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Morphodynamic response of nearshore bars to a shoreface nourishment

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Abstract

The autonomous nearshore bar behaviour along the barrier island of Terschelling, The Netherlands, is characterised by the presence of net seaward cyclic migrating sand bars generated near the shoreline. In 1993, a perturbation of the cyclic bar system was introduced by the implementation of a 2 Mm^3 shoreface nourishment supplied to the nearshore bar zone, filling up the trough between the middle and outer bar. The morphodynamic response of the nearshore bars to the nourishment perturbation is investigated using a bathymetric data set with an alongshore extent of 12 km and sampled for 10 years. Bar behaviour is quantified in terms of bar crest position in relation to morphometric parameters such as bar depth, height, width and volume. Along with a pronounced development of a three-dimensional bar system unseen in the autonomous behaviour, the nearshore bars exhibited a 6–7 year arrest in their migrational behaviour during which bar morphology remained stable at immediate pre-nourishment morphometric values. At the subsequent onset of bar movement, bars resumed their migration at a rate predicted by autonomous behaviour in parallel development with morphometric parameters along their predicted trends. It is shown that the observed onshore transport of nourished sediment in the 6–7 year arrest results from a gradual deepening of troughs. Cross-shore sediment transport modelling is used to assess the effect of the nourishment on yearly averaged onshore (short-wave nonlinearity) and offshore (undertow) sediment transport rates. The gradual reappearance of the pre-nourishment bar-trough morphology is shown to engender a normalisation in the cross-shore distribution of sediment transport rates to pre-nourishment rates.

Keywords: Nearshore bars; Shoreface nourishment; Coastal morphodynamics; Process-based modelling

1. Introduction

Nearshore bars are reservoirs of sand and modify the response of beaches to variable wave conditions; accordingly, their position and size are expected to have implications for beach behaviour. With the recognition of bars in promoting beach growth and protecting beaches, placement of sand on the shoreface has become common practice in the mitigation of coastal erosion along the sandy shorelines of the North Sea basin, specifically in the Netherlands and

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Denmark (Hamm et al., 2002). In 1993 the NOURTEC shoreface nourishment project (Hoekstra et al., 1994) was carried out at Terschelling in the Netherlands followed by an extensive spatio-temporal monitoring of the response of the nourished bar zone. Three decades of monitored autonomous bar behaviour prior to the implementation of the nourishment at Terschelling offer a unique opportunity to study the morphodynamic response of nearshore bars to a significant perturbation introduced by a shoreface nourishment.

Owing to the implementation of the Terschelling nourishment more than a decade ago, several studies on the morphological response of the nearshore zone have already been reported (e.g. Kroon et al., 1994; Hoekstra et al., 1996; Spanhoff et al., 1997). However, these studies were often based on phenomenological observations of nearshore bathymetric data and were limited to the first 3–4 year development following the nourishment. In an attempt to understand the end effects of the shoreface nourishment, focus was mostly on the volumetric response of the nearshore zone to identify areas of sedimentation and erosion, such as to quantify the intended lee and feeder effects of the nourishment at the shoreline. Processes associated with short-wave nonlinearity have been speculated to be partly responsible for the redistribution of nourished sediment following the nourishment (e.g. Hoekstra et al., 1996). However, no attempts have been made to relate post-nourishment changes in the cross-shore distribution of on/offshore sediment transport fluxes with the redistribution of the nourished sediment across the nearshore zone.

In this paper, we investigate the long-term (years to decade) morphodynamic behaviour of the Terschelling nearshore bars following the shoreface nourishment. The data relates to nourishing the outer trough in a multi-bar system (Section 2). A descriptive overview of the readjustment of the barred system to pre-nourishment behaviour over a 10-year period is presented in Section 3. Morphometric analysis (Section 4) was applied to quantify the post-nourishment cross-shore evolution of bar behaviour in terms of bar depth, height, width and volume. While nearshore profiles gradually recovered their pre-nourishment bar-trough morphology, the redistribution of the nourished sediment was observed to engender a multi-year arrest of bar development subsequently followed by a sudden normalisation in bar behaviour. Apparently, the nourishment disturbed the relative importance of onshore versus offshore sediment transport, at least in the 6–7 years following its implementation. Using process-based numerical simulations, the evolution of the cross-shore balance in on/offshore sediment transport fluxes was explored (Section 5). With these simulations the nourishment-induced changes on onshore versus offshore sediment transport are quantified in an attempt to understand why the nearshore bars suddenly resumed their pre-nourishment behaviour. Finally, our main conclusions are discussed in Section 6.

2. Field site and data gathering

Terschelling is an island along the northern part of the Dutch coast characterised by a chain of barrier islands separating the North Sea from the back-barrier system of the Wadden Sea (Fig. 1). The orientation of Terschelling is roughly WSW–ENE. The central part of Terschelling has retreated by about 2–3 m/year over the last decades (Hoekstra et al., 1994). The study area is situated along this eroding coast between km section 10 and 22 (Fig. 1). Along the study area, the shoreline is slightly curved and concave; the coastline orientation in the study area is about 73°N. The coast consists of sandy beaches and dunes.

The nearshore zone is characterised by the presence of two to three sandbars (see inset in Fig. 1) which behave in a repetitive offshore-directed manner on the time scale of years. The cycle return period is ~12 years (Ruessink and Kroon, 1994; Grunnet and Hoekstra, 2004). The overall nearshore slope between the high-water line (HWL) and the outer margin of the nearshore bar zone at a depth of approximately 8 m below mean sea level (MSL) is about 1:180. The median grain size (D_{50}) varies from 220–260 μm on the intertidal beach to 150–160 μm in the lower shoreface (Guillen and Hoekstra, 1996).

The mean annual significant offshore wave height ($H_{s,o}$) at the −15 m isobath is about 1.1 m and the mean annual significant offshore wave period ($T_{s,o}$) is about 7 s. During storms $H_{s,o}$ increases to 5–6 m

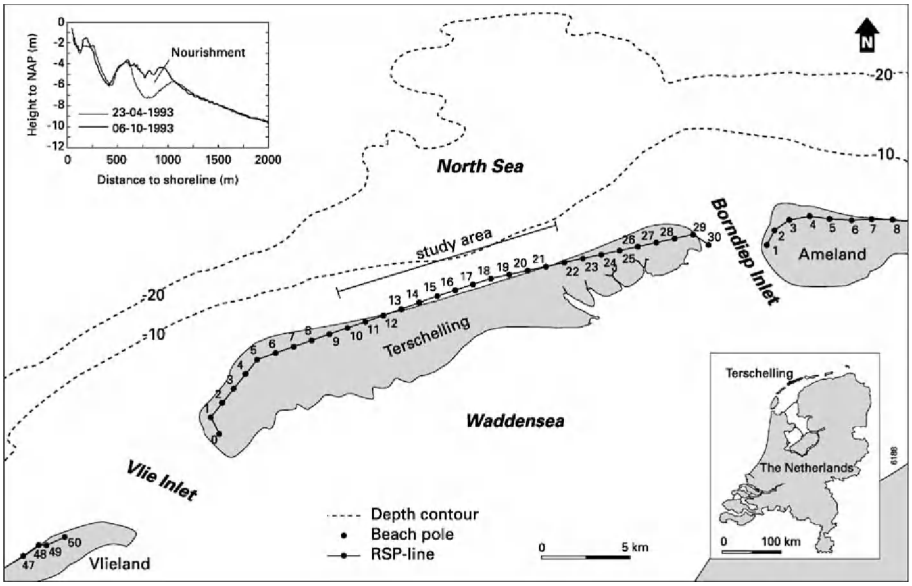

Fig. 1. Location and study area. The cross-shore location of the nourishment is shown in the inset for the profile at km-section 17.

with corresponding $T_{s,o}$ of about 10–15 s. These storm waves are commonly incident from W to NW. Predominant winds are from W, roughly parallel to the coastline. Tides are semidiurnal and mesotidal with a neap tidal range of about 1.2 m and a spring tidal range of about 2.8 m. Tidal flood currents are in the ENE direction and are slightly stronger, but of shorter duration than the WSW flowing ebb currents; tidal current ellipses are oriented parallel to the shore and are almost flat and rectilinear (Hoekstra et al., 1996).

The barrier island of Terschelling is flanked by the Vlie Inlet to the west and the Borndiep Inlet to the east (Fig. 1). Both inlets have ebb tidal deltas extending seaward over 9 and 6 km from the inlet, respectively. Sandwave-like undulations are found on the NE facing part of the Vlie Inlet; the maximum amplitude of these undulations is on the order of 2 m and their alongshore wavelength is nearly constant at about 1 km (Biegel and Spanhoff, 1996). This bar pattern migrates in a southeasterly direction with an average rate of about 500 m/year and eventually makes landfall along the western part of the island, approximately up to section 14. The longshore sediment transport in the nearshore zone is predominantly towards the east; estimates of net yearly averaged longshore transport rates vary from 0.5 to 0.6 Mm^3/year (Tànczos et al., 2001) to 1.0 Mm^3/year (Spanhoff et al., 1997).

To counteract the ongoing erosion along the central part of Terschelling, a shoreface nourishment of 2.1 Mm^3 of sand (D_{50}=200 μm) was carried out in the period from May to November 1993 in the framework of the NOURTEC project (Hoekstra et al., 1994). The nourishment, which filled up the trough between the middle and outer breaker bar in depths of 5–7 m below MSL (see inset in Fig. 1), had a length of about 4.5 km and stretched from km-section 13.7 to 18.2. The amount of nourished sediment was about 450 m^3/m.

The bathymetric data set consists of series of echo-sounding data obtained from two monitoring programmes, the annual JARKUS programme activated on Terschelling since 1965 and the 3-year NOURTEC programme launched in 1993. Within the NOURTEC monitoring scheme, a total of 14 surveys were carried at an approximately 3-month interval from February 1993 to December 1996. In both programmes, surveys lines were oriented perpendicular to a longshore reference line (RSP-line, see Fig. 1) and extended from the foredune to the outer margin of the nearshore bar zone. The soundings were carried out with a longshore spacing of 200 m. The vertical sounding accuracy is estimated at 0.1–0.2 m and the inaccuracy in positioning is up to 10 m (Westlake et al., 1996).

Cross-shore profile data were made equidistant with an interval of 10 m between two consecutive measuring points of depth. In order to yield depth estimates at common cross-shore points, the reference line in each cross-shore profile was set at the +1 m height above MSL (~HWL along the coast of Terschelling). The +1 m contour was preferred over some deeper datum because of its position above the day-to-day fluctuations resulting from short-term phenomena such as swash bars. The +1 m floating datum is hereafter referred to as the shoreline. Consequently, in the following, the nourishment-induced changes in shoreline position are removed from the data set.

3. General data set description

This section presents an overview of 10 years of morphodynamic response of the nearshore zone in relation to 28 years of autonomous behaviour. The overall behaviour of the nearshore zone is analysed in terms of changes in bar migrational patterns, in the alongshore structure of barred features and in shoreline evolution. A more detailed analysis of morphometric bar parameters, such as bar height, depth, width and volume, follows in Section 4.

3.1. Autonomous bar behaviour: 1965–1993

Yearly soundings of the nearshore zone of Terschelling since 1965 have provided data for nearly three decades of autonomous bar behaviour prior to the implementation of the nourishment in 1993. The data show that the long-term nearshore bar behaviour at Terschelling has a cyclic offshore-directed character (Ruessink and Kroon, 1994; Grunnet and Hoekstra, 2004). A bar cycle comprises three distinct stages: bar generation close to the shoreline, offshore migration through the surf zone and degeneration in the outer margin of the nearshore. The cyclicity points to a morphological feedback mechanism in which bar degeneration in the outer nearshore is associated with the onset of net offshore migration of the next shoreward-located bar and the concurrent generation of a new bar near the shoreline. Bars along Terschelling have an oblique orientation relative to the shoreline with an angle of about 3–4°. Despite this obliqueness, coherence of alongshore variation in bar behaviour is found along the 12-km study area (Grunnet and Hoekstra, 2004), and accordingly, the offshore migrational pattern does not result from the alongshore propagation of shore oblique bars. This would, at any given alongshore location, in fact result in an apparent onshore movement of bars. Alongshore increasing surf zone width follows from the bar obliqueness and engenders an alongshore variability in cross-shore bar behaviour. For instance, net offshore cross-shore migration rates gradually increase from 35 to 70 m/year from one end of the study area to the other. The number of bars is constant throughout the study area as the bar cycle regulates itself by adjusting the time of residence during the migrational stage: the duration of net seaward migration concurrently increases from 9 to 15 years. The cycle return period and total life spans of bars are, however, alongshore uniform on the order of 12 and 22 years, respectively.

The nearshore zone of Terschelling is also characterised by a 3-dimensional (3D) structure in alongshore bar shape. Alongshore non-uniformities, such as longshore periodic crescentic bar shapes, originate and are most apparent in the inner nearshore zone and subsequently migrate offshore while migrating alongshore in the eastward direction at a rate on the order of 600–700 m/year, with yearly fluctuations observed in the range 200–900 m. Alongshore wavelengths are about 1200–1500 m (with variations in the range 1000–2000 m) with cross-shore amplitudes on the order of 100 m (with individual amplitudes in the range 80–150 m). The shape of these 3D-features flatten out with increasing offshore distance, accordingly alongshore variability in bar shape characterises the inner bar and to a much lesser extent the middle bar with nearly no variability in the outer bar.

On a larger spatial scale, bars can be discontinuous because of bar switching (Shand et al., 2001). In the case of Terschelling (Grunnet and Hoekstra, 2004), bars become alongshore discontinuous with a well-developed seaward bar on the western side of the discontinuity realigning and joining with a landward bar on the eastern side. Switching episodes can include the outer bar joining the middle bar and the middle bar joining the inner bar; multiple bar realignments have also been observed to occur simultaneously (Grunnet and Hoekstra, 2004).

3.2. Post-nourishment bar behaviour: 1993–2003

At the time of the implementation of the nourishment in 1993 (Fig. 2a), three nearshore bars were present in the study area: the outer bar was degenerating in the seaward margin of the nearshore, the middle bar had been underway for 3–4 years with its net offshore migration through the surf zone, and a new inner bar had emerged near the shoreline. The outer bar in the western part of the study area (km-sections 10–14) originated from a bar switching episode in 1991 (Grunnet and Hoekstra, 2004) in which it temporarily joined the middle bar; by 1993 it had separated from the middle bar and realigned with the adjacent eastern outer bar (km-sections 14–18) resulting in a lowering of the outer bar crest in the centre of the study area. In the years following the nourishment (Fig. 2b–e), the western outer bar became highly 3D as it temporarily bifurcated into 2 bars in 1996 (Fig. 2d) but rejoined in 1998 (Fig. 2e). By 1999 (Fig. 2f), the alongshore migration of this bar resumed at a rate of ~800 m/year. The outer bar in the eastern part of the study area had reached its most seaward position by the time of the nourishment (Fig. 2a) and apparently uninterrupted degenerated while migrating alongshore at a rate of about ~800 m/year (Fig. 2b–f); it eventually vanished from the study area by 1999–2000 (Fig. 2f–g).

In the 4–5 years following the nourishment, the middle bar in the nourished zone (km-sections 14–18) was strongly 3D with the appearance of large-scale drumstick-shaped nearshore bars separated by obliquely oriented rip channels (Fig. 2c); during this period, the middle bar was arrested at its immediate pre-nourishment cross-shore location. By 1999–2000 the middle bar in the nourished zone resumed its offshore migration (Fig. 2f). The 3D development effectively separated the middle bar in a western and eastern part around the centre of the study area in km-section 16. Upon being arrested for 3–4 years, the eastern middle bar pursued its offshore migration with an alongshore-regular shape. In 1998 and 2000 it appeared as if the eastern middle bar would realign itself with the outer bar; however, as the middle bar in the nourished zone resumed its offshore migration, bar switching did not occur. West of the nourishment (km-sections 10–14), the middle bar appeared to be arrested in the inner nearshore throughout the study period (Fig. 2); its alongshore shape evolved from crescentic in the first 3–4 years to more alongshore regular afterwards. In the years following the nourishment (Fig. 2b–c), an eastward migration of the nourished sediment on the order of 400 m/year is observed.

The alongshore-coherent inner bar that had emerged in the years prior to the nourishment was constrained close to the shoreline throughout the study period; the inner bar appeared to be locked in its cross-shore position by the middle bar. The inner bar was highly 3D with an alongshore-irregular shape often characterised as crescentic (e.g. Fig. 2d). At the end of the study period, a more alongshore-coherent regular shape emerged (Fig. 2h).

An illustration of the post-nourishment morphological development of cross-shore profiles is presented in Fig. 3. In a first stage (Fig. 3a), the troughs shoreward of the nourishment quickly filled in, presumably by nourished sediment. In a second stage (Fig. 3b), these troughs slowly but gradually reappeared. A concurrent development of the nourished outer trough is observed: upon a rapid onshore loss of nourished sediment in the first half-year during which most of the nourished sediment welded onto the middle bar, a much slower onshore loss of sediment occurred in the following years. In essence, at first the disturbed bar-trough morphology quickly adjusted itself to the nourishment perturbation (during ~0.5 year) with the reappearance of the outer trough and the filling up of shoreward troughs, then a considerable slowing down (during the next ~6 year period) of the readjustment process followed. Overall, a gradual normalisation towards pre-nourishment profiles occurred as the disturbed bar-trough morphology was restored.

Incidentally, an additional perturbation of the nearshore zone was introduced by the landfall of sandwave-like undulations in the western part of the study area until km-section 14; entering the study area from the west suddenly around 1990, these sandwaves are believed to result from a natural inlet-bypassing mechanism. These undulations reached their maximum amplitude around 1993–1994 and by 2000 vanished from the study area. It is possible that the short-lived 3D development of the outer bar in the western part of the study area (Fig. 2b–d) resulted from the interaction with the sandwaves.

In summary, a pronounced development of a 3D morphological system with bar behaviour unseen in the autonomous situation was experienced as a result

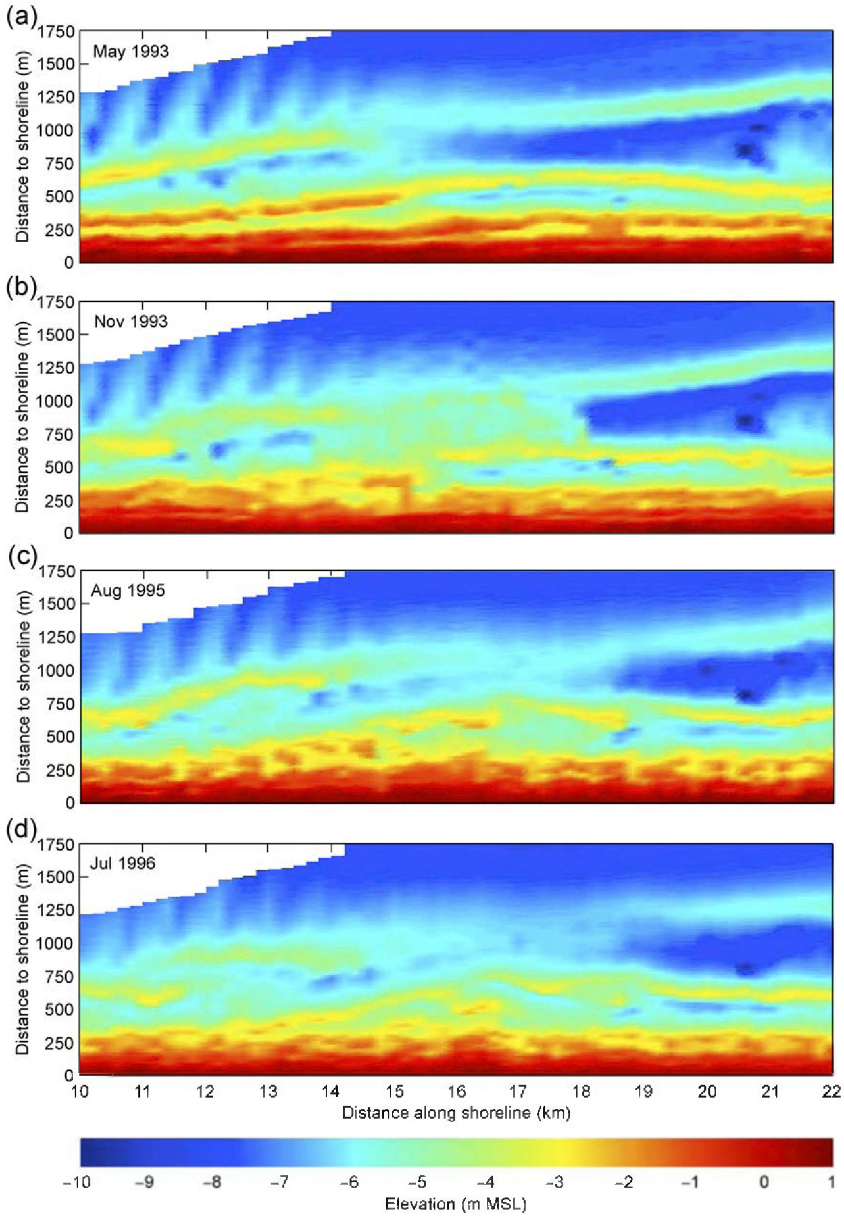

Fig. 2. Plan view of nearshore bathymetry based on NOURTEC and JARKUS surveys: (a) May 1993, (b) November 1993, (c) August 1995, (d) July 1996, (e) April 1998, (f) March 1999, (g) June 2001 and (h) March 2003. Note that cross-shore distance is with respect to the HWL floating datum, i.e. nourishment-induced changes in shoreline position are removed.

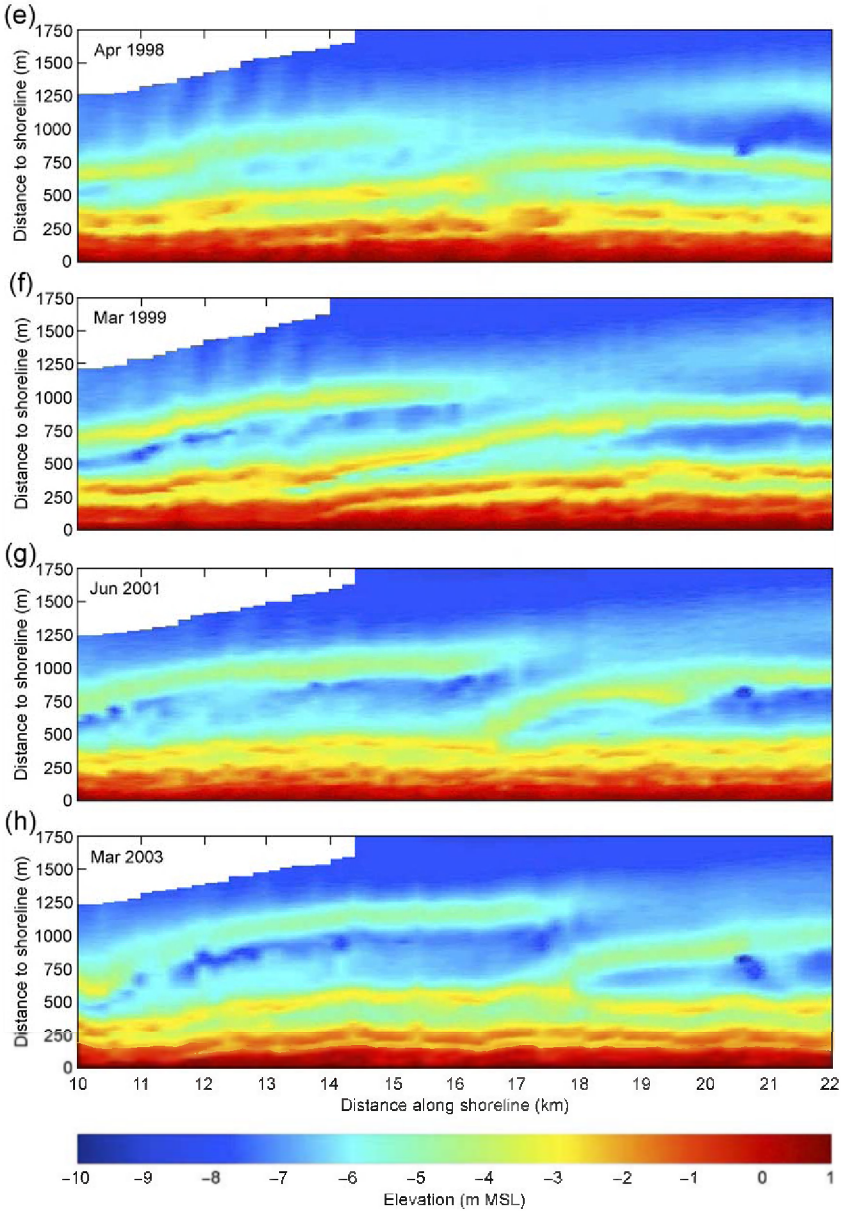

Fig. 2 (*continued*).

of the nourishment in 1993. The impact of the nourishment was strongest shoreward of the nourished zone and consequently significantly perturbed the behaviour of the middle bar. Along with the 3D morphology, the middle and inner bars exhibited a multi-year arrest at their pre-nourishment location; a slow normalisation towards autonomous bar cycle behaviour occurred as the middle resumed its interrupted offshore migration around 1999–2000. In essence, the bar cycle was set back in time for a period of 6–7 years. Only the outer bar appears to have been uninterrupted by the presence of the nourishment.

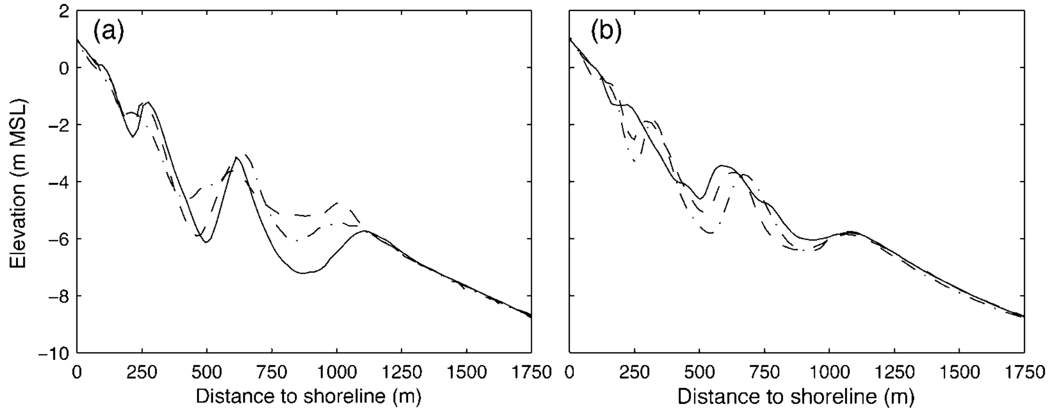

Fig. 3. Depth versus cross-shore distance, here shown for km-section 16 (longshore-averaged over six neighbouring profiles) in (a) May 1993 (solid line), November 1993 (dashed line) and June 1994 (dash-dotted line), and (b) July 1995 (solid line), May 1997 (dashed line) and March 1999 (dash-dotted line).

3.3. Shoreline response

The implementation of the nourishment also affected shoreline evolution. The autonomous long-term retreat of the shoreline at a rate of ~3 m/year was reversed into a shoreline advance at an average rate of ~15 m/year, shown for the central part of the nourishment in Fig. 4. The effect of the nourishment on the shoreline was strongest shoreward of the nourishment with a concurrent eastward migration of this effect on the order of 400 m/year (Fig. 5). By 2000, some 6–7 years after the nourishment was implemented, the shoreline resumed its pre-nourishment ~3 m/year retreat. Interestingly the landfall of the sandwave-like undulations changed the shoreline evolution in a similar way as the nourishment did. The advance of the shoreline in km-sections 10–14 was of comparable magnitude to that in the nourished zone in km-sections 14–18 (Fig. 5).

The volumetric effect of the nourishment on the beach area has been reported in the literature (e.g. Hoekstra et al., 1996; Spanhoff et al., 1997; Hamm et al., 2002). Herein, it follows that a number of trends in the first 3–4 years following the nourishment were very consistent: the nourishment area clearly eroded and the areas landward accreted at about twice the rate the nourishment was eroding; at the end of the third year, ~40% of the total gain of sediment in the inner nearshore could be accounted

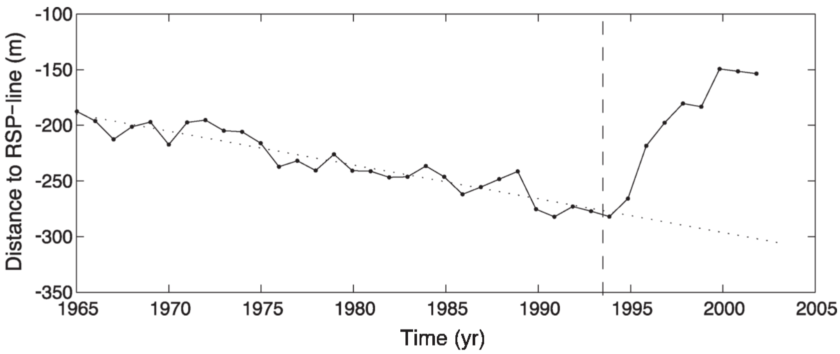

Fig. 4. Cross-shore position of the HWL shoreline at km-section 16 (longshore-averaged over six neighboring profiles) versus time. Also given is the autonomous trend (dotted line) of the shoreline retreat prior to the implementation of the nourishment (dashed line).

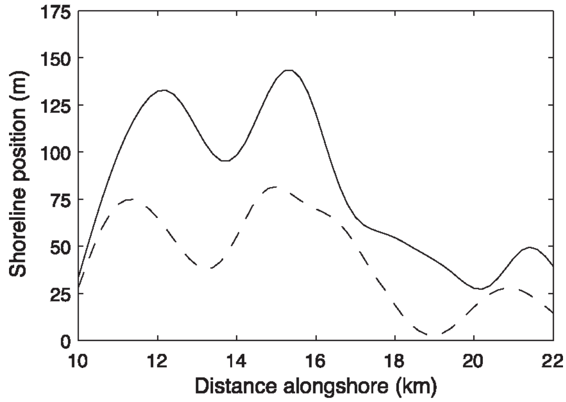

Fig. 5. Change in shoreline position with respect to the pre-nourishment shoreline of May 1993 versus alongshore distance, here shown for May 1997 (dashed line) and May 2000 (solid line).

for by direct losses in the nourished zone. Consequently, the success of the nourishment in promoting beach growth was not only attributed to the onshore movement of the nourished sediment, but accretionary processes in relation to gradients in longshore sediment transport appeared to be of equal importance.

4. Nourishment effects on cross-shore profile development

4.1. Methodology

In autonomous profile development, at each alongshore position a cross-shore profile is composed of a mean (in time) profile and perturbations around this mean related to the evolution of the bar-trough morphology. Upon nourishing the shoreface, an additional perturbation is introduced. In the following, a clear distinction is made between the bar-related perturbations and the nourishment-induced perturbation.

Bars are usually defined as perturbations to an underlying smooth profile with cross-shore positions identified at the location of the maximum perturbations. In the literature, an underlying smooth profile is often derived as a time-averaged mean profile over an undisturbed period; at Terschelling, a 28-year data set of autonomous behaviour provides adequate data to derive such a mean profile (Ruessink and Kroon, 1994; Grunnet and Hoekstra, 2004). Upon introducing a nourishment perturbation in the nearshore zone, the underlying profile to which bar-related perturbations relate becomes time dependent: the underlying profile is composed of the spatio-temporal evolution of the nourishment perturbation superimposed to the time-averaged mean profile. A filter was designed to create such a time dependent profile aiming at removing barred features from the profile but including the nourishment perturbation. This time dependent mean profile is henceforth referred to as a non-barred profile; the time-averaged mean profile is based solely on the autonomous pre-nourishment data.

The cross-shore profile data were low-pass filtered with a Hanning filter with filtering properties controlled by a smoothing scale parameter λ_x (Plant et al., 2002), where x denotes cross-shore distance (x=0 at the shoreline). Here, bar width, as determined from the autonomous behaviour by Grunnet and Hoekstra (2004), was taken as λ_x. The cross-shore distribution of λ_x (Fig. 6), which is alongshore constant (Grunnet and Hoekstra, 2004), increases with increasing distance offshore until the outer margin of the nearshore zone. Outside the bar zone, λ_x was reduced to zero over a relatively short distance (~250 m); the resulting non-barred profiles were not very sensitive to the precise shape of the λ_x reduction to zero.

The similarities and differences between the non-barred and time-averaged profiles are illustrated for an autonomous and nourished profile in Fig. 7. As

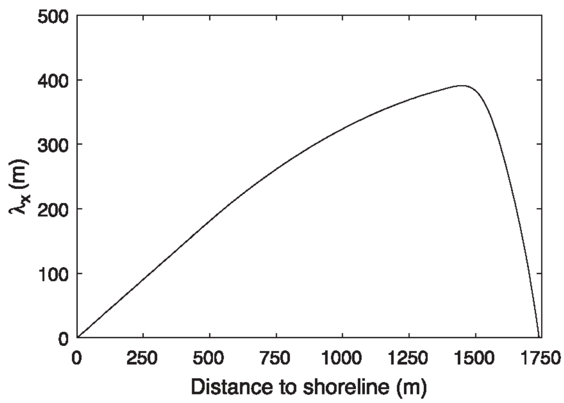

Fig. 6. Smoothing scale versus cross-shore distance.

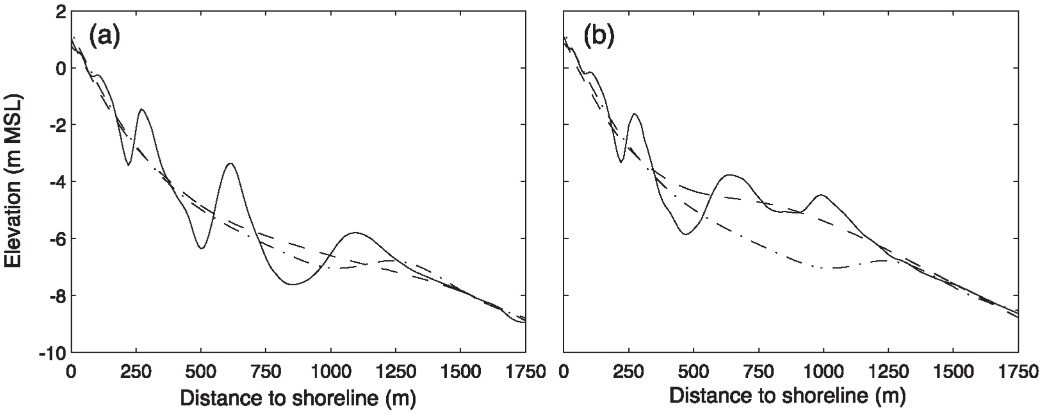

Fig. 7. Measured profile (solid), non-barred profile (dashed line) and 28-year mean profile (dash-dotted line) versus cross-shore distance, here shown for km-section 17 in (a) May 1993 and (b) November 1993.

can be seen in Fig. 7a, the non-barred and time-averaged profiles are about the same in the autonomous case, except in the outer bar area where the time-averaged profile shows a small bar-trough relief of ~0.4 m; recall that the non-barred profile is based on low-pass filtering (Fig. 6) of the shown barred profile, whereas the time-averaged profile is based on 28 years of annual survey data. The difference between the non-barred and time-averaged profiles is, obviously, larger after the implementation of the nourishment (Fig. 7b). In the example, the non-barred profile contains the nourishment between ~400 and 1250 m from the shoreline and is identical to the time-averaged profile further onshore and offshore. With the non-barred profile it is possible to detect the middle bar near ~600 m and the outer bar at ~1000 m from the shoreline. This detection fails with the time-averaged profile as there is now no negative perturbation (trough) separating both bars.

Subtracting a non-barred profile from a surveyed profile results in the bar-trough perturbations. From these perturbations a number of morphometric parameters were computed, as outlined in Fig. 8. The parameters include the bar crest position P_b with respect to the shoreline, the depth of bar crest d_b below MSL, the bar height h_b, the bar width W and the bar volume V. Bars with h_b<0.3 m (~order of sounding accuracy) and bars located within the intertidal zone (i.e. with d_b<1 m) were culled from the analysis.

To average out over alongshore non-uniformities, morphometric parameters per bar were alongshore averaged for six 2-km alongshore windows: A (km 10–12), B (km 12–14), C (km14–16), D (km 16–18), E (km 18–20) and F (km 20–22). Each window includes 11 cross-shore survey transects. Despite the increased 3D character of the nearshore zone following the nourishment (e.g. Fig. 2c and d), the response exhibited by the bars was largely alongshore-coherent: in addressing the morphological response of bars on the order of km, along shore uniformity is described by a shore-parallel morphodynamic behaviour of bar morphology.

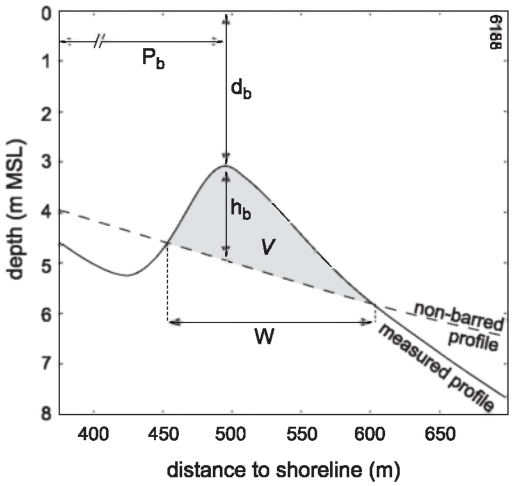

Fig. 8. Definition of morphometric parameters.

4.2. Results

To quantify the magnitude of the perturbation in bar morphology and migrational pattern, the post-nourishment behaviour is related to characteristic trends derived from autonomous bar behaviour. Focus is on the response of the middle bar because systematic offshore migration is the dominant type of behaviour exhibited at the time of the implementation of the nourishment.

4.2.1. Morphometric analysis

The window-averaged P_b of the middle bar are presented in Fig. 9 as a function of time. Evidence of a change in behaviour is apparent west of the nourishment (windows A and B) and in the nourishment area (windows C and D) in causing a multi-year arrest of the bar migration pattern. Despite a similar behaviour in these two areas, a causal association with the presence of the nourishment is unlikely to have perturbed the area updrift of nourishment, since as mentioned earlier, the perturbed behaviour in this area coincides with the appearance of sandwaves in 1990–1993. Following the onset of net offshore migration around 1989–1990, the middle bar in the nourishment area was migrating at a rate on the order of 60–70 m/year. From the time of the implementation of the nourishment in 1993 and 6–7 years onward, the middle bar did not move; only by 1999–2000 did the middle bar resume its migrational pattern and interestingly, at the same rate as prior to the nourishment. East of the nourishment (windows E and F), only a negligible perturbation of the migrational pattern is observed: the reduction of the migration rate for a couple of years following the nourishment corresponds to the order of magnitude of the observed natural variability. The nourishment-induced perturbation in bar migration cycle appears only to be significant in the nourished km-sections 14–18, subsequently the effect on bar morphology will focus on the nourished windows C and D. As can be inferred from Fig. 2 in km-sections 14–18, a similar development in migrational pattern is exhibited by the inner bar, probably

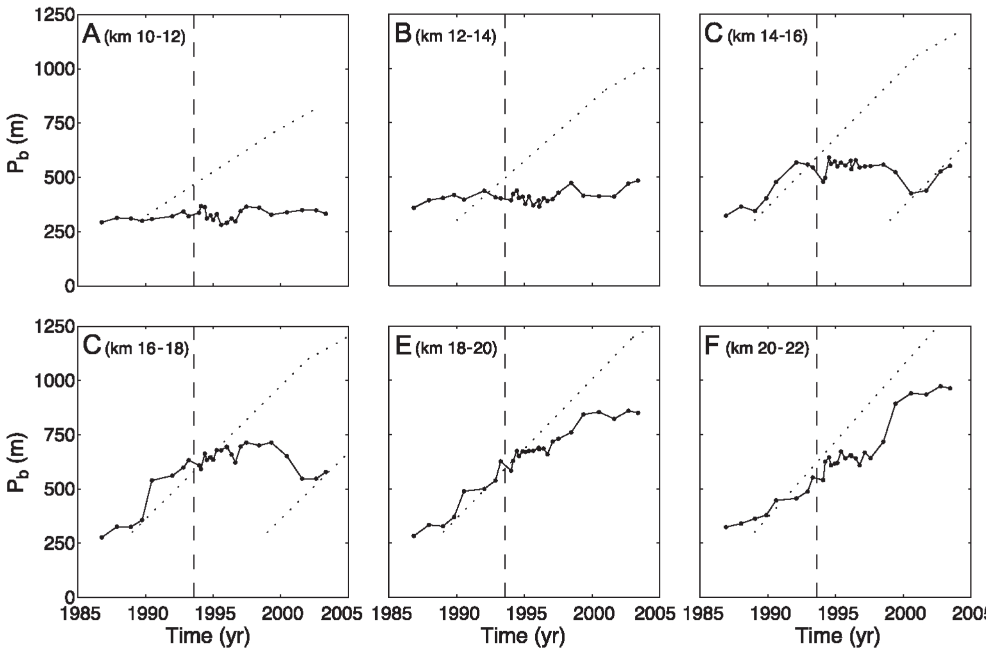

Fig. 9. Window-averaged cross-shore position P_b of the middle bar versus time (solid line and symbols) for windows A–F, respectively. The dotted lines indicate the projected net seaward migration of the middle bar estimated from the 28-year data of autonomous bar behaviour (Grunnet and Hoekstra, 2004). The vertical dashed lines indicate the time of the implementation of the nourishment.

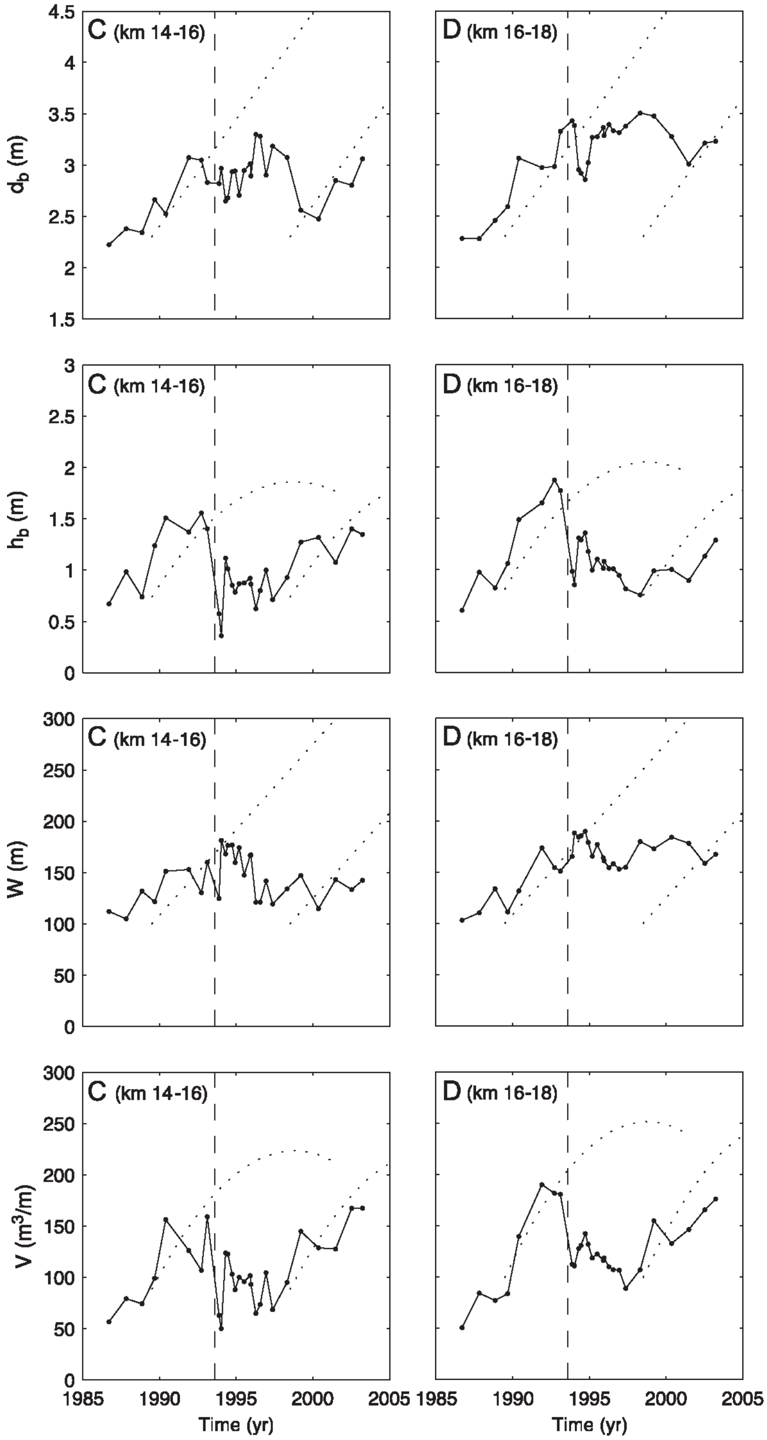

Fig. 10. Morphometric parameters of the middle bar versus time; from top to bottom: depth, height, width and volume for window C (left column) and window D (right column), respectively. The dotted lines indicate the projected behaviour of the middle bar estimated from the 28-year data of autonomous bar behaviour (Grunnet and Hoekstra, 2004). The vertical dashed lines indicate the time of the implementation of the nourishment.

as a result of the temporary cross-shore arrest of the middle bar.

A significant change in the temporal development of all other morphometric parameters of the middle bar followed after the implementation of the nourishment (Fig. 10). Clearly, the multi-year arrest in P_b engendered a parallel development in bar morphology. The effect of the perturbation was particularly strong on h_b: following an immediate reduction of ~70%, h_b stabilised around half its pre-nourishment height at ~0.75 m across km-sections 14–18; this height remained the same for 6–7 years, after which h_b resumed its projected autonomous development. Similarly V showed a rapid initial decrease followed by a stabilisation around 100 m^3/m, corresponding to ~2/3 of its pre-nourishment value; V also resumed its projected autonomous development after 6–7 years. After an initial strong reduction in bar crest depth, d_b remained at its pre-nourishment value of ~2.75 (3.25) m in km-sections 14–16 (16–18) the following 6–7 years. Bar width also exhibited a ~70% reduction across km-sections 14–18, again for a period of 6–7 years before eventually resuming its pre-nourishment development. During the 6–7 years, in which bar parameters did not change notably, the variability of each of the morphometric parameters around their new trend appeared to be on the same order of magnitude as the natural variability observed prior to the nourishment. It is noticeable that all morphometric parameters upon having been stable for 6–7 years resumed their development virtually following their expected pre-nourishment trend. It appears that bar development was simply postponed for a period of 6–7 years.

4.2.2. Redistribution of nourished sediment

The evolution of the nourishment-induced changes in profile response was obtained by quantifying horizontal excursions of non-barred profile changes as a function of depth. The resulting vertical distribution of profile changes is presented in Fig. 11 for successive characteristic periods of the nearshore profile response. Upon the initial advance in depths of −4 to −8 m (in total ~450 m^3/m) resulting from the implementation of the nourishment in the period May–November 1993 (Fig. 11a), a redistribution of ~50% of the nourished sediment upwards in the profile took place over the following 3 years (Fig. 11b with maximum advance (retreat) on the order of 19 (35) m/year in depths of 2–3 (5–6) m), eventually followed by a somewhat slower retreat of the entire profile over the next 6 years (Fig. 11c with maximum retreat on the order of 20 m/year in depths of 5–6 m). Following a decade of profile readjustment, the shape of the non-barred cross-shore profile was by 2003 in essence equal to the shape of the pre-nourishment time-averaged profile.

The tilting of the profile around a pivotal point located at a depth of about 4 m (with profile advance above and retreat below, Fig. 11b) and the subsequent overall retreat of the profile (with maximum retreat at nourishment depths of 4–7 m, Fig. 11c) appear to be two distinct stages in the response of the nearshore profile to the nourishment

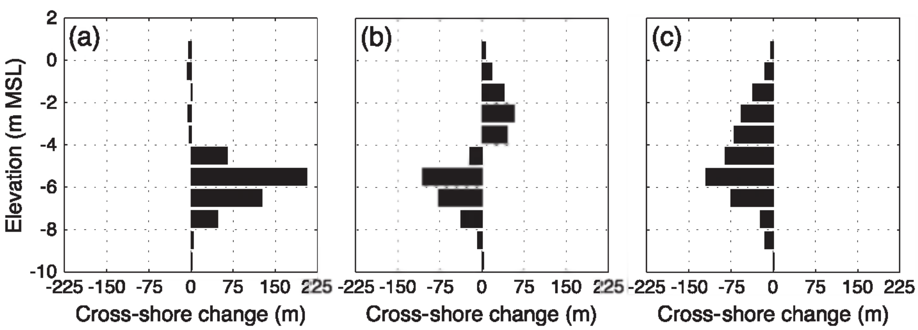

Fig. 11. Vertical distribution of non-barred profile changes for nourished sections C and D (longshore-averaged over km-sections 14–18): (a) May 1993 to November 1993, (b) November 1993 to May 1997, and (c) May 1997 to July 2003.

perturbation. Note that the cross-shifting of the shoreline has been removed from the non-barred profiles, thus the advance of the shoreline with corresponding gain of sediment in the inner nearshore is not accounted for in the non-barred profiles. In each of these stages, the relative influence of cross-shore versus longshore transport processes in the redistribution of nourished sediment is suggested by the response of the profile. In the first stage, onshore transport processes appear to dominate with a subsequent shoreward deposition of eroded sediment in what appears to be essentially a cross-shore redistribution of sediment within the profile. In the second stage, however, longshore transport processes appear to dominate as erosion occurs across the entire profile. The observed alongshore migration of the nourishment on the order of 400 m/year to the east (Fig. 2b–c) is consistent with the relative dominance of longshore transport processes in the second stage.

5. Modelling of yearly onshore and offshore sediment transport

In the previous section it was shown that the nourishment interrupted the interannual offshore-directed bar cycle for some 6–7 years; during the same period, a considerable portion of the nourished sand moved to shallower depths. Ruessink and Terwindt (2000) hypothesized that the net offshore migration of the middle bar was associated with a dominance of yearly offshore transport (q_{off}) over onshore transport (q_{on}). Apparently, the nourishment disturbed the relative importance of q_{on} and q_{off}, at least in the 6–7 years following its implementation. In this section we quantify this suggestion using version 2.04 of the process-based numerical simulation model UNIBEST-TC (e.g. Van Rijn et al., 2003) developed by WL|Delft Hydraulics.

5.1. Model description and set-up

The process-based cross-shore profile (2DV) model UNIBEST-TC includes the morphodynamic coupling of bathymetry, wave-averaged hydrodynamics and cross-shore sediment transport. A full description of the model can be found in Bosboom et al., (1997); a detailed description of the wave and current modules can be found in Reniers and Battjes (1997) and Reniers et al. (2004), respectively. Here we focus very briefly on the sediment transport formulations.

In UNIBEST-TC the sediment transport flux $q(x,t)$ is the sum of the bedload flux $q_{\mathrm{bed}}(x,t)$ and the current-related suspended load flux $q_{\mathrm{s,c}}(x,t)$, where t is time. The bedload flux, computed following Ribberink (1998), comprises contributions to the (1) non-linear short-wave orbital motion estimated with the stream function theory of Rienecker and Fenton (1981), (2) bound infragravity orbital motion based on the method of Sand (1982), and (3) near-bed (=1 cm) mean currents based on Reniers et al. (2004). In practice, short-wave nonlinearity dominates q_{bed}. The suspended load flux is computed as the product of the vertical profiles of the cross-shore mean currents (Reniers et al., 2004) and the concentration (Van Rijn et al., 2003). Because the currents are offshore directed, we can state that $q_{\mathrm{off}}=q_{\mathrm{s,c}}$ and $q_{\mathrm{on}}=q_{\mathrm{bed}}$. All free model parameters were set to values based on studies in similar southern North Sea coastal environments (Van Rijn et al., 2003).

Five simulations were run, each with different bottom profiles, corresponding to the pre-nourishment survey of May 1993 and four successive post-nourishment surveys carried out in November 1993, July 1995, May 1997 and March 1999, respectively (see former Fig. 3). These surveys were chosen in order to follow the temporal changes in cross-shore transport patterns during the 6–7 year readjustment period of the disturbed bar-trough morphology; the last survey is March 1999 as the bars resumed their offshore migration around 1999–2000.

The offshore boundary conditions (wave height, period and direction, water level, wind speed and direction) in each run were identical and are the hourly sampled values from November 1993 up to and including October 1994; details on data acquisition and processing can be found in Ruessink et al., (1998). In this period, several storms with $H_{\mathrm{s,o}}$>3 m, occasionally with wave heights on the order of 5–6 m, occurred at the nourishment site immediately following the implementation of the nourishment. Van Beek (1995) found that the wave conditions in the first post-nourishment year did not statistically differ from a 10-year period prior to the nourishment. The selected 1-year simulation period is thus representative of yearly conditions normally encountered at the Terschelling site. No morphological bed-update was done during each run. Note that there are two-time scales: the hourly forcing time scale t and the slower morphological (survey) time scale, henceforth denoted $\bar{t}$.

5.2. Quantifying changes in transport patterns

The part of the profiles included in the sediment transport analysis was delimited by external boundaries corresponding to the −1 and −8 m contours, denoted x_{shore} and x_{sea}, respectively. The bounded profiles were subsequently divided into three cross-shore sections corresponding to the inner, middle and outer bar, respectively. Internal boundaries delimiting barred sections were derived from the deepest location of the inner and outer trough, respectively; internal boundaries were thus cross-shore varying following the development in bar-trough morphology.

For each survey, the yearly averaged onshore and offshore sediment transport rates were computed as

$$\bar{q}_{\mathrm{on}}(x,\bar{t}) = \frac{1}{N_t}\sum_{t=1}^{N_t} q_{\mathrm{on}}(x,t)$$

$$\bar{q}_{\mathrm{off}}(x,\bar{t}) = \frac{1}{N_t}\sum_{t=1}^{N_t} q_{\mathrm{off}}(x,t) \tag{1}$$

respectively, where N_t (=8760) is the number of timesteps in the simulation period. To relate the nourishment-induced changes in $\bar{q}_{\mathrm{on}}(x,\bar{t})$ and $\bar{q}_{\mathrm{off}}(x,\bar{t})$ to pre-nourishment transport rates, $\bar{q}_{\mathrm{on}}(x,\bar{t})$ and $\bar{q}_{\mathrm{off}}(x,\bar{t})$ were normalised as

$$\bar{q'}_{\mathrm{on}}(x,\bar{t}) = \frac{\bar{q}_{\mathrm{on}}(x,\bar{t})}{\int_{x_{\mathrm{sea}}}^{x_{\mathrm{shore}}} \bar{q}_{\mathrm{on}}(x,\bar{t}_{\mathrm{o}})\mathrm{d}x}$$

$$\bar{q'}_{\mathrm{off}}(x,\bar{t}) = \frac{\bar{q}_{\mathrm{off}}(x,\bar{t})}{\int_{x_{\mathrm{sea}}}^{x_{\mathrm{shore}}} \bar{q}_{\mathrm{off}}(x,\bar{t}_{\mathrm{o}})\mathrm{d}x} \tag{2}$$

respectively, where t_{o} denotes the pre-nourishment conditions in May 1993. Finally, normalised onshore and offshore transport ratios were computed for each section bounded by x_1 and x_2 as

$$n_{\mathrm{on}}(\bar{t}) = \frac{\int_{x_1}^{x_2} \bar{q}_{\mathrm{on}}(x,\bar{t})\mathrm{d}x}{\int_{x_1}^{x_2} q_{\mathrm{on}}(x,\bar{t}_{\mathrm{o}})\mathrm{d}x}$$

$$n_{\mathrm{off}}(\bar{t}) = \frac{\int_{x_1}^{x_2} \bar{q}_{\mathrm{off}}(x,\bar{t})\mathrm{d}x}{\int_{x_1}^{x_2} q_{\mathrm{off}}(x,\bar{t}_{\mathrm{o}})\mathrm{d}x} \tag{3}$$

respectively. In this way $n_{\mathrm{on}}(\bar{t}_{\mathrm{o}})=n_{\mathrm{off}}(\bar{t}_{\mathrm{o}})=1$. For other $\bar{t}$, an increase (decrease) in n implies an increase (decrease) in the yearly averaged sediment transport rate. For instance, $n_{\mathrm{on}}=1.5$ implies that in the cross-shore section bounded by x_1 and x_2, the yearly averaged onshore transport rate has increased by 50% compared to the pre-nourishment $\bar{t}_{\mathrm{o}}$ situation.

5.3. Readjustment of transport patterns

The evolution of normalised transport rates versus cross-shore distance is presented in Fig. 12 alongside with readjusting bottom profiles with increasingly pronounced bar-trough morphologies; corresponding transport ratios are quantified in Table 1. Following the implementation of the nourishment, the distribution of $\bar{q'}_{\mathrm{on}}$ and $\bar{q'}_{\mathrm{off}}$ in both the inner and middle bar areas (Fig. 12) become less peaked: while $\bar{q'}_{\mathrm{on}}$ broadens, $\bar{q'}_{\mathrm{off}}$ reduces. In the outer bar area, however, the distribution of $\bar{q'}_{\mathrm{on}}$ and $\bar{q'}_{\mathrm{off}}$ both become more peaked. The magnitude of these changes in $\bar{q'}_{\mathrm{on}}$ and $\bar{q'}_{\mathrm{off}}$ with respect to pre-nourishment conditions in May 1993 are observed to reduce with time. An overall trend for all cross-shore sections is observed in Table 1: upon an initial strong response to the nourishment, both n_{on} and n_{off} are converging to unity in the following years. This convergence is specifically pronounced in the outer bar area: the initial increase in both onshore and offshore transport in November 1993 rapidly reduced to near pre-nourishment values; by July 1995, n_{on} had decreased from 1.17 to 1.04 and n_{off} from 1.56 to 1.09, and by March 1999 further decreased to 1.01 and 1.02, respectively. In the middle bar area, upon a similar rapid adjustment by July 1995, a normalisation to pre-nourishment conditions occurred at a slightly slower rate: by March 1999, the initial increase (decrease) in

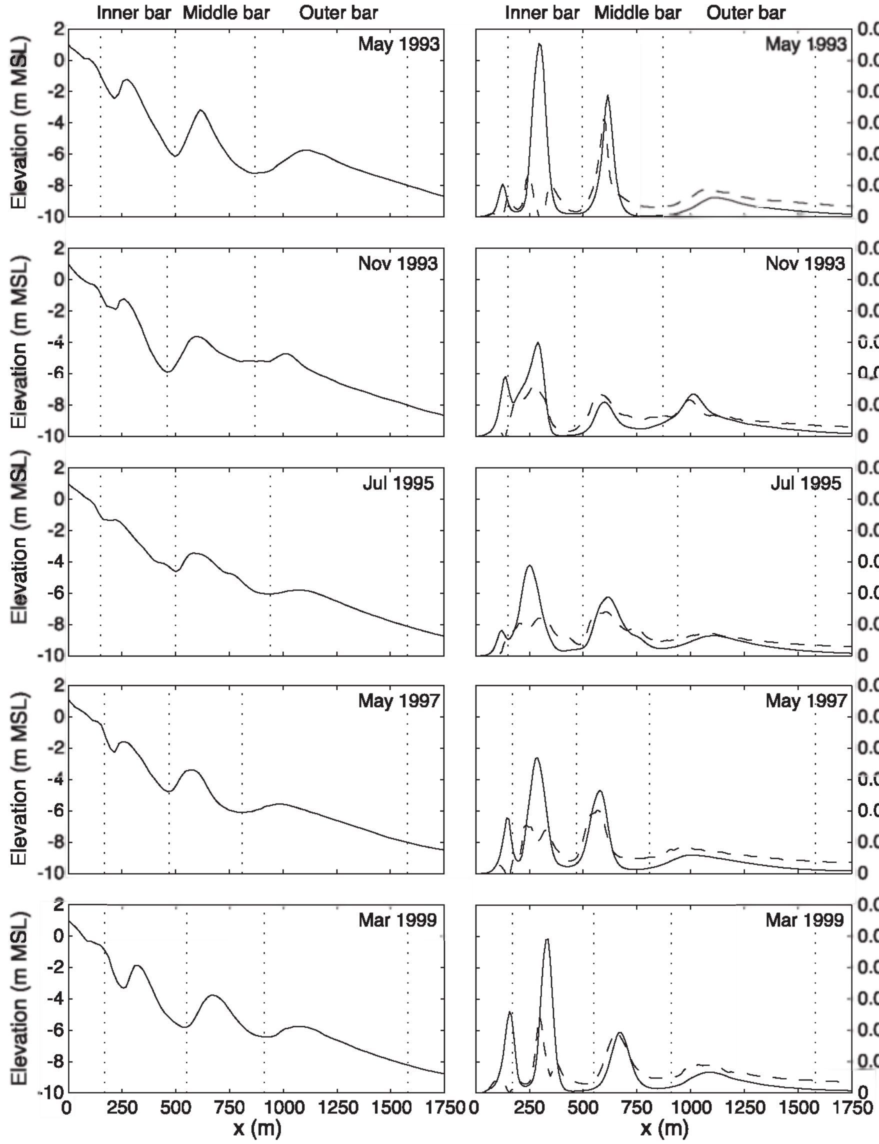

Fig. 12. Depth (left column) and yearly-averaged normalised transport rates i.e. $\overline{q'}(x,\overline{t})$ (right column) versus cross-shore distance. Onshore (offshore) transport rates are indicated in dashed (solid) lines. The time-varying boundaries of the barred sections are indicated with vertical dotted lines.

onshore (offshore) transport in November 1993 had readjusted with corresponding n_{on} (n_{off}) converging from 1.21 (0.59) to 1.04 (0.94). The inner bar area exhibits the strongest changes in transport rates and readjusts at a much slower rate: from November 1993 to March 1999, n_{on} decreased from 1.89 to 1.37 while n_{off} increased from 0.71 to 0.93. Overall, in time, all cross-shore bar areas essentially readjust to pre-nourishment transport patterns, and in space, this readjustment occurs at a decreasing rate from the outer nearshore to the inner nearshore: the readjustment of the outer bar area is essentially achieved within a few years while the inner bar area is still readjusting during several years.

On the whole, our suggestion that the nourishment affected $\overline{q'}_{\mathrm{on}}$ and $\overline{q'}_{\mathrm{off}}$ is confirmed by Table 1. It is of

Table 1
Normalised on/offshore transport ratios

Bar	May 1993		Nov 1993		Jul 1995		May 1997		Mar 1999	
	n_{on}	n_{off}	n_{on}	n_{off}	n_{on}	n_{off}	n_{on}	n_{off}	n_{on}	n_{off}
Inner	1.00	1.00	1.89	0.71	1.98	0.79	1.57	0.82	1.37	0.93
Middle	1.00	1.00	1.21	0.59	1.07	0.88	1.06	0.92	1.04	0.94
Outer	1.00	1.00	1.17	1.56	1.04	1.09	1.03	1.03	1.01	1.02
$\bar{n}$[a]	1.00	1.00	1.34	1.04	1.28	0.95	1.15	0.96	1.11	0.97

[a] $\bar{n}$ is a weighted average with respect to varying widths of bar areas.

interest to see that the onshore transport of the nourished sand (Fig. 11) is not only due to an increase in $\overline{q'}_{\mathrm{on}}$ in the middle bar area but also to a reduction in $\overline{q'}_{\mathrm{off}}$ in this area.

6. Discussion and conclusions

The nearshore bar zone at Terschelling is characterised by a state of dynamic equilibrium in which a morphological feedback mechanism engenders a cyclic offshore-directed bar behaviour. Implementing a nourishment in the trough between the middle and outer bar had a significant impact on the stability of this dynamic bar system: unprecedented bar behaviour resulted in a 6–7 year postponement in cross-shore autonomous bar development during which morphometric bar parameters such as bar depth, height, width and volume stabilised around immediate pre-nourishment values with fluctuations in their natural order of variability (Fig. 10). Eventually, the bar system returned to its former state of dynamic equilibrium: the natural sequence in bar cyclicity survived the nourishment perturbation as bar behaviour readjusted to pre-nourishment migrational patterns. The readjustment occurred at two different time lags: the process of recovering the disturbed bar-trough morphology was initiated immediately after the implementation of the nourishment whereas bar migrational patterns only resumed after 6–7 years. Both cross-shore and longshore transport mechanisms played an important role in there distribution of nourished sediment as it was concurrently transported upwards in the profile and along shore towards the east; the nourishment was thereby only partially acting as a feeder berm. The upwards transport of the nourished sediment results from a perturbation in the bar-trough morphology which for the duration of 6–7 years changed the cross-shore balance of on/offshore sediment transport in favour of increased onshore transport and decreased offshore transport. A normalisation of cross-shore transport patterns occurred gradually as the nearshore profile was recovering its pre-nourishment bar-trough morphology. Concurrently, the cross-shore distribution of the longshore current changed significantly in the nourishment area as a former trough initially was filled with nourished sand; to what extent longshore processes interacted in restoring the bar-trough morphology is at present unknown. However, resulting from nearshore-parallel western winds, wind- and wave-driven transport by longshore currents resulted in significant eastward migration of the nourished sediment on the order of 400 m/year. Alongshore transport results from autonomous behaviour and appeared uninterrupted by the implementation of the nourishment.

The post-nourishment development of the morphometric bar parameters here based on non-barred profiles differs substantially from previously reported behaviour (e.g. Kroon et al., 1994; Hoekstra et al., 1996) based on pre-nourishment time-averaged mean profiles. Herein for instance, the middle bar exhibited an extreme growth in h_{b} in the years following the nourishment, whereas by using the non-barred profiles h_{b} actually reduced. Non-barred profiles were here introduced to follow the spatio-temporal evolution of the nourishment-induced perturbation of the mean profile. By applying non-barred profiles to derive bar morphology, the depths at bar locations thus relates to an underlying profile including the nourishment perturbation—a perturbation by definition not accounted for in time-averaged mean profiles, thereby challenging its validity following a perturbation. As a result hereof, the obtained pattern in bar morphology corresponds to the observed pattern in bar migration and is thereby consistent with autonomous bar behaviour in which bar development is intrinsically coupled to bar migration.

Although the nourishment was originally designed to act as a feeder berm (Hoekstra et al., 1994), the observed gain of sediment shoreward of the nourishment has largely been attributed to induced gradients in the longshore transport (e.g. Hoekstra et al., 1996;

Spanhoff et al., 1997), resulting from the intended lee effects by which the constructed berm partly acts as a submerged breakwater. We here find that the onshore transport of nourished sand results from an increase in onshore transport concurrent with a decrease in offshore transport. As a result hereof, shoreline retreat (3 m/year) was reversed into shoreline advance (~15 m/year) for a 6–7 year period in which migrational bar behaviour was postponed. It is noticeable that an identical pattern in profile development was exhibited updrift of the nourishment, thus westward of the wave shadow zone resulting from the breaker berm effect of the nourishment; the lack of causal association with the nourishment is consistent with the alongshore-migrating eastward skewed effect on the shoreline with respect to the initial placement of the nourishment (~400 m/year to the east). The behaviour in the western part of the study area coincides with the landfall of sandwave-like undulations that are believed to be part of a natural inlet-bypassing mechanism. Little is known about the transport capacity of these migrating bed forms. The virtually parallel development of the nearshore response in these two areas suggests that the sand waves also partially act as a submerged breakwater. Incidentally, the maximum amplitude of these undulations is ~2 m thus in the same order as the initial height of the nourishment.

For a period of 2–3 years following its implementation, the nourishment also engendered a pronounced development of a 3D morphological system with a bar behaviour unseen in the preceding 28 years of autonomous behaviour. In this period, a lowering of both d_b and h_b (Fig. 10) by ~0.5 and ~0.75 m, respectively, occurred in the nourished area, in essence resulting in a temporary raising of the profile at the location of the middle bar by ~1.25 m. Apparently, this temporary elevation of the profile induced changes in the horizontal circulation of flow patterns: the return flows evolved from being nearly alongshore-uniform to concentrated in rips, a 3D pattern usually descriptive of the inner nearshore i.e. at shallower depths. The nourishment-induced development of 3D features is qualitatively consistent with the pronounced presence of 3D features in the inner bar prior to the nourishment (rather than in the middle bar and outer bar, see Section 2) and with theoretical studies (Klein et al., 2002; Caballeria et al., 2003) that show that a reduction in the water depth over a bar causes an increase in the growth rate of 3D features by an increase in wave dissipation. As cross-shore profiles in the middle bar area gradually lowered in the subsequent years, the non-uniformities decreased. The post-nourishment non-uniformities of the middle bar, however, occurred on a much larger spatial and temporal scale than normally encountered in the inner nearshore zone of Terschelling, likely as a result of a larger bar size.

Acknowledgments

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References

Biegel, E.J., Spanhoff, R., 1996. Effectivity of a shoreface nourishment, Terschelling, the Netherlands. Tech. rep. National Institute for Coastal and Marine Management /RIKZ and SEPRA BV.

Bosboom, J., Aarninkhof, S.G.J., Reniers, A., Roelvink, J.A., Walstra, D.J.R., 1997. UNIBEST-TC 2.0, overview of model formulations. Report H2305, WL|Delft Hydraulics.

Caballeria, M., Coco, G., Falqués, A., 2003. Crescenticpatterns and self-organization processes on barred beaches. Proc. 5th Int. Conf. on Coastal Sediments '03. ASCE, Reston, Virginia.

Grunnet, N.M., Hoekstra, P., 2004. Alongshore variability of the multiple barred coast of Terschelling, the Netherlands. Mar. Geol. 203, 23–41.

Guillen, J., Hoekstra, P., 1996. The equilibrium distribution of grain size fractions and its implications for cross-shore sediment transport: a conceptual model. Mar. Geol. 135, 15–33.

Hamm, L., Capobianco, M., Dette, H.H., Lechuga, A., Spanhoff, R., Stive, M.J.F., 2002. A summary of European experience with shore nourishment. Coast. Eng. 47, 237–264.

Hoekstra, P., Houwman, K.T., Kroon, A., Van Vessem, P., Ruessink, B.G., 1994. The NOURTEC experiment of Terschelling: process-oriented monitoring of a shoreface nourishment (1993–1996). In: Arcilla, A., Stive, M.J.F., Kraus, N.C. (Eds.), Proc. 1st Int. Conf. on Coastal Dynamics '94. ASCE, New York, pp. 402–416.

Hoekstra, P., Houwman, K.T., Kroon, A., Ruessink, B.G., Roelvink, J.A., Spanhoff, R., 1996. Morphological development of the Terschelling shoreface nourishment in response to hydrodynamic and sediment transport processes. In: Edge, B.L. (Ed.), Proc. 25th Int. Conf. on Coastal Engineering. ASCE, New York, pp. 2897–2910.

Klein, M.D., Schuttelaars, H.M., Stive, M.J.F., 2002. Linear stability of a double-barred coast. Proc. 28th Int. Conf. on Coastal Engineering, pp. 3396–3408.

Kroon, A., Hoekstra, P., Houwman, K.T., Ruessink, B.G., 1994. Morphological monitoring of a shoreface nourishment—NOURTEC experiment at Terschelling, Netherlands. In: Edge, B.L. (Ed.), Proc. 24th Int. Conf. on Coastal Engineering. ASCE, New York, pp. 2222–2236.

Plant, N.G., Holland, K.T., Puleo, J.A., 2002. Analysis of the scale of errors in nearshore bathymetric data. Mar. Geol. 191, 71–86.

Reniers, A.J.H.M., Battjes, J.A., 1997. A laboratory study on the shear instability of longshore currents. J. Geophys. Res. 102, 8597–8609.

Reniers, A.J.H.M., Thornton, E.B., Stanton, T.P., Roelvink, J.A., 2004. Vertical flow structure during Sandy Duck: observations and modeling. Coast. Eng. 52, 237–260.

Ribberink, J.S., 1998. Bed-load transport for steady flows and unsteady oscillatory flows. Coast. Eng. 34, 59–82.

Rienecker, M.M., Fenton, E.B., 1981. A fourier approximation method for steady water waves. J. Fluid Mech. 104, 119–137.

Ruessink, B.G., Houwman, K.T., Hoekstra, P., 1998. The systematic contribution of transporting mechanisms to the cross-shore sediment transport in water depths of 3 to 9 m. Mar. Geol. 152, 295–324.

Ruessink, B.G., Kroon, A., 1994. The behaviour of a multiple barsystem in the neashore zone of Terschelling, the Netherlands: 1965–1993. Mar. Geol. 121, 187–197.

Ruessink, B.G., Terwindt, J.H.J., 2000. The behaviour of nearshore bars on the time scale of years: a conceptual model. Mar. Geol. 163, 289–302.

Sand, S.E., 1982. Long wave problems in laboratory models. J. Waterw. Port Coast. Ocean Div., Am. Soc. Civ. Eng. 108, 492–503.

Shand, R.D., Bailey, D.G., Shepherd, M.J., 2001. Longshore realignment of shore-parallel sand-bars at Wanganui, New Zealand. Mar. Geol. 179, 147–161.

Spanhoff, R., Biegel, E.J., Van de Graaff, J., Hoekstra, P., 1997. Shoreface nourishment at Terschelling, the Netherlands: feeder berm or breaker berm? In: Thornton, E.B. (Ed.), Proc. 3rd Int. Conf. on Coastal Dynamics '97. ASCE, New York, pp. 863–872.

Tànczos, I.C., Aarninkhof, S.G.J., Weck, A.W.v.d., 2000. Ruimte voor de zandrivier. Report Z3200, WL|Delft Hydraulics.

Van Beek, L.P.H., 1995. Wave climate of Terschelling. A statistical analysis for the NOURTEC project. Report R95-10, Institute for Marine and Atmospheric Research Utrecht.

Van Rijn, L.C., Walstra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S., Sierra, J.P., 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models. Coast. Eng. 47, 295–327.

Westlake, S.J., Heinen, P.F., Knudsen, S., Heddinga, P., 1996. Accuracy of NOURTEC bathymetric surveys. Tech. rep, National Institute for Coastal and Marine Management (RIKZ), The Hague, Netherlands.