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Modelling of Coastal Evolution on Yearly to Decadal Time Scales

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ABSTRACT

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There is still no universal model for analysing and predicting coastal evolution and its governing processes on yearly to decadal time scales. Instead, depending on the nature of the problem and project objectives, there is a wide range of models available, each focusing on the problem complex from a specific standpoint. The present paper gives an overview of available numerical model types. A differentiation is made between equilibrium and non-equilibrium model types as well as between longshore uniform and non-longshore uniform model types. These models are discussed in terms of their general assumptions, approaches, and applicability. Most of the model descriptions are supplemented by an illustrative example. In addition, generic issues, such as level of knowledge on different scales, selection of model type on the basis of the nature of the application, the concept of equilibrium, model validation and utilisation are discussed.

ADDITIONAL INDEX WORDS: *Equilibrium, chronology, shoreline evolution, profile evolution.*

INTRODUCTION

The scales of primary concern to coastal planners and managers are time frames of years to decades, longshore length scales of 10's–100's of kilometers, and cross-shore length scales of 1–10's of kilometers. Within coastal zone management, prediction of coastal evolution with numerical models has proven to be a powerful technique to assist in the understanding of processes involved and, in the case of necessary interventions, selection of the most appropriate project design. Models provide a framework for organizing the collection and analysis of data and for evaluating alternative future scenarios of coastal evolution. In situations where engineering activities are involved, models are preferably used in developing problem formulation and solution statements, and, importantly, for efficiently evaluating alternative designs and optimizing the selected design.

The objective of this paper is to discuss different types of numerical models for yearly to decadal modelling of coastal evolution, including under what circumstances they should be used and their capabilities and limitations. Emphasis is given to model *types* rather than to individual models. The use of each type of model is illustrated by a small example.

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COASTAL SCHEMATIZATION AND OUTLINE OF MODELING APPROACHES

Scale Levels

There is a growing awareness that changes in coastal systems are forced by large-scale processes and are realized over relatively long (decadal) time scales. These changes have both natural and anthropogenic causes, *e.g.,* erosion caused by sea level rise or changing supply and transport patterns of sediment caused by large coastal engineering projects. These changes highlight the importance of adequate quantitative tools to analyse and predict changes at these scales. A short-term, process-based approach is not directly suited for the prediction of longer-term coastal evolution, not only because of lack of computer power, but also because it is unclear whether these models include the relevant physics. In general, short-term morphological processes are dominated by time-varying phenomena such as waves, tides, *etc.* Most of their effects, however, average out in the long run, whence the longer-time evolution is determined by much weaker residual effects, which are often disregarded in short-term models. The time-scales of interest for the present study regarding longer-time coastal evolution are from years to decades. The interesting aspect in this context is the cumulative morphologic effect of events at a decadal scale.

At present, knowledge is very limited on the motion of sediment particles in spatially varying flows of a combination of mean and oscillatory currents, especially together with turbulence induced by the breaking waves. Numerous other complicating factors, such as the complex fluid motion over an irregular bottom and absence of rigorous descriptions of broken waves and sediment-sediment interaction, also make the problem of computing sediment transport and associated beach change essentially impossible if a first-principles approach at the micro-scale is taken. The upscaling of first-physical principle or process-based modelling approaches to decadal scale coastal evolution is hampered by a range of theoretical and practical limits (CAPOBIANCO *et al.,* 2003). Based on "circumstantial evidence" discussed in DE VRIEND (1998), we must consider the possibility of intrinsic predictability limits, constraining the possibility to integrate small-scale models into larger scales, irrespective of if we have a big enough computer and a robust enough numerical scheme.

It is for this reason, that traditionally, and still in most everyday practices, a more aggregated view is taken, which basically implies the adoption of the existence of an explicit morphological equilibrium state under constant external forcing. These, quite simplified models have proven to be able to reproduce different aspects of beach change successfully. In the following we refer to this as Class I models. Certainly, when considering even longer, say recent geological, time-scales, the modelling efforts are still limited to this type of approach (COWELL *et al.,* 2003). While we have relied on the above class of models mostly in practice, at the same time we have been searching for models, based on a more physical principles approach, to bypass the explicit assumption of equilibrium, and let a potential (dynamic) equilibrium evolve from this more first physical principles approach. As we will describe in the following, this class of models—named Class II models—is nearly within the reach of decadal scales, although it will require some time before these approaches will display the same robustness as Class I models. Theoretical efforts, such as linear and nonlinear stability analyses of the fundamental process formulations of process-based models, form an indispensable contribution to validate these formulations (DODD *et al.,* 2003).

Matching Models and Applications

Selecting models for long-term predictions in a specific case is not a trivial task. It requires a thorough analysis of the problem under consideration, and a clear definition of the objectives of the prediction. With that in mind, the appropriate spatial and temporal scales of the problem must be determined and matched with those covered by the available models. Figure 1 gives an overview of scales of applicability for available model types for modeling on yearly to decadal scale.

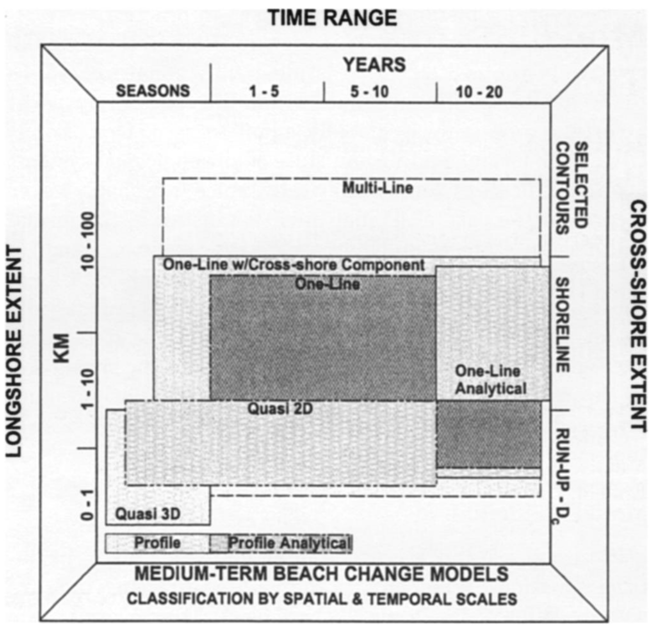

Figure 1. Classification of beach change models by spatial and temporal scales. (Modified from HANSON and KRAUS, 1989)

The selection of an appropriate model also requires a good insight into the functioning of the morphodynamic system, its forcing and its free and forced behaviour, as well as into the capabilities of the available models. The physical knowledge incorporated in the present morphodynamic models concerns mainly small-scale processes (waves, currents, sediment transport). In view of the possible occurrence of predictability limits, either inherent to the system or of other origin, it is not obvious that these models can be integrated through to essentially larger scales.

An alternative approach to long-term morphological predictions is to define macro-variables (process-, input- or state-related) and formulate a model in terms of these variables. Such a model is supposed to describe the physics directly at the relevant scale level, with the resolution and the reliability belonging to that level. Since in such aggregated models observational knowledge usually replaces part of the small-scale physics, it is sometimes referred to as "behaviour-oriented" modelling.

Equilibrium

Static equilibrium in coastal morphology is a controversial issue: equilibrium can also be dynamic, or even non-existent. In situations with complex sediment transport processes occurring at many scales and in many different patterns, with ever-changing forcing conditions, it is hard to imagine that all transport components exactly cancel out and lead to a static equilibrium state. Yet, the concept of equilibrium, even if it is never reached, is extremely useful in coastal morphology, also from a practical point of view. The equilibrium profile concept, for instance, is widely used in practice.

In the formal definition of static equilibrium, the time-derivative of the bed elevation is identically equal to zero. In the weaker form of quasi-equilibrium, the time-derivative at a certain time scale is globally equal to zero. Unless it is trivial, the formal equilibrium state of morphological systems is often difficult to verify empirically, since it probably never occurs. In the case of a tidal inlet, for instance, the formal equilibrium state is probably trivial: the basin is filled up entirely with sediment. In the case of the profile of a longshore uniform coast, however, the equilibrium is probably dynamic and therefore difficult to measure, since it requires averaging over very long data records. Both in the strong and in the weak definition, the nature of the equilibrium state produced by a mathematical model is often a severe test of that model's validity.

Model Validation

Process-based models are often validated against schematised situations. When applied to real-life situations, they are usually calibrated on a case by case basis. Investigations into the system's characteristics, *e.g.* via formal analysis of the model equations, are seldomly undertaken. One example of such an investigation is the stability analysis of perturbations with respect to a given basic state (DODD, 2003).

Process-based models of practical situations are often so complex, that their confrontation with reality requires a special view. It is of paramount importance that the validation be projected against the objectives of the model application. If one is interested in long-term trends, for instance, the trends in the model results have to be compared with trends in the data. If, at the same site, one is interested in the effects of extreme events, model results and data should rather be de-trended.

Calibration involves another risk, viz. that of overdoing it, thus reducing the predictive capability of the model (CUNGE, 1998). Calibration should always be attended with a critical evaluation of the parameter values found, otherwise the model may become more of a statistical extrapolator than a physics-based predictor.

Model Utilisation

After being properly calibrated and verified for a specific site the model may be applied in different ways, depending on the modeling objectives:

- ***Analysis***: given a fixed input, the system's natural behaviour and/or its response to a certain interference (*e.g.* an engineering structure) are assessed;
- ***Scenario evaluation:*** on the basis of "what if" questions, the possible consequences of proposed (non-)interferences with the system are assessed;
- ***Forecast:*** given the present or future conditions, the response of the system to (non-) interferences are predicted, preferably with an indication of the range of uncertainty.

These are different forms of model utilisation, of which the first is the most commonly used at the moment. The first two forms are usually applied in a relative sense, *i.e.* the changes with respect to the present state are considered. This is thought to make the conclusions less sensitive to errors in the description of the present state. Forecasting is much more associated with weather and climate forecasts. The "filtering capacity" of the morphodynamic system (*i.e.,* not every little change in the input is reflected in important morphological changes) has a mitigating effect. Yet, it is important to be aware of the fact that the future input is at best predictable in statistical terms. The present lack of clarity on which statistical aspects of the input time series that have to be taken into consideration (*e.g.* chronology) constitutes an important knowledge gap.

Wave Chronology

Coastal morphodynamics can be regarded as a strongly non-linear dynamical system, and generally the response of such a system will be sensitive to the sequence of forcing events. Wave chronology refers to the effects on coastal morphology of different sequences of waves (or, in general, any random forcing conditions) with the same overall statistical properties. Chronology is only an issue if sequences of forcing conditions cannot be predicted over a future time span. This is the case for forcing parameters such as waves, wind and surges, but not for tides which are largely deterministic and predictable over many years into the future. However, although the future sequence of wave conditions cannot be predicted, their overall statistics (usually expressed as probability distribution tables) can often be estimated to a reasonable level of accuracy. In addition, modulation of mean energy over the year (seasonal effects) can be more or less estimated, which reduces the randomness of this sequence.

It is very difficult to detect evidence for chronology effects from field data. One reason is that response of the morphology to the sequencing of waves needs to be distinguished from other sources, such as chaotic behaviour, that can have a similar appearance and statistical properties. Another important reason is that nature provides only one 'realisation' of wave conditions, whereas a study of chronology needs to compare the morphological effects of several realisations.

Mostly, evidence for chronology effects comes from computer model tests. The procedure for calculating the effects of chronology, either for diagnosis or prediction, is quite straightforward. The starting point is a single wave sequence covering the timespan of interest. This can be either as measured wave data or derived from a probability distribution. The sequence is divided into segments and then reordered in a number of different ways (usually about 30 ways is sufficient (LOPEZ DE SAN ROMAN and SOUTHGATE, 1998)). A morphological model is then run separately using each of these sequences, and the morphological output can be processed as probability of exceedance envelopes of seabed levels. Although straightforward, this procedure is quite demanding on computer time, and is therefore suitable for quick model types such as planshape models.

Figure 2 shows results of a similar type for beach planshape with a groyne, using wave data covering 5 years. For each wave sequence, the maximum (most seaward) position

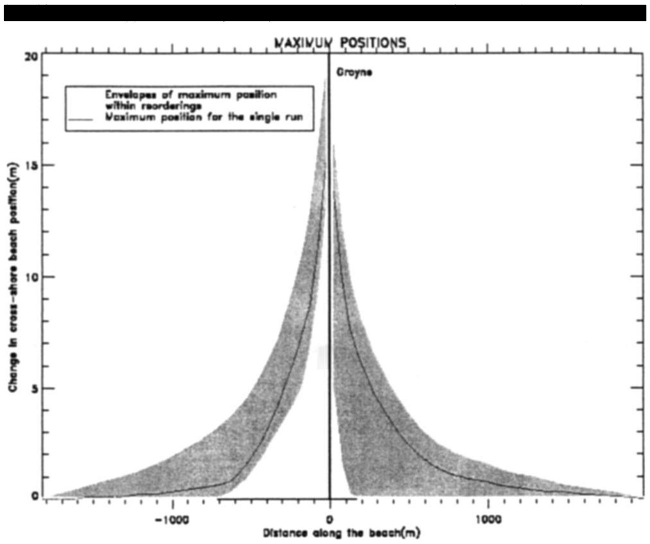

Figure 2. Envelope of changes in a straight beach following construction of a groyne, showing the effects of wave chronology using a planshape model. Duration = 5 years. Number of reorderings of the wave sequence = 40.

of the beach during that sequence is recorded. One can then draw 40 separate envelopes of maximum beach position. The shaded area shows the region covered by these 40 envelopes. The continuous line shows the envelope of maximum beach positions from one of the wave sequences. Note that the wave conditions were distributed approximately evenly about the groyne direction, accounting for similar accretion patterns on both sides of the groyne. Wave chronology is covered in more detail in SOUTHGATE (1995), SOUTHGATE and CAPOBIANCO (1997) and LOPEZ DE SAN ROMAN and SOUTHGATE (1998).

Model Types

Analytical models are closed-form mathematical solutions of a simplified version of the equation for shoreline and profile change, respectively (LARSON *et al.,* 1997) often with a schematized geometry. The application of these models also require that geometries, boundary conditions, and wave conditions are not too complex. By developing analytical or closed-form solutions originating from mathematical models that describe the basic physics involved, essential features of beach response may be derived, isolated, and more readily comprehended. Also, with an analytical solution as a starting point, direct estimates can be made of characteristic parameters associated with a phenomenon, such as the time elapsed before bypassing of a groin occurs, percentage of volume lost from a beach fill, and growth of a salient behind a detached breakwater. Thus, analytical solutions serve mainly as a means to identify characteristic trends in beach change through time and to investigate basic dependencies of the change on the incident waves and water levels as well as the initial and boundary conditions. As a result, analytical models will typically have a longer time perspective than their numerical counterparts.

Morphologic State Models aim to predict the evolution of, usually, a small number of parameters that describe the coastal profile. The morphologic state may be described subjectively, as in the case of beach state models based on visual observations (LIPPMANN and HOLMAN, 1990; SHORT, 1975; WRIGHT and SHORT, 1984), which led to classification of beaches within dissipative, intermediate, and reflective states. By relating observed beach states (or changes in state) to measured forcing, a predictive model can be developed (*e.g.,* WRIGHT *et al.,* 1985). Also, a morphologic state can be described objectively by extracting state descriptors from, for instance, surveyed bathymetry (AUBREY *et al.,* 1980). Predictions based on empirical relationships between observed states and measured forcing parameters have been shown to have significant predictive skill (LARSON *et al.,* 2003; SOUTHGATE *et al.,* 2003). Limitations of the morphologic state models stem from their dependence on observational data, which resolve a finite range of length and time scales. In addition, the predictive ability of these models may be degraded due to the use of empirical relationships between forcing and response. The approach resolves time scales ranging from 1 month to several years. The length scales that are resolved range from a bar length, O(100 m), to the maximum surf zone width, O(1000 m).

Class Ia: Longshore Non-Uniform, Equilibrium-Based Models

For longshore non-uniform[1] shoreline (one- to multi-line) models we assume that both the equilibrium profile shape is known, and that the equilibrium shoreline orientation is known. What we simulate is the adjustment of the profile (in case there's more than one-line) and the shoreline orientation to a change in the forcing and boundary conditions or constraints, where the degree of deviation from equilibrium is proportional to the degree of adjustment. Obviously, adopting the idea of (dynamic) equilibrium is an important issue. There are observational indications for systems to evolve towards an equilibrium state, *viz.* the upper shoreface profile seems—under certain conditions—to obey the shape predicted by BRUUN (1954) or DEAN (1977). Also, around boundaries like a groin or in between two groins, the shoreline orientation is observed to be perpendicular to the local mean or representative incident wave direction.

One-line shoreline evolution models have demonstrated their predictive capabilities in numerous projects (HANSON *et al.,* 1988; HANSON and KRAUS, 1989). This class of models calculates shoreline position changes that occur over a period of years to decades. The spatial extent varies from the single project scale of hundreds of meters to the regional scale of tens of kilometers (Figure 1). Changes in shoreline position are assumed to be produced by temporal evolution of spatial differences in the *longshore* sand transport rate (HANSON and KRAUS, 1989; STEETZEL and VROEG, 1999). Thus, this type of model is best suited to situations where there is a system-

[1] Nonuniform is implied here as nonuniform in one or more aspects; for one-line models it is only in the aspect of shore orientation relative to the wave direction, but for multi-line models also in profile shape.

atic trend in long-term change in shoreline position, such as recession down-drift of a groin. Cross-shore transport effects, such as storm-induced erosion and cyclical movement of shoreline position associated with seasonal variation in wave climate, are assumed to cancel over a long enough simulation period or are accounted for through external calculation.

In *multi-layer models* the cross-shore profile is schematised as a sequence of mutually interacting layers (*e.g.,* BAKKER, 1969; PERLIN and DEAN, 1979). Compared to one-line models, the evolution of the cross-shore profile is now taken into account by describing this interaction. The spatial extent of this type of models varies from the single project scale of hundreds of meters to a scale of hundreds of kilometres, whereas the temporal scale reaches from seasons up to centuries (Figure 1). Changes in the position of depth contours are caused by a combination of net cross-shore and longshore sediment transport. Though the concept of multi-layer or multi-line modelling is not new (BAKKER, 1968; PERLIN and DEAN, 1983), some recent developments have substantially increased its applicability (STEETZEL and VROEG, 1999; HANSON and LARSON, 1999). However, these approaches have not yet found their way into engineering practice.

Class Ib: Longshore Uniform, Equilibrium-Based Models

The equilibrium approach may also be adopted to simulate the evolution of the beach profile, exemplified by the models of SWART (1975), KRIEBEL and DEAN (1985), and LARSON and KRAUS (1989). A property of these models is that the chronology of the hydrodynamic forcing has negligible effects, provided that the forcing is allowed to act long enough for equilibrium to occur. Thus, under such conditions, if the same amount of forcing is applied but in a different sequence, the end result will still be the same. Because of this response to external forcing, it is expected that the models will show little intrinsic dynamic behaviour (see LOPEZ DE SAN ROMAN and SOUTHGATE, 1998). In practice, predictions of beach response in the past have heavily relied on Class I models, although we realize that we do not always have confidence in the existence of an equilibrium state, or the possibility to accurately determine this state. Another limitation of these models is their ability to only describe forced behaviour, that is, the beach response due to an external forcing (*e.g.,* waves, currents, tide, wind). However, it is a class of important models, which has proven significant skill and usefulness, but the limitations should be kept in mind.

Profile evolution models predict beach change as a result of cross-shore transport while longshore processes are omitted or described in a schematized fashion (LARSON and KRAUS, 1989; STEETZEL, 1993). This type of models has been quite successful in predicting short-term events such as the erosive impact of storms and the dispersion of placed mounds in the offshore (KRIEBEL and DEAN, 1985; LARSON and KRAUS, 1989; SCHOONEES and THERON, 1995). In these short-term applications the transport equations have typically been based on physical models, albeit sometimes fairly ad hoc. However, applications for medium- and long-term predictions have been limited because of difficulties in formulating sediment transport formulas that produce reliable and robust profile evolution at these time scales. On the other hand, profile models have been highly useful as a modeling tool to describe very long-term profile evolution, for example to simulate response to sea level rise or barrier island formation and movement (COWELL *et al.,* 1994; NIEDORODA *et al.,* 1995). The very long-term profile models rely on transport formulas that are based on some sort of equilibrium profile theory. Similarly, short-term profile response models often employ transport formulas that result in a specific profile shape at equilibrium. Thus, it seems reasonable to assume that satisfactory modeling results at medium- and long-term scales could also be achieved through formulations that rely on equilibrium concepts.

Recently, *semi-empirical profile evolution models* have been developed based on equilibrium theory to simulate the profile response over seasonal, annual, and even decadal scales. Some of these models employ a purely empirical description of the equilibrium beach profile (EBP) shape and the rate at which this state is approached (CAPOBIANCO *et al.,* 1994), whereas other models start with a physically based description of the cross-shore sediment transport (LARSON *et al.,* 1999b; STEETZEL and de VROEG, 1999). Although both types of models rely on data for calibration and verification, the former type requires a larger amount of data and the calibrated model is only applicable at the specific site. An example of applications where the profile evolution models have been employed over longer time periods with satisfactory results are the response of mounds placed in the offshore for nourishment purposes.

Class IIa: Longshore Uniform, Non-Equilibrium-Based Models

While we have relied on the above class of models mostly in practice, at the same time we have been searching for models, based on a more physical principles approach, to bypass the explicit assumption of equilibrium, and let a potential (dynamic) equilibrium evolve from this more first physical principles approach. This concerns so-called process-based models. This class of models (Class II) basically simulates hydrodynamics and sediment dynamics on the actual scale of the forcing, although mostly at least averaged over the short-wave time scale. In principle, bed updating is done on the same scale. By repeating this procedure for a range of true or climate-equivalent forcings these models aim to let the morphology evolve, without an explicitly defined equilibrium. In principle, these models account for strongly nonlinear internal dynamics, so that both effects of chronology and effects of inherent morphological behaviour may be expected.

For profile evolution the *process-based models* were introduced in the early 1980's, while applications have been in practice since the late 1980's (*cf.* ROELVINK and BRØKER, 1993; SCHOONEES and THERON, 1995). Models of this class aim at a detailed description of the hydrodynamics (waves and currents) along a cross-shore array, that is used to estimate the near-bed flow field and its associated transport rates. The resulting changes of bathymetry are computed from gradients in these transport rates, yielding so-called profile evolution models in the case that only gradients in cross-shore sense are taken into account. Model application has been successful in the case of short-term erosional events and for the design of beach nourishments. However, though meant to be generic, these models are generally less successful in accretive mode.

The increased computer power is not a limiting factor for applying these models on decadal time scales. However, their calibration, verification and validation has not yet led to generally accepted concepts, such as exist for shoreline models for example. An important reason is that, while it seems that the first-order dynamics are reasonably described, the more subtle higher-order effects are responsible for the bed profile evolution, which becomes especially relevant if we are trying to simulate on longer time-scales. As morphological time evolves, small inaccuracies in the higher-order dynamics accumulate, not seldomly leading to unrealistic mean profile shapes and/or bar geometries. Yet, progress is such that application on decadal scales must be considered of value for engineering practice, especially in cases where enough confidence in performance can be gained through calibration and verification in a well-defined situation.

Class IIb: Longshore Non-Uniform, Non-Equilibrium-Based Models

For longshore non-uniform situations this class of models was introduced in the mid 1980's (DE VRIEND and STIVE, 1987), while procedures to apply these models to so-called medium-term scales[2] have been reported in the mid 1990's (DE VRIEND *et al.,* 1993). The important extensions compared to profile models consist of the inclusion in the modelling of wave-averaged flows due to tidal and wind forcing and wave-induced radiation stresses. This is specifically required because of the alongshore non-uniformity, which promotes the importance of gradients in the alongshore flow field, creating sediment transport divergences and convergences. While initially depth-averaged approaches (so-called 2-DH models) have been formulated, the necessity to include depth-varying wave-effects—such as included in profile models—has led to quasi-3D (Q3D) models, where the assumption is made that the depth-dependent effects may be incorporated by a locally determined momentum balance. Recent developments in the introduction of depth-varying effects, such as those due to flow curvature, have led to attempts for 3D-approaches.

In contrast to the situation for profile models, computing capabilities are not such yet that straightforward application on the scale of the forcing can be done for the 'medium-term' and certainly not for decadal scales. It is for this reason that a number of reduction methods have been introduced. One concerns so-called input reduction, where the actual or climate-equivalent hydrodynamic forcing is reduced to a computationally less intensive set of conditions. These conditions are determined by searching a representative forcing which approximates, as regards its effects on morphodynamics, the actual forcing for a restricted, but assumed representative part of the solution domain. A second method concerns reduction of computational calls to the hydrodynamic flow modules, assuming either that the flow field varies more slowly that the wave field or by applying methods like the continuity correction for the flow field. A third method uses the fact that the morphology evolves on a slower scale than the hydrodynamics and sediment transport, so that bed updates and associated hydrodynamic updates are made on a scale slower than that of the forcing.

Another, rather different method to reduce computational efforts uses the concept of hybrid modelling. Hybrid modelling seeks to combine complimentary modelling approaches, viz. process-based and behaviour-oriented, such that an appropriate concept is applied for each time and length scale of consideration. In practice, this means that larger-scale models use the output of smaller-scale models (for instance an initial transport field or an indication of the equilibrium state of a system) to arrive at mega time scales (decades—centuries). So far, behaviour-oriented concepts have successfully been used to model the very large scales, as well as a reduced process-based concept, which is funded on the parameterization of an initial transport field as a function of local depth.

In agreement with the situation for profile models, the calibration, verification and validation of this model class have not yet led to generally accepted concepts, for the same reasons as described before. Further, it can be stated that the applications reported have been more successful in regions where 2DH-flow processes are important than in pure wave-dominated environments like the surf zone.

1D-SHORELINE EVOLUTION

Basic Assumptions

The foundation of the one-line theory rests on the common observation that some beaches remain steep and while others remain gently sloping (PELNARD-CONSIDERE, 1956). Thus, one contour line can be used to describe change in the beach plan shape and volume as the beach erodes and accretes. The model presumes that the total longshore sand transport rate may be parameterized in terms of breaking wave quantities. Thus, it does not describe transport resulting from tidal currents, wind, or other forcing agents, implying that the model should not be used if breaking waves are not the dominant sand transporting mechanism. Finally, it is assumed that there is a clear long-term trend in shoreline behavior. If not, it is not possible to separate a steady "signal" of shoreline change from the "noise" in the beach system produced by storms, seasonal changes in waves, tidal fluctuations, and other cyclical and random events.

Governing Equations

As the principle of mass conservation applies to the system at all times, the following differential equation is obtained,

$$\frac{\partial Q}{\partial x} + D\frac{\partial y}{\partial t} = 0 \qquad (1)$$

where Q = longshore particulate sand transport rate, x =

[2] In the DE VRIEND *et al.* (1993) paper medium term refers to scales larger than that of single forcing events, practically up to years.

space coordinate along the axis parallel to the trend of the shoreline, D = vertical extension of the active part of the profile = $D_C + D_B$ where D_C is the depth of closure and D_B is the berm crest elevation, taken as the upper profile limit, y = the shoreline position, and t = time. Eq. (1) states that the longshore variation in the sand transport rate is balanced by changes in the shoreline position. In order to solve (1), it is necessary to specify an expression for the longshore particulate sand transport rate. A general expression for this rate is $Q = Q_0 \sin 2\alpha_b$, where Q_0 = amplitude of longshore sand transport rate, and α_b = angle between breaking wave crests and shoreline. This angle may be expressed as $\alpha_b = \alpha_0 - \arctan(\partial y/\partial x)$ in which α_0 = angle of breaking wave crests relative to an axis set parallel to the trend of the shoreline, and $\partial y/\partial x$ = local shoreline orientation. A wide range of expressions exists for the amplitude of the longshore sand transport rate, mainly based on empirical results.

Analytical One-Line Models

Analytical solutions to mathematical models provide a concise, quantitative means of describing systematic trends in shoreline evolution commonly observed at groins, jetties, and detached breakwaters. For example, LARSON *et al.* (1987) and LARSON *et al.* (1997) give comprehensive surveys of new and previously derived analytical solutions of the shoreline change equation. For beaches with mild slopes, it can safely be assumed that the breaking wave angle relative to the shoreline and the local shoreline orientation, with respect to the chosen coordinate system, are small. Under these assumptions, the generalized transport relation, as discussed in the previous section, may be linearized to yield $Q = Q_0 2(\alpha_0 - \partial y/\partial x)$. If, in addition, the amplitude of the longshore sand transport rate and the incident breaking wave angle are constant (independent of x and t) the transport relation may be combined with Eq. (1) to yield:

$$\frac{\partial y}{\partial x} = \varepsilon \frac{\partial^2 y}{\partial x^2} \tag{2}$$

where $\varepsilon = 2Q_0/D$. Eq. (2) is formally identical to the one-dimensional equation describing conduction of heat in solids or the diffusion equation. Thus, many analytical solutions can be generated by applying the proper analogies between initial and boundary conditions for shoreline evolution and the processes of heat conduction and diffusion. CARSLAW and JAEGER (1959) provide many solutions to the heat conduction equation, and CRANK (1975) gives solutions to the diffusion equation. The coefficient ε, having the dimensions of length squared over time, is interpreted as a diffusion coefficient expressing the time scale of shoreline change following a disturbance.

Example Application at a Single Groin with Varying Wave Direction

Waves having a constant breaking height and angle alongshore are in a dynamic equilibrium with a straight beach without any structures, because the longshore sand transport rate is constant alongshore. If a groin is placed on such a beach, blocking the transport, sand will begin accumulating on the updrift side and eroding on the downdrift side. The groin is represented by the boundary condition $Q = 0$ at the groin location. Mathematically, this boundary condition can be expressed as $\partial y/\partial x = \tan \alpha_o$, $x = 0$, stating that the shoreline at the groin is at every instant parallel to the breaking wave crests. If the incident breaking wave angle is varying sinusoidally with time, some interesting features of shoreline evolution may be noted on the updrift side of the groin. The breaking wave angle is assumed to vary according to $\alpha_o(t) = \alpha_{ao}(1 + \sin \omega t)$ where α_{ao} is the average breaking wave angle and ω is the angular frequency of the wave direction. The analytic solution may be derived by means of the Laplace transform technique to yield (CARSLAW and JAEGER, 1959; HANSON and LARSON, 1987):

$$y(x, t) = \alpha_{ao}\left[2\sqrt{\frac{\varepsilon t}{\pi}}\,\mathrm{ierfc}\left(\frac{x}{2\sqrt{\varepsilon t}}\right) + \frac{\exp\left(-\sqrt{\frac{\omega}{2\varepsilon}}x\right)}{\sqrt{\frac{\omega}{\varepsilon}}}\sin\left(\omega t - \sqrt{\frac{\omega}{2\varepsilon}}x - \frac{\pi}{4}\right) + \frac{1}{\pi}\int_0^{\infty}\frac{\omega\cos\left(\sqrt{\frac{\rho}{\varepsilon}}x\right)e^{-\rho t}}{\sqrt{\frac{\rho}{\varepsilon}}(\rho^2 + \omega^2)}\,d\rho\right] \tag{3}$$

for $t > 0$ and $x \geq 0$, where *ierfc* is the integral of the complementary error function and ρ is an integration variable.

The integral part of the solution is a transient, which will disappear with time. Accordingly, the solution consists mainly of two parts, one identical to the shoreline updrift of a groin exposed to waves with a constant breaking wave angle, α_{ao}, and one part expressing a damped sinusoidal variation, with the attenuation proportional to the distance from the groin by a factor $\sqrt{\omega/2\varepsilon}$. As seen from Eq. (3), the "crests" of the wave-shaped shoreline travel with the speed $\sqrt{2\varepsilon\omega}$ updrift from the groin, and the phase lag between the variation in shoreline position at the groin and at specific location x is $\sqrt{\omega/2\varepsilon}\, x$. In Figure 3, the shoreline evolution at five different locations alongshore is plotted as a function of time. The nondimensional frequency used in Figure 3 was $\omega L^2/\varepsilon = 10$. As indicated, the shoreline positions move rhythmically in time, with the fluctuations decreasing with the distance from the groin. However, the long-term trend is accretion on all locations along the beach.

The above example may provide an explanation for the presence of sand waves along some coastlines (VERHAGEN, 1989; THEVENOT and KRAUS, 1995). A periodic variation in the wave climate together with a barrier for longshore transport could induce waves that propagate alongshore with properties as predicted by Eq. (3). For example, using $\varepsilon = 2.0$ m^2/hr as representative for Southampton Beach (see following

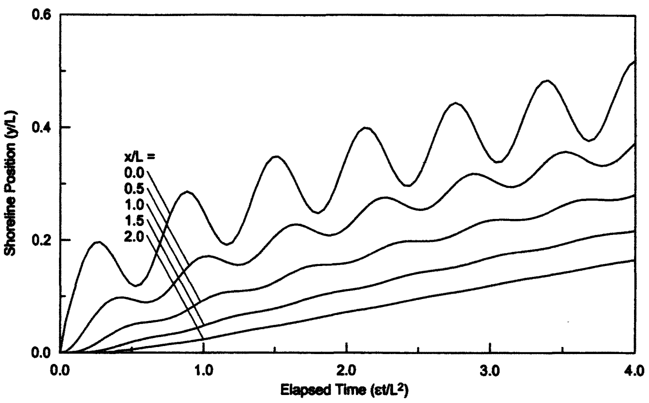

Figure 3. Accumulation updrift of groin exposed to waves with sinusiodally varying angle. (Modified from LARSON *et al.,* 1997)

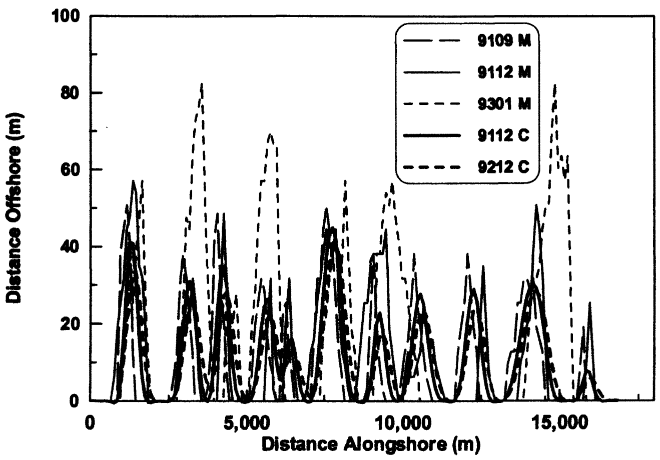

Figure 4. Measured and calculated longshore sand wave movement at Southampton Beach, New York. Legend shows year and month with M = measured and C = calculated. (Modified from HANSON *et al.,* 1996)

section) and a periodic variation of 1 year yield a representative celerity of 1.3 m/day and wavelength of 470 m. These values are of the same order of magnitude as those presented by THEVENOT and KRAUS (1995). However, the fairly strong dampening of the sand waves in Eq. (3) exceeds what is encountered in the field, and if a variable wave climate is responsible for generating the sand waves additional mechanisms must be present to maintain there shape at longer times.

Numerical One-Line Models including Longshore Sand Waves

It is well known that because the one-line model reduces to the diffusion equation, with a particulate transport rate formula dependent upon wave angle, perturbations in shoreline position will tend to be smoothed, unless controlled or sustained by a boundary condition or other constraint. Particulate transport rate formulas pertain to micro-scale or meso-scale motion (minutes to hours or days) and are stepped through time at typically 3- to 6-hour intervals for cell widths on the order of 50 to 500 m. Engineers are becoming aware of morphologic features in the nearshore having much longer time and space scales that may impact project prediction and performance. Such features maintain their identities for months to years and move while preserving form. One such phenomena of consequence is that of longshore sand waves (LSWs) (see THEVENOT and KRAUS, 1995; HANSON *et al.,* 1996 for a literature review of LSWs), large wave-like features that migrate alongshore with a characteristic speed of kilometers per year. VERHAGEN (1989) examined a 100-year record of LSWs present along 20 km of Dutch coast and concluded that periodic accretion observed in the groin field coincided with the passage of LSWs and not to trapping of littoral (particulate) drift by the groins. LSWs have been associated with intermittency in sand supply, such as the discharge of river sediments, sediments discharged from inlets, artificial injection of a large quantity of sand, and welding of shoals on to the shore.

As shown by INMAN (1987) and LARSON and KRAUS (1991), the longshore movement of LSWs may be incorporated into Eq. (2) by including a form-advective term $V(\partial y/\partial x)$ to yield the advection-diffusion equation for a conservative substance

$$\frac{\partial y}{\partial t} + V\frac{\partial y}{\partial x} = \varepsilon\frac{\partial^2 y}{\partial x^2} \tag{4}$$

where V = the migration speed of the LSW, may be calculated from wave parameters and geometric properties of the LSW (HANSON *et al.,* 1996).

Example Application to Southampton, NY

In an attempt to at least qualitatively validate the preliminary approach to modeling LSW migration, the method was applied to the situation at Southampton Beach, Long Island, New York. Here, eleven LSWs were identified from aerial photos (THEVENOT and KRAUS, 1995). The LSWs have an average length of 0.75 km and a amplitude of about 40 m. Their average migration speed was reported to 0.35 km/yr.

Available aerial photos dated September 4, 1991, December 20, 1991, and January 2, 1993 were used as reference for the simulations that were performed with a traditional 1-line model, "enhanced" with an advective term as in Eq. (4). The simulated shoreline covers 16.9 km, with a spatial resolution of 100 m and a time step of 3 hrs. Results of a simulation is shown in Figure 4. A WIS hindcast wave time series representing the time period September 4, 1991 to January 2, 1993, was used in the simulations. The period was selected to represent typical conditions at the site.

As specified, the LSWs were moving with a net direction to the West (right in Figure 4). A comparison between measured and calculated LSW locations show reasonable agreement for most of the LSWs. However, in terms of amplitudes the agreement is quite poor. The reason for this is, that the model cannot produce growth in amplitude, which seems to be quite significant in the measured data. It is not clear at this point what actually causes the drastic amplitude increase.

Due to limited migration speed relative to LSW length this type of modeling is best suited for time scales of a few LSW periods or in the order of years to decades. In space, the lower end of the scale would be a few LSW lengths or in the order of kilometers. This type of model has also been applied to situations involving structures, but with limited results so far.

One-Line Models for Highly Curved Coasts

Traditional one-line models are not applicable to situations with highly curved coasts such as "logarithmic bays", tombolos behind detached breakwaters, and spits. In these cases, the large coastal curvature makes the use of the numerical model formulated in Cartesian co-ordinates a less useful tool because it would tend to smooth this curvature since shoreline changes are calculated normal to the system of reference.

To solve this problem, which is not uncommon in field applications, it is possible to formulate the model in such a way that coastline changes are calculated normal to the local coastal orientation. This would permit to simulate the retreat and/or advance of highly curved coasts maintaining its shape. Thus, the shoreline evolution model has to be formulated in curvilinear coordinates. In this system, the orientation of any point of coordinates (x,y) can be written in terms of local coordinates normal to and tangential to the actual shoreline by using complex notation (LEBLOND, 1972; SÁNCHEZ-ARCILLA and JIMÉNEZ, 1996).

Example Application to Spit Growth at the Ebro Delta

To illustrate the applicability and potential of this shoreline model, an example follows regarding the simulation of spit growth. This case, which is very common in nature, has not been previously analysed by means of numerical models. Most of the existing studies are based on extrapolations of past shoreline migration rates to predict the future spit growth. An exception to this is the forecasting of the La Banya spit (JIMÉNEZ, 1996; SÁNCHEZ-ARCILLA and JIMÉNEZ, 1996; JIMÉNEZ and SÁNCHEZ-ARCILLA, 1999).

This spit is located in the Ebro delta (NW Spanish Mediterranean coast) and the system is composed by a 5.5 km-long barrier beach connecting the spit with the main body of the delta. The spit has been growing during this century due to the sediment eroded upcoast and transported towards the south by the Eastern dominant waves (JIMÉNEZ *et al.,* 1997). Figure 5 shows the evolution of the spit from 1957 until 1989, where it can be seen that besides the spit growth at the apex, the barrier has suffered a seashore retreat and a backbarrier advance. The seaside erosion has been associated with the existence of a positive gradient in the longshore sediment transport rates whereas the backbarrier response is mainly product of overwash transport towards the bay during storms. This overwash was included in the model (JIMÉNEZ *et al.,* 1997) but will not be discussed here.

To forecast the spit evolution for the next decades a shoreline model in curvilinear coordinates was applied. The model was developed to be used at a temporal scale of decades and with a spatial scales of kilometers to represent the overall spit behaviour. The time step used in the simulations was 1

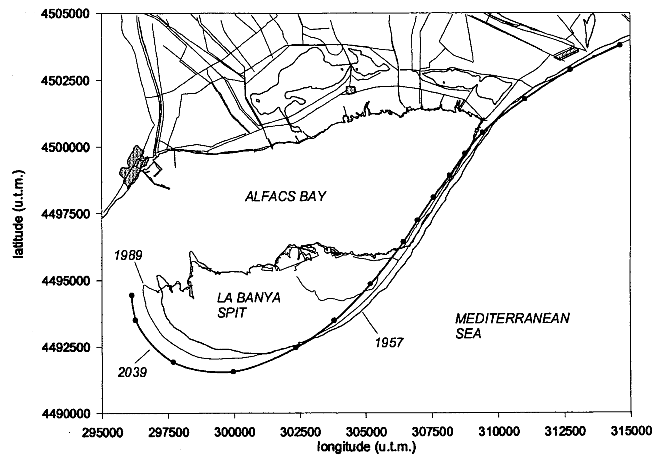

Figure 5. Measured evolution of the La Banya spit (Ebro delta, Spain) from 1957 to 1989 and simulated evolution for the year 2039 (Modified from JIMÉNEZ and SÁNCHEZ-ARCILLA, 1999).

year and the cell length varied between 1 and 2 km. The model was calibrated/verified by doing a hindcast of the Trabucador-La Banya system evolution from 1973 to 1989 with root mean squared deviations between modelled and observed shorelines of 15% (SÁNCHEZ-ARCILLA and JIMÉNEZ, 1996).

Figure 5 also shows the predicted evolution of the spit on a 50-year time span up to the year 2039. It can be seen that the system will evolve in a similar way to the evolution experienced during the last decades, with a pronounced barrier seashore retreat and an advance of the apex of the spit. The model predicts a retreat of the outer coast of the barrier towards the present position of the bayshore, *i.e.* the barrier will experience a total rollover as it did during the period 1957/1989.

1D-SHOREFACE-BEACH PROFILE EVOLUTION

Traditionally, short-term process-based models for cross-shore transport and associated beach profile evolution have not been applied in case of the modeling of time scales of years to decades, the primary reason being that available models have not succeeded so far to produce realistic profile evolution at these time scales. This can be attributed to the accumulation of small errors in subtle high order processes over longer time scales. As models funded on analytic solutions explicitly assume an equilibrium state, these type of models do not face the problem of accumulation of high-order effects and may therefore be used at longer time scales.

Analytical Model of Profile Evolution

The sediment transport relationship for the offshore (*i.e.,* non-breaking waves) developed by LARSON *et al.* (1999a) may in some cases be simplified so that analytical solutions can be obtained for the profile evolution in this region. Such analytical solutions, although describing highly schematized situations, may be useful to derive quantities that provide characteristic time and space scales of profile response. These quantities could be used for first-order estimates of the profile response or for preliminary design of, for example, offshore mounds created from dredged material (Larson and Ebersole, 1999). The transport equation is combined with the conservation equation for sediment volume, and after certain simplifications the heat diffusion equation will result for which many analytical solutions are available.

Assuming that bottom changes are small in the area of interest, at least with respect to the water depth, the bottom orbital velocity will approximately be a constant and the sediment transport equation derived by Larson *et al.* (1999a) is written,

$$q_c = K_c \frac{u_{oc}^2}{g}\left(\frac{\partial h}{\partial x} - \frac{dh_e}{dx}\right) \tag{5}$$

where q_c is the net cross-shore transport rate, u_{oc} the (constant) maximum bottom orbital velocity, K_c a non-dimensional transport rate coefficient, h is the local depth, and h_e the equilibrium beach profile (EBP) shape. It should be noted that in this type of models, the x-coordinate is directed offshore in the cross-shore direction (as opposed to alongshore as in previous Eqs.). Combining Eq. (5) with the sediment volume conservation equation, and assuming that the EBP corresponds to a flat or linearly sloping bottom, the governing equation can be written,

$$\frac{\partial h}{\partial t} = \varepsilon_d \frac{\partial^2 h}{\partial x^2} \tag{6}$$

where:

$$\varepsilon_d = \frac{K_c u_{oc}^3}{g} \tag{7}$$

Eq. (6) is formally identical to the heat diffusion equation and, as pointed out above, there are many analytical solutions available for this equation. Larson *et al.* (1987) presented many such solutions to the one-line model of shoreline change. These solutions have direct analogies to simulating the profile evolution at mounds or dredged holes in the offshore using Eq. (6). An example will be shown next to illustrate the usefulness of simple analytical models to predict profile evolution.

If the variable h in Eq. (6) is replaced with $\Delta h = h - h_e$, a more general equation is obtained that controls the profile evolution with respect to an arbitrary equilibrium profile shape (Larson and Ebersole, 1999). In fact, the shape of the EBP does not have to be determined, if only the deviation from the EBP is of interest. Such a formulation might be convenient for the simple analytical case where h_e is a constant in time, although the more straight-forward formulation given in Eq. (6) is retained in the following example for convenience. However, if the EBP is a function of the wave conditions a numerical solution is required and a formulation in Δh might not have any particular advantage (see numerical example below).

Example Application to an Offshore Mound (Hole)

The following solution describes the evolution of a rectangular mound (hole) in the offshore (see Larson *et al.*, 1987),

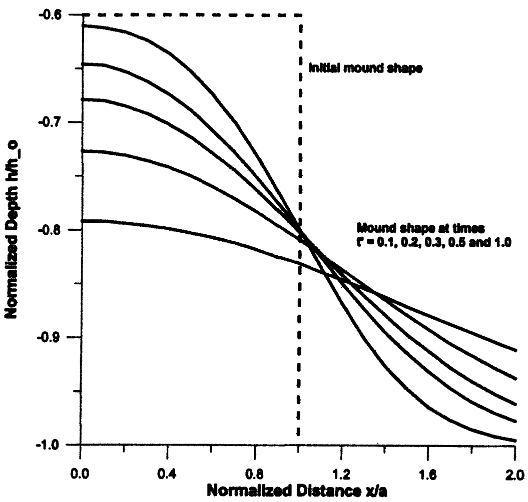

Figure 6. Analytical solution describing the diffusion of an initially rectangular offshore mound exposed to non-breaking waves.

$$h(x, t) = h_o - \frac{1}{2} z_b \left[\operatorname{erf}\left(\frac{a - x}{2\sqrt{\varepsilon_d t}}\right) + \operatorname{erf}\left(\frac{a + x}{2\sqrt{\varepsilon_d t}}\right)\right] \tag{8}$$

where h_o is the constant water depth, z_b is the initial mound height over sea bottom, a is half the mound width, and *erf* denotes the error function. Figure 6 illustrates the evolution of an initially rectangular mound with the height $z_b/h_o=0.4$ (only half of the mound is shown because of symmetry). If the height of the mound is given a negative sign, the solution will instead describe the filling up of a hole in the offshore. By non-dimensionalising solutions to Eq. (6), the leading quantities may be identified, which can provide insights to the governing time and space scales. Also, these quantities will allow for comparison of, for example, different mound designs and how their configurations will influence the mound response.

The evolution of a mound with the initial width a placed in the offshore will be governed by the non-dimensional time scale $t' = \varepsilon_d t/a^2$. Two mounds with the same overall configuration will display the same non-dimensional evolution in time, if appropriately scaled. Thus, the effect of various geometrical parameters on the evolution may be easily assessed by comparing the non-dimensional quantities for various cases. By expressing ε_d in terms of the local wave climate, the effects of the wave properties can more easily be assessed. Assuming shallow-water theory gives the following expression for the diffusion coefficient,

$$\varepsilon_d = \frac{K_c \sqrt{g}}{8} \frac{H_o^3}{h_o^{3/2}} \tag{9}$$

where H is a characteristic wave height and subscript o denotes conditions at the mound. For example, the maximum non-dimensional height of two mounds with the same initial geometric shape will be the same after time t'. Translating this relationship into dimensional time yields,

$$\frac{t_1}{t_2} = \left(\frac{a_1}{a_2}\right)^2 \left(\frac{H_{o2}}{H_{o1}}\right)^3 \left(\frac{h_{o1}}{h_{o2}}\right)^{3/2} \qquad (10)$$

where index 1 and 2 refer to the two different conditions. This equation shows that a twice as wide mound requires four times as long time of wave action to experience the same relative decrease of the maximum height. The effect of the diffusion coefficient ε_d is linear, but inverse, implying that a doubling of ε_d causes the time to reduce to half for the mound to experience the same reduction. This equation also clearly illustrates the influence of the wave height and the water depth when comparing the evolution of two mounds of identical initial shapes. For instance, a wave climate with a characteristic height that is doubled causes a mound response in ⅛ of the time compared to the original conditions. LARSON and EBERSOLE (1999) discussed how ε_d may be related to the local wave conditions and also showed that the analytical solutions could be successfully used to describe the evolution of mounds in the field.

(Semi)-Empirical Multi-Line Models

Equilibrium profiles can, thus, be used for the assessment of cross-shore interaction. In the multi-layer model developed by STEETZEL (1995) the rate of cross-shore transport is based on the principle of a single wave-based equilibrium profile. Deviations from the equilibrium slope result in a cross-shore exchange of sediment between the layers. The rate of adjustment varies with the depth and is amongst others depending on relative water depth and local sediment characteristics. For both the equilibrium slope and the transport rates, formulations have been derived, partly based on empirical formulae and partly based on the results of a series of computations carried out with a process-based model. The process-based computations involved the main processes determining the cross-shore transport, *i.e.,* wave asymmetry, gravity, and the undertow compensating for the mass-flux above the wave troughs.

The wave-induced cross-shore transport $q_{y,w}$, for a specific hydraulic condition (water level and waves) at a certain depth is computed as a product of three parts according to:

$$q_{y,w} = q_o F_b \left(\frac{s}{s_e} - 1\right) \left|\frac{s}{s_e} - 1\right|^{\beta - 1} \qquad (11)$$

The coefficient q_0 is used for calibration, whereas the F_b-function describes the vertical distribution of the transport rate according to $F_b = \exp(-d/\alpha H_s)$ where d is the water depth, α is a parameter set to 1.5, and H_s is the significant breaking wave height. The right-hand part consist of two terms expressing the relative slope, where the s denotes the actual local bed slope and s_e refers to the local equilibrium slope and β is a parameter set to 2.0. Thus, a relatively too steep slope, viz. $s > s_e$, yield offshore directed, defined as positive, transport. In the model, the equilibrium slope s_e is expressed in terms of the offshore hydraulic conditions and the characteristics of the bed material. In Figure 7, as an illustration, the cross-shore evolution is given for an initially steep vertical cross-shore profile (the dashed vertical line in the left-hand panel) using one single wave condition as the forcing agent. The equilibrium profile shown in the left-hand panel by both a (dashed) continuous shape and the layer profile. As can be seen from the right-hand panel, the final equilibrium profile (and the associated depth contours) is reached asymptotically in time.

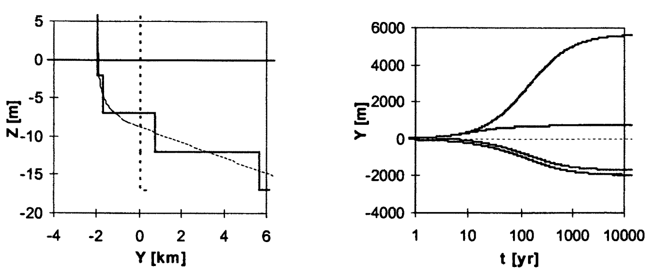

Figure 7. Equilibrium profile evolution.

BEHAVIOUR-ORIENTED MODELLING AND DIFFUSION-TYPE FORMULATIONS

Behaviour-oriented modelling tries to overcome the practical difficulties by directly reproducing the qualitative behaviour of the profile evolution while maintaining a parametric representation. In practice this approach tries to "implicitly filter" both inputs and processes. The qualitative behaviour to be reproduced may be based on field evidence and on specific aspects of behaviour inferred from the use of process models. The practical idea behind the approach is to map the behaviour of the coastal system, as observed in the field or from process-based model runs with real life input conditions onto a simple mathematical model that exhibits the same behaviour under well defined operating conditions. In this sense the model does not need to have any explicit relationship with the underlying physical processes.

Diffusion is considered as the tendency to "smooth gradients". Thus, declining may be seen as a local diffusion as a function of the cross-shore position and inclining as a local diffusion as a function of depth. To support the hypothesis of diffusion there is also the way the profile responds in time (fast initial response and slow settlement). These observations allow us to apply *diffusion-type formulations* for models, thus identifying the fundamental parameters as the space-varying coefficients of a rather simple dynamic equation. The variation of the coefficients, in particular the diffusion coefficient, permits the representation of the variation of the morphological time scales along the profile. It is important to note that the choice of the class of diffusion-type model equations is not derived rigorously from any basic process-based model equations, it is selected only because its solution exhibits the proper behaviour for our application.

With appropriate initial and boundary conditions the *cross-shore position* can be described as a function of *profile depth x(z).* The following advection-diffusion formulation is an extension of the n-line model with an infinite (but finite in the numerical discretisation) number of contour lines

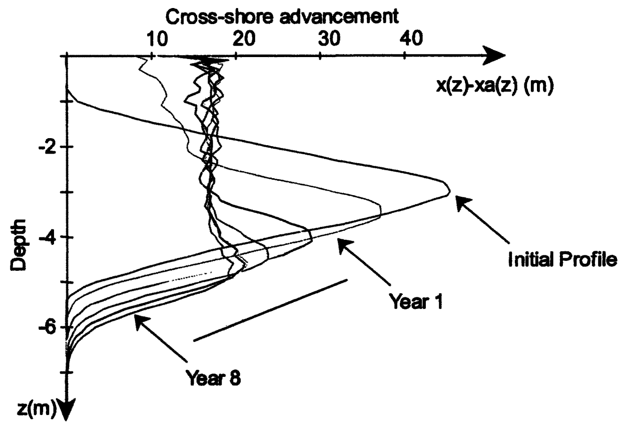

Figure 8. Spreading of nourishment on time scale of years.

$$\frac{\partial x}{\partial t} = \frac{\partial}{\partial z}\left(D(z)\frac{\partial x}{\partial z}\right) + S(t, x, z) \tag{12}$$

where $S(t,x,z)$ is an external source function which depends on time, on the cross-shore distance (x) and on the profile depth (z) and $D(z)$ is a depth dependent diffusion coefficient. The vertical variation of the diffusion coefficient allows us to represent the variation of morphological timescale with the vertical position, and an asymmetry in the long-term residual sand displacement across the profile. The idea is to have all the information about the typical site climate, the sand characteristics and the degree of activity of the various profile zones summarised into $D(z)$.

The calibration of this parameter is the key element of the model definition: all information, on hydraulic and sediment characteristics as well as on shorter-term dynamics is stored in it. All the human induced inputs as well as other "natural corrective" terms are summarised into $S(t,x,z)$.

In order to identify interesting behaviour in the smaller scales we have evidences and data from the field to rely on. On the contrary, in the longer scales, as far as field data are missing, we may rely on simulations with short-term process based models. By using a synthesized or schematized wave climate as an input, STIVE *et al.* (1992) generated pairs of profile evolutions using a behaviour-oriented (diffusion-type) model, one for an undisturbed, ideal profile (giving the "autonomous" development) and one for a disturbed, ideal profile, which is identical to the former except for the "disturbance", in this case a nourishment. The basic assumption is that the spreading can be derived by comparing a nourished profile development with an autonomous profile development. This smoothing process shows a shoreward asymmetry: the smoothing is stronger at the shoreward side. Associated with this asymmetry, the part of these artificial disturbances tending to move onshore exceeds the part tending to move offshore (Figure 8).

Semi-Empirical Profile Evolution Modeling Based on Equilibrium Concepts

As indicated by the example discussed in the section above concerning an analytical model of profile evolution, models of cross-shore transport and profile evolution often employ an advection-diffusion equation as the main governing equation. In some profile evolution models this equation is postulated at the outset and various coefficients are identified through comparison with measurements (*e.g.*, CAPOBIANCO *et al.*, 1994). However, in other models based on EBP theory these coefficients emerge as functions of wave and sediment characteristics. Thus, the latter type of models are typically more suitable for general application than the former type, although calibration and validation against data are still required. Hereafter, an example is given of a diffusion model derived from EBP theory that describes the sediment transport and profile evolution in the offshore where wave asymmetry and gravity controls the transport. Similar formulations for other sediment transport mechanisms were presented by LARSON *et al.* (1999a) resulting in other forms of diffusion equations.

In employing EBP theory it is assumed that equilibrium occurs when there is a balance between different transport mechanisms (LARSON *et al.*, 1999b). If this balance is not fulfilled a net transport takes place that redistributes the sediment across the profile towards equilibrium conditions. Each wave condition is associated with a corresponding EBP. LARSON *et al.* (1999a) showed that different types of relationships for the net transport could be written in terms of the deviation from the EBP and a forcing function. Such a formulation might be advantageous since it ensures a development of the profile towards an equilibrium state for steady forcing conditions. Also, representative EBP shapes may be derived from laboratory and field data giving the transport relationships a robust behaviour where unrealistic fluctuations in profile shape are avoided. Here, an example of a medium-term model based on EBP concepts will be discussed that involves the transport and profile change in the offshore where non-breaking waves dominate. The resulting governing equation is basically Eq. (5) with a varying diffusion coefficient that makes it possible to reproduce, for example, the advective behaviour of an offshore mound subject to onshore net transport.

Example Application to Modeling Offshore Mound Movement at Silver Strand

Measurements taken in connection with the placement of a mound off Silver Strand State Park (ANDRASSY, 1991; LARSON and KRAUS, 1992) were used to calibrate and validate a beach profile change model for the offshore based on EBP theory. Wave measurements were carried out between January and May 1989 during which four surveys were taken (890119, 890215, 890315, and 890518). The January survey was made just after the completion of the offshore mound, and the following surveys displayed how the mound deflated and most of the material moved onshore. During this period the wave climate was quite mild and no major storms were recorded. Thus, these data constitute an excellent set for testing a model for predicting beach profile change in the offshore under non-breaking waves. In the effort presented here to simulate the mound movement, the profile change model developed by LARSON (1996) was enhanced to describe sediment transport in the offshore by employing Eq. (5) with a varying

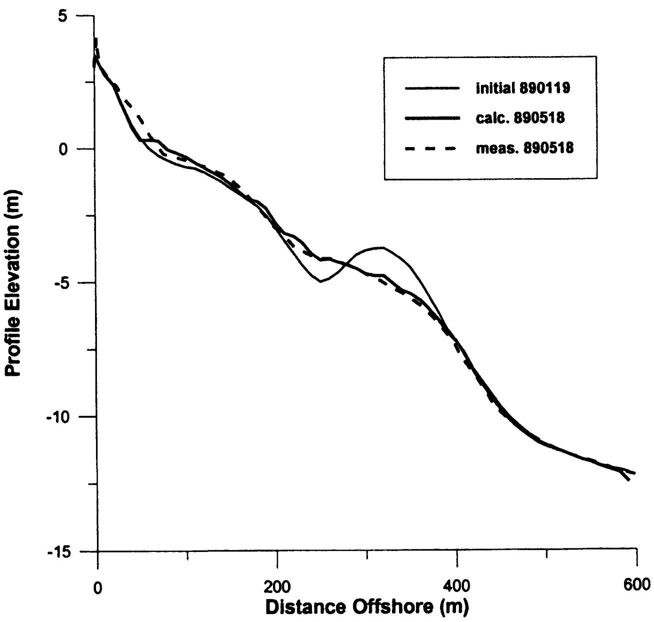

Figure 9. Calculated and measured profiles at Silver Strand after about four months of wave action on the placed mound.

u_o and an EBP for the offshore that depended on the wave and sediment properties.

Measured significant wave height, mean wave period, and mean incident wave angle were available about every three hours (in 10.9 m water depth) for a period of about 114 days. The water level elevation was not recorded, but an hourly time series of tidal elevations were generated using a numerical model. The model simulations started with the measured profile at 890119 and comparisons were made between calculated and measured profiles for the three other surveys. The only calibration coefficient were K_c and all other coefficients were held constant in the simulations according to standard values (ROSATI *et al.,* 1993). A time step of 20 min was used in the computations and the length step was set to 10 m. The median grain size used in the simulations was 0.20 mm based on field sampling.

Figure 9 displays the calculated profile after the entire simulation period (890518) together with the measured initial and final profile. Overall the model prediction was satisfactory, although the accumulation above mean sea level was not well described. This is probably a result of the model's limited ability to simulate accumulation in the swash zone. The deflation of the mound, with most of the material moving onshore, was correctly reproduced by the model. Thus, the calculated profile shape in the surf zone and the offshore zone were in close agreement with the measured profile. In order to validate the model comparisons were made with the intermediately measured profiles. The agreement was quite good for these profiles, especially regarding the overall mound shape. For the survey made 890215 the trough seaward of the mound was more pronounced in the measurements, implying that the model filled up the trough too quickly.

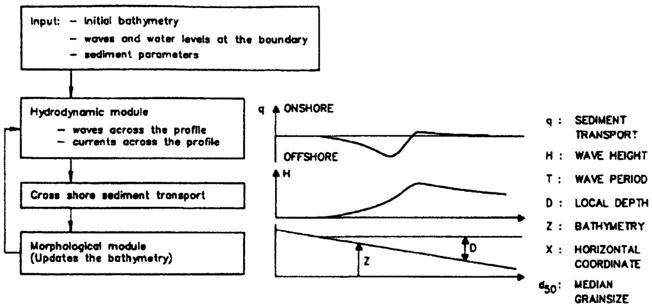

Figure 10. Basic structure of process-based dynamic model concepts (after ROELVINK and BRØKER, 1993).

Process-Based Dynamic Profile Models

'Process-based' or 'deterministic' dynamic models aim at a deductive description of relevant physical processes, which contribute to beach profile evolution. Their deductive approach makes these models relatively complicated and their computational efforts are considerable compared to the more inductive model concepts discussed above. Their strong point, on the other hand, is that they do not rely on an equilibrium assumption, which depends on local conditions and is often determined from measured data. Instead, process-based models rely on processes alone, which in principle should enhance their generic applicability.

One important difference between process-based models and other concepts lies in the way they estimate the time-averaged cross-shore transport rate $\bar{q}(x)$. In a process-based profile model, the sediment transport distribution over the profile is computed as a function of the local bottom elevation z_b, cross-shore sediment properties and seaward boundary conditions, such as wave height, period and angle of incidence. The rate of change of the bottom level is computed from the continuity equation for the sediment volume

$$(1 - n)\frac{\partial z_b}{\partial x} + \frac{\partial \bar{q}}{\partial x} = 0 \qquad (15)$$

where n is the pore content of the bed material. The profile after a time step Δt is estimated, followed by an update of the associated hydrodynamics and transport field. It is the repetition of this procedure which makes this type of models dynamic in character, see Figure 10.

ROELVINK and BRØKER (1993) present an overview of 5 different deterministic cross-shore profile models, including an intercomparison of their performance. All models assume that the sea state and other boundary conditions are stationary over the duration of a morphological time step, that the motion of the bottom does not affect the hydrodynamics and that the porosity of the bed material is constant. Formulated in general terms, the time-averaged cross-shore transport rate can than be written as

$$\bar{q}(x) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\int_{z_b}^{z_s} u(x, z, t)\cdot c(x, z, t)\, dz\, dt \qquad (16)$$

where u is the horizontal velocity and c the volume concen-

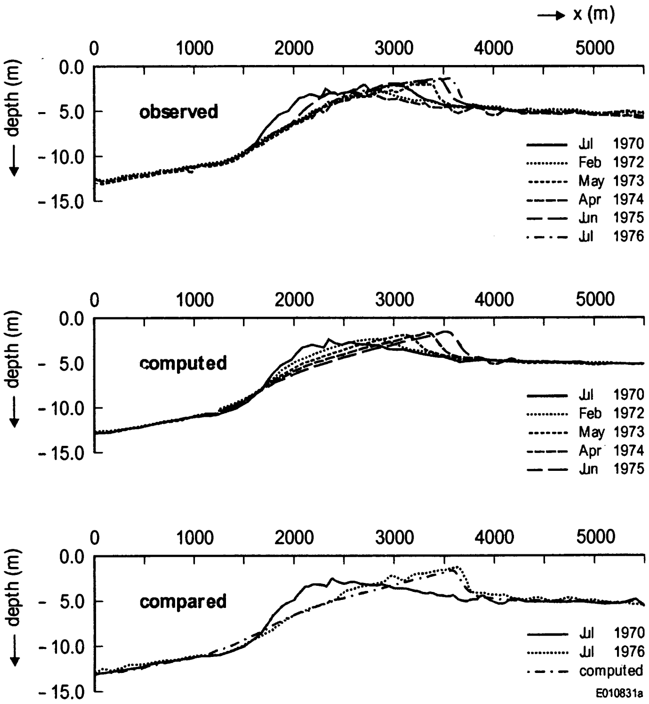

Figure 11. Comparison between profile development at the Voordelta and present theoretical prediction (after STIVE, 1985).

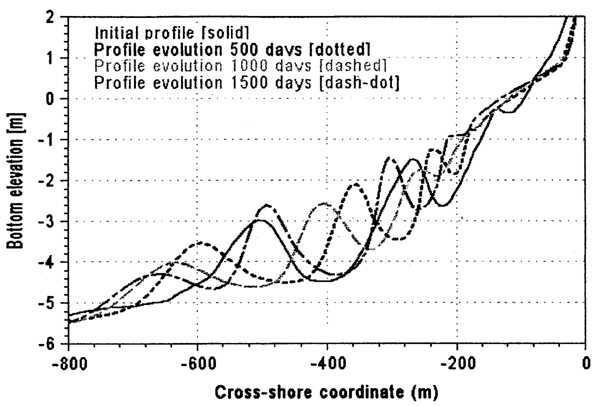

Figure 12. Model simulation of the Noordwijk 4-year bar cycle.

tration of sediment. Solution of this equation would require a time-dependent solution of the complete velocity and concentration field down to turbulence time and length scales, which would be impractical. Therefore, drastic schematizations have been made to arrive at workable model concepts.

Most process-based profile models distinguish processes at 4 different time scales, viz. (i) turbulence, (ii) wind waves, (iii) wave groups/infragravity waves and (iv) mean variations of the wave field on the time scale of the tide. Processes of class (iv) can be tidal currents or the time-averaged return flow under breaking wave conditions. They are usually dominant in cases of severe erosion. Class (iii) processes are related to wave groups. Long wave motions, associated with slow wave group induced variations in wave energy, are unable to stir up much sediment themselves. However, due to the wave group related slow variation in the orbital velocity amplitude, a variation in sediment concentration occurs on the same time scale. The long wave contribution to the cross-shore transport can then be explained from a strong correlation between the long wave motions and the variation of the sediment concentration. In class (ii) we find processes on the intra-wave time scale, like wave asymmetry and time lag effects within the wave period. When shoaling, the wave shape becomes asymmetric, which results into relatively strong, onshore velocities over a relatively short period of time, alternating with moderate seaward velocities over a longer period. Assuming an instantaneous response of the near-bottom concentration, this yields net onshore transport rates due to the strongly non-linear relationship between near-bed velocity and sediment transports. However, if the sediment concentrations further up in the water column lag behind the velocity variation, this effect is reduced and may even be reversed. The effect of class (i) turbulent fluctuations on the horizontal velocity is generally very small compared to the other contributions and is, hence, usually neglected.

Example Prediction of Shoreface Changes with Unibest-TC

Process-based coastal profile models have frequently been applied in consultancy practice, amongst others for the design of subaerial and subaqueous beach nourishments. Numerous validation studies have aimed to assess model performance towards one of the processes identified above. A characteristic and rather unique example regarding the shoreface is given by STIVE (1985). It concerns the transition of an originally ebb-dominated outer tidal delta towards a wave(-asymmetry) dominated shoreface. This occurred after the virtually complete closure of the Grevelingen tidal inlet in the southwest of the Netherlands (Figure 11). As long as cross-shore transports dominate the transport alongshore (say the first 10 years after closure), model results are in good correspondance with measurements. In the longer term, when 3D-effects become more significant, model performance gets less satisfactory, a phenomenon which is commonly observed with 1DV coastal profile models.

A second example concerns a study by AARNINKHOF *et al.* (1998) who aimed to investigate the sensitivity of model-predicted breaker bar behaviour to chronology effects in the input conditions. Unibest-TC was used to simulate bar dynamics through the surf zone at Noordwijk, The Netherlands (Figure 12). During the first few years, the behaviour of the seaward migrating bars is in good correpondance with the 4-year bar cycle as observed from field measurements (WIJNBERG, 1995). However again, on the longer term when 3D-effects become more significant, model performance gets less satisfactory.

Morphological State Models

Depth of Closure Model

Morphodynamic variability across a profile decreases in the seaward direction towards some "closure" beyond which morphodynamic changes are less than the resolution of the profile measurements (NICHOLLS *et al.,* 1998a). Thus, closure defines a seaward boundary condition for morphological modelling and related applications, but should not be confused with a sediment transport boundary. Closure is both time- and space-scale dependent: at longer time scales there is more likelihood of significant depth changes in deeper water and closure tends to increase (CAPOBIANCO *et al.,* 1997).

At scales from years to a decade, closure is usually found on the upper shoreface and is an integrated product of three interacting processes (NICHOLLS *et al.,* 1998a): (1) cross-shore sediment redistribution, (2) internal bar dynamics, and (3) net profile translation due to gradients in longshore transport. At decadal scales, closure may move to the lower/middle shoreface due to additional shoreface processes (HINTON *et al.,* 1999). At the annual scale, HALLERMEIER (1981) suggested that closure is controlled by the extreme wave conditions occurring within the annual period. Validation of this analytical method at several microtidal to low mesotidal wave-dominated sites found that the predicted closure (d_l) provides a robust *limit* to the observations (NICHOLLS *et al.,* 1998a). Although Hallermeier's approach was presented for an annual timescale, the model can be generalized for any time interval. Agreement between predictions and data appears to be best at the annual scale: at longer time scales the predictions grow more quickly than the observations. A key control on the scatter below the model limit appears to be the internal bar dynamics. This is illustrated on the Holland coast where HINTON and NICHOLLS (1998) found that two distinct closure provinces exist with closure depths of about 5 and 8 m, respectively. Wave and sediment characteristics are very similar and the only significant difference between these areas are the time scales and modes of offshore bar migration (see WIJNBERG, 1995). Therefore, a better understanding and prediction of bar behavior would seem essential to improve closure predictions at the years to decade scale. The data from the Holland coast also show that Hallermeier's method could not predict closures on the lower/middle shoreface and is not appropriate to large scales.

Based on the above, the entire shoreface can be morphologically active at decadal scales. A division of the cross-shore profile using the closure concept to define two distinct boundaries is useful: (1) the shoreward closure on the upper shoreface and (2) the lower/middle shoreface closure (HINTON and NICHOLLS, 1998). A seaward limit of the shoreward closure can be predicted using Hallermeier in its annual form. Based on observations on the Holland coast, there is a slow increase in the depth of shoreward closure with time, but this effect is negligible when considering the limit nature of the Hallermeier predictions. Landward of the shoreward closure, sand is exchanged both on- and offshore and any modelling needs to evaluate the net effect of these processes. At decadal scales, there is a potential for a deeper time-evolving closure on the shoreface which would be associated with a net source

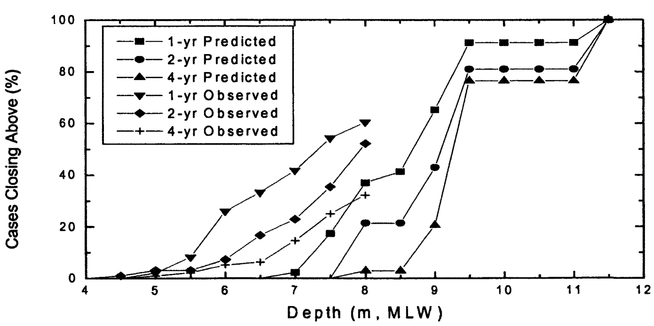

Figure 13. Predicted and observed depth of closures at Duck, NC (from NICHOLLS *et al.,* 1998b).

or sink of sand to the active zone (see COWELL *et al.,* 2003, this volume). In terms of shoreline change, the nature of the net source/sink term can be evaluated using basic sediment transport approaches (ROELVINK and STIVE, 1990), or more detailed process knowledge, if available (GARCIA *et al.,* 1998).

Closure remains to be rigorously evaluated near inlets, or on high mesotidal and macrotidal coasts. In these areas there are significant non-wave-induced currents, so while closure may remain a valid concept, d_l is expected to underpredict the annual closure. It also requires further investigation for sites that are accreting rapidly due to a gradient in longshore transport as local water depth rather than wave conditions starts to control closure.

Example Application of Closure at Duck, North Carolina

Closure has a number of potential applications related to a seaward boundary condition, including cross-shore survey design, sediment budget analysis, beach fill calculations, and model design (HALLERMEIER, 1981; COWELL *et al.,* 2003). Under appropriate conditions, this work shows that d_l (HALLERMEIER, 1981) is useful to define the shoreward closure. At Duck, accurate profile data has been collected every two weeks and after storms. This allows a rigorous definition of the shoreward closure using a 6-cm change criteria (95% confidence of real change) (NICHOLLS *et al.,* 1998b). Within the measured profile (to nearly 8.5-m depth), the data closes for 66% of annual periods, 60% of 2-year periods, 44% of 4-year periods and only 3% of 8-year periods. It is our assumption that non-closing cases normally close in deeper water. As already noted, d_l acts as a robust limit to these observations. The distribution of an annual d_l based on 42 partly overlapping samples of wave climate over 12 years is shown in Figure 13. The range from the 20 to 80 percentile of d_l is nearly 2 m. A target depth for routine surveys to define the bulk of annual closure events is the 80 percentile of d_l (>9-m depth at Duck).

A best-fit regression shows that $D_C = 0.76\ d_l$ where D_C is the observed annual closure. While the general applicability of this result to other microtidal, wave-dominated sites is uncertain it shows how empirical modifications might make HALLERMEIER (1981) suitable for applications which require a best-fit rather than a limit. One can also extend the concept of closure to a family of depth change contours at the seaward limit of the profile envelope. CAPOBIANCO *et al.* (1997) examined biweekly 5-cm, 10-cm and 20-cm changes at Duck. Empirical relationships with extreme wave heights were derived. Again, the generic suitability of these relationships is uncertain (see NICHOLLS *et al.*, 1998a), but they provide useful engineering tools which allows the user to select the depth change relevant to their problem.

Bar Migration Model

The temporal evolution of sand bars includes variations in bar position, and (not discussed in this section) variations in amplitude, wave length, and alongshore structure. On beaches where bars persist for periods of years (such as along the Dutch and US east coasts) much of the total beach profile variability is associated with changes in the cross shore position of bars (PLANT *et al.*, 1999). Thus, bar position represents an efficient and objective description of morphologic state.

On time scales associated with the passing of individual storms, bars typically move offshore during high wave conditions and onshore during milder conditions. However, on decadal time scales, net seaward bar migration can dominate bar variability (RUESSINK and KROON, 1994). PLANT *et al.* (1999) developed a heuristic model which explains interannual bar behavior. The model assumes that bar migration depends only on the incident wave height and the current bar position. The migration rate is assumed to vary with the wave height cubed (*i.e.*, proportional to the wave-driven sediment transport rate (BAGNOLD, 1963) and it is assumed that the bar migrates toward an equilibrium position that also depends on the wave height:

$$\frac{dX(t)}{dt} = -a_1H^3(t)[X(t) - a_2H(t)] \qquad (17)$$

where X is the bar position, H is a measure of the incident wave height, and a_1 and a_2 are adjustable coefficients. The parameter a_1 scales the response time of the bar, while the parameter a_2 relates the equilibrium bar position to the wave height. PLANT *et al.* (1999) verified this model at Duck, NC. The calibration coefficients (estimated from 3 different bars) showed that the response time of bars was considerably longer than 1 year, leading to significant interannual variations of the cross-shore position of bars. The parameter a_2 was found to be consistent with an equilibrium bar position located at the time-varying wave break point.

The model contains no implicit restrictions on the time scales for which model predictions (obtained by integrating (17) using a measured wave height time series) are valid. To date, however, the model parameters (a_1 and a_2) have been estimated from observations of the forcing (wave height) and response (bar migration rate). The finite sample interval of the bathymetric data (*e.g.*, $\Delta t = 1$ month) introduces a time scale limitation. Estimates of the migration rate are sensitive to high-frequency "noise" in the bar position time series. A filter must be applied to eliminate variability with time scales shorter than $2\Delta t$, which represents the shortest prediction time scale. Clearly, a future task is to quantify the model parameters based on physical conditions.

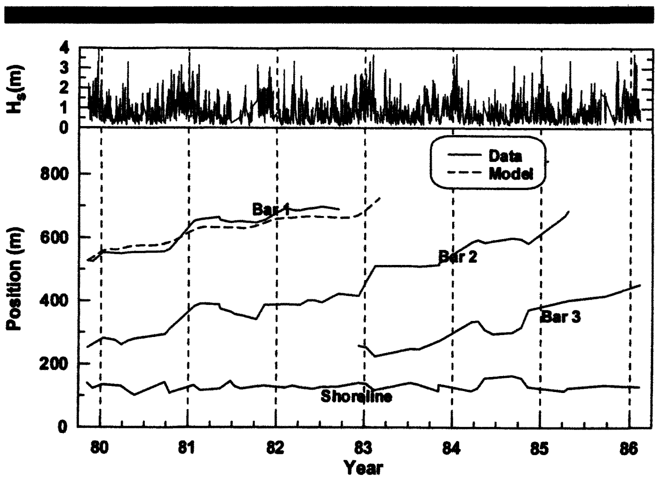

Figure 14. Comparison of field observations and model predictions of bar position variation at Katwijk. Time series of the bar positions (top) were extracted from TAW surveys along the Dutch Coast. (Data courtesy of RIKZ (Dutch Public Works Dept.) and Dr. K. Wijnberg)

Example Application to Katwijk, NL

So far, the simple equilibrium model has been tested only at the Duck (USA) field site, where the model skill over a 6 year period exceeded 0.8. The skill is defined as the squared correlation between predicted and observed bar positions. To complement the Duck application, the model was applied to a time series of monthly beach profile surveys near Katwijk, The Netherlands, to re-evaluate the model assumptions and prediction skill. The survey period was 1979 to 1986, and bar crest positions were extracted from this data set using a simple decomposition of the profile. The lower part of Figure 14 shows the position time series of 3 different bars identified at this site.

Only the response of the first outer bar has been compared to the model. Model predictions were driven by estimates of the wave height at breaking. The wave heights were measured offshore in 21 m water depth. The breaking wave height (upper part of Figure 14) was estimated using linear wave theory to extrapolate the wave height to a breaking condition: $H = \gamma h$, where h is depth, and $\gamma = 0.4$ (THORNTON and GUZA, 1982), assuming normal incidence angle. Then, the time series filter was applied to the right hand side of Eq. (17). The model parameters (a_1 and a_2) were estimated using a nonlinear regression technique, which minimized the squared deviation between the observed and predicted bar migration rates. The model prediction skill over the test period was 0.97, which was significant at the 95% level. This modeling approach is very robust, after calibration of at least one parameter (the equilibrium position at the break point applied to the Duck case as well, and can be constrained *a priori*). Finally, the approach applies to existing bars, and will not predict bar formation or destruction.

The model parameters provide physical insight into the behavior of sand bars. The estimated value of the scale for the equilibrium position (a_2 = 550) indicates that, for example, the equilibrium position of the bar is 550 m offshore for a 1 m wave height. For the mean slope at Katwijk (1/200 in the vicinity of the bars), this places the equilibrium bar position in 2.75 m depth. This is consistent with the wave break point (H/h = 0.36). The scaling for the bar migration rate (a_1 = 0.1 m^{-3} yr^{-1}), suggests that, under the forcing by the largest waves (99% of waves heights were less than 2.25 m), the maximum migration rate is about 1,500 m/yr. Under seasonal oscillations of the wave height, a bar formed near the shore could migrate only a fraction of the distance to the corresponding equilibrium position (1,200 m offshore for H = 2.25). The response rate of this bar is not fast enough for it to keep up with the seasonal variations in wave height.

2DH-SHOREFACE-BEACH EVOLUTION

(Semi-)Empirical Multi-Line Models

Multi-line models have been developed to describe the movement of selected depth contours in a similar way as one-line models. The cross-shore exchange of sand between the various cross-shore subsections and associated changes in the bed profile can to some extent be taken into account. This was first accomplished by BAKKER (1968), later by PERLIN and DEAN (1983), by DE VRIEND and BAKKER (1993), and STEETZEL (1995). In spite of the additional detail given by the multi-line models, they have not been very successful, mainly because it has been difficult to specify realistic relations for cross-shore sediment transport and for the cross-shore distribution of the longshore transport. The initial result was a model that is more detailed than the one-line model, but also requires much more calibration and in the end does not provide significantly more new information than it requires for calibration.

Some recent developments have substantially increased the applicability of these models. Starting with the BAKKER's two-line model (1968), STEETZEL (1995) extended the concept by incorporating the morphological behaviour of mixed tidal inlets based on work by DE VRIEND and BAKKER (1993) and more recently by adding more layers and improving the way in which both the cross-shore and longshore interaction was taken into account. A similar model, called INSHORE, was developed for modelling of shoreline response near inlets (HANSON and LARSON, 1999) but also applicable to open coasts.

In the present version of the so-called PONTOS-model (STEETZEL, 1995), the cross-shore profile is schematised into five horizontal layers and two additional zones. The first physical layer refers to the dune layer, whereas subsequent layers refer to profile sections positioned further seaward. The actual position of a layer has to be assessed from the sediment balance of the cross-shore profile. The individual layers within the model respond to gradients in the longshore transport generated at the profile regions they represent. Using the concept of a layer-approach, the volume in a specific cell or layer is represented by the specific position of the layer in cross-shore direction. Thus, a change of volume within a cell yields a cross-shore shift in the characteristic position of layer.

The mathematical model uses yearly mean wave climates at the seaward boundary as input. Specifically, wave conditions must be described on the most seaward depth contour. This climate schematization forms the main driving force of the model. New formulations for both the cross-shore interaction and the longshore transports had to be developed and implemented in the model. The cross-shore interaction is based on the principle of a single wave-based equilibrium profile as discussed above with regards to 1D multi-line models.

Formulations for both the wave-induced and the tide-induced longshore transport are based on series of computations carried out with a process-based model. Relevant input parameters are wave climate, (horizontal and vertical) tide and sediment characteristics. The wave-induced transport rate mainly depends on the incoming wave energy and the direction of wave propagation relative to the coastline. For the cross-shore distribution of the longshore transport a relation has been defined to distribute the transport over the individual layers. Furthermore, a schematised formulation for wave diffraction and refraction has been implemented to account for the modified wave field around structures. In a later stage it is envisaged to also include the effect of flow contraction around structures (GRAAFF *et al.,* 1998) as discussed in STEETZEL and VROEG (1999).

Example Application of INSHORE Model to Duck, North Carolina

Simultaneously collected data on waves and beach profiles from the US Army Field Research Facility at Duck, North Carolina (HOWD and BIRKEMEIER, 1987; LEE and BIRKEMEIER, 1993) were used to investigate the predictive capability of the proposed algorithm over a longer time period. The data set comprised shoreline positions extracted from surveys taken approximately biweekly during 11 years. Wave properties (significant height and peak period), recorded at least every 6 hours, were available for the same period.

Based on the wave time series, the cross-shore sediment transport rate was calculated at each time step. The time period 1981–85 was used for calibration and the period 1986–91 was used for validation. In the calibration procedure, a best fit value on the calibration coefficient was determined by minimizing the difference between measured and calculated *shoreline* positions. The result of the model calibration and verification is shown for the shoreline position together with calculated positions of all the model layers in Figure 15. As seen in the figure the shoreline and the 4-m contour (closely associated with the outer bar) show an opposite response, where an eroding shoreline corresponds to a seaward migration of the offshore bar, which is commonly observed in the field. An analysis where the changes at the −2, −4, and −6-m contours were correlated with the shoreline changes resulted in correlation coefficients of (contour levels in parentheses): 0.60(−2), −0.87(−4), and −0.67(−6) implying a continuous exchange of material between the inner and the outer parts of the profile. These numbers are in qualitative agreement with observations at Duck.

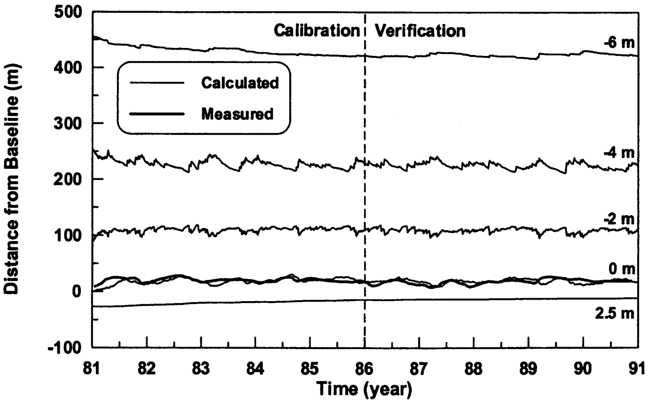

Figure 15. Calculated temporal variation of contour levels and measured shoreline variation at Duck, NC. (Modified from HANSON and LARSON, 1999)

Process-Based 2DH/Q3D Models

Process-based 2DH/Q3D-shoreface-beach models aim at a description of relevant physical processes, that contribute to changes of nearshore morphology over an area, where phenomena in the horizontally two-dimensional space cannot be neglected. At both the conceptual level and the numerical implementation level, these models commonly start from a number of more or less standard models of the constituent processes (waves, currents, sediment transport), which are coupled via a bottom evolution model based on sediment conservation. DE VRIEND *et al.* (1993) discuss various aspects, such as the mathematical character, the inherent stability and possible equilibrium states of these models. With regard to process-based models they distinguish two basic concepts:

(1) "initial sedimentation/erosion" (ISE) models, which go only once through the sequence of constituent models; these are in fact morphostatic models, since the hydrodynamic and sediment transport computation is based on the assumption of an invariant bed topography and only the rate of sedimentation or erosion for that topography is computed;
(2) "medium-term morphodynamic" (MTM) models, in which the new bottom topography is fed back into the the hydrodynamic and sediment transport computations; this yields a looped system which describes the dynamic time-evolution of the bed.

Being complicated in terms of spatial process resolution and computationally intensive, model applications used to be limited to ISE-approaches, determining an initial transport field. Using a sediment balance approach, the pattern of accretion/erosion can then be determined from the divergence of the transport field. This type of modelling has fruitfully been in applied in comparative studies, *e.g.* to predict the effects of different designs of coastal structures, and to test the contributions of various individual sets of conditions (like storms, spring tide, *etc*).

Temporal extension of the divergence of the initial transport field will generally not suit to attain a state of equilibrium. Especially, this morphostatic approach yields inaccurate results in case of coastal systems of high morphodynamic activity (like rip-currents). These factors have stimulated the development of medium-term dynamic models. An important limitation is that the morphological timescale of these essentially deterministic "morphodynamic" simulations cannot be substantially larger than the hydrodynamic time scale (duration of an event, tidal period). Therefore, initially, these dynamic models could be applied on the event time scale only, due to limited computational power. However, recently this time horizon was extended up to 5 years, in case of medium-term morphodynamic computations for the Maasvlakte-2 land reclamation in The Netherlands (WALSTRA *et al.,* 1997). A key-element to reach these medium-term time scales is the introduction of a so-called morphological tide, which is a representative tide that yields a residual transport similar to a full spring-neap tidal cycle (LATTEUX, 1995; DE VRIEND *et al.,* 1993). In this way, computation time is strongly reduced.

Generally, morphodynamic area models consist of a wave, flow, sediment transport, and bed level change module. Usually, the wave and flow modules of various modelling systems do not differ significantly (NICHOLSON *et al.,* 1997). In search of a classification of transport models, we need to distinguish between the dimension of the flow model (2DH/Q3D/3D) and the dimension of the transport model. Transport models of lower dimension can be applied in one context with flow models of equal or higher dimension, the other way around being rather unlikely.

Empirical transport formulations (like the well-known Bijker formula or the Bailard approach) assume an *instantaneous* response of the sediment load to *local* hydrodynamic conditions. In that sense they can be considered as 0D transport models, which might suit well for the modelling of bed load transport. However, when modelling suspended sediment loads, the vertical concentration distribution and associated time lag effects are important. These elements are not covered by a 0D transport model, therefore models of higher dimension are needed to enable the modelling of the suspended component.

At the intra-wave level, 1DV transport models (*e.g.* FREDSOE and DEIGAARD, 1992) have been developed which estimate—after averaging over the wave period—suspended transport rates as a function of local hydrodynamic conditions. These schemes account for time-lag effects down to the intra-wave time scale. Being 1DV, they can only be applied in absence of significant spatial gradients. By nature, 1DV intra-wave models account for cross-shore transport induced by undertow and/or wave asymmetry.

At the wave-averaged level, Q3D (*e.g.* KATOPODI and RIBBERINK, 1992) and 3D (*e.g.* VAN RIJN, 1993) transport models have been developed which aim to estimate the dynamic sediment load, by solving the diffusion-advection equation for suspended sediment concentrations (either quasi- or fully-3D) This diffusion-advection equation is time-dependent, though on a time scale larger than the intra-wave scale. Q3D and 3D transport models are appropriate for the modelling of suspended sediments in spatially-varying flow conditions. Inclusion of cross-shore transport induced by undertow and/or

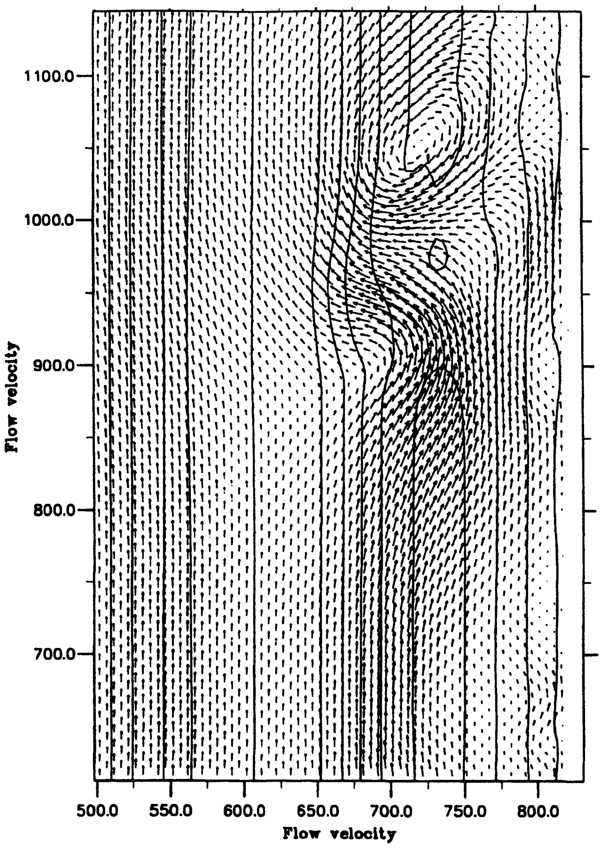

Figure 16. Outflow of rip-current (after VAN NOORT, 1997).

wave asymmetry can be achieved, though only by means of additional, empirical formulations or under some specific conditions.

Example Application to Morphodynamic Modelling of a Rip-Current System with Delft3D-MOR

With the help of a Q3D flow model and a 0D transport model (Bijker formula), VAN NOORT (1997) simulated the morphologic evolution of a rip-current system. Starting from a small initial rip-channel across the inner bar, rip-currents tend to grow during moderate wave conditions (H_{sig} about 1.5 m), with small angles of incidence (smaller than 10° with respect to shore-normal) and a moderate longshore current. These conditions match well with those mentioned in literature to be favorable for the generation of rip currents (*e.g.* AAGAARD *et al.,* 1997). Figure 16 shows an example of the resulting flow pattern, where the dry beach is located at the right hand side of the figure. Although the model behaviour was correct in a qualitative sense, the magnitude of the transport rates turned out to be underpredicted, whence the morphological time scale was too long.

Hybrid 2DH/Q3D Models

Morphodynamics of larger scale problems (relative to surfzones), like the seabed and nearshore vicinity of coastal inlet systems, include a wide spectrum of time and length scales: days/meters for tidal flats, years/kilometers when considering migrating tidal channels and decades/tens of kilometres for large-scale morphological changes like shoreface steepening. No process-based modelling concept is available yet that can account for all these scales simultaneously. This has promoted the application of so-called hybrid modelling systems.

A hybrid modelling system combines modelling tools, both process-based and behaviour-oriented, in which an appropriate model concept is applied for the various time and length scales of consideration. Generally, larger scale models need input from smaller scale models, for instance an initial transport field or an indication of the equilibrium state. To arrive at larger time scales (decades to centuries) the use of behaviour-oriented models is indispensable, however, for decadal modelling a (reduced) process-based approach will do.

Generally, the deterministic 2DH/Q3D-models as discussed above can be used for the modelling of decadal seabed and outer delta evolution as well. However, because of the large spatial scales involved, the computational efforts can be considerable. Therefore, a reduced concept has been developed, which can be considered as a parameterized extension of the deterministic 2DH/Q3D models (ROELVINK *et al.,* 1998). The reduced concept assumes that the flow and wave patterns do not change significantly as a result of small bottom changes. Starting from the well-known continuity correction, local flow velocity and orbital motion can be parameterized as a function of local depth only. As sediment transport can be modelled as flow velocity to some power combined with the orbital velocity to some power, also the local transport rate can be parameterized as a function of local depth, starting from an initial transport field. The availability of a good-quality transport field, obtained from 2DH/Q3D deterministic modelling, is of crucial importance in view of successful application of the parameterized concept. In this way, the time horizon of process-based modelling capability can be extended up to decades.

A clear example of the application of such a hybrid modelling system is given by WALSTRA *et al.* (1997). They predict the changes of morphology along the Dutch coast, including the Zeeland tidal inlets, on time scales that vary from days to centuries, making use of model concepts that cover the full spectrum between small-scale process-based and large-scale behaviour-oriented. Application of this type of hybrid systems is expected to contribute substantially to the time-efficient modelling of coastal inlet evolution on the medium term time scale.

CONCLUSIONS AND CLOSING REMARKS

The paper presents some twenty different types of models for describing coastal evolution on yearly to decadal time scale. Even with this restriction in time scale, there are still a large variety of problems that these models need to address in order to describe differences in spatial scales and governing processes. Each type of model typically focuses on a limited range of processes acting over a certain scale. Thus, every model application should include careful considerations regarding the processes primarily governing the beach evolution.

Short-term, process-based models are typically not well suited for the prediction of longer-term coastal evolution. In these models, the physical processes relevant for the longer-time evolution are generally not included. Instead, these models focus on short-term morphological processes that are dominated by time-varying phenomena such as waves, tides, *etc.* Most of their effects, however, average out in the long run, whence the longer-time evolution is determined by much weaker residual effects, which are often disregarded in short-term models.

At the same time, it seems like models with a more simplified approach, such as 1D-shoreline evolution models, are better suited for longer-time simulations as most of the non-linear interconnections and feed-back mechanisms between different processes are ignored or parameterized in a simplified manner. Thus, it may be concluded that different models are best suited to describe a limited range of situations and that each specific situation can only be studied, using one or two specific types of models. To be able to address problems spanning over different scales and processes we, thus, need to use more than one type of model. However, much more effort is required to bring the different model concepts together to bridge the gap between scales and processes. Based on this, it is recommended that future efforts should be directed towards model integration rather that enhancement of individual model concepts.

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