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Rijksinstituut voor Kust en Zee/RIKZ

Analysis and modelling of shoreface nourishments

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L.C. van Rijn and D.J.R. Walstra

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ABSTRACT:

Shoreface nourishments are regularly carried out at many beaches along the coast of The Netherlands with the aim to maintain the sand budget in the nearshore zone at a predefined volume and the supply of sand to the beaches in the lee of the nourishments. This study is focussed on the evaluation of these types of nourishments with regard to both the physical characteritics and the performance of modelling approaches.

Three shoreface nourishment in The Netherlands are studied in more detail:

- Terschelling nourishment project,
- Egmond nourishment project,
- Delfland nourishment project.

These projects have been selected because they represent typical examples of the varying hydrodynamic and morphodynamic conditions in The Netherlands. The Terschelling nourishment case concerns a shoreface nourishment along a barrier island coast (in the Dutch Wadden Sea) with a pronounced three bar system and a dominant net longshore drift to the east. The Egmond case is situated along the straight northern Holland coast with a two bar system and a relatively small net longshore drift. The Delfland case is located along the straight southern Holland coast (close to the access channel to the Port of Rotterdam) without major breakers bars and a relatively small net longshore drift.

Both the results of earlier field data analyses including data form outside The Netherlands (Chapter 2) and mathematical model studies (Chapter 3) related to the period 2000 to 2004 are considered in this report, which has been composed by L.C. van Rijn and D.J.R. Walstra and reviewed by R. Spanhoff of Rijkswaterstaat/RIKZ.

The results of the data analysis and model exercises broadly confirm the hypotheses on the hydrodynamic and morphodynamic functioning of shoreface nourishments, which can be summarized as lee effects (partly blocking of littoral drift) and feeder effects (onshore movement of sand).

REFERENCES: Contract RKZ 1392

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Contents

1 Introduction

1.1 Problem and approach

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Both the results of earlier field data analyses including data form outside The Netherlands (Chapter 2) and mathematical model studies (Chapter 3) performed in the period 2000 to 2004 are discussed in this report.
Model results based on the profile model UNIBEST-TC for the shoreface nourishments at Terschelling, Egmond and Delfland in the period before 2000 have been presented by Roelvink et al. (1995), Boers (1999) and Delft Hydraulics (1997), but these latter publications are not discussed extensively in this report.

The present report has been composed by L.C. van Rijn and D.J.R. Walstra and reviewed by R. Spanhoff of Rijkswaterstaat/RIKZ.

1.2 Types of nourishments

Sand nourishment is the mechanical placement of sand on the beach and/or shoreface to advance the shoreline or to maintain the volume of sand in the littoral system. It is a soft protective and remedial measure that leaves the nearshore zone in a more natural state than hard structures and preserves its recreational value. The method is relatively cheap if the sand mining area is not too far away.

The objectives of nourishments generally are (see Figures 1.1 and 1.2):

- maintenance of shoreline (chronic erosion or lee-side erosion);
- formation/restoration of recreational beach;
- land reclamation;
- reinforcement of dunes against breaching (landward or seaward);
- protection of coastal structures (seawalls, groynes,etc.);
- filling/closure of scour channels or tidal channels close to shoreline.

A sand nourishment area functions as an eroding buffer zone. Therefore, the initial volume should be as large as possible (overfill). It also is a temporary measure as the natural littoral processes (causing erosion) remain unaltered. Regular maintenance is required. Maintenance can be reduced by using relatively coarse sand as fill material.
Nourishment volumes in Europe are about 30 million m^3 per year (about 6 million m^3/yr in The Netherlands and 3 million m^3/yr in Denmark). A similar volume is nourished in the USA. Sand nourishment can be carried out at various locations in the profile and along the shoreline (Figure 1.1).

The options are:

- ***shoreface zone*:** nearshore nourishments, berms or mounds are constructed from dredged material; two types of berms have been applied:
  - feeder berms: placement of sediment material in shallow water to create an artificial longshore bar and to promote the feed of sediment to the beach by onshore transport processes; if bars are present the berm generally is placed on the seaward flank of the most offshore bar (draft of dredger is mostly larger than water depth above bar crest);
  - reef berms: placement of sediment material seaward of closure depth to act as a reef-type wave filter for storm waves;
- ***beach and surf zone*:** sand is dumped as high as possible on the beach to obtain a recreational beach in combination with revetments, groynes, detached breakwaters and submerged sills; dumping of sand can be done as:
  - an elongated buffer layer of sand on the beach (direct placement for recreational beach or for protection of a structure or in an environment with dominant offshore transport), or
  - a continuous source at one or more specific locations (dump site of bypassing plant or stock pile); landward of high tide line at updrift side of eroded section for maintenance of shoreline;
- ***dune zone*** (landward and seaward above dune toe level): dune is reinforced/protected against breaching during storms.

Sand nourishment can be seen as a perturbation to the littoral system, both in planform and in profile, resulting in:

- steeper initial beach profile and hence increased wave attack and relatively large initial erosional losses; the profile will adjust exponentially to the original profile;
- generation and growth of the offshore bar due to deposition of sand eroded from the nourished zone, reducing nearshore wave energy;
- longshore redistribution of the planform of the beach fill by wave- and current-induced processes, starting at the end sections.

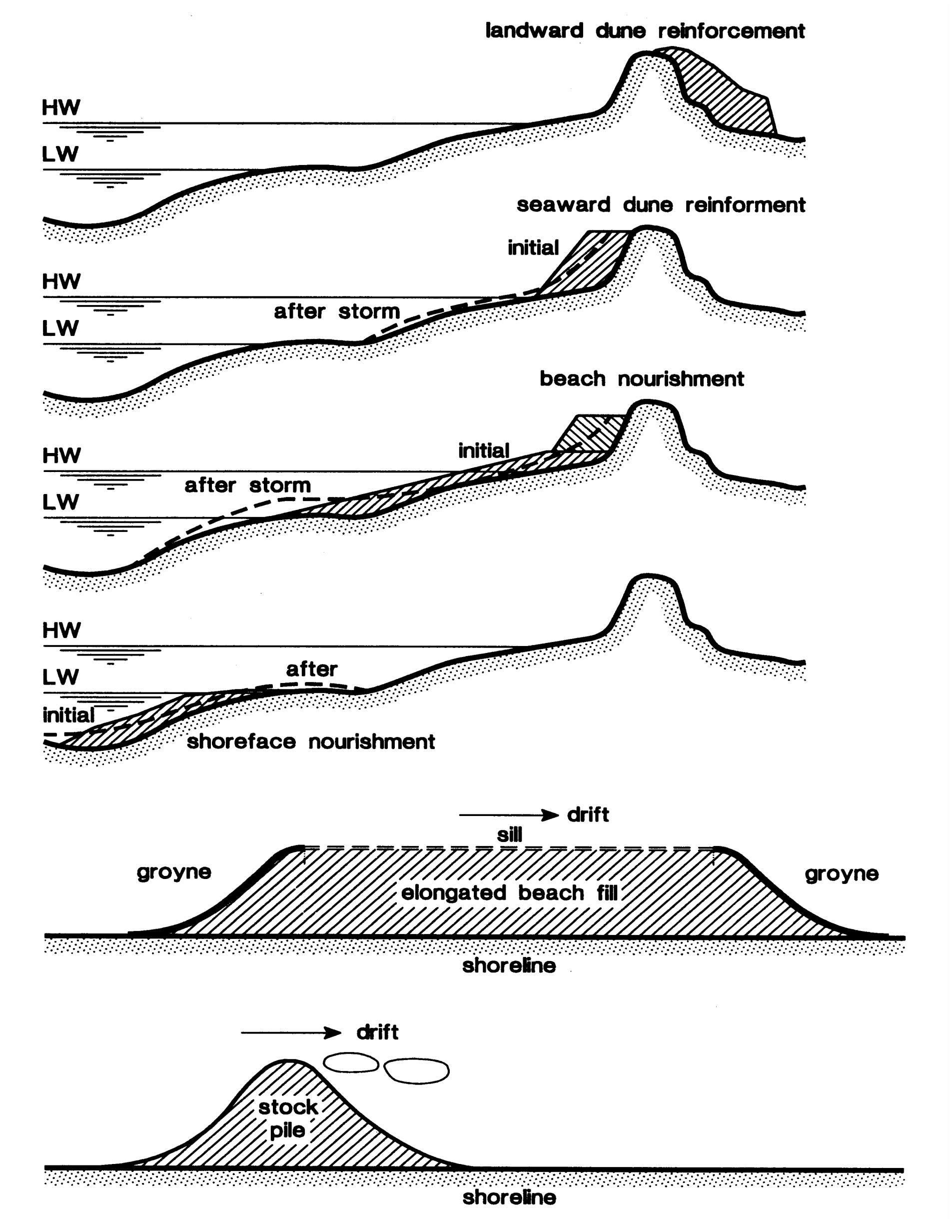


Figure 1.1 *Dune, beach and shoreface nourishments*
Top: Cross-shore profiles
Bottom: Planforms

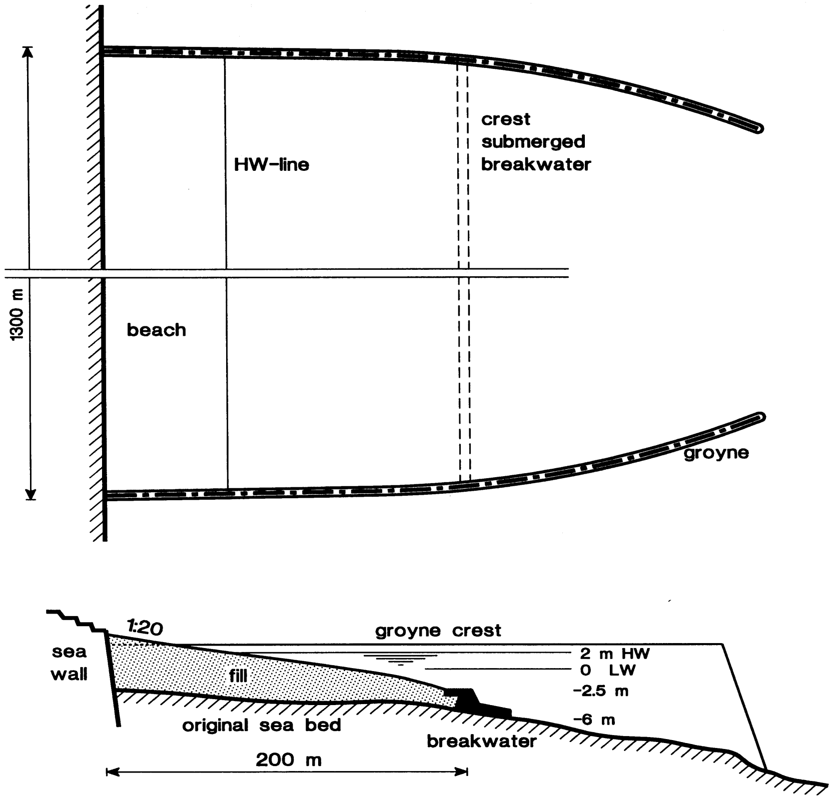


Figure 1.2 *Recreational beach fill in front of seawall*

1.3 Shoreface nourishments

Herein, the attention will be focussed on shoreface nourishments which are also known as artificial feeder berms or artificial reef berms.

Two types of submerged nearshore berms can be distinguished:

- stable reef berms and
- active feeder berms.

Submerged berms can be designed as ‘stable’ or as ‘active’ bodies of sand. Stable means that the berm only has a hydrodynamic effect by functioning as a wave filter dissipating the energy of the larger breaking waves and creating a sheltered area in the lee of the berm. Most of the original volume of a stable berm is retained and the berm may remain at the placement site in deeper water (water depth > 10 to 15 m) for years. An active feeder berm is placed at a nearshore site in relatively shallow water (water depth < 8 m), where it will show significant dispersal of sediment within a few years. It is supposed to act as a feeder berm for the adjacent beaches. Regular maintenance of the feeder berm is required to ensure a continuous flow of sediment to the beaches.

The basic characteristics of these berm-type structures are:

- dissipation of wave energy by breaking processes during storm events; the berm acts as a selective wave filter; low waves can pass unhindered, whereas large erosive waves will break;
- reduction of wave-driven longshore currents in the lee of the berm;
- generation of set-up currents at end sections;
- generation of low-frequency waves in lee of the berm;

- trapping of sand in the lee of the berm and updrift of the berm due to partial blocking of the wave-driven longshore current; downdrift erosion may occur;
- flow of sediments to beach in the case of the presence of a feeder berm.

Low-frequency waves will be present in the lee of berms. The low-frequency wave field will consist of bound long waves, if the incident short wave groups do not break on the berm slope. Free long waves may be generated at the discontinuity at the edge of the berm slope. Both types of low-frequency waves may generate large second order water level fluctuations, which may be as large as 15% to 25% of that of the incident short waves . In conditions with breaking short waves on the berm slope, the short wave group structure is greatly disturbed and the bound long waves are released as free long waves.

Nearshore feeder berms are designed with the intent of creating a submerged berm dissipating wave energy in combination with feed of sediment to the beach. The berm should be parallel to the shoreline with a length of at least 10 times the local wave length. The crest width should be about 0.5 to 1 times the local wave length (about 5 to 10 times the local water depth). The side slopes should be about 1 to 30/50. The end slopes should be gentle (say 1 to 100) to reduce wave focusing effects by refraction at more inshore locations. The dump location should be relatively far away from nearby sinks (deep navigation channels, back-barrier basins).

1.4 Objectives of shoreface nourishment design in The Netherlands

The primary objective of shoreface nourishments in The Netherlands is to maintain the momentary coast line (MCL) seaward of a predefined Basal Coastline (BCL) during the design life, which typically is 5 year as in the case of recent beach nourishments (see **Spanhoff et al., 2003**).

Shoreface nourishments also have the additional purpose to extend the life's of corresponding beach nourishments placed at roughly the same time (and location).

Other objectives of shoreface nourishments are to maintain the dune foot position, beach volume and beach width.

In 1990 the Dutch Government adopted a national policy of "Dynamic Preservation" in order to stop any further structural recession of the Dutch coast beyond an adopted minimum "Basal Coast Line (BCL)". The MCL position is derived from the measured sand volumes (JARKUS database) while the position for the year(s) to come is derived from an extrapolation of a linear regression to the MCL positions in the last 10 years. The MCL volume is bounded by two adopted horizontal levels, one at dune foot level (most places NAP+3m, NAP being the Dutch ordnance datum that roughly lies at mean sea level) and the other a distance 2H lower (H = distance dune foot level to MLW level), by the profile, and by a vertical line through the crossing of the profile and the dune foot level. Part of the crest of a breaker bar, when close enough to sea level, may contribute to the volume. Dividing this volume by 2H gives a horizontal distance from the measured dune foot position, which is next related to a fixed reference system to obtain the MCL in that system. Deriving the MCL from a volume, rather than taking an occasional position, as well as from a 10-year trend, rather than taking a single value from one survey, makes the extrapolated value less prone to intra- and interannual fluctuations.

Shoreface nourishments are placed (largely) below the MCL zone and the expectation is that in time the MCL zone will gain sand in response to the nourishment (*e.g.* by cross-shore profile adjustments). Usually, the maximum gain in the MCL zone will only be a fraction of the initial nourished volume. To account for this relatively small contribution, twice as much sand (per meter along the shore) is nourished as would have been done in case of a beach nourishment. As the price per m^3 sand of a shoreface nourishment is (less than) half of that of a beach nourishment, the total costs for both options (shoreface or beach nourishment) are of the same order.

1.5 Hypotheses with respect to functioning of shoreface nourishments

The morphological effects (herein referred to as hypotheses) of properly designed feeder berms can be schematized, as follows (see also Figure 1.3):

1) longshore effect: large waves break at the shoreface nourishment causing a calmer wave climate directly behind the shoreface nourishment area (wave filter) and a reduction of the longshore current and hence the transport capacity. The shoreface nourishment acts as a blockade, resulting in (see also **Delft Hydraulics, 2001**):

- a decrease of the longshore transport;
- updrift sedimentation;
- downdrift erosion.

2) cross-shore effect: during fairweather conditions (post –storm events) larger waves break at the seaward side of the shoreface nourishment; remaining shoaling waves generate onshore transport due to wave asymmetry over the nourishment area; the smaller waves in the lee-side generate less stirring of the sediment and the wave-induced return flow (cross-shore currents) reduces resulting in a decrease of the offshore sediment transport; both effects correspond to sediment increase in the area shoreward (lee-side) of shoreface nourishment area (see also **Delft Hydraulics, 2001**).
This results in:

- an increase of the onshore sediment transport;
- a reduction of the offshore sediment transport.

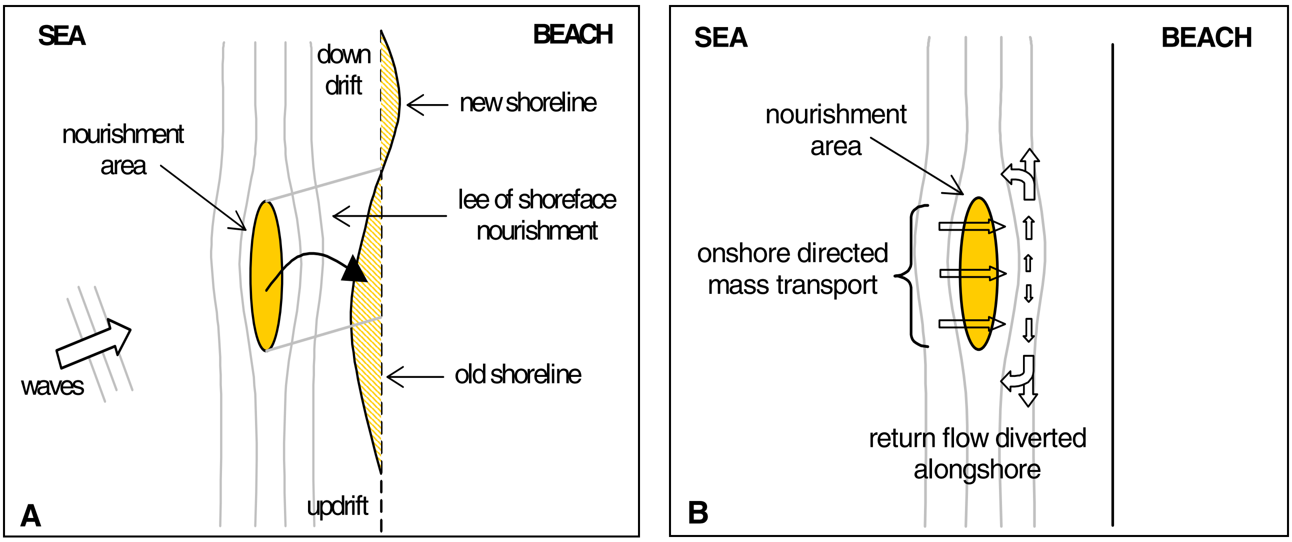


Figure 1.3 *Effects expected to occur as a consequence of the placement of a shoreface nourishment*

1.6 Bars in the surf zone

As shoreface nourishments in shallow water (surf zone) will interfere with surf zone bars, these bars and available bar generation concepts are briefly discussed.

Sand bars are major features of many surf zones found in nature. Bars usually contain large volumes of sand, which is of importance for the nearshore sediment budget and beach variability. Bars also provide a natural barrier to incident wave attack by dissipating wave energy through the process of wave breaking (front line of coastal defence). At places where the bar system is interrupted by rip channels, often localized shoreline erosion is observed indicating the importance of the protective function of the bar system.

The bars of the surf zone, also known as longshore bars, submarine bars, nearshore bars or break-point bars, are always submerged (submarine or subtidal); break-point bars do not grow above the high water level to become offshore barriers

Various types of subtidal surf zone bar systems have been observed in the nearshore area:

- straight shore-parallel (continuous or discontinuous/segmented) bars,
- oblique shore-attached bars,
- three-dimensional irregular bars and/or rhythmic bars (cusp-type form, sinuous, single/double crescentic),
- shore-normal (transverse) bars.

Straight shore-parallel bars are common features along uniform dissipative beaches. They are also described as longshore bar and trough systems. Generally, the cross-shore shape of shore-parallel bars is almost symmetric in the outer surf zone and more asymmetric in the middle and inner surf zone. Sand bars are rarely in equilibrium, because the response time of a bar often is longer than the time period with approximately steady wave conditions. The outer bar of the surf zone usually is much larger than the inner bar and consequently the response time also is larger. Small isolated bars (mini-bars) with minor relief may locally be present between the middle and the inner bar, crossing the trough between both bar systems in landward direction. These mini-bars seem to be generated at discontinuities of the middle bar system.

Facies analysis shows the presence of small-scale bed forms (wave-induced ripples) on the seaward slopes of the longshore bar systems, parallel laminations and cross-bedding lunate megaripples on the bar crests, low-angle laminations and cross-bedding ripples on the landward slopes of the bars and cross-bedding ripples (current-induced) in the bar troughs.

Oblique shore-attached bars are features that are attached to the shore at their landward side. Their seaward side may be recurved, ending parallel to the shore. Generally, they are located just below the low-tide water level. Their morphology includes rip and feeder channels.

Three-dimensional Rhythmic bar patterns in longshore direction may be the result of periodic (meandering) longshore currents due to periodic longshore variations in wave set-up produced by small perturbations of the (oblique) incident wave field or may be the result of meandering mass transport velocities due to longshore standing wave systems.

Shore-normal (or transverse) bars with heights between 0.2 and 1 m and lengths of the order of 100 m are bars with their crest axis more or less normal to the shore and are often connected to the beach by cusp-type features (horns). Rip-type currents may be generated through the trough zone of these features. Generally, these low-relief bars have been observed in shallow surf zones with slopes flatter than 1 to 100 in low wave-energy conditions.

The following bar generation concepts have been proposed in the literature (see **Van Rijn, 1998**):

a. Harmonic wave overtake concept,

b. Break-point concept,

  b1 Plunging breaker concept,

  b2 Spilling-shoaling convergence concept,

c. Low-frequency wave concept,

  c1 Standing wave-mass transport concept,

  c2 Short wave-long wave interaction concept.

Recently (**Reniers et al., 2004**) using a two-dimensional horizontal model approach showed that horizontal circulations due to wave group forcing can result in the morphodynamic development of an alongshore quasi-periodic bathymetry of shore-normal shoals cut by rip channels in the nearshore zone.

2 Review of shoreface nourishment projects

2.1 Introduction

In this chapter 2 various shoreface nourishment projects both in The Netherlands and elsewhere, will be reviewed based on field data analysis.
Section 2.2: Shoreface nourishments in micro-tidal conditions outside The Netherlands;
Section 2.3: Shoreface nourishments in meso-tidal and macro-tidal conditions;
2.3.1 Outside the Netherlands
2.3.2 Inside The Netherlands
Section 2.4: Conclusions

2.2 Shoreface nourishments in micro-tidal conditions outside The Netherlands

McLellan (1990) summarizes field experiences with berm construction in the USA. Ten sites have been identified where nearshore berms have been made by using suitable dredged materials with the aim to reduce erosive energy on the coastline and to increase the net volume of material in the sediment transport system.

Hands and Allison (1991) propose a new method for estimating the design depth for either stable reef berms or active feeder berms of dumped dredgings. This method is based on the use of Hallermeier's limits of profile zonation and defined as Hallermeier's Inner Limit (HIL) and Hallermeier's Outer Limit (HOL). These limits bound a buffer zone in which surface waves have neither strong or negligible effects on the sand bed during a typical year. Active feeder berms must generally be placed landward of the HIL to ensure its inclusion in the annually active littoral zone. HOL is the maximum water depth of sediment movement initiation by annual mean wave conditions. A reef berm must be placed seaward of the HOL to remain stable on long term. The method was confirmed by results of the behaviour of eleven berms at various USA sites. The berms were classified as active or stable based on repeated surveys.

Ahrens and Hands (1998) have summarized the morphological data of 12 dredged mounds (feeder berms) in depths between 2 and 16 m (grain sizes d_{50} between 0.13 and 0.5 mm) at various USA-sites. Most berms were observed to move onshore; some berms remained stable; no berms were observed to move seawards.

Andrassy (1991) and **Larson and Kraus (1992)** describe the behaviour of a nearshore feeder berm of sand off Silver Strand State Park (near San Diego) facing the Pacific Ocean (USA). The dimensions of the berm were approximately 360 m alongshore and 200 m across shore, with an average relief of 2 m. The seaward toe of the berm was at the -9 m contour (about 450 m offshore); the landward toe was at the -5 m contour (about 250 m offshore). The local bottom slope is quite steep (1 to 50). The water depth above the crest of the berm is about 3.5 m. The native sediment at the placement site consisted of well-sorted fine to medium sand (0.25 mm) down to a water depth of 5.5 m (below MLLW= 0.85 m below MSL), and of fine-grained silty sand seaward of this depth. The median grain size of the berm was about 0.2 mm. The response of the berm was monitored along eight profile lines between 19 January 1989 and 18 May 1989. Waves were recorded at 10 m water depth. The mean significant wave height for the measurement period between January and May was 0.62 m; the mean spectral peak period was about 13 s. The maximum significant wave height was about 1.65 m. The mean water temperature during the measurement period was about 15 °C.

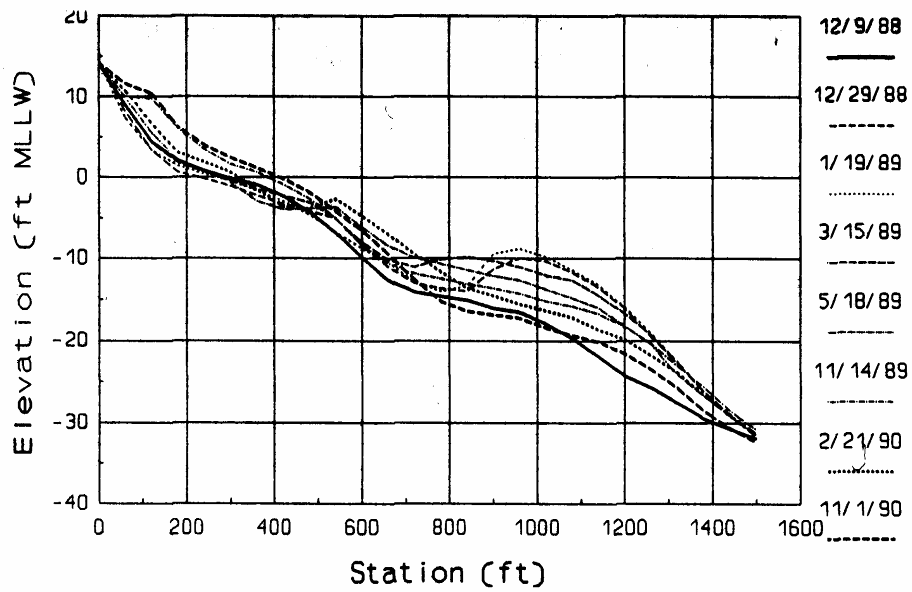


Figure 2.1 *Cross-shore morphological behaviour of nearshore berm at Silver Strand, Pacific Ocean, USA(12/9/88= pre-construction profile; 1/19/89= first undisturbed post-construction profile)*

The berm volume in the middle transect (with respect to an assumed equilibrium reference profile) decreased by about 10% from about 580 to 520 m^3/m over the period of 5 months due to onshore sand transport. The berm flattened out and the center of mass was displaced shoreward over a distance of about 10 m. The maximum berm height decreased almost 1 m. The beach profile showed accumulation of sand. After about 1.5 years the berm was almost completely removed, but the beach had accreted considerably, see Figure 2.1. The shoreline was situated more seawards (about 30 m) and the beach and inner surf zone were raised (about 1 m) over a width of 200 m. This data set is valuable for verification of cross-shore profile models.

Work and Dean (1995), Otay (1995) and Work and Otay (1996) studied the morphological behaviour of a reef berm (0.3 mm sand) under micro-tidal conditions at Perdido Key, northwest Florida, USA. The berm (length of about 4000 m, width of about 300 m, relief of 1.5 to 2 m) was placed at a depth of about 6 m in 1991; the crest level was at -4 to -4.5 m, as shown in Figure 2.2. Two-years of post-placement survey data indicated that the berm did not migrate during this period, although it had been smoothed slightly. The largest significant wave height measured in the nearshore area was about 2.9 m (period of 13 s). As the water depth above the crest is about 4 to 4.5 m, wave breaking on the berm will be rather infrequent. The wave energy reaching the shoreline during non-storm events will be more or less the same, whether or not the berm is present. Given the relatively small current velocities of about 0.1 to 0.2 m/s, the net annual transport rates will be extremely small and hence migration will be small (as observed).
Between 1992 and 1993, shoreline erosion at the (nourished) beach within the alongshore limits of the nearshore berm was significantly smaller than the erosion occurring outside the limits at the unprotected beach. This favourable effect was caused by the sheltering effect of

the berm during storm events. Thus, the nearshore berm exerted some protective influence on the leeward beach.

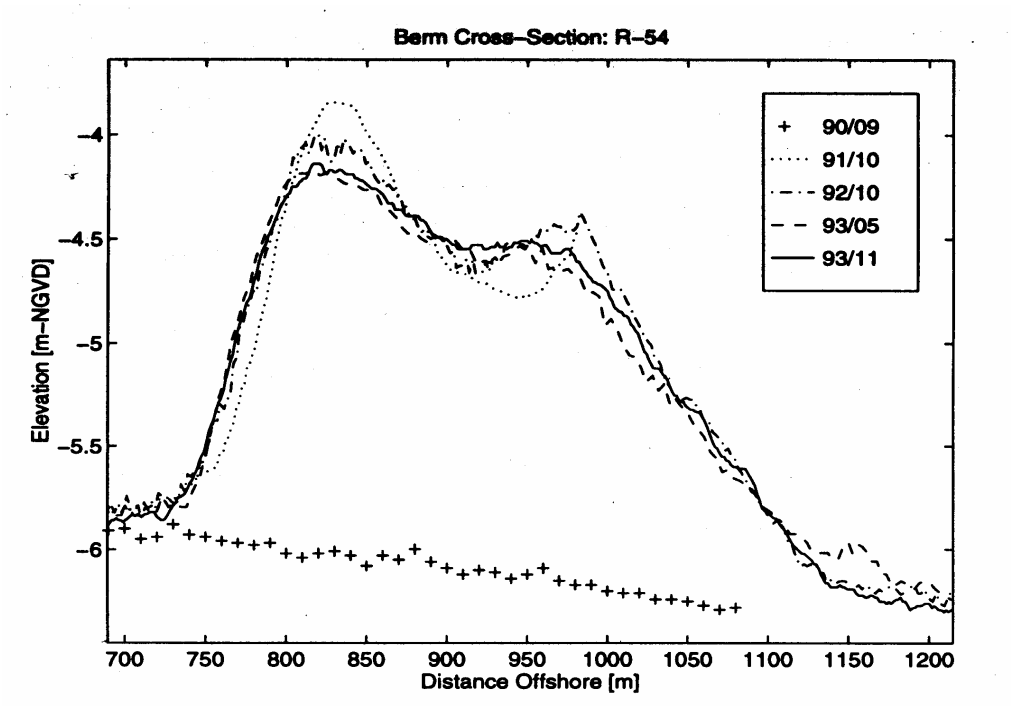


Figure 2.2 *Cross-shore morphological behaviour of nearshore berm at Perdido Key, Florida, USA (90/9= pre-construction profile; 91/10= first undisturbed post-construction profile)*

2.3 Shoreface nourishments in meso-tidal and macro-tidal conditions

2.3.1 Outside The Netherlands

Murden (1995) describes various examples of feeder and reef-type berms constructed in Australia, USA, South Africa, Japan and New Zealand. The feeder berms had lengths between 1000 and 3000 m, heights between 1 and 3 m and were placed in depths between 4 and 8 m. Most feeder berms were found to migrate slowly in onshore direction. The reef-type berms had lengths between 1000 and 3000 m, heights between 6 and 8 m and were placed in depths between 10 and 15 m.

Foster et al. (1996) discuss the response of a feeder berm placed between the -4 and -7 m depth contours (to MLWS, which is about 1 m below MSL) at Mount Maunganui Beach, New Zealand. This beach has a length of about 700 m and is located immediately downdrift to an ebb tidal delta on the northeastern coast of New Zealand. The tidal range is about 2 m. Historically, the beach experienced erosion. In December 1990, some 80,000 m^3 of maintenance dredging from a nearby shipping channel was dumped in a strip of 200 m by 600 m at about 500 m from the shore. The maximum thickness of the dump was about 2 m. Tracer experiments showed the movement of bed material in onshore direction. By February 1991 and later in May 1991, the feeder berm had been significantly reduced in height, with predominant movement of sediment towards the beach.

Charlier and De Meyer (2000) report about a successful feeder berm project near De Haan at the Belgium coast. Early 1991, a feeder berm of approximately 600,000 million m^3 of sand (0.2 to 0.3 mm) was put in place in the North Sea (tidal range of 2 to 3 m). The berm had a length of 2.2 km and was constructed at 600 m from the shoreline on the low water bar. Detailed information is given by Malherbe and Lahousse (1998).

2.3.2 Inside The Netherlands

Spanhoff et al. (2003) present an overview of the shoreface nourishment practices in The Netherlands. Since 1997 more than 10 new shoreface nourishments have been performed (length scale of 2 to 4 km; total volumes of 1 to 2 million m^3; 300 to 600 m^3/m). Most shoreface nourishments were carried out by dumping sand just seaward of the outer bar at the edge of the surf zone. These nourishments were rather successful with respect to the design objective to maintain the position of the shoreline and the volume of sand in the beach and surf zone. As regards cross-shore movements, three phases can be detected:

- significant change of the nourishment surface from an originally more or less horizontal surface into a bar like form with a trough emerging landward of it during the first few months after completion of the project;
- significant onshore movement of this bar during the initial period (first year);
- onshore and offshore movements in line with the natural bar behaviour (after first year).

As regards longshore movements, the shoreface nourishments are quite stable in the central part of the Dutch coast. Some nourishments experienced relatively large alongshore changes in regions where the net longshore transport rates are relatively large (northern part of Holland coast and barrier island of Terschelling in the north). There, the shoreface nourishments seem to move eastward as a whole. The longshore migration rates are of the order of 200 to 400 m/year, which is equivalent with a longshore transport of 50,000 to 100,000 m^3/year. These latter values are about 25% of the net longshore transport rates at these locations.

Hereafter, shoreface nourishments at three different locations will be described in more detail, being:

- Terschelling; barrier island in the north with shoreline orientation to main wave direction of about 20 to 30 degrees;
- Egmond; straight beach along North-Holland coast with shoreline orientation to main south-west wave direction of about 30 to 45 degrees;
- Delfland; straight beach along South-Holland coast with shoreline orientation to main south-west wave direction of about 30 to 45 degrees.

A. Terschelling shoreface nourishment

Hoekstra et al. (1996) and **Spanhoff et al. (1997)** studied the morphological behaviour of a feeder berm under meso-tidal conditions along the central section of the North Sea barrier island of Terschelling, The Netherlands. The spring tidal range is about 2.8 m; the peak tide- and wind-driven longshore currents are between 0.5 and 1 m/s. The wave energy climate is moderate to high (annual mean significant wave height of about 1.1 m, period of about 7 s). The bed material consists of sand with median diameter between 0.24 mm (beach) and 0.16 mm (outer surf zone). About 2.1 million m^3 of sand (0.2 mm) was dumped in the trough between the middle and outer longshore bars to create a feeder supply for the beach (length of 4400 m, placed between -4.5 and -7 m depth contours, volume of about 450 to 500

m^3/m). The dumping of sand was completed in October 1993. The supplied sand is expected to act as a feeder berm. The most important results are:

- rapid adjustment of disturbed bar-trough morphology (in about 6 winter months) to former patterns;
- growth of the middle bar (increase of height by about 1.5 m) and landward migration of this bar by about 50 m over about 8 months (November 1993 to June 1994);
- strongly three-dimensional beach morhology (not observed before);
- migration of fill (cross-shore area of about 400 m^2) in dominant alongshore drift direction (eastwards) at a rate of about 350 m/yr;
- the nourishment area shows an erosion volume of about 0.6 million m^3 after about 24 months; about 0.15 million m^3 is lost in offshore direction (across -7 m), about 0.3 million m^3 in alongshore direction and about 0.15 million m^3 in onshore direction over 24 months; this latter amount is about 20 m^3/m/yr onshore across the -4 m line; the zone landward of the nourishment zone shows a volume increase of about 1.2 million m^3 in 24 months, which is much larger (8 times) than the value of the onshore migrated volume (0.15 million m^3); thus about 1 million m^3 sand in 24 months or 0.5 million m^3/yr must have entered the study area by longshore transport processes due to the breakwater effect of the enlarged middle bar, creating a lee-zone landward of the middle bar;
- the median grain size (d_{50}) of the fill material was about 0.18 to 0.19 mm after placement; the grain size of the native material in the nourishment area was about 0.17 to 0.18 mm; after about 6 months the grain size of the fill material (surface sample) was the same as that of the original material (fining process).

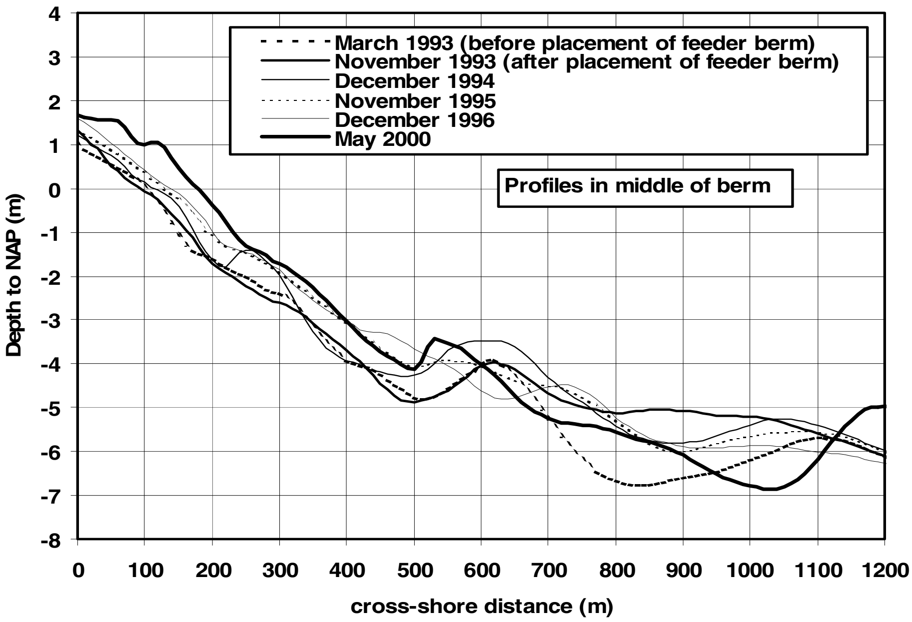


Figure 2.3 *Cross-shore profiles in middle of feeder berm at Terschelling Beach, The Netherlands (feeder berm between 700 and 1100 m, in trough landward of outer bar; about 450 m^3/m)*

Grunnet (2002) also studied the Terschelling nourishment case and performed a volume analysis in three alongshore sections (west section with length of 4 km; middle section of 4 km and east section of 4 km) over 4 years. The cross-shore length of the sections was about 1.5 km. The net longshore transport is from west (updrift) to east (downdrift) and is of the

order of 0.3 million m^3/yr. Cross-shore profiles (averaged over length of 750 m in alongshore direction) before and after construction of the berm are shown in Figure 2.3. The cross-shore profiles show the regeneration of the trough landward of the former outer bar and the migration of a new middle bar toward the shoreline. During the period November 1993 to May 2000, a layer of sand with a thickness of about 1 m has accumulated in the inner beach and bar zone (0<x<500 m) due to onshore transport processes (feeding effect) and longshore trapping processes (lee effect).
After 4 years (1993 to 1997), the following results can be observed for three sections (west and east of nourishment location) :

West section: accretion of 1.3 milion m^3; (autonomous behaviour of this section was erosion; estimated to be of the order of 0.3 million m^3 over 4 years); most of this accretion volume is from updrift longshore transport blocked by the berm effect;

Nourishment section: gain of 2.8 million m^3 (including berm volume of 2.1 million m^3); net gain after placement of berm is about 0.7 million m^3; mainly in inner bar zone and in beach zone due to onshore feed from the berm and due to trapping of sand from updrift;

East section: accretion of 0.1 million m^3; (autonomous behaviour of this section was erosion; estimated to be of the order of 0.5 million m^3 over 4 years); actual accretion probably is estimated to be of the order of 0.6 million m^3 from longshore directions.

B. Egmond shoreface nourishment

Van Duin and Wiersma (2002) and **Van Duin et al. (2004)** studied the morphological behaviour of a feeder berm at Egmond beach, The Netherlands. Egmond is located near a null point of longshore transport; south of Egmond the net longshore transport is about 100,000 m^3/yr to the south and north of Egmond it is of the same order of magnitude to the north. The site suffers from long-term beach erosion of the order of 10 m^3/m/yr. The spring tidal range is about 2 m. The beach sand is about 0.2 to 0.25 mm. The longshore tidal currents in the surf zone are in the range of 0.2 to 0.4 m/s. The flood current to the north is dominant. The berm with a volume of about 400 to 450 m^3/m (length of about 2 to 2.5 km; total initial volume of about 900,000 m^3) was placed in the summer of 1999 at the seaward side of the outer surf zone bar (offshore distance of about 500 to 800 m) in water depths between 6 and 8 m (below MSL). The berm material was dredged from the shoreface of the North Sea at depths beyond the -20 m depth contour. Cross-shore profiles (averaged over length of 750 m in alongshore direction) before and after construction of the berm are shown in Figure 2.4. The cross-shore profiles show the migration of the outer bar towards the shoreline. In the summer of 2000 a beach nourishment of the order of 200,000 m^3 was carried out in the lower beach zone.
Three-dimensional plots of the bathymetric data for the period of September 1999 to April 2001 are presented in Figure 2.5, showing a shoreward migration of the outer bar and the formation of a trough between outer bar and shoreface nourishment. The shoreface nourishment seemed to act as the new outer bar and hardly changed in height and location. Therefore it has not increased the beach sand volume directly, i.e. by redistribution of the nourished sand. In the same period the inner bar also migrated shorewards. Both the outer and inner bar transformed into a boomerang shape (planform), which is also observed to some extent at the shoreface nourishment location. The latest surveys however (June 2001 to April 2002, Figure 2.5c) showed no further shoreward migration of the inner and outer bar. The outer bar had straightened completely and formed a continuous bar again. The shoreface nourishment decreased in height and lost its reef effect. It seems that the system is returning to its natural situation of a three bar system: outer bar, inner bar and swash bar.

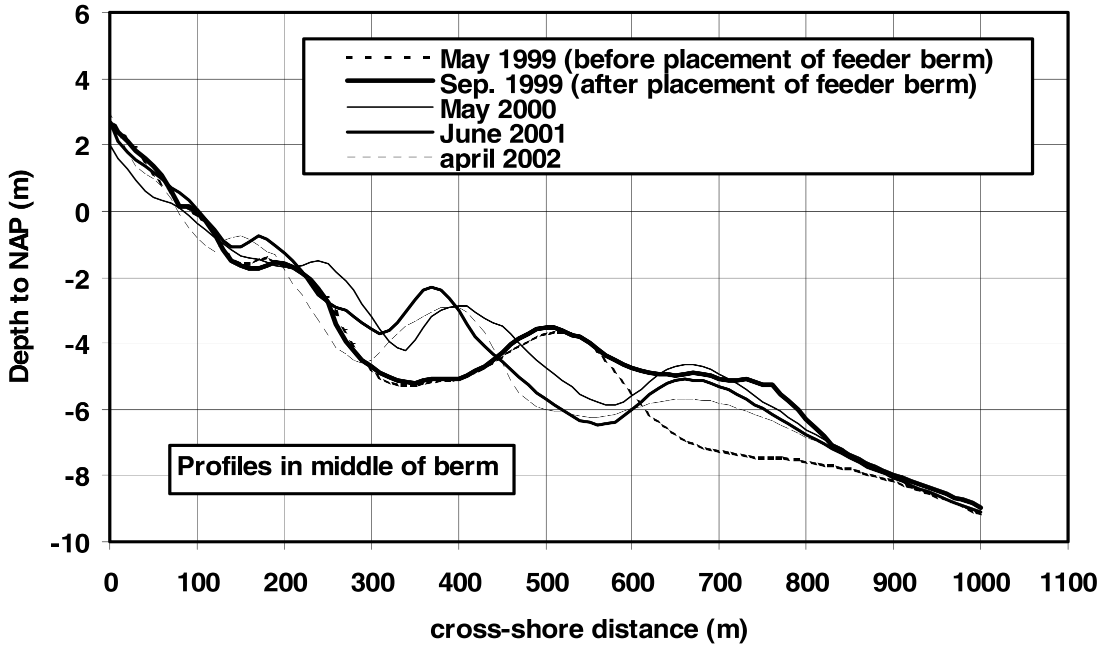


Figure 2.4 *Cross-shore profiles in middle of feeder berm at Egmond beach, The Netherlands (feeder berm between 600 and 900 m, at seaward side of outer bar; about 450 m^3/m)*

Surveyed data showed that the shoreface nourishment did not diffuse much in the first two years. After a period of two years the shoreface nourishment started to diffuse and the bar amplitude at the shoreface nourishment area showed a substantial decrease.

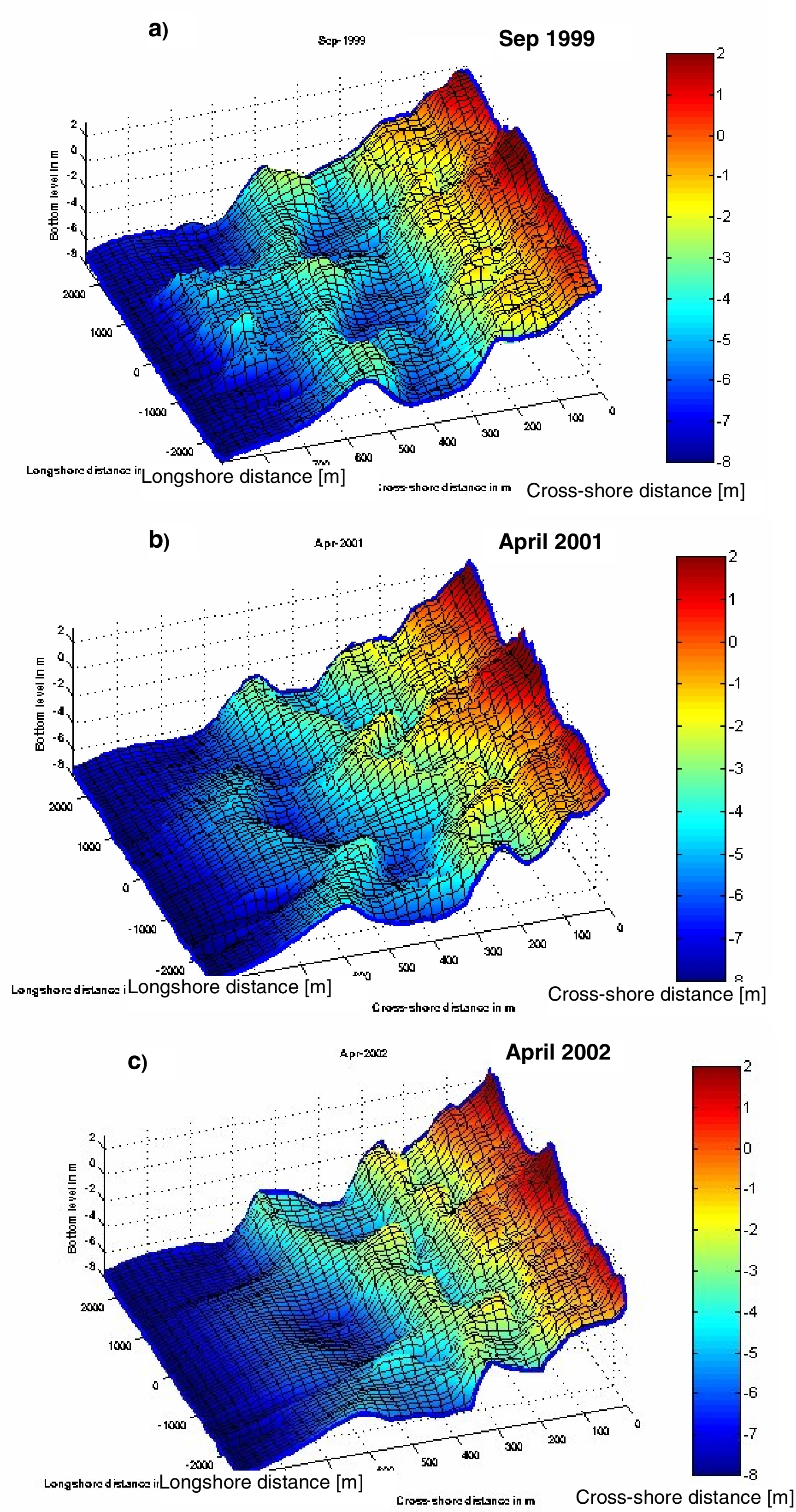
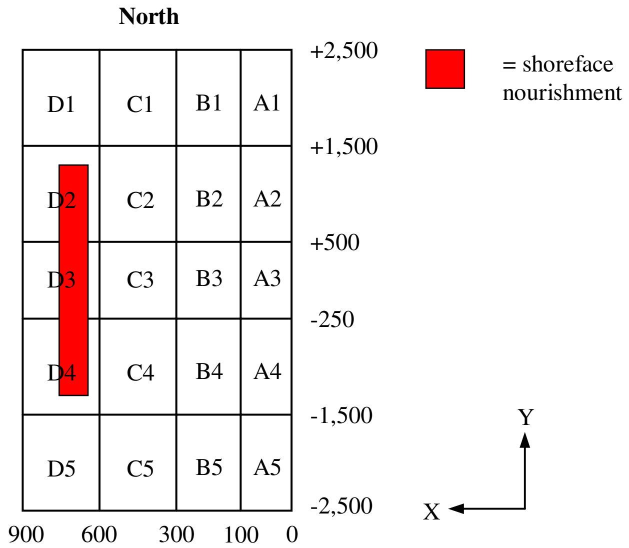


Figure 2.5 *Measured Egmond bathymetries (colour-scale in meters w.r.t. NAP): a) September 1999 b) April 2001 c) April 2002*



Subsections:	Area [m²]	Subsections:	Area [m²]
A1	100,000	C1	300,000
A2	100,000	C2	300,000
A3	75,000	C3	225,000
A4	125,000	C4	375,000
A5	100,000	C5	300,000
B1	200,000	D1	300,000
B2	200,000	D2	300,000
B3	150,000	D3	225,000
B4	250,000	D4	375,000
B5	200,000	D5	300,000

Figure 2.6 *Location of the subsections (measures in m) and corresponding areas (measures in m^2)*

To determine the observed morphological changes and derive a sediment balance, the area is divided into 20 subsections. The main criterion for the choice of the shore-parallel boundaries was to keep the (moving) bars in one subsection. The shore-parallel boundaries are therefore chosen at the troughs between the bars at x = 600 m and x = 300 m. The shoreface nourishment remains seaward of the x = 600 m shore-parallel boundary. Shore-perpendicular boundaries were located at stable cross-sections. The nourishment area is split up into three subsections, containing a centre part, a northern part and a southern part. The location of the subsections is given in Figure 2.6. Longshore-averaged volume changes are presented in Table 2.1

Shore perpendicular subsections (see Figure 2.6)	Area [m²]	Alongshore length [m]	Volume change [m³/m¹] May99-Sep99 (nourishment period)	Volume change [m³/m¹] May99-Apr02 (overall period)	Total volume change [m³] May99-Jun01	Total volume change [m³] May99-Apr02 (overall period)
North of shoreface nourishment (subsections 1)	900,000	1,000	+20	-150	-76,000	-150,000
Northern part of shoreface nourishment (subsections 2)	900,000	1,000	+300*	+390*	+441,500*	+390,000*
Centre part of shoreface nourishment (subsections 3)	675,000	750	+440*	+110*^	+286,000*^	+82,500*^
Southern part of shoreface nourishment (subsections 4)	1,125,000	1,250	+190*	+220*^	+268,500*^	+275,000*^
South of shoreface nourishment (subsections 5)	900,000	1,000	-180	-120	-186,500	-120,000

* including shoreface nourishment volume
^ including beach nourishment volume in July 2000 (about 55 m^3/m^1 in

Table 2.1 *Volume changes per shore-perpendicular subsection*

The sand volume change for each subsection in time is shown in Figure 2.7a to 2.7e. Each plot shows the sand volume change relative to May 1999 per shore-perpendicular subsection

and the total sand volume change of all these shore-perpendicular subsections. In Figure 2.7f the sand volume change of the total area is shown. The sand volume change is expressed in m and is calculated by dividing the sand volume change by the surface of each area (m^3/m^2). In Table 2.1 the volume change per shore-perpendicular area is shown.
The subsections including the shoreface nourishment (subsections D2, D3 and D4) show a large volume increase caused by the construction of the shoreface nourishment in the period of May 1999 to September 1999. Over the total studied period these three shoreface subsections show a volume increase of 550,000 m^3, including the placement of the shoreface nourishment, which means that 60% of the applied sand is still present. The second beach nourishment of July 2000 can be seen by the volume increase in the period of May 2000 to September 2000 in the beach subsections A3 and A4.
The shoreface nourishment shore-perpendicular subsections (subsections 2 to 4) all show a net increase of sediment for the period of May 1999 to April 2002. The total net gain of these three shore-perpendicular subsections, including the placement of the shoreface nourishment and beach nourishment, is 747,500 m^3. The total sand volume of the shoreface nourishment is 900,000 m^3 and of the beach nourishment 207,000 m^3, which means that 65% of the supplied sand is still present.
The sand volume change of the total area (Figure 2.7f) shows an increase for the first period, May 1999 to September 1999, which is due to the placement of the shoreface nourishment. This caused an average bed level rise of approximately 0.16 m, a sand volume increase of 710,000 m^3. The total volume of the shoreface nourishment is 900,000 m^3. A volume of 190,000 m^3 is not recovered. Possible explanations can be: measurement errors, truncation errors, transport of sediment out of the area, etc. The volume increase continued until September 2000 and caused an extra average bed level rise of about 0.05 m, a sand volume increase of 240,000 m^3. For the period of September 2000 to April 2002 the average bed level shows a decrease. The total decrease is about 0.10 m and corresponds to a volume decrease of 470,000 m^3. In total the area has lost a net sand volume of 230,000 m^3 after placement of the shoreface nourishment (September 1999 to April 2002), but a net gain of 477,500 m^3 for the overall period (May 1999 to April 2002) including placement of the shoreface nourishment. The total sand volume of the shoreface nourishment is 900,000 m^3 and of the beach nourishment 207,000 m^3, which means that 45% of the supplied sand is still present after three years.
The northern and southern sections (Profiles 1 and 5) both show relatively large volume decreases (erosion of 120,000 to 150,000 m^3) over three years, which is much larger than the natural autonomous erosion.

Table 2.2 shows the overall sand volumes after 2 and 3 years: south section with a length of 1 km, middle section of 3 km (including feeder berm) and north section of 1 km. The vertical cross-shore boundaries are set at +3 m and –8 m to MSL (cross-shore length scale of about 900 m). The feeder berm does not seem to loose much sand in alongshore directions, as the South and North sections are both eroding at a rate much larger than before the construction of the feeder berm. After 2 years the inner bar zone (between 100 and 300 m, Fig. 2.4) of the Middle section has experienced a gain of about 100,000 m^3, partly from the feeder berm and partly from the beach nourishment in the summer of 2000. After 3 years this inner bar zone shows a loss of about 50,000 m^3. The beach zone in the lee of the berm did not show any benefit from the feeder berm. A supplementary beach nourishment had to be carried out in the summer of 2000 to mitigate the beach erosion effects. Overall, the beach zone landward of x=100 m in the Middle section experienced a net loss of 50,000 m^3 after 2 years and 100,000 m^3 after 3 years, despite the beach nourishment of 200,000 m^3 (100,000 m^3 within defined control domain) in the summer of 2000. After 3 years a total quantity of about 750,000 m^3 of the initial nourishment volume of 1,000,000 m^3 (berm volume of 900,000 m^3 plus beach nourishment volume of 100,000 m^3) is still present in the Middle section. Thus, an overall efficiency of about 75% after 3 years.

It can be concluded that the sand budget in the surf zone is positively affected by the presence of the feeder berm. This is important for the development and maintenance of the breaker bars. As a result of the presence of pronounced breaker bars, less wave energy is transmitted to the beach zone. The beach zone at Egmond has not directly benefitted from the feeder berm. The supply of sand from the feeder berm to the beach takes place on a relatively long time scale (10 years or so), while it is also required that the feeder berm is maintained continously (by dumping of sand) to be fully effective.

Section	**After 2 years**	**After 3 years**
North	erosion of 80,000 m^3; (autonomous erosion is estimated to be of the order of 20,000 m^3)	erosion of 150,000 m^3; (autonomous erosion is estimated to be of the order of 30,000 m^3)
Middle	gain of 1,000,000 m^3 (including berm volume of 900,000 m^3); net accretion after placement of berm is about 100,000 m^3; mainly in inner bar zone landward of -5 m contour (100 to 300 m)	gain of 750,000 m^3 (including berm volume of 900,000 m^3); net erosion after placement of berm is about 150,000 m^3
South	erosion of 180,000 m^3; (autonomous erosion is estimated to be of the order of 20,000 m^3)	erosion of 120,000 m^3; (autonomous erosion is estimated to be of the order of 30,000 m^3)

Table 2.2 *Nourishment data of Egmond, The Netherlands*

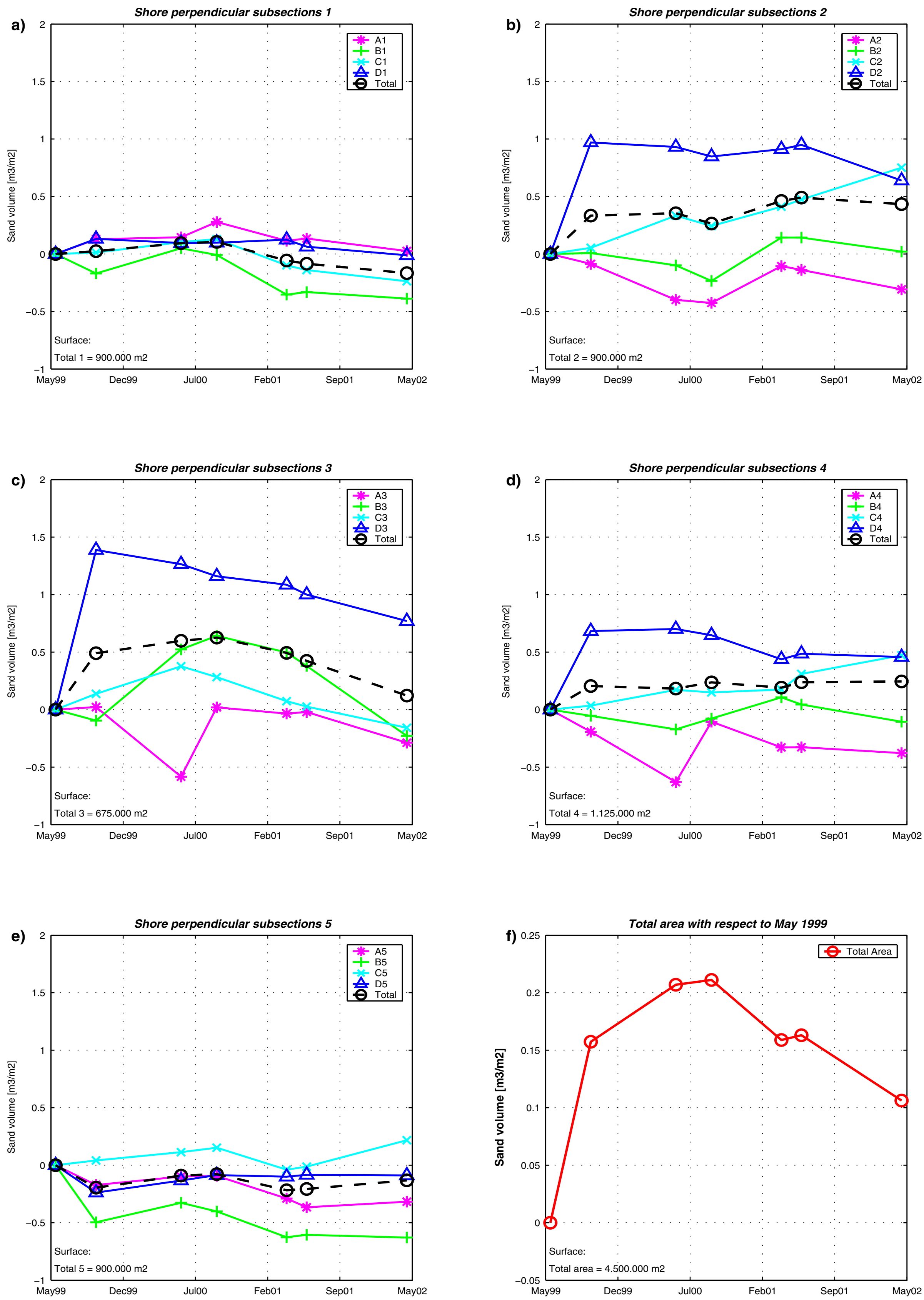


Figure 2.7 *Sand volume change of shore perpendicular subsections relative to May 1999*

C. Delfland shoreface nourishment

The Delfland case is located along the straight southern Holland coast (close to the access channel to the Port of Rotterdam) without major breakers bars and a relatively small net longshore drift.
Near the village of Ter Heijde in the Delfland area , two nourishment projects have been carried out in 1997 (Rijkswaterstaat/RIKZ, 2002):

- beach nourishment of 834.000 m^3 (based on information of dredging contractor) between km 107.5 and km112.5;
- shoreface nourishment of 1,000,000 m^3 (based on information of dredging contractor) or about 500 m^3/m between the depth contours -5 m NAP and -7 m NAP in the Section between km 113.150 and 114.850 km.

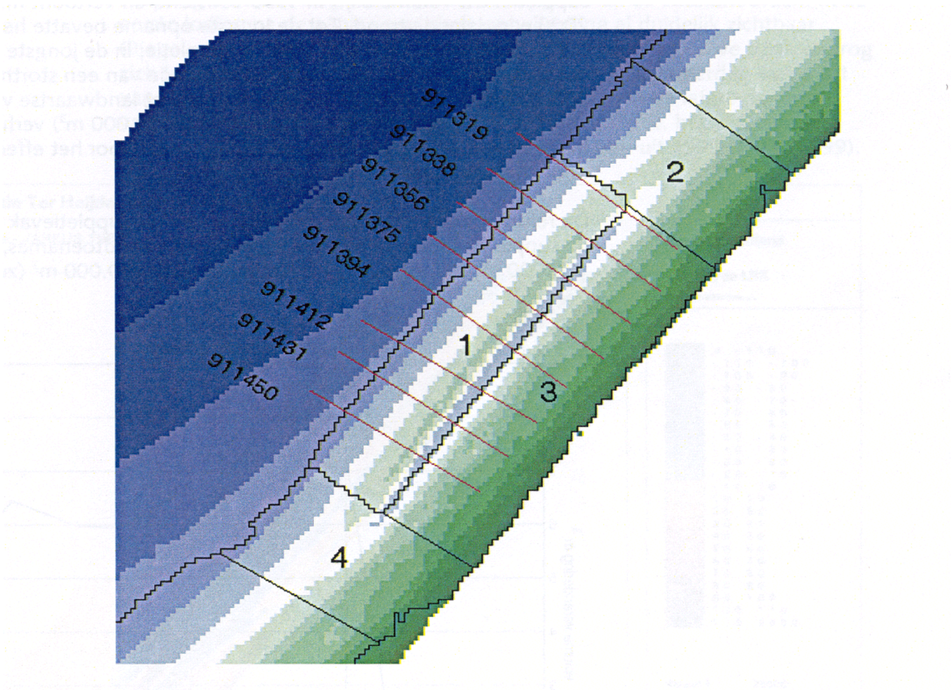


Figure 2.8 *Sections of shoreface nourishment 1997, Delfland, The Netherlands Section1= Nourishment Section; Section 2= North Section; Section 3= Beach Section; Section 4= South Section (land on right; sea on left) (Rijkswaterstaat/RIKZ, 2002)*

Analysis of post-nourishment soundings shows that about 800.000 m^3 is present in Section 1 immediately (January 1998) after completion of the shoreface nourishment, see Figures 2.8 and 2.9. The sand volumes of Sections 1 to 4 show the following behaviour:

- volume decrease of about 200, 000 m^3 in Nourishment Section 1 after about 2 years (up to January 2000); the volume of Section 1 remains almost constant up to Januay 2002
- volume increase of about 300,000 m^3 in Beach Section 3 after 2 years (up to January 2000); the volume of Section 3 reduces with about 200,000 m^3 in the following 2 years (January 2000 to January 2002);
- volume increases of 100,000 to 150,000 m^3 in the North section 2 and in the South Section 4 after 2 years, remaining almost constant up to January 2002;
- the total volume in Sections 1 to 4 is about 900,000 m^3 at January 1998, increasing to 1,150,000 m^3 at January 2000 and decreasing to 800,000 m^3 at January 2002.

Analysis of the cross-shore profiles shows that a pronounced breaker bar is formed in the Nourishment Section, which migrates in onshore direction, uniformly over the entire section.

Figure 2.9 *Volume changes of shoreface nourishment 1997, Delfland, The Netherlands(Rijkswaterstaat/RIKZ, 2002)*

2.4 Summary of conclusions

Based on observations in the USA, Australia, South-Africa, New Zeeland and Japan, it is concluded that:

- shoreface nourishments (feeder berms) placed in the nearshore zone (between -5 and -10 m) in micro-tidal and meso-tidal conditions show berm flattening and onshore sand movement;
- the lifetimes are of the order of to 2 to 10 years depending on the wave climate;
- no berms were observed to move seawards;
- beaches in the lee of the nourishments showed accumulation of sand.

The most important results of the Terschelling shoreface nourishment (1993) in The Netherlands are:

- rapid adjustment of disturbed bar-trough morphology (in about 6 winter months) to former patterns;
- growth of the middle bar (increase of height by about 1.5 m) and landward migration of this bar by about 50 m over about 8 months;

- strongly three-dimensional beach morhology (not observed before);
- migration of fill in dominant alongshore drift direction (eastwards) at a rate of about 250 to 500 m/yr;
- after 2 years (1993 to 1995), the zone landward of the nourishment zone showed a large volume increase due to longshore transport processes as result of the breakwater effect of the enlarged middle bar, creating a lee-zone landward of the middle bar;
- after 4 years (1993 to 1997), the nourishment section up to the beach showed a gain of almost 0.7 million m^3; mainly in inner bar zone and in beach zone due to onshore feed from the berm and due to trapping of sand from updrift;
- after 4 years, the section south of the nourishment showed large accretion; (autonomous behaviour of this section before the nourishment was erosion); most of this accretion volume is from updrift longshore transport blocked by the berm effect;
- after 4 years, the section north of the nourishment showed minor accretion; (autonomous behaviour of this section also was erosion).

The most important results of the Egmond shoreface nourishment (1999) in The Netherlands are:

- migration of the outer bar including nourishment towards the shoreline and the formation of a trough between outer bar and shoreface nourishment; the shoreface nourishment seemed to act as the new outer bar and hardly changed in height and location;
- relatively strong three-dimensional behaviour of the nourishment bar and the beach in the lee of the nourishment; after two years the outer bar was almost straightened and formed a continuous bar again; the shoreface nourishment started to diffuse resulting in relatively low bar heights;
- the nourishment did not loose much sand in alongshore directions; after 3 years, a total quantity of about 75% of the initial nourishment volume is still present in the nourishment section;
- the sections south and north of the nourishment section showed relatively large erosion (much larger than before the nourishment);
- supplementary beach nourishments had to be carried out to mitigate the beach erosion effects;

The most important results of the Delfland shoreface nourishment (1997) in The Netherlands are:

- formation of pronounced outer bar at nourishment location and migration of the outer bar towards the shoreline and the formation of a trough landward of the nourishment location;
- almost two-dimensional behaviour of the shoreface nourishment;
- the nourishment did not loose much sand in alongshore directions; after 4 years, a total quantity of about 70% of the initial nourishment volume is still present in the nourishment section; most of the sand eroded from in the nourishment section is carried into the beach section in the lee of the nourishment ;
- the sections south and north of the nourishment section showed minor accretion.

Overall, it can be concluded that the sand budget in the surf zone is positively affected by the presence of shoreface nourishments (feeder berms). This is important for the development and maintenance of the breaker bars, which react relatively rapid (6 to 12 months) to shoreface nourishment. As a result of the presence of more pronounced breaker bars, less wave energy is transmitted to the beach zone. The beach zones in the lee of the nourishment do not always benefit directly (on short term) from the nourished sand. Sometimes, additional beach nourishments have to be carried out to mitigate local erosion.

The supply of sand from the feeder berm to the beach takes place on a relatively long time scale (10 years or so), while it is also required that the feeder berm is maintained continously (by dumping of sand) to be fully effective. Sand losses to offshore areas do occur, but are often rather (negligible) small.
Shoreface nourishments in areas with a relatively large net longshore drift show migrational tendencies in the direction of the net longshore drift. The sections downdrift of the nourishment will benefit from the sand supply by the longshore drift.

3 Results from morphological model studies

3.1 Introduction

Coastal Line, Profile and Coastal Area models are the three main generic types of process-based models.

Coastal Line models (one-line models such as UNIBEST-CL and n-line models such as PONTOS) mainly schematize the longshore transport processes without taking the cross-shore effects into account explicitly.

Coastal Profile models (**Brøker Hedegaard et al., 1992**) reflect the physical processes in a cross-shore direction, assuming longshore uniformity. All relevant transport components in the cross-shore direction such as wave asymmetry and the presence of mean cross-shore currents are included. Bed level changes follow from numerical solution of the mass conservation balance. Longshore wave-driven and tide-driven currents and the resulting sediment transport are included.

Coastal Area models (**De Vriend et al., 1993**) are 2 or 3-dimensional horizontal models consisting of, and linking, the same set of submodels of the wave field, the tide-, wind- and wave-driven flow fields, the sediment transport fluxes and the bed evolution. Fully 3D-models describing the currents on a three-dimensional grid are in a very early stage of development, and require large computer-memory and power at present stage, but have the advantages of including the vertical structure of the velocity and concentration profiles.

The process-based models typically operate on short-term and medium-term time scales up to 5 years, corresponding with tidal, storm and seasonal events. The spatial scales involved vary from a few metres and larger with a total area coverage of several hundred metres to a few kilometres square.
The quality and use of process-based models is still seriously affected by a number of limiting conditions. In general, one can summarize a number of shortcomings with respect to the randomness and directionality of the waves, the near-bed wave velocity asymmetry (higher harmonics), the wave breaking processes, the wave-induced streaming in the boundary layer, the wave-induced cross-shore and longshore currents, the generation of low-frequency processes and the wave-induced sand transport components. The sand transport module generally is a critical key element and still requires a substantial input of information from empirical data sets; these data sets usually do not cover the total range of conditions and processes. Furthermore, the sand transport models generally are transport capacity models, which means that the spatial phase lags effects between hydrodynamics and sediment transport are not taken into account. As a consequence of all these shortcomings, the predictive capability of the process models generally is rather low in quantitative sense. Actually, these models are still in their infancy. In the best cases, models are useful qualitative tools that can be operated to compare relative performance of one solution versus another.
In this chapter 3 the available model concepts are discussed and applied to nourishment projects, as follows:
Section 3.2: One-dimensional shoreline modelling;

3.2 One-dimensional shoreline modelling (UNIBEST-CL)

3.2.1 Model approach

Shoreline changes can be simply determined by considering the sediment continuity equation for the littoral zone (roughly the surf zone) with alongshore length Δx, cross-shore length Δy and vertical layer thickness (h), see Figure 3.2.1.

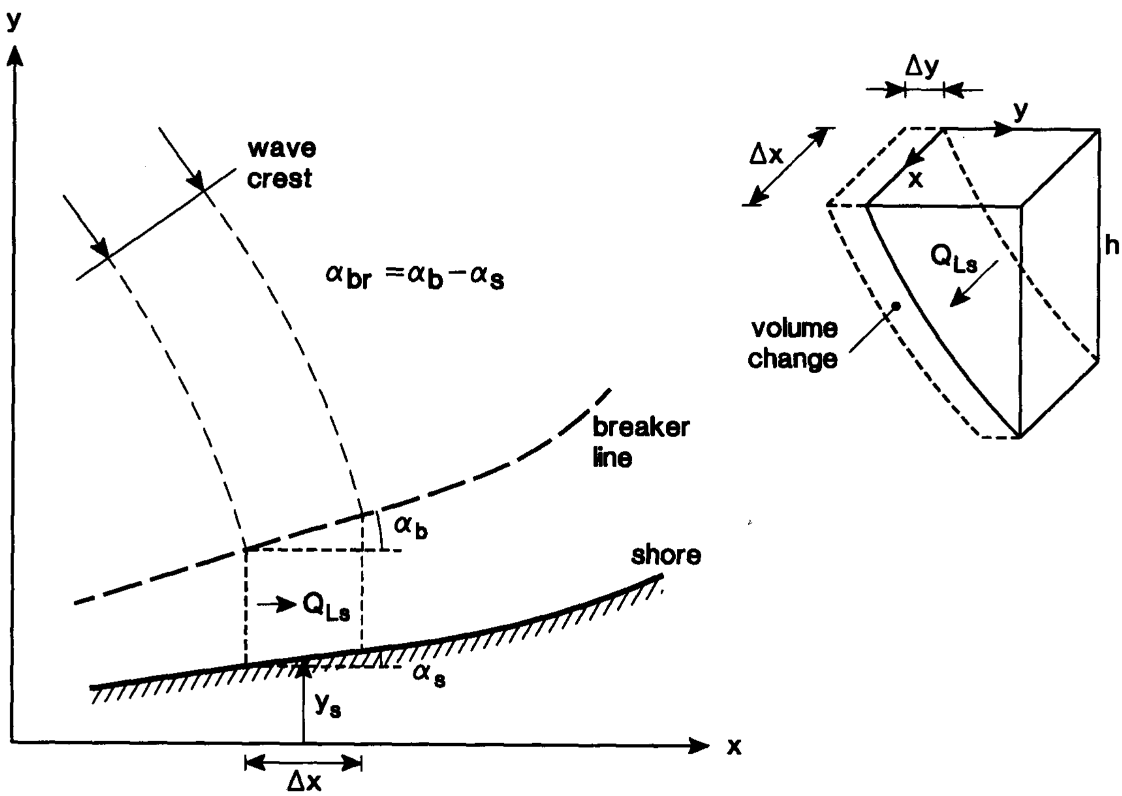


Figure 3.2.1 *Definition sketch of shoreline configuration and sand volume balance*

The sand volume balance reads:
$h\ (\Delta y_s/\Delta t) + \Delta Q_{LS}/\Delta x - q_S = 0$ with: y= cross-shore coordinate, x= longshore coordinate, y_s= shoreline position, h= thickness of active littoral zone layer, Q_{LS}= longshore transport rate or littoral drift (bed-load plus suspended load transport in volume including pores per unit time, in m^3/s) and q_S= source, sink or cross-shore transport contribution (in m^2/s).

The longshore sand transport (Q_{LS}) under wave-dominated conditions can be estimated by the CERC-formula (Van Rijn, 1993): $Q_{LS} = 0.025\ g^{0.5}\ \gamma^{-0.5}\ (H_{br})^{2.5}\ \sin(2\alpha_{br})$ with γ= breaker coefficient=H_{br}/h, H_{br}= significant wave height at breaker line and α_{br}= angle between breaker line and local shoreline.

Waves arriving from deep water are transformed in shallow water according to the laws of refraction (Snell's law for gradually varying bathymetry; $\sin\alpha_{br} = L_{br}/L_0\ \sin\alpha_0$) and shoaling, yielding $H_{br} = k_{r,br}\ k_{s,br}\ H_0$ with $k_{r,br}$= refraction coefficient at breaker line and $k_{s,br}$= shoaling coefficient at breaker line. For a gradually varying bathymetry these values are: $k_{r,br} = (\cos\alpha_0/\cos\alpha_{br})^{0.5}$ and $k_{s,br} = (n_0c_0/n_{br}c_{br})^{0.5}$ with c= wave propagation velocity, n= coefficient, α= wave angle, index br= at breaker line and index 0= at deep water. The wave height at the breaker line $H_{br} = \gamma h_{br}$ can be computed if the breaker depth h_{br} and the breaker coefficient γ (=0.6 to 0.8) are known. Generally, this procedure requires iterative computations. Thus, wave refraction largely controls the orientation of the shoreline, when relatively smooth and regular depth contours are present (neglecting cross-shore contributions).

Based on the applied longshore transport equation, the longshore transport rate depends on the angle α_0 between the shoreline and the deep-water wave direction. If the shoreline orientation varies and the wave direction is constant, the longshore transport rate can be expressed as a function of α_0. The transport rate is maximum for a shoreline orientation of about $\alpha_0 = 40^o$ to 45^o (depending on refraction effects) and zero for angles of 0^o (wave crests parallel to coast) and 90^o (wave crests normal to coasts). The longshore transport will be in opposite direction (negative Q_{LS}) for $\alpha_0 < 0^o$. The longshore transport can also be expressed as a function of the shoreline angle α_s ($\alpha_s = \alpha_n - \alpha_o$, α_n= constant if wave direction is constant and shoreline is varying) with respect to the x-axis. In case of a wave climate with various wave classes, directions and probabilities of occurrence the net longshore transport rate can be expressed as a function of shoreline orientation.
The CERC-equation is only valid for wave-induced longshore transport in the absence of tide- or wind-driven currents. The effect of quasi-steady currents superimposed on the wave-induced longshore current will result in a shift of the transport curve.

3.2.2 Model results

Van Rijn (2004) used the LONGMOR model (similar to UNIBEST-CL) to compute the shoreline changes for a submerged feeder berm (shoreface nourishment) with an alongshore length of 2000 m at a distance of about 400 m from the shoreline.
The active layer thickness of the coastal profile is assumed to be 8 m. The beach sediment is sand with d_{50}= 0.2 mm and d_{90}= 0.3 mm. The local beach slope is assumed to be $\tan\beta$=0.01 (slope from waterline to 8 m depth contour). The tidal longshore velocities in the surf zone are assumed to be zero. The local wave breaking coefficient is assumed to be γ_{br}=0.6. The longshore grid size is 50 m and the time step is 0.05 days. The shoreline changes over a period of 6 to 18 months have been determined using a wave climate with offshore waves of

$H_{s,o}$= 2 m, T_p= 7 s and an offshore wave incidence angle of θ_o= 30° degrees (waves coming from left of shore normal). The longshore transport rates have been computed by using the methods of CERC and VAN RIJN. The transport rates in the lee (between x= 5000 and 7000 m) of the submerged berm are reduced by 50% to simulate the lee effect.

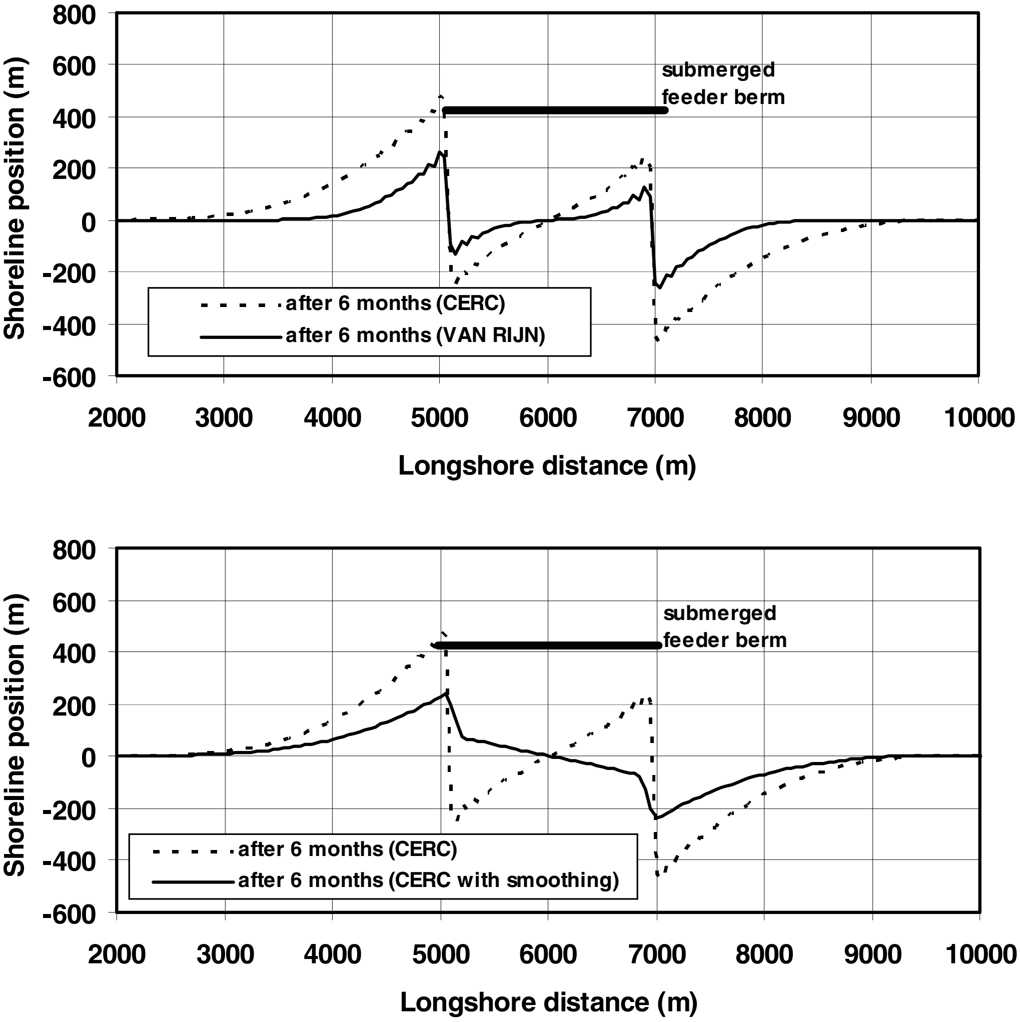


Figure 3.2.2 *Effect of shoreface nourishment (feeder berm) on computed shoreline; offshore wave incidence angle of 30° degrees; $H_{s,o}$= 2 m*
Top: methods of CERC and VAN RIJN
Bottom: methods of CERC with and without numerical smoothing

Figure 3.2.2 presents the computed shoreline changes after 6 months based on the methods of CERC and VAN RIJN. The shoreline shows accretion on the updrift side and erosion on the downdrift side of the feeder berm. The maximum shoreline accretion according to the method of VAN RIJN is about 200 m after 6 months. The method of CERC yields much larger shoreline variations (about 400 m after 6 months) due to larger updrift transport rates (CERC: 22000 m^3/day; VAN RIJN: 7300 m^3/day). The shoreline in the lee of the berm shows a pattern with erosion on the updrift side and accretion on the downdrift side. As the shoreline builds out on the left of the berm, the longshore transport rate is reduced because the wave incidence angle with respect to the local shore normal reduces (blocking effect).

This leads to erosion immediately downdrift of the blocking location. The sharp transitions will be much smoother in nature due to longshore spreading effects by smaller waves passing over the accretion zone on the updrift side and by diffractional effects in the lee of the reef. This has been simulated by using slight smoothing (3%), yielding a salient-type behaviour of the accretion zone, see Figure 3.2.2Bottom

Based on the results of these computationial studies, it is concluded that submerged feeder berms result in deposition in the lee of the berm (longshore effect; see Hypotheses of Section 1.5) and in erosion downdrift of the nourishment location.

3.3 Cross-shore profile modelling (UNIBEST-TC and DELFT-2DV)

3.3.1 Model approach

The Profile models integrate and synthesize our theoretical and experimental knowledge in the nearshore coastal zone. The process-based Profile models have a common structure, consisting of submodels, representing: (i) the hydrodynamics such as wave propagation, wave-asymmetry; tide-, wind- and wave-driven currents including the vertical structure of the currents, (ii) the associated sediment transport patterns and (iii) bed level changes, implemented in a loop system to ensure feedback and dynamic interaction of the elements of the morphodynamic system.
The application of Profile models to a coastal system is based on the assumption of alongshore uniformity of the morphological system (2-dimensional onshore-offshore behaviour), which means that the hydrodynamics, sand transport and morphology only have gradients in the cross-shore direction, but not in the alongshore direction. These idealized 2D conditions rarely exist in nature. Analysis of field data shows that the assumption of longshore uniformity for Profile models often is severely violated because of the presence of rythmic and non-rythmic features. Thus, a basic question is whether a Profile model can be applied to an individual transect, because longshore variability may be so large that bed level changes of individual transects over short periods are not significantly different in statistical sense. The best approach is to apply the Profile models to longshore-averaged profiles. The effects of longshore variability can to some extent be represented by introducing a longshore-averaged bed profile in combination with a variation band (standard error), based on longshore averaging of individual transects. The longshore averaging distance should be so large that the longshore rythmicity including rip channels is fully covered.

3.3.2 Terschelling model results

Roelvink et al. (1995) have used an early version of the UNIBEST-TC model to study the effects of the shoreface nourishment at Terschelling. A series of calibrations runs without nourishment was made to simulate the observed bar behaviour as good as possible. The model results show that the inclusion of the breaker delay effect is essential in describing the behaviour of the breaker bars; leaving the effect out leads to a rapid decay in bar height. The shape of the bar is modified by the bed slope effect. The grain size distribution and the wave breaking parameters have a quantitative effect, but donot alter the profile behaviour significantly.

The nourishment was represented in the model by filling the trough between the outer bar and the second bar in a way similar to the actual measurement and the model was run over a period of 10 years. The morphological bar system undergoes rapid changes as the natural bar system is restored. The profile after 10 years is very similar to the undisturbed profile, but shifted in seaward direction. After 10 years there still is a positive effect throughout the profile with a gain in the zone above the -4.5 m depth contour of about 40% of the initial nourishment volume.

3.3.3 Egmond model results

Wiersma (2002) used the UNIBEST-TC model (see **Bosboom et al., 1997**) to simulate the behaviour of the Egmond nourishment.

Model

The model was calibrated using the bathymetry changes between September 1999 and June 2001 of Profile 5, south of the shoreface nourishment. Profile 5 is assumed to be relatively undisturbed as the dominant longshore transport direction is from south to north. Using the same settings, the model was applied to Profile 3, containing the shoreface nourishment.
The model is driven by prescribed time series of tidal elevation, wave height, wave period and peak wave period at the model boundaries based on data supplied by Rijkswaterstaat for the location ‘IJmuiden’. Gaps in these data sets were filled with data from measurement station ‘Europoort’.

Run parameter	Explanation	Dimension	Default value
DT	time step	days	0.125
F_LAM	number wave lengths	-	1
FCVISC	viscosity coefficient	-	0.1
GAMMA	breaking parameter	-	Battjes&Stive
VARGAMM	varying gamma switch (on/off : 1/0)	-	0
FWEE	friction factor	-	0.01
RKVAL	friction factor	-	0.03
BETA	roller parameter	-	0.15
BVAR	varying beta switch (on/off : 1/0)	-	0
D50	D50 grain diameter	m	0.000240
D90	D90 grain diameter	m	0.000480
DSS	suspended grain diameter	m	0.000240
DVAR	varying grain size switch (on/off : 1/0)	-	0
RC	friction factor current	-	0.03
RW	friction factor waves	-	0.01
TEMP	temperature	°C	10
SALIN	salinity	‰	28
C_R	correlation wave groups	-	0.25
FACQB	factor of fraction of breaking waves which does not contribute to wave velocity moment	-	0.35

Table 3.3.1 *Parameter settings based on calibration*

Parameter settings:
The parameters used to calibrate the model in the undisturbed situation, thus without shoreface nourishment area, are given in Table 3.3.1. The selection of these parameters is based on results of previous studies on the optimization of the UNIBEST-TC model (Boers 1999; Walstra et al., 2001).

Results
The prediction of the UNIBEST-TC model for Profile 3 gives the bottom profile shown in Figure 3.3.1 based on gamma (wave breaking coefficient) according to Battjes & Stive (1985, calibrated settings). The prediction appears to give a fairly reasonable result in the zone the beach zone (x<4650 m). Although the prediction is not exactly equal to the real profile in June 2001, it shows the same landward movement of the outer breaker bar. Also a reasonable prediction of the shoreface nourishment is given, which reshapes into a smooth bar and remains at its location. The model predicts volume changes which are much too high in subsections A3 and B3 (see Figure 3.3.3). Therefore in this study the focus will be on the model performance in subsection C3, in particular the behavior of the outer breaker bar, and also subsection D3, since this is the section in which the shoreface nourishment is located.

The absolute RMS-error (Root Mean Square error) is 0.72 m for the total profile, 0.19 m for subsection D3, 0.81 m for subsection C3 and 0.93 m for subsections A3 and B3. These values also show that the prediction for subsections A3 and B3 is strongly over-estimated. In subsection C3 a large error is found as well, although the profiles show a reasonably good prediction. The generation of the trough between the shoreface nourishment and the outer breaker bar and the shoreward movement of the outer breaker bar is predicted correctly by the UNIBEST-TC model. However, both processes are underestimated. The results above the 2 m line are not reliable and are not shown here.

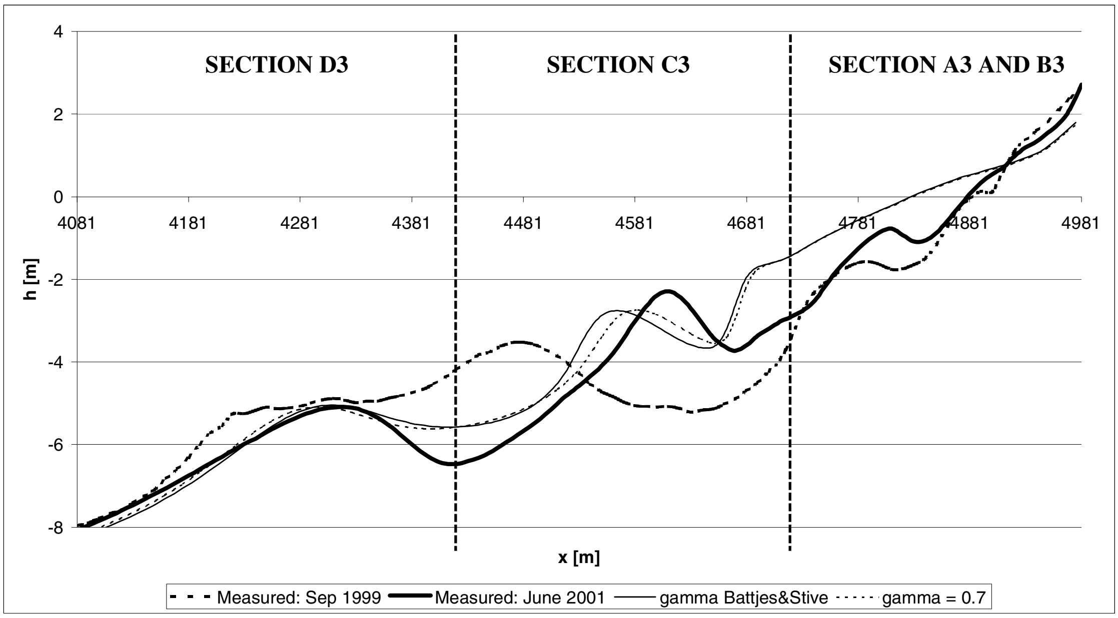


Figure 3.3.1 *Prediction for subsections 3 over a two year period with variations in wave breaking factor GAMMA*

Another breaking parameter was used (gamma= 0.7), resulting in a better model performance (see Figure 3.3.1). Gamma = 0.7 yields a slight increase of the movement of the outer bar compared to the calibrated run with the Battjes-Stive gamma-parameter.

The results of the study show that the model is able to compute profile changes for a cross-section including a shoreface nourishment in a qualititative sense. The detachment of the outer breaker bar from the shoreface nourishment as well as the generation of a trough between the shoreface nourishment and outer breaker bar is correctly simulated by the UNIBEST-TC model. Both processes are under-estimated though. In quantitative sense the model predcitions are not very good yet. For subsections A3 and B3 the predicted bed level is much too high.
In order to analyse where, according to the UNIBEST-TC model, sedimentation or erosion occurs in the cross-shore profile and how the sediment is redistributed in the cross-shore profile during the considered period, the Momentary CoastLine volume (MCL volume) is determined. The MCL volume is an indicator used by Rijkswaterstaat for the determination of beach sedimentation or erosion and nourishment quantities. The MCL volume is herein defined as the sand volume of the zone with a bed level between NAP -5 m and NAP +3 m. The UNIBEST-TC predictions of the MCL volumes for Profile 3 are compared to the MCL volumes derived from the data (Van Duin and Wiersma, 2002) for the period of September 1999 to June 2001.

The results are presented in Figure 3.3.2, showing the computed MCL volume, the measured MCL volume based on data analysis (Van Duin and Wiersma, 2002) and the computed MCL volume minus the sediment import volume over the seaward area boundary (depth = NAP -8 m).

Figure 3.3.2 shows that the UNIBEST-TC model is not able to compute realistic values of the MCL volume. The computed volumes are too large. Subtraction of the sediment import volume over the seaward boundary reduces the values, but the computed MCL value is still too large. This leads to the conclusion that the model ‘error’ of importing sediment over the seaward boundary is not the main reason for the over-estimation of the MCL volumes. Not only the amount of sediment in the MCL zone is over-estimated, but also the development of the MCL volume in time is not predicted correctly by the UNIBEST-TC model. Since the sediment transport over the landward boundary is zero, a possible explanation for these results can be that the model computes too much onshore sediment transport, especially at deep water. Another possible explanation is the loss of sand due to longshore transport, which is not taken into account by the UNIBEST-TC model.

To study why the calculated UNIBEST-TC volumes are not correct, the sediment transport in the area is calculated. Therefore the cross-shore Profile 3 is divided into the corresponding subsections A3 to D3. In Figure 3.3.3 the sediment exchange between the different parts of the subsections is presented. Both the results of the UNIBEST-TC model as well as the results of the data analysis are shown. Areas that have net sediment export are dark grey, areas that have net sediment import are light grey.

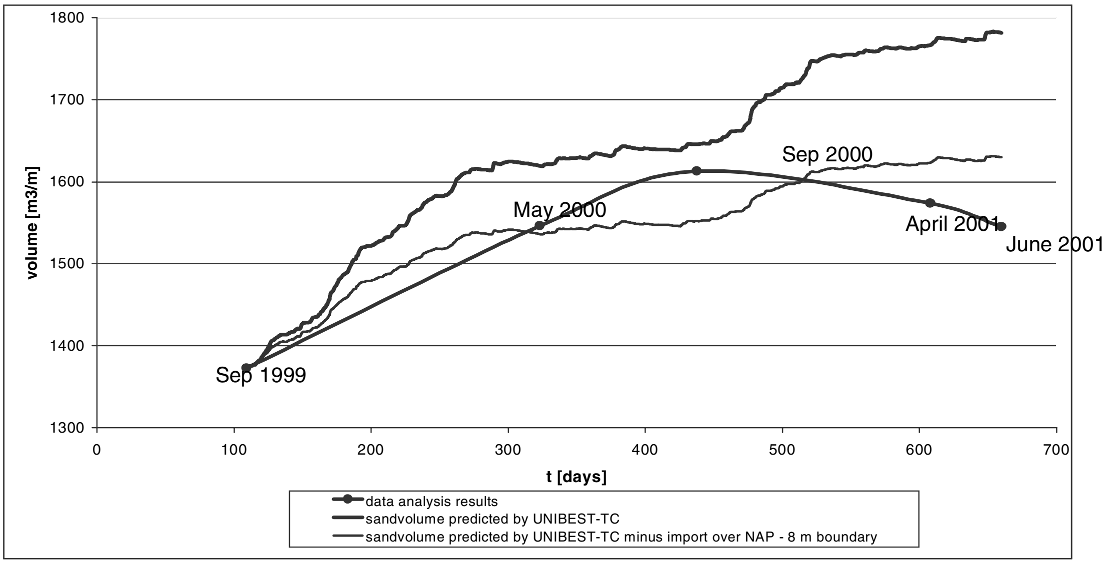


Figure 3.3.2 *MCL volume calculations for Profile 3 (in entre of shoreface nourishment)*

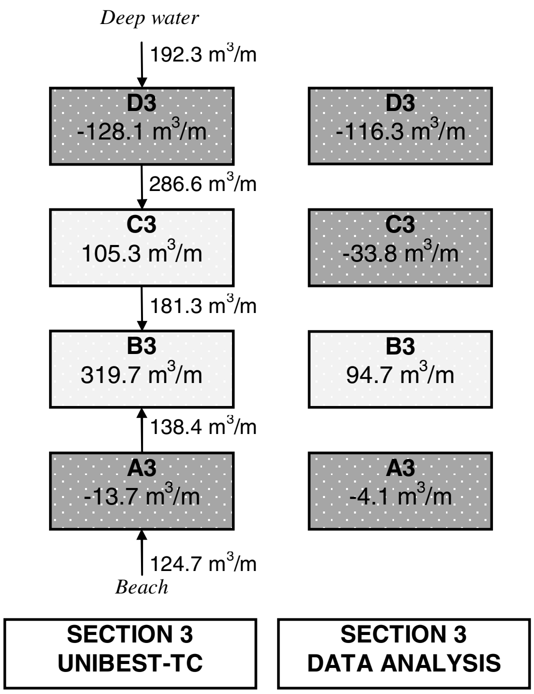


Figure 3.3.3 *Sediment exchange between subsections of Profile 3*

The transport diagram of the UNIBEST-TC results shows large sediment import values from deep water and large sediment export values from the beach area to B3 and C3. Future research should be focused on improving these transport processes.

3.3.4 Delfland model results

Burger (2001) has used the UNIBEST-TC model to hindcast the shoreface nourishment carried out in 1997 at the Ter Heijde location (between 113.4 and 114.6 km). The total nourishment volume was about 1 million m^3. The UNIBEST-TC model was used to

hindcast the morphological developments of Profile 113.94 (middle profile at nourishment location) between 8 April 1998 and 1 April 1999. As the nourishment data shows an almost two-dimensional behaviour, a cross-shore profile approach using the middle profile as representative profile seems reasonable.
Wave data were taken from the Europlatform records. Water levels were taken from Scheveningen harbour records. The most optimum model settings (see Table 3.3.2) were determined by trial and error to obtain the best agreement over the period of about 1 year (8 April 1998-1 April 1999). The results are given in Figure 3.3.4.

Parameter	Waarde	Parameter	Waarde	Parameter	Waarde
Dt	0.041667	K_ijl	on	Hdia0	0
Nt	6096	Flam	2	Hdia1	3
Ustra	0	Pow	1	Hdia2	9
Tdry	25	D50	215	Ibod	Yes
Temp	10	D90	300	Remlg	2
Salin	0	Dss	215	Rc	0.001
Alfac	1	Dvar	yes	Rw	0.0002
Gamma	0	Fdia0	1.8	Tanphi1	0.6
Betd	0.1	Fdia1	1.8	Facqb	0.0
Fwee	0.001	Fdia2	1.8		
C_r	0.25				

Table 3.3.2 *Optimum parameter settin s of UNIBEST-TC model for shoreface nopurishment Delfland over period 8 April 1998-1 April 1999.*

As can be observed, the onshore migration of the nourishment bar feature is hindcasted reasonably well. However, the relatively deep trough landward of the bar can not be represented. Furthermore, the beach volume (between –2 m and +2 m NAP) is considerably overestimated.
Using the parameter settings from the hindcast run, a forecast run for the period 8 April 1998 to 14 July 2001 was made. The results are shown in Figure 3.3.5. As can be observed, the onshore migration is somewhat overestimated. The beach volume between –2 m and +2 m NAP is severely overestimated. This latter oversetimation of the beach volume could be reduced by adjusting the parameter settings.

Finally, the UNIBEST-TC model was used to evaluate the effectiveness of various nourishment schemes over a period of 5 years. The effectiveness was defined as the increase of the sand volume within predefined nearshore zones (MCL zone between –4.3 m and +3 m NAP and Active zone between –8 m and +3 m NAP). The most important conclusions are:

- all schemes result in an increase of the sand volume in the MCL zone and in the Active zone;
- the volume increase is smaller for a deeper nourishment location;
- the offshore sand loss to deeper water is negligibly small.

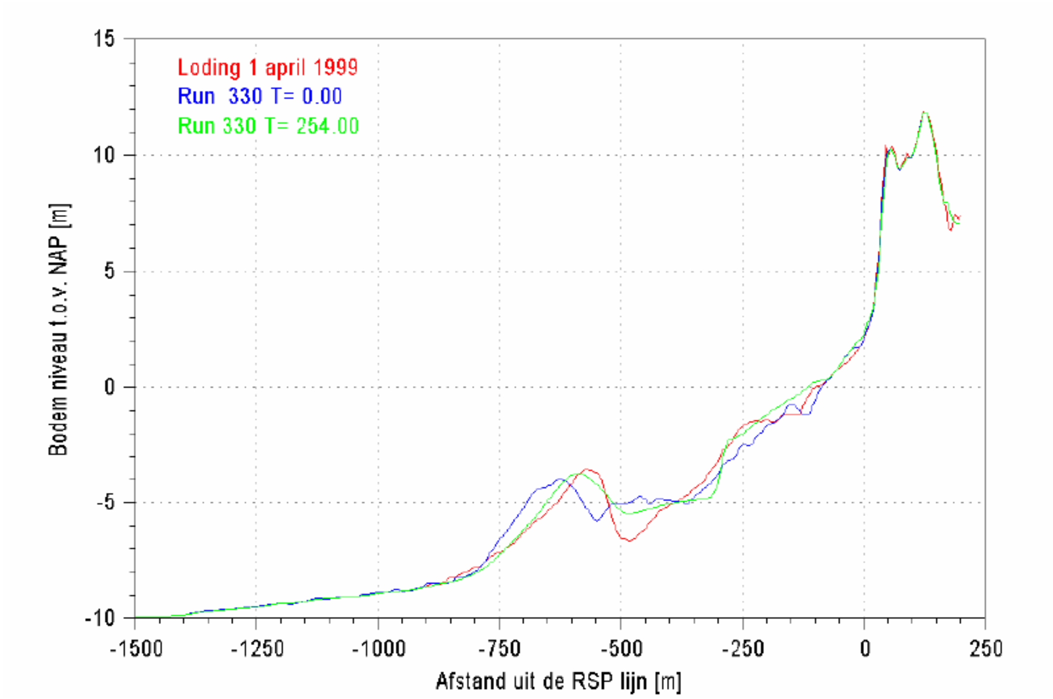


Figure 3.3.4 *Measured and computed profiles (113.94 km) for hincast period between 8 April 1998 and 1 April 1999 (254 effective days with waves).*

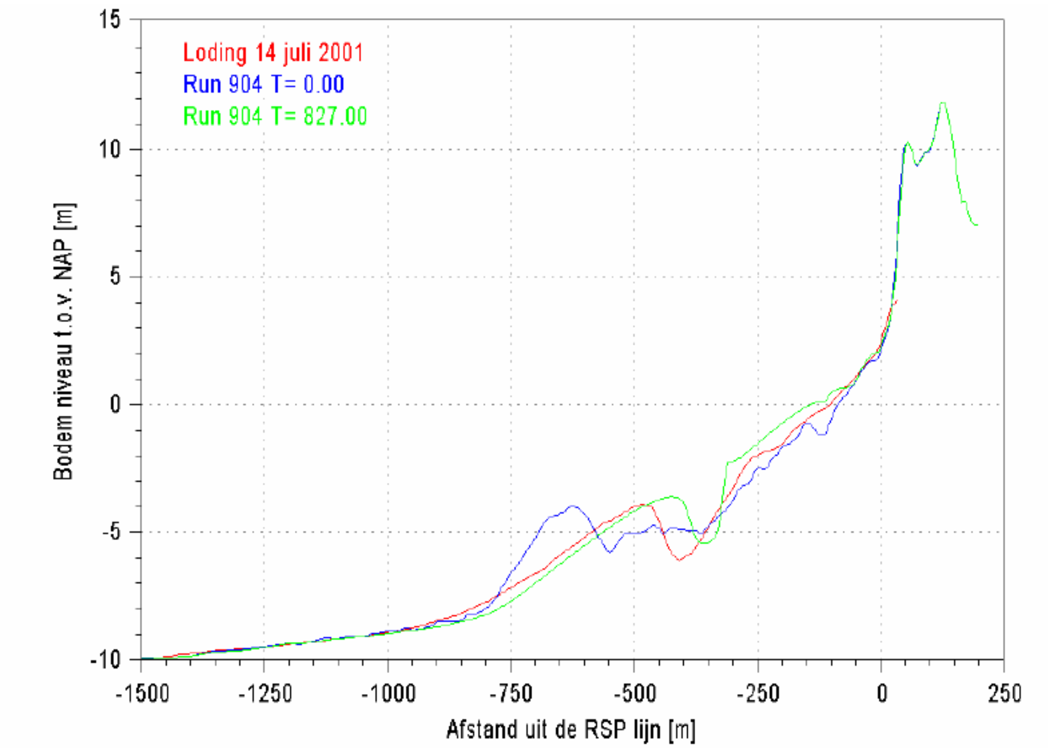


Figure 3.3.5 *Measured and computed profiles (113.94 km) for hincast period between 1 April 1999 and 14 juli 2001 (827 effective days with waves).*

3.4 Two-dimensional horizontal and three-dimensional modelling approaches (DELFT2DH and DELFT3D)

3.4.1 Model approach

The DELFT3D modelling system fully integrates the effects of waves, currents and sediment transport on morphological development in coastal, river and estuarine areas (**Roelvink and Van Banning, 1994; Roelvink et al., 1998; Lesser et al., 2004**). Similar models (in various degrees of sophistication) are available elsewhere.

Flow module
The DELFT3D-FLOW module can be used to compute tidal and wind- and wave-driven currents. It solves the unsteady shallow-water equations in three dimensions on a curvilinear, boundary-fitted grid. The system of governing equations consists of the horizontal momentum equations, the continuity equation, the transport equation and a turbulence closure model.
A number of modifications have recently been incorporated in the DELFT3D-FLOW module to account for the three-dimensional effects of waves on the computed flow velocities and turbulent mixing values. Recent improvements concern the wave asymmetry effects, the wave-averaged currents including major wave-current processes such as wave-induced mass flux, wave-induced turbulence, the effects of streaming and forcing due to wave breaking and the low-frequency effects.

Wave module
To simulate the evolution of wind-generated waves in coastal waters, the DELFT3D-WAVE module can be coupled to wave propagation models. Most often, the SWAN (Simulating WAves Nearshore; **Booij et al., 1999; Ris et al., 1999**) third generation numerical wave model is used. The SWAN model is driven by wind and wave boundary conditions and is based on a discrete spectral balance of action density that accounts for refractive propagation of random, short-crested waves over arbitrary bathymetry and current fields. In SWAN, the processes of wind generation, whitecapping, nonlinear triad and quadruplet wave-wave interaction, bottom dissipation and depth-induced wave breaking are represented explicitly. The numerical scheme for wave propagation is implicit and therefore unconditionally stable at all water depths. To model the energy dissipation in random waves due to depth-induced breaking, a spectral version of the bore-based model of Battjes and Jansen (1978) is used, applied with a time-independent constant breaker parameter. To model bottom-induced dissipation, the JONSWAP formulation is applied to compute bottom friction. Various formulations for wave-induced bottom stress can be used. Field verifications of the SWAN model have proven its ability in accurately reproducing wave height and period distribution, even in complex coastal areas such as barrier islands and tidal flats.

Morphodynamic model
Conventional morphological modelling is carried out using a morphodynamic feed-back loop and consists of a number of integrated modules in which the wave and flow fields, sediment transport and bed-level changes are computed sequentially. A new approach is the implementation of sediment transport and bed level updating as an integral part of the flow module (on-line approach). The main advantages of this recent development are that density effects of suspended sediment are automatically included in the hydrodynamic calculations. Three-dimensional sediment transport calculations are carried out by solving the advection-

diffusion equation for suspended sediments without resorting to the use of shape functions for concentration or flow velocity profiles, and any changes in bathymetry are immediately fed back to the hydrodynamic calculations.
The core of the sediment transport model is the state-of-the-art Van Rijn 2004-model, which is in essence an upgraded version of the Van Rijn 1993-model. This engineering model approach is motivated by the need to reduce computational efforts, allowing for 3D morphodynamic modelling in large spatial scale (10 to 100 km) and temporal scale (years to decades. The sediment transport model can be used for the computation of sediment transport in combined steady and oscillatory flow (waves and current), for rippled and flat beds, and uniform or graded bed materials with particle sizes between 0.1 and 2 mm. The bed-load transport vector due to both current and wave effects (including wave asymmetry) represents a current-related conribution and a wave-related contribution. The suspended load transport represents the current-related contribution due to advective processes and the wave-related contribution mainly due to wave asymmetry effects. In the DELFT3D implementation, all transport vector contributions are transformed into the local coordinate system of the curvilinear grid to determine the spatial gradients of the total transport rate. All transport contributions are time averaged over the wave period.

DELFT3D operates on a staggered grid in which depth points are defined at the vertices of a computational cell, velocity points at the mid-points of a grid cell side, and water level points at the center of a grid cell (computed from the four surrounding depth points). Bed-load sediment transport vectors are calculated and stored at the velocity points, and subsequent bed-level changes in depths points are computed from the bed-load sediment transport gradients between adjacent water level points. The resulting change in the bottom sediment in each grid cell is added to the change due to the suspended sediment deposition and erosion rates and included in the bottom updating scheme, thereby assuring that the hydrodynamics are always calculated with the correct bathymetry. The bottom is updated at every computational time-step. Morphological changes take place on a time scale several times longer than typical flow changes; in the sediment version of DELFT3D-FLOW, the morphological acceleration factor is used to deal with the difference in time scale between hydrodynamic and morphological development thereby effectively extending the morphological time step by allowing accelerated bed-level changes to be incorporated dynamically into the hydrodynamic flow calculations.
DELFT3D can also be operated in a 2DH mode. The main difference is related to the magnitude of the offshore transport rates. In 2DH mode, the undertow is included by correcting the depth-averaged cross-shore velocity with the mass flux. A logarithmic velocity distribution is used to estimate the velocity profile, which is then used in the sediment transport computations. This logarithmic profile has much lower near-bed velocities (where sediment concentrations are highest) than the typical belly-shaped profile produced by the k-eps turbulence closure model in 3D mode, causing 2DH offshore transports to be somewhat lower than in 3D mode resulting in the reduction of the sediment volumes in the surf zone. A 2 DH simulation can be performed essentially by decreasing the number of vertical layers from 10 to 1 and adapting accordingly the model boundary definitions.

3.4.2 Terschelling model results

Grunnet et al. (2004) used a numerical 2DH and 3D model to study the behaviour of the Terschelling nourishment.

Terschelling characteristics

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 backbarrier system of the Wadden Sea. The orientation of Terschelling is roughly WSW-ENE. The central part of Terschelling has retreated by about 2-3 m/yr over the last decades. The study area is situated along this eroding coast between km section 10 and 22. Along the study area, the shoreline is slightly curved and concave; the coastline orientation in the study area is about 73^{o} N. The coast consists of sandy beaches and dunes. The nearshore zone is characterised by the presence of 2 to 3 sandbars which behave in a repetative offshore-directed manner on the time scale of years (the cycle return period is about 12 years. 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 NAP (Dutch Ordnance Level; about mean sea level) is about 1:180. The median grain size (d_{50}) varies from 0.22 to 0.26 mm on the intertidal beach to 0.15 to 0.16 mm in the lower shoreface. The mean annual significant offshore wave height at the -15 m isobath is about 1.1 m and the mean annual signifcant onshore wave period is about 7 s. During storms the wave height increases to 5–6 m with corresponding periods of about 10 to 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 than the WSW ebb currents; tidal current ellipses are oriented parallel to the shore. The barrier island of Terschelling is flanked by tidal inlets. 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 southern inlet; the maximum amplitude of these undulations is on the order of two meters and their wavelength is nearly constant at about 1 km. This bar pattern migrates in a southeasterly direction with an average rate of about 500 m/yr 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 0.5–0.6 Mm3/yr to 1.0 Mm3/yr.

To counteract the ongoing erosion, a shoreface nourishment of 2.1 Mm3 of sand (0.22 mm) was carried out in the period from May to November 1993, filling up the trough between the middle and outer breaker bar in depths of 5 to 7 m below MSL. The length of the shoreface nourishment was 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. By spring 1994, most of the nourished sediment had been redistributed onshore and welded onto the middle bar where it remained in the following years. The morphodynamic model is applied to the prediction of this rapid nearshore profile behaviour.

Model results

The applied morphodynamic model is DELFT3D for fully threedimensional flow and sediment transport in coastal environments. Owing to a complex geomorphological setting of the study area, the curvi-linear model includes adjacent tidal inlets and covers 40 km by 70 km with an increasing grid size resolution towards the nourishment site in the center of the island. The calibration of the model against an extensive set of full-scale hydrodynamic data at several locations throughout the nearshore bar zone shows a good representation of the measured hydrodynamics. The morphodynamic model simulates the 5-month period after the nourishment during which most of the morphological changes took place.

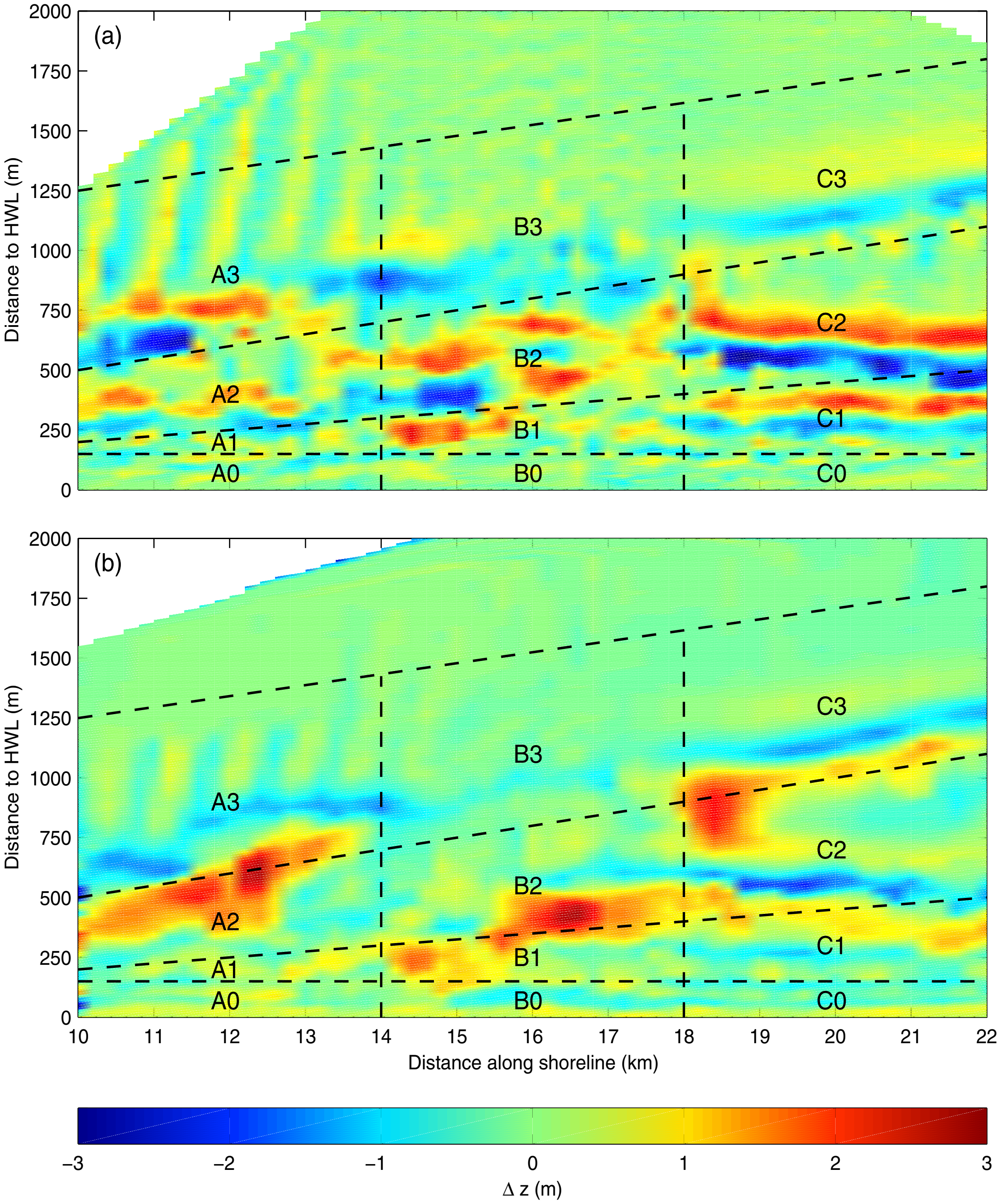


Figure 3.4.1 *(a) Measured and (b) predicted sedimentation (positive z) and erosion (negative z) patterns for the period from November 18, 1993 to April 20, 1994. The study area was divided into cross-shore sections containing distinct morphological features corresponding to the intertidal beach and each of the inner, middle and outer bars, numbered 0–3, respectively. Note the obliqueness of the alongshore boundaries as a result of the seaward-increasing location of the nearshore bars towards the east. Alongshore sections were determined with a length of 4 km around the location of the nourishment corresponding to a western, central and eastern zone, labelled A–C, respectively. Also note that cross-shore distance is with respect to HWL, thereby removing the concavity of the shoreline.*

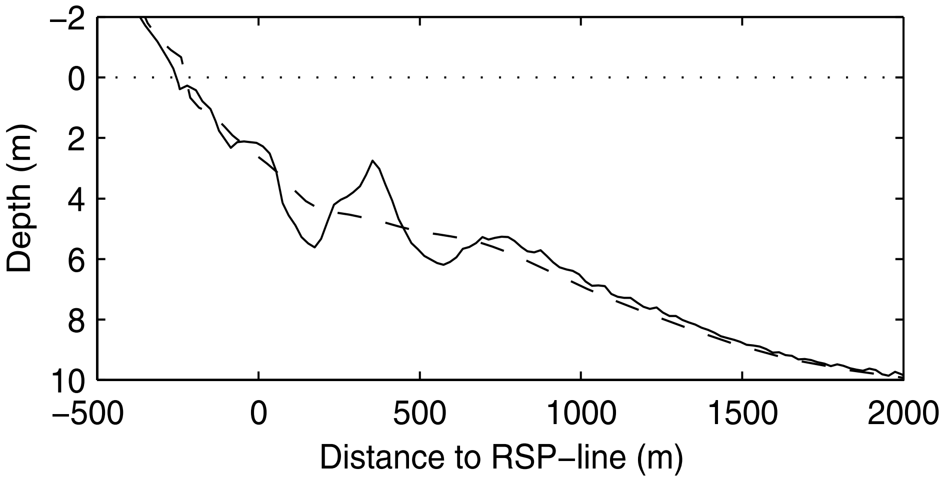


Figure 3.4.2 *Observed (solid line) and predicted (dashed line) depth relative to MSL (dotted line) in km-section 17 versus cross-shore distance on April 20, 1994*

The morphological boundary conditions are the bathymetries sounded on November 18, 1993 and April 20, 1994 corresponding to the first and second postnourishment monitoring of the study area. A choice of 6 representative wave conditions, each representing a directional sector including a range of wave heights and directions, was made to schematise the wave input.

Key sand transport parameters were used to calibrate the model. Analysis of the results show that the modelling of cross-shore bed-level changes is extremely poor and the observed cross-shore migration and development of bars is not well reproduced; bars appear to diffuse rather than migrate. When viewed on a larger spatial scale, however, using alongshore averaged bulk volumes (V) of the boxes shown in Fig. 3.4.1, the model results are more favorable.

Bed-level changes in the period November 1993 to April 1994 derived from the soundings and the calibrated morphodynamic simulation are presented as sedimentation/erosion plots of the study area in Figure 3.4.1.

In relation to measured bed levels in Fig. 3.4.1a, alongshore-parallel adjacent areas of sedimentation and erosion indicate bar migration activity. Held in comparison with the profile development shown in Fig. 3.4.2, a similar pattern in relation to predicted bed levels in Fig. 3.4.1b is more an artefact of bar diffusion. Measured bed levels exhibit a distinct offshore migration of all 3 bars east of the nourishment with the largest bed level changes for the middle bar in C2 on the order of ±2–3 m with a corresponding seaward migration of about 100 m. In the same section C2, the predicted bed level pattern corresponds to the filling up of the landward and seaward troughs on either side of the middle bar as a result of vertical decrease in bar height. The onshore movement of the nourishment onto the middle bar is described by the generally positive values for both measured and predicted bed level in B2, although the measured sedimentation pattern is more dispersed due to the alongshore variability of the middle bar crest line. This onshore movement is coupled with the generally negative values for both measured and predicted bed level in B3.

An accurate prediction of sediment volumes is generally reproduced at the shoreline, specifically in relation to the sedimentation shoreward and downdrift of the nourishment in B0 and C0 (see Table 3.4.1). The model gives an overall good representation of sediment volumes in the middle bar sections A2, B2 and C2. Large volumetric changes related to the cross-shore redistribution of the supplied sediment are well reproduced; measured (predicted) volumes in section B2 increases by 128 (149) m3/m and in B3 decreases by 62 (87) m3/m. The eastward alongshore movement of the nourishment along the middle bar in C2 is however overestimated both in distance and bed level (on the order of +2.1 against

+1.4 m). The poorest estimates of integrated volume changes occur in outer bar sections A3 and C3. Less attention should be given to the extremely poor volume prediction updrift of the nourishment in A3 as little is known about the transport capacity of the sandwaves. Surprisingly however, the shore-oblique eastward propagation of the sandwaves in A3 is well reproduced by the model although slightly underpredicted (bed level on the order of ±0.8 against ±0.5 m).

Section	$\Delta V_{observed}$ (m^3/m)	$\Delta V_{modelled}$ (m^3/m)
A0	-3	5
B0	6	7
C0	7	5
A1	-1	8
B1	71	96
C1	19	26
A2	54	82
B2	128	149
C2	83	68
A3	3	-91
B3	-62	-87
C3	43	-8

Table 3.4.1 *Observed and modelled volume changes (longshore-averaged per m; compartments in Figure 3.4.1)*

A sensitivity analysis was performed focussed on key calibration factors in the sediment transport formulations and therefore was limited to the various calibration factors and the median grain size. A total of 13 sensitivity runs was performed by varying one parameter at the time while keeping all other parameters at their respective calibrated value; all sensitivity runs were subject to the same forcing conditions as the calibrated simulation. The variation range of transport calibration parameters was on the order of ±50% in relation to recommended values for field cases, and d_{50} was varied ±25% in accordance with the measured cross-shore variation of median grain size with depth. These ranges are based on common engineering practice but whether these ranges are actually representative of the uncertainties in the parameters is not known. The model predictions for the various sensitivity runs were quantified with emphasis on the large-scale sediment budget in the nourished central part of the study area, i.e. modelled volumes for sections B0 to B3. The model predictions are sensitive to the variation in the transport factors. The resulting volume-range, relative to the respective calibrated value in each section, is largest in the intertidal zone B0, often with a change in the order of magnitude of the predictions in this section, decreases seaward with maximum deviations of about 100% in B1 and B2, and further decreases to about 20% in the outer nearshore bar zone B3. The predictions are specifically sensitive to the magnitude of the offshore current-related suspended load factor and to a lesser extent to the magnitude of the onshore bed load factor and the onshore wave-related suspended load factor. A smaller variation on the order of ±15% across all sections results from the variation in d_{50}. The pronounced sensitivity of model predictions to the setting of free parameters in the sediment transport formulations strongly suggests that such a model should only be applied following a thorough morphodynamic calibration and thus not be based on default settings.

Discussion

The 3D morphodynamic computations are found to be potentially feasible for the simulation of nourishment behaviour. On a large scale of overall profile behaviour derived through bulk volumes integrated over large spatio-temporal scales (several kilometres and months), the predictive capability of the model was found to give a reasonable representation of the nourishment development. The overall effect of the nourishment related to lee and feeder effects are reproduced: integrated over distances on the order of the alongshore length of the nourishment, the sedimentation at the shoreline and the onshore movement of nourished sediment are well predicted. However, for detailed morphodynamic predictability on the scale of sandbar behaviour, process-based 3D modelling does not yet appear to be suitable. Predictions of nearshore bar migration and development remain poor. Bar flattening was found for all parameter settings tested in the calibration phase, thus at present these parameters just appear to control the large-scale sediment budgets. The sensitivity of profile evolution to forcing chronology was tested; changing the order of the forcing conditions revealed negligible changes in cumulative predicted bed level changes at the end of the simulation period. Model predictions showed a tendency towards flattening of the nearshore bars. The relatively poor performance of the present 3D process-based model with respect to the bar morphology is not a specific feature of the present model. Sufficient accuracy in the prediction of bar behaviour is also not obtained in most 2D process-based cross-shore profile models (Van Rijn et al., 2003), often with decreasing predictability as time scales increase as involved errors tend to accumulate with longer time scales.

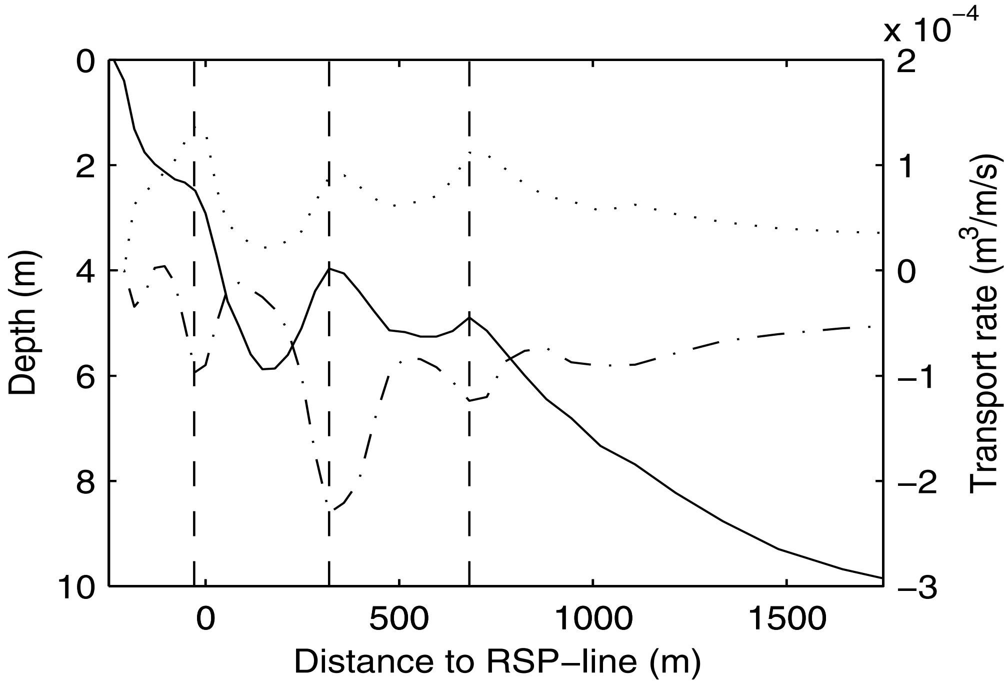


Figure 3.4.3 *Predicted distribution of depth-averaged cross-shore transport rates (positive onshore) for suspended load (dash-dotted line) and bed load (dotted line), here shown for H_s = 3.75 m. The cross-shore profile (full line) corresponds to section 17 after the implementation of the nourishment. The locations of bar crests are shown with vertical dashed lines.*

The process of systematic bar flattening is strongly related to the direct response of the hydrodynamics of breaking waves and derived undertow, and the corresponding sediment transport. A typical example of the cross-shore distribution of transport rates (see Figure

3.4.3) shows that the predicted location of maximum transport rate coincides with the location of bar crests resulting in erosion of bar forms and deposition in the direct vicinity of bar crests. Although this will result in bar migration, the dominant effect on the time scale of months is diffusion, inevitably leading to the decay of the sandbars. The inclusion of a phase lag between sediment transport and bathymetry appears to be essential for bar survival. Model-data comparison of the flow field indicates that the model performs well in calm conditions whereas during storms errors increase; this is likely due to the wave forces driving the flow model as suggested by the inaccuracies in wave height predictions during high-energy events. Model improvement of wave height predictions could probably have been achieved by applying an improved breaker height-to-depth parameter. Research efforts on 2DV profile modelling suggest that promising ways of improving the predictive capability of process-based models are related to wave energy decay concepts, specifically surface roller delay and wave breaker delay; both effects relate to a spatial shift between the morphology and sediment transport gradients resulting in bar migration and development. Including a surface roller in the wave energy dissipation model has been shown to be important for both the structure of the alongshore current and the undertow. Laboratory and field observations show that waves do not break at bar crests but in the trough behind them, thus with observed maximum undertow velocities located further shoreward than usually predicted by process-based models in their present state. In 2D cross-shore profile models, surface roller models are already included and have proven to favourably change the cross-shore location of gradients in transport rates. The presence of a surface roller significantly influences the vertical velocity profile of the undertow leading to a shoreward shift of the maximum cross-shore current velocities. Introducing a wave breaker delay, a first successful attempt at modelling bar behaviour on decadal time scale was made by Roelvink et al. (1995). Breaker delay was of vital importance for the simulation of long-term nearshore bar behaviour at Terschelling; leaving the breaker delay effect out lead to a rapid decay in bar height. The fraction of breaking waves at a certain depth was made dependent on a water depth weighted over a certain distance seaward of that depth, thereby allowing waves to start breaking over a distance away from bar crests. At present these effects are not included in the 3D model, therefore the model can only be applied to compute bulk volumes integrated over large spatio-temporal scales.

Since DELFT3D can also be operated in a 2DH mode, a morphodynamic simulation in the computationally much less extensive 2DH mode was also carried out to illustrate the differences with the 3D approach. The main difference is related to the magnitude of the offshore transports. In 2DH mode, undertow is included by correcting the depth-averaged cross-shore velocity with the mass flux. Then, a logarithmic velocity distribution is used to estimate the velocity profile, which is then used in the sediment transport computations. This logarithmic profile has much lower near-bed velocities (where sediment concentrations are highest) than the typical belly-shaped profile produced by the k-eps turbulence closure model in 3D mode, causing 2DH offshore transports to be lower than in 3D mode. Based on the readily available 3D model set-up, a 2 DH simulation was achieved essentially by decreasing the number of vertical σ-layers from 10 to 1 and adapting accordingly the model boundary definitions; all forcing conditions were kept identical to those of the 3D simulations. The calibrated parameter setting for the flow and wave modules in the 3D mode were initially also applied in 2DH mode. Virtually identical cumulative predicted bed level changes at the end of the simulation period could be achieved mainly by increasing the offshore-directed transport i.e. by adjusting the calibration sand transport factors, thereby counteracting the inaccuracies in the 2DH undertow induced sediment transports. The 2DH approach exhibited the same dependency on spatial scale as the 3D approach: 2DH model predictions also showed a tendency towards flattening of the nearshore bars at approximately the same rate as for the 3D predictions and a good model-data comparison of volumetric changes was only obtained when resorting to integrated changes over a large spatial scale. The merits of a 3D approach versus a 2DH approach thus lies in the accurate representation of measured hydrodynamics since it does not provide noteworthy

improvements in terms of morphological predictions. In view of the limited added contribution of a fully 3D approach coupled with the prohibitively time consuming computations thereby required, it appears that a 2DH approach performs as well although not supported by the same accurate representation of flow phenomena. If the desired end result of a modelling study is bathymetric evolution solely, a 2DH approach may be sufficient (albeit for the wrong hydrodynamical reasons, counteracted mainly by adjusting the free parameters).
Summarizing, the morphodynamic results show a dependency on spatial scale: on the scale of precise bed level evolution with respect to bar migration and growth, model predictions are poor as the nearshore bars are predicted to flatten out. Resorting to bulk volumes integrated over larger spatial scales, the model clearly has skill in predicting the overall effects of the nourishment. The lack of phase shift between sediment transport and bathymetry is identified as the key controlling factor for the poor sandbar predictions. The short-term behaviour of the bulk volumes could be described reasonbly well, but the detailed cross-shore behaviour of the nourishment material (artificial bar) could not be represented. The nourished material showed a diffusive behaviour rather than a migration-type (as observed) behaviour.

3.4.3 Egmond model results

Van Duin and Wiersma (2002) used the DELFT 2DH-model model to simulate the behaviour of the Egmond nourishment case.

Computational grid , bathymetry and boundary conditions
The curvilinear computational grid is chosen alongshore with a rotation of 9° (clockwise) in relation to the true North. In the area of interest, the shoreface nourishment area, the grid resolution is relatively high and has a distance of 20 m cross-shore and 40 m longshore. The grid distance increases towards the boundaries. The boundaries are situated relatively far from the area of interest in order to prevent boundary effects in the area of interest. The total grid size is kept as small as possible to minimize the calculation time. The total longshore grid length is approximately 10.4 km. The total cross-shore grid length is 2.3 km. The total amount of grid cells is 10,374.
The bathymetry at Egmond aan Zee is based on WESP (Water En Strand Profiler) and ship soundings. The initial batymetry is the first available data set after the placement of the shoreface nourishment (01-09-1999). At the seaward boundary a uniform depth value of 22 m is applied; at the landward boundary a uniform depth value of -3 m.
Prescribed water levels and currents drive the Egmond model at the model boundaries. The northern and western boundaries have prescribed water levels, whereas the southern boundary has currents prescribed. The tidal boundary conditions have been obtained by nesting of the Egmond model in the North Sea model, resulting in time series of water levels and currents at the boundaries of the Egmond model. The North Sea model is driven by the schematized morphological tide from another study (Maasvlakte-2 study; Roelvink et al., 1998).

The parameter settings are shown in Table 3.4.2.

Parameter	Value	Parameter	Value
Flow:		***Transport:***	
water temperature	8 °C	density of sediment	2,650 kg/m^3
water density	1,023 kg/m^3	D_{50} grain size	0.2 mm
gravity	9.81 m/s^2	D_{90} grain size	0.3 mm
latitude	55 °	transport time step	30 min
computational time step	30 s	particle fall velocity	0.023 m/s
bottom roughness (Manning)	0.026 m$^{1/3}$/s	***Bottom:***	
horizontal eddy viscosity	1 m^2/s	Courant number limitation	0.8
Wave:			
width energy distribution	4		

Table 3.4.2 *Parameter settings applied*

Wave heights and wind

To minimize the computation time of the simulation, a wave schematization is made. This schematization should result in a reliable description of the net longshore transports. The schematized wave climate is referred to as a morphological wave climate. The longshore sediment transport calculated by the UNIBEST model (Wiersma, 2002) has been used to derive the morphological wave climate. The wave climate used in this study is from 'IJmuiden' for the period of September 1999 to May 2000. The schematization results in twelve wave conditions (six directions times two wave heights), which result in an overall net sand transport equal to the sand transport based on all available wave conditions.

Since no wind data are available, the wind effect has been neglected in the modelling approach. Only for some sensitivity runs of one day, to study the influence of the shoreface nourishment, the wind effect has been taken into account. For those sensitivity runs the wind is set on 20 m/s and the direction is chosen equal to that of the wave direction.

Model results: currents

Detailed results have been presented by Van Duin (2002). Here only the most striking results will be discussed. The simulations can be divided into two different type of runs: short-term runs of one day, called the (hydrodynamic) sensitivity runs, and long-term runs covering a period of eight months (September 1999 till May 2000), called the hindcast (morphodynamic) simulations.

The short sensitivity runs are used to study the influence of the shoreface nourishment area, under storm and normal conditions, on the hydrodynamics (water motion and waves). The hindcast simulations are used for comparison of model results and measured data and for analysis of the sensitivity. The emphasis is laid on the morphodynamics (sediment transport).

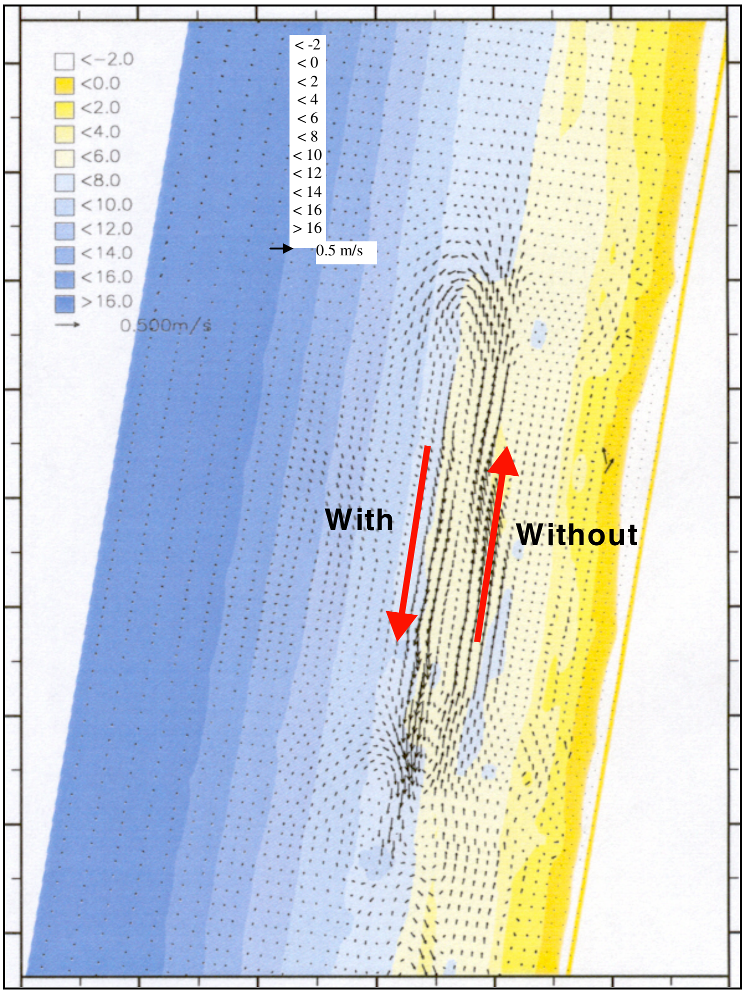
As regards the most important sensitivity runs, the flow velocity with and without shoreface nourishment was calculated. In order to see what the influence is of the shoreface nourishment on the flow velocity, the difference in flow velocity in the situation with and without shoreface nourishment area is studied. This is done by subtracting the flow velocity field without shoreface nourishment area from the flow velocity field with shoreface nourishment area, which results in a "difference"-flow velocity field (flow velocity northward is positive, flow velocity southward is negative):

Difference-flow velocity field= flow velocity field <u>with</u> shoreface nourishment - flow velocity field <u>without</u> shoreface nourishment

The difference-flow velocity field for the Northwest-high waves condition is shown in Figure 3.4.4. The arrows directed northward indicate a higher flow velocity for the situation without a shoreface nourishment area, the arrows directed southward indicate a higher flow velocity for the situation with a shoreface nourishment area. The two large arrows illustrate the directions of the plotted smaller arrows.
The difference-flow plot shows a higher flow velocity at the location of the shoreface nourishment area and a lower flow velocity just shoreward of the location of the shoreface nourishment area, all compared to the flow velocity without shoreface nourishment area. This substantiates the hypothesis of a decrease of the flow velocity shoreward of the shoreface nourishment as a result of the shoreface nourishment area (lee effect). A decrease of the flow velocity will lead to more sedimentation, whereas an increase of the flow velocity will lead to more erosion.

Along several longshore sections the flow velocities of the DELFT 2DH model are calculated and plotted. In the upper plot of Figure 3.4.5 the location of the longshore section near the shore (approximately shore-parallel subsections C, see Figure 3.4.5) is shown. The lower plot shows the longshore flow velocities including tidal velocities for Northwest high and Northwest low wave conditions and for situations with and without shoreface nourishment area. NWH- / NWL- stands for the Northwest high/low condition without shoreface nourishment area, whereas NWH+ / NWL+ stands for the Northwest high/low condition with shoreface nourishment area. The negative sign in the longshore distance is to the South, positive is to the North. The shoreface nourishment area is located more or less between longshore distance –1,000 m and +1,250 m.

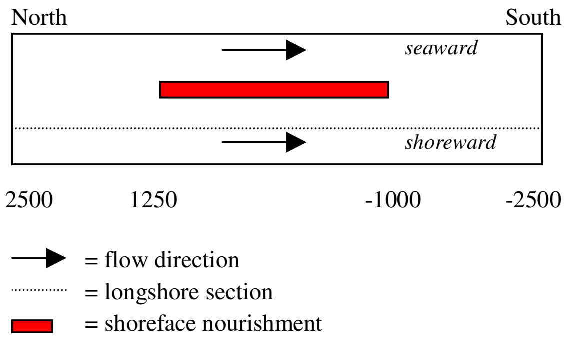
As can be seen from Figure 3.4.5, the flow velocities in the case of a Northwest high condition with shoreface nourishment (NWH+) are lower in the area from longshore distance +1,250 m to longshore distance –1,000 m, than for the Northwest high condition without a shoreface nourishment (NWH-). This is the area in which the shoreface nourishment is located. Therefore it can be said that the shoreface nourishment causes a reduction of the flow velocity in case of relatively high waves. The reduction is approximately 30% in case of relatively high waves (NWH+). It can also be seen that the longshore velocity decreases continuously in the lee of the shoreface nourishment; outside the shoreface nourishment the longshore velocities are larger than those in the lee area. The flow velocities discussed above are an indication of the flow velocities in the subsections C.



↓ = higher flow velocity <u>with</u> shoreface nourishment than without shoreface nourishment

↑ = higher flow velocity <u>without</u> shoreface nourishment than with shoreface nourishment

Figure 3.4.4 *Difference-flow velocities (in m/s) for condition Northwest high at maximum ebb; depth colour-scale (in m)*



NWH- = Northwest, high waves, without shoreface nourishment
NWH+ = Northwest, high waves, with shoreface nourishment
NWL- = Northwest, low waves, without shoreface nourishment
NWL+ = Northwest, low waves, with shoreface nourishment

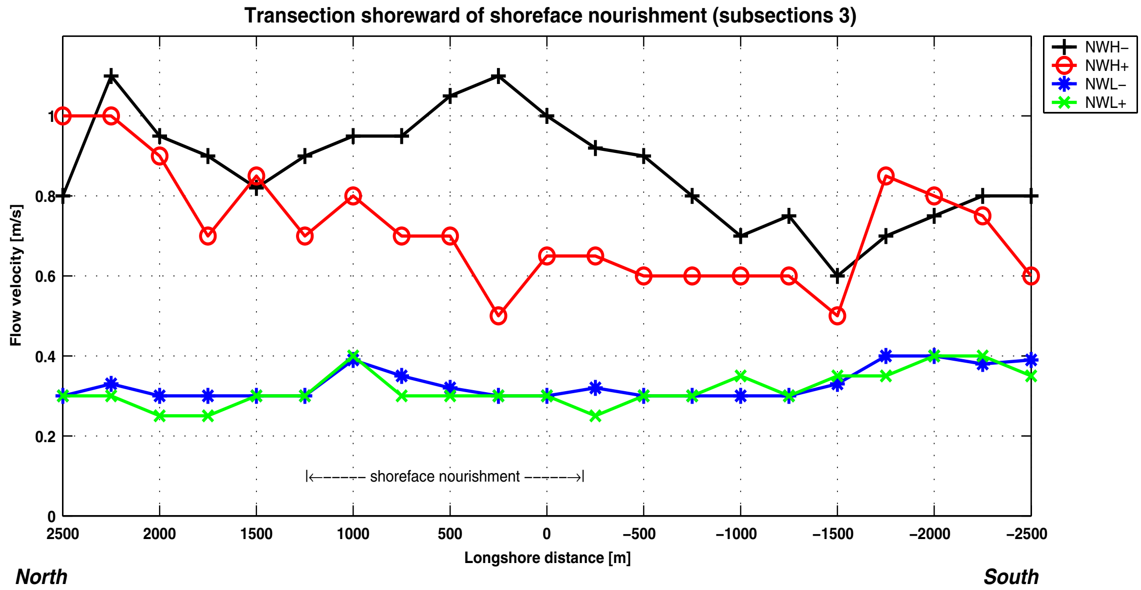


Figure 3.4.5 *Flow velocities alongshore for waves coming from the Northwest*

Model results: waves

In order to see what the effect is of the shoreface nourishment area on the waves in the model, the wave energy dissipation is studied. In Figure 3.4.6 the wave dissipation for the Northwest high condition with and without shoreface nourishment area is shown in N/m/s. Most of the wave energy dissipation is caused by breaking of waves. The largest difference in wave energy dissipation in the situation with and without shoreface nourishment area can be seen on the outer bar. In the case of no shoreface nourishment area (right plot Figure 3.4.6) the wave energy dissipation on the outer bar is very high, indicated by the oval curve. The figure with shoreface nourishment area (left plot Figure 3.4.6) shows a reduction of the wave energy dissipation shoreward of the shoreface nourishment area, indicated by the oval curve. Overall, it can be seen that the shoreface nourishment causes a reduction of the energy dissipation on the outer bar. In the trough area shoreward of the shoreface nourishment area (between outer and inner bar), a slightly higher wave energy dissipation can be seen for the situation without the shoreface nourishment area (less white, indicating a wave dissipation of < 2 N/m/s). For the beach zone no significant changes in wave dissipation can be noticed. The wave heights at the edge of the shallow beach zone are depth-limited in that zone (about 0.8 of the local water depth).

Figure 3.4.7 shows the computed wave height in an alongshore section (shoreward of nourishment area; approximately subsections C, see Figure 3.4.9) for situations with and without shoreface nourishment area, Northwestern wave condition and for high and low wave conditions. Differences in wave height occur for the high wave conditions (NWH- and NWH+). Between longshore distance +750 m and –500 m in the lee of the shoreface nourishment area the wave heights are approximately 15% lower due to the presence of the shoreface nourishment.

The shoreface nourishment area causes a slightly calmer wave climate shoreward of the shoreface nourishment area, see lower plot Figure 3.4.7. Sediment supplied by the longshore transport can settle in the lee of the shoreface nourishment area.

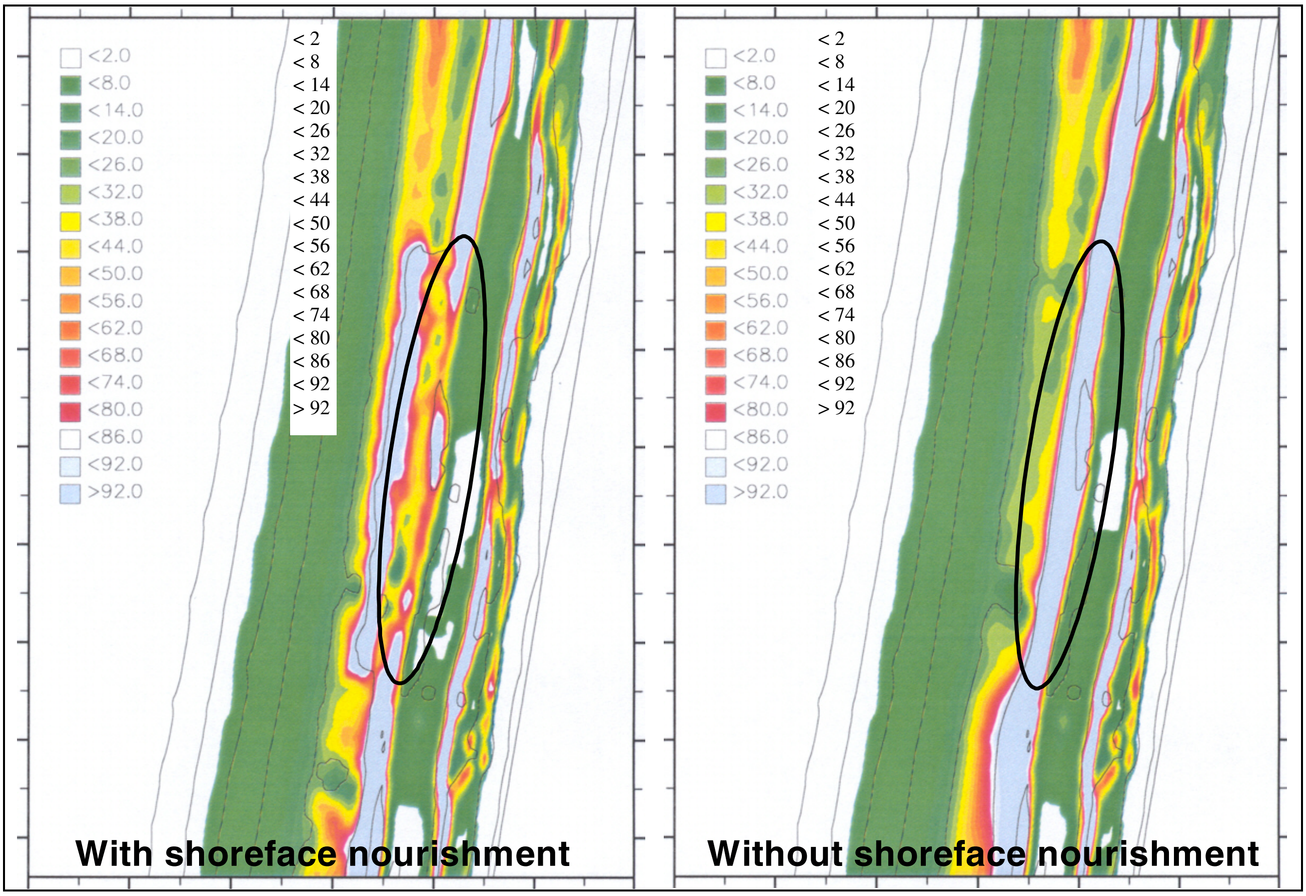
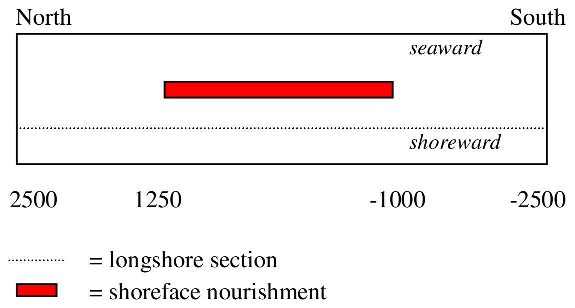


Figure 3.4.6 *Wave dissipation (in N/m/s) for condition Northwest high with and without shoreface nourishment area*



NWH- = Northwest, high waves, without shoreface nourishment
NWH+ = Northwest, high waves, with shoreface nourishment
NWL- = Northwest, low waves, without shoreface nourishment
NWL+ = Northwest, low waves, with shoreface nourishment

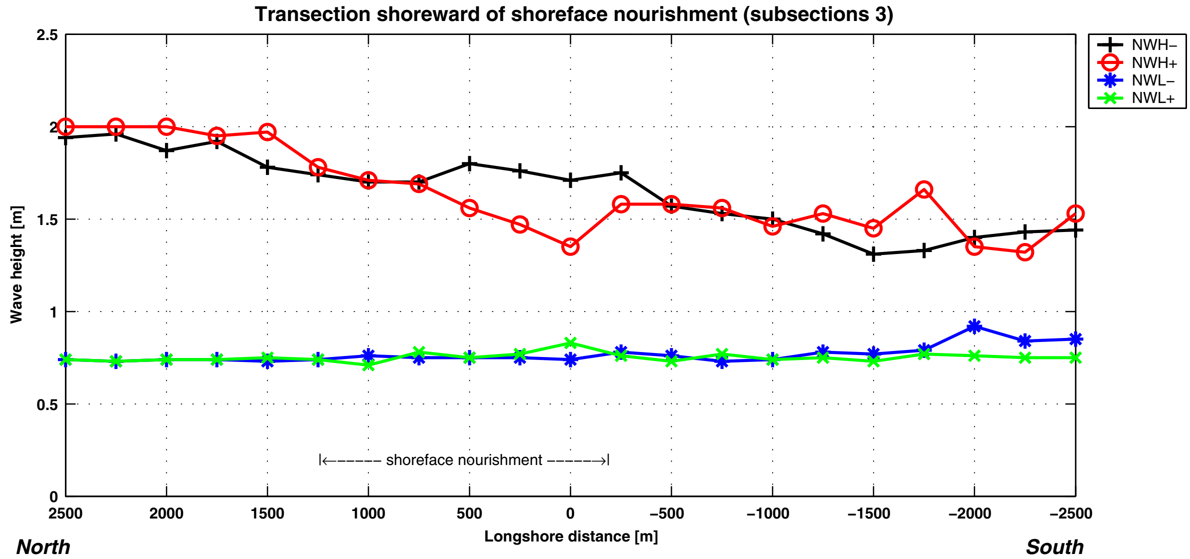


Figure 3.4.7 *Wave heights alongshore for waves coming from the Northwest*

Model results: Cross-shore profiles

The profile changes for several DELFT 2DH hindcast simulations as well as the measured data are shown in Figure 3.4.8. The plot shows the measured profile of September 1999, which also is the reference date for the DELFT 2DH simulation runs. The measured profile after eight months (May 2000) clearly shows the movement of the outer bar to the shore and the separation of the outer bar from the shoreface nourishment. The result of the DELFT3D hindcast run shows weak onshore movement of the profile, much smaller than that based on the measured profile at May 2000. Furthermore, the separation of the shoreface nourishment from the outer bar is not realized in the DELFT 2DH model. The outer bar stays attached to the shoreface nourishment. A possible explanation is the mechanism of wave asymmetry, which causes sediment transport in the wave propagation direction. The mechanism of wave asymmetry and the resulting transport is not taken into account by the DELFT 2DH model as used by Van Duin and Wiersma (2002).

In order to try to simulate this cross-shore movement of the outer bar, the sediment transport in the wave direction due to wave asymmetry was included for the sensitivity runs following the Bailard approach, see Bailard (1981), Stive (1986). The cross-shore profile resulting from the simulation run including Bailard is also shown in Figure 3.4.8. As a result of the inclusion of the Bailard approach a small improvement in the movement of the outer bar can be seen, but the separation of the outer bar from the shoreface nourishment is still not modelled properly and a larger flattening of the profile does occur.

The sensitivity of the Egmond model to the effect of bottom roughness on the flow is studied by changing the Manning coefficient. For the hindcast settings a Manning coefficient was used of n = 0.026 $m^{1/3}$/s, which is C_{2D} = 56 $m^{1/2}$/s. The effect of almost doubling the Manning coefficient to n = 0.040 $m^{1/3}$/s is shown in the profile change of Figure 3.4.8. The increase of the Manning coefficient is equal to a decrease of the Chézy coefficient and equal to an increase of the flow resistance and hence lower velocities. The cross-shore profile resulting from the increase of the Manning coefficient shows a more shoreward movement of the outer bar compared to the hindcast run. Still the separation of the outer bar from the shoreface nourishment is not modelled correctly.

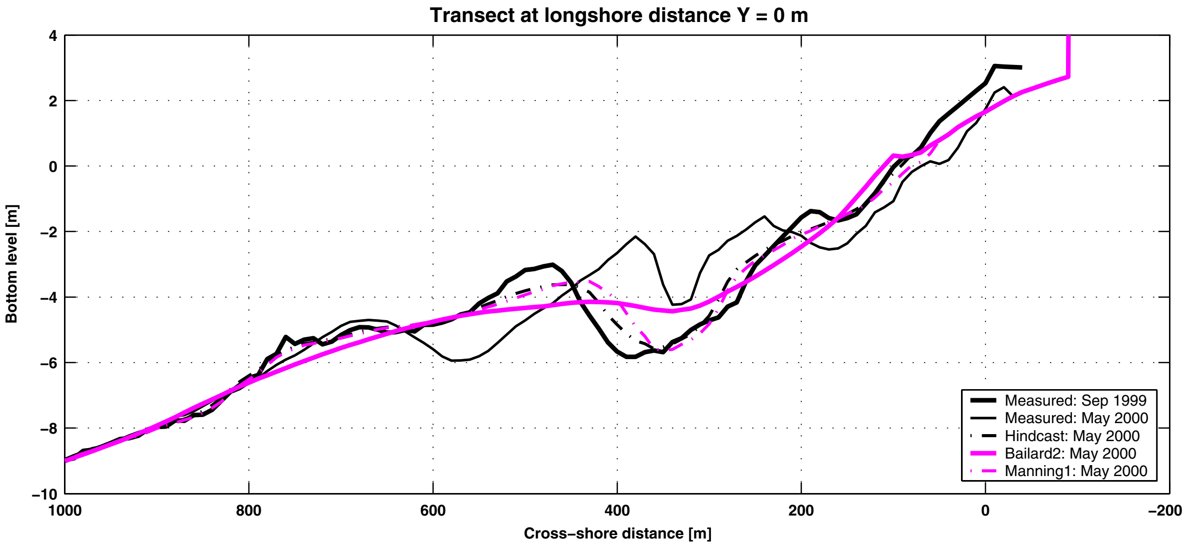


Figure 3.4.8 *Modelled profile changes of DELFT 2DH compared to the measured data profiles*

Model results: volumes

The bed level changes (sedimentation/erosion values) of the computed DELFT 2DH simulations have been compared to the bed level changes of the measured data. All the DELFT 2DH simulation runs show a sedimentation/erosion pattern corresponding qualitatively to the measured data, but the quantitative values are different. The high erosion at cross-shore distance 550 m, the area between shoreface nourishment and outer bar, and the high sedimentation at cross-shore distance 400 m are not modelled correctly. As a result of the inclusion of the Bailard approach an increase of the sedimentation and erosion values can be seen, compared to the hindcast run. High erosion occurs at 550 m cross-shore distance and high sedimentation at 400 m cross-shore distance. Also the amount of erosion of the shoreface nourishment is very similar to the measured amount of erosion. In the beach zone the Bailard run shows relatively high sedimentation, whereas the measured data showed erosion in the beach zone. The run with the increased Manning coefficient also shows a small increase in sedimentation and erosion values compared with those of the hindcast run.

The total sand volume change relative to May 1999 for the total area shows an increase of 0.05 m for the measured sand volume. The hindcast model data shows a sand volume increase of 0.03 m.

For each of the twenty subsections (see Figure 3.4.9) the measured and computed (Hindcast run) sediment volume change have been calculated for the period of September 1999 to May 2000. The sediment volumes (modelled and measured) for eight months and per subsection are shown in Table 3.4.3. Figure 3.4.9 shows the sedimentation/erosion per subsection for the measured and computed results.

Section	Measured [m^3]	Computed [m^3]	Section	Measured [m^3]	Computed [m^3]
A1	1656	-1265	**C1**	27305	18887
A2	-31360	-1886	**C2**	84011	3918
A3	-45442	-259	**C3**	53667	22069
A4	-54818	-1023	**C4**	51469	-24861
A5	7335	488	**C5**	21604	10695
B1	43752	13897	**D1**	-10636	11916
B2	-21407	8419	**D2**	-11725	20340
B3	92868	10592	**D3**	-27722	-7002
B4	-29612	19677	**D4**	7117	36780
B5	33740	-9250	**D5**	31425	6272

Table 3.4.3 *Measured and computed sediment volume change per subsection for the period of September 1999 to May 2000 [m^3]*

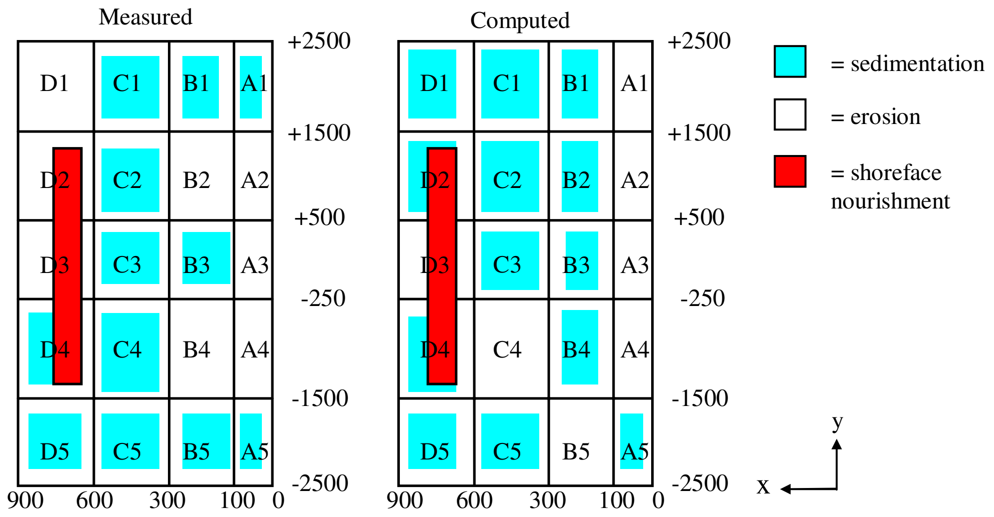


Figure 3.4.6 *Overview sedimentation and erosion of subsections for measured and computed results*

As can be seen from Figure 3.4.9 the computed sedimentation volumes of subsections A1, B2, B4, C4, D1 and D2 do not correspond in sign with the measured sediment volumes. A possible explanation for these differences is the incorrect modelling of sediment transport in cross-shore direction by the DELFT 2DH model. If for example rip currents are present or a strong undertow, the model will not produce accurate results, which can lead to a lower amount of computed sediment transport. For the Egmond area it is known that strong rip currents do occur. In the data analysis (Van Duin and Wiersma, 2002) rip channels were found in subsection C4 (secondary subsections C7 and C8) in the outer bar and in subsection B4 (secondary subsections B7 and B8) in the inner bar. These are exactly the subsections were the computed data show the opposite sign of the measured data. The dominant processes in the swash zone are very complicated and especially in the beach zone. The subsections A are in this zone and therefore errors in the modelled results can be expected. The errors for subsection D1 and D2 are however more difficult to explain. Probably the incorrect modelling of the cross-shore sediment transport as a result of wave asymmetry is also the cause of these errors. The sedimentation volume (per subsection) corresponds reasonably for subsections C1, C3 and C5 (respectively 70%, 40% and 50%). The model shows a strong overall under-estimation of the sediment volumes.

Summation of the sediment volumes in longshore direction results in relatively good correspondence for the shore-parallel subsections A, B and C. The beach area shows erosion for the eight-months period, whereas the inner bar area (shore-parallel subsections B) and the outer bar area (shore-parallel subsections C) show accretion. A possible explanation can be the reef effect of the shoreface nourishment area (see Figure 1.3). Large waves break at the shoreface nourishment causing a calmer wave climate directly behind the shoreface nourishment area. The wave heights in the shallow beach zone are depth-limited (about 0.8 of the local depth) and are not much affected by the nourishment. The shoreface nourishment area creates a lee area where sand, supplied by longshore transport, can settle. The amount of sediment change according to the DELFT 2DH results for the shore-parallel subsections A, B and C is, however, considerably smaller than those of the measured results. Shore-parallel subsections D show erosion whereas the DELFT 2DH model shows accretion.

Summation of the sediment volumes in cross-shore direction results in relatively good qualititive correspondence for Profiles 1, 3 and 5. Only opposite signs in sediment volume change are found for Profile 2 and 4 (subsections A2+B2 and A4+B4). The erosion values observed in these latter subsections may have been caused by offshore-directed rip currents, which have been observed in Profile 4 (Van Duin and Wiersma, 2002). A possible explanation for the accretion of Profiles 1, 3 and 5 is the presence of lee effects (reduced velocities) of the shoreface nourishment area.

Bo Sun (2004) also studied the Egmond nourishment case over the period September 1999 to may 2000 using a 2DH approach and a 3D approach, referred to as *Egm2004*. The 2 DH approach is similar to that of Van Duin and Wiersma (2002), referred to as *Egm2002*. According to the schematised tide information, the tide boundary conditions are regenerated to match the new computational grid. Riemann-type boundary conditions have been used as the lateral boundary conditions other than the fixed water levels or the uniform inflow velocities used in the previous study. The computational results of the tidal currents show that the new model not only well reproduces the tidal currents in the area, but also yields more stable results.
The wave computation of the model is based on the default settings of the SWAN system. The wave boundary conditions uses the schematised wave conditions of the previous study (based on UNIBEST-runs) , which reflects the effects of the wave climate on the local morphological evolution. The results accurately produce the processes of offshore wave propagation over the domain, and the wave field for the morphological run. Most of wave breaking occurs on the longshore bars and the nourishment location. The wave energy dissipation mainly concentrates on the longshore bars. Wave-current interactions significantly change the flow pattern within the surf zone.

The local sediment transport is dominated by the wave boundary conditions. Moreover, the computed transport relies on the settings of the transport factors used in the specified formula (VR; van Rijn 1993). With the default settings of transport factors, there are larger discrepancies between the present study and the previous studies on the net longshore transport. Therefore, the related transport factors have been calibrated before the final morphodynamic runs. The Bijker formula has also been used (Bk).

A 2DV profile model has been set-up using the DELFT3D system to calibrate the transport factors against the results of UNIBEST (the latter based on more detailed time-series of wave parameters). The results of the profile modelling indicate that the net transport is more sensitive to the wave-related suspended transport factor. Moreover, the results of profile modelling show good compatibility between both models (UNIBEST and DELFT system). The differences of sediment transport and morphological evolutions between the two models are quite small. It is concluded that the UNIBEST-profile model can substitute the 2DV profile model in present study, since the former has faster computation effectivity without loss of accuracy. With respect to the results of UNIBEST, the calibated factors are finally employed by the area morphological modelling.

Following the prescribed morphological scenario, two 2DH and two 3D area morphodynamic modelling cases are eventually carried out.

Measured and computed profile developments (North, Middle and South; which are located nearly at 1500m, 0m, and -1500m) are given in Figure 3.4.10.

From the measured data, the outer bar moves onshore and the inner bar moves offshore, which makes the trough between two longshore bars narrower. The computed results of the middle section which cuts across the nourishment, has the largest changes compared with the initial situation. The results of the north section show the smallest changes relatively. The natural bar-trough structure is flattened in all modelled results. Larger discrepancies between the modelled bottoms occur inside the surf zone. The nearshore swash bar is overestimated in *Egm2004-VR2DH*, however results of other cases are too flat to show a swash bar. At the steeper slopes of the initial profile, i.e. the outer slopes of the nourishment and the inner bar, the bottom levels predicted by *Egm2004-VR2DH* are much lower than those of other cases. It is possible that *Egm2004-VR2DH* has stronger onshore transport than other *Egm2004-#* cases. In general, there are no significant differences between all the modelled profiles. The BSS method (Brier Skill Score: 1 means perfect agreement; 0 means that initial profile is better than the computed end profile results) is used to give a quantitative criterion to assess the quality of modelled result.

The BSS values of the modelled results based on the initial bathymetry (September 1999) as the baseline prediction, are shown in the legends of Fig. 3.4.10. The skill scores of each case on the north section and the south section are negative, which means the modelled profile results are further away from the measured end profile than the initial profile. However, the scores of all modelled results get positive marks on the middle section, which is caused by the larger difference between the initial profile and the measured end profile around the nourishment. This profile also indicates that the larger morphologaical evolutions take place in the nourished zone. *Egm2004-VR3D-sw* has the highest score.

Volume changes have been computed for the compartments defined by Van Duin and Wiersma (2002) in Figure 3.4.9. The sedimentation/erosion volumes have been determined by subtraction of two different bathymetries. According to the measured data, the main sediment deposit took place in the sections behind the nourishment, and the accretion area extended southwards and northwards about 500m along the inner slope of the outer bar. At relatively shallow areas of the trough (-2000m and +2000m), significant sedimentation volumes occurred against the outer slope of the inner bar. Main erosion volumes occurred on the outer bar and close to the nourishment. The front of the nourishment also suffered from erosion, but in a weaker intensity. Minor sedimentation/erosion appeared here and there in the surf zone and the swash zone. Although all the modelled results can not exactly reproduce the measured sedimentation/erosion pattern, *Egm2004-#* model results show somewhat bettter performances than *Egm2002-Bk2DH*.

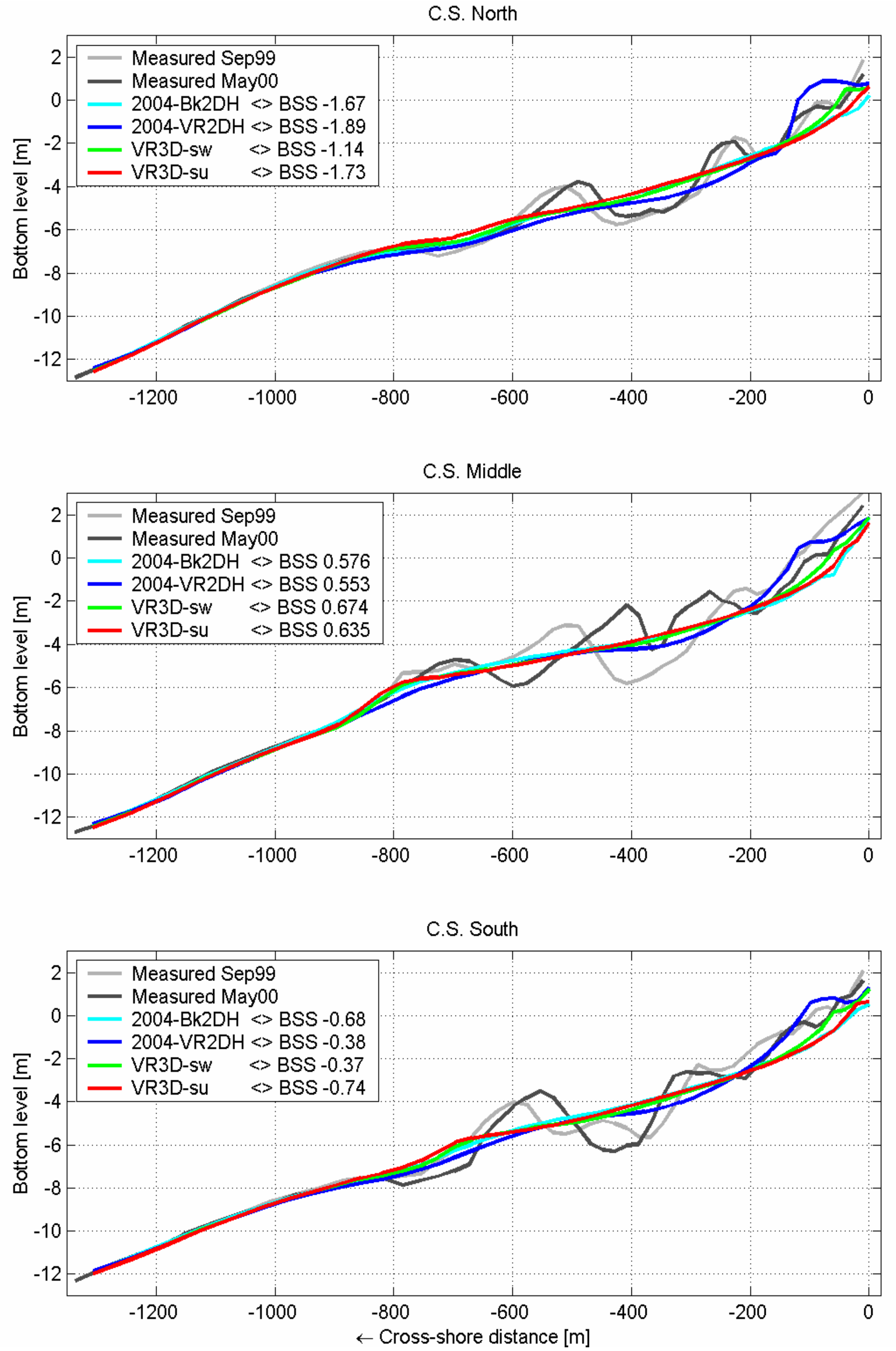


Figure 3.4.10 *Measured can computed bed profiles over period September 1999 to May 2000 (BK=Bijker; VR=Van Rijn; BSS=Brier Skill Score)*

To provide a quantitative expression on the volume changes, the detailed magnitudes in the boxes of each modelling case are summarised in Table 3.4.4, in which the results of *Egm2002-Bk2DH* are taken directly from the previous study. The table not only gives the volume changes in each box, but also shows the volume changes in each longshore/cross-shore section. The quantities of volume change are also represented in Fig. 3.4.11. The volume changes now are expressed as the averaged sedimentation/erosion thickness (unit: m) in each box. Figure 3.4.12 shows the integrated volume changes in longshore and cross-shore sections.

The total volume change in the whole area (derived from the measured data) is 217,903m^3 sedimentation. All model results with exception of *Egm2004-Bk2DH* show sedimentation in the area. The total change of *Egm2004-Bk2DH* is 4,896m^3 erosion, which is equivalent to –1 mm over the evaluated area 5000×900m^2. The result of *2004-VR3D-su* is closest to the measured data. The ratios of the modelled sedimentation volumes to the measured data are 93% for *Egm2004-VR3D-su*, 74% for *Egm2004-VR3D-sw*, 73% for *gm2004-VR2DH*, and 51% for *Egm2002-Bk2DH*.
The modelled results reflect a reasonable trend of volume changes in Section D, C, and A, except for the case *Egm2004-VR2DH*. But in the longshore section B, most modelled results show erosion other than the measured sedimentation. The relatively complex bathymetries and hydrodynamic conditions in this section may cause difficulties for modelling. Although the total volume of *Egm2004-VR3D-su* is closer to the measured results, its magnitudes in each longshore section are much larger than the measured volumes. The total volume changes of *Egm2004-VR2DH* and *Egm2004-VR3D-sw* are close to each other, but their volume changes in each section are quite different. The cases *Egm2004-VR3D-sw* and *Egm2004-VR3D-su* have good compatibility, since the only difference between them is the value of the suspended transport (f_{SUS}-factor). The measured data show that the sedimentation mainly goes to Section 5 and 3, which take 37% and 35% of the total sedimentation volume. The sedimentation in Section 2 is about half of Section 1, while a small volume is eroded in Section 4. However, all the modelled results show sedimentation in Section 4 and 2. The modelled erosion takes place almost fully in Section 3. So, the total volume changes in area are well predicted, but the model performance is poor for the prediction on detailed morphological developments.

According to the final measured bottom, the bar-trough structure still existed at the end of the considered period (September 1999 to May 2000). The outer bar migrated onshore due to the redistribution of trapped sand in the area. At the same time, the outline of the inner bar became more curved than in the initial condition. In the swash zone, the bathymetry is still complex with swash bars and rip channels.
In *Egm2002-Bk2DH*, the modelled sedimentation/erosion was quite small. The outer bar almost remained at its original place, and the trough also didn't change its outline much. The bar-trough structure was not evidently effected. The longshore bathymetries in the swash zone became uniform, and the outline of the swash bar seemed obscure. The bar migration could not be represented in the modelling.
In *Egm2004-#* cases, the offshore bars completely disappear, and the trough is filled up. The bar-trough structure is flattened. Although the sedimentation/erosion pattern is quite reasonable, the longshore bar migration is not exactly realised in these modelling cases.

There are many differences between *Egm2002-Bk2DH* and *Egm2004-Bk2DH*, though both were run in 2DH and used the same transport formula with identical settings. Differences between both runs are the computational grids, the types of tide boundary conditions, and implementations of morphodynamic simulations, i.e. "offline" or "online" transport approach. As regards the total volume changes, *Egm2002-Bk2DH* yields sedimentation equal to 51% of the measured sedimentation, while the *Egm2004-Bk2DH* run yields an overall erosion volume of about 5000 m^3 in the area. As regards the modelled bottom, the former didn't change it significantly and remained the bar-trough structure, but the latter flattened the bottom.

According to the analyses of modelled results, each case of *Egm2004-#* has similar sedimentation/erosion patterns. The modelled bottoms of *Egm2004-#* cases also have similar appearances.The main differences between these cases are the transport formula and the dimensions of computational grids. *Egm2004-Bk2DH* uses *Bijker 1971* formula, while other three cases all use *van Rijn 1993* formula. Focussing on the three cases with *van Rijn 1993* formula, all these cases have good results in predicting the sediment budget. The performances of *Egm2004-VR3D-sw* and *Egm2004-VR3D-su* are much the same on profile evolutions and on volume changes in each box and therefore long-/cross-shore sections, since the only difference is the suspended sand transport. In contrast to these two 3D cases, *Egm2004-VR2DH* shows stronger onshore transport, which causes larger discrepancies in cross-shore sedimentation/erosion distribution.
The area modelling cases with *van Rijn 1993* formula appear good performances to predict the total volume changes, and quite reasonable results to model morphological evolutions. More detailed calibrations may result in better outcomes for large-scale sand budget prediction, even for local morphological developments.

The main conclusions of the morphodynamic simulations are:

- All the cases show more reasonable results on morphological evolutions of the present model (Egm2004) than the previous model results (Egm2002), but the locally detailed morphological features (bars) are still not properly modelled.
- The cases with van Rijn 1993 formula well predict the sand budget in the area of interest. The 2DH case show stronger onshore transport than the 3D cases.
- The profile models and the area models have quite good agreements as regards the final computed bottoms. The results prove that profile model not only can be used to calibrate the modelling factors for the corresponding area models, but also can be used to predict the morphological bulk volumes. The bar behaviour can not yet be modelled properly.

L.S. Box	A1	A2	A3	A4	A5	Sum A
Measured	-265	-28744	-45005	-49085	5713	-117387
Egm2002-Bk2DH	-1294	-1837	-187	-514	787	-3046
Egm2004-Bk2DH	-72872	-76022	-79026	-98944	-82081	-408945
Egm2004-VR2DH	37482	59334	14899	74458	61556	247728
Egm2004-VR3D-sw	1165	-17427	-37737	-37491	-23520	-115010
Egm2004-VR3D-su	-45727	-61853	-72239	-96633	-74098	-350550
L.S. Box	B1	B2	B3	B4	B5	Sum B
Measured	41394	-24238	100463	-30238	30319	117700
Egm2002-Bk2DH	13634	7490	12737	18173	-11004	41030
Egm2004-Bk2DH	-41965	-32201	-52222	-40641	-72372	-239403
Egm2004-VR2DH	76923	-16709	17615	-37809	-36412	3608
Egm2004-VR3D-sw	-41267	-27225	-25353	-40439	-68730	-203013
Egm2004-VR3D-su	-70430	-32110	-33950	-41753	-74732	-252975
L.S. Box	C1	C2	C3	C4	C5	Sum C
Measured	21972	89258	43330	49895	11858	216314
Egm2002-Bk2DH	16429	1565	9818	-27171	8492	9133
Egm2004-Bk2DH	31240	139860	98923	171074	106298	547396
Egm2004-VR2DH	-84424	51037	49954	76131	27793	120491
Egm2004-VR3D-sw	-15547	113221	75143	146916	59000	378733
Egm2004-VR3D-su	1975	158546	89126	212502	88849	550997
L.S. Box	D1	D2	D3	D4	D5	Sum D
Measured	-11778	-11309	-22089	12841	33610	1276
Egm2002-Bk2DH	10612	17384	-7859	37104	7681	64923
Egm2004-Bk2DH	54190	11920	-14212	-249	44407	96056
Egm2004-VR2DH	5334	-42230	-77904	-79958	-17284	-212041
Egm2004-VR3D-sw	71515	10260	-29359	-3179	51604	100841
Egm2004-VR3D-su	118167	37844	-14821	26540	87972	255701
C.S. Section	1	2	3	4	5	Total
Measured	51323	24966	76699	-16586	81501	217903
Egm2002-Bk2DH	39382	24602	14509	27591	5956	112040
Egm2004-Bk2DH	-29408	43556	-46538	31241	-3748	-4896
Egm2004-VR2DH	35315	51432	4564	32822	35653	159785
Egm2004-VR3D-sw	15867	78829	-17307	65808	18354	161551
Egm2004-VR3D-su	3985	102427	-31884	100655	27992	203174

L.S. : longshore; C.S. : cross-shore.

Table 3.4.4 *Measured and computed volume changes over September 1999 to May 2000 (Bk=Bijker; VR=Van Rijn)*

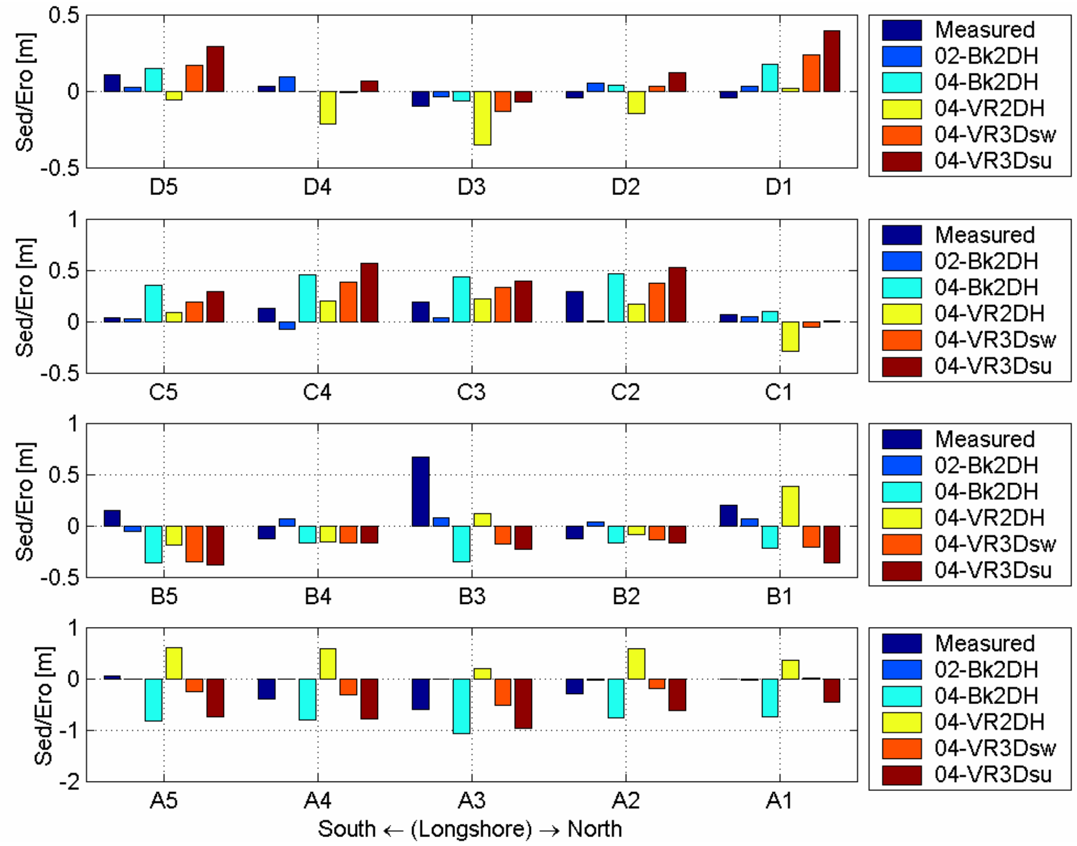


Figure 3.4.11 *Average sedimentation and erosion thickness (sedimentation=+)*

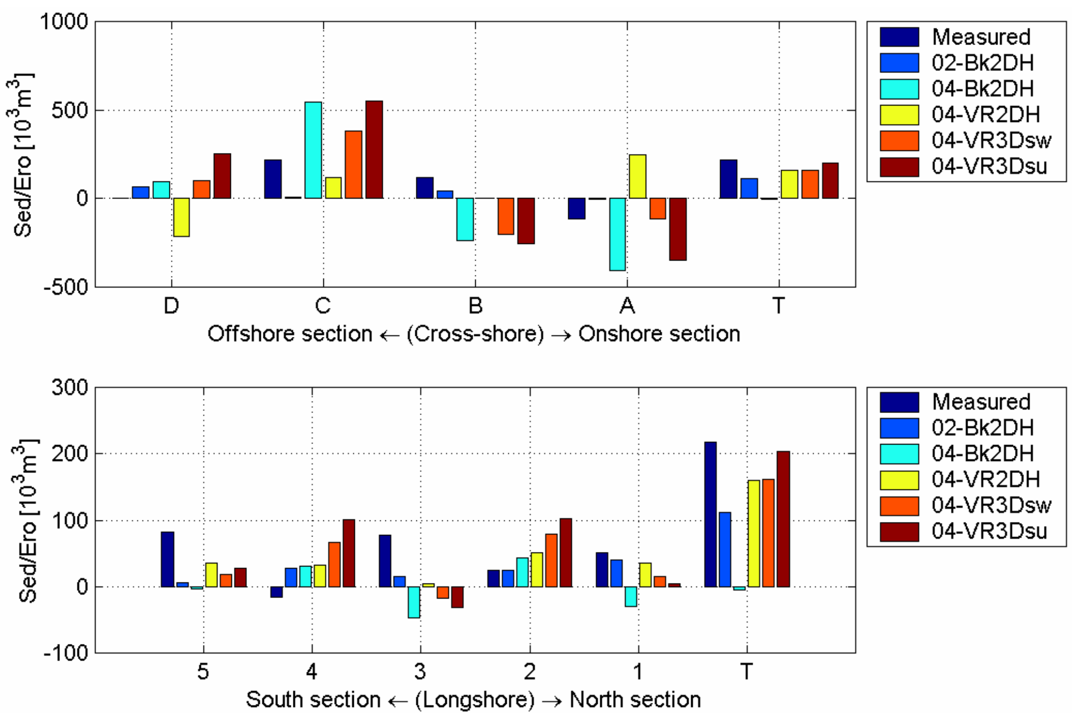


Figure 3.4.12 *Sedimentation and erosion volumes (sedimentation=+; T=total)*

3.5 Summary of conclusions

3.5.1 Coastline models

Coastline models can be used to obtain an indication (order of magnitude) of the shoreline changes updrift, downdrift and in the lee of the nourishment location, provide that sufficient bathymetry data are available for calibration of the model. The shoreline in the lee of the berm shows a pattern with erosion on the updrift side and accretion on the downdrift side. As the shoreline builds out on the updrift side of the nourishment berm, the longshore transport rate is reduced because the wave incidence angle with respect to the local shore normal reduces (blocking effect). This leads to erosion immediately downdrift of the blocking location. The reduction of the longshore transport capacity in the lee of the nourishment berm is unkown and has to be estimated by the modeluser (calibration of bathymetry using input parameters).

3.5.2 Coastal profile models: UNIBEST-TC

Egmond nourishment case

The UNIBEST-TC model was used to hindcast the Egmond shoreface nourishment case (period between September 1999 and June 2001). Comparison of UNIBEST-TC model results and measured results showed that the UNIBEST-TC model is able to calculate cross-shore profiles that include a shoreface nourishment. The model predicts the detachment of the outer bar from the shoreface nourishment and to some extent the shoreward bar movements. The nearshore area (beach and inner bar) however is not modelled accurately. The UNIBEST-TC model overpredicts sediment volumes in the surf zone, resulting in bed levels which are too large. The model imports a considerable quantity of sediment from deep water. The volume changes due to longshore transport gradiensts are not taken into account in the UNIBEST-TC model. The UNIBEST-TC model confirms the assumption that the shoreface nourishment creates a lee area in which sediment can easily settle.

Delfland nourishment case

The UNIBEST-TC model was used to hindcast the morphological developments of the middle profile at the nourishment location over a period of about 1 year (between 8 April 1998 and 1 April 1999). The onshore migration of the nourishment bar feature was hindcasted reasonably well. However, the relatively deep trough landward of the bar could not be represented. The beach volume (between –2 m and +2 m NAP) was considerably overestimated. Using the parameter settings from the hindcast run, a forecast run for the period 8 April 1998 to 14 July 2001 was made. The onshore migration was somewhat overestimated. The beach volume between –2 m and +2 m NAP was severely overestimated.
Finally, the UNIBEST-TC model was used to evaluate the effectiveness of various nourishment schemes over a period of 5 years. The effectiveness was defined as the increase of the sand volume within predefined nearshore zones (MCL zone between –4.3 m and +3 m NAP and Active zone between –8 m and +3 m NAP). All schemes resulted in an increase

of the sand volume in the MCL zone and in the Active zone. The volume increase was smaller for a deeper nourishment location; the offshore sand loss to deeper water was found to be negligible small.

3.5.3 Coastal area models: DELFT2DH and DELFT3D

Terschelling shoreface nourishment case

The 3D morphodynamic computations are found to be potentially feasible for the simulation of nourishment behaviour of Terschelling between November 1993 and April 1994. On a large scale of overall profile behaviour derived through bulk volumes integrated over large spatio-temporal scales (several kilometres and months), the predictive capability of the model was found to give a reasonable representation of the nourishment development. The overall effect of the nourishment related to lee and feeder effects are reproduced: integrated over distances on the order of the alongshore length of the nourishment, the sedimentation at the shoreline and the onshore movement of nourished sediment are reasonably well simulated. However, for detailed morphodynamic predictability on the scale of sandbar behaviour, process-based 3D modelling does not yet appear to be suitable. Predictions of nearshore bar migration and development remain poor. Bar flattening was found for all parameter settings tested in the calibration phase, thus at present these parameters just appear to control the large-scale sediment budgets.

Model predictions using the 2DH approach exhibited the same dependency on spatial scale as the 3D approach. The 2DH model predictions also showed a tendency towards flattening of the nearshore bars at approximately the same rate as for the 3D predictions and a good model-data comparison of volumetric changes was only obtained when resorting to integrated changes over a large spatial scale. The merits of a 3D approach versus a 2DH approach thus lies in the accurate representation of measured hydrodynamics since it does not provide noteworthy improvements in terms of morphological predictions. In view of the limited added contribution of a fully 3D approach coupled with the prohibitively time consuming computations thereby required, it appears that a 2DH approach performs as well although not supported by the same accurate representation of flow phenomena. If the desired end result of a modelling study is bathymetric evolution solely, a 2DH approach may be sufficient (albeit for the wrong hydrodynamical reasons, counteracted mainly by adjusting the free parameters).

Modelling of the wave and currents showed very reasonable agreement between computed and measured values in a profile in the middle of the nourishment section at Terschelling

Egmond shoreface nourishment case

Modelling of the shoreface nourishment at Egmond between September 1999 and May 2000 using the 2DH approach shows an increase of the flow velocity in the shoreface nourishment area and a decrease of the flow velocity just shoreward of the shoreface nourishment area, both compared to the flow velocity without shoreface nourishment. The wave energy dissipation showed a relatively large dissipation on the outer bar in the case of no shoreface nourishment. In the case with shoreface nourishment a reduction of the wave energy dissipation behind the shoreface nourishment was obtained. Thus, the shoreface nourishment causes a reduction of the wave energy dissipation on the outer bar. The computed wave heights showed a decrease directly shoreward of the shoreface nourishment as a result of the placement of the shoreface nourishment. The wave heights at the edge of the shallow beach zone are not affected, as these wave heights are strongly depth-limited (about 0.8 of local water depth).

Comparison of the model and measured results shows that the DELFT 2DH model computes a similar trend in sedimentation/erosion patterns, but the magnitude of the sedimentation/erosion values is smaller. The sand volume changes show a clear sedimentation in the area just shoreward of the shoreface nourishment and erosion in the area south and seaward of the shoreface nourishment. The bar behaviour at the shoreface nourishment site could not be modelled accurately, as the cross-shore transport caused by wave asymmetry is not taken into account in the standard version of DELFT 2DH model. The model results support the hypotheses about the hydrodynamic and morphodynamic functioning of the shoreface nourishment (see Section 1.5). Large waves break at the shoreface nourishment instead of the outer bar, causing a calmer wave climate directly behind the shoreface nourishment (wave filter) and a reduction of the longshore current. This reduction in flow velocity causes a reduction of the transport capacity and hence trapping of the sand shoreward of the shoreface nourishment area. The breaking of large waves at the seaward side of the shoreface nourishment also results in remaining shoaling waves that generate an onshore transport due to the wave asymmetry over the nourishment area. The smaller waves generate less stirring of the sediment and a decrease of the wave-induced return flow (cross-shore currents) resulting in a decrease of the offshore sediment transport (see Section 1.5); both effects correspond to sediment increase in the area shoreward (lee-side) of shoreface nourishment area. The shoreface nourishment acts as a blockade leading to updrift sedimentation and downdrift erosion. However, on long-term the erosion dominates in both sections north and south of the nourishment area.

Results of the 3D model approach shows somewhat better agreement with the measured bulk volumes than those of the 2DH model, but the detailed bar behaviour could not be represented properly using the 3D model. The model tends to flatten the bars.

4 Summary, conclusions and recommendations

4.1 Introduction

Shoreface nourishments are regularly carried out at many beaches along the coast of The Netherlands with the aim to maintain the sand budget in the nearshore zone at a predefined volume and the supply of sand to the beaches in the lee of the nourishments.

This study is focussed on the evaluation of these types of nourishments with regard to both the physical characteristics and the performance of modelling approaches.

Three shoreface nourishment in The Netherlands have been studied in more detail:

- Terschelling nourishment project,
- Egmond nourishment project,
- Delfland nourishment project.

These projects have been selected because they represent typical examples of the varying hydrodynamic and morphodynamic conditions in The Netherlands. The Terschelling nourishment case concerns a shoreface nourishment along a barrier island coast (in the Dutch Wadden Sea) with a pronounced three bar system and a dominant net longshore drift to the east. The Egmond case is situated along the straight northern Holland coast with a two bar system and a relatively small net longshore drift. The Delfland case is located along the straight southern Holland coast (close to the access channel to the Port of Rotterdam) without major breakers bars and a relatively small net longshore drift.

4.2 Physical behaviour of shoreface nourishments

Terschelling shoreface nourishment case

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 backbarrier system of the Wadden Sea. The orientation of Terschelling is roughly WSW-ENE. The central part of Terschelling has retreated by about 2-3 m/yr over the last decades. The study area is situated along this eroding coast between km section 10 and 22. Along the study area, the shoreline is slightly curved and concave; the coastline orientation in the study area is about 73^o N. The coast consists of sandy beaches and dunes. The nearshore zone is characterised by the presence of 2 to 3 sandbars which behave in a repetative offshore-directed manner on the time scale of years (the cycle return period is about 12 years.
To counteract the ongoing erosion, a shoreface nourishment of 2.1 Mm^3 of sand (0.22 mm) was carried out in the period from May to November 1993, filling up the trough between the middle and outer breaker bar in depths of 5 to 7 m below MSL. The length of the shoreface nourishment was 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. By spring 1994, most of the nourished sediment

had been redistributed onshore and welded onto the middle bar where it remained in the following years.
Analysis of the post-nourishment morphology showed rapid adjustment of disturbed bar-trough morphology (in about 6 winter months) to former patterns; growth of the middle bar (increase of height by about 1.5 m) and landward migration of this bar by about 50 m over about 8 months. The beach morphology was strongly three-dimensional beach morhology (not observed before). The migration of the nourishment volume was in the dominant alongshore drift direction (eastwards) at a rate of about 250 to 500 m/yr. After 2 years (1993 to 1995), the zone landward of the nourishment zone showed a large volume increase due to longshore transport processes as result of the breakwater effect of the enlarged middle bar, creating a lee-zone landward of the middle bar. After 4 years (1993 to 1997), the nourishment section up to the beach showed a gain of almost 0.7 million m^3; mainly in inner bar zone and in beach zone due to onshore feed from the berm and due to trapping of sand from updrift. The section south of the nourishment showed large accretion after 4 years (autonomous behaviour of this section before the nourishment was erosion). Most of this accretion volume was from updrift longshore transport blocked by the berm effect. The section north of the nourishment showed minor accretion after 4 years (autonomous behaviour of this section also was erosion).

Egmond shoreface nourishment case

Egmond is located near a null point of longshore transport along the norhtern part of the Holland coast; south of Egmond the net longshore transport is about 100,000 m^3/yr to the south and north of Egmond it is of the same order of magnitude to the north. The site suffers from long-term beach erosion of the order of 10 m^3/m/yr. The spring tidal range is about 2 m. The beach sand is about 0.2 to 0.25 mm. The longshore tidal currents in the surf zone are in the range of 0.2 to 0.4 m/s. The flood current to the north is dominant. The berm with a volume of about 400 to 450 m^3/m (length of about 2 to 2.5 km; total initial volume of about 900,000 m^3) was placed in the summer of 1999 at the seaward side of the outer surf zone bar (offshore distance of about 500 to 800 m) in water depths between 6 and 8 m (below MSL).
The bathymetry data of Egmond aan Zee, covering a period of May 1999 to April 2002, has been analyzed to study the influence of the shoreface nourishment area on the morphodynamics. During the first two years of the studied period the shoreface nourishment hardly changed in height or location and therefore did not contribute to the beach sand volume directly, i.e. by redistribution of the nourished sand. Relatively strong three-dimensional behaviour of the nourishment bar and the beach in the lee of the nourishment were observed. The inner and outer bar showed a large shoreward migration and a trough was generated between the outer bar and the shoreface nourishment area. The shoreface nourishment area seemed to act as the new outer bar, taking over the function of the original outer bar. After two years the outer bar was almost straightened and formed a continuous bar again. The system seemed to return to its natural three bar system.
Surveyed data showed that the shoreface nourishment did not diffuse much in the first two years. After a period of two years the shoreface nourishment started to diffuse resulting in a lower amplitude. Accretion occured shoreward of the shoreface nourishment indicating that the shoreface nourishment functions as a reef with a lee-side effect shoreward of the nourishment area.
The shoreface nourishment has positively contributed to the development of bars. As a result of the shoreface nourishment the bars have increased in height and moved shoreward. Since bars are the first line of defence for the mainland against the sea, this bar growth is a

positive effect of the placement of the shoreface nourishment. Another positive effect of the placement of the shoreface nourishment is its contribution to the sand budget in the surf zone landward of the nourishment location. After a two year period (May 1999 to June 2001) the sediment volume in the area of interest has increased by about 730,000 m^3 and after three years (May 1999 to April 2002) the sediment volume still shows an increase of about 480,000 m^3 relative to May 1999.
The shoreface nourishment has not had a direct effect on the sand volume of the beach zone (from beach pole to 100 m seaward) on the short-term time scale of September 1999 to May 2000 (Sections A2 to A4 show erosion , Figure 3.4.6). The time scale of sediment feed to the beach zone probably is much larger (order of 5 to 10 years).
The sections south and north of the nourishment area showed relatively large erosion after 2 years (much larger than before the nourishment).

Delfland shoreface nourishment case

The Delfland shoreface nourishment case is located along the straight southern Holland coast (close to the access channel to the Port of Rotterdam) without major breakers bars and a relatively small net longshore drift. The shoreface nourishment of 1997 consists of about 1,000,000 m^3 or about 500 m^3/m between the depth contours -5 m NAP and -7 m NAP in the Section between km 113.150 and 114.850 km.
Analysis of post-nourishment soundings shows that about 800.000 m^3 is present in the nourishment section immediately (January 1998) after completion of the shoreface nourishment. The nourishment section did not loose much sand in alongshore directions. After 4 years, a total quantity of about 70% of the initial nourishment volume is still present in the nourishment section; most of the sand eroded from the nourishment section is carried into the beach section in the lee of the nourishment The sections south and north of the nourishment section showed minor accretion.
Analysis of the cross-shore profiles shows that a pronounced breaker bar is formed in the Nourishment Section, which migrates in onshore direction, uniformly over the entire section (almost two-dimensional behaviour).

4.3 Modelling approaches of shoreface nourishments

4.3.1 Coastline models

Coastline models can be used to obtain an indication (order of magnitude) of the shoreline changes updrift, downdrift and in the lee of the nourishment location. The shoreline in the lee of the berm shows a pattern with erosion on the updrift side and accretion on the downdrift side. As the shoreline builds out on the updrift side of the nourishment berm, the longshore transport rate is reduced because the wave incidence angle with respect to the local shore normal reduces (blocking effect). This leads to erosion immediately downdrift of the blocking location. The reduction of the longshore transport capacity in the lee of the nourishment berm is unkown and has to be estimated by the modeluser by calibration using measured bathymetry data..

4.3.2 Coastal profile models

Egmond nourishment case

The UNIBEST-TC model was used to hindcast the Egmond shoreface nourishment case (period between September 1999 and June 2001). Comparison of UNIBEST-TC model results and measured results showed that the UNIBEST-TC model is able to calculate cross-shore profiles that include a shoreface nourishment. The model predicts the detachment of the outer bar from the shoreface nourishment and to some extent the shoreward bar movements. The nearshore area (beach and inner bar) however is not modelled accurately. The UNIBEST-TC model overpredicts sediment volumes in the surf zone, resulting in bed levels which are too large. The model imports a considerable quantity of sediment from deep water. Profile models are not sufficiently accurate to predict the sand volumes in the beach zone (including beach width), see also Van Rijn et al., 2003. The volume changes due to longshore transport gradiensts are not taken into account in the UNIBEST-TC model. The UNIBEST-TC model confirms the assumption that the shoreface nourishment creates a lee area in which sediment can settle more easily.

Delfland nourishment case

The UNIBEST-TC model was used to hindcast the morphological developments of the middle profile at the nourishment location over a period of about 1 year (between 8 April 1998 and 1 April 1999). The onshore migration of the nourishment bar feature was hindcasted reasonably well. However, the relatively deep trough landward of the bar could not be represented. The beach volume (between –2 m and +2 m NAP) was considerably overestimated. Using the parameter settings from the hindcast run, a forecast run for the period 8 April 1998 to 14 July 2001 was made. The onshore migration was somewhat overestimated. The beach volume between –2 m and +2 m NAP was severely overestimated.
Finally, the UNIBEST-TC model was used to evaluate the effectiveness of various nourishment schemes over a period of 5 years. The effectiveness was defined as the increase of the sand volume within predefined nearshore zones (MCL zone between –4.3 m and +3 m NAP and Active zone between –8 m and +3 m NAP). All schemes resulted in an increase of the sand volume in the MCL zone and in the Active zone. The volume increase was smaller for a deeper nourishment location; the offshore sand loss to deeper water was found to be negligible small.

4.3.3 Coastal area models

Terschelling nourishment case

The 3D morphodynamic computations are found to be potentially feasible for the simulation of nourishment behaviour of Terschelling between November 1993 and April 1994. On a large scale of overall profile behaviour derived through bulk volumes integrated over large spatio-temporal scales (several kilometres and months), the predictive capability of the model was found to give a reasonable representation of the nourishment development. The overall effect of the nourishment related to lee and feeder effects are reproduced: integrated over distances on the order of the alongshore length of the nourishment, the sedimentation at the shoreline and the onshore movement of nourished sediment are well predicted. However, for detailed morphodynamic predictability on the scale of sandbar behaviour, process-based 3D modelling does not yet appear to be suitable. Predictions of nearshore bar migration and development remain poor. Bar flattening was found for all parameter settings tested in the calibration phase, thus at present these parameters just appear to control the large-scale sediment budgets.

Model predictions using the 2DH approach exhibited the same dependency on spatial scale as the 3D approach. The 2DH model predictions also showed a tendency towards flattening of the nearshore bars at approximately the same rate as for the 3D predictions and a good model-data comparison of volumetric changes was only obtained when resorting to integrated changes over a large spatial scale. The merits of a 3D approach versus a 2DH approach thus lies in the accurate representation of measured hydrodynamics since it does not provide noteworthy improvements in terms of morphological predictions. In view of the limited added contribution of a fully 3D approach coupled with the prohibitively time consuming computations thereby required, it appears that a 2DH approach performs as well although not supported by the same accurate representation of flow phenomena. If the desired end result of a modelling study is bathymetric evolution solely, a 2DH approach may be sufficient (albeit for the wrong hydrodynamical reasons, counteracted mainly by adjusting the free parameters).

Modelling of the wave and currents showed very reasonable agreement between computed and measured values in a profile in the middle of the nourishment section at Terschelling

Egmond nourishment case

Modelling of the shoreface nourishment at Egmond between September 1999 and May 2000 using the 2DH approach shows an increase of the flow velocity in the shoreface nourishment area and a decrease of the flow velocity just shoreward of the shoreface nourishment area, both compared to the flow velocity without shoreface nourishment. The wave energy dissipation showed a relatively large dissipation on the outer bar in the case of no shoreface nourishment. In the case with shoreface nourishment a reduction of the wave energy dissipation behind the shoreface nourishment was obtained. Thus, the shoreface nourishment causes a reduction of the wave energy dissipation on the outer bar. The computed wave heights showed a decrease shoreward of the shoreface nourishment as a result of the placement of the shoreface nourishment.
Comparison of the model and measured results shows that the DELFT 2DH model computes a similar trend in sedimentation/erosion pattern, but the magnitude of the sedimentation/erosion values is smaller. The sand volume changes show a clear sedimentation in the area just shoreward of the shoreface nourishment and erosion in the area south and seaward of the shoreface nourishment. The bar behaviour at the shoreface nourishment site could not be modelled accurately, as the cross-shore transport caused by wave asymmetry is not taken into account in the standard version of DELFT 2DH model. The model results support the hypotheses about the hydrodynamic and morphodynamic functioning of the shoreface nourishment. Large waves break at the shoreface nourishment instead of the outer bar, causing a calmer wave climate directly behind the shoreface nourishment (wave filter) and a reduction of the longshore current. This reduction in flow velocity causes a reduction of the transport capacity and hence trapping of the sand shoreward of the shoreface nourishment area. During fairweather conditions the breaking of the larger waves at the seaward side of the shoreface nourishment also results in remaining

shoaling waves that generate an onshore transport due to the wave asymmetry over the nourishment area. The smaller waves generate less stirring of the sediment and a decrease of the wave-induced return flow (cross-shore currents) resulting in a decrease of the offshore sediment transport; both effects correspond to sediment increase in the area shoreward (lee-side) of shoreface nourishment area (see Section 1.5). The shoreface nourishment acts as a blockade leading to updrift sedimentation and downdrift erosion. However, on long-term the erosion dominates in both sections north and south of the nourishment area.
Results of the 3D model approach shows somewhat better agreement with the measured bulk volumes than those of the 2DH model, but the detailed bar behaviour could not be represented properly using the 3D model. The model tends to flatten the bars.

4.4 Overall conclusions

Physical behaviour of shoreface nourishments

Based on observations in the USA, Australia, South-Africa, New Zeeland and Japan, it is concluded that:

- Shoreface nourishments of fine sand (feeder berms) placed in the nearshore zone (between -5 and -10 m) in micro-tidal and meso-tidal conditions show berm flattening and onshore sand movement.
- The lifetimes of the shoreface nourishments are of the order of to 2 to 10 years depending on the wave climate.
- No berms were observed to move seawards.
- Beaches in the lee of the nourishments showed accumulation of sand.

Based on observations of three shoreface nourishments in The Netherlands, it can be concluded that:

- The sand budget in the surf zone is positively affected by the presence of shoreface nourishments (feeder berms), which is is important for the development and maintenance of the breaker bars. These bars react relatively rapid (6 to 12 months) to shoreface nourishment. As a result of the presence of more pronounced breaker bars, less wave energy is transmitted to the beach zone.
- The additional bulk sand volume in the nourishment section often is of the order of about 50% to 70% after 3 to 5 years.
- Shoreface nourishments in areas with a relatively large net longshore drift show migrational tendencies in the direction of the net longshore drift. The sections downdrift of the nourishment will benefit from the sand supply by the longshore drift.
- The beach zones in the lee of the nourishment do not always benefit directly (on short term) from the nourished sand. Sometimes, additional beach nourishments have to be carried out to mitigate local erosion. The supply of sand from the feeder berm to the beach takes place on a relatively long time scale (10 years or so), while it is also required that the feeder berm is maintained continously (by dumping of sand) to be fully effective.
- Sand losses to offshore areas do occur, but are negligible small.
- The sections south and north of the nourishment area may show considerable erosion (much larger than before the nourishment) in situations with relatively large gross longshore transport rates (Terschelling and Egmond).

The observations broadly confirm the hypotheses on the hydrodynamic and morphodynamic functioning of shoreface nourishments (see Section 1.5), which can be summarized as lee effects (partly blocking of littoral drift) and feeder effects (onshore movement of sand).

Modelling approaches of shoreface nourishments

Based on mathematical modelling of shoreface nourishments in The Netherlands, it can be concluded that:

- Profile and area models can be used to predict the wave and flow fields (including rip currents) in the nearshore zone with reasonable accuracy.
- Profile and area models are not (yet) accurate enough to predict the sand volume changes in the nearshore zone (including beach), which is dominated by rather subtle three-dimensional processes (delicate balance of onshore and offshore transport rates). Generally too much sediment is imported from deeper water and deposited in the beach zone by the models.
- Profile and Area models can be used to predict the short-term (2 to 3 years) behaviour of bulk sediment volumes in the outer surf zone (excluding beach zone) with reasonable accuracy, provided that the models have been calibrated properly; 3D models yield slightly better morphological results than 2DH models.
- Profile models can to some extent simulate the outer bar behaviour at the nourishment location (bar detachment and onshore migration), as shown for the Egmond case but not for the Delfland case. The reasons for the different bar behaviour (in the model) at Egmond and at Delfland are not yet clear. The nearshore bar behaviour can not yet be represented sufficiently accurate.
- Area models can not yet represent the bar behaviour; area models should include wave asymmetry effects and wave breaking delay effects (roller model) to be able to simulate the bar behaviour. Neglecting these effects, the bars are flattened out by the models because the basic onshore and offshore transport processes are not included (wave asymmetry, wave breaking delay causing a shift between the bar crest and the location of maximum sand transport).

The results of the model exercises broadly confirm the hypotheses on the hydrodynamic and morphodynamic functioning of shoreface nourishments (see Section 1.5), which can be summarized as lee effects (partly blocking of littoral drift) and feeder effects (onshore movement of sand).

4.5 Recommendations

The following recommendations are given:

Physical behaviour of shoreface nourishments

- Field data information on the two basic nourishment processes: the lee effects (blocking of longshore currents and associated longshore transport rates in the lee of shoreface nourishments) and the feeder effects (onshore movement of sediment by shoaling waves) is almost completely missing. Hence, the performance of mathematical models with respect to these two basic processes can not be properly evaluated. It is recommended to perform field surveys focussing on the processes in the lee of a shoreface nourishment to indentify the basic lee and feeder processes and to produce a database for process validation of mathematical models.

- The beach zone in the lee of the nourishment does not always benefit directly (on short term) from the nourished sand. Sometimes, additional beach nourishments have to be carried out to mitigate local erosion. As the supply of sand from the feeder berm to the beach takes place on a relatively long time scale (5 to 10 years), it is recommended to study whether it is better or not to maintain the shoreface berms by dumping of sand on a more regular basis (each two years) to create a more continuous flow of sand to the beach zone.
- The moment of shoreface nourishment at a certain location along the coast with respect to the position and movement of the outer and inner bars within the bar migration cycle should be studied more properly.
- The effect of rip channels (erosional hot spots along the coast) on the three-dimensional behaviour of the beach in the lee of shoreface nourishments should be studied more properly. It may be advantageous to (temporarily) close local rip channels in the area of a shoreface nourishment.

Modelling approaches

- Area models should be improved with respect to the modelling of bar behaviour by including wave breaking delay effects and wave asymmetry effects.
- Area models should be more properly evaluated with respect to their performance on the longshore and on/offshoretransport rates in the lee of shoreface nourishments based on the results of detailed field surveys.
- Area models should be improved with respect to the inclusion of sediment grading effects (fractional approach), as the study of the Terschelling nourishment shows a clear spatial and temporal variation of the sediment sizes.
- Improved area models should be applied to determine the most effective dimensions and location of shoreface nourishments and the proper moment of nourishment within the bar migration cycle (sensitivity studies).

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