MATHEMATICAL MODELLING OF 3D COASTAL MORPHOLOGY

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1. Introduction

Coastal evolution processes are often three-dimensional, probably even more often than not. Still, important aspects of the coastal behaviour can be understood and predicted on the bases of lower-dimensional model concepts, due to the circumstance that the physical system often exhibits a different behaviour with essentially different length scales in three mutually orthogonal space directions (vertical, cross-shore and longshore). This has led to a range of practically useful numerical model concepts, such as

- coastline models, which describe only the largest-scale behaviour (longshore) after having integrated over the smaller scales (vertical, cross-shore),
- coastal profile models, which ignore the longshore variation, parameterize the vertical dimension and concentrate on the medium-scale cross-shore evolution,
- local models, which ignore the larger and intermediate horizontal scales and concentrate on small-scale phenomena (e.g. ripple formation) in which the vertical dimension cannot be ignored or parameterized.

Between these main concepts, numerous intermediate model types have been developed (e.g. multi-line models, multi-profile models). Some of them have been described in the previous lectures (for instance, see Kamphuis).

The present lecture deals with models for situations in which the spatial dimensions cannot be separated according to the scales of the morphological processes. Rather common examples of such situations are the morphological evolution near structures (e.g. breakwaters), river outflows, tidal inlets, etcetera. But also in the absence of such distinct disturbances, the system can be more complex than one might expect at first sight, for instance due to the presence of a rip channel and bar system.

After an outline of the basic concepts of various state-of-the-art models which are claimed to describe 3-D coastal evolutions, the potentials and shortcomings of the various model types will be discussed and the role of the constituent process models will be considered from a morphological modelling point of view. Subsequently, the methodology and some pitfalls of practical application will be discussed, and, finally, I will identify the principal needs for further research and the approaches which may be taken.

In their book entitled 'Nearshore Dynamics and Coastal Processes' (1988), Horikawa and his colleagues give an excellent review of the state of the art in 3D coastal morphological modelling, though with the emphasis on Japan. In this lecture, I will not attempt to redo their work, but I will give some additions and comments, based on my own experience and recent European research (see De Vriend, 1991a).

2. Basic model concepts

Both at the conceptual level and at the numerical implementation level, multi-dimensional coastal evolution models usually start from a number of more or less standard models of the constituent physical processes (waves, currents, sediment transport), which are coupled via a bottom evolution module based on the sediment balance. Figure 1 summarizes the model concepts of this type.

The figure represents three basic concepts, viz.

1) "initial sedimentation/erosion" (ISE) models, which go only once through the sequence of constituent models; in fact, 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 at every location,

2) "medium-term morphodynamic" (MTM) models, in which the new bottom topography is fed back into the hydrodynamic and sediment transport computations; this yields a looped system which describes the dynamic time-evolution of the bed; the time-scale of
this "morphodynamic" (Wright and Thom, 1977) simulation is not far from the hydrodynamic time scale (duration of a storm, tidal period), although the time-stepping techniques are becoming more and more efficient, and

(3) "long-term morphological" (LTM) models, in which the constituting equations are not describing the individual physical processes, but integrated processes at a higher level of aggregation; these equations have been derived from the process models via formal mathematical operations (time-averaging), physical reasoning and/or empiricism (closure hypotheses); the methodology strongly resembles the one in turbulent flow modelling.

In the next sections, each of these concepts will be discussed in further detail.

Fig. 1. Compound morphological model concepts

3. Model composition

The series of constituent process models is an essential element in all model concepts. Even the long-term models, though solving a different system of equations, have to make use of information from ISE-computations, in order to determine the coefficients. The composition of this series turns out to be a key part of morphological modelling, which is far from trivial and determines to a high extent the quality of the final result. Morphological modelling therefore requires a thorough knowledge of wave, current and sediment transport modelling, at the conceptual as well as the application level. Still, I will not revisit the constituent models in detail, assuming that they have been discussed at length in the previous lectures. Here these models will be discussed at a higher level of aggregation, as elements in a compound morphodynamic model.

In general, the constituent models have to meet the following requirements:

(1) the physical phenomena which are relevant to the morphological evolution have to be included,
(2) unimportant phenomena included in the model may not have a noticeable morphological impact,
(3) the combination of constituent models has to include the morphologically relevant interactions, and
(4) this combination may not lead to spurious interactions.
It is very important that the constituent model properties be considered from a morphological point of view. Even a combination of models which yield acceptable results when considered separately, can yield very poor morphological predictions (see De Vriend, 1987a).

In this chapter, the "minefield" of morphological model composition will not be discussed at length, but a few aspects will come forward in the next sections.

4. ISE-models: Potentials and limitations

The part of the compound model system which is used for initial sedimentation/erosion models is highlighted in Figure 2.

As one might expect, models of the ISE-type are the widest used in practice. The computational effort involved is relatively small and the implementation is relatively easy. Besides, the latest process descriptions can usually be included without too many unexpected complications (although there is still a risk; for instance, see Dingemans at al., 1987, or De Vriend and Ribberink, 1988).

Models of this type, however, are difficult to interpret in terms of longer-term morphological evolutions. Actually, they only provide information on phenomena at a time scale much smaller than the morphological one. Depending on the latter, they may be good enough to represent only part of a storm, or as much as a number of years. Given these inherent potentials and limitations, the question is how to make optimum use of ISE-type models.

In order to structure the discussion, three main axes of model quality are distinguished (Figure 3), which indicate the degree of representation of the real-life conditions, the constituent physical processes, and the inherent morphological behaviour, respectively.

Obviously, ISE-models are close to the real-life conditions/constituent processes plane, since they do not represent the morphodynamic behaviour of the system, at all. This means, that these models should be utilized to investigate the effects of real-life conditions and constituent processes on the initial hydrodynamic and transport phenomena.
Fig. 3. Schematic classification of model types

The principal output of an ISE model is the sediment transport field, rather than the sedimentation/erosion pattern. Experiments with 3D medium-term morphodynamic models show, that the initial sedimentation/erosion rate is not necessarily representative for what happens after some time, whereas the transport pattern is much more so (see the example in Figure 4).

Also, the interpretation of ISE-model results in terms of longer-term morphological evolutions is often easier on the basis of the residual transport field.

One way to utilize ISE-models is to test the contributions of various individual sets of conditions (storms, moderate wind periods from various directions, calm weather periods, spring tide, neap tide) to the residual transport and sedimentation/erosion fields. In complex situations, such as tidal inlets, the answer is not obvious, especially as proposed engineering works tend to have different effects under different conditions. Examples of such studies are described in Steijn et al. (1989) and Steijn and Louters (1992).

Another way of utilizing these models is the analysis of the overall transport processes in the area of interest, before and after the changes which have to be investigated. Once the model has been validated and has shown its reliability, it can be used to unravel the physical processes at a global level (in contrast with the constituting differential equations, which describe the processes at a local level). An example of such an analysis is shown in Figure 5.

This way of utilizing ISE-models can be integrated with field data analyses into a hybrid prediction methodology (De Vriend, 1991c). The number of applications of such hybrid models, however, is still very limited, and there remains much work to be done before this has become a robust and ready-to-use technique.

The use of ISE-models is not necessarily restricted to sand transport: the transport and fate of cohesive sediment can also be described by this type of models (for instance, see Fritsch et al.; 1989; Villaret and Latteux, 1992).
Fig. 4. Representativeness of ISE-model results for medium-term morphological evolutions
(a) initial bathymetry and transport pattern
(b) bathymetry and transport pattern after 5 days
(c) initial rate of bed level change
(d) bed level changes after 5 days
[from: J.A. Roelvink, private communication]
Fig. 5. Global process analysis based on an ISE-model

5. MTM-models: Potentials and limitations

Figure 6 indicates which part of the compound model system is used in medium-term morphodynamic models.

Fig. 6. Medium-term morphodynamic (MTM) models

In contrast with ISE-models, MTM-models, at least in the present state of development, are located in Figure 3 near the inherent behaviour/constituent process, still
rather close to the origin. Although some interesting applications have been shown (Watanabe et al., 1986; Murayama and Takagi, 1988; Shimizu et al., 1990; Andersen et al., 1991; Watanabe et al., 1991), these models are still in a rather early stage of development, and there are still elementary problems at the conceptual and implementation level. Some of these will be discussed later in this Section.

Sooner or later, most of these problems will be solved, and also the high computational expenses will decrease. By that time, MTM-models can be a powerful tool for morphodynamic simulations up to time spans of the order of the time scale of the relevant morphological evolutions, provided that the physical understanding keeps up with the potentials of the numerical models.

MTM-models are not likely to be able to cover time spans which are much larger than the inherent time scale of the relevant morphological evolutions. The described process is non-linear, and the input conditions are uncertain and include extreme events, so the predictability of the morphological evolution must be expected to decrease as the time span increases. The further quantification of this statement, however, is still a research issue.

6. 2DH MTM-models

When describing potentials and limitations of 3D coastal morphodynamic models, it is essential to distinguish between 2D depth-integrated (2DH) models and (quasi-)3D models.

The composition of a 2DH model is generally as follows:

- a wave field model of the usual kind;
- a wave-driven force computation, on the basis of radiation stresses or wave energy dissipation,
- a depth-integrated current model, describing the depth-averaged velocity field without vertical resolution; all information on the vertical flow structure is lumped into the closure hypothesis for the bottom shear stress, which assumes plane shear flow including wave effects; external forces cannot be distinguished by the level at which they act;
- a sediment transport formula or a depth-integrated suspended load model, which describes the depth-averaged sediment concentration without vertical resolution;
- a sediment balance module, which computes the bed level changes from the divergence of the transport field.

2DH morphodynamic models are developed at various places all over the world, also in Europe (Coeffé and Péchon, 1982; De Vriend, 1987a; Gallerano and Ruffini, 1989; O'Connor and Nicholson, 1992; Andersen et al., 1991).

The 2DH concept involves a number of fundamental problems, in the hydrodynamic and sediment transport parts, as well as in the morphodynamic system as a whole. Since this chapter is on morphodynamics, the hydrodynamic and sediment transport problems will not be treated here, unless they have a direct bearing on the morphodynamic process.

The principal morphodynamic problems originate from the absence of a number of important slope-related transport mechanisms, which can have implications for the inherent stability of the system and for the equilibrium bed topography. These problems become the most manifest if the sediment transport model consists of an algebraic formula which relates the transport rate to the depth-averaged velocity and the wave orbital velocity at the same location. There are many such sediment transport formulae (see Horikawa, 1988, or Van Rijn, 1989, for a review), and they are widely applied, so the case is relevant.

6.1 INHERENT STABILITY

A morphodynamic model with a transport module like this is easily shown to be inherently unstable if its flow module is a rigid-lid model without wave-driven currents. In that case, infinitesimal harmonic perturbations of any wavelength, which are not affected by the boundaries, tend to grow exponentially (Figure 7a; also see De Vriend, 1986).
As this is a property of the system of differential equations, it cannot be removed by improving the numerical implementation. Inversely, if the numerical implementation of this model gives a stable solution, this must be due to numerical smoothing effects.

![Figure 7](image)

**Fig. 7.** Growth rate of harmonic bottom perturbations, with the downslope gravitational transport (a) ignored, (b) included, and (c) included only in the flow direction.

The remedy against this is to include the slope-limiting effects which are present in nature. The most effective one is the down-slope gravitational transport component, which can be included as follows (also see Horikawa, 1988)

\[
q_x = q_x^1 - \beta |q_t^1| \frac{\partial z_b}{\partial x} \quad \text{and} \quad q_y = q_y^1 - \beta |q_t^1| \frac{\partial z_b}{\partial y}
\]  

(1)

in which \(x\) and \(y\) are horizontal cartesian coordinates, \(q_x\) and \(q_y\) are the transport components, \(q_x^1\) and \(q_y^1\) are their equivalents for a horizontal bed, \(|q_t^1|\) is the total transport rate for a horizontal bed, \(z_b\) is the bed level, and \(\beta\) is a constant coefficient.

Some authors propose different versions of Eq. (1), e.g. with different coefficients for the downstream and the cross-stream components (Struiksma et al., 1985). The modelling of the down-slope gravitational transport is still a research topic, which is the most advanced in river dynamics (for instance, see Ikeda and Parker, 1989). In coastal dynamics, it is still highly empirical.

The effect of this additional transport component is shown in Figure 7b. In physical terms, the effect is diffusive, as becomes evident when taking the divergence of the transport rates according to Eq. (1).

Figure 7b also shows that not all modes are damped: there is a class of modes, with their crests under a sharp angle with the transport direction, which remain growing. This concerns very large and slowly growing features, which occur in nature, indeed (linear sand banks; see Huthnance, 1982; also see Pattiaratchi and Collins, 1987, for a review).

Various authors propose to include only part of the downslope gravitational transport, e.g. the upstream/downstream component

\[
q_x = q_x^1 [1 - \beta (\frac{\partial z_b}{\partial x} \cos \alpha + \frac{\partial z_b}{\partial y} \sin \alpha)] \quad \text{and} \quad q_y = q_y^1 [...]
\]

(2)

in which \(\alpha\) denotes the transport direction.

The extension of the transport model with this downstream gravitational component turns out to increase the stability of the model significantly, but not enough (see Figure 7c).
The actual hydrodynamic modules in coastal morphodynamic models use to be more complicated than the rigid-lid model in the above analyses. They include stabilizing elements such as a free surface, horizontal diffusion of momentum and, to some extent, wave-driven currents (cf. the diffusive effect of the wave-driven longshore current in a coastline model). This may explain why test runs with such models yield stable results, even if the numerical scheme is free from numerical diffusion (Zyserman, 1992; Roelvink, 1992; both private communications). A rigorous stability analysis for these models remains to be made.

Coastal morphodynamic models contain a multitude of non-linear elements (e.g. advection, bottom friction, transport model), which may lead to non-linear instability. This may explain two independent observations from tidal morphodynamic models (Latteux, 1992; Chesher, 1992; both private communications): after a seemingly stable and sound computation over a large number of tides, the model suddenly produces nonsensical results or becomes unstable.

6.2 EQUILIBRIUM BED TOPOGRAPHY

The problems concerning the equilibrium bed topography have to a large extent the same cause as those with the inherent stability, viz. the inadequate modelling of slope-related transport mechanisms. If these effects are ignored, the model can be inherently unstable, but it can also yield an unrealistic equilibrium state.

A simple illustration of this statement is a beach which is uniform alongshore and which is exposed to a stationary obliquely incident wave field.

![Fig. 8. Alongshore uniform equilibrium beach](image)

(a) without cross-shore transport mechanism,
(b) cross-shore slope-induced transport included,
(c) all cross-shore transport mechanisms included.

If this situation is modelled without the downslope gravitational transport, the mechanisms which relate the various depth zones with each other are very weak (horizontal diffusion of momentum), or physically unrealistic (numerical diffusion). Each depth zone in such a model, however narrow, is therefore virtually independent of its neighbours. Hence the beach profile can take any shape (Figure 8a), as long as it complies with the upstream boundary condition.

This is in contrast with various observations, in laboratory experiments and in nature, e.g.
- the shape of the coastal profile, especially the upper part, evolves much faster than the longshore topography (Péchon et al., 1988; Howd and Birkemeier, 1987); in fact, this is why coastline models, which are based on the assumption of profile similarity, work so well (cf. Horikawa, 1988);
- the beach profile tends towards an equilibrium shape which is a function of the hydrodynamic conditions and the sediment properties, but not of the longshore topography (Dean, 1977; also see Horikawa, 1988).
In mathematical terms, the bed evolution has too much of a propagation character and too little of a diffusion character, as is illustrated by reworking the mass conservation equations for the water and the sediment into (for instance, see De Vriend, 1988)

\[
(1 - \varepsilon_p) \frac{\partial z_b}{\partial t} + \frac{|q_t|}{h} \left( b_1 \frac{\partial z_b}{\partial s} + b_2 \frac{h}{R_n} \right) - \beta \left[ \frac{1}{l_n} \frac{\partial}{\partial s} (|q_t| l_n \frac{\partial z_b}{\partial s}) + \frac{1}{l_s} \frac{\partial}{\partial n} (|q_t| l_s \frac{\partial z_b}{\partial n}) \right] = 0
\]

in which \(t\) is time, \(s\) is the metric distance along the streamline, \(n\) is the metric distance along the normal lines, \(R_n\) is the radius of curvature of the normal lines, \(l_n\) and \(l_s\) are the metric coefficients of the curvilinear natural coordinate system (for instance, see Rouse, 1965), \(\varepsilon_p\) is the porosity of the bed, \(h\) is the water depth, and \(b_1\) and \(b_2\) are constants.

Although Eq. (3) does not describe all of the bed behaviour, but only the "kinematic" part, it does show the effect of ignoring the downslope gravitational transport \((\beta = 0)\): only the propagation terms and the source term with \(R_n\) remain. As the source term only represents the effect of convergence and divergence of the streamlines, this implies that the equilibrium bed topography depends very strongly on the upstream boundary condition, irrespective of how far the boundary is away.

Although the above does not formally prove the deficiency of models which ignore the cross-stream gravitational transport, it strongly suggests that this effect ought to be included, especially in nearshore applications.

This may still be not enough for the equilibrium bed topography to make sense. In the case of the alongshore uniform beach, for instance, the bed will become horizontal if the dune front does not act as a source of sediment (Figure 8b). This is readily shown by omitting the \(s\)- and \(t\)-derivatives and the \(R_n\)-term from Eq. (3).

The diagnosis of this problem is simple: for the model to give sensible results in the longer run, it is necessary to include all important slope-affecting mechanisms, the generating as well as the reducing. Because a significant part of these effects is related to the 3D flow structure, however, the implication can be rather dramatic: this rules out the 2DH model concept for the medium-term simulation of wide range of multi-dimensional coastal morphodynamic evolutions.

This does not mean, of course, that all the work which has been done, and is still being done, to develop these models is wasted. Slope-related effects are not always and everywhere important, as is shown by the performance of a simplified 2DH model concept, which describes the scour due to flow contraction near structures. The key element in this concept is the following truncated steady state version of Eq. (3),

\[
b_1 \frac{\partial z_b}{\partial s} + b_2 \frac{h}{R_n} = 0
\]

Since, by definition,

\[
\frac{1}{R_n} = \frac{1}{l_n} \frac{\partial l_n}{\partial s}
\]

we find that

\[
h \frac{b_1}{l_n} = \text{invariant}
\]

along a streamline. Hence, if we know the flow field after construction, and \(h\) and \(l_n\) at the upstream boundary of the model domain, we can calculate the water depth and the bed topography throughout the area.

This concept can be extended rather easily to situations with tides and waves.
2DH models can also be of use to simulate the early stages of morphological evolutions, covering time spans which are small as compared with the time scale of the cross-stream profile evolution which is relevant to the case. Thus they can be a useful extension of the ISE-models.

In the next part of the Section, 2DH models will be shown to be a suitable basis for a more sophisticated class of models, which do take the 3D flow structure into account.

7. Quasi-3D models

The conclusion that in a wide range of situations all important slope-affecting mechanisms should be included necessitates an inventory of these mechanisms. Although a good deal of them seems to be known, this is still very much a research issue, and the state-of-the-art knowledge is probably not sufficient to give a complete picture.

It may be useful to start from an overall notion of how the system works as far as the slope-effects are concerned. In principle, there are three kinds of transport agents:

- slope-independent transport mechanisms,
- slope-dependent "active" transport mechanisms, where the sediment-carrying water motion is slope-dependent, but does not necessarily vanish as the slope goes to zero, and
- slope-dependent "passive" transport mechanisms, which are due to the slope as such and vanish as the slope goes to zero.

Depending on the outflow conditions for the sediment, or rather the amount of sediment which can be carried through the system, these mechanisms tend towards an equilibrium.

In the extreme case of a uni-directional current on a horizontal bed in an unbounded domain, all the sediment can be carried through the system and the bed remains horizontal. In the other extreme case of an alongshore uniform beach with a fixed dune front and normally incident waves, no sediment can be carried through the coastal boundary and a sloping profile develops. Figure 9 gives an illustration of an intermediate case: a situation where part of the onshore transport is carried out of the system, for instance near the tip of a barrier island. Here the profile slope is smaller than in a situation where all the sediment remains within the profile (i.e. at an alongshore uniform coast).

![Fig. 9. Effect of beach sediment removal on the cross-shore slope](image)

(a) no net sediment removal of sediment,
(b) net sediment removal from the active zone

So slope formation is related not only to transport mechanisms, but also to transport boundary conditions.

It seems obvious to start investigating these phenomena by their most extreme manifestation: the coastal profile evolution. Research in this area is in full swing (for instance, see a large number of papers at the "Coastal Sediments '91" Conference (Kraus et al., 1991); also see Wright et al., 1991). It has revealed, or shed a new light on, many morphologically relevant cross-shore transport mechanisms, such as (also see Horikawa, 1988)
- the asymmetry of the shallow-water wave motion,
- swash, including the modulating effect of long wave phenomena such as surf beat,
- residual cross-shore currents in the surf zone, such as wave-induced undertow,
- residual cross-shore currents outside the surf zone, e.g.
  + wave-induced streaming,
  + wind-driven currents,
  + tide- and density-driven currents,
- non-linear interactions between sediment-moving agents, such as
  + waves and longshore currents,
  + short waves and group-bound or free long waves (Roelvink, 1991, 1992).

Most probably, this is not all. Research on intra-wave transport models (Horikawa, 1988; also see Montefusco, 1991), which are essential to identify these mechanisms, is in full swing and even reveals new mechanisms from time to time. Besides, the limitation to the cross-shore plane probably excludes a number of mechanisms, such as the effects of a net throughflow due to a horizontal circulation (cf. Hansen and Svendsen, 1986), or those of a strong oscillatory flow due to longshore current instabilities (Bowen and Holman, 1989), or the complications which arise when waves and currents interact under an oblique angle (cf. Davies et al., 1988).

Bearing in mind, that horizontal circulation currents also have their vertical structure, superposition of all these phenomena leads to complex 3D flow and transport structures (Figure 10).

Fig. 10. 3D nearshore flow structure on a plane beach
[from: A.S.-Arcilla, private communication]

In spite of this complexity, a large part of the practically relevant 3D current and sediment transport patterns can probably be described with a relatively simple model concept, viz. the quasi-3D (q3D) approach. In fact, this is the mathematical representation of the above composition of a 3D field from two essentially simpler lower-dimensional descriptions, viz.

1. the "primary" field, which represents the 2DH velocity or concentration field, provided

   with the vertical distribution which corresponds with the horizontally uniform situation
   (plane shear flow profile, equilibrium concentration profile),
(2) the "secondary" field, which represents the deviation from the primary field and has a depth-averaged value zero, by definition; the secondary flow field represents the vertical circulation, e.g. in the cross-shore plane; the secondary concentration field represents the deformation of the concentration profile, e.g. due to the pick-up or deposition of sediment at the bed.

The essential simplification in the q3D approach is a series of similarity assumptions, for the vertical profile shapes of the dependent variables. Thus the system can be split into a series of 1DV computations and an extended 2DH computation. The 1DV part determines the basic profile shapes and the closure relationships in the depth-integrated model, the 2DH part solves the depth-integrated model.

Since the extended 2DH part of the model is usually quite similar to the "traditional" 2DH models, the latter can easily be integrated into a q3D system.

The q3D concept has been described by various authors, e.g.
- for nearshore currents: De Vriend and Stive (1987), Svendsen and Putrevu (1990), Arcilla et al. (1990, 1992),

Since this Chapter is not meant to treat hydrodynamic or sediment transport modelling in detail, reference is made to these publications. Suffice it to conclude here that there is a conceptual framework which allows for the incorporation of the most important slope-generating and slope-reducing mechanisms in morphodynamic models.

To the author's knowledge, quasi-3D MTM-models have not yet been applied to nearshore problems. The q3D current modelling concept has been used in an ISE-model application (De Vriend and Ribberink, 1988), but with limited success, due to an error which has been traced afterwards.

Another test application, a morphodynamic simulation of the evolution of a tidal inlet (disregarding wave effects), is described by Wang et al. (1991).

8. Watanabe's model

Watanabe et al. (1986; also see Horikawa, 1988) include in their 2DH model a semi-empirical cross-shore transport formula, which relates the magnitude of the transport to the wave orbital motion (rather like the transport due to wave-asymmetry), whereas the direction is derived from an empirical profile evolution relationship (i.e. including all profile-forming mechanisms).

As this model also includes the downslope gravitational transport component, it can be considered as an "empirical emulation" of a quasi-3D model. In any case, it does not exhibit the deficiencies of a strictly 2DH model: the inherent instability is suppressed and the model tends towards an equilibrium topography which seems to make sense (cf. Watanabe et al. 1986).

Nevertheless, the concept is disputable because of the omission of important transport mechanisms, such as 3D circulations and non-linear interactions between sediment moving agents. The argument that the effect of cross-shore circulations is included in the empirical direction formula is only partly valid, since this formula lumps all mechanisms together and does not reflect the driving forces of each of them in an arbitrary 3D setting.

In general, the applicability of this semi-empirical wave-borne transport model will be restricted to the area of validity of the empirical component, i.e. to situations which are not too far away from a uniform beach.

This is illustrated in the simulation of the 3D beach response to a detached breakwater (Figure 11), which is described in detail in Horikawa (1988).

Although the beach in this case becomes strongly curved, the behaviour of its upper part will be dominated by the same mechanisms as in the alongshore uniform case. This explains why the model performs very well there.
Near the tip of the breakwater, however, and also in the produced part of the breakwater axis, the situation is less standard. As the authors indicate, the near-bed velocity there is quite different from the 2DH circulation, probably due to undertow and curvature effects. This means that the actual flow structure is 3D, but essentially different from the uniform beach case, and that its morphological impact is not likely to be reproduced correctly. Figure 11 shows that, especially after some time, systematic discrepancies between measurements and computations are found in these areas, indeed.

![Fig. 11. Detached breakwater case (Watanabe et al., 1986) from Horikawa, 1988, courtesy Univ. of Tokyo Press.](image)

Similar problems can be found in other applications (e.g. Maruyama and Takagi, 1988), and they are also likely to arise in the case shown in Figure 4, where the strong offshore current on top of the reforming straight foreshore is a non-standard feature.

On the other hand, this is one of the few (if not the only) MTM-models which have reached a more or less operational stage, and the results of various practical applications (Maruyama and Takagi, 1988; Shimizu et al., 1990; Watanabe et al., 1991) are quite impressive in many respects. In the framework of the EC-MAST marine research programme, O'Connor and Nicholson (1992) are applying this model to a number of standard test cases, in cooperation with other European modellers, who are doing the same with their models. This work is still on its way and has not yet led to definitive conclusions.

**9. Fully 3D-models**

MTM-models based on fully 3D descriptions of currents and sediment transports are not yet available, and if they were, the physical knowledge would be lagging so far behind, that they would not be suited for practical use. Fully 3D coastal current models are still in their infancy, and there are still important consistency problems to be solved there (De Vriend and Kitou, 1990). Besides, there is hardly any 3D validation material available, at best data in horizontal or vertical planes.

Fully 3D sediment transport models are more or less operational (see O'Connor, 1991, for a review), but they mostly ignore the wave-borne transport and the downslope gravitational effect, whence they will probably not be suited as a module in MTM-models for nearshore cases, at least in their present form.
10. Concluding remark on medium-term models

The discussion in the previous parts puts much emphasis on the equilibrium bed topography. One might argue, that static equilibrium is never reached and that coastal morphology is rather the result of an ever changing system, which may be at most in a state of dynamic equilibrium. Obviously, this is true, but it does not lead to the conclusion that the slope-affecting mechanisms are unimportant. Otherwise, the coastal profile would be the sum of residues of information passed alongshore. As was stated before, this is in contrast with observations in nature (for instance, the formation of summer and winter profiles, even at alongshore uniform beaches).

11. Long-term morphological models: Potentials and limitations

11.1 General

Long-term morphological (LTM) processes take place at time scales which are not only much larger than the hydrodynamic time scale (tidal period, duration of a storm), but also much larger than the time scale of the predominant morphodynamic processes. The spatial scales are correspondingly large. Modelling of these processes leads to what Horikawa (1988) calls "macro-models".

Even if the necessary computer capacity would be available, it must be doubted whether the accuracy and reliability of MTM-models would stand such a long simulation. Probably, small systematic errors, which do not harm the MTM-applications, become important in the longer run, when much of the medium-term dynamics averages out (for instance, see the extensive large-scale study of the Dutch coast, which was reported by various authors at ICCE'90 (Edge, 1991)).

The notion that relatively weak rectification mechanisms can have important consequences in the longer run, is a very important element in LTM-modelling. On the one hand, this implies research on topics which seem rather irrelevant from a nearshore dynamics (= MTM) point of view, such as 3D tidal rectification, coastal upwelling, coastal density fronts, etcetera.

On the other hand, it puts much emphasis on the non-linearity of the coastal morphodynamic system, and even raises the question of uniqueness (irreversible developments due to extreme events, or bifurcating inherent behaviour) and predictability limits. Here the latest advances in non-linear dynamics have to be called upon.

This important role of relatively small and largely unknown phenomena seems to have discouraged coastal morphologists from mathematical-physical modelling of long-term coastal behaviour. Fortunately, some of them have not turned away from long-term morphology, but they have concentrated on data analysis and empirical methods, such as the empirical orthogonal function technique. This work is of paramount importance for the description of the coastal behaviour in a manageable number of parameters (also see Terwindt and Battjes, 1990).

In the meantime, LTM modelling is gradually taking off, probably stimulated by the attention for long-term issues, such as the morphological impact of sea level rise. A range of more or less physics-based model concepts has recently been proposed, or receives new attention (see De Vriend, 1991b, for a review). Some of them will be discussed hereafter.

11.2 Empirical models

One class of LTM models does not describe the bed topography as a function of space and time, but the evolution of large-scale morphological elements (e.g. an outer delta) and their mutual interactions, under the constraint of sediment conservation. These models, which are usually highly empirical, will not be discussed here (see De Vriend, 1991b).
An empirical model at the geological time scale is proposed by Cowell and Roy (1988). It describes the coastal profile as a set of coupled geometrical curves of a fixed form, which take the role of large morphological units (e.g. the dunes, the subaerial beach, the active zone, and the shoreface). The behaviour of these units is forced by external inputs and constrained by their mutual coupling and by the sediment balance. Clearly, this model is still in its research and validation phase, and it has not yet reached robust applicability, but, in principle, the concept could be extended to two horizontal dimensions. The major difficulty is, how to describe the long-term 3D bed evolution by a limited number of geometrical standard elements. To the author’s knowledge, the answer has not been given, so far.

Another empirical concept, meant for time-scales of the order of decades, is described by Stive et al. (1991), again for coastal profile evolution. It starts from the long-term profile behaviour, as observed in nature and in validated medium-term models in a range of situations. When considering the deviations from what is supposed to be the equilibrium profile, their evolution seems to exhibit a diffusion behaviour (Figure 11), which corresponds with the multi-line concept in coastline modelling (Bakker, 1968; Perlin and Dean, 1983). Therefore, an empirical diffusion-model is fitted to the data (also see Capobianco, 1992).

![Fig. 12. Evolution of a hypothetical underwater nourishment](image)

(a) situation, (b) MTM model prediction, (c) LTM diffusion model prediction

Once this concept has been validated, it can easily be integrated with the coastline model concept, which also leads to diffusion-type behaviour, though with different coefficients (cf. De Vroeg et al., 1988). Stive et al. (1992) show, that the diffusion concept is probably also valid for profile evolutions at a somewhat shorter timescale (e.g. a season).

11.3 MATHEMATICAL-PHYSICAL MODELS

A more physics-based LTM model concept starts from the same process descriptions as ISE and MTM models. Instead of attempting to solve the mathematical system as such, the equations are formally integrated up to the required time (and space) scales. The resulting mathematical system, at larger space and time scales, is solved.

In fact, the approach is quite similar to the one in turbulence modelling (for instance, see Launder and Spalding, 1972) and in wave-driven current modelling. Like in these cases, the principal difficulty originates from the non-linear terms, which lead to residual effects (cf. the Reynolds stress in turbulent flow models and the radiation stress in wave-driven current models). The trick is to relate these residual effects to the "slow" dependent variables of the LTM-model, via so-called closure relationships.

There are various ways to establish closure relationships. One is empirical (e.g. the parabolic eddy viscosity distribution, which is chosen because it leads to a logarithmic
velocity profile), another is straightforward evaluation on the basis of simplified theory (e.g. the radiation stress formula based on linear progressive wave theory).

The situation in long-term morphodynamics is somewhat more complicated. The morphodynamic system is compounded from a series of subsystems (waves, currents, sediment transport) with complicated interactions, and a clear picture of how the system works in the long run is still lacking. Hence it is difficult to underpin closure relationships other than purely empirical.

One way to circumvent the closure problem is to linearize the system, assuming small perturbations of the bed level. A nice example is the tidal averaging technique proposed by Latteux (1987; also see Latteux and Peltier, 1992) and De Vriend (1988). It starts from the assumption that the bed level changes per tidal cycle are small enough to linearize their impact on the hydrodynamics and the sediment transport, and that the most important part of the hydrodynamic impact goes through the mass conservation, but leaves the dynamics of the flow unaffected (the horizontal circulation pattern remains the same). If so, the part of the model involved in the morphodynamic interaction consists of the equation of continuity, the sediment transport formula and the sediment balance. After linearization, these can be combined to an equation in the bed level, very similar to Eq. (3). In general

$\frac{\partial z_b}{\partial t} + \vec{c}(t) \cdot \vec{V} z_b - \vec{V} \cdot [D(t) \vec{V} z_b] = S(t)$

(7)

The coefficients in this equation vary during the tidal cycle, and so does the bed level. If the tidal variation the latter is neglected and only the "secular" bed evolution is taken into account, the bed level varies at a much larger time scale than the coefficients. In that case, Eq. (7) can be averaged over the tide, to yield

$\frac{\partial \bar{z}_b}{\partial t} + \bar{c} \cdot \vec{V} \bar{z}_b - \vec{V} \cdot [\bar{D} \vec{V} \bar{z}_b] = \bar{S}$

(8)

in which the overbar denotes the tidal average.
After the coefficients in Eqs. (7) and (8) have been determined from an ISE-model, Eq. (8) can be solved to simulate the bed evolution at the morphological time scale, which may cover many tidal periods.

Although Eq. (8) can be considered as a long-term model, it mostly functions as a time-step amplifier in an MTM-model, since sooner or later the horizontal circulation pattern will have to be updated via another ISE-computation, etcetera.

The derivation procedure, however, is rather general. Also in more complicated models, it is important to separate fast and slow variations and to integrate over the former. Recent advances in applied mathematics enable us to do this even for complicated mathematical systems (Krol, 1990).

A key element in this process is a proper understanding of the inherent long-term behaviour of the morphodynamic system. The analyses of this behaviour, which is to a large extent non-linear, is a major challenge for present research. Here, again, river dynamics leads the way (Struiksm et al., 1985; Tubino and Seminara, 1990; Schielen et al., 1992; also see Ikeda and Parker, 1989), but the same techniques are applicable to coastal dynamics (Hino, 1974; Blondeaux and Vittori, 1990; Vittori and Blondeaux, 1991; Hulscher et al., 1992).

It seems as though mathematical-physical LTM models are still far from operational use, but research in this area has already produced a wealth of spin-off, in terms of a better understanding of the coastal system, also at shorter time scales.

12. Needs for further research

12.1 CONSTITUENT PROCESSES

It would not be difficult to fill another number of pages with process research needs originating from morphodynamic modelling (see De Vriend, 1991a). Suffice it to stress here, that the morphodynamic system has to be the starting point. The non-linearity of this system can lead to a different picture of the importance of phenomena than one might expect at first sight.

In long-term models, this effect is the most apparent, but also in medium-term models it may be present. For example, the common spectral description of a natural wave field, based upon random-phase Fourier components, may be good enough to describe the wave height and direction fields, but it is not so for the description of the wave-borne sediment transport (Guza and Thornton, 1985). There one needs additional information, which has to do with the non-linearity of the waves, so with the phase-relationship between Fourier components.

At the moment, the morphodynamic system is still insufficiently known for morphodynamicists to be able to specify what exactly they have to know about natural wave fields, nor about wave and wind climates. This situation should change as soon as possible.

12.2 SHORT- AND MEDIUM-TERM MORPHODYNAMICS

As was stated before, there remains a lot of research to be done on MTM modelling. This concerns

(1) the physical contents of the model, such as
   + interaction with the dunes and the subaerial beach, via dune erosion, swash zone processes and, in the longer run, aeolian transport (see Horikawa, 1988, for a review),
   + inclusion of the various transport processes, in such a way, that 3D consistency is achieved, especially of the slope-affecting mechanisms,
   + interactions between constituent processes, such as waves and currents, and the wave-current-bedform-transport chain,
   + related to the latter: roughness prediction.

(2) the morphodynamic interaction process, in nature and in the model, e.g. via
   + theoretical analysis of the inherent behaviour of the system,
   + mathematical analysis (propagation of information, boundary conditions required, well-posedness),
   + simple diagnostic numerical model experiments,
   + experiments with state-of-the-art numerical models ("playing" with them!),
   + verification of the inherent behaviour against data, from laboratory experiments and from nature (note that the latter is extremely difficult!).
(3) numerical and physical accuracy, e.g.
+ numerical scheme for morphological time integration (cf. Peltier et al., 1991),
+ "propagation" and amplification of errors during the computation process (cf. De Vriend, 1987a),
+ simple updating techniques for wave and current fields after small topographic changes, as a means to increase the effective time step of the computation.

(4) test and verification studies
+ against common sense, benchmark tests, other models, (cf. O’Connor and Nicholson, 1992; Andersen et al., 1991),
+ against controlled laboratory experiments (cf. Watanabe et al., 1986),
+ against field data (cf. Maruyama and Takagi, 1988; Shimizu et al., 1990).

(5) sensitivity test programmes
+ for extraneous conditions,
+ for physical contents and simplifications,
+ for geometrical schematization (domain, computational grid),
+ for boundary conditions.

(6) input schematization, or: how to drive a 3D coastal evolution model in a natural case, if real-time input is not feasible?
+ characterization of impact per condition,
+ predominant conditions (impact-wise),
+ role of chronology,
+ representative condition sets and input time series.

(7) interpretation of model output
+ from ISE-models (from residual transport patterns and initial sedimentation/erosion rates to longer-term evolutions),
+ from MTM-models (from one realization of a stochastic process to a quantitative prediction with reliability bounds),
+ quantitative characterization of model quality.

Some of these research issues may seem "high-brow luxury", which can be avoided by a practical attitude. 3D morphodynamic systems in full interaction, however, are extremely complicated and can yield good-looking results, which can still be totally wrong.

A thorough understanding of the behaviour of this system is an absolute necessity for the modeller to be able to judge the results, and to keep the model under control.

This is the more so, if, sooner or later, the model will be applied to cases of a longer duration than one or a few storms.

Then the input statistics plays a role, and since the system acts as a non-linear filter, this can lead to totally unexpected results (cf. a noise signal put into a non-linear resonator). If the model is to add any value to "rule-of-thumb" predictions, these aspects have to be investigated.

12.3 LONG-TERM MORPHODYNAMICS

What has been stated in the foregoing about stochastic inputs goes in principle even stronger for long-term models: before simplifications can be made and long-term models can be formulated, it is necessary to have a picture of the "input-output" relationships of the system, i.e. how strongly does the final result respond to the various input properties, and what is important, what not?

The understanding of the coast as a dynamic system is expected to be the key research issue in physics-based long-term modelling for the next few years. It involves supplementary issues like
- the characterization of measured or computed bed topographies by a manageable number of parameters, taking the limited pre-dictability of the input into account,
- the fitting of semi-empirical models to available and newly acquired data,
- the application of formal non-linear averaging techniques to derive long-term model formulations.

Similar techniques have been developed and are being applied in other areas of science and engineering under the heading System Dynamics. This discipline must be able to give long-term coastal modelling a major impulse (also see De Vriend, 1991b).
12.4 METHODOLOGY

In practice, models are not utilized on their own, and they don't automatically produce answers to practical questions. Their application is embedded in a methodology, which also involves other elements, such as data collection, interpretation of the problem and the situation, model selection and composition, model domain and types of boundary conditions, geometrical schematization, definition of model runs, input schematization, run control, output validation and data management, output composition and interpretation, and combination with other results into an answer to the question.

These activities, as such, cannot be called research. However, it is very important to have as much physical knowledge and model experience as possible available during the process, through specialists, but also through easy-to-handle tools which present the knowledge in an accessible form (e.g. a "knowledge base", which contains all sorts of estimators for relevant parameters).

The identification of the required knowledge and its transformation into an easily accessible form can certainly be called research.

12.5 THE RESEARCH ENVIRONMENT

Research on the constituent processes waves, currents and sediment transport tends to be directed towards the stand-alone application of the process models. This tendency is enhanced by an extreme specialization of scientists.

Morphodynamic modelling, however, is based on the integration of process knowledge. This raises new process research questions, but only part of them is highly sophisticated and leads to publishable answers. The other part is "gap-filling", very useful and absolutely necessary, but maybe not very publishable in its own right.

Therefore, it is very important to have morphodynamic models developed by teams of specialist, each of which feels responsible for the result and is willing to carry out this "gap-filling" work to achieve it. This is probably why so many of the leading publications in this area are multi-authored.

13. Conclusion

The foregoing leads to the conclusion, that significant achievements have been made in the numerical modelling of 3D coastal morphology, but that more research over a wide area is needed to make these models robustly applicable to arbitrary situations.

Initial sedimentation/erosion models definitely deserve their place in coastal morphological modelling, though not as a quantitative predictor of morphological evolutions, but rather as a tool for process analysis and orientation.

The prediction potential of strictly 2D-horizontal morphodynamic models will probably remain restricted to special classes of problems, and to short-term evolutions.

The highest expectations concern quasi-3D models, which include the vertical structure of the water and sediment motion. The first results of the "empirical emulation" of such a model by Watanabe and his co-workers are very encouraging.

Part of the future research will have to deal with the physical processes which constitute the morphodynamic system. As these can have very complicated interactions in the longer run, especially if the extraneous conditions are stochastic, it is important to have their further investigation defined from a morphodynamic point of view.

Another part concerns the 3D morphodynamic process, as such. The present understanding of this process is not good enough to judge the results of 3D coastal evolution models in arbitrary situations.

Long-term modelling, at least its physics-based branch, is a new and challenging field, which certainly deserves further exploration. No doubt, this will also be beneficial to medium-term morphodynamics.
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