997 as reference. c. Yearly change of dune volume. d. Dune volume normalised by the profile average value. Y-axis represent the alongshore position, whereas X-axis represent time. Left panel used for spatial reference.

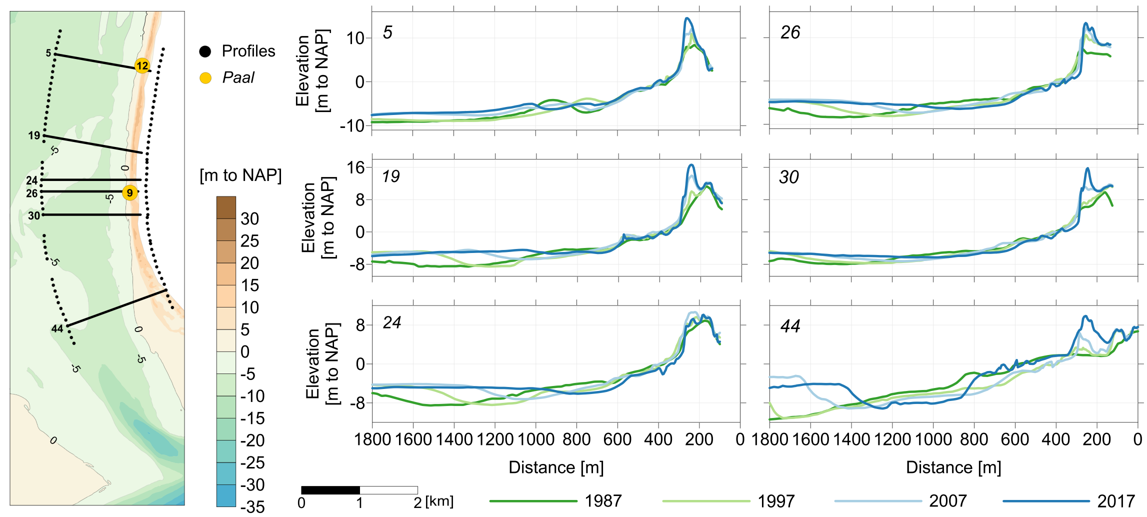

Fig. 14. Topographic evolution of the beach-dune system for profiles 5, 19, 24, 26, 30 and 44.

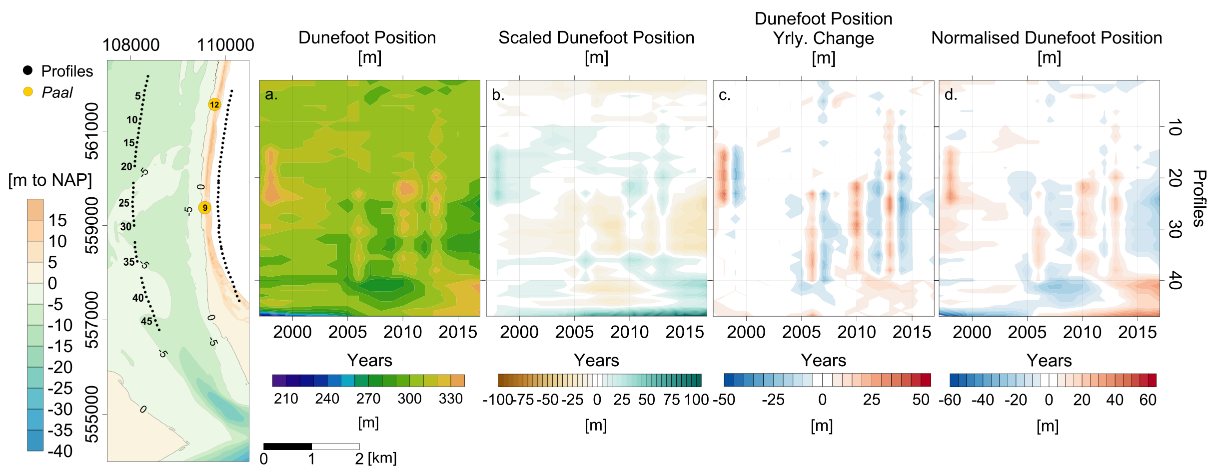

Fig. 15. a. Annual estimates for dunefoot position for profiles 1–47 between 1997 and 2017. b. Annual estimates for dunefoot position using the position of 1997 as reference. c. Yearly change of dunefoot position. d. Dunefoot position normalised by the profile mean value. Y-axis represent the alongshore position, whereas X-axis represent time. Left panel used for spatial reference.

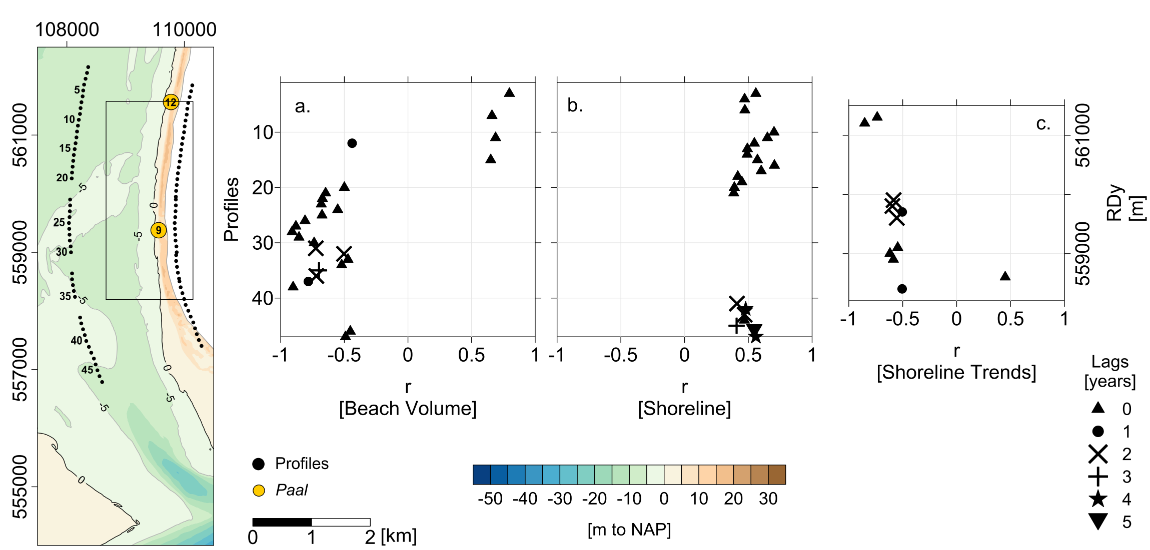

Fig. 16. Correlation coefficients from a cross-correlation analysis done in time for each profile between dune volume and beach volume, shoreline position, and shoreline trends. Only most significant values plotted. Panels positioned to sit in their approximate alongshore position based on the map on the left.

the longshore did occur but was not reflected in the shoreline position itself, but only in lower portions of the nearshore.

On the other hand, the accretion on the adjacent beach of S2 might be explained as a cuspate effect. The accretion of the beach between profiles 38–45, starting around 2009, is located close to the lee side of S2. The formation resembles what has been reported in literature. Different than S1, the region has been less affected by direct nourishments. Another possibility is that S2 is shallower than S1, which makes it more competent in sheltering the coastline from wave-driven processes. Such a sheltering would potentially lead to an accreting nearshore, driven by the mechanisms explained earlier. Another hypothesis would be that that the accretion is driven by alongshore gradients in the ebb-tidal re-circulation pattern. A combination of both is also possible. A predominantly southern sediment supply may explain the shoreline accretion together with alongshore transport gradients.

Therefore, before attachment, the landward movement of S1 and the adjacent channel induced scouring and local erosion at the adjacent shoreline, whereas the development of S2 induced a cuspate effect on the adjacent shoreline.

5.2. *Erosive shores and accreting dunes*

Despite the increased shoreline erosion along some stretches, dunes still kept growing along most of the coastline (Fig. 11). This pattern has been reported previously (Arens and Wiersma, 1994; Davidson-Arnott, 2010; Davidson-Arnott, 2005; Hesp et al., 2016; Psuty, 2004; Ruz and Allard, 1994). We will try to explain the observed behaviour by reference to existing models on beach-dune development: the surfzone-beach-dune model of Hesp (2002) and Short and Hesp (1982), and the sediment budget model of Psuty (2004).

From the perspective of the surfzone-beach-dune model, changes in the beach state would influence foredune behaviour and potential of aeolian transport. Thus, despite the erosion of the beach on Texel, the local dune growth implies that beach characteristics such as width and slope were (still) not limiting factors in terms of sediment transfer between beach and dune. Nourishment were then essential on considerably reducing the rate of erosion of the shoreline. By retaining the shoreline erosion, nourishments kept the beach state in such conditions that ensured a positive transfer between subtidal and supratidal zones. Nonetheless, the mild erosive trend of the shoreline also implies that beach width is reducing and, therefore, also aeolian potential. Whether or not beach width remains sufficiently large for a positive transfer of sediment to the foredune until full attachment remains unclear. Nonetheless, it is safe to say that the nourishment strategy over time positively affects the transfer of sand to the dunes from the perspective of Short and Hesp (1982).

From the perspective of the sediment budget model, the dune growth amid the shoreline erosion suggests a period of negative to stable littoral budget with positive dune budget. The reduction of dune growth (and sometimes erosive trend) in some stretches between profiles 20–38 suggest that current beach budget (i.e. before attachment and sediment input from the shoal, but with nourishment) may be close to the point where a single high foredune ridge may shift towards dune breaching, overwash and sand sheet development. Thus, a small decrease in beach sediment budget may have strong impacts on dune morphology. A slight reduction in beach budget may move the foredune system from a maximum dune volume towards a strongly negative foredune budget. In our particular case, nourishments may have played a role to ensure that such behaviour were sustained throughout the whole approximation period. The qualitative nature of the sediment budget model does not allow us to assess quantitatively to what extent nourishments played a role in maintaining the beach budget in appropriate levels to keep dune growth. However, considering our observations regarding different shoreline trends, nourishments have been essential in affecting the beach budget and preventing (or slowing down) a system shift.

Similar principles apply for stretches that are not eroding, such as between profiles 38–47, where a seaward movement of the shoreline (and, consequently, a natural increase in beach width) was followed by an increase in dune growth (Figs. 9 and 13). A momentary increase in beach budget lead to an increase in beach width. The sudden increase in beach width lead to appropriate conditions for enhancing dune growth (e.g. accommodation space, potential aeolian transport) and the creation of a new foredune system roughly around 2006. Considering the sediment budget model, that would lead to the system shift to the left (i.e. increased beach budget), away from the tipping point. For the surfzone-beach-dune model, the increase in beach width maximize potential aeolian transport and thus would reflect a larger foredune or creation of a new foredune system.

Several studies confirm that changes in the shoreline and beach width can influence coastal dune behaviour (Aagaard et al., 2004; Anthony et al., 2006; Cohn et al., 2017; Ruessink and Jeuken, 2002; Silva et al., 2019). Silva et al. (2019) show that beach width can control the position where foredunes tend to be built and that an apparent threshold in beach width increase needs to be crossed for a significant seaward extension and/or increase in dune growth at a decadal scale. In case of a retreating shoreline, Guillén et al. (1999) observed that the dunefoot position of a well-developed foredune followed the shoreline, although state changes of the foredune were not addressed. Our results also show that the increase in beach width, when induced by beach nourishment, is immediately reflected in the dunefoot position, but hardly in the dune volume. The latter, however, may be due to relaxation time. Although the signal in the dunefoot position may be related to direct dumping of the sand at the dunefoot, van der Wal (1999) shows that nourishment can promote dune building by aeolian transport and may drive a transient increase in sand transport. The magnitude and duration of this increase will vary depending on various factors such as surface texture, material characteristics (e.g. sorting, density), nourishment design.

It is important to note that, for both perspectives, the picture will likely change after attachment. Considering the long period without shoal attachment, the analysed situation is a picture where supply from the shoal and direct changes due to attachment should not be counted yet, even though indirect effects such as enhanced beach erosion should be included. In the near future, it will be possible to also evaluate dune development after attachment, when beach supply will increase and beach characteristics will change due to the attachment.

Beach-dune behaviour during the approximation phase of the shoal could be qualitatively framed on both existing beach-dune interaction models in different levels and is summarized on Fig. 17. The surfzone-beach-dune model could be well framed with the relation between beach width and dune development and the importance of nourishment in maintaining appropriate beach characteristics for dune growth, whereas the sediment budget model gave insights on how sand nourishment seemed essential on maintaining current beach-dune morphology during the near-attaching phase of the shoal.

Therefore, for beach-dune systems close to inlets, current existing beach-dune interaction models seem to remain valid and very useful, though examples from other systems and the analysis of the full attachment cycle are necessary for a potential conceptualization in terms of a model for beach-dune systems near inlets.

5.3. *Coastal management perspectives*

From a coastal management perspective, it is highly desirable to understand how shoal dynamics in a tidal inlet change the dynamics of the beach and the dunes. Current derived insights suggest that, even though shoals can introduce large amounts of sediment to the beach-dune system, morphological changes during the approximation phase may induce changes that hinder flood protection levels depending on the beach state.

Beach-dune interaction models can be seen as a tool to understand on a conceptual level the changes in the morphology of a beach-dune system driven by shoal attachment processes. Using the models, we

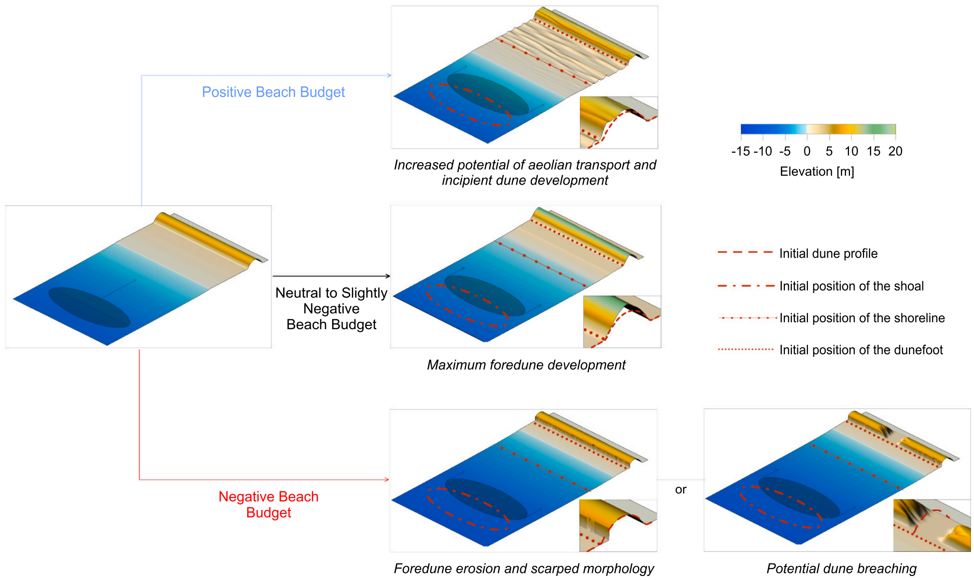

Fig. 17. Schematisation of potential beach-dune developments affected by the onshore movement of a shoal. Shoal movement is represented by simple head arrows. When shoal movement induces a positive increase in beach budget/increase in beach width, the potential for aeolian transport increases, leading to an increase in foredune budget and potential development of incipient dunes. When the shoal movement induces a slight reduction of beach budget, the system may develop towards a maximum foredune development while space and supply exist. When the movement induces a greater reduction in beach budget, current morphology may rapidly change to scarped/eroded foredunes, with the potential for dune breaching and ridge dissection. The level of development of all conditions strongly depends on the time between shoal-induced budget changes by onshore movement until actual attachment, which will induce an increase in beach budget.

identified not only the current state of the beach-dune system but also the indirect role of nourishments during the approximation phase. Our analysis showed that nourishments have been essential to keep the sediment budget at a sufficient level to maintain the dune morphology in a positive sediment budget state. Future planning on nourishments for areas close to tidal inlets might use the concepts used here for planning and evaluation during the approximation phase.

However, for such qualitative assessments, long-term monitoring data are indispensable. Without information on the evolution of beach and dune volume, shoreline changes and shoal displacement, framing the system within the model would be troublesome. Nonetheless, our analysis shows that it could be a valuable tool with such a dataset available.

Thus, understanding the state of the beach-dune system through beach-dune interaction models might be a potential tool for coastal managers. For example, if the adjacent beach-dune system is very close to the tipping point in the beach budget model and the landward movement of the shoal enforces erosion of the shoreline (e.g. S1), the system may quickly evolve towards a complete erosion of the dune before attachment if not compensated by a proportional increase in nourishment volumes (i.e. increasing the beach budget). Considering the time-scale of the approximation of the shoal (in our case, more than a decade), this may lead to a weak point in terms of flood protection for a considerable time. One may argue that the attachment of the shoal will shift the tipping point back by introducing very large amounts of sediment to the beach-dune system. However, the relaxation time required for dune building may be enough for a sustained period of low level of protection.

6. Conclusion

A case study on the island of Texel (NL) is used to understand the beach-dune behaviour during the approximation of a large ebb-tidal shoal to the coast. Multi-annual topographic and bathymetric monitoring data were analysed to understand the recent morphological developments of the shoal and the beach-dune system. Results show that before actual attachment there is an erosive pattern along the adjacent coastline where the shoal is bound to attach. The erosive trend of the shoreline, compensated by regular nourishments over the last decades, has resulted in a dune growth pattern implying a net positive transfer of sand from the beach to the dunes. The growth of dunes in the area, during the erosion phase, suggests that the beach-dune system stays close to the negative beach budget on the morphological continuum proposed by the sediment budget model or in the erosional continuum on the surfzone-beach-dune model. The beach-dune system may only sustain such behaviour while a sufficient budget remains at the beach, which will be site-specific. This implies that shoal attachment processes can change beach-dune morphological state momentarily depending on budget characteristics before the attachment phase. From a management perspective, it may be troublesome. If the adjacent beach does not have a sufficient beach budget, and coastline erosion is not compensated by a proportional increase in nourishment volumes, the erosion may lead to a complete erosion of the dune before attachment which will lead to a weak point in terms of flood protection. Even though the attachment will lead to an increased budget for likely several years, large erosion of the dune may take time to recover completely after attachment, which may lead to several years of a weakened level of protection until dune recovery. Therefore, even though shoals will eventually induce considerable beach budget increase, monitoring of the beach state before large shoal attachments are extremely relevant to ensure that levels are appropriate to maintain dune morphology and potential flood protection levels in barrier islands.

Data availability

All datasets are available in an OPeNDAP repository (https://opendap.deltares.nl/), whereas the reports are accessible via *Rijkswaterstaat* (https://puc.overheid.nl/rijkswaterstaat/).

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Filipe Galiforni-Silva reports financial support was provided by Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and the Water Board Hollands Noorderkwartier.

Acknowledgements

This research forms a component of the CoCoChannel project (Co-designing Coasts using natural Channel-shoal dynamics), which is funded by the Netherlands Organization for Scientific Research, Earth Sciences division (NWO-ALW), and co-funded by Hoogheemraadschap Hollands Noorderkwartier. We further wish to acknowledge

Rijkswaterstaat for making their valuable bathymetric and topographic data sets freely available. We also would like to thank Petra Goessen for all discussions involved in the process of this manuscript, and the kind and highlighting comments from both Prof. Patrick Hesp and an anonymous reviewer.

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