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Behaviour of subtidal sandbars in response to nourishments

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ABSTRACT

The behaviour of subtidal sandbars can be strongly influenced by the introduction of sand nourishments in the coastal system. This study focuses on the impact of nourishments on subtidal bar behaviour at spatio-temporal scales beyond a single nourishment project. It aims to determine the long-term behaviour of subtidal sandbars along an entire coastal cell, taking into account both the unnourished and nourished regime, and covering various types of nourishments. The analysis is based on over 50 years of sandbar evolution along the Delfland coast, a 17-km long coastal cell at the Dutch North Sea coastline protected by groynes and maintained with frequent sand nourishments. Observations reveal clearly different sandbar behaviour during the unnourished (first 20 years) and nourished periods of the dataset. Introduction of the first beach nourishments (nourished sand primarily placed at the subaerial beach) was found to stimulate sandbar development along previously unbarred sections of the coast. Shoreface nourishments (nourished sand placed at the seaward face of the pre-existing subtidal sandbar) tended to migrate shoreward rapidly at a rate of 20 to 60 m/year at this coast, thereby forcing the pre-existing sandbar to weld to the dry beach. An abrupt transition of sandbar dynamics was observed following a major nourishment operation (~37.5 Mm^3 of nourished sand) that covered the entire coastal cell. A new, shallow sandbar formed with a degree of alongshore variability that was unprecedented at the Delfland coast over the full study period. These results imply that individual nourishments can influence the formation and migration of individual sandbars, while continued nourishments can fundamentally change long-term sandbar dynamics along an entire coastal cell.

1. Introduction

Sand nourishments are commonly used as a ‘soft’ engineering strategy to mitigate coastal erosion problems (Hamm et al., 2002). Nourishments are constructed in a wide variety of sizes and shapes, and in contrast to ‘hard’ engineering measures (e.g. groynes or breakwaters) they are eventually absorbed by surrounding morphology. Notably, the development of nearshore sandbars can be influenced by the presence of a sand nourishment (Grunnet and Ruessink, 2005; Ojeda et al., 2008). Sandbars can be found along many sandy coastlines worldwide. Their presence plays an important role in the morphodynamic evolution of a beach, as wave breaking and associated wave-driven sediment transport typically occurs at or near a submerged sandbar (Ruessink et al., 2001; Mil-Homens et al., 2013).

The natural behaviour of nearshore sandbars, in the absence of nourishments, has been studied for many decades based on field observations and various modelling frameworks. Typically, the behaviour of sandbars is described in terms of (1) their cross-shore migration and (2) alongshore variability. Cross-shore migration refers to the temporal evolution of cross-shore sandbar position and secondary characteristics such as sandbar volume, amplitude and crest level. At timescales from months to decades, sandbars are found to exhibit a net offshore migration (NOM; Ruessink and Kroon, 1994; Plant et al., 1999; Shand and Bailey, 1999; Ruessink et al., 2003; Tătui et al., 2016; Walstra et al., 2016). NOM can either occur at a relatively constant rate over time (mainly in wind-sea climates), or occur rapidly in response to storm events (episodic NOM, mainly in swell wave climates; Ruessink et al., 2009). Offshore migrating bars are typically found to originate near to the shoreline, migrate offshore and finally diminish outside the surfzone.

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The return timescale associated with this cyclic behaviour varies strongly between different sites and has been linked to the steepness of the cross-shore profile (Walstra et al., 2016). Net onshore migration has been reported less frequently (Aagaard and Kroon, 2007).

Alongshore sandbar variability is associated with the development of three-dimensional patterns in the sandbar at length scales ranging between $\mathcal{O}(100\,\mathrm{m})$ and $\mathcal{O}(1\,\mathrm{km})$ (Holman, 2001). Short-scale sandbar variability is typically observed as an alongshore alternation of shoals and rip channels, which can be found along many open ocean coastlines (e.g. Wright and Short, 1984; Holman et al., 2006). At marginal sea coasts with predominantly wind-sea climates, alongshore variability is characterised by subtle crescentic bar crest shapes (Van Enckevort and Ruessink, 2003) or sudden discontinuities in the bar crest (Grunnet and Ruessink, 2005; Ruessink et al., 2012). This kilometre-scale sandbar variability is often attributed to alongshore differences in the phase of the NOM cycle (Walstra et al., 2015; Aleman et al., 2017), as opposed to surfzone flow circulation patterns that govern the generation of short-scale alongshore variability (Reniers et al., 2004; Coco and Murray, 2007). Eventually, differential NOM may lead to rupture of the bar crest. If this occurs in a multiple bar system, bars may reattach to another bar crest at the location of the rupture, referred to as bar switching (Wijnberg and Wolf, 1994; Shand, 2003; Walstra et al., 2015).

Sand nourishments impact nearshore sandbar evolution, depending on the location, size and shape of the nourishment. Nourishments can roughly be subdivided into three different categories (Fig. 1). In beach and dune nourishment operations (first category) the sand is placed at or adjacent to the dry beach and dune, directly leading to a larger volume and subaerial width of the beach (Dean, 2002). Beach and dune nourishments are often designed with a relatively steep cross-shore beach slope near the waterline. If the nourishment covers pre-existing sub-tidal bars, a barless profile remains. The first high wave energy events following execution of the nourishment will flatten the profile, thereby moving sand from the waterline towards deeper water. This typically results in the creation of a subtidal bar, as observed by Elko and Wang (2007), Yates et al. (2009), Roberts and Wang (2012) and De Schipper et al. (2013) at individual nourishment projects.

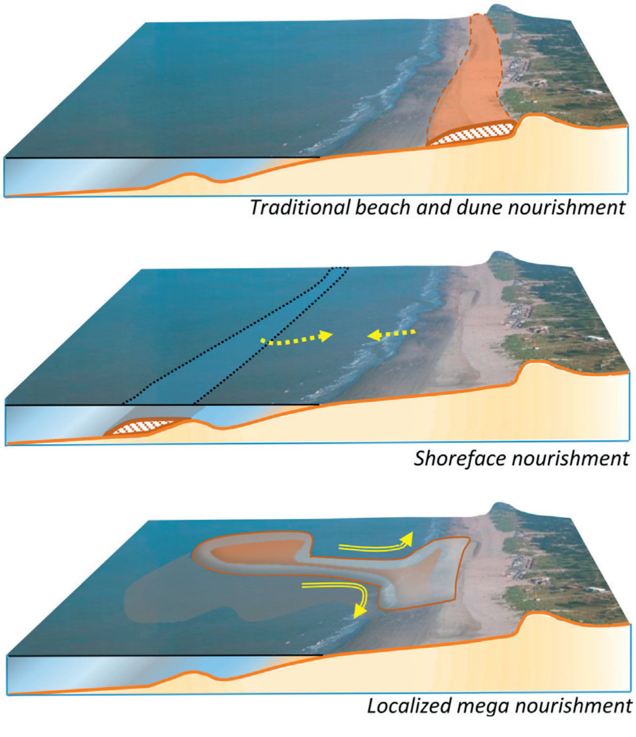

Fig. 1. Different types of sand nourishments, after Stive et al. (2013).

Shoreface nourishments (second category) are placed lower in the cross-shore profile, mostly at the seaward face of the subtidal bar (Kroon et al., 1994). The nourished sand may redistribute over the active beach profile, thereby indirectly nourishing the dry beach. Furthermore, the presence of a shoreface nourishment might directly contribute to offshore dissipation of incoming storm wave energy. At the multi-barred Dutch North Sea coast, shoreface nourishments have been applied in coastal maintenance since the 1990's (Hamm et al., 2002). Here, the effect of shoreface nourishments on subtidal sandbars has been studied at the beaches of Noordwijk, Egmond and Terschelling. The NOM cycles that characterise the natural dynamics at these three sites were disturbed by the presence of the nourishment for a period of several years. Instead of offshore migration, bars were observed to stop migrating (Grunnet and Ruessink, 2005; Ojeda et al., 2008; Ruessink et al., 2012) or even migrate slightly onshore (Kroon et al., 1994; Van Duin et al., 2004; Lodder and Sørensen, 2015) for periods of multiple years following execution of the shoreface nourishment.

While beach and shoreface nourishments primarily strengthen the coastline locally, mega-nourishments (third category) are intended to act as a long-term (decades) source of sediment for a larger stretch of coast through naturally occurring alongshore sediment transport. To date, only very few mega-nourishments have been executed, one of them being the Sand Motor (Stive et al., 2013) in the focus area of the present study (further discussed in Section 2).

The impact of sand nourishments (of any type) on alongshore sandbar variability has only been addressed by a few studies. The emergence of large-scale three-dimensional sandbar patterns was reported following a shoreface nourishment at Terschelling (Grunnet and Ruessink, 2005). The presence of the shoreface nourishment along part of the beach induced spatial differences in cross-shore bar migration rate, as offshore bar migration was halted along the nourished section of the beach. This resulted in bar crest ruptures, yielding alongshore variability of the subtidal sandbars. A similar evolution was observed after a shoreface nourishment at Egmond and Noordwijk (Van Duin et al., 2004; Ojeda et al., 2008; Ruessink et al., 2012). At the Sand Motor mega-nourishment, highly pronounced sandbar patterns and clear alongshore differences in the response of sandbars were reported (Rutten et al., 2017c), which contrast common sandbar behaviour at the Dutch coast.

Existing studies into the effect of nourishments on sandbar dynamics focussed either on one single nourishment project over the first years after its construction or on a limited alongshore extent. While this yields valuable insights into the joint morphologic development of nourishments and sandbars at relatively short and small scales, it remains unclear how repeated nourishments and implementation of different nourishment types affect the natural, unnourished behaviour of the system. The present study focuses on spatio-temporal scales beyond a single nourishment project and aims to determine the long-term behaviour of subtidal sandbars along an entire coastal cell, taking into account both the unnourished and nourished regime, and covering various types of nourishments.

The analysis makes use of a 52-year bathymetric dataset of the 17-km long Delfland coast, a coastal cell at the Dutch North Sea coastline that has received a wide range of sand nourishments over the last decades. Having a low-lying hinterland that represents a large economic value, the Delfland coast plays an important role in the coastal flood protection system of The Netherlands. The construction of the Sand Motor mega-nourishment in 2011 has drawn large scientific attention to the Delfland coast, adding to the importance of an adequate understanding of its long-term sandbar dynamics. Firstly, the field site and methodology are introduced (Sections 2 and 3). Subsequently, fifty years of observations of

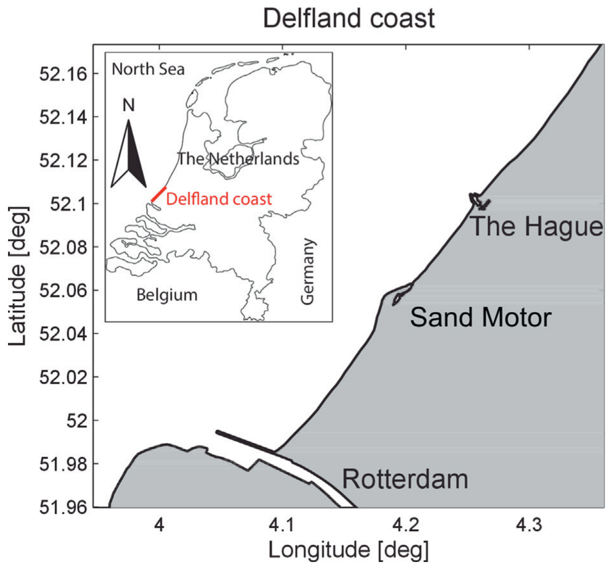

Fig. 2. Setting of the Delfland coast. The Sand Motor is visible as a seaward perturbation in the middle of the coastal cell.

sandbar dynamics at the Delfland coast are presented in Section 4. Finally, these observations are analysed and discussed (Section 5).

2. Field site

Sandbar dynamics are analysed here for the Delfland coast, a 17 km-long sandy beach at the Dutch North Sea coastline. It is constrained by the long harbour breakwater (3.5 km) of Rotterdam in the southwest and the relatively short harbour breakwaters (0.5 km) of The Hague in the northeast (Fig. 2). The cross-shore profile slope of the Delfland coast typically is around 1:80 in the upper part of the profile (between 0 and 7 m depth with respect to Mean Sea Level (MSL)) and 1:400 in the lower part of the profile (below −11 m MSL). The average shore-normal orientation of the coast is 310° North, which deviates locally around the harbour breakwaters in Rotterdam and The Hague. The wave climate at the south-eastern North Sea is bimodal, with energetic waves arriving from the South-West or from the North. The annual mean significant wave height is 1.3 m, with typical wave periods around 5 to 6 s (Wijnberg, 2002). Sediment at the Delfland coast consists of medium-sized sand in the surf and swash zone, with the median sediment diameter ranging between approximately 200 and 400 μ m (Huisman et al., 2016). The tidal range varies between 1.4 m and 1.8 m over a spring-neap cycle (Wijnberg, 2002) and drives an alongshore directed tidal current with peak flow velocities in the order of 0.7 m/s depth-averaged at a water depth of 9 m (Radermacher et al., 2017a).

Similar to other parts of the Dutch coastline, the Delfland coast has been subject to structural erosion for the last 2000 years (Beets and Van der Spek, 2000) in response to Holocene sea-level-rise and changing sediment supply. In order to protect coastal towns and their low-lying hinterland, humans have made attempts to stop coastal erosion or mitigate its adverse effects. First, this was done by the creation of artificial dykes. Later, wooden and stone groynes were built perpendicular to the beach in order to obstruct the alongshore sediment transport, which are still in place nowadays. At the Dutch coast, beach and dune nourishments have been a standard coastal maintenance practice since the 1970s. The Dutch national government has actively increased sand volumes at the Delfland coast (Hillen and Roelse, 1995) by the execution of over 20 different sand nourishments in the area (Fig. 3). While early sand nourishments were placed directly onto the beach and the dunes (beach and dune nourishment), from the late 1990s onwards it became more common to place the nourished sand in the subtidal part of the beach

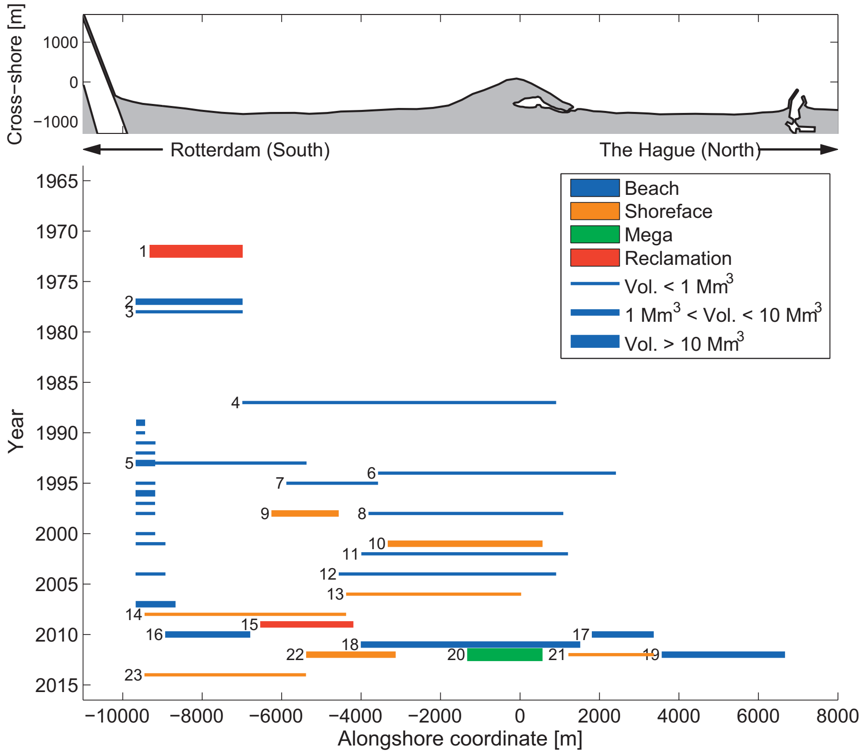

Fig. 3. Overview of all sand nourishments executed at the Delfland coast until 2016 based on nourishment type and nourished volume per alongshore metre of beach. Unnumbered nourishments are considered insignificant and are omitted from further analysis. Nourishment data were obtained from the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat).

profile (shoreface nourishment). A large-scale human intervention took place in 2011, when an experimental mega-scale nourishment (the Sand Motor, Stive et al., 2013) of 17 $\mathrm{Mm^3}$ (9000 $\mathrm{m^3/m}$ alongshore) was implemented at the Delfland coast. The Sand Motor, which originally formed a hook-shaped sandy peninsula, does not only strengthen the beach and dune system locally (Hoonhout and De Vries, 2017; Nolet et al., in press), but also feeds sand to adjacent beaches along the Delfland coast (De Schipper et al., 2016; Luijendijk et al., 2017; Arriaga et al., 2017).

Most of these nourishments were placed at the southern and central parts of the coastal cell, while the northern part (alongshore coordinate >2000 m, Fig. 3) only received its first nourishments after 2010. Several small, localised nourishments near the southern end of the coastal cell are related to sediments dredged from the Rotterdam harbour entrance channel for navigability purposes. Their repetitive character, very limited spatial extent and proximity to the Rotterdam harbour mole obscure the morphodynamic development of the individual nourishments. These nourishments are therefore omitted from further analysis.

3. Methodology

Bathymetric data of the Delfland coast were obtained from the JARKUS dataset. Since 1965, the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) has collected annual cross-shore beach elevation profiles over the full length of the Dutch coastline at fixed intervals of 150–250 m in alongshore direction (Southgate, 2011). The annual surveys are always collected in spring in order to create a consistent dataset and avoid the influence of seasonal fluctuations. An overview of sandbar evolution was created by detecting the crest level and location of subtidal sandbars in the cross-shore profiles. Downward zero crossings of the smoothed first derivative of cross-shore beach elevation were identified as bar crests (Fig. 4, smoothing length scale of 50 m). Only bar crests situated at a water depth between −1.5 m and −7 m with respect to mean sea level (MSL) were accepted for analysis. Subsequently, bar crests identified in individual profiles were linked to nearby bar crests in adjacent profiles to define coherent sandbars with a certain alongshore coverage. Every bar crest was linked to a neighbouring bar crest in alongshore direction, provided that both were <150 m apart and the line connecting the two bar crests made an angle of $< 40^\circ$ with the average coastline orientation. Sandbars with limited alongshore size (i.e. covering < 3 adjacent profiles) were omitted. As an example, the results for five different years are shown in Fig. 5. The bar detection algorithm is able to detect natural sandbars as well as shoreface nourishments appearing in the profile as an artificial sandbar (e.g. the double bar crests in 2006 and 2012, see Fig. 5 panels D and E).

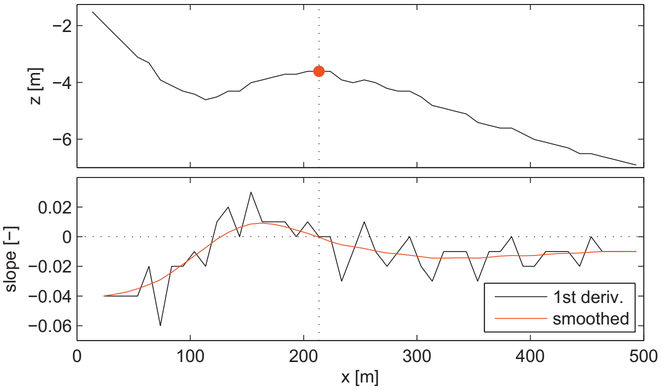

Fig. 4. Demonstration of the bar crest detection method, based on downward zero crossings of the smoothed cross-shore beach slope.

Additionally, alongshore sandbar variability and cross-shore migration rates were determined. Alongshore sandbar variability σ is computed as the root-mean-squared cross-shore bar position within an alongshore window of 1500 m, reading

$$\sigma(y) = \sqrt{\frac{\sum_{w} x_{b,u}^2}{n_w}} \tag{1}$$

where x_b denotes the cross-shore bar crest position (subscript u indicates linear trend removal), w is a sliding 1500 m window in y and n_w is the number of bar crests within w. If a double sandbar is present, which occasionally occurs due to the placement of a shoreface nourishment, values are shown for the inner bar only (the outer bar being the nourishment). Finally, year-to-year bar migration rates were calculated as the difference between the subsequent (in time) cross-shore barcrest positions, a positive migration rate indicating offshore migration. Earlier work in this coastal cell based on monthly surveys showed that sandbar characteristics change relatively slowly (De Schipper et al., 2013), such that surveys of subsequent years can safely be used to follow individual bar development without the risk of aliasing.

4. Observations of sandbar evolution

4.1. Cross-shore evolution

An overview of bar crests detected in the full JARKUS dataset reveals large variations in the presence of sandbars in space and time along the Delfland coast (Fig. 6). The unnourished evolution, which can be observed until 1986, was characterised by the absence of subtidal sandbars along a large part of the coastal cell. At the start of the study period, a subtidal sandbar was only present along the northern half of the coast ($y > -2000$ m). Between 1968 and 1987, the alongshore length of the sandbar gradually decreased from 6 km to 3 km, while the crest level lowered approximately from −3 m to −4 m and the bar moved further offshore (Figs. 7 and 8). The average offshore migration rate of the bar section between $y = 2000$ m and $y = 3000$ m over this period was 5.0 m/year. Although the observed offshore migration did not describe a full cycle including the generation of a new bar near the shoreline, it indicates that the unnourished bar behaviour along the northern part of the Delfland coast was characterised by net offshore migration. This is in line with observations further north along the Dutch coastline at Noordwijk and Egmond (Ruessink et al., 2003; Walstra et al., 2016).

The nourished evolution of subtidal sandbars can be observed from 1987 onwards. Following execution of the first nourishment at the central part of the Delfland coast (nourishment number 4 in Fig. 3), an 8 km-long sandbar was established. This bar expanded 3 km along the coast towards $y = -6000$ m until 1997, coinciding with subsequent beach nourishments in the same area (nourishments 6 and 7). Meanwhile, the sandbar migrated steadily offshore at a rate of approximately 15 m/year. A series of shoreface nourishments between 1998 and 2008 (nourishments 9, 10 and 13) locally and temporarily created double bar systems, one of the bars being the (remnant of the) nourishment. All shoreface nourishments rapidly migrated shoreward at rates ranging between 20 and 60 m/year, thereby forcing the inner sandbar to weld to the beach in the nourished area (an example is presented in Fig. 9). Both ends of the nourishment connected to the adjacent sandbar, effectively taking over the position of the pre-existing bar.

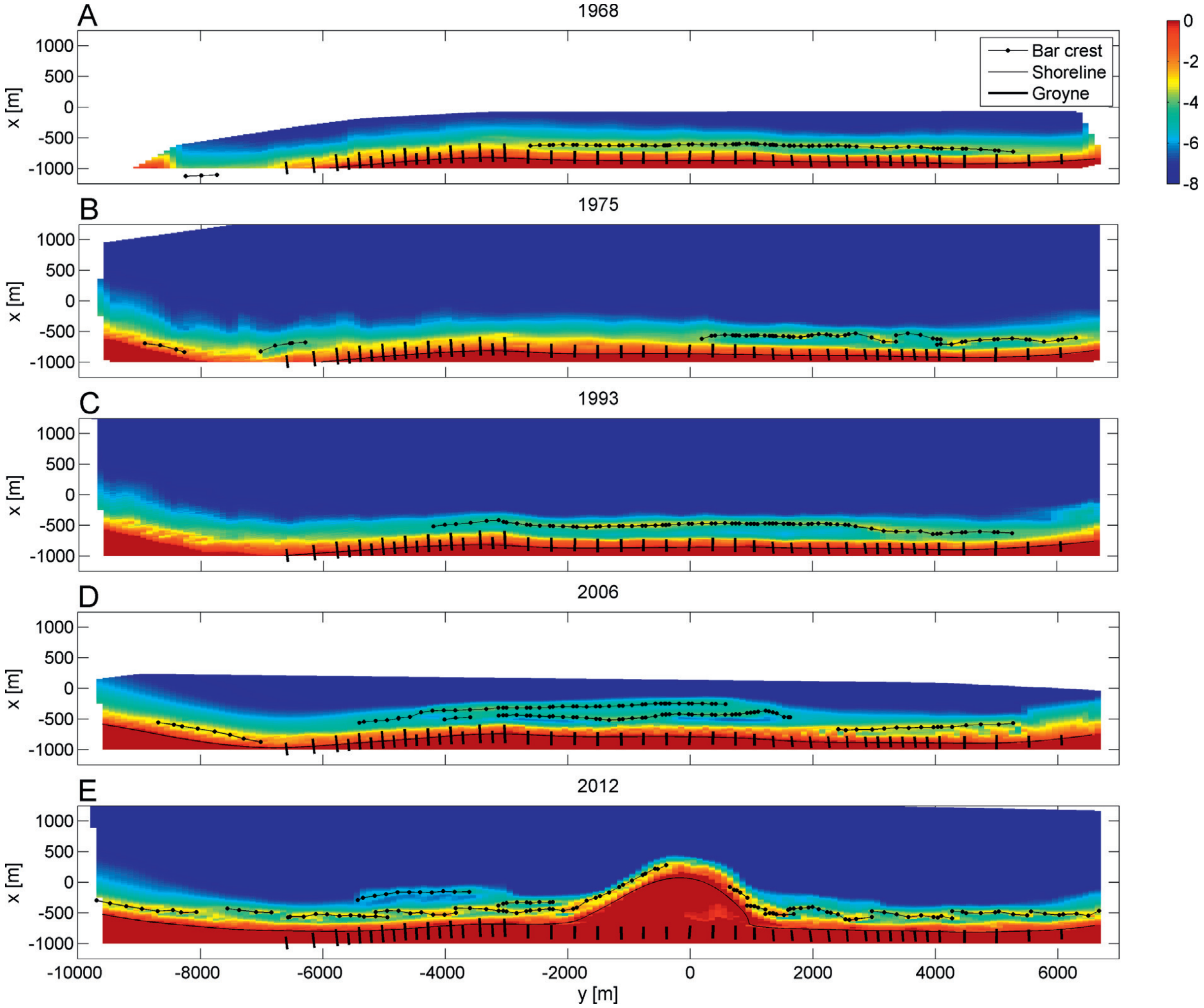

Fig. 5. Five JARKUS surveys including detected sandbars. The shading indicates bed level with respect to the local datum (≈ mean sea level). Detected bar crests, the shoreline and the locations of rubble-mound groynes are indicated with markers and lines (see legend). The local coordinate system is aligned with the average coastline orientation and has its origin at the tip of the Sand Motor.

After 2000, a shallow bar with a crest level around −2.5 m formed in the northernmost part of the coastal cell ($y > 2000$ m). The cross-shore position of this bar was very stable and its crest level persisted around −2.5 m. The first nourishment in the northern part of the domain was only executed in 2010, but the evolution of this sandbar might have been influenced by potential alongshore spreading of nourished sand from the central part of the domain. Therefore its evolution cannot be regarded as strictly unnourished behaviour.

The southern end of the domain was characterised by shallow, dynamic, sandbars with a lifetime of several years, that typically formed after the execution of beach nourishments in the area. Shoreface nourishments (numbers 14 and 23) temporarily created double bar systems for a period of 1–2 years. Similar to the evolution of shoreface nourishments 9, 10 and 13, nourishment 23 rapidly moved onshore.

Between 2009 and 2012, a very large amount of sediment (37.5 Mm^3) was added to the Delfland coast. First, a relatively small land reclamation project was executed between $-7000 < y < -4000$ (nourishment 15), which effectively straightened the local coastline (De Schipper et al., 2013). Shoreface nourishment number 14 was covered by the reclamation project and ceased to exist as a separate sandbar. Subsequently, three large beach (and dune) nourishments were placed, covering a large part of the coastal cell (nourishments 16 through 19). In 2011 the Sand Motor was constructed (nourishment 20, showing in 2012 as construction finished in the second half of 2011), along with two adjacent shoreface nourishments (nourishments 21 and 22). The relatively deep sandbar that had existed in the central part of the domain since the 1987 beach nourishment and the shallower bars at the southern and northern end of the domain were almost entirely covered by the nourished sand. A new, shallow sandbar formed along almost the entire Delfland coast. The cross-shore migration rate of this bar was highly variable in space and time. Shoreface nourishment number 22 migrated landward, albeit at a slower rate (around 20 m/year) than observed previously in that area. The other shoreface nourishment (number 21) was covered soon after its construction by massive sand deposition due to the presence of the Sand Motor. This situation, with a shallow sandbar along the full Delfland coast and onshore migration of shoreface nourishments 22 and 23, persisted until the end of the dataset in 2016.

4.2. Alongshore variability of sandbars

Although most of the subtidal sandbars that were present at the Delfland coast between 1965 and 2016 were relatively straight, alongshore perturbations can be observed at several instances in

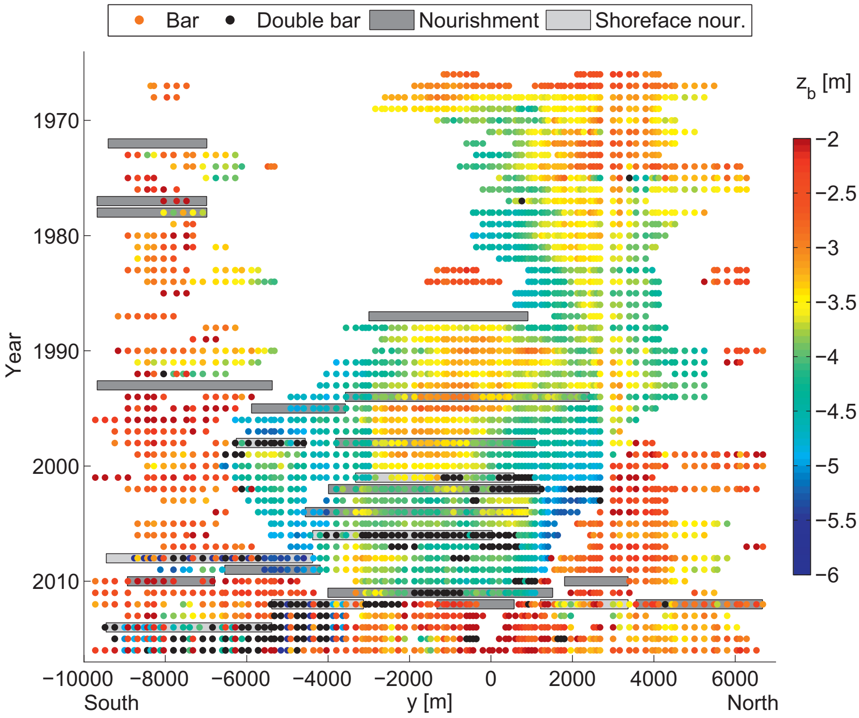

Fig. 6. Occurrence of subtidal sandbars along the 17 km long Delfland coast between 1965 and 2016. Years are shown on the vertical axis, while the horizontal axis represents the alongshore coordinate. Markers indicate the year and alongshore location of barred profiles in the dataset. Shading of the markers indicates bar crest level with respect to the local datum, while black markers indicate the presence of a double sandbar. Execution of nourishments is indicated for reference in grey shading. Irregular alongshore spacing is related to non-constant transect intervals.

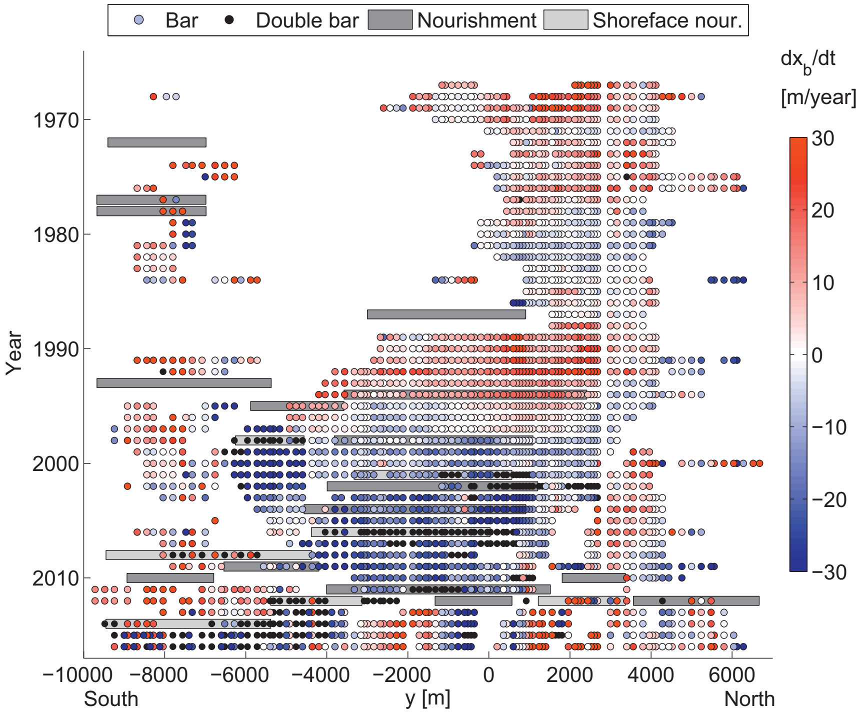

Fig. 7. Five-year averaged cross-shore migration of subtidal sandbars at the Delfland coast, represented by the shaded markers in m/year. Positive migration is offshore directed.

the dataset (Fig. 10, notably the last years). In the mid-1970s, prior to the implementation of nourishments at the central part of the Delfland coast, three-dimensional bar patterns developed at 2000 m $< y <$ 4000 m ($\sigma \sim$ 50 m). The initially straight sandbar attained a crescentic shape in 1974, subsequently broke up in two obliquely oriented sections in 1975 (Fig. 5, panel B) and finally straightened again. Until 2009, alongshore sandbar variability remained fairly limited. Only near the alongshore ends of sandbars and during the onshore

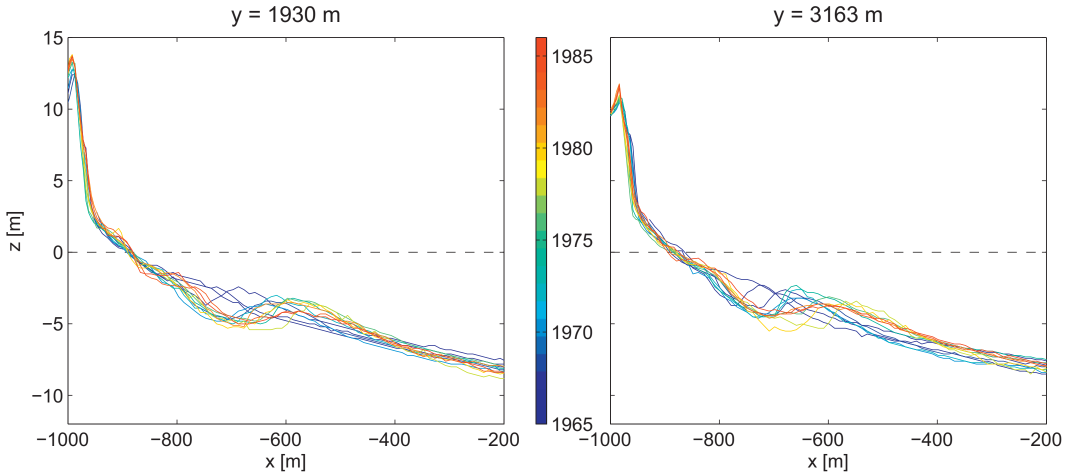

Fig. 8. Gradual offshore migration of the sandbar in the northern half of the domain in two arbitrary profiles, before any nourishments have been carried out along this section of the Delfland coast.

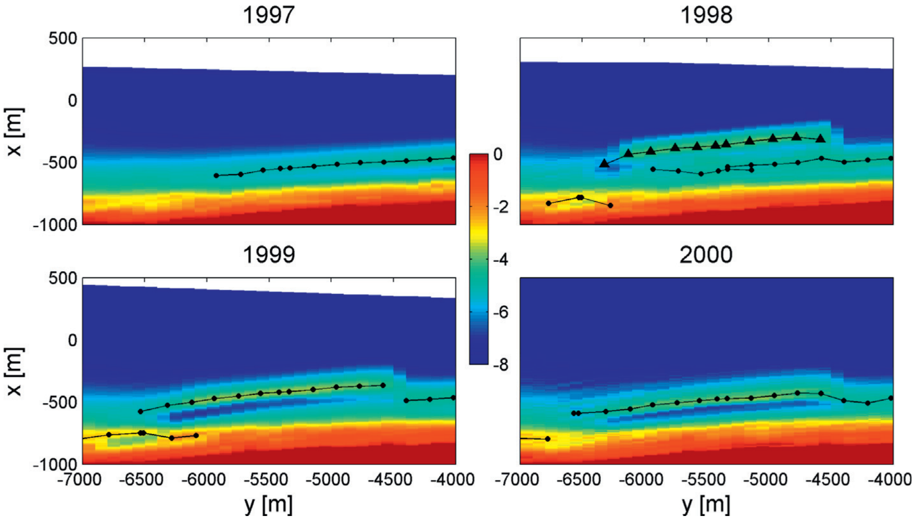

Fig. 9. Morphological development of the 1998 shoreface nourishment (indicated with triangles in 1998), exhibiting rapid onshore migration of the nourishment. Onshore migration of the pre-existing bar is even faster and occurs during less than one year (1998–1999).

merging sequence of shoreface nourishments, moderate variability was observed over a period of several years (e.g. 2004–2006, $y = 1000$ m).

Following the extensive nourishment operations between 2009 and 2012, the system changed drastically. As mentioned before, a shallow nearshore bar was formed along the full Delfland coast, fronted by shoreface nourishments at several locations. This shallow sandbar exhibited a degree of alongshore variability in bar crest position (σ between 20 and 50 m along large parts of the Delfland coast) that was significantly higher than elsewhere in the dataset analysed here (disregarding the mid-1970s event described above, which had a very limited spatial extent). In 2012 several sections of the newly formed sandbar attained an oblique orientation (see Fig. 5, panel E), attaching to the shoreline on one end while creating a gap in the bar crest on the other end at intervals in the order of 1 km. This pattern slightly resembles the discontinuous sandbar observed in 1975, although extending along a much larger part of the coast. Around the connections of the Sand Motor to the adjacent coastline ($y = -1500$ m and $y = 1500$ m), discontinuities were found between the newly formed sandbars at the mega-nourishment and the pre-existing shallow sandbar that borders it. Along the northern half of the Sand Motor, short-scale bar patterns developed with moderate alongshore variability (Radermacher et al., 2017b; Rutten et al., 2017c). Finally, in 2015, the subtidal bar attained a highly pronounced crescentic shape ($25 < \sigma < 60$ m) at $-4000 < y < -500$ m. Based on data obtained from coastal imagery, Rutten et al. (2017b,c) showed that this pattern formed during several weeks of weakly-oblique incidence of energetic waves in the 2014/2015 winter. From high-resolution bathymetric surveys of the Sand Motor (De Schipper et al., 2016), it was confirmed that the dominant scale of these patterns was around 400–500 m. This length scale is adequately represented in the JARKUS dataset, given the relatively dense spacing of survey profiles along that section of the Delfland coast (150–200 m). The presence of such repetitive, pronounced crescentic bar patterns at the Delfland coast did not occur elsewhere in the 50-year analysis period.

5. Discussion

5.1. Unnourished cross-shore sandbar behaviour

The unnourished sandbar behaviour at the Delfland coast was inferred from the observations between 1965 and 1986. A sandbar was only present along a limited section of the coastal cell over this

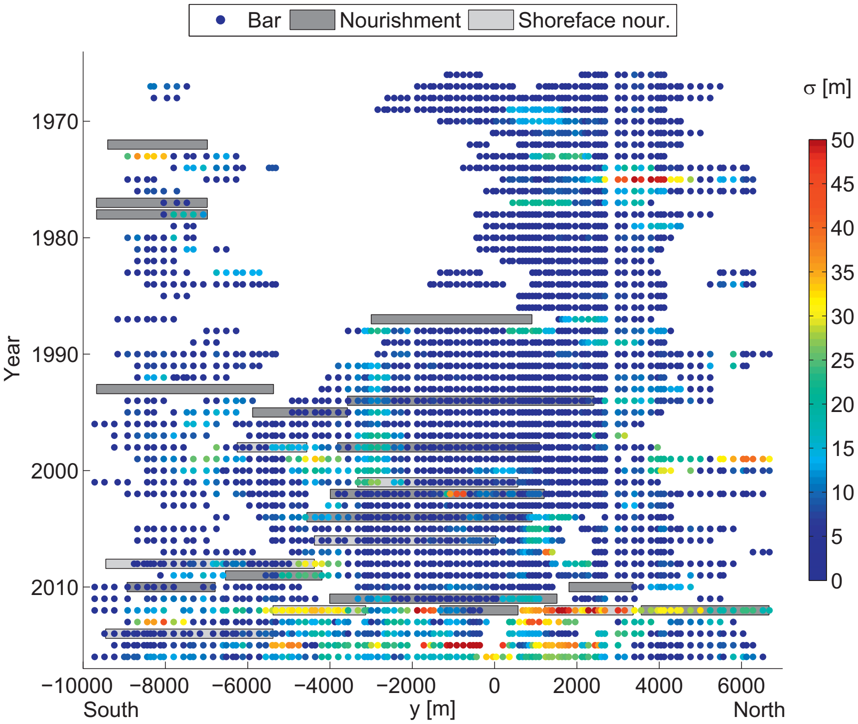

Fig. 10. Alongshore variability of subtidal sandbars at the Delfland coast, represented by the shaded markers.

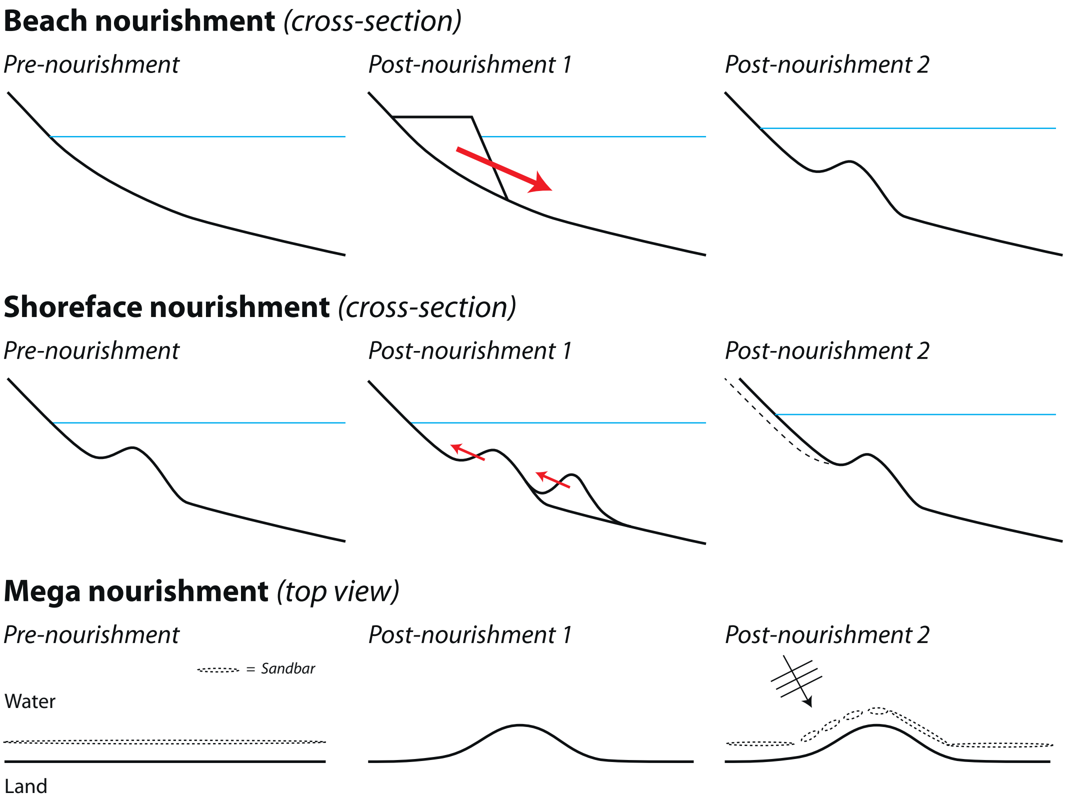

Fig. 11. Schematic overview of the observed impact of different types of nourishments on subtidal sandbar dynamics at the Delfland coast.

period (Fig. 6). These data suggest that the central part of the Delfland coast has a different equilibrium profile shape (unbarred) than the northern part (barred) over this period. While it remains difficult to determine the actual cause of this difference, one potential mechanism can be identified. The harbour of Rotterdam, which protrudes > 4 km into the sea, partly blocks south-westerly waves (Fig. 2).

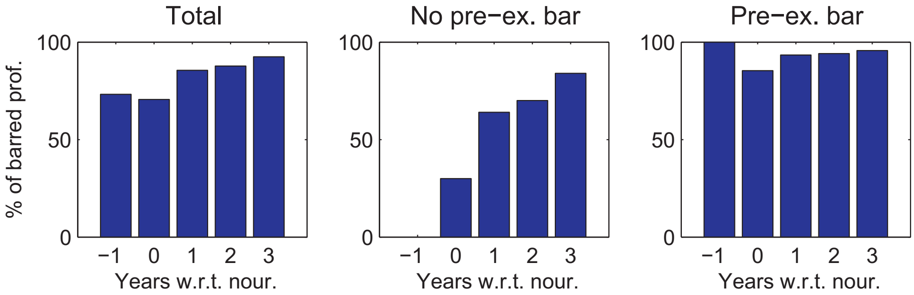

Fig. 12. Percentage of cross-shore profiles with a sandbar in the years before and after a beach nourishment was carried out (nourishment in year 0). The left panel represents statistics over all profiles, the middle panel only includes profiles that were unbarred before execution of the nourishment (year −1, 100% equals 50 profiles), while the right panel only includes profiles that did have a pre-existing bar (100% equals 137 profiles).

This sheltering effect is strongest at the southern end of the Delfland coast and progressively weakens towards the North. The amount of incoming wave energy and the wave obliqueness influence the delicate balance of cross-shore forcing terms that governs sandbar growth and cross-shore migration (Walstra et al., 2012). Therefore, alongshore differences in local wave climate caused by the harbour of Rotterdam may induce alongshore differences in equilibrium profile shape. Similar alongshore differences in sandbar behaviour have been observed at beaches with strong alongshore variations in wave climate due to sheltering by headlands (Wright and Short, 1984; Thornton et al., 2007; Blossier et al., 2016). Alternatively, alongshore differences in cross-shore beach slope can lead to varying sandbar behaviour along a coastline (Tătui et al., 2016). However, alongshore differences in cross-shore beach slope are minor at the Delfland coast and are therefore unlikely to cause the observed differences in sandbar presence. Finally, it may seem plausible that the structurally eroding character of the Delfland coast leads to the occurrence of unbarred profiles in the absence of nourishments. Yet no evidence for such relation was found in scientific literature.

The unnourished bar in the northern half of the Delfland coast was observed to migrate offshore at a very slow rate (Fig. 8). Within the 20-year observation window of unnourished sandbar development, less than one full offshore migration cycle is completed. The offshore migration rate at this part of the coastline is low compared to locations further north along the Dutch coastline. Faster offshore migration has been observed at Noordwijk (period of ~4 years) and Egmond (~15 years) by Ruessink et al. (2003). According to Walstra et al. (2016), the offshore bar migration cycle period is primarily governed by the cross-shore beach slope. A steep profile is characterised by fast initial migration, which slows down drastically as the bar migrates offshore, eventually resulting in a relatively long migration cycle period. The slope of the upper shoreface around $y = 3000$ m is slightly steeper (1 : 80) than the slope at Egmond (1 : 110), which may explain the longer migration cycle period.

5.2. Influence of beach nourishments on cross-shore sandbar behaviour

Over the full period analysed in the present study, 13 beach nourishments were executed. Beach nourishments were found to stimulate the formation of subtidal sandbars (Fig. 11, top row), which is reflected in statistics of sandbar presence in the years surrounding execution of a beach nourishment. When an unbarred profile was nourished, a new bar developed within 3 years in 84% of all cases (Fig. 12, middle panel). If profiles are included that already had a subtidal sandbar before the nourishment, the share of profiles with a sandbar 3 years after the nourishment even rises to 93% (left panel). The formation of a sandbar following execution of a beach nourishment is in line with earlier observations (Benedet et al., 2004; Elko and Wang, 2007; Yates et al., 2009; Roberts and Wang, 2012). In general, beach nourishments are placed around the waterline and typically have a steeper cross-shore slope than the pre-nourishment profile. After execution of the nourishment the beach slope is restored towards the equilibrium situation. The surplus of (nourished) sediment in the upper part of the profile is redistributed in cross-shore direction, leading to sandbar formation.

The crest depth of newly formed bars was variable. The bar in the central part of the domain that formed after nourishment 4 was situated in relatively deep water (bar crest around $z = -4$ m; Fig. 6). The large-scale nourishment scheme carried out between 2009 and 2012 buried the groyne field and the pre-existing subtidal bar, followed by the formation of a relatively shallow sandbar along the entire coastal cell from 2012 onwards (bar crest around $z = -2.5$ m; Fig. 6).

The Sand Motor mega-nourishment (nourishment number 20 in Fig. 3) behaved as a regular beach nourishment in terms of its profile development. A sandbar formed along the entire contour within one year after completion of construction and remained in place until the end of the analysis period.

5.3. Influence of shoreface nourishment on cross-shore sandbar behaviour

In total, 7 shoreface nourishments were placed at the Delfland coast within the study period. The first shoreface nourishments (numbers 9, 10 and 13), as well as the last two (numbers 22 and 23) migrated onshore (Table 1), thereby forcing the pre-existing sandbar to move shoreward and weld to the beach in most cases (Fig. 11, middle row). The onshore migration rates of nourishments 9, 13 and 23 were very high (−62, −39 and −47 m/year respectively in the first year after execution), while the migration rates of nourishments 10 and 22 were lower (−16 and −24 m/year respectively in the first year after execution). Based on these observations alone the cause of this difference cannot be identified, although such spatial differences in cross-shore migration rate and direction of shoreface nourishments have been observed before (Wilmink et al., 2017).

Table 1
Cross-shore migration rates (m/year, positive offshore) of shoreface nourishments over the first years after their implementation; n/a values indicate that sandbar evolution was disturbed by subsequent nourishments or extended beyond the end of the dataset.

Nourishment	Year 1	Year 2	Year 3	Year 4
#9	−62	−58	−28	−32
#10	−16	−12	−20	n/a
#13	−39	−29	−7	−21
#14	n/a	n/a	n/a	n/a
#21	n/a	n/a	n/a	n/a
#22	−24	−17	−25	n/a
#23	−47	−44	n/a	n/a

The observed rapid onshore migration of shoreface nourishments contrasts with reported shoreface nourishment evolution at Noordwijk, Egmond and Terschelling. At these locations, the nourishment and the natural sandbar(s) were found to keep their position or slightly migrate shoreward (Kroon et al., 1994; Van Duin et al., 2004; Grunnet and Ruessink, 2005; Ojeda et al., 2008). Rapid onshore migration of the nourishment was only reported at Bloemendaal in The Netherlands (Lodder and Sørensen, 2015), while onshore welding of the pre-existing bar after implementation of a shoreface nourishment has not been reported before in scientific literature.

The evolution of the other two shoreface nourishments (numbers 14 and 21) was strongly influenced by subsequent large-scale nourishments. The trough landward of nourishment 14 was filled up by the 2009 land reclamation, effectively covering the shoreface nourishment and thereby halting its evolution. Nourishment 21 was placed close to the pre-existing bar at a section of the coastline that was rapidly covered by deposits from the nearby Sand Motor.

The final beach profiles shown in the last column of Fig. 11 are very similar, regardless of the type of the implemented nourishment. This supports the common view that it does not matter where nourished sediment is placed, as long as it stays within the active part of the beach profile (Hamm et al., 2002). Nevertheless, the initial phase following construction of the nourishment may be characterised by different nearshore hydrodynamics and morphodynamics depending on the nourishment type.

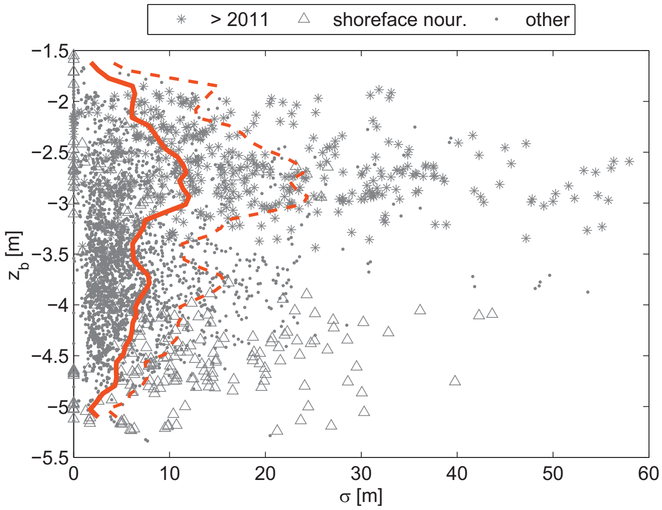

Fig. 13. Comparison of sand bar variability (horizontal axis) and bar crest depth (vertical axis). Data points obtained around the end points of shoreface nourishments have been marked with triangles, while data points obtained after 2011 have been marked with stars. The solid line represents a window-averaged variability in a sliding depth window of 0.25 m (excluding shoreface nourishment data points). The windowed average plus one windowed standard deviation is indicated with a dashed line.

5.4. *Influence of nourishments on alongshore sandbar variability*

The alongshore variability of natural and human-influenced sandbars at the Delfland coast was derived in the previous section (Fig. 10). The unnourished and nourished bar systems between 1965 and 2011 were both largely characterised by straight bars ($\sigma \approx$ 5–10 m). Local increases were only observed around the edges of shoreface nourishments, where discontinuities developed between the nourishment and the adjacent sandbar (Wijnberg and Wolf, 1994; Ojeda et al., 2008). This is in agreement with earlier observations of subtidal sandbars at the Dutch North Sea coastline, which all indicate that bar crest variability is relatively low compared to the distinct, rhythmic, three-dimensional bar patterns that are found at open ocean beaches (Short and Aagaard, 1993; Van Enckevort and Ruessink, 2003; Ojeda et al., 2008; Ruessink et al., 2012; De Schipper et al., 2013; Walstra et al., 2015). After the implementation of extensive beach and shoreface nourishments along almost the entire coastal cell between 2009 and 2012, a degree of alongshore variability arose that was unprecedented in the 50-year study period (Radermacher et al., 2017b).

These results are reflected in a direct comparison of bar crest depth and alongshore variability (Fig. 13). Sandbars were more variable in general from 2011 onwards (stars in Fig. 13), while before that year alongshore variability mainly occurred near the end points of shoreface nourishments (triangles in Fig. 13). If data points obtained near the end points of shoreface nourishments are ignored, it appears that variable sandbars on average had a relatively shallow bar crest depth, while deeper bar crests had low alongshore variability (reflected by the lines in Fig. 13). A possible cause for the emergence of shallow, variable sandbars after 2011 is the burial of groynes by the 2009–2012 beach nourishment operation. Groynes impact hydrodynamics (Scott et al., 2016) and morphodynamics (Short, 1992) in the inner surfzone. Their presence may prevent the formation and evolution of nearshore sandbars, which could lead to the observed differences in sandbar dynamics before and after 2011. The alongshore variable, obliquely oriented bar crests that arose after 2011 resemble observations along the French Mediterranean coast (Aleman et al., 2017). There, this particular bar pattern was linked to alongshore variations in the phase of net offshore sandbar migration. Whether such variations in NOM phase also caused the observed variability at the Delfland coast remains difficult to determine due to the short observation period of these recent bar patterns.

Finally, the formation of crescentic sandbars at the Sand Motor is remarkable. During the first 3 years after construction of the Sand Motor, the alongshore variability of these sandbars remained moderate. However, the patterns that emerged in early 2015 are unique for the Dutch North Sea coastline in terms of their rhythmicity and amplitude. This is confirmed by the fact that these patterns are associated with the highest σ in the entire dataset analysed here (Fig. 10). Rutten et al. (2017a) and Rutten et al. (2017c) found that the Sand Motor mega-nourishment plays an important role in the formation of these patterns. Very large nourishments are associated with changes in the local coastline angle, changing the orientation of the coast with respect to the local wave climate. The wave climate at the Dutch North Sea coast is dominated by southwesterly and northerly waves, both of which correspond with highly oblique wave incidence given the overall orientation of the Delfland coast. In contrast, the curved coastline at the Sand Motor received more normally-incident wave energy, associated with a higher probability of three-dimensional bar pattern generation (Calvete et al., 2005; Price and Ruessink, 2011; Thiébot et al., 2012). As such, very large nourishments may give rise to unprecedented sandbar morphodynamics by locally changing the coastline orientation (Fig. 11, bottom row).

6. Conclusions

The behaviour of sandbars at the Delfland coast has been studied at spatio-temporal scales beyond a single nourishment project, revealing the long-term behaviour of subtidal sandbars along an entire coastal cell, taking into account both the unnourished and nourished regime, and covering various types of nourishments. The results presented in this study imply that individual nourishments can influence the formation and cross-shore migration of individual sandbars, while continued nourishments can fundamentally change long-term presence, cross-shore migration and alongshore variability of sandbars over an entire coastal cell.

It was found that in the unnourished system (first 20 years of the study period), a subtidal sandbar was present in only a part of the coastal cell. This sandbar exhibited net offshore migration at a low average rate. The initial migration rate was high, but slowed down several years after formation of the sandbar. Alongshore variability of unnourished sandbars along the Delfland coast was very low. The unnourished sandbar behaviour at the Delfland coast is consistent with earlier observations further north along the Dutch coastline.

Clearly different sandbar behaviour was observed in the nourished system. Placing nourished sediment at the subaerial beach, as done with regular beach nourishments and mega-nourishments, resulted in the formation of subtidal sandbars. Shoreface nourishments on the other hand, which are typically placed on the seaward face of the pre-existing sandbar, quickly migrated onshore at rates up to 60 m/year, thereby pushing the pre-existing bar onto the intertidal beach. This behaviour is different from most observations of shoreface nourishment development along other parts of the Dutch North Sea coastline, where onshore migration of the nourishment is typically slow or absent.

The alongshore variability of sandbars at the Delfland coast in part depended on the bar crest depth. Sandbars in shallow water were more likely to exhibit three-dimensionality than sandbars in deep water. At the only mega-nourishment in the dataset considered here, subtidal sandbars were found to exhibit high alongshore variability and clear alongshore differences in behaviour. Due to its large size, the mega-nourishment changed the local coastline orientation with respect to the wave climate, leading to different sandbar dynamics compared to the adjacent parts of the Delfland coast.

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