

The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based Profile models

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Abstract

Deterministic and probabilistic Profile models have been compared with hydrodynamic and morphodynamic data of laboratory and field experiments on the time scale of storms and seasons. The large-scale laboratory experiment is a pure 2D case and offers an ideal test case for cross-shore Profile models, as disturbing alongshore non-uniformities are absent. The field experiments are performed at the Egmond site (The Netherlands) during the EU-COAST3D project and represent storm time scale (Oct.–Nov. 1998) as well as seasonal time scale conditions (May 1998–Sep. 1999). The objective of the paper is to present information of coastal processes on these time scales and to assess the predictive capabilities of Coastal Process-based Profile models with respect to hydrodynamics and morphodynamics at sandy beaches on the time scales of storms and seasons. Profile models can quite accurately (errors smaller than 10%) represent the cross-shore significant wave height distribution in the surf zone, if the wave breaking model is properly calibrated. The wave breaking coefficient should be a function of local wave steepness and bottom slope for most accurate results. Profile models can reasonably represent the cross-shore and longshore currents (undertow) in a pure 2D case and in 3D field conditions. Profile models including cross-shore mixing effects and breaker delay effects do not produce better predictions of the longshore and cross-shore current velocities. Profile models using default settings can quite reasonably simulate the behaviour of the outer and inner bars on the storm time scale; the behaviour of the beach cannot be modelled with sufficient accuracy on the storm time scale. Profile models can reasonably simulate the post-storm onshore bar migration, provided that the near-bed orbital velocities and wave asymmetry-related sand transport are represented in a sufficiently accurate way (using non-linear wave theories). Profile models cannot simulate the beach recovery processes on the post-storm time scale, because these essentially 3D processes are not sufficiently known to be included in the models.

Profile models using default settings cannot simulate the behaviour of the outer and inner bars and the beach on the seasonal time scale; the behaviour of the outer bar on the seasonal time scale can only be represented properly after tuning using

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measured bed profiles. The simulation of the inner bar and beach morphology on the seasonal time scale could not be improved by tuning.

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1. Introduction

This paper is focussed on the evaluation of Coastal Process-based Profile models for simulation of hydrodynamics and morphodynamics at sandy beaches on the time scales of storms and seasons. Profile models are being used for the estimation of longshore transport rates, the development of cross-shore bed profiles due to the sand nourishments and the prediction of dune erosion volumes, but the inaccuracies of the predicted parameters on the various time scales involved are largely unknown. To address these problems, it is of essential importance to have sufficient insight of the natural profile developments on the various time scales.

The time scales that are of relevance for Profile models are: the storm time scale of hours to days, the seasonal time scale of months to years and the decadal time scale (up to 10 years). Storms attacking the coast, operate on a time scale of hours to days and generally cause erosion of the dune and beach zones and offshore bar migration depending on the storm surge levels involved. Beach recovery (herein defined as the foreshore) generally takes place during fair weather wave conditions as present during the summer season.

Beach behaviour usually is expressed by the temporal position of the high water line (HW), low water line (LW) or dune foot line (DF), but spatial beach variations due to alongshore migrational features such as sand waves, crescentic bars, rip channels, etc can also be observed. Temporal and spatial variations of the shoreline are closely related and often are manifestations of the same phenomena. Temporal variations generally show a mean component (time-averaged trend) and a fluctuating component (variability). The mean component can be a linear trend (erosion or accretion), but most often it is a long-term oscillation cycle (erosion followed by accretion or vice versa) and generally is of the order of 1 m/year for straight coasts. Near inlets these mean

(trend) values may be somewhat larger (up to 10 m/year) due to the interaction of the beach with large scale bars and flats detaching from or attaching to the coast (bar–channel interaction). The temporal variability of the shoreline is of the order of 10 m for straight coasts up to 100 m/year for inlet coasts (Van Rijn, 1998a). Temporal beach variability of straight coasts on the seasonal time scale is most closely related to seasonal variations in wave conditions (storm–fair weather cycle, storm intensity) and the local breaker bar configuration.

The typical beach-bar behaviour on the time scale of the seasons is the offshore–onshore migrational cycle with offshore migration of the bar system during the winter season and onshore migration and beach recovery during the summer season (low waves). Seasonal variation resulting in so-called winter and summer profiles is a general characteristic of nearshore morphological behaviour, but the degree of seasonality varies widely. Along Pacific coasts the nearshore bars often disappear during the summer period (bar welding to beach); along many other coasts the nearshore bars are permanent features. The knowledge of the seasonal variability of nearshore bars has increased considerably during recent years due to the use of video remote sensing techniques (Lippmann et al., 1993; Van Enckevort, 2001). Lippmann et al. studied the onshore and offshore migration cycle of the breaker bar (cross-shore bar length L of about 100 m; defined as crest to crest length) at the Duck site (USA) and found offshore migration rates up to 100 m and onshore migration rates up to 50 m on the seasonal time scale. Van Enckevort analysed seasonal variations of bar crest positions (bar length of about 150 m) at the Noordwijk site in the Netherlands. Based on analysis of alongshore averaged (over 2 km) bar crest positions, the cross-shore variability on the seasonal time scale was found to be about 20 m for the outer bar migration and about

10 m for the inner bar migration at the Noordwijk site. Both onshore and offshore migration was observed on the seasonal time scale at both sites, but offshore migration (during storm conditions) was found to be dominant. These results show that the nearshore bars can migrate over a distance up to their own cross-shore length scale (0.2 to $1L$) on the seasonal time scale of a few months up to a year. The alongshore variability (planform) of the inner bar at Noordwijk was found to have an amplitude of about 0.1 to $0.2L$ and a length scale of about 5 to $10L$ on the seasonal time scale. Hence, the alongshore bar variability is of the same order as the net cross-shore bar movement on the seasonal time scale expressing a typical 3D behaviour.

On the decadal time scale the bars often show a migrational cycle in offshore direction over several bar length scales (up to $5L$) with decay of the outer bar at the edge of the surf zone and generation of a new bar at the foot of the beach (Wijnberg, 1995). During storm conditions, the outer bar decays due to erosion of sand at the bar crest and transport of the eroded sand to the seaward flank of the inner bar, resulting in offshore migration of the inner bar. During (minor) storms, the conditions are also favourably for generation of a new bar at the foot of the beach. These phenomena have clearly been observed at the Duck site and at the Dutch coast (Hoekstra et al., 1996; Van Rijn, 1998a; Shand et al., 1999). The cycle time of the bars at the central Dutch coast and at the US-Duck site is in the range of 5 to 15 years depending on the size of the bars. Realizing that these time scales are closely related to spatial scales, it can be stated that the behaviour of the outer and inner bars generally is two-dimensional on long term (years) and on large alongshore scale (10 km), in the sense that the bars are continuous and of the same form in alongshore direction and show the same overall migrational pattern (onshore and offshore migration). On short and medium time scales of storms and seasons, the bars are not completely straight or linear, but alongshore non-uniformities are present as local disturbances superimposed on the overall straight base pattern yielding a three-dimensional morphological system. Examples of these local disturbances are the development of depressions (rip channels), crescentic and meander patterns, introducing an alongshore wave length of

the bar system of the order of 100 to 1000 m (Lippmann and Holman, 1990; Van Rijn, 1998a; Ruessink et al., 2000; Van Enckevort and Ruessink, 2001; Van Enckevort, 2001). The cross-shore amplitude of the planform was found to be about 15 to 20 m for the outer bar and 10 to 15 m for the inner bar at the Noordwijk site. Residence times of the 3D features were found to be on the time scale of months to a year, but no distinct seasonal trend was observed at the Noordwijk site. The 3D features of the outer bar were more persistent than the inner bar features. These 3D features have been observed to migrate along the shore under the direct influence of the wave-induced longshore currents. The mean longshore migration rates were of the order of 20 to 40 m/day for the outer bar (mainly meander type features) and 10 to 20 m/day for the inner bar (mainly rip channel features) at the Noordwijk site. No consistent relation between the amplitude and the wave conditions was found. The alongshore migration of the planform of the bars yields an onshore–offshore behaviour superimposed on the overall offshore migration of the bars.

Summarizing, the onshore–offshore bar migration of individual profiles is of the order of 0.2 to $1L$ (with L being the cross-shore bar length) on the time scale of storms and seasons and is caused by both cross-shore and alongshore transport processes (3D behaviour). On decadal time scales the cross-shore migration of individual profiles is of the order of 3 to $5L$ and mainly caused by cross-shore transport processes (2D behaviour).

Applying 2D Coastal Profile models to model the cross-shore bar behaviour, the coastal system is simplified to a 2D system assuming uniformity in the alongshore direction. The nearshore breaker bars are considered to behave as shore-parallel morphodynamic features, thereby neglecting the existence of meandering and/or crescentic patterns and the existence of local rip channels. The question must be raised to what extent this approach is ever applicable. Are there any fundamental problems in addressing coastal processes as a 2D system by use of Profile models. Is this approach in general acceptable and reliable enough or is a 3D approach by use of Area models the only solution to achieve good predictability? These questions were addressed within the EU-COAST3D project (Soulsby, 2001).

Based on the available information of cross-shore variability of individual profiles due to both cross-shore and longshore transport processes, it is clear that a 2D Profile model cannot be applied to individual profiles on the time scale of storms and seasons, but only to an alongshore-averaged profile, provided that the averaging zone is sufficiently large to remove the effects of alongshore variability. The application of 2D Profile models on the decadal time scale seems to be more appropriate, but it is an open question whether the accuracy of 2D Profile models is sufficient to predict the net bar migration on this long-term time scale.

Herein, the coastal predictability of three distinct zones: outer bar, inner bar and beach (foreshore) on the time scale of storms and seasons will be considered, realizing the general basic principle: “predictability will be low, where variability is large”. Intuitively, one can expect better predictions for the slowly varying outer bar in deeper water than for the highly variable beach and dune zone at the end of the profile, responding to almost each wave arriving there.

Both 2D laboratory and 3D field experiments have been selected for comparison with Profile model results, as explained in Section 2. Detailed results of the model simulations in comparison to measured data are presented in Sections 3, 4 and 5. All results are summarized and synthesized by a set of conclusions on the predictability of sandy beaches on various time scales by use of Profile models in Section 6.

2. Modelling approaches and selected experiments

2.1. Available model approaches

The “state of art” on the present knowledge of morphodynamic processes is reflected by the current generation of mathematical, process-based models. These models integrate and synthesize our theoretical knowledge based on experiences gained during many field and laboratory experiments. The process-based models have a common structure, consisting of submodels, representing: (i) the hydrodynamics such as wave propagation, tide-, wind- and wave-driven 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.

Coastal Profile and Coastal Area models are the two main generic types of process-based models. Coastal Profile models reflect the physical processes in a cross-shore direction, assuming longshore uniformity (see for overview: Roelvink and Brøker, 1993). 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 in most models. Coastal Area models are two- or three-dimensional horizontal models consisting of, and linking, the same set of submodels of the wave field, the tide-, wind- and wave-driven flow field, the sediment transport fluxes and the bed evolution (see for overview: De Vriend et al., 1993). Fully 3D-models describing the currents on a three-dimensional grid are in a very early stage of development, and require excessive computer-memory and power at present stage.

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.

Herein, the attention is focussed on the application and accuracy of 2D Profile models with respect to the predictability of sandy beaches. The application of Profile models to a coastal system is based on the assumption of alongshore uniformity of the bar system (two-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. The ideal test case for a 2D Profile model is a 2D experiment in a large-scale wave flume to determine the reliability of the model formulations of the pure cross-shore processes. Herein, the results of the LIP experiments (Arcilla et al., 1994) performed in the Delta Flume of Delft Hydraulics will be briefly discussed for 2D testing of Profile models. These idealized 2D conditions rarely exist in nature. Analysis of field data shows that the assumptions of longshore uniformity for Profile models often are severely violated because of the presence of rhythmic and non-rhythmic 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. A better 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. Bed level changes at two different dates are only significant in zones where there is no overlap of the error bands. The longshore averaging distance should be so large that the longshore rhythmicity including rip channels is fully covered. This approach has been followed in the present paper, using the experimental data of two field experiments (storm and seasonal time scales) performed near

Egmond along the central Dutch coast. It is noted that the averaging of individual profiles is not trivial, as most processes are highly nonlinear. Another problem may be the presence of single, isolated bars which are smeared out by longshore averaging and in that case the average profile may not represent any of the individual profiles. Obviously, the longshore averaging procedure is only valid for conditions with a pronounced, elongated longshore bar as present along the barred Dutch coast (relatively small error bars, see Fig. 4.3) and many other barred coasts (Duck site, USA). An alternative procedure is the simulation of the morphological development of individual profiles followed by averaging of the individual profiles to obtain the final profile to be compared with the measured longshore-averaged profile. The suitability of this alternative method was studied by Grasmeijer (2002) for the barred Duck coast (USA) showing only minor differences with the method of longshore-averaged profiles before simulation. Therefore, this latter method was adopted as sufficiently adequate for morphological simulations of barred cross-shore profiles as present along the Dutch coast. All hydrodynamic runs were done by applying the individual profiles of the measurement transect.

2.2. Experiments

Summarizing, the following three experimental data sets have been used for model comparisons.

- LIP experiments in 2D large-scale wave flume of Delft Hydraulics;
- COAST3D-Storm Experiment at 3D field site of Egmond (The Netherlands) during period of 18 Oct. to 12 Nov. 1998; hydrodynamic and morphodynamic data are available; as this storm dataset is the most relevant dataset for assessing the skill of profile models for extreme conditions, all models were used;
- COAST3D-Seasonal Experiment at 3D field site of Egmond during period of 11 May 1998 to 14 Sep. 1999; only morphodynamic data are available; model runs by UNIBEST of DH and CROSMOR of UU; the other models were typical storm models and could not be used on this longer seasonal time scale.

2.3. Description of applied Profile models

Model runs have been made by the following models:

- UNIBEST-TC of Delft Hydraulics (DH) (Reniers et al., 1995; Bosboom et al., 1997);
- COSMOS of HR Wallingford (HR) (Southgate and Nairn, 1993; Nairn and Southgate, 1993);
- CROSMOR2000 of University of Utrecht (UU) (Van Rijn and Wijnberg, 1994, 1996; Van Rijn, 1997a, 1998b, 2000b);
- BEACH1/3D of University of Liverpool (UL) (O'Connor et al., 1998; O'Connor and Nicholson, 1999);
- CIIRC of University of Catalunya (UC) (Rivero et al., 1993; Rivero and Sánchez-Arcilla, 1991, 1994; Siera and Sánchez-Arcilla, 1999; Sierra et al., 1997).

The basic characteristics of the models are described in Table 2.1 (see references for model formulations and equations). Hereafter, the most important model differences and similarities are presented.

2.3.1. Wave height

All models are based on the well-known wave energy balance including the momentum equation for wave-induced setup. All models include a roller model to represent the dissipation of roller energy by breaking waves. The UNIBEST, COSMOS and CIIRC models are based on a deterministic approach as proposed by Battjes and Janssen (1978). The CROSMOR and BEACH models are based on a wave by wave (probabilistic) solution of the wave-energy balance to better represent the wave spectrum. The models differ in the representation of the wave breaking coefficient (γ =ratio of wave height and water depth at breaking; in the range of 0.5 to 1). The CROSMOR model is the only model that is based on a local breaking coefficient depending on the ratio of local wave steepness and local bottom steepness. The other models are based on a constant breaking coefficient depending on offshore conditions. The breaking coefficients of the UNIBEST, COSMOS and CROSMOR models were set to their default values (no calibration); the breaking coefficients of the BEACH and CIIRC models were determined by

calibration. The CIIRC and BEACH model used γ -values in the range of 0.5 to 0.8 for the hydrodynamic runs and default values for the morphodynamic runs. Roller model coefficients were set to their default values. Other model coefficients affecting the wave model were set to their default values.

2.3.2. Longshore current

All models are based on a numerical solution of the depth-averaged momentum equation for the longshore current. The UNIBEST, COSMOS and CROSMOR models include the tide-induced longshore current velocity based on the longshore water surface gradient term in the momentum equation; the other two models do not include this term. Cross-shore exchange (mixing) of longshore momentum is only modelled by the CROSMOR and the CIIRC models. The cross-shore mixing coefficient is constant along the bottom profile and was determined by calibration (see Table 4.1). Realistic values are in the range of 0.5 to 2 m²/s. The COSMOS model includes a smoothing length scale applied on the cross-shore radiation stress gradients. This smoothing length scale was determined by use of preliminary runs and kept constant during all other runs.

2.3.3. Cross-shore current

The UNIBEST, COSMOS, BEACH and CIIRC models are based on a numerical solution of the balance equation for local cross-shore momentum neglecting cross-shore advection terms. Local means that the variation of the shear stress and the velocity over the depth is included through an eddy viscosity approach. All coefficients used were set to their default values (no additional calibration). The CROSMOR model computes the depth-mean cross-shore velocity below the wave trough from a local mass transport equation based on linear wave theory. The vertical velocity distribution is determined from a pre-assumed shape function and the computed depth-mean cross-shore velocity using the mass continuity equation below the wave trough. The method does not include any calibration.

2.3.4. Asymmetry of near-bed orbital velocities

The UNIBEST, COSMOS and CROSMOR models include the asymmetry of the near-bed orbital velocities (herein defined as the ratio of the peak onshore orbital velocity and the peak offshore velocity) to

Table 2.1
Basic characteristics of applied Profile models

Processes	UNIBEST (DH; Delft Hydraulics)	COSMOS (HR; Hydr. Res. Wallingford)	CROSMOR (UU; University of Utrecht)	BEACH (UL; University of Liverpool)	CHIRC (UC; University of Catalunya)
Waves	Deterministic	Deterministic	Probabilistic (wave by wave)	Probabilistic (wave by wave)	Deterministic
Wave breaking	Battjes and Janssen (1978), Battjes and Stive (1985) Roller model	Battjes and Janssen (1978), Optional: parameter-rised roller length scale	Wave height–depth criterion as function of wave steepness and bottom slope, Roller model (optional)	Wave height–depth criterion, Roller model	Battjes and Janssen (1978), Roller model
Asymmetry of near-bed orbital velocity	Fourier approximation of stream function	Isobe and Horikawa (1982)	Modified Isobe and Horikawa (1982)	Not included	Not included
Low-frequency wave effects	Bound-long wave are included	Not included	Not included	Not included	Not included
Longuet-Higgins streaming (1953) near bed	Included	Not included	Included	Not included	Not included
Undertow	Momentum balance over depth; mass flux balance, incl. wave drift and surface roller; three-layer approach; eddy viscosity by mixing length	Momentum balance over depth; mass flux balance, incl. wave drift; three-layer approach; eddy viscosity by mixing length	Depth–mean undertow from mass transport from linear waves; assumed velocity profile (weighted over all wave classes)	Momentum balance over depth; mass flux balance, incl. wave drift and surface roller; assumed velocity profile; eddy viscosity by mixing length	Momentum balance over depth; mass flux balance, incl. wave drift and surface roller; three-layer approach; eddy viscosity by mixing length
Longshore current	Including wind and tide-induced flow; excluding lateral mixing	Including wind and tide-induced flow; excluding lateral mixing	Including wind and tide-induced flow; including lateral mixing	Excluding wind and tide-induced flow; excluding lateral mixing	2DH model applied in 1D profile mode; excluding wind and tide-induced flow; including lateral mixing
Sand transport	Bed load transport Ribberink (1998) using intra-wave approach; Time-averaged suspended transport of Van Rijn (1993); High-frequency suspended transport excluded	Bailard–Bagnold (1981) model based on intra-wave approach	Bed load transport Ribberink using intra-wave approach; Time-averaged suspended transport of Van Rijn (1993); High-frequency suspended transport included	Bed load and suspended transport model of Watanabe (1980). Sand transport due to wave asymmetry effect is modelled by transport direction indicator of Watanabe	Bed load and suspended transport model of Watanabe (1980). Sand transport due to wave asymmetry effect is modelled by transport direction indicator of Watanabe

determine the sand transport related to these effects. The UNIBEST model is based on a Fourier approximation of the streamfunction method to include non-linear effects. The COSMOS and CROSMOR models are based on the parameterization method of [Isobe and Horikawa \(1982\)](#). All coefficients were set to their standard default values. The BEACH and CIIRC models do not include the asymmetry effect and hence the wave-related sand transport is also not included.

2.3.5. Longuet-Higgins streaming

This streaming effect which occurs in the wave boundary layer due to an unbalance of shear stresses, yields a net onshore velocity near the bed. This effect was only represented by the CROSMOR model using the standard analytical equations formulated by [Longuet-Higgins \(1953\)](#) in addition to the cross-shore velocity derived from the mass transport effect. The coefficients were set to the default values, yielding a streaming velocity in the range of 0.05 to 0.15 m/s, depending on wave conditions.

2.3.6. Low-frequency effects

The bound-long wave effect was only represented by the UNIBEST model.

2.3.7. Sand transport

All models use a different method to compute the sand transport along the bed profile. The UNIBEST-model is based on a local intra-wave sand transport equation ([Ribberink, 1998](#); [Van Rijn, 1993](#)) as a function of the local instantaneous near-bed velocity. The net transport is obtained by integration over the wave period. The COSMOS model uses a similar approach based on the Bailard–Bagnold approach ([Bailard, 1981](#)). The CROSMOR model also uses this approach based on the [Van Rijn \(1993\)](#) method applied to individual waves (wave by wave approach); the high-frequency suspended load transport is included. The UNIBEST and COSMOS models were used in the default mode. The CROSMOR model was calibrated based on preliminary runs by varying a transport multiplication factor (constant along profile; default value of 1 used in LIP tests; value of 0.5 used in field experiments). This latter factor implies that the default sand transport capacity at each location along the profile is multiplied by the factor used (a factor between 0.5 and 2 is reasonable). The UNIBEST,

COSMOS and CROSMOR models require the input of a bed roughness (ripple roughness) value which was determined according to experience (in the range of 0.01 to 0.06 m). The BEACH and CIIRC models use the sand transport model of [Watanabe et al. \(1980\)](#), which generates either net onshore or net offshore transport based on a transport direction indicator (onshore or offshore). The coefficients involved (A_{waves} and A_{currents}) were calibrated based on preliminary runs. The runs of the CIIRC model were based on $A_{\text{waves}}=0.2$ and $A_{\text{currents}}=0.1$ ([Watanabe](#) suggested a range of 0.2 to 0.9 for A_{waves} and 0.1 to 1 for A_{currents}). The runs of the BEACH model were based on $A_w=0.15$ for non-breaking waves and $A_{w,br}=0.02$ for breaking waves; the current-related transport component (A_c) was not included.

As regards model similarities and differences, the following model aspects will be specifically addressed in this paper (see Section 6 on conclusions):

- is it important to represent a variable wave breaking coefficient along the profile or not?
- is a probabilistic wave model essential or not?
- is it important to represent tidal longshore velocities in the surf zone or not?
- is it important to represent cross-shore mixing effects in the surf zone or not?
- is it important to represent the variable bed roughness along the profile or not?

2.3.8. Calibration procedure

Throughout the model comparison exercise, it became clear that the models can only produce meaningful results after proper calibration using measured results of hydrodynamics and morphodynamics. The calibration procedure was applied, as follows:

- *LIP2D experiment*; sand transport was calibrated based on adjustment of bed roughness;
- *COAST3D-Storm experiment*; The modellers were free to set (calibrate) the coefficients of the various submodels according to experience and given practice based on preliminary runs. Only *one* set of coefficients was allowed for the final runs (six hydrodynamic events and three morphological events) to be used for determination of statistical performance parameters;

- *COAST3D-Seasonal experiment*; The coefficients of the hydrodynamic models were kept constant (as used in the storm experiment), but additional calibration of the sand transport models was necessary to obtain stable and meaningful results; the COSMOS, BEACH and CIIRC models could not be applied on the longer time scale due to various problems (non-realistic results); the COSMOS, BEACH and CIIRC models basically are models tuned for the storm time scale (storm models).

The model comparison has been initiated to study whether process-based models are useful tools (with or without calibration) for prediction of coastal morphodynamic processes and on what space and time scales? It is not the aim of this study to point out the best model, as it is believed that all models can be forced to produce reasonable results after sufficient calibration and that no model can produce good results without any calibration at present stage of research. Therefore, it was not felt necessary to apply all models to all data sets. Each institute focussed on different subjects and methods to cover a wide scope of interest within the project. The basic features of the models and applied calibration methods should become as clear as possible. More of the same runs have been avoided wherever possible.

As the modelling of the storm experiments at Egmond was the main exercise of this study, all models were used to simulate the more complicated storm experiments at the Egmond site on the time scale of days to weeks to see what level of calibration is required to simulate the more complicated conditions with longshore currents and rip currents at a field site. Ranges of calibration coefficients are given in Table 4.1.

Only two models (UNIBEST and CROSMOR) could be applied after additional calibration to the seasonal experiments on the time scale of summer and winter months. Preliminary runs showed that the other models could not produce meaningful results on this time scale and were therefore not used.

2.4. Model performance and statistics

The question of how good a model is should be defined in a more quantitative manner than the usual

qualitative ranking (excellent, good, reasonable or poor) that is normally applied. This section defines a number of statistical parameters that can be used to assess the quality of the performance of models. Herein, it is proposed to evaluate the performance of the models on the basis of the Relative Mean Absolute Error (RMAE) and the Brier Skill Score (BSS); (Murphy and Epstein, 1989; Peet et al., 2002). The formulae are as follows:

wave height:

$$\text{RMAE} = \langle |H_c - H_m| - \Delta H_m \rangle / \langle H_m \rangle$$

longshore velocity:

$$\text{RMAE} = \langle (|V_c - V_m| - \Delta V_m) \rangle / \langle |V_m| \rangle$$

cross – shore velocity:

$$\text{RMAE} = \langle (|U_c - U_m| - \Delta U_m) \rangle / \langle |U_m| \rangle$$

morphology:

$$\text{BSS} = 1 - [(\langle |z_{b,c} - z_{b,m}| - \Delta z_{b,m} \rangle^2) / (\langle (z_{b,0} - z_{b,m})^2 \rangle)]$$

in which: H =wave height, ΔH_m =error of measured wave height, V =longshore velocity (+ = north-going, – = south-going), ΔV_m =error of measured longshore velocity, U =cross-shore velocity (– = seaward-directed, + = landward-directed), ΔU_m =error of measured cross-shore velocity, z_b =bed level, $\Delta z_{b,m}$ =error of measured bed level, $z_{b,0}$ =initial bed level, index m =measured, index c =computed, $\langle \dots \rangle$ =averaging procedure over time series.

It is noted that the statistic parameters of wave height, current velocity and bed level are corrected for the measurement errors (Van Rijn et al., 2000), being $\Delta H_m = 0.1$ m for wave height, $\Delta V_m = \Delta U_m = 0.05$ m/s for current velocity and $\Delta z_{b,m} = 0.1$ m for bed level in field conditions and 0.02 m for laboratory conditions. This latter procedure means that the difference between the computed value and the error band envelope of the measured parameter is considered (see Fig. 2.1). The absolute difference of the computed and measured values minus the measurement error cannot be smaller than zero (e.g. $|H_c - H_m| - \Delta H_m$ is zero, if < 0). Basically, it means that the computed value is within the error band range of the measured value (Fig. 2.1, Left).

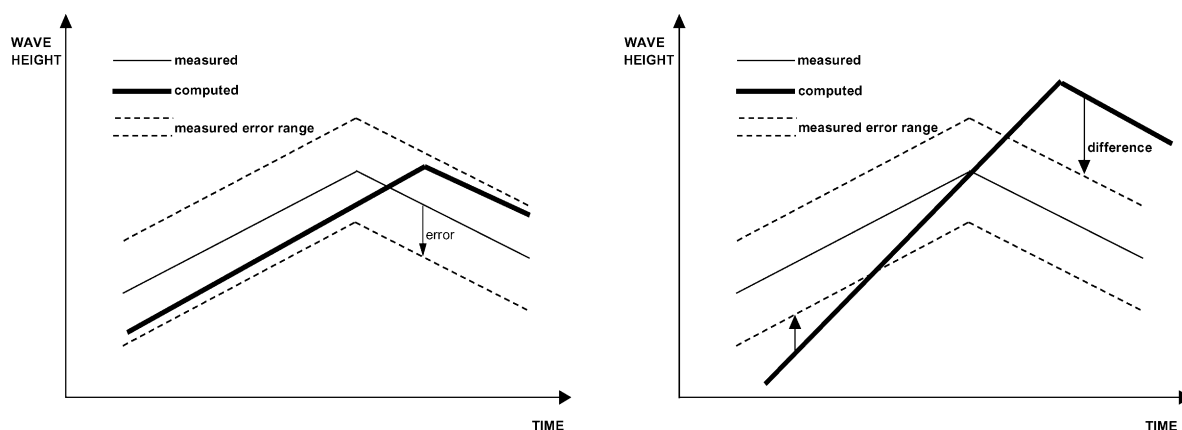


Fig. 2.1. Examples of time series of measured and computed wave height. Left: Computed value is everywhere within error band range of the measured value (excellent agreement), difference is zero everywhere. Right: Outside the error band range, the computed value deviates significantly from the measured value; the difference is defined as $\text{diff} = |H_c - H_m| - \Delta H_m$.

The Relative Mean Absolute Error is preferred above the Relative Mean Square Error, because the presence of a few outliers will have a greater influence on RMSE than on RMAE as RMSE squares the differences. The RMAE is therefore less susceptible to the presence of outliers. Relative errors can be obtained by scaling the error with the average of the measured value. The relative errors will be relatively large, if the average value is close to zero (such as for a tidal current varying around zero). In this case the RMAE can give very high values that are exceptionally sensitive to small perturbations in the average. Therefore, it is better to non-dimensionalise the errors by the average of the absolute measured values.

The performance of a model relative to a baseline prediction can be judged by calculating the Brier Skill Score.

This skill score compares the mean square difference between the prediction and observation with the mean square difference between baseline prediction and observation. Perfect agreement gives a Brier score of 1, whereas modelling the baseline condition gives a score of 0. If the model prediction is further away from the final measured condition than the baseline prediction, the skill score is negative. The BSS is very suitable for the prediction of bed evolution. The baseline prediction for morphodynamic modelling will usually be that the initial bed remains unaltered. In other words, the initial bathy-

metry is used as the baseline prediction for the final bathymetry. A limitation of the BSS is that it cannot account for the migration direction of a bar; it just evaluates whether the computed bed level (at time t) is closer to the measured bed level (at time t) than the initial bed level. If the computed bar migration is in the wrong direction, but relatively small; this may result in a higher BSS compared to the situation with bar migration in the right direction, but much too large. The BSS will even be negative, if the bed profile in the latter situation is further away from the measured profile than the initial profile. The limitation shown here is that position and amplitude errors are included in the BSS. Telling position errors from amplitude errors, requires a visual inspection of measured and modelled profiles or the calculation of further statistics (Murphy and Epstein, 1989; Peet et al., 2002).

The BSS can be extremely sensitive to small changes when the denominator is low, in common

Table 2.2
Qualification of error ranges of process parameters

Qualification	Wave height; RMAE	Velocity; RMAE	Morphology; BSS
Excellent	<0.05	<0.1	1.0–0.8
Good	0.05–0.1	0.1–0.3	0.8–0.6
Reasonable/fair	0.1–0.2	0.3–0.5	0.6–0.3
Poor	0.2–0.3	0.5–0.7	0.3–0
Bad	>0.3	>0.7	<0

with other non-dimensional skill scores derived from the ratio of two numbers.

The qualification of model performance is given in the following Table 2.2. The value ranges of Table 2.2 give a tough set of standards for models to achieve.

3. Modelling of hydrodynamics and morphodynamics during storm and post-storm events in large-scale 2D wave flume

The ideal test case for a cross-shore Profile model is a 2D experiment in large-scale conditions to evaluate the overall accuracy and reliability of the model formulations of the pure cross-shore processes. Within the framework of the European Large Installations Plan (LIP) a programme of detailed measurements along a sloping cross-shore profile (0.2 mm sand) has been carried out in the large-scale Deltaflume of Delft Hydraulics (Arcilla et al., 1994; Roelvink and Reniers, 1995). Only the UNIBEST and CROSMOR models, being typical examples of process models, have been used for simulation of these two tests 1B (storm event: wave height of 1.4 m, period of 5 s) and 1C (post-storm swell event: wave height of 0.9 m, period of 8 s) to evaluate whether process-based models can, in principle, simulate the basic processes (wave height, undertow, sand transport and morphology along the cross-shore profile). In both tests (1B and 1C), the maximum bar height was of the order of 0.3 m. Detailed results are presented by Van Rijn et al. (2002). Herein, it is sufficient to state that the wave

height can be accurately simulated ($\text{RMAE} < 0.1$) without calibration. The simulation of the undertow around the breaker bar is less good ($\text{RMAE} < 0.3$). The net sand transport rates and the generation of the breaker bar after 18 h in test 1B can be modelled quite reasonably (BSS of about 0.65 in bar zone), provided that the variable bed roughness (ripples in the bar trough; no ripples on the bar crest) and the high-frequency suspended sand transport are taken into account. As an example the computed bed profiles for test 1B of the CROSMOR model are shown in Fig. 3.1. The UNIBEST model produced similar results. The onshore migration of the bar after 13 h in test 1C could only be simulated accurately by increasing the onshore orbital velocities (by about 15%) to better represent the observed orbital velocities. These simulations prove that process-based models can simulate the wave height and undertow in a pure 2D case reasonably well. The simulation of the onshore orbital velocities in typical swell conditions was less good. Calibration of the sand transport formulations using the observed bed form characteristics (bed roughness) was found to be essential for adequate simulation of the cross-shore morphology (generation of breaker bar). Without this type of calibration the computed bed profiles are not very good at present stage of research (see Fig. 3.1).

In Section 4, the process-based models will be applied to a more complicated 3D field site with nearshore circulations and longshore currents. This will show in what way the model performance will be modified due to the presence of longshore processes.

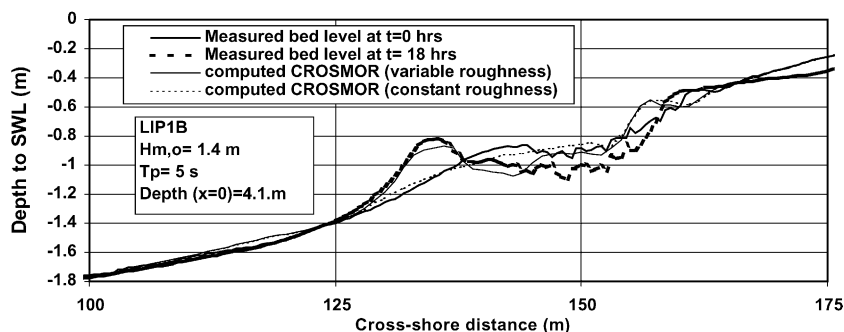


Fig. 3.1. Measured and computed bed profiles for test 1B of LIP experiments.

4. Modelling of hydrodynamics and morphodynamics during storm and post-storm events at 3D field site of Egmond

4.1. Boundary conditions and observed phenomena

4.1.1. Field site

The Egmond site is located in the central part of the Dutch North Sea coast and consists of a sandy beach (about 0.3 mm sand). The local morphology is 2.5 dimensional exhibiting two longshore bars intersected by local rip channels; the bars are aligned parallel to the shore most of the time, but crescentic bar forms do also occur. The bars show a long-term migration of about 20 to 40 m/year in seaward direction. The beach width is about 100 to 125 m with a slope between 1 to 30 and 1 to 50. The meso-tidal range varies between 1.4 m (neap) and 2 m (spring). The tidal peak currents in the offshore zone are about 0.5 m/s; the flood current to the north is slightly larger than the ebb current to the south. The offshore significant wave height at 15 m depth may be as large as 5 m during major storms from southwest or northwest directions. The yearly average wave height is about 1 to 1.2 m. At Egmond, the general coast line orientation is 7°N (topographic North), which results in 277°N for the shore normal direction.

Hydrodynamic process measurements have been carried out in an area of about $500 \times 500 \text{ m}^2$ near the beach of Egmond by use of instrumented tripods and poles during the period 12 Oct. to 20 Nov. 1998 (Soulsby, 2001). The main transect is shown in Fig. 4.1. The stations 18A, 7A, 2, 1A, 1B, 1C, 1D and 13B

are supposed to be representative for the processes in the main transect, although not all stations (18A, 7A, 2) are located in the main transect.

Station 7A is a fixed pole for wave height and water level measurements. Stations 18A and 13B are small frames for current velocity measurements (S4 instrument). Stations 2, 1A to 1D are tripods for wave height and velocity measurements. The parameters measured by the tripods and poles are: water levels and wave parameters by pressure sensors and capacity wires, instantaneous fluid velocities by electromagnetic current meters. The bed morphology in the area was sounded regularly (WESP and ship). The WESP is an approximately 15 m high amphibious three-wheel vehicle. Background parameters of interest are the water temperature, which varied between 9 and 12 °C and the salinity, which varied between 20 and 25 promille. The maximum wind speed was about 20 m/s (Beaufort 8) from western directions (normal to shore) on 29 Oct. The wind and waves generally were in the same directions. Detailed descriptions of the experimental results are given by Ruessink (1999), Kleinhout (2000) and Van Rijn (2000a).

4.1.2. Wave conditions during Main Experiment (Oct.–Nov. 1998)

The wave conditions between 18 Oct. and 17 Nov. can be divided into four subperiods:

- Pre-storm period between 18 and 24 Oct.: mean offshore wave height $H_{s,o} = 1.5 \text{ m}$; three minor storm events with $H_{s,o}$ up to 3 m;

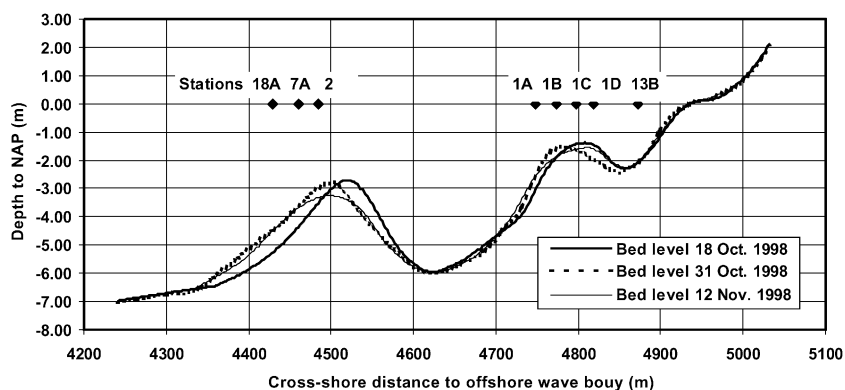


Fig. 4.1. Location of measurement stations during Main Experiment Oct.–Nov. 1998: Stations 1A, 1B, 1C, 1D and 13B are in main transect; Stations 18A, 7A and 2 are about 300 m north of main transect.

- Major storm period between 24 and 31 Oct.: mean offshore wave height $H_{s,o} = 3.2$ m; rapid succession of four major storm events with $H_{s,o}$ up to 5 m;
- Minor storm period between 31 Oct. and 6 Nov.: mean offshore wave height $H_{s,o} = 1.5$ m; one major storm event with $H_{s,o}$ up to 4 m;
- Post-storm period between 6 and 17 Nov. 1998: mean offshore wave height $H_{s,o} = 1$ m; two minor storm events with $H_{s,o}$ up to 2 m.

During conditions with waves from south–west directions, the maximum incident wave angles were about $+20^\circ$ to shore normal at location 2 at the seaward flank of the outer bar for major storm events and about $+25^\circ$ for minor storm events. During conditions with waves from north–west directions, the maximum incident wave angles were about -15° to shore normal at location 2 for major storm events and about -20° for minor storm events. During the storm period between 24 and 31 Oct. four major events with significant offshore wave heights between 4.5 and 5 m (waves from southwest) did occur, see Fig. 4.2. The wave

heights in the surf zone are considerably smaller due to refraction, bottom friction and wave breaking. Roughly, it can be said that during major storm events ($H_{s,o} = 4$ to 5 m) the significant wave height at the crest of the outer bar (crest level of about -3 m) is reduced to about 75% of the offshore significant wave height and to about 50% of the offshore significant wave height at the crest of inner bar (crest level at -1.5 m; 200 m from dunefoot). The effect of the tide level on the wave height can be clearly observed during the experiment.

4.1.3. Longshore currents

The nearshore current velocity field is strongly affected by tide-, wind- and wave-driven processes. The maximum tidal longshore current-velocities near the bed in the surf zone vary in the range of 0.3 to 0.5 m/s. These values occur during calm weather conditions with significant offshore wave heights up to about 1 m. Storms from the southwest strongly enhance the flood currents to the north, but reduce the ebb currents to the south. The longshore velocity

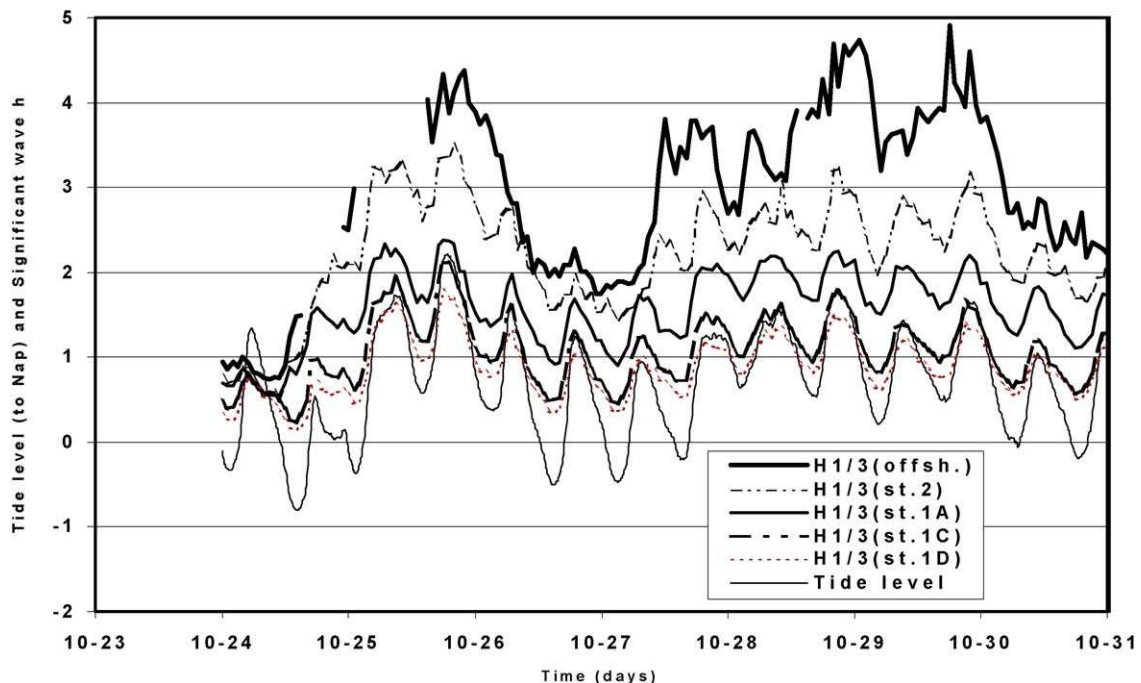


Fig. 4.2. Significant wave height and tide level in offshore station and in nearshore stations 2, 1A, 1C, 1D during storm period of Main Experiment between 24 and 31 Oct. (7 days).

shows maximum values up to about 2 m/s on the seaward flank of the outer breaker bar during a major storm event with wind velocities of about 20 m/s from southwest. The maximum values in the crest zone of the inner bar are about 1.3 m/s under these conditions (Van Rijn, 2000a).

4.1.4. Cross-shore currents

The cross-shore velocities at the inner bar strongly depend on the local wave height, local mean water depth, tide level and the presence (position) of rip channels in the bar crest. The largest cross-shore current velocities (up to -0.65 m/s offshore-directed) have been measured on the seaward flank of the outer bar during storm conditions with an offshore significant wave height of about 4.5 m (storm waves from southwest with angle of 20° to 30° to shore normal). Similar values have been measured at the crest of the inner bar inside a rip channel (local depression) during major storm events. Offshore-directed currents are almost absent in the outer bar zone during minor storm events with significant offshore wave heights smaller than 3 m ($H_{s,o} < 3$ m).

The cross-shore current shows a strong pulsating character at the inner bar with large (-0.6 m/s at low tide) and small (-0.2 m/s at high tide) velocity fluctuations due to tide level variations during fair weather as well as during minor storm conditions (Van Rijn, 2000a).

4.1.5. Bar morphology

On large alongshore scale (10 km) and on long term (years), the behaviour of the outer and inner bars at Egmond is two-dimensional in the sense that the bars are continuous and of the same form in alongshore direction and show the same overall migrational pattern (onshore and offshore migration). On small scale (1 km) and on the short time scale of a storm month, alongshore non-uniformities may develop as local disturbances that are superimposed on the overall straight base pattern yielding a three-dimensional morphological system. Rip channels (with length of 200 to 300 m and depth of 0.5 to 1 m) are generated in the crest zone of the inner bar on the time-scale of a few days during minor storm conditions. Rip channels generally are washed out during major storm conditions. Longshore-averaged bed profiles (based on 7

transects with spacing of 100 m) are shown in Fig. 4.3 for the periods 18–24 Oct., 24–31 Oct., 31 Oct.–12 Nov. 1998. Longshore variability is represented by the standard error band.

Based on Fig. 4.3, the basic overall features of the bars at the Egmond site are:

- 18–24 Oct. (pre-storm period): erosion of outer bar (maximum erosion is about 0.5 m; about $10 \text{ m}^3/\text{m}$ of sand is carried offshore); slight erosion of inner bar (about 0.3 m); beach is almost stable;
- 24–31 Oct. (major storm period): significant offshore migration of outer bar (about $20 \text{ m}^3/\text{m}$ of sand is carried offshore) and inner bar (about $15 \text{ m}^3/\text{m}$ of sand is carried offshore); beach is almost stable;
- 31 Oct.–12 Nov. (minor storm period): slight onshore migration of inner bar (about $5 \text{ m}^3/\text{m}$ of sand is carried onshore); onshore bar migration is promoted by bores produced after wave breaking, which are especially effective during low tide conditions with water depths of about 1 m; beach is almost stable;
- 12–19 Nov. (post-storm period): no significant changes.

Overall, it can be concluded that the net changes at the inner bar and at the beach are relatively small, considering the severe wave conditions during the period of about 4 weeks (five major storms with offshore wave heights up to 5 m). The largest changes can be observed at the outer bar.

4.2. Selected events and model settings

Six hydrodynamic events (Burst 9402, 9412, 9416, 9424, 9431 of storm period and Burst 9525 of post-storm period) have been selected for model comparisons (see Van Rijn, 2001). Two typical hydrodynamic events of the storm period with a relatively large wave angle (24° to shore normal) and a relatively small wave angle (3°) are shown herein. The characteristics of these two events are:

- *Burst 9416*: 28-10-98 08:00–09:00; flood case, $H_{s,\text{offshore}} = 3.16$ m, $T_p = 8.3$ s, angle = 24° from the southwest quadrant, water level elevation of +1.4 m, longshore velocity to the north;

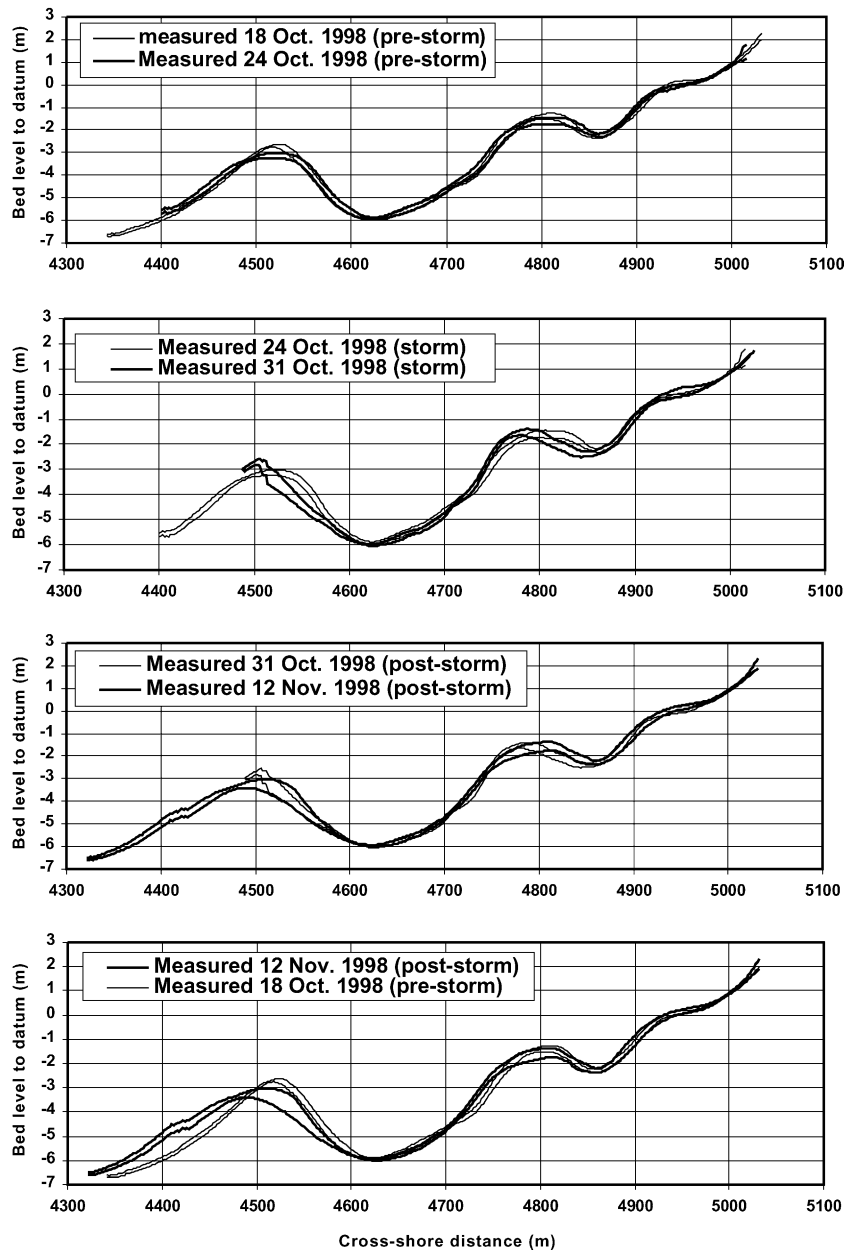


Fig. 4.3. Morphological changes (in m below NAP-datum) of the longshore-averaged bed profiles represented by variation bands (standard error bands).

- *Burst 9431*: 28-10-98 23:00–24:00; flood case, $H_{s, \text{offshore}} = 4.55$ m, $T_p = 8.3$ s, angle = 3° , waves almost perpendicular to the shoreline, water elevation +1.6 m, longshore velocity to the north.

Three morphodynamic periods have been selected for model comparison, as follows:

- Pre-storm period 18 to 24 Oct. 1998 (Bursts 9168–9312);

- Storm period 24 to 31 Oct. 1998 (Bursts 9312–9480);
- Post-storm period 31 Oct. to 12 Nov. 1998 (Bursts 9480–9768).

Several sensitivity runs and calibration runs have been made to account for the variation of input conditions, bed roughness and model coefficients, focussing on the morphodynamic results for the three periods (Pre-storm, Storm and Post-storm). The model settings giving the best BSS values (best run) for all three morphodynamic runs, have been defined as the best settings (model parameters and input data; see Table 4.1). The same settings have also been used to compute the RMAE for the time series of wave height, longshore velocities and cross-shore velocities between 26 Oct., 23 h and 28 Oct., 23 h 1998 (storm period).

4.3. Modelling results of UNIBEST, COSMOS, CROSMOR, BEACH and CIIRC models

4.3.1. Hydrodynamic results

The computed hydrodynamic results for two events, based on the best run, are shown in Figs. 4.4 and 4.5. RMAE-values (average values per zone) are given in Fig. 4.6. All hydrodynamic runs were done by using the individual measured profiles (closest to the date of the event considered) of the measurement transect.

These figures show computed and measured significant wave heights, longshore current velocities, cross-shore current velocities and significant peak orbital velocities. As most of the models compute the rms-value of the wave height, this value has been multiplied by $\sqrt{2}$, assuming a Rayleigh-type wave distribution. Analysis of field data at Egmond shows that the ratio H_s/H_{rms} roughly is 1.35 for breaking waves in the surf zone, which is close to the Rayleigh-related value ($\sqrt{2}$). The computed current velocities are depth-averaged values, whereas the measured velocities are local values at about 1 m above the bed in most cases. The significant peak orbital velocity near the bed has only been computed by the model of UU.

The computed results can be summarised as follows.

4.3.1.1. Wave height.

- The wave heights seaward of the surf zone show differences up to 2 m, due to differences in bed roughness;
- the computed wave heights at the outer bar are reasonably close (within 0.4 m) and show good agreement with measured values (Figs. 4.4 and 4.5); the model results generally are good to excellent;
- the computed wave heights of the DH, UU, and UL models at the inner bar are reasonably close together (within 0.5 m); the model results generally are excellent (1A) to reasonable (1D); the least satisfactory results are obtained for Station 1D on the landward flank of the inner bar, where waves are reforming; the wave height in this latter station is over-predicted by most models; the computed wave heights of the models of HR and UC are systematically too large (20% to 30%);

4.3.1.2. Longshore velocity.

- The type of applied boundary condition (tidal velocity, no tidal velocity or water surface slope) has a strong effect on the computed longshore velocities seaward of the outer bar;
- the computed longshore velocities at the *outer bar* show a large variability; the largest difference between the model results including tidal velocities is about 0.8 m/s (Fig. 4.4);
- the models of HR and UC yield peak values at the seaward flank of the *outer bar* (Fig. 4.4), where the waves are breaking (no breaker delay effects; no spatial lag between point of breaking and point of maximum longshore current), which is in reasonably good agreement with measured results; the model results of HR and UC generally are reasonable to good in this zone; the models of DH and UU produce peak values at the bar crest or just landward of the bar crest due the modelling of breaker delay effects; the inclusion of breaker delay effects yields less good results; the results of DH and UU are poor to reasonable;
- the model results of UL are poor to bad (based on RMAE-values) in this zone (Fig. 4.4);

Table 4.1
Summary of calibration parameters

Calibration parameters	DH	HR	UU	UC	UL
Wave breaking model	γ -parameter of B-J method (γ in range 0.6 to 0.7); Parameters of roller model	None; default values of B-J method (γ in range of 0.7 to 0.85); No roller model	None; default values (γ in range of 0.45 to 1); Parameters of roller model (not used)	Calibrated α (1 to 1.5) and γ (0.55 to 0.75) parameters of B-J method; Default values for roller model	Calibrated γ -parameter (0.5–0.8; height/depth breaker criterion); Default values for roller model
Bed roughness for wave model	Friction factor $f_w = 0.01$	Offshore ripple height $k_s = 0.056$ m	$k_s = 0.01$ to 0.05 m (varying)	Grain roughness to 0.01 m (varying)	Grain roughness $6d_{50}$
Longshore current at seaward boundary	Computed from measured longshore surface slope	Tidal velocity derived from measured values in Station 18B	Tidal velocity derived from measured values in Station 18B	No tidal velocity.	No tidal velocity
Longshore current model	No calibrated coefficients; No horizontal viscosity coefficient	Calibrated smoothing parameter; No horizontal viscosity coefficient	Calibrated horizontal mixing coefficient (0.5 to 2 m ² /s)	Calibrated horizontal mixing coefficient (0.5 to 0.9 m ² /s)	No horizontal viscosity coefficient
Cross-shore current model	No calibrated coefficients	No calibrated coefficients	No calibrated coefficients	No calibrated coefficients	No calibrated coefficients
Bed roughness for currents	$k_s = 0.03$ m	Offshore ripple height $k_s = 0.056$ m	$k_s = 0.01$ to 0.05 m (varying)	Grain roughness to 0.01 m (varying)	Grain roughness $6d_{50}$
Coefficients of current-related sand transport model	Default values; Van Rijn method	Default values; Bailard–Bagnold method	One coefficient calibrated: Van Rijn method (0.5)	One coefficient calibrated, $A_c = 0.1$; Watanabe method	Not used
Coefficients of wave-related sand transport	Default values; Van Rijn method	Default values; Bailard–Bagnold method	One coefficient calibrated: Van Rijn method (0.5)	One coefficient calibrated, $A_w = 0.2$; Watanabe method	Two coefficients calibrated; $A_w = 0.15$; (default = 0.15); $A_{w,br} = 0.02$; (default = 0.03) Watanabe method and smoothing
Bed roughness for sand transport model	$k_{s,w} = 0.01$ m, $k_{s,c} = 0.03$ m	Offshore ripple height $k_s = 0.056$ m	$k_s = 0.01$ to 0.05 m (varying)	Grain roughness to 0.01 m (varying)	Not used

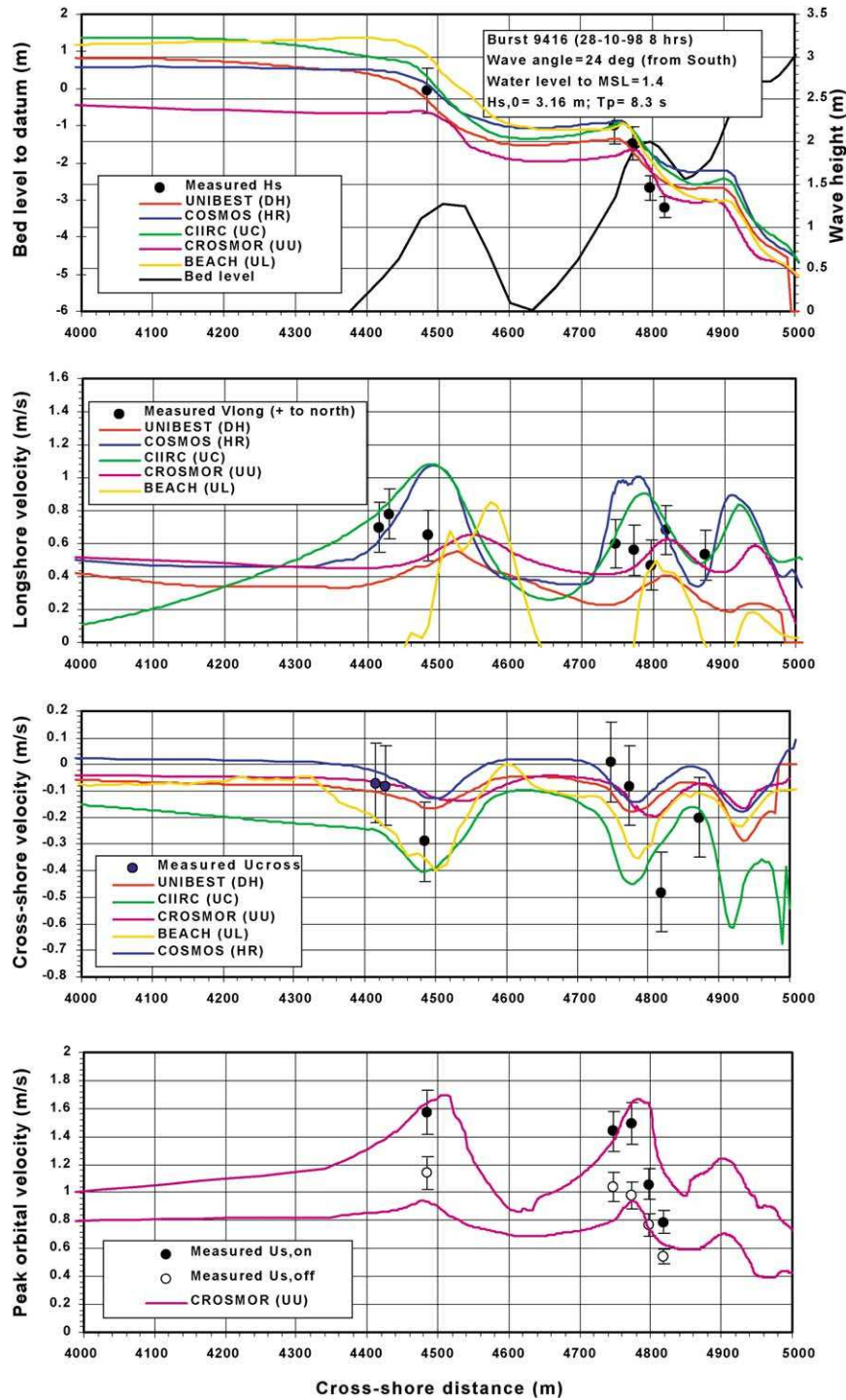


Fig. 4.4. Computed and measured significant wave heights, longshore current velocities, cross-shore current velocities and peak orbital velocities, Burst 9416 (28 Oct., 8 h).

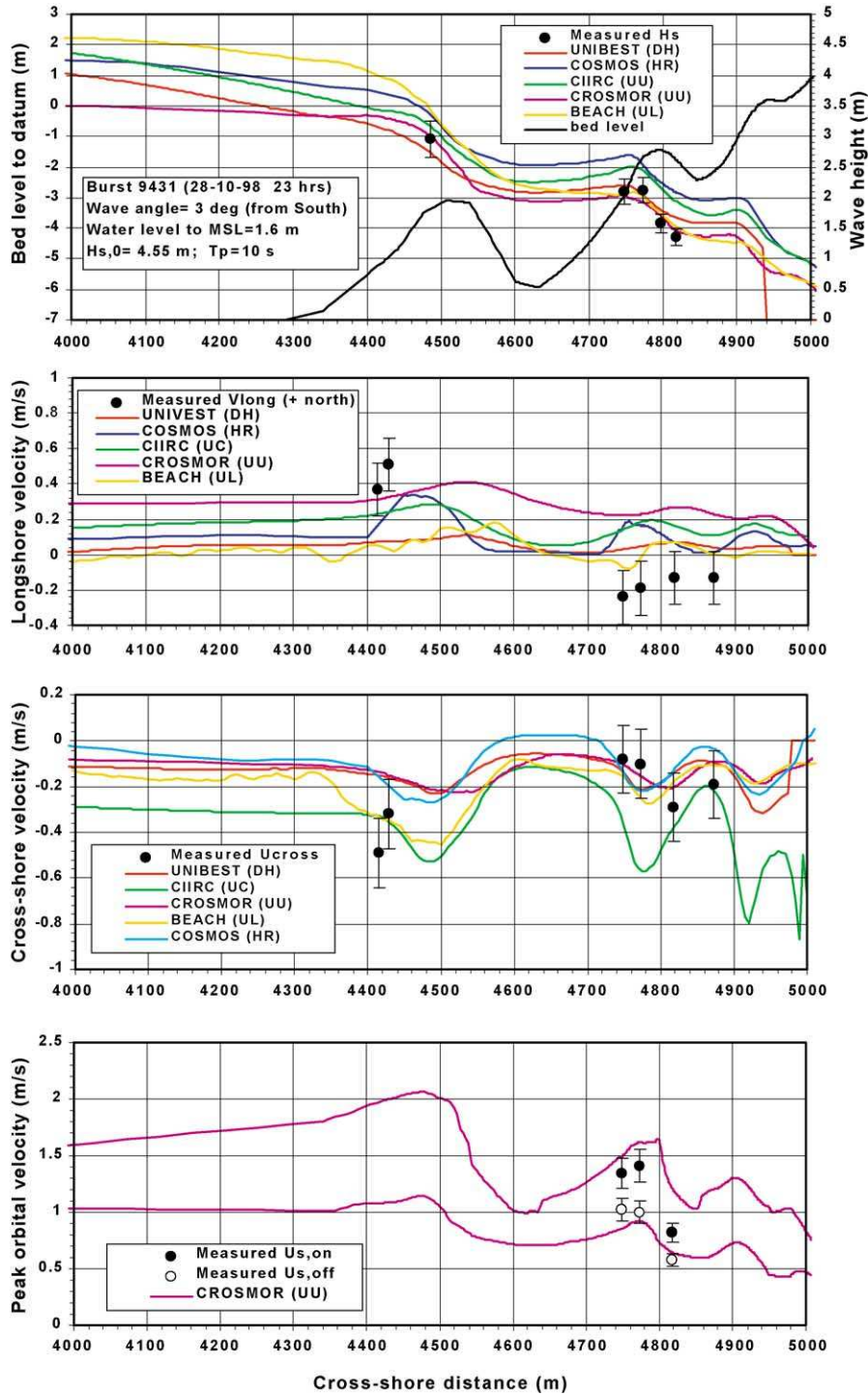


Fig. 4.5. Computed and measured significant wave heights, longshore current velocities, cross-shore current velocities and peak orbital velocities, Burst 9431 (28 Oct., 23 h).

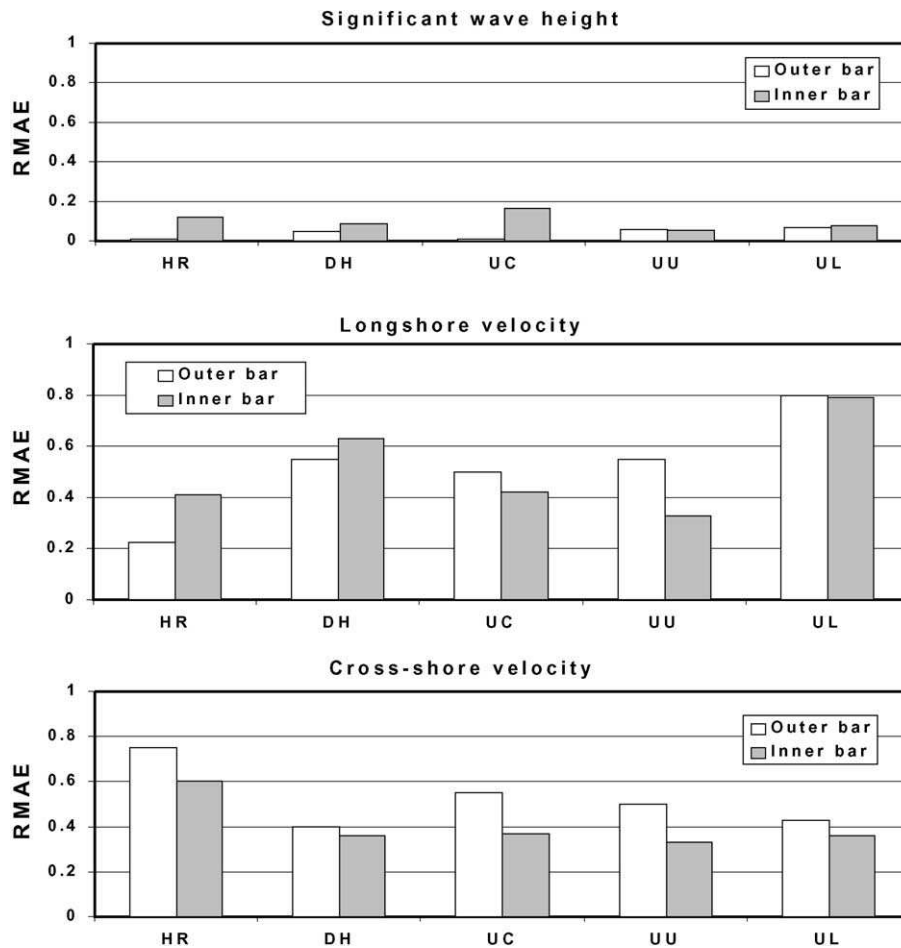


Fig. 4.6. Statistics (RMAE) for wave height, longshore velocity and cross-shore velocity.

- the computed longshore velocities at the *inner bar* also show a large variability; the largest difference between the model results is about 0.8 m/s; the HR and UC models (no breaker delay effects included) show peak values at the seaward flank of the bar in agreement with the measured data (Fig. 4.4); the peak values of the HR and UC models show reasonable to good agreement for the storm events; the peak values of the HR model are somewhat over-predicted; the DH and UU models show a more gradual behaviour with peak values at the landward flank of the inner bar; the peak values of the DH and UU models are somewhat under-predicted for most events; the model results of DH are poor to reasonable in this zone, whereas the model results of UU are reasonable to good; the

computed longshore velocities of the UL model generally are too small; model results are reasonable (1C, 1D) to poor (1B) and bad (1A);

- generally, most models produce reasonable results in the surf zone for incident wave angles (to shore normal) larger than 5° ; the computed longshore velocities deviate substantially from measured values for incident angles smaller than 5° (Burst 9431, Fig. 4.5);

4.3.1.3. Cross-shore velocities.

- The models produce velocities in the range of 0 to -0.1 m/s seaward of the surf zone; the computed velocities of the DH, UU, and UL models are

reasonably close together at the seaward flank of outer bar (Figs. 4.4 and 4.5); the model of UC yields substantially larger offshore-directed velocities up to -0.3 m/s;

- most models yield offshore-directed velocities in the range of -0.1 to -0.25 m/s at the *outer bar* in reasonable agreement with measured values during minor storm events; onshore-directed velocities are also present, but the models (except the model of HR) cannot predict onshore-directed velocities; the relatively large offshore-directed velocities (up to -0.6 m/s) just seaward of the outer bar crest during storm events are considerably under-predicted by the models of DH, UU and HR; the model results generally are poor to reasonable in this zone; the models of UL and UC produce peak velocities (about -0.2 to -0.4 m/s) in agreement with measured values; the model results are good during storm events; the measured data have a less peaked distribution than the model results; the model of HR yields a small onshore-directed velocity;
- most models yield offshore-directed velocities in the range of -0.1 to -0.25 m/s at the *inner bar* in reasonable agreement with measured values during minor storm events; the relatively large offshore-directed velocities (up to -0.5 m/s in Station 1C) at the bar crest during storm events are considerably under-predicted by all models except the model of UC; the model results generally are very variable from bad in one station to good in another station; the model results of UU, yielding reasonable agreement for all stations, are most consistent in this zone;
- offshore-directed rip currents due to circulation effects (rips) have been observed during post-storm events with relatively low waves; the profile models do not include these effects.

4.3.1.4. Morphodynamic results. Fig. 4.7 shows measured and computed bed profiles for the storm period between 24 and 31 Oct. 1998. The measured bed profiles are represented as variation bands based on longshore averaging. The computed bed profiles represent the results of the single best run of each model, using the best settings derived from the hydrodynamic simulations. All three morphodynamic sim-

ulations are based on only one setting of model coefficients without additional calibration. The statistic Brier Skill Scores (BSS) are shown in Fig. 4.8 for the three defined cross-shore zones: outer bar ($4450 < x < 4660$ m), inner bar ($4660 < x < 4870$ m) and beach ($4870 < x < 5000$ m). It is noted that the beach zone herein represents the foreshore only.

The results can be summarised as follows:

- all models predict minor erosion at outer bar crest and minor deposition of sand at seaward flank of outer bar; net offshore migration of the outer bar is predicted in agreement with measured values;
- all models yield slight erosion at inner bar crest and deposition at seaward flank of inner bar; net offshore migration of the outer bar is predicted in agreement with measured values;
- models of UU and HR predict minor changes for the beach zone in agreement with the measured values; model of DH yields relatively large deposition around -1 m depth contour; model of UC seems to smooth out the bed profile in the beach zone.

As regards the Pre and Post-storm periods, all models predict minor changes at the outer and inner bar crests in agreement with observed values; the models of UU and HR predict minor changes for the beach zone in agreement with the measured values; the model of DH yields relatively large deposition around -1 m depth contour; model of UC seems to smooth out the bed profile in the beach zone.

4.4. Discussion and conclusions

Overall, it can be concluded that most models produce reasonably good results for wave height ($\text{RMAE} < 0.1$) and reasonable results for longshore current velocity ($\text{RMAE} < 0.4$) after proper calibration of key parameters and coefficients. None of the models can represent the relatively large reduction in wave height across the inner bar completely, but the probabilistic UU model performs best in this zone (good to excellent results for all stations), probably due to the use of a locally varying wave breaking parameter (being a function of local wave steepness and local bed slope). The probabilistic UU model yields excellent results for the significant wave height

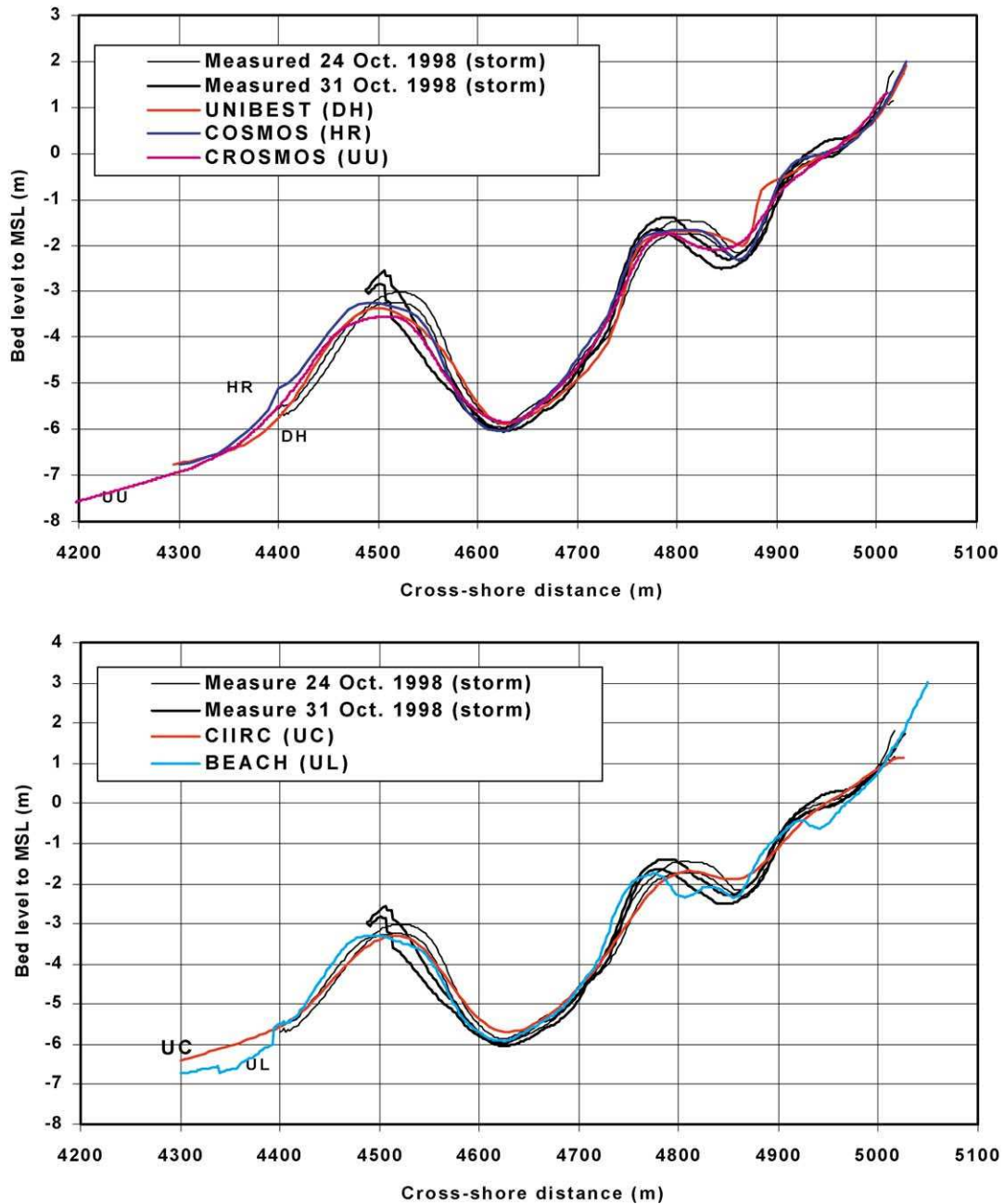


Fig. 4.7. Computed and measured bed profiles, Storm period. Top: Models of DH, HR and UU. Bottom: Models of UC and UL.

H_s , but the H_{rms} -values were over-predicted systematically by 10% to 15%. The H_s/H_{rms} ratio of the model results were around 1.25 for the surf zone, whereas the measured values were 1.35 close to the

Rayleigh-related value of 1.41 (Van Rijn, 2000a). However, analysis of the field data shows that the wave height distribution was bimodal rather than Rayleigh-distributed.

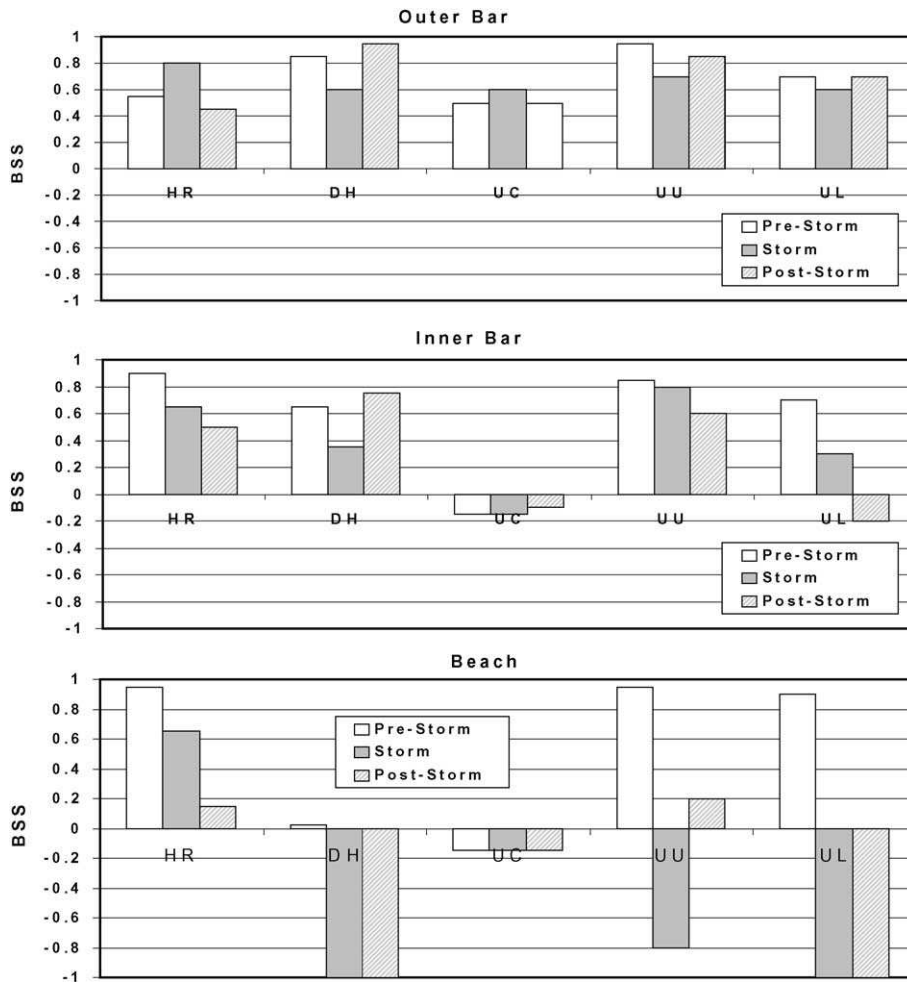


Fig. 4.8. BSS values for three cross-shore zones: outer bar, inner bar and beach.

Most models produce reasonable results for the longshore current velocity distribution in the surf zone. The modelling of tidal velocities is not so important for the surf zone during storm conditions, when the wind- and wave-induced effects are dominating. The bed roughness was found to have a significant effect on the computed longshore velocities seaward of the surf zone. The horizontal viscosity coefficient did not have a significant effect on the computed velocities.

The cross-shore undertow velocities can be predicted at a reasonable level of accuracy ($RMAE < 0.4$), but the offshore-directed velocities of the observed peak currents (up to -0.6 m/s) are under-predicted by most models. Offshore-directed current velocities

near the bed of about -0.6 m/s suggest the presence of rip currents, but it is very unlikely that cross-rips can prevail in the presence of relatively large longshore currents up to 1.3 m/s during storm events. The relatively large offshore-directed velocities of about -0.6 m/s during storm events are most probably related to local wave breaking in combination with return flow due to storm set-up (about 1.5 m during major storms). Results of Area models (Van Rijn, 2000a) show that circulation cell effects are absent during storm events, but these circulation effects are rather pronounced at depressions in the inner bar during low tide (ebb) in combination with low-wave energy conditions (offshore wave heights of 1 to 2 m).

Most Profile models (DH, HR, UC) contain some site-specific model coefficients which need proper calibration, in particular the wave breaking model should be based on a varying breaking coefficient dependent on local wave steepness and local bottom slope (as applied in the UU model). Most longshore current models produce reasonable results after proper calibration of the bed roughness; some models require calibration of specific parameters (smoothing length scale by HR; horizontal mixing coefficient by UC). Especially, the smoothing length scale applied by HR may be strongly site-specific.

As regards the morphology, it can be concluded that the models can simulate the offshore migrational behaviour of the outer bar during storm events quite well (BSS values of 0.4 to 0.9). The simulation of the inner bar behaviour during storms is reasonable for most models (BSS values between 0.4 and 0.8); but the beach zone cannot be simulated with great accuracy due to the dominant effect of three-dimensional phenomena in this nearshore zone. The model of HR performs relatively well in this latter zone, but this is partly related to the applied smoothing procedure.

Wave chronology (re-ordering of wave events) was studied by using two extreme cases: a time series with waves of descending wave height and with ascending wave height. The effects on the computed bed profile development after 7 days (24–31 Oct.) were quite small; the bar location and the bar height were more or less the same. Wave chronology does not seem to have a large effect on the storm time scale, probably because the variation of the wave heights within a storm event is not very large.

Finally, it is noted that the net cross-shore bed-level changes (based on the longshore-averaged profiles) at the inner bar and beach zones are quite small, especially for the Pre-storm and Post-storm periods. In fact, the beach and inner bar are quite stable on the time scale of a storm month with five major storms (offshore wave heights up to 5 m) attacking the beach in the Autumn of 1998, which is an amazing result. The alongshore changes were often much larger than the cross-shore changes (based on longshore-averaged profiles); at some transects the overall beach face level was about 0.3 m lower or higher due to the presence of alongshore sand waves. Furthermore, the inner bar was dissected by a rip channel (local depression of

about 0.5 to 1 m), which moved up and down the shore over a length of about 100 m during the storm period. As the simulation of these small natural (autonomous) changes is extremely difficult, the performance of the profile models for the outer and inner bar zones is rather encouraging. The prediction of the relatively small cross-shore changes in the beach zone seems to be a ‘beach too far’ for most models. However, it is encouraging that most models (except UL and UC) also yield relatively small beach changes but mostly not at the right locations, yielding relatively large negative BSS-values. It would have been much worse, if the models had predicted relatively large beach changes in response to the major storm events.

5. Modelling of morphodynamics at Egmond site on seasonal time scale

5.1. Boundary conditions and observed phenomena

The COAST3D Season Experiment at the Egmond beach (The Netherlands) was focussed on the seasonal behaviour (18-month period; summer, winter and summer) of the morphology in the area concerned.

The morphodynamic periods considered are:

- 11 May 1998 to 24 Oct. 1998 (summer period 1998);
- 24 Oct. 1998 to 25 Feb. 1999 (winter period 1998–1999);
- 25 Feb. 1999 to 14 Sep. 1999 (summer period 1999).

The winter period is dominated by 11 moderate storms ($H_{s, \text{offshore}} = 3\text{--}4$ m) and five major storms (>4 m) in combination with storm surge levels of 2 to 3 m above MSL. The cross-shore bed profiles based on longshore averaging of 6 to 10 transects with spacing of 100 m are shown in Fig. 5.1. The sections are defined as: outer bar ($325 < x < 600$ m), inner bar ($100 < x < 325$ m) and beach ($-20 < x < 100$ m).

The basic patterns are offshore migration of the bars with subsequent offshore sand transport during major storms in the winter period and onshore migration of the bars due to onshore sand transport during moderate storms in the summer periods. Overall, the

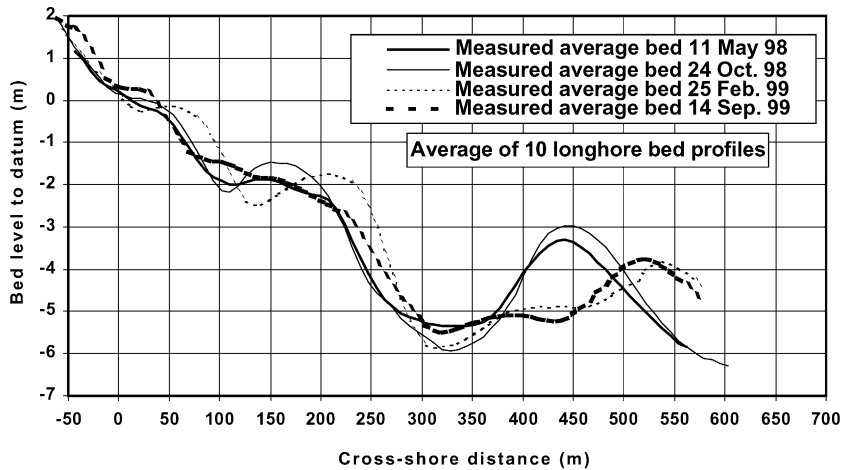


Fig. 5.1. Cross-shore bed profiles on seasonal time scale (based on longshore-averaged profiles).

bed profile changes over the three seasons are quite small in the beach and inner bar zone; the trough level remains quite stable at -5.5 m, but there is a major effect in the outer bar zone with substantial offshore migration of the outer bar in combination with lowering of the bar.

5.2. Modelling results

The UNIBEST and the CROSMOR model have been applied on this seasonal time scale. The other models are typical storm models and did not produce meaningful results on this longer time scale.

The UNIBEST settings are the same as those used in the storm simulations, but an additional morphological calibration has also been used to improve the results (Walstra, 2001). This additional calibration was done by modifying (i) the onshore bed-load transport due to wave asymmetry and (ii) the breaker delay factor. The onshore transport contributions are determined by the velocity moments (central odd velocity moments). Comparison of computed and measured (COAST3D experiment) velocity moments showed that these velocity moments were significantly over-predicted by the model in the surf zone. Due to overprediction of the asymmetry effect, the onshore bed-load transport rates were much too large. This was taken into account by reducing the onshore bed-load component through a constant factor (0.35). In this way, the model results were tuned to achieve

better agreement between the measured and predicted bed profiles.

The settings of CROSMOR model are similar to those of the storm simulations (Section 4). Runs have been made for all three periods. Additional sensitivity runs have been made by tuning the undertow velocity (delay factor) to obtain better agreement with the measured cross-shore bed profiles. The undertow was modified by using spatial averaging (cross-shore). The best results were obtained for a spatial averaging over $5L$ with L =local wave length. This means that the undertow at a certain location is averaged over a cross-shore distance of $5L$ seaward of that location, resulting in a delayed response of the undertow and hence transport rate in relation to the local wave height. Without spatial averaging, the undertow and transport rate in the model are directly related to the local wave height. The computed bed profiles based on the default run (without additional calibration) and the best tuned run of both models are shown in Fig. 5.2. The BSS values are given in Table 5.1.

Analysis of the results show that there is tendency for flattening of the inner and outer bars on the seasonal time scale, using the default settings. The flattening process proceeds relatively fast in the inner bar zone, because this inner bar is much smaller (volume of about 100 to 150 m^3/m) than the outer bar (volume of about 400 m^3/m). During low wave conditions (wave height between 1 and 2 m) the transport at the inner bar crest is onshore-directed

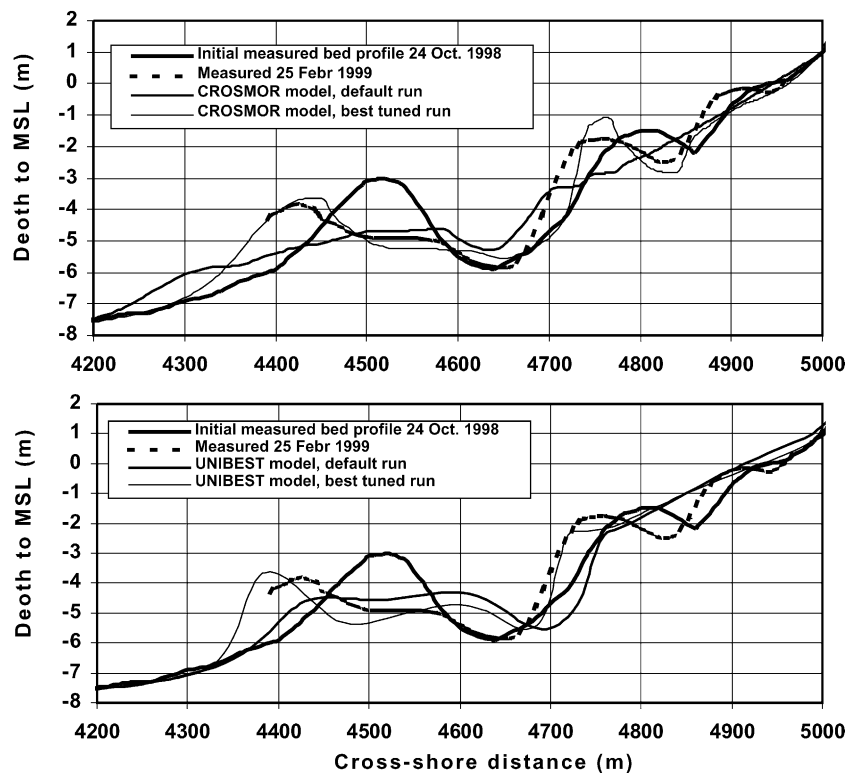


Fig. 5.2. Seasonal morphology at Egmond site; Winter period of 24 Oct. 98–25 Feb. 1999 (cross-shore coordinates with respect to offshore wave station).

and of the order of $1 \text{ m}^3/\text{m}/\text{day}$. Due to this onshore transport process related to the wave asymmetry, the inner bar is eroded and flattened on a time scale of the order of 3 months. The tendency for flattening due to erosional processes can also be observed from the field data during the last summer period (Fig. 5.1).

The process of the systematic bar flattening on longer time scales is strongly related to the direct

response of the hydrodynamics (breaking waves and undertow) and corresponding sand transport to the bar form resulting in maximum transport at the bar crest and maximum erosion and deposition in the direct vicinity of the crest. The research on stability of bars (see, for example, Hulscher, 1996) has clearly shown that phase lags between hydrodynamics, sand transport and the bar form is essential for bar growth and

Table 5.1

Brier Skill Scores for seasonal morphology; first value based on default settings; second value based on tuned settings

Section	UNIBEST				CROSMOR		
	Summer 98: 11 May 98 to 24 Oct. 98	Winter 98–99: 24 Oct. 98–25 Feb. 99	Summer 99: 25 Feb. to 14 Sep. 99	Total period: 11 May 98 to 14 Sep. 99	Summer 98: 11 May 98 to 24 Oct. 98	Winter 98–99: 24 Oct. 98 to 25 Feb. 99	Summer 99: 25 Feb. to 14 Sep. 99
Outer bar ($4365 < x < 4640$)	<0; <0	0.7; 0.9	0.0; 0.9	0.2; 0.9	<0; <0	0.7; 0.9	0.5; 0.4
Inner bar ($4640 < x < 4865$)	<0; <0	<0; 0.6	0.9; 0.9	<0; <0	<0; 0	0.4; 0.5	0.3; 0.3
Beach ($4865 < x < 4985$)	<0; <0	0.6; 0.9	0.7; 0.5	<0; <0	0; <0	0.6; 0.4	0.6; 0.6

migration; bars can only grow and migrate if there is a distinct phase shift between the peak of the transport distribution and the bar crest (non-local response). This was also demonstrated by Roelvink et al. (1995), who showed that the behaviour of breaker bars in the surf zone strongly depends on the delayed response length of the wave breaking process and the effect of bottom slope on sand transport.

Analysis of the results shows that bars are eroded and moved in offshore direction by storm waves, whereas the bars are flattened and moved in onshore direction by fair weather waves. Fair weather waves are essential for damping of the outer bar at the edge of the surf zone. This means that the complete wave climate with storm and fair weather waves should be used for realistic simulations. Correct modelling of the bar migration cycle requires the proper percentages of high and low wave conditions; a schematised storm simulation is not sufficient. The effect of wave chronology (re-ordering of wave events; see also Southgate, 1995; Aarninkhof et al., 1998) was studied by using two extreme cases for the period 24 Oct. 1998–25 Feb. 1999: a time series with waves of descending wave height and with ascending wave height (CROSS-MOR model; Grasmeijer, 2002). The coupling between tide level and wave height was kept in tact. The effects on the computed bed profile development after about 4 months were quite small; the bar location and the bar height were more or less the same. The intermediate results were, however, strongly related to the wave schematization, but not the end result after 4 months as long as the percentages of time periods with high and low waves are correct and the tide and surge levels are coupled in the right way to the wave heights.

The importance of delay effects stresses the proper simulation of the suspended transport processes. The adjustment of the suspended transport processes around the bar crests may proceed over relatively large distances (a few wave lengths or about 50 to 100 times the water depth) as indicated by the required spatial averaging length scale of $5L$ in the model computations. Van Rijn (1993, Fig. 10.3.1) has shown that the adjustment length scale of the suspended transport rate can be rather large. The implementation of an advection–diffusion scheme for the modelling of the spatial variations of the suspended sediments may be a basic requirement for realistic

modelling of bar migration in the surf zone (see work of Katapodi and Kitou, 1995). Overall, it can be concluded that only two models are able to simulate the offshore migrational behaviour of the outer bar on the seasonal time scale (many storms). Furthermore, these two models have been tuned considerably by modifying the model settings to obtain meaningful results. The vertical bar growth during the summer 98 period cannot be simulated by the present models. The simulation of the inner bar behaviour on the seasonal time scale is problematic; the models often produce a flattened and smoothed profile on this time scale, because the basic bar generation and development mechanisms are absent. This exercise very well demonstrates that we are still far away from adequate nearshore morphological modelling on the seasonal time scale. It is realized that the present tuning is a rather crude first approach to identify the basic effects. Further research using more refined 3D suspended transport models is required to reveal the basic underlying mechanisms of the delays involved (breaker delay, roller effect, non-local suspended transport).

6. Overall synthesis and conclusions

Deterministic and probabilistic process-based Profile models have been compared with hydrodynamic and morphodynamic data of laboratory and field experiments on the time scale of storms and seasons. The large-scale laboratory experiment is a pure 2D case and offers an ideal test case for cross-shore Profile models, as disturbing alongshore non-uniformities are absent. However, the ultimate objective is the proper simulation of morphodynamic features in field conditions, no matter how difficult this is. Both cases have been studied in the present paper.

6.1. Storm and post-storm time scales

The bed profile evolution with offshore bar migration in 2D storm conditions (large scale laboratory experiment) can be modelled reasonably well by Profile models, provided that the variable bed roughness in the bar trough-crest zone and the high-frequency suspended sand transport are taken into account. The bed profile evolution with onshore bar

migration in 2D post-storm conditions can also be modelled reasonably well by Profile models, provided that the near-bed orbital velocities and the variable bed roughness are represented in a sufficiently accurate way.

Most models produce reasonably good results for wave height and current velocities in 3D field conditions after proper calibration of key parameters and coefficients. None of the models can represent the relatively large reduction in wave height across the inner bar at Egmond completely, but the probabilistic UU model performs best in this zone (good to excellent results for all stations), probably due to the use of a locally varying wave breaking parameter. The probabilistic model yields excellent results for the significant wave height H_s , but the H_{rms} -values were over-predicted systematically (10% to 15%). The measured values of H_s/H_{rms} were about 1.35 close to the Rayleigh-related value of 1.41 (Van Rijn, 2000a). However, analysis of the field data shows that the wave height distribution was bimodal rather than Rayleigh-distributed. More research is necessary to improve the simulation of the wave spectrum in the surf zone with breaking waves.

Most models produce reasonable results for the longshore current velocity distribution in the surf zone at Egmond after proper calibration of the bed roughness; some models require calibration of specific parameters (smoothing length scale by HR; horizontal mixing coefficient by UC). The modelling of tidal velocities is not so important for the surf zone during storm conditions, when the wind- and wave-induced effects are dominating. The bed roughness was found to have a significant effect on the computed longshore velocities seaward of the surf zone. A variable (along the profile) bed roughness was found to be essential in the 2D laboratory conditions with relatively small bars, but not at the field site of Egmond with large bars. The cross-shore mixing effect did not have a significant effect on the computed velocities. The models neglecting the cross-shore mixing effect did not produce less satisfactory results.

The cross-shore undertow velocities can be predicted at a reasonable level of accuracy in field conditions, but the offshore-directed velocities of the observed peak currents (up to -0.6 m/s) are

largely under-predicted. Offshore-directed current velocities near the bed of about -0.6 m/s suggest the presence of rip currents, but it is very unlikely that cross-rips can prevail in the presence of relatively large longshore currents up to 1.3 m/s during storm events. The relatively large offshore-directed velocities of about -0.6 m/s during storm events are most probably related to local wave breaking in combination with return flow due to storm setup (about 1.5 m during major storms). Results of Area models (Van Rijn, 2001) show that circulation cell effects are absent during storm events, but these circulation effects are rather pronounced at depressions (rip channels) in the inner bar during low tide (ebb) in combination with low-wave conditions (offshore wave heights up to 2 m).

As regards the morphodynamics in field conditions, it can be concluded that the models can simulate the offshore migrational behaviour of the outer bar during storm events quite well. The simulation of the inner bar behaviour during storms is reasonable for most models; but the beach zone cannot be simulated with great accuracy due to the dominant effect of three-dimensional phenomena in this zone. It is noted that the observed net cross-shore bed-level changes (based on the longshore-averaged profiles) at the inner bar and beach zones are quite small, especially for the Pre-storm and Post-storm periods. In fact, the beach and inner bar are quite stable on the time scale of a storm month with five major storms (offshore wave heights up to 5 m) attacking the beach in the Autumn of 1998, which is an amazing result. As the simulation of these small natural (autonomous) changes is extremely difficult, the performance of the profile models for the outer and inner bar zone is rather encouraging. The prediction of the relatively small cross-shore changes in the beach zone seems to be a 'beach too far' for most models. However, it is encouraging that most models also yield relatively small beach changes but mostly not at the right locations.

The modelling of low-frequency (lf) wave mechanics does not seem to be very important for the simulation of the inner and outer bar behaviour on the storm time scale, as the models neglecting lf-effects performed reasonably well. This cannot be stated for the beach zone, where lf-effects may be of crucial importance.

6.2. Seasonal time scale

The Profile models using the default settings exhibit the tendency for flattening of the inner and outer bars on the seasonal time scale. The process of systematic bar flattening is strongly related to the direct response of the hydrodynamics (breaking waves and undertow) and corresponding sand transport to the bar form resulting in maximum transport at the bar crest and maximum erosion and deposition in the direct vicinity of the crest. The presence of phase lags between hydrodynamics, sand transport and the bar form is essential for bar growth and migration; bars can only grow and migrate if there is a distinct phase shift between the peak of the transport distribution and the bar crest (non-local response).

The models can only simulate the offshore migrational behaviour of the outer bar on the seasonal time scale (many storms) after sufficient tuning of the model settings. The vertical bar growth during the summer 1998 period cannot be simulated by the present models. The simulation of the inner bar behaviour on the seasonal time scale is problematic; the models often produce a flattened and smoothed profile on this time scale, because the basic bar generation and development mechanisms are absent. Bars are initiated at the lower beach, grow in height and length and migrate intermittently in offshore direction. Fair weather waves are essential for damping of the outer bar at the edge of the surf zone due to onshore transport processes. One of the basic driving mechanisms for the intermittent offshore migration cycle is the spatial phase shift between hydrodynamics, sand transport and bar form. As the models do not sufficiently represent these effects, the modelling of the bar migration over longer seasonal time scales is extremely poor for the inner bar zone and beach, because the errors involved tend to accumulate. Bars are flattened and smoothed out by the models, if the spatial phase shifts are too small or absent. At present, these relatively small phase lags are not known with sufficient accuracy. They can be represented to some extent by tuning from case to case, using measured bed profiles on the relevant time scales. However, this empirical approach will reduce the generality and predictive capabilities of process-based models, while measured profile data should be available for tuning. Furthermore, it is questionable whether this type of

calibration can be successfully applied in a sand transport capacity model, which does not include the phase lags of the suspended transport, which is the dominant transport mode in the surf zone. The implementation of an advection–diffusion for the modelling of the spatial variations of the suspended sediments may be a basic requirement for realistic modelling of bar migration in the surf zone.

6.3. Overall conclusions

Based on the present findings, the following overall conclusions are presented:

- Profile models can quite accurately (errors smaller than 10%) represent the cross-shore significant wave height distribution in the surf zone, if the wave breaking model is properly calibrated; errors are relatively large (up to 15%) in the zone of reforming waves landward of the inner bar crest; the wave breaking coefficient should be a function of local wave steepness and bottom slope for most accurate results.
- Profile models can quite reasonably represent the cross-shore currents (undertow) in a pure 2D case; Profile models can reasonably simulate the longshore and cross-shore currents in 3D field conditions with relative accuracies of 30% to 50%; the inaccuracies in 3D field conditions are much larger than in a pure 2D case due to the presence of 3D effects (rip currents; storm-induced return flows); Profile models including cross-shore mixing effects and breaker delay effects do not produce better results of the longshore and cross-shore current velocities.
- Profile models showing reasonably good results for hydrodynamics do not automatically yield good results for morphodynamics; often additional calibration using measured bed profile changes is required to obtain good morphodynamic results on the seasonal time scale; the calibration coefficients involved are highly empirical and not yet proven to be site-independent.
- Profile models using default settings can quite reasonably simulate the behaviour of the outer and inner bars on the storm time scale; the behaviour of the beach cannot be modelled with sufficient accuracy on the storm time scale.

- Profile models can reasonably simulate the 2D post-storm onshore bar migration, provided that the near-bed orbital velocities and wave asymmetry-related sand transport are represented in a sufficiently accurate way (using non-linear wave theories).
- Profile models cannot simulate the 3D beach recovery processes on the post-storm time scale, because these essentially 3D processes are not sufficiently known to be included in the models.
- Profile models using default settings cannot simulate the behaviour of the outer and inner bars and the beach on the seasonal time scale; the behaviour of the outer bar on the seasonal time scale can only be represented properly after tuning using measured bed profiles. The simulation of the inner bar and beach morphology on the seasonal time scale could not be improved by tuning. The tuning coefficients are highly empirical.

6.4. Consequences for predictability

What are the consequences of these conclusions for the predictability of morphological processes in the three characteristic zones (outer bar, inner bar and beach/foreshore zone)?

Overall, it can be concluded that Profile models can be used to simulate the behaviour of the outer bar system on the time scale of storms and seasons. This encouraging result offers a good opportunity to study the storm and seasonal behaviour of shoreface nourishments (feeder berms), which are most often situated in the outer bar region for practical reasons (draft of dredgers). The forced behaviour of a relatively large sand nourishment in the outer bar zone may be considerably less difficult to model than the natural (autonomous) behaviour of the inner bar, which is dominated by small residual transport processes (delicate balance of onshore and offshore transport components; see Van Rijn, 1997b). The simulation of the inner bar behaviour on the storm time scale and seasonal time scale is rather problematic due to the presence of 3D effects (rip currents, etc.). At present stage of research, the behaviour of the inner bar system cannot be simulated with sufficient accuracy on the seasonal time scale. The predictability of the inner bar will however increase for increasing time scales (5 to 10 years), because the net bar migration

will increase. Modelling of the bar system on the decadal time scale has hardly been performed. A first approach has been made by Roelvink et al. (1995) simulating the cyclic bar behaviour (excluding the beach zone) at the barrier island coast of Terschelling (The Netherlands). Morphodynamic calibration focusing on the breaker delay effects and the bar slope terms of the sand transport model appeared to be of vital importance. Much more research is required to improve on this (including the chronology of wave events).

The time scale of predictability of the bar system may be strongly related to the effect of forcing chronology (sequencing of stochastic hydrodynamic forcing events) on profile evolution, because the morphodynamics involved is a strongly non-linear process. In general, it can be said that the larger the effect of forcing chronology on morphological response (bar behaviour, shoreline change), the smaller is the time scale of predictability. For example, if re-ordering of wave events within a wave record of 1 year has a relatively large effect on predicted bar behaviour over 1 year, then the time scale of predictability will be considerably shorter (say, 1 month). The available results show that the height of the bars is dominated by wave chronology on the decadal time scale (Aarninkhof et al., 1998), but not so much on the seasonal and storm time scales (this study and Southgate, 1995). The bar location was not much influenced by wave chronology.

The Profile models are not yet suitable for detailed modelling of the beach (foreshore) and dune zones at the end of the profile on the seasonal time scale. These complex zones are dominated by the tide and storm surge levels, low-frequency and wave runup phenomena and 3D morphology (cusps, swash bars, ridge-runnel systems, alongshore sand waves). Variability is relatively large and hence morphodynamic predictability is relatively low, because accurate predictions of the relatively small residual transport rates are difficult and low-frequency phenomena are largely neglected by most Profile models. At present stage of research, the accurate prediction of the precise profile development to derive beach levels and widths is a “bridge too far” for the Profile models on the seasonal time scale. Simple longshore averaging of the profiles cannot eliminate the effect of circulation (rip currents) in the beach zone (forshore); hence, the

2D approach of Profile models fails in this zone. Basically, a 3D modelling approach is required to deal with the complicated phenomena in the inner bar and beach zones. These types of models are already explored (Walstra et al., 2000), but morphological computations are not yet feasible. It should be realized, however, that the modelling of small residual transport processes as present in natural situations close to equilibrium is inherently difficult and perhaps impossible. Errors will accumulate leading to large deviations increasing with time and ultimately to model failure. At present stage of research, it may be well concluded that the prediction of the precise bed evolution in the inner surf and beach zone is not feasible, no matter what type of model is used. The only solution here is to focus on the prediction of bulk volumes integrated over larger space and time scales rather than on the prediction of precise bed levels. Hindcast studies of dune erosion assuming the storm surge level to be known, have shown that dune erosion as a bulk volume can be simulated quite well on the storm time scale (Steetzel, 1993). From a predictive point of view, the models may then be used to evaluate worst-case scenarios for assumed storm surge levels.

A similar approach should be feasible for beach nourishment, focussing on the behaviour of bulk volumes (averaged over sufficient alongshore distance of about 1 to 2 km) rather than on precise beach profile development. Studies on beach nourishment using process-based Profile models have not been performed in great detail and are highly recommended to reduce the empiricism of beach nourishment design.

The application of 2D Profile models to field data is not straightforward. The application of Profile models to a coastal system is based on the assumption of alongshore uniformity of the bar system (two-dimensional onshore–offshore behaviour). The short-term Egmond bathymetry data clearly shows that these assumptions are severely violated; individual cross-shore profiles do not show an alongshore uniform behaviour. The effects of longshore variability can to some extent be taken into account by longshore averaging of individual transects resulting in a longshore-averaged profile and a variation (standard error) band. Bed level changes at two different dates are only significant in zones where there is no overlap of the error bands. The longshore averaging

distance should be so large that the longshore rhythmicity including rip channels is fully covered. This method works well for the outer bar zone, but more studies are required for the inner bar and beach (foreshore) zone.

Finally, some suggestions for future research on Profile models are presented. This should be focussed on the: effect of spatially varying bed roughness (bed-roughness predictor); undertow in storm conditions (vertical structure, roller contribution, storm setup-related return flow); inclusion of overall rip current effect on profile evolution; inclusion of beach, swash processes and cliff-type erosion processes to better model beach and dune erosion, and inclusion of non-local suspended sand transport processes (lag effects) by solving the 2DV mass balance equation for the suspended sediments. Field work on suspended sand transport in the surf zone under storm conditions is highly recommended as one the most basic research topics of direct interest for modelling of sand transport and associated morphology.

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