CHAPTER 161

# MORPHOLOGICAL MONITORING OF A SHOREFACE NOURISHMENT
## NOURTEC Experiment at Terschelling, The Netherlands

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*Abstract*

The morphological behaviour of a shoreface nourishment site is studied. The originally observed patterns in bar development before the nourishment are disturbed by the extra volume of sediment in the cross-shore profile. Attention is focused on the morphological development of the nearshore bars and troughs after the nourishment.
After almost a year, the bar at the landward site of the nourishment showed a reversal in bar behaviour in comparison with the natural conditions as described by Ruessink and Kroon (in press). The bar was slightly moving landward and was growing in height, whereas a similar bar at this position within a non-nourished environment would move seaward and reduce in height. The bar at the seaward side of the nourishment is quickly adjusting itself to the situation before the nourishment.
The bar behaviour after the nourishment is accompanied by a redistribution of the sediments over the profiles. The net amount of sediment losses in the nearshore area is negligible. This also means that the nourished volume of sediments is still available in the central part of the nourishment area. Longshore movements of the nourished volume are in the order of 400 m to the east over a period of about a year, and are not observed in the cross-shore profiles with a longshore spacing of 1000 m.

*Introduction*

The coastline of the northern part of the Netherlands consists of a chain of barrier islands alternating with tidal inlets. The beaches and nearshore zones of these barrier islands are composed of sandy sediments. The central parts of the barrier islands do suffer from erosion over the last decades. At Terschelling (figure 1) the shoreline of the central part of this barrier island retreated over the last decades with an average, annual rate of 2.5 to 3 $m.year^{-1}$, which means an average, annual volumetric loss of 110.000 $m^3$ of sediment within the nearshore zone.

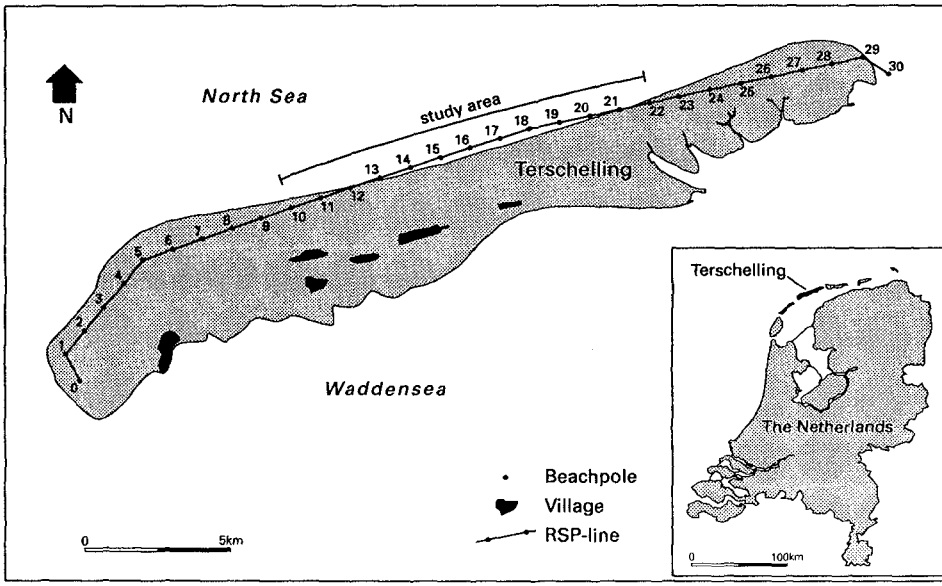



*Figure 1 Location of the study area*

Since the seventies, the eroding coastal stretches along the Dutch coast are mainly defended by beach nourishments. However, in the early nineties other kinds of soft engineering structures are considered. This resulted in the decision to execute another type of nourishment in 1992, a shoreface nourishment consisting of a submerged volume of sediment filling up a trough between two shore-parallel bars in the outer nearshore zone. Hereby, the design of the shoreface nourishment has to guarantee the same degree of safety as the other measures of shore protection. This means that the artificial volume of sediments must be beneficial for the coastal system for at least period of 10 years.
The scientific EC-MAST2 programme NOURTEC has the objective to describe and explain the behaviour of this shoreface nourishment. The behaviour of the nourishment is analyzed in different phases. An evaluation of the behaviour before the nourishment is made by studying the evolution of the barred morphology in the nearshore zone over the last decades (Ruessink and Kroon, in press). The hydrodynamic processes and sediment properties in the barred nearshore zone just prior to the nourishment have been subject of study within a relatively small field campaign ($T_0$; Hoekstra et al., 1994). The behaviour of the barred morphology and the morphodynamics after the nourishment is studied since 1993 by means of detailed process-oriented measurement campaigns.

In this paper, the morphological behaviour of the nourishment site is studied. Attention is paid to the morphological development of the nearshore bars and troughs after the nourishment. These observations are than compared with the natural behaviour of these bars in cross-shore and longshore direction before the nourishment (Ruessink and Kroon, in press). In addition, the sediment budgets within the cross-shore profiles along the nourishment site are computed.

*Study area and previous results*

The shoreface nourishment is situated at the north coast of the barrier island Terschelling, The Netherlands (figure 1). This north coast of Terschelling is facing the semi-enclosed North Sea and is made of a sandy shoreface, beaches and dunes.

The morphology of the nearshore zone, defined as the upper shoreface, is characterized by two or three nearshore bars. The width of the nearshore zone is about 1400 m and the mean slope is about 1:180. The shoreface nourishment is placed in a trough between two shore-parallel nearshore bars at a depth of -5 to -7 m below mean sea level. The length of the nourishment in a longshore direction is 4.4 km. The median grain size ($D_{50}$) of the sediments in the intertidal zone is about 200 to 250 $\mu$m. At the seaward side of the shoreface nourishment site, at a water depth of about 10 m, the median grain size is reduced to about 160 to 180 $\mu$m.

The morphological behaviour of the multiple bar system in the nearshore zone of Terschelling, The Netherlands between 1965 and 1993 is analyzed in Ruessink and Kroon (in press). Herein, both the cross-shore and longshore tendencies of the bar behaviour before the nourishment are described. The morphodynamical development of the nearshore bars over the last decades results in the following tendencies:

- The net cross-shore migration of the nearshore bars is in a seaward direction and shows different behaviour with distance offshore. Close to the shore, the volume of the bar is small and the behaviour is quite chaotic, hardly showing any net tendency (stage 1). Further offshore the nearshore bars constantly migrate in a seaward direction until the outer margin of the barred nearshore area (stage 2). At this position the outer nearshore bar declines (stage 3).
  The plane view of the bar is changing from crescentic to straight in an offshore direction. Overall, the bar feature has a 'life-cycle' of about 12 to 15 years;
- The net longshore migration of the nearshore bars is in an eastward direction with an average rate between 800 and 1250 m.year$^{-1}$ over the period 1975 - 1993.

The general hydrodynamic conditions are mainly determined by the processes related to the waves and tides. The sea and swell waves are coming from the North Sea from western to northern directions. The mean annual significant offshore wave height is about 1.5 m and has a period of about 6 to 8 s. The highest waves are incident from the west to northwest and have a significant height of about 5 to 6 meter and a period of 10 to 15 s. The wave-related undertow and the longshore and cross-shore wind-driven currents are of major importance in the nearshore zone of Terschelling (Hoekstra et al., 1994). The tides are semi-diurnal and have a neap-tide range of 1.2 m and a spring-tide range of 2.8 m (meso-tidal). The tidal current ellipses in the nearshore are shore-parallel oriented and the eastward flowing flood currents exceed the westward flowing ebb currents.

*Methods of analysis*

**Data set**

The present data set consists of five soundings carried out in lines perpendicular to a longshore reference line which connects the beach poles (the RSP-line, see figure 1). These soundings were executed in April 1993 (just before the nourishment), November 1993 (after the nourishment), January, April, and June 1994. The length of the cross-shore profiles is about 2000 m, and always covers the zone between the beach and the

lower shoreface at -10 m NAP. The longshore spacing between the studied profiles is 1000 m. The cross-shore profiles in the nourishment area are used to describe the morphological development in a morphometric and a volumetric sense.

**Morphometric analysis**

The quantitative description of the cross-shore profiles in a morphometric way requires a mean profile equation to which the single measured profiles at different time steps are compared. This mean cross-shore profile equation is determined in two steps. The first step concerns the computation of the mean of all the measured cross-shore profiles at one location over the period 1964 to 1993 (dataset Ruessink and Kroon, in press). This mean cross-shore profile can not be used as a reference profile because it still contains some barred features, due to the limited amount of profile measurements in comparison to the 'life-cycle' of the system. The second step concerns the fit of a mathematical expression to the computed mean profile. An exponential curve fitting procedure was chosen for the nearshore profile between the beach and the lower shoreface. This exponential curve is expressed by:

$$d = d_0 \cdot [1 - e^{-ax}] \tag{1}$$

in which

$d$ = computed depth of the average profile below NAP [m]
$d_o$ = depth at the location where the slope of the bed is almost zero [m]
$a$ = coefficient [$m^{-1}$]
$x$ = horizontal coordinate, positive in seaward direction [m]

In the Terschelling case, the $d_0$-value is 8.7 and the a-value is 0.0018 (see also Ruessink and Kroon, in press).

The residual profile, which is defined as the individual measured profile minus the fitted profile is used for the description of the bar morphology. The dimensions of the bar features are defined in figure 2. The studied dimensions are the depth of the bar crest to NAP ($d_c$ in m), the position of the bar ($P_c$ in m), the height of the crest of the bar ($h_b$ in m) and the width of the bar ($W_b$ in m) (figure 2).

**Volumetric analysis**

The volumetric analysis of the cross-shore profiles is executed in several successive steps. The first step is the determination of the seaward boundary of the dynamic part of the nearshore. This boundary must be located seaward of the closure depth of the cross-shore profiles (see Kroon, 1994). At Terschelling, the location of the -8 m depth contour in the cross-shore profiles matches this requirement.

Thereafter, the sediment volume between the measured cross-shore profile and the -8 m depth is computed across the profile. These computed sediment volumes are determined in a cumulative way from the seaward boundary towards the beach. The trends in the cumulative sediment volumes are finally compared along the nourishment site. Three volumes are hereby selected:

- the nearshore zone, defined as the area between the 0m and -8m depth contour. The width of the nearshore zone was constant for each profile location during the 1993 to 1994 period;
- the seaward half of this nearshore zone;
- the seaward quarter of this nearshore zone.

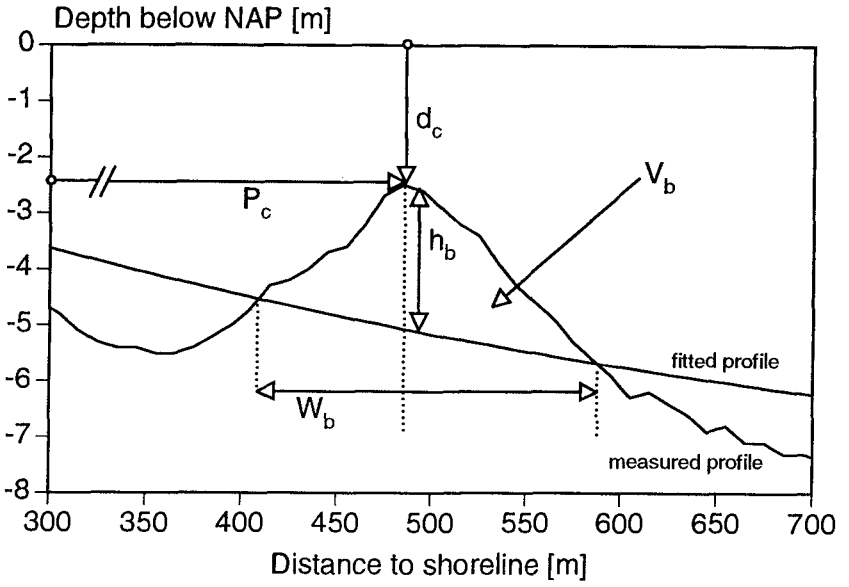



*Figure 2 Definition sketch of morphometric variables*

*Results*

**Morphological development after the nourishment**

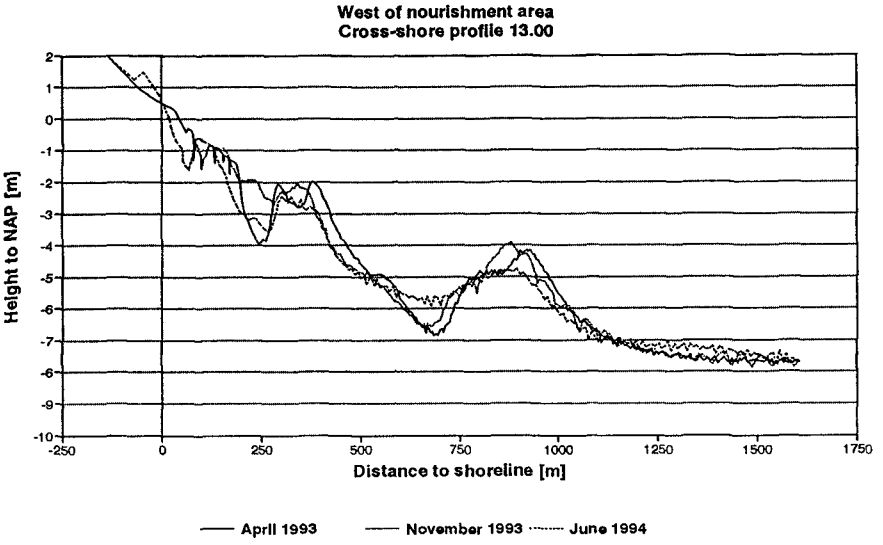
The overall characteristics of the nearshore zone along the nourishment site are summarized in Table 1. The width of the nearshore zone slightly increases from the central nourishment area (profile 16) to the western (profile 13) and eastern (profile 19) side.

Table 1 Bar characteristics profile 17

| time | distance offshore [m] | bar crest depth [m] | bar crest height [m] |
|---|---|---|---|
| April 1993 | 597 - 1077 | 3.6 - 5.7 | 2.1 - 1.7 |
| November 1993 | 607 - 912 | 3.8 - 4.4 | 1.9 - 2.7 |
| January 1994 | 546 - 922 | 3.5 - 4.6 | 1.9 - 2.4 |
| April 1994 | 562 - 978 | 2.7 - 5.2 | 2.9 - 2.0 |
| June 1994 | 530 - 922 | 2.5 - 5.2 | 2.8 - 1.9 |

The cross-shore profile behaviour at several locations along the nourishment site are presented in figure 3.

At about 800 m west of the nourishment (profile 13), the positions of the nearshore bars are almost stable in time. The trough between the two outer bars is slowly filling up from -7 to -5.5 m NAP.



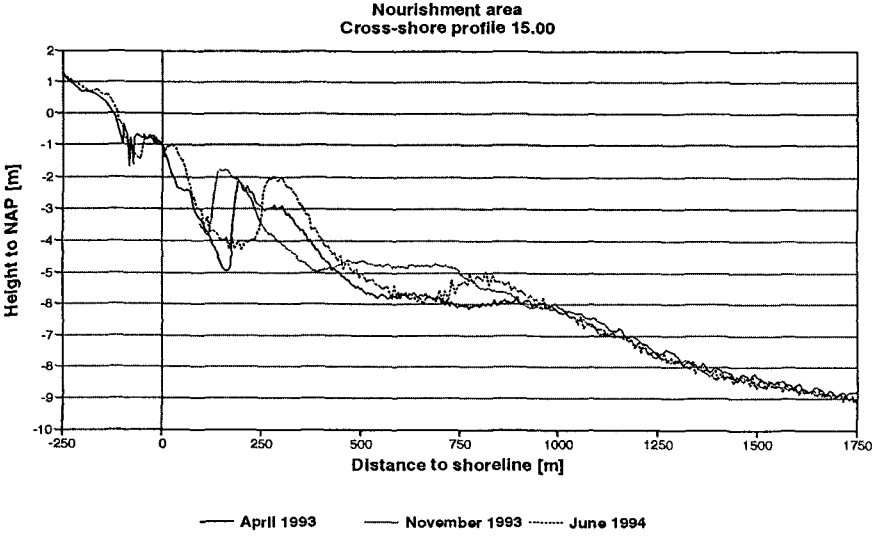
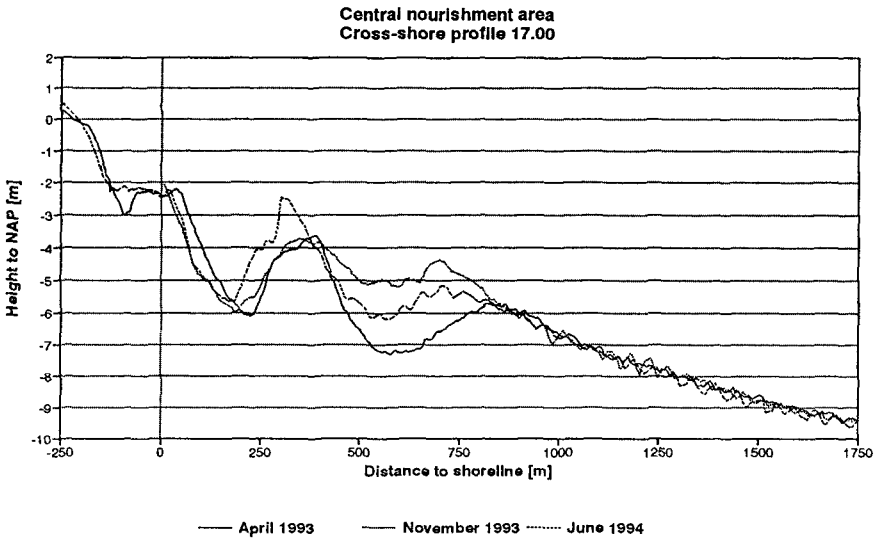




*Figure 3 Cross-shore profiles*



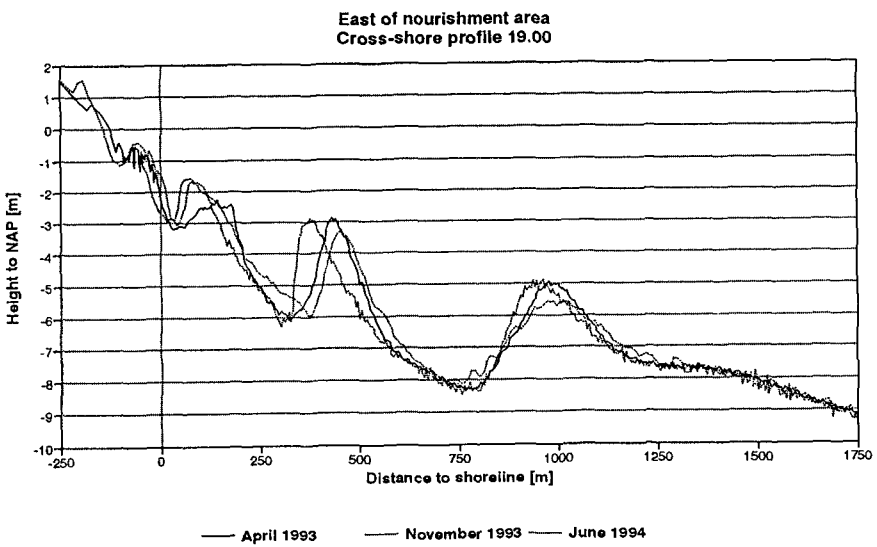




*Figure 3 Cross-shore profiles (continued)*

At about 800 m east of the nourishment (profile 19), the position of the most seaward, nearshore bar hardly changes in time. The landward located nearshore bar is moving onshore over a distance of about 50 m between April and November 1993, followed by a seaward shift over the same distance between November 1993 and June 1994.
At the central part of the nourishment area (profile 17), the nourished volume of sediment in the trough between the two outer nearshore bars is easy to trace. The morphological developments in this cross-shore profile can be summarized in three phases:

- filling up of the trough in the nourishment period (April November 1993);
- development of a barred topography at the nourishment site. The outer bar is reduced in height, the trough is increased in depth and the inner bar is increased in volume in a landward direction;
- the bar topography is even more pronounced. The most seaward bar is further reduced in height, while the landward bar at the nourishment site is increasing in height to a value of -2.5 m NAP. The offshore position of this bar crest is stable over the January to June 1994 period.

At the western part of the nourishment (profile 15), the morphological development of the bars is more complex. Before the nourishment, the outer nearshore bar had just disappeared, due to the longshore migration of a bar attachment point that came from the west (Ruessink and Kroon, in press). This means that the morphological development of bars in the cross-shore profile can be better studied at profile 17 where the longshore movements of sediment volumes are only caused by the nourishment in the 1993-1994 period.

For the central part of the nourishment (profile 17), the morphometric variables of the bar topography in time are presented in figure 4. The different lines in this figure represent the successive nearshore bars in the period 1964 to 1994. The two nearshore bars before the nourishment (bar 4 and bar 5 in figure 4) have changed in one large double crested bar (see figure 5). However, for the comparison of the bar behaviour with the autonomous behaviour before the nourishment, both crests are regarded as two bars.
The distance to the shoreline of the inner bar crest (5 in figure 4a) in time is almost constant. The distance to the shoreline of the outer bar crest (4 in figure 4a) is reduced with about 100 m as a result of the nourishment (difference between April and November 1993). Thereafter, the position of the outer bar crest is quite constant in time.
The depth of the inner bar crest to NAP subsequently decreases after the nourishment (5 in figure 4b). The depth of the outer bar crest to NAP is decreasing during the nourishment period (4 in figure 4b) and increasing in the period after the nourishment.

The relation between the bar crest depth and the distance to the shoreline for the autonomous system is presented in figure 6a. According to the three stages of bar behaviour as defined by Ruessink and Kroon (in press), both the inner and the outer crest are in stage 2. This means that the crests should normally have a seaward migrating tendency. However, as a result of the increased volume of sediment due to the nourishment, both the inner and outer crest are firstly moving in the direction of the first stage. The reversal of this tendency to an expected offshore migration has already started at the outer crest position (see April to June 1994).
The relation between the bar height and the distance offshore is presented in figure 6b.
The height of the inner crest of the bar is obviously deviating from the previously observed patterns: the crest is located at greater heights than has ever been recorded in the past (Ruessink and Kroon, in press). The outer crest of the bar is positioned at a location where the observed relation in the autonomous behaviour was weak.

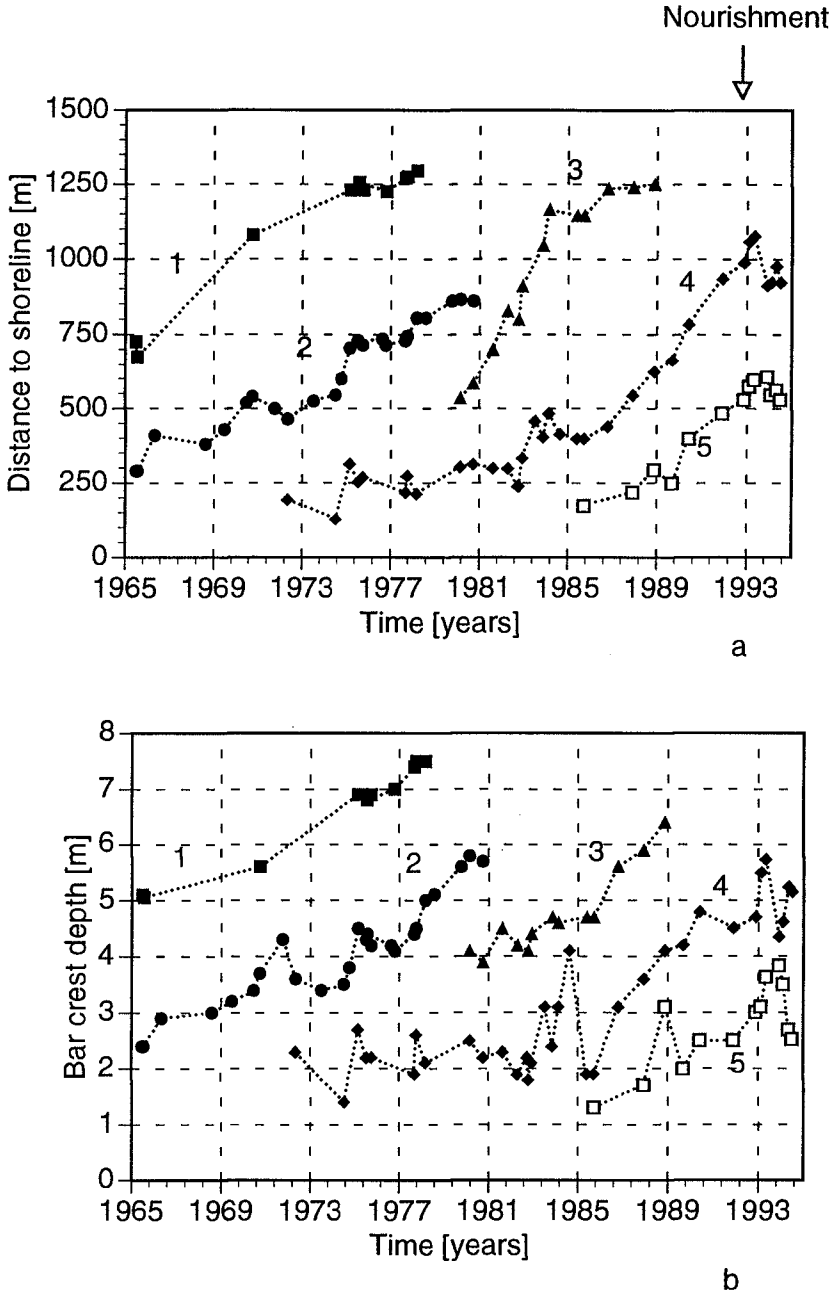



*Figure 4 Position of bar crests (a) and depth of bar crests (b) in time*

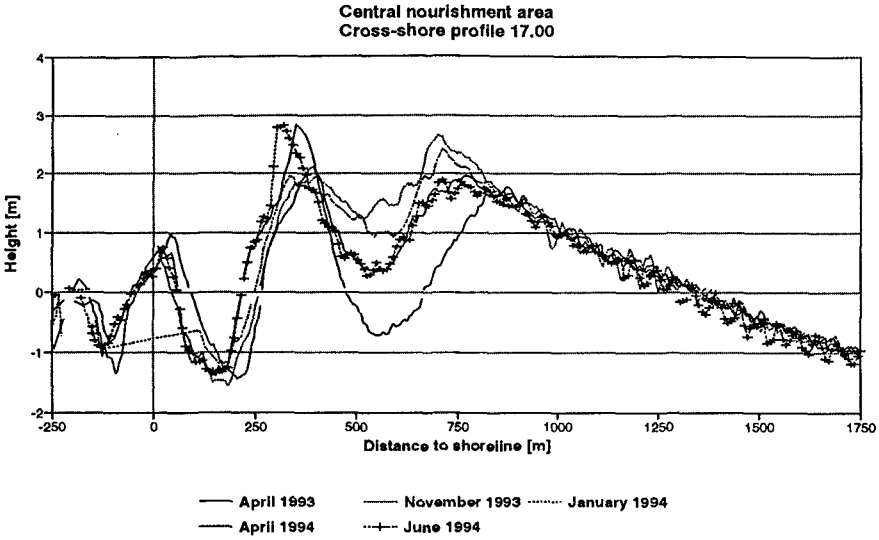



*Figure 5 Detailed bar developments using residual profile 17*

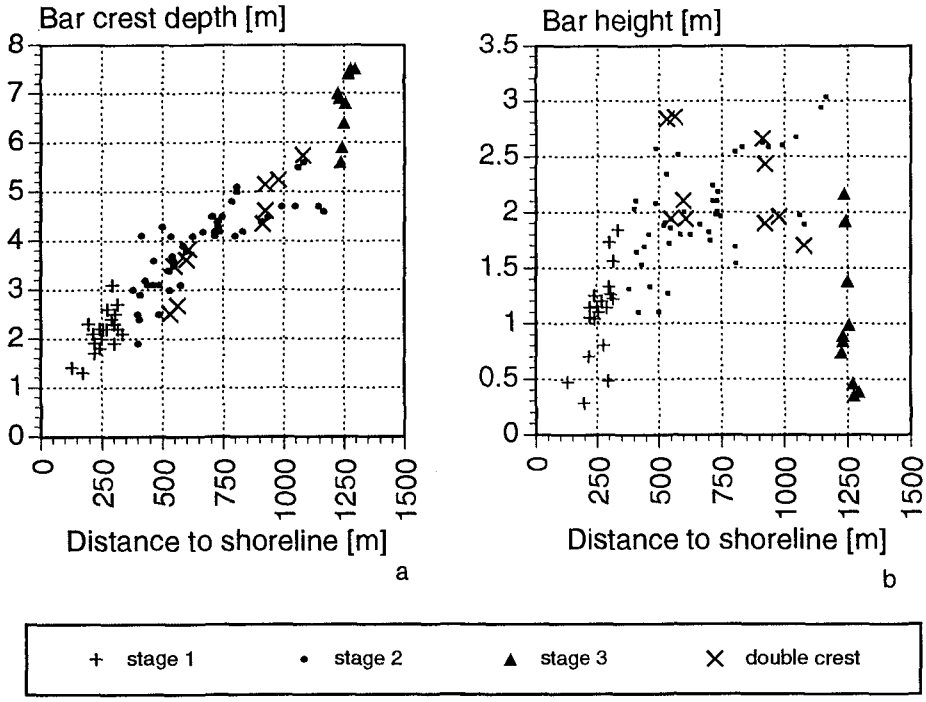



*Figure 6 Position of the bar crests versus bar height (a) and depth of bar crest (b)*

Longshore patterns in bar behaviour are observed. The development of the bar patterns in the cross-shore profiles over the nourishment site do suggest a shift in the bar variables towards stage 1. The nourishment will thus increase the duration of stage 2. The relation between the development of the bar pattern at the central part and those at the western and eastern sides of the nourishment area are still not clear. The alongshore shift of the nourishment volume can not be measured with an alongshore profile spacing of 1000m. Detailed soundings in the area have shown a eastward shift of the sediment volume of about 400 m over the period November 1993 to June 1994.

**Volumetric development**

The cumulative sediment volumes within the cross-shore profiles are shown in figure 7.
At about 800 m west (profile 13.00) and east (profile 19.00) of the nourishment, the differences in sediment volumes are not influenced by the nourishment. At profile 14.00, there is an overall decrease in the sediment volume over the 1993 to 1994 period. At profile 19.00, the cumulative sediment volumes are almost constant.
At the central part of the nourishment area (profile 17), the sediment volume is increased between April and November 1993, due to the nourishment. Thereafter, there is a slight decrease in the sediment volume.

The spatial distribution of the cumulative sediment volumes in the cross-shore profiles is presented in figure 8. The volumetric changes within the nearshore zone, defined as the area between the 0m and -8m depth contour, are showing an increase of sediment volume after the nourishment in the central part of the nourishment (compare 1 and 2 for profile 15 to 18 in figure 8a), followed by an almost constant volume after this period. At the western end of the nourishment area (profile 14), this tendency is not observed.

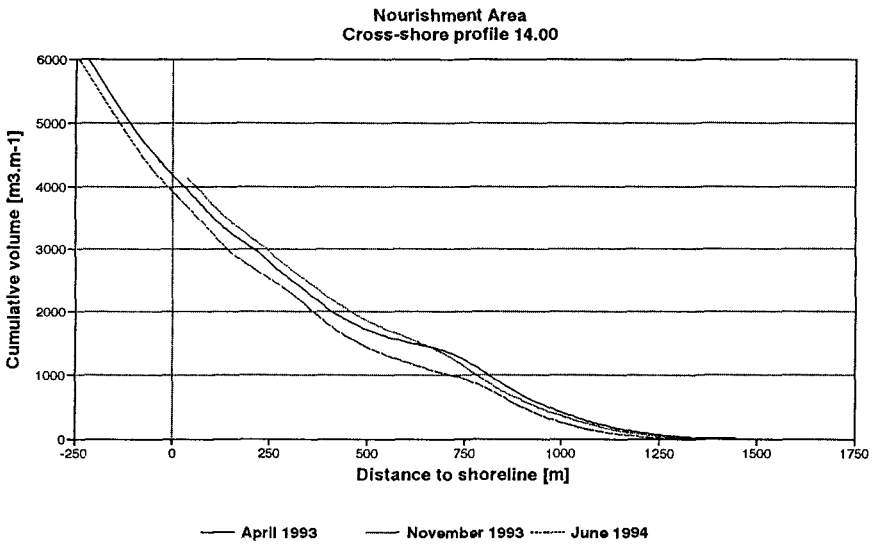
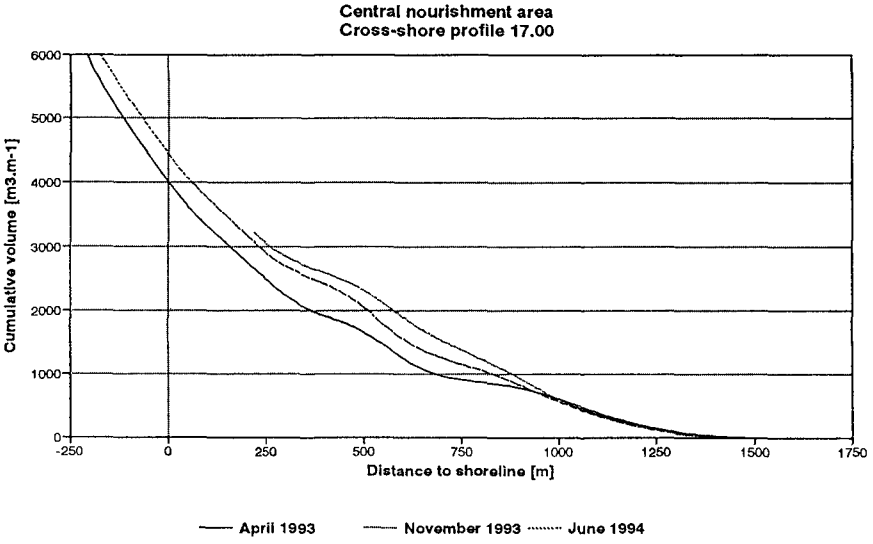



*Figure 7 Cumulative sediment volumes at certain cross-shore profiles*



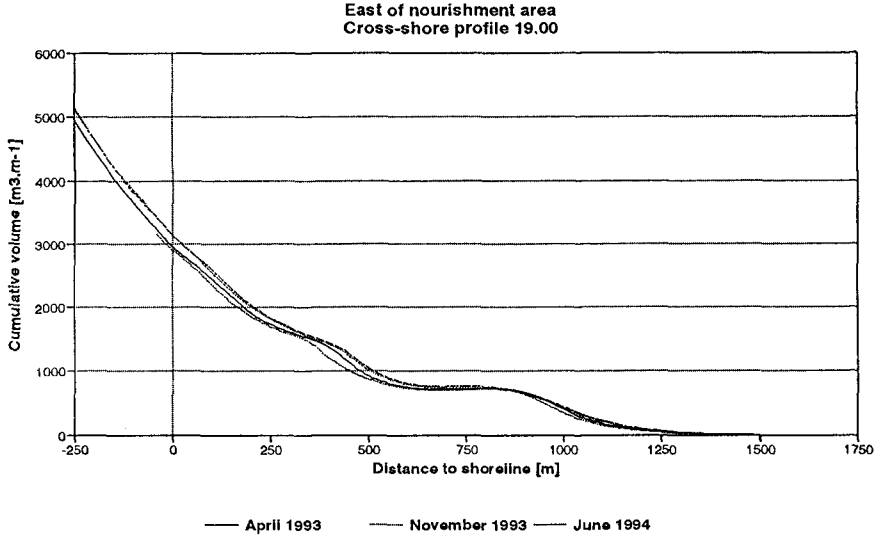




*Figure 7 Cumulative sediment volumes at certain cross-shore profiles (continued)*

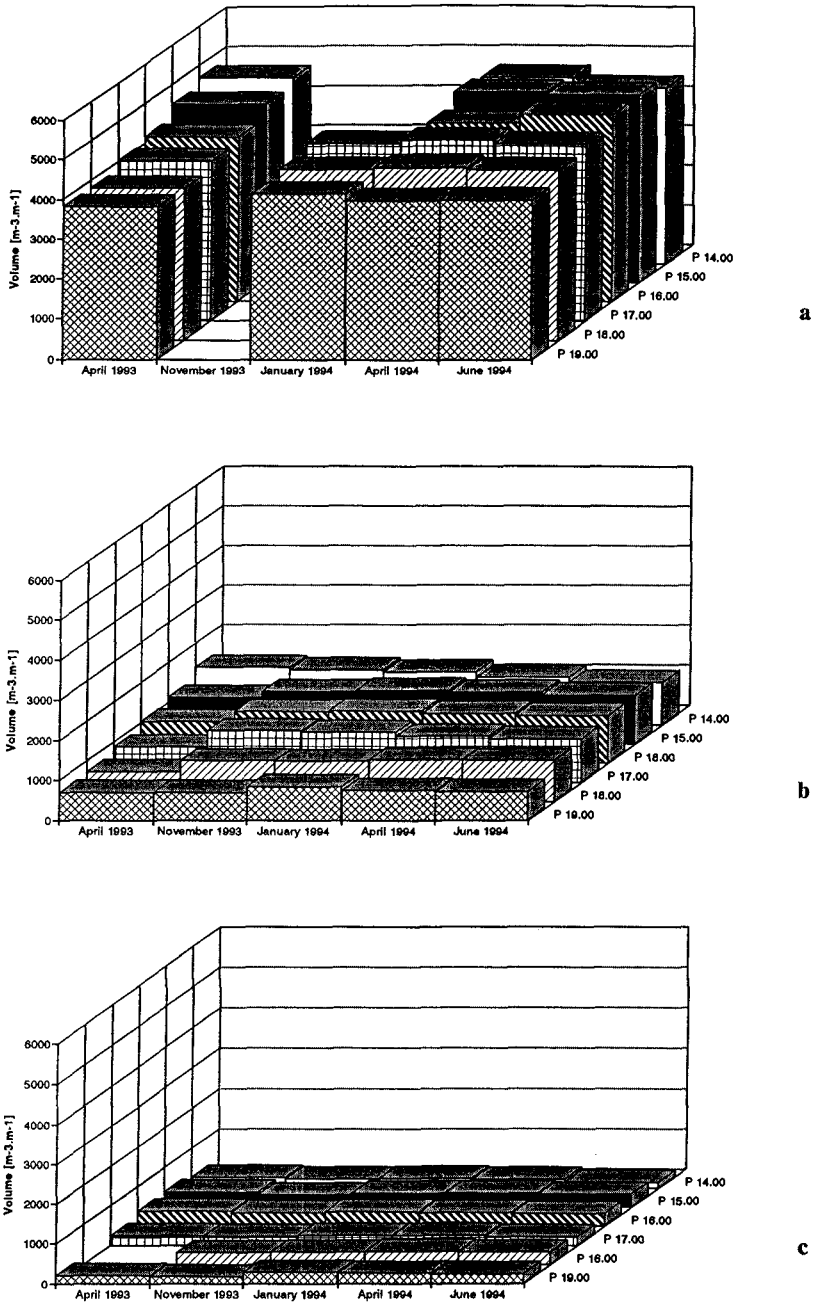



*Figure 8 Spatial distribution of nearshore sediment volumes: a. nearshore area, b. seaward half, c. seaward question.*

The influence of the nourishment is even better to see in the volumes of the seaward half of the nearshore zone (figure 8b). It is obvious that the nourishment is effective in the central area (profile 15 to 18). The western area (profile 14) is rather complex. The influence of the nourishment is interfering with the longshore migration of a bar attachment point from the west.
The spatial pattern of the cumulative sediment volumes in the seaward quarter of the nearshore zone is presented in figure 8c. The changes in volumes are negligible small over the period April 1993 to June 1994.

### *Discussion*

The morphological development of the breaker bars in the central nourishment area consists of three phases:

- the pattern of the bars and troughs are disturbed in the nourishment period. The trough between the two outer bars is filled up, and the bar topography has changed in a shore platform with two small undulations at the landward and seaward side. The total volume of sediment in the cross-shore profile between the -8 m to the 0 m depth contours has increased with about 450 $m^3.m^{-1}$;
- just after the nourishment, the profiles are quickly adjusting to the former bar and trough topography. The outer bar crest depth and trough depth are increasing and the inner bar crest depth is decreasing. However, along the nourishment the total volume in the cross-shore profiles between the -8 m to the 0 m depth contours is almost constant, which implies a redistribution of the sediment over the nearshore part of the profile;
- in the period between January and June 1994, the bar and trough topography becomes more pronounced. This is especially the case for the inner bar. The crest of this bar is further growing in height and the depth of the crest is now at about -2.5 m NAP. However, according to the morphometric relations for the natural bars in the period 1964 to 1993, the inner bar must be out of equilibrium and may be flattened off. The behaviour of the outer bar is already typical for stage 2 again. The total volume in the cross-shore profile between the -8 m to the 0 m depth contours is almost constant. The small changes in bar patterns are thus made by the redistribution of sediments over the cross-shore profile.

The observed patterns in time are still not related to the observed hydrodynamics. The observed adaptations of the cross-shore profile to the pre-existing bar morphology is however within the time-span of a month. This means that the modulating mechanisms of the barred topography immediately act upon the disturbed profile.
The increase in the height of the inner bar in the period January to June 1994 may be partly caused by the onshore directed sediment transport by wave-asymmetry processes. However, this remark is still very tentative and will be verified in the next future in two steps by:

- analyzing detailed process-oriented field measurements (see Hoekstra et al., 1994). These measurements are used to verify different wave-, tide- and wind-related processes over the barred cross-shore profile;
- analyzing the type of combined wave- and tidal-sequences over this period (see Kroon, 1994). The analysis of the sequences of the waves (e.g. storm-related events) will be executed in order to understand the representativeness of the observed period within the average, long-term wave climate.

The combined morphometric and volumetric analysis of the cross-shore profiles in the nourishment areas has clearly shown that significant changes in the cross-shore bar and trough patterns may occur with hardly any changes in the nearshore volume over the same period.
The disturbed pattern of the cross-shore morphology due to the nourishment is quickly adjusted. These adjustments, striving to attain a new type of quasi-equilibrium are good indicators of the morphodynamics of the bars on the longer term.

### *Conclusions*

The morphological development of the nearshore bars and troughs after the nourishment is showing the following aspects:

- the disturbed bar morphology caused by the nourishment is quickly adjusting itself to the previously observed pattern. The bar pattern in the central part of the nourishment area is already back within a month after the completion of the works. The former trough at the position of the nourished volume has a similar time of adjustment;
- the bar and trough morphology is still out of dynamic equilibrium. The inner bar crest is growing in height and almost stable at its position, at a location where the previous observed patterns in bar behaviour would suggest a seaward migration and with an almost constant height. The nourishment volume has thus decreased the rate and even reversed the pattern of bar behaviour.

The overall behaviour of the nourishment volume over the year 1993 to 1994 is showing the following aspects:

- after November 1993, no significant net change in sediment volume at the studied cross-shore profiles along the nourishment are observed;
- the only transport of the nourished sediment volume is observed in an eastward longshore direction. This can be expected because the major components of the wind-, wave-, and tide-driven currents are also directed towards the east;
- despite the lack of net changes in the nearshore sediment volumes, there is a redistribution of sediments within the nearshore zone which may be coupled to the behaviour of the bars.

### *Acknowledgements*
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