CHAPTER 224

Morphological development of the Terschelling shoreface nourishment in response to hydrodynamic and sediment transport processes

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Abstract

The Terschelling shoreface nourishment was studied over a period of about 2.5 years. The nourishment was originally designed to act as a feeder berm. Since its implementation, the nourishment has completely satisfied the design objectives. However, the nourishment only partly acts as a feeder berm and the actual success of the nourishment is also based on its breaker berm function. The creation of a wave shadow zone leads to an interception of part of the longshore drift and the development of a salient effect.

Introduction

The Dutch barrier island of Terschelling is part of the northern coastline of the Netherlands. The island is facing the North Sea and separates the North Sea from the backbarrier system of the Wadden Sea (Fig. 1). The North coast of the island consists of a sandy shoreface, flanked by sandy beaches and dunes. In the last decades the central part of this coastline has chronically suffered from erosion. Over an alongshore distance of 5 km, the average annual coastal retreat was about 2-3 m/yr. This corresponds with an estimated, average annual loss of sand of 110.000 m^3. In 1993 a shoreface nourishment was implemented along the Terschelling coast to stabilize the existing coastline. The main design objective of this nourishment was (and is) "to return the Transient Coastline to a position seaward of the Basal Coast Line (Dutch BKL concept; NOURTEC, 1995) and to ensure that this Transient Coast Line will not retreat landward of the Basal Coast Line during the next 8 years" (Biegel and Spanhoff, 1996). In terms of design dimensions in total 2.1 million m^3 of sediment was involved and this sediment was supplied to the nearshore zone, filling up the trough between the middle and outer breaker bar (Fig. 1).

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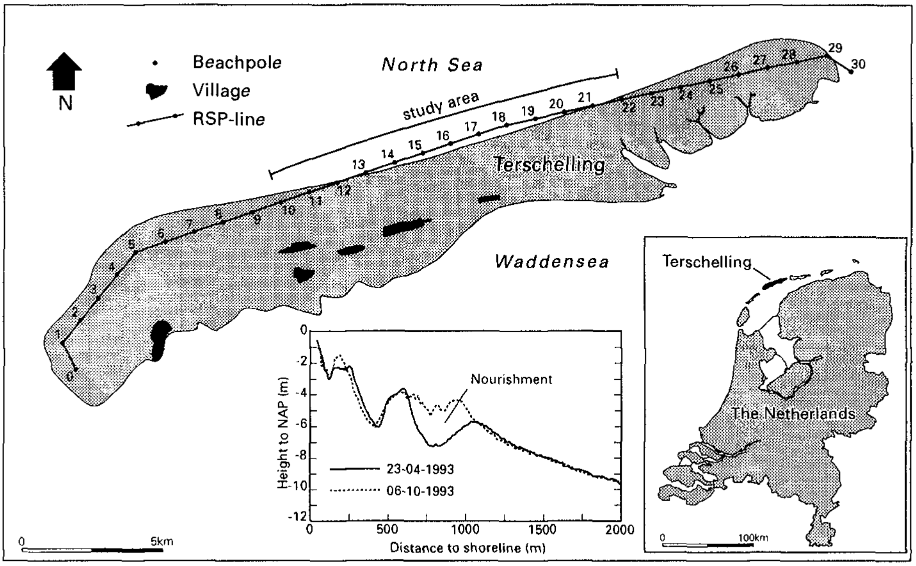

Figure 1. The North coast of the island of Terschelling with the study area. The beachpole (RSP)-line indicates the location of the cross-shore transects; the main measuring array is located in section 17

For the nourished zone, the amount of sediment supplied was equivalent to an average, vertical change in sea bed elevation of about 1 m and, in a longshore direction, the amount of nourished sediment per cross-section was in the order of 450 m^3/m. The nourishment, with a total length of about 4.4 km and extending from km section 13.7 to 18.1 (Fig. 1), is located in the depth interval between -5 and -7 m below NAP (Dutch Ordnance Datum; the zero - NAP level approximately equals mean sea level).

In 1993 the EC-MAST2 programme NOURTEC was launched to study and explain the behaviour of shoreface nourishments in different European coastal environments (Hoekstra et al., 1994, Knaack et al, 1997 and Laustrup et al, 1997). The final objective of the NOURTEC programme is to study, determine and explain the feasibility, effectiveness and optimum design characteristics of shoreface nourishment techniques for different environmental conditions.

The basic assumption underlying the design and implementation of the Terschelling shoreface nourishment is that eventually sand will be carried to the shore. The nourishment is expected to act as a feeder berm. In case of a feeder berm there has to be a significant net onshore directed sediment transport due to the presence of the nourishment.

Apart from being a potential feeder berm, a shoreface nourishment may also start acting as an offshore located breaker berm or as a combination of these two features. A shoreface nourishment acting as a breaker berm is able to reduce the erosional power of the waves by increasing the degree of wave energy dissipation, in particular due to wave breaking. The nourishment creates a "wave-shadow zone" landward from the nourishment which will locally reduce the strength of the wave-driven longshore current and the littoral drift.

This paper will focus on the developments at the Terschelling site in the first 30 months after the implementation of the nourishment. The aim of the present study is to analyse and evaluate the potential role as both a feeder berm and submerged breakwater. First of all, the bathymetric data set is used to determine the main morphological evolution in the nearshore zone and to compute changes in sediment volumes for specific horizontal and vertical control sections. The second way of adressing the problem is by analyzing the available process measurements and model computations on (suspended) sediment transport in the nearshore zone. It comprises an analysis of the dominant role of wave- and flow-driven processes in generating cross-shore (and landward-directed) and/or longshore fluxes of sediment.

Methods of research

Bathymetry

Bathymetric surveys were frequently carried out with varying time intervals and the total number of surveys until January 1996 is 12. After the nourishment the time interval varied from 53 to 182 days between two consecutive soundings. The surveyed area North of Terschelling covers approximately 25 km^2 and measurements were performed along survey lines perpendicular to the coast. Inside the nourished area the longshore spacing of these survey lines varied from 25 to 100 m; outside the nourished area the longshore spacing was about 200 m. The supra- and intertidal part of the cross-shore survey line, starting at the dunefoot, was done by leveling. The subtidal section until a depth of at least 10-12 m was measured by a Rijkswaterstaat survey vessel using a digital acoustic depth sounder (ATLAS DESO, 210 kHz), in combination with an accurate positioning system (Syledis and dGPS).

Hydrodynamics

The hydrodynamic field measuring programme of Terschelling consisted of two main activities: a long-term, continuously recording monitoring network and a series of process-oriented measuring campaigns (4). The monitoring network has been operational for about 2.5 years and almost all measurements were more or less concentrated around cross-sectional transect 17 (Fig. 1), covering the central part of the nourishment.
Tidal water levels have been measured by a tide station, located in cross-section 14.60 and in a water depth of approximately 10 m. Every 10 minutes a mean value of the water level has been recorded. Offshore wave conditions were registered with a wave-directional buoy (WAVEC) positioned in the central measurement section in a water depth of about 15 m. The WAVEC measured continuously with a frequency of 1.28 Hz. Each block of 10 minutes was automatically processed using standard zero down-crossing and spectral methods. Information on the time-dependent variation in water levels (waves and tides) was also obtained from 2 measuring poles positioned in the surfzone (section 17.00; Fig.2). Both poles were equipped with a pressure transducer and a capacitance wire, measuring water levels for 40 minutes per hour with a frequency of 4 Hz. The fourth element of the monitoring network consisted of an instrumented tripod, equipped with 2 electro-magnetic flow meters at about 0.25 and 1.2 m. above the bed and with a pressure sensor. Occasionally, the tripod also carried two Optical Back Scatter (OBS) sensors to measure suspended sediment concentrations (0.15 and 0.25 m above the bed).

The instrumented tripod measured in a burst mode sampling scheme with a burst interval of one hour, a burst length of 2048 s. and a sampling frequency of 2 Hz. The tripod was located at the seaward margin of the nourishment, at a water depth of approximately 5.5 m.

During the process-oriented measuring campaigns the monitoring network was substantially expanded and consisted of the following configuration: 2 offshore located wave directional buoys, 6 instrumented tripods in the nearshore zone - including 3 tripods with OBS's - and 2 poles. Emphasis in the measuring programme was given to processes operating in a cross-shore direction and, consequently, a cross-shore array of instruments was installed in section 17 (Fig. 2). Four concentrated measuring campaigns were carried out in the period November 1993 until November 1995; each campaign lasted for approximately 5 to 6 weeks. Data calibration, validation and analysis is discussed in further detail by Houwman and Ruessink (1997) and Hoekstra et al (1996).

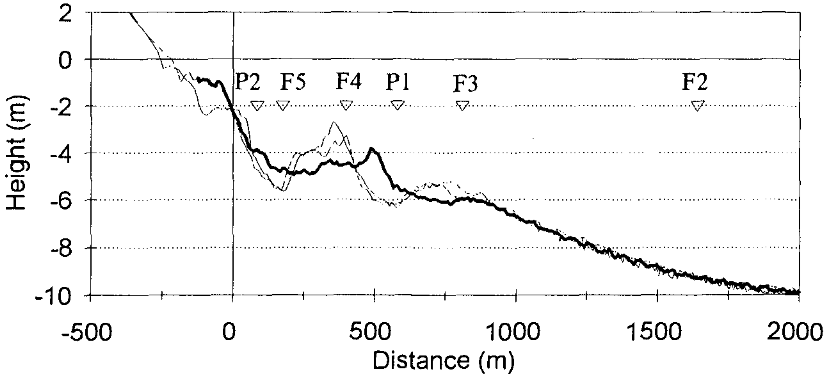

Figure 2. Measuring array in the cross-shore profile of section 17 (T2 campaign drawn line, T3 dashed line and T4 thick line); P = Poles and F = Frames or instrumented tripods

Hydrodynamic boundary conditions

Tidal conditions

Tides along the North coast of the island of Terschelling are semidiurnal and are characterized by a mixed micro- to mesotidal range. A maximum range of about 2.8 m is recorded at spring tide whereas the neap tide range is about 1.2 m. Associated tidal currents are basically flowing shore-parallel. The tidal flow during flood is in an ENE direction and the ebb tidal flow is directed towards the WSW. Especially at neap tide, the tidal ellipse is almost flat and rectilinear.

As expected, tidal flow is considerably modified by the presence of wind- and wave-driven currents (compare Whitford and Thornton, 1993). Earlier observations (Hoekstra et al., 1994) make clear that during moderate winds (< 8 Bf) wind-driven flow has the same order of magnitude as the tidal flow. During storm and heavy storm conditions, the wind- and wave-driven longshore flow, in combination with cross-shore (mean) flow patterns, will even fully dominate the nearshore flow regime.

Wind and waves

The wind climate of Terschelling shows a clear predominance of westerly winds with a prevailing wind force of 4 to 5 Bf. In the period 1984-1994 the predominant wind direction for each year is in the sector between 210 and 300 degrees. This is more or less parallel to the coastline in the nourished zone (Kruyt, 1995). More than 12% of the total number of observations is in the sector 210-240 degrees. In addition, wind forces between 3 and 6 Bf make up 79% of the total number of observations in the data set. The year 1994, just following the nourishment, appears to be a year with a relatively large number of storms with a considerable duration (Kruyt, 1995).

The wave climate of Terschelling has been analysed by Van Beek (1995). Nearly 65% of the total number of wave observations is related to obliquely incident waves from the West to North (270-360 degrees; Fig. 3). The most energetic wave fields are incident from the NW to NNW. This almost coincides with a shore-normal direction (Fig. 3). The average annual significant wave height ($H_{1/3}$) and significant wave period ($T_{1/3}$) for 1994 are 1.08 m (st.dev. ± 0.67 m) and 7.0 s (st.dev ± 1.4 s), respectively. For only 2% of the total distribution, wave heights are higher than 3 m (Van Beek, 1995). However, as already mentioned before, in the first three months following the nourishment a number of significant storm events with high seas and swell have been recorded in the study area: November 15, 1993 ($H_{1/3}$ = 5.50 m; data correspond to peak of the storm), December 10, 1993 ($H_{1/3}$ = 5.50 m), December 20, 1993 ($H_{1/3}$ = 5.00 m), January 24, 1994 ($H_{1/3}$ = 4.25 m) and January 28-29, 1994 ($H_{1/3}$ = 8 m; all data based on WAVEC observations offshore).

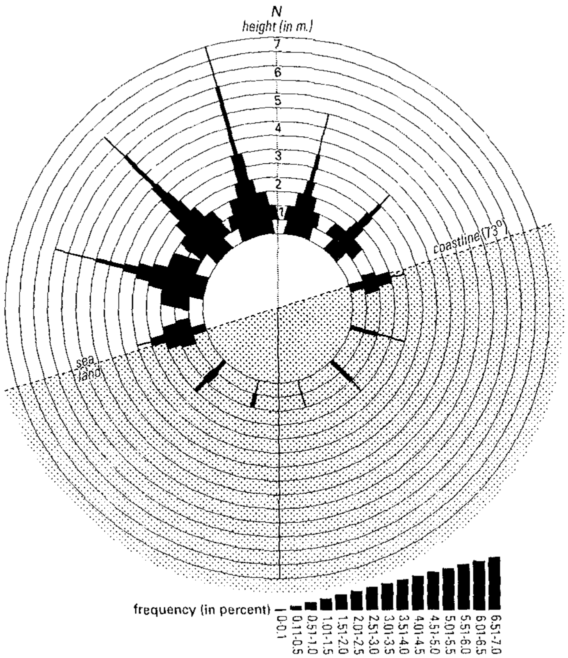

Figure 3. Offshore wave climate for the coast of Terschelling

Morphological evolution and sediment volumes

Coastal behaviour prior to the nourishment

The natural behaviour of the nearshore zone before the nourishment was studied in detail by Ruessink and Kroon (1994). Herein, both the alongshore and cross-shore tendencies of especially the long-term evolution of the nearshore breaker bars was discussed. In particular, the (geometrical) properties and dynamics of these bars, like their position and depth, were documented in time from 1965 to 1993. With the results of this study, the following conclusions were obtained:

- The cross-shore behaviour of bars is strongly influenced by an alongshore migration of bar attachment-points. Migration rates of these attachment-points are highly variable and can be in the order of 1200 m.year^{-1}.
- The cross-shore behaviour of a bar is schematized in *three phases*: 1) generation close to the shore; 2) seaward migration from 300 to 1300 m offshore and 3) bar degeneration when the crest of the bar is at a depth of about -5.5 m NAP. There is a coupling mechanism involved: as soon as the outer bar disappears the inner is triggered, leaves phase 1 and enters phase 2.

This typical cyclic behaviour, also found along other parts of the Dutch coast (see for example Wijnberg, 1995), has a total period of about 12-15 years (Ruessink and Kroon, 1994).

Morphological response of the nourishment

The morphological behaviour of the nearshore zone in the post-nourishment conditions has been studied and reported by e.g. Kroon et al (1995) and Westlake (1995) and summarizing their results indicates the following trends (Hoekstra et al, 1996):

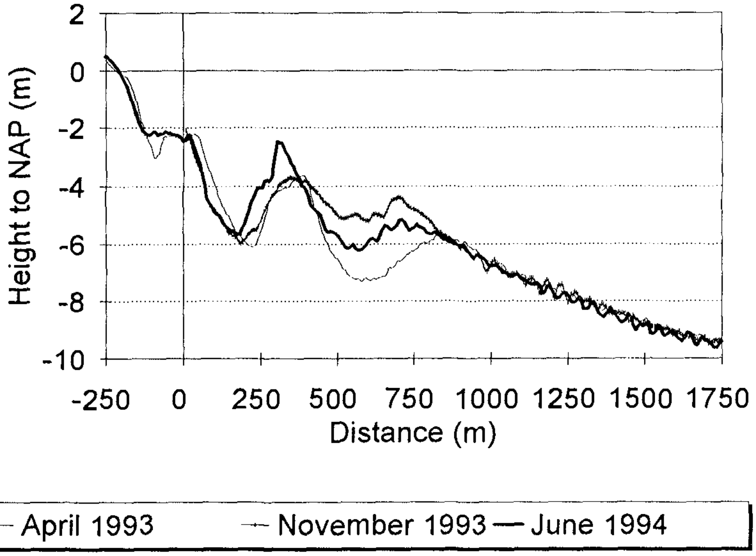

Figure 4. Morphological development of the cross-shore profile of section 17 after the nourishment

- the nearshore morphology inside and outside the nourished zone is becoming strongly 3-dimensional due to the presence of crescentic bars, the presence and migration of bar attachment points and drumstick-shaped nearshore breaker bars, separated by obliquely oriented rip channels. Such a pronounced development of a 3D morphological system has never been experienced in the past (Ruessink and Kroon, 1994);
- the disturbed bar-trough morphology caused by the nourishment is quickly adjusting itself and the former bar-trough pattern appears again (Fig. 4); the time of adjustment is rather short and the strongest response is visible in the first 150 days following the nourishment and the process slows down afterwards;
- the initial morphological response results in an extreme growth of the landward located middle bar and the adaptation of the profile is associated with a dominantly onshore movement of sediment (Fig.4);
- the western part of the nourishment is predominantly eroding whereas the eastern part shows accretion: the nourishment clearly migrates in an alongshore direction, towards the ENE (Fig. 1) at a variable rate of 280-320 m/yr (1994) or 400-420 m/yr (1995; Westlake, 1995).

As a matter of fact, (nourished) sediment is dominantly moving in an onshore and longshore (eastward) direction.

Sediment volumes

The consecutive bathymetric maps are now used in a more quantitative sense to identify areas of erosion and deposition and to compute the change in sediment volume in well-defined control sections. The computations have been reported previously by Westlake (1995). The selected control-sections are presented in Fig. 5 and are related to the nourished zone itself, areas landward and seaward of the nourishment and "reference" areas in both the East and West.

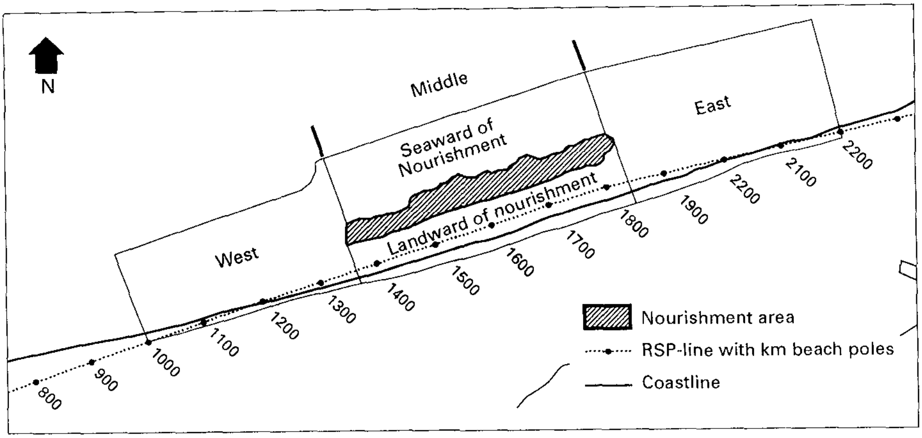

Figure 5. Control sections for volumetric computations of sediment budgets

The analysis of individual soundings occasionally shows the presence of systematic errors in the data sets and related bathymetric maps which may cause substantial inaccuracies in volume calculations. To reduce the effect of individual errors, results concerning the behaviour and effectiveness of the nourishment are based on the average linear trends in volumes, deduced from the total sequence of soundings, rather than the individual difference calculated for just two separate soundings (Westlake, 1995).
In total, the nourished volume of sediment is about 2.0 million m^3. In general it's rather difficult to assess whether there is an overall conservation of sediment volumes in the entire research area. For the most important sections though a number of trends are very consistent, as illustrated by Fig. 6. The nourishment area clearly shows erosion and the areas landward of the nourishment are definitely accreting. Remarkably though is the fact that the area landward of the nourishment is accreting at about twice the rate the nourishment is eroding. The nourished surface has lost about 560.000 m^3 of sediment. Part of this sediment - a conservative estimate is approximately 100.000 m^3 - is related to the alongshore migration of the nourishment. Meanwhile though, landward of the nourished zone a total gain of about 1.1 million m^3 of sediment is observed. And even if potential survey errors are taken into account, the order of magnitude of the difference suggests that the landward gain of sediment is not simply explained by a cross-shore redistribution of sediment. Significant longshore sediment transport gradients have to exist as well.

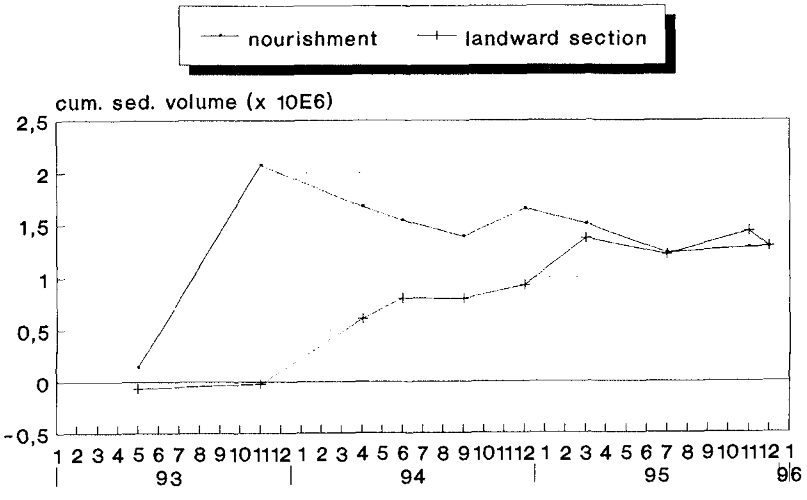

Figure 6. Cumulative sediment volumes for the nourished zone and the section landward of the nourishment

The frequent occurrence of storms and heavy storms in the period after the nourishment is predominantly held responsible for the relative rapid evolution of the nourished profiles and sediment volumes. This rapid response of the nearshore morphology is probably not fully representative for average conditions along the Terschelling coast.

The onshore directed redistribution of sediment certainly implies that the Terschelling shoreface nourishment has satisfied the design objective: the momentary or yearly computed coastline is estimated to have migrated seaward over a distance of about 16 m/yr (Biegel and Spanhoff, 1996). This totally reverses and exceeds the assumed retreat over the same period which should have been approximately 3 m/yr.
Based on the results of the present analysis, the Terschelling shoreface nourishment *only partly acts as a feeder berm.* Approximately 40% of the total gain of sediment in the inner nearshore can be explained by direct losses in the nourished zone. The success of the nourishment is not simply the result of the onshore movement of sediment from the nourishment. Accretionary processes in relation to longshore sediment transport gradients are probably equally important.

Cross-shore sediment transport processes

The partially, onshore-directed movement of sediment from the feeder berm has to be the result of cross-shore sediment transport processes. The transport study carried out in the framework of the Terschelling shoreface nourishment has focussed on both the dominant processes as well as dominant conditions that are mainly responsible for the onshore-directed fluxes of sediment. In this sediment transport analysis (Houwman and Ruessink, 1997) four main issues are adressed:

1) the contribution of oscillating and mean suspended transport to the net suspended transport;
2) the relative importance of high- and low-frequency suspended transport to the total oscillating suspended transport;
3) the ratio between hedload and suspended load;
4) the transport conditions under which most sediment is transported on the time scale of months to years.

Sediment transport measurements carried out in October and November 1995 (T4 campaign) at location F3 (Fig. 2) are selected to illustrate a numher of features. Location F3 is one of the most interesting positions with respect to the hydrodynamic and sediment transport processes affecting the behaviour of the nourishment.

Some additional information is given here (Houwman and Ruessink, 1997):

- time series of u (cross-shore), v (longshore) and c (concentration) were divided in a mean and oscillating part; the net cross-shore suspended sediment transport, for example, is given hy:

$$<u.c> = <\bar{u}.\bar{c}> + <u'.c'>$$

  The net suspended sediment transport (left hand side) is hased on the transport by mean currents (first term right hand side) and the oscillating transport (e.g the effect of wave asymmetry; 2nd term on the right). A positive cross-shore and longshore transport is onshore and eastward directed, respectively;
- the oscillating term is sub-divided into a high- and low-frequency part; the separation frequency between hoth was set to 0.04 Hz;
- cross-spectral analysis was applied to yield information about phase and coherence between u' and c' as a function of frequency.

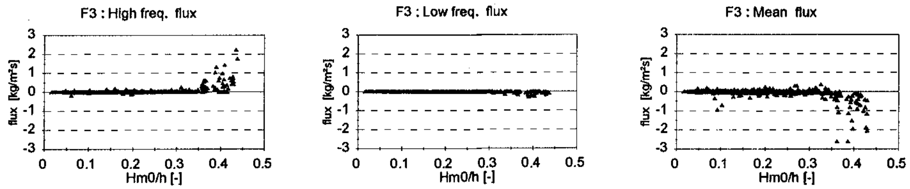

Figure 7. Cross-shore sediment fluxes measured at tripod F3 at 0.15 m above the bed (T4 campaign): high- and low-frequency ($f < 0.04$ Hz) fluxes and mean fluxes, respectively

Burst-averaged values (burst: measuring series of 34 minutes per hour with a sampling frequency of 2 Hz) of the high- and low-frequency oscillating fluxes in a cross-shore direction and at a height of 0.15 m above the bed are plotted in Fig. 7 as a function of local relative wave height (Hm0/h). The factor Hm0/h accounts for both variations in wave climate as well as (tide-induced) fluctuations in water depth. Non-zero fluxes only occured for Hm0/h larger than about 0.30-0.35, in other words, during situations that were just outside, or inside the surfzone. High-frequency fluxes were in an onshore direction and were associated with the horizontal asymmetry of the incident short waves, i.e. the difference in magnitude between onshore and offshore orbital velocity. Low-frequency fluxes were seaward directed and were caused by the dominance of bound long waves in the total long wave field (Ruessink, 1996). For this sensor height, the low-frequency sediment flux was only about 16% of the high-frequency one, averaged over the entire campaign.

Burst-averaged values of the mean flux for the T4 campaign are shown in Fig.7 as well, again as a function of relative wave height Hm0/h. The largest fluxes, which were in a seaward direction, occured for situations with the ratio Hm0/h above 0.3-0.35. This indicates that these negative fluxes were associated with wave-driven undertows. The mean flux was larger than the total oscillating flux (i.e. the sum of high- and low-frequency flux) averaged over the entire campaign. Consequently, the net flux was in an offshore direction. In addition, it is also clear that the (high-frequency) oscillating fluxes can not be neglected.

To estimate the long-term bedload and suspended load transport in the surfzone, the sediment transport is calculated with the Bailard model (Bailard, 1981) and the adapted Van Rijn/Ribberink model (Van Rijn, 1993). The suspended load component of the Van Rijn model does not include the oscillating suspended load transport. For that reason, Houwman and Ruessink (1997) incorporated an oscillating suspended load term in the model in a parameterized way.

Summarizing all measurements and modelling results (Houwman and Ruessink, 1997) it becomes obvious that the measured and computed cross-shore sediment transport fluxes (for Terscheling) are reasonably related to a dimensionless wave height (Hm0/h). This term can also be interpreted as a breaker coefficient and it turns out that sediment fluxes increase with Hm0/h. By making use of a probability density function for the term Hm0/h, it appears that the suspended sediment transport on a time scale of months to years is typically related to breaking wave conditions ($Hm0/h > 0.33$); in other words is limited to situations inside the surfzone. It also supports the view that the relative rapid evolution of the Terschelling shoreface nourishment is partly related to the frequent occurrence of storms in the period just following the nourishment.

Both measurements and modelling efforts also demonstrate that wave asymmetry is primarily responsible for the potential onshore movement of sediment; this sediment is mainly transported as suspended load by the oscillating flow related to seas and swell (high-frequency oscillating suspended load). Bedload, according to results obtained with the Van Rijn/Ribberink model, is of lesser importance.

However, the actual fate of the feeder berm is determined by a delicate balance of offshore directed mean fluxes and onshore directed oscillating fluxes. Paradoxically, in these conditions the contribution of some minor transport components, such as bedload and the effect of low-frequency waves, may eventually explain the success or failure of the nourishment. It's clear though that there is no significant and consistent net landward directed sediment transport in the nearshore zone. Therefore, it's not surprising that only part of the nourished sediment is moving in an onshore direction.

The observations make clear that it's not realistic to come up with a proper and reliable sediment balance for the area, based on sediment transport measurements and model computations.

Longshore sediment transport processes

Breaker berm and longshore sediment transport

The classic concept of a feeder berm is the idea that a cross-shore redistribution of sediment is mainly responsible for nourishing the upper part of the profile. Meanwhile, for the Terschelling coast, it's becoming quite evident that longshore processes are expected to be equally important. This is, for example, illustrated by the computations of sediment budgets inside and landward of the nourished zone, the longshore migration of the nourishment and the potential breaker berm function of the combination shoreface nourishment/nearshore breaker bar.

The breaker berm function is evaluated by using the UNIBEST-TC model. UNIBEST-TC is a morphodynamic coastal profile model (Roelvink et al, 1996). Application of the model required quite a lot of validation and calibration runs. During this process the model was further modified by using Terschelling data. Results of wave decay were obtained with the UNIBEST-TC model after considerable tuning of the model for wave heights using the breaker index (H/h) and the bottom friction factor f_w (Bakker, 1995 and Roelvink et al, 1996).

Model computations were carried out using measurements and conditions observed during the T2 campaign (May-June, 1994). The morphological boundary conditions are presented in Fig. 4. For all computations it is clear, that there commonly is a gradual reduction in wave heights across the seaward side of the profile and over the nourished zone. The wave dissipation is primarily due to bottom friction. A rapid decay in wave heights, though, is observed across the landward located middle bar (Fig. 1 and 4; Hoekstra et al, 1996). Here, wave breaking is the prime reason for a rapid decay in wave heights. In the landward located trough the wave field propagates without any major modifications. The model simulations definitely indicate that the design of the present shoreface nourishment not necessarily leads to an increase in wave energy dissipation: it is essentially the interaction of the shoreface nourishment with the nearshore breaker bars (Fig. 4) that is effective in reducing the landward propagating wave energy. Indirectly nourishing the middle bar is considered to be an effective method to construct or maintain a natural breaker berm.

The longshore transport module of the UNIBEST-TC model is further applied to study to what extent longshore sediment transport rates and gradients in these rates are initially affected by the presence of the nourishment. The influence of the nourishment on longshore sediment transport patterns was determined by computing the cumulative longshore transports for a profile with (T1-condition) and without (T0-condition) a nourishment (Fig. 8). The measured wave climate for approximately the first 160 days since the implementation of the nourishment was used as input for the model, in combination with the recorded (tidal) water levels. The effect of tidal currents, however, was omitted. Every 3 hours a longshore transport computation was carried out; results are given in Fig. 8.

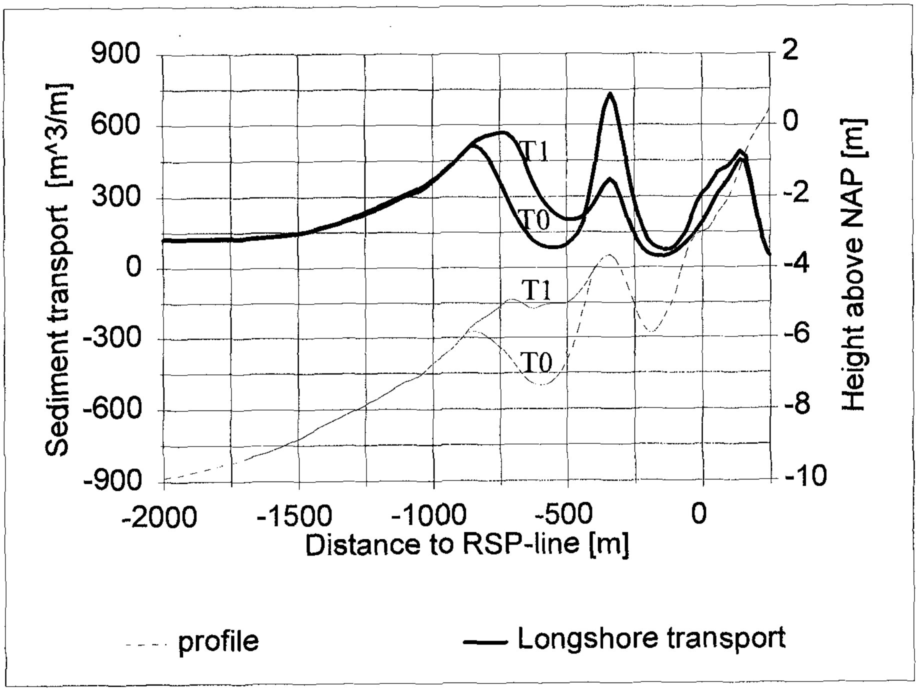

Figure 8. Cross-shore distribution of cumulative longshore sediment transport for conditions with and without a nourishment and for a period of about 160 days just following the nourishment

The net longshore sediment transport in the nearshore zone is predominantly towards the East (compare Fig. 3). Going from West to East - or from a non-nourished profile to a nourished one - longshore sediment transport in the trough is smaller than on the nourishment (Fig. 8). As a result, the West side of the nourishment will be eroding.

Sediment transport on the middle bar, by contrast, will be lower upon entering the nourished zone, which creates accretion on top of the bar (Fig. 8). On the nourished surface no transport gradients are expected to develop due to the longshore uniformity. On the downdrift side, however, longshore sediment transport patterns change again. The sediment transport on the nourished surface is larger than in the trough and the trough is gradually filled up with sediment. Simultaneously, the top of the middle bar shows erosion. The net effect is a gradual longshore migration of the nourishment towards the East, as observed for the Terschelling case.

The leeside deposition on the updrift side of the nourishment or breaker berm is commonly referred to as the salient effect. It probably partly explains the fact that the accretion in the cross-shore profiles landward of the nourished zone may exceed the losses from the nourishment. A salient is also frequently associated with erosion at a downdrift section of the coast. For the time being, no clear erosional patterns have developed yet.

In conclusion, longshore sediment transport gradients are important for understanding the behaviour of the nourishment. These gradients are responsible for the longshore migration of the nourishment and they can also partly explain the additional input of sediment in the inner nearshore zone.

Conclusions

The Terschelling shoreface nourishment has completely satisfied the design objectives in the first 2.5 years since the implementation. The nourishment not only compensates for the annual coastal retreat of about 3m/yr, but results in a net seaward migration of the momentary or yearly computed coastline of about 16 m/yr. The nourishment only partly acts as a feeder berm and the actual success of the nourishment is also based on the "interception" of longshore sediment transport due to the creation of a wave shadow zone and the salient effect. The combination of middle bar and shoreface nourishment effectively acts as a breaker berm.

Wave asymmetry is primarily responsible for the potential onshore movement of (nourished) sediment. This sediment is mainly transported in the form of a high-frequency oscillating suspended flux due to seas and swell. Bedload transport is of minor importance. In addition, the long-term suspended sediment transport from the nourished zone into an onshore direction is mainly related to breaking wave conditions (Hm0/h > 0.33). The net cross-shore suspended load flux, however, is determined by a very sensitive balance of two large components: a large offshore directed mean suspended flux due to currents is opposed by a large onshore directed oscillating flux due to waves. In these conditions the contributions of some minor transport components, such as bedload and the oscillating flux due to low-frequency waves, may eventually determine the behaviour of the nourishment.

Acknowledgements

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