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A review of the latest theories on sand transport and methods for making long term predictions

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ABSTRACT

Sediment transport in exposed shallow waters is such a complex subject that is extremely difficult to give estimates of siltation, maintenance dredging rates etc, within precise limits. The main factors contributing to uncertainties are:

- inadequacies in the understanding of the physics of sand transport (eg due to the unsteadiness of flow and supply of sediment, the interaction of sand of different sizes, sand pick-up relations and the role of wave stirring).

- the sensitivity of transport to wave climate and the sensitivity of the wave climate itself to the water depths which vary during the tide and may change due to deposition or erosion and/or due to dredging during the simulation period.

- the mechanics and logistics of obtaining long term (annual) predictions from a limited number of short term simulations.

This report covers the first part of this study and comprises a review of the latest theories on sediment transport and methods used in making long term predictions.

CONTENTS

# 1. INTRODUCTION

Sediment transport in exposed shallow waters is such a complex subject that it is extremely difficult to give estimates of siltation, maintenance dredging rates, etc within precise limits. The main factors contributing to uncertainties are:

- inadequacies in the understanding of the physics of sand transport (eg due to the unsteadiness of flow and supply of sediment, the interaction of sand of different sizes, sand pick-up relations and the role of wave stirring).

- the sensitivity of transport to wave climate and the sensitivity of the wave climate itself to the water depths which vary during the tide and may change due to deposition or erosion and/or due to dredging during the simulation period.

- the mechanics and logistics of obtaining long term (annual) predictions from a limited number of short term simulations.

Recent research has explored sediment pick-up relations, sand transport in unsteady flow, the simulation of sand transport under wave dominated conditions with a small longshore or tidal current, and the theoretical treatment of mixtures of sand sizes. Thus the basic understanding of the physical processes continues to advance, and computer models need to be updated to incorporate it.

A crucial problem in providing firm estimates of siltation is that significant sediment transport and bed change can result from a single extreme event. It is therefore important to know how the bed resulting from such an event affects the response to subsequent events, and, more importantly, to investigate whether the final outcome is sensitive to the order in which the events are assumed to occur. These factors can only be rigorously assessed and quantified through the use of computer models. It is, however, unlikely that running flow and sand transport models interactively for long periods will be an acceptable solution in the foreseeable future because the computing will be prohibitively expensive and/or because the system is not expected to be statistically well enough behaved to make this meaningful. There is thus a need, strongly supported by the HR Research Advisory Panel, to find ways of using models that can be validated and run economically for only a few tidal cycles to make long term predictions of sedimentary changes. This requires original and radical re-thinking of how computer sediment models should be validated and applied for long time scales.

The objectives of this research study are:

- To review current knowledge on sand transport by currents with wave stirring and include the latest theories in existing computer models.

- To devise a new approach for dealing with the long (seasonal) scale of the wave climate and the short (tidal) scale of the tide effects.

- To improve the calibration and validation of sediment models.

- To recommend how these models can be efficiently applied to give long term predictions with confidence at reasonable cost.

This report covers the first part of this study and comprises a review of the latest theories on sediment transport and methods used in making long term predictions.

## 2. A REVIEW OF THE LATEST THEORIES ON SEDIMENT TRANSPORT UNDER COMBINED WAVES AND CURRENTS

In combined wave and current flows, wave stirring is the dominant mechanism for entrainment of the sediment, which is then transported by the current.

A number of sediment transport formulae have been proposed for combined wave-plus-current (w+c) flows (Bijker (1967), Swart (1976), Graff and Overeem (1979), Willis (1978), and Grass (1981)). These all involve the adaption of existing unidirectional formulae by dividing them into a 'stirring' term (modified by the presence of waves) and a 'transporting' term (Assumed proportional to the mean current speed). With the exception of the Grass (1981) formula, these have been reviewed and compared by Bettess (1985) who found them all to be similarly unreliable except when the effect of currents dominated that of waves. The Grass formula (1981) is discussed by Soulsby (1987) and is used in the long-term sediment transport model described in Section 3.2.2. There is no reason to expect this formula to behave substantially better than the others, although all these formulae are in frequent use in the absence of better alternatives.

Soulsby (1988) investigates the transporting term in detail, and shows that the assumption that it is simply proportional to the mean current speed is invalid. A general method of deriving a wave-plus-current sediment transport formula, from any chosen unidirectional formula, via any chosen w+c shear-stress theory, is given. This allows a formula to be derived for any given site where an empirical relationship between sediment transport rate and current speed is known (from measurements taken at times when waves are not present).

Soulsby (1991) derives a new formula for the suspended sediment transport rate in strong w+c flows. He argues that it is important to have a formula whose accuracy is greatest for such flows, since the overall transport at a given site depends critically on the interplay between the rate of increase of sediment transport and the rate of decrease of frequency-of-occurrence of the largest waves and currents (see Soulsby, 1987). The prediction method is found to give good agreement to within a factor of two with field data and should be well suited to practical applications in coastal engineering.

In addition to the above formulae, some other methods of calculating sediment transport under w+c are widely used. The profile models discussed in Section 3.4 can allow the use of various alternative sediment transport calculation methods, based on the fairly detailed hydrodynamics calculated by such models.

For example, the Nearshore Profile Model (NPM) discussed in Section 3.4.1 uses three alternative sediment transport predictors. The first is based on the energetics approach introduced by Bagnold (1963, 1966) and adapted by Bowen (1980) and Bailard (1981). This method assumes that the sediment is mobilised by wave action and transported by three different mechanisms:

(i) time-averaged flows;
(ii) asymmetric orbital velocities,
and (iii) gravity in the downslope direction.

Since this method is strictly only applicable to the surf zone (where the seabed is non-rippled) the Nielsen (1988) 'grab and dump' method is used for cross-shore transport outside this region. This predicts sediment transport rates over rippled beds in the opposite direction to wave propagation. An alternative approach for longshore transport is based on integration through the vertical of the product of suspended sediment load and mean longshore velocity. A logarithmic velocity distribution and the Nielsen (1979) expression for suspended sediment concentration are used.

Application of the NPM to practical situations has resulted in the energetics method being favoured as more reliable and less sensitive to small errors in the velocity and concentration profiles. All the other profile models mentioned in Section 3.4 also currently use this method.

In contrast, parametric models such as that described in Section 3.4.2 include no detailed calculations of velocities or concentrations. The morphodynamic processes are described by the diffusion coefficient, which must be specified as a function of depth, but is still not well known. De Vriend and Roelvink (1991) use a constant value from the surface down to 3m below mean sea level and an exponentially varying value below this, but they suggest that the function is still very tentative and needs further substantiation.

Recent studies using a depth-averaged area model to calculate sediment transport in Poole Bay (HR Wallingford, (HR) 1991) employed a combination of the van Rijn (1984) currents-only formulae and the stirring enhancement according to Grass (1981). The effects of waves breaking in a shallow offshore area were included by enhancing the stirring term. This was first calculated by assuming that the turbulence generated by breaking waves has the same efficiency as the wave bed stresses in the entrainment and transporting of sand, and the effect was simulated by adding the wave breaking stress to the wave bed stress in the sand transport relation.

Sensitivity tests revealed that this produced extremely high concentrations of suspended sediments locally on the offshore sandbank known as Hook Sand where most wave breaking occurs. Consequently a modified approach was adopted which involved adding a wave breaking contribution calculated on the assumption that only a few (two or three) percent of the available power is expended in supporting sediment.

# 3. LONG-TERM MORPHODYNAMIC MODELLING: A REVIEW OF NUMERICAL TECHNIQUES

## 3.1 Introduction

A wide variety of morphodynamic models are available for predicting coastal and estuarine evolution. In using these models for long-term predictions, various problems are encountered. The relevant processes occur on a wide variety of timescales and it is not clear what determines long-term trends and how these can be identified, given large short-term variability. In addition, most long-term applications require prohibitively large computer run-times.

Two principal techniques have been used to overcome these problems:

(i) Input Filtering : Simplifications are made to the hydrodynamic inputs of a sophisticated short-term model. The aim is to reduce the number of wave and tide conditions for which the model must be run, but it is necessary to choose these in such a way as to be representative of the wave/current climate as a whole, so that the combined/ extrapolated results show the correct long-term morphological behaviour.

(ii) Process Filtering : A simplified model is used that can be run for a full chronological series of inputs.

Research into formal application of these techniques is not yet well advanced (see De Vriend, 1991a, b, for further discussion). However, they have been used informally in practical applications for a number of years. The following review gives details of the various types of morphological models available and their uses for long-term predictions. Emphasis is given to studies that provide useful conclusions for the future development of long-term morphodynamic modelling.

## 3.2 Zero-dimensional models

### 3.2.1 Sedimentation at a point (SAP) model

Delo and Ockenden (1989) present a zero-dimensional model for cohesive sediments. The model uses ten discrete layers within the bed. At each time-step the density and thickness of each layer is calculated. The uppermost layer undergoes erosion and deposition, the layers are then consolidated and the excess pore pressures within the bed are dissipated. The model calculates bed shear stresses throughout a spring-neap cycle based on interpolation between spring and neap tide flows which are calculated by a separate model.

An example of the use of the model is given in Delo and Ockenden (1989). Changes in the bed are predicted over a one year period and extrapolated to cover a twelve year period. Comparison with surveyed bed levels suggested that adjustments were necessary to account for the effects of ships and wind induced waves on the mud flats. The results also show that neap tide processes provide an important mechanism (ie consolidation period) in cohesive sediment modelling, in contrast to the frequently made assumption that only spring tides are significant.

### 3.2.2 Long-term sediment transport model

Soulsby (1987) calculates the long-term mean sediment transport rate as:

$$\langle Q_{cw} \rangle = \sum_{ij} p_{cw} (U_i, W_j) \, Q_{cw} (U_i, W_j)$$

Where $Q_{cw}$ (U,W) is the sediment transport rate resulting from the combination of a current of velocity U with waves of orbital velocity W, and $p_{cw}$ (U,W) is the probability of occurrence of that wave and current combination. The probability $p_{cw}$ can be found by assuming that waves and currents are independent and that the waves are part of a Jonswap spectrum. The Grass (1981) formula is used for $Q_{cw}$.

The model allows the proportion of long-term mean transport given by a particular wave-current combination to be calculated. It is found, using wave and current data from the North Sea, that the most important contributions are made by fairly large but not too infrequent waves, combined with tidal currents lying between neap and spring maxima.

The results provide some justification for the use of input filtering in more complex models, as extreme events make small contributions to the long-term transport. However, no sequential information is retained here and there is no interaction with morphological changes. Hence the potential of an isolated extreme event to change overall transport patterns is not included.

### 3.2.3 Morphological model of tidal lagoons

Di Silvio (1989) presents a zero-dimensional, parameterized model of tidal lagoons. The model includes channels, shoals and tidal flats. It requires numerous parameters representing, for example, the erodibility of the bed, which must be calibrated against historical data.

The model is applied to the northern basin of the Lagoon of Venice the predict the evolution of channels and shoals. Preliminary results seem reasonable.

The model needs extensive calibration of parameters and is dependent on whether there is sufficient data on past changes to justify future predictions.

## 3.3 Line models

One-line models represent the plan shape of a beach as a single contour. The displacement of the line as a function of time and longshore position can be used to predict the long-term evolution of a beach. Reviews of such models are given by Le Mehaute and Soldate (1977) and, more recently, by Hanson (1987). An example is described below.

Multi-line models also exist, schematizing the coast into several non-parallel contours which can move independently, for example see Perlin and Dean (1985). Such models are obviously more complex though, and not generally used for long-term predictions.

### 3.3.1 Model for predicting shoreline evolution of beaches

Ozaza and Brampton (1979) describe a one-line model for changes in the plan shape of a beach backed by a sea wall. The beach is assumed to have a constant slope between the swash limit and some offshore contour, beyond which profile changes are assumed negligible. Alongshore sediment transport is calculated taking into account the oblique breaking of waves and alongshore wave height gradients, and the movement of the beach contour determined by the continuity equation. Onshore-offshore sediment transport is also included.

The model has been used in numerous studies. Changkuan and Brampton (1988) use it to consider the effect of variability of alongshore transport on the modelling of beaches. They carry out eight separate runs of the model, each starting with a straight beach and using a period of four years of consecutive wave data. Beach changes are calculated throughout each period and the final beach positions compared. It is shown that the beach response is strongly influenced by variations in alongshore drift. Predictions using relatively short periods of sequential wave data may differ substantially from each other and from those made using average wave conditions.

Studies with this model have shown that it is essential to have sufficient sequential data for calibration. It has been shown that the order of wave events is important, although this of course cannot be predicted. It is necessary to assume that sequential wave data over several past decades is representative of what will happen in the future. However, it is not clear how predicted changes are then related to the long-term mean.

## 3.4 Profile models

Profile models assume a straight coastline with parallel depth contours, reducing the problem of beach evolution to one of calculations in the cross-shore horizontal dimension only. Such models are suited to describing evolution of the underwater profile with the emphasis on the active zone. Profile models have been developed by Roelvink (1991), Broker-Hedegaard et al (1991a) and Southgate (1991) amongst others. A comparison of these is given in Broker-Hedegaard et al (1991b) and one is described below in section 2.4.1.

Parametric models of long-term profile evolution have been developed by Cowell and Roy (1988) and De Vriend and Roelvink (1988, 1991) to describe long-term evolution only. One of these is described below in ection 2.4.1.

### 3.4.1 Near-shore profile model (NPM)

A detailed description of this model is given in Hydraulics Research (1989) and subsequent papers (Southgate, 1989; Nairn, 1990; Southgate and Nairn, 1991; Nairn and Southgate, 1991). The main physical processes included in the model are:

(a) Wave transformation by refraction (by depth variations and currents), shoaling, Doppler shifting, bottom friction and wave breaking.

(b) Wave set-up determined from the gradient of wave radiation stress.

(c) Driving forces for longshore wave-induced currents, determined directly from the spatial rate of wave energy dissipation.

(d) Longshore currents from pressure-driven tidal forces and wave-induced forces, and the interaction between the two types of current.

(e) Cross-shore undertow velocities using a three-layer model of the vertical distribution of cross-shore currents (De Vriend and Stive, 1987).

(f) Cross-shore and longshore sediment transport rates using an 'energetics' approach (Bailard, 1981; Stive, 1986; HR, 1989a).

(g) Seabed level changes due to cross-shore sediment transport using a Lax-Wendroff scheme (see, for example, Broker-Hedegaard and Deigaard, 1988).

(h) Downcutting of a cohesive layer (if one exists) by a mechanism of sand abrasion (HR, 1989a).

(i) Incorporation of some long wave effects using a bichromatic approach (Nairn, 1990).

The model allows input of a sequence of wave and tidal conditions and can run thousands of conditions in a reasonable length of time.

The model reproduces fairly well features such as bars in the cross-shore profile over periods of several hours (see, for example, Southgate, 1991). However, the development of such features over long time-scales is less well understood and will probably require further refinement of the model.

A profile model such as this one could be useful for comparison tests of various input schematization techniques involving combined waves and currents. However, use of such models for long-term predictions requires rather long run-times and also some improvements in the models.

#### 3.4.2 A parametric model of long-term coastal profile evolution

De Vriend and Roelvink (1991) develop a parametric profile model which describes long-term behaviour only and can be run on a long-term timescale. They define an equilibrium profile, such that the actual coastal profile always tends towards this shape. The model is a simple one, which retains the overall sediment balance and includes some of the generally observed long-term behaviour of the profile. The profile behaviour is described by an equation which includes a source term allowing for human interference, longshore sediment losses or gains, influx from rivers, etc. Its solution is much faster than long-term simulations run with a real-time model.

Various experiments have been performed with the model, and results agree qualitatively with expectations. However, further work is needed and calibration with field data or real-time profile models.

The parametric model provides an alternative approach to long-term modelling that has considerable potential. However, adequate validation and calibration are essential.

### 3.5 Tidal channel models

For narrow estuaries, one-dimensional models of tidal flow, mud and sand transport are often used. For long-term predictions, some kind of input filtering and extrapolation of results is required.

An alternative approach is to use a regime relationship, based on the existing cross-sectional area and tidal flows in an estuary, to estimate the near equilibrium shape resulting from a change in the tidal flow regime.

### 3.5.1 Sand siltation in a narrow estuary

A one-dimensional, two-layer model of tidal flows, saline intrusion, mud and sand transport in the Great Ouse Estuary (HR, 1979), was calibrated by simulating sand accretion in the upper estuary during 30 months with two dry winters in succession. The model simulated the formation of a saline wedge in the winter period and the transport of mud and two separate sand size fractions. The bed had a layered structure and allowed for a mixture of mud and sand fractions. The bed had a layered structure and allowed for a mixture of mud and sand fractions. The model allowed for a full interaction between changes in the bed level and the tidal flows.

The methodology to extrapolate short term predictions was as follows:

(i) The 29 tide neap-spring tidal cycle was schematised to a representative 6 tide neap-spring cycle, incorporating one tide in each tide class.

(ii) A matched set of 1-D tidal flow, saline intrusion and sand/mud transport models was run using the shortened 6-tide neap-spring cycle.

(iii) The sand transport was amplified by the product of two factors; one being the frequency of occurrence of each tide class through the full spring-neap cycle, the other being a constant applied to all classes. In this way a 30 month simulation of sand transport was possible by running six 6-tide cycles, instead of calculating the minute effects of 1680 individual tides.

(iv) The bed level was changed time step by time step ($\Delta t$ = 5 minutes) modifying the flow and the rate of sand transport.

(v) Mud transport had to be treated differently. During a prolonged period of low fluvial flows, the concentrations of mud in the estuary build up until a rough balance is achieved, with little net deposition in the upper estuary. An artificial acceleration of mud deposition during this period would have magnified transient effects out of proportion to reality. Since neither the initial mud concentrations nor the seaward boundary concentrations could be defined with any degree of accuracy, it was decided not to accelerate the rate of mud deposition, but to use the model to indicate regions of accretion/erosion and give a rough guide to the magnitude of the problem.

The model simulated the accretion of more than two metres of sand on the bed of the upper estuary, and matching erosion in the wider lower estuary, during the 30 month period between May 1972 and October 1974. The bed levels in the upper estuary reached an upper equilibrium level, with a net balance between flood and ebb transports.

The model was used to predict the effect of truncating the estuary with a new sluice on long term sandy siltation downstream. The model could not predict accurate rates of long term muddy siltation without simulating the full 29 tide neap-spring cycle.

The model was used successfully to predict the effect of the closure of Denver Sluice for 44 months - for major repairs - on bed levels in the upper estuary.

The following conclusions were drawn:

(i) The net rate of landward or seaward movement of sand was sensitive to the numerical method, the length of the elements and the method of defining the composition of the bed surface sand mixture, especially in the eroding reaches in the lower estuary.

(ii) The accelerated sand transport and the shortened neap-spring cycle could exaggerate, and give undue weight to, short periods of inaccurate transient flow conditions at the start of a run. The method works best for situations with a fairly steady fluvial flow. A shortened 6-tide neap-spring cycle might produce an unrealistic response and incorrect tidal flows in a deeper estuary, but the Great Ouse Estuary almost dries out at low water.

(iii) The extrapolation of mud siltation rates may exaggerate the influence of short periods of transient adjustment shortly after the construction of a structure.

### 3.5.2 Effects of a bridge embankment on mud siltation in a bay

An assessment has been made of the effect of a new bridge embankment across part of Holes Bay in Dorset

(HR, 1989b). The part of the study concerned with long term bed level changes comprised the modelling of mud transport on spring tides, and a method known as regime analysis was used to predict bed level changes for a variety of proposed bridge openings. Regime analysis involves relating the magnitude of the tidal discharge (in this case the peak tidal discharge) to the cross-sectional area of the flow in existing bridge openings, so that increases/decreases in flow can be used to indicate the likely equilibrium bed levels. By running a mud transport model for a representative spring tide, the main areas of erosion and accretion can be identified and the amount of scour in the bridge opening, estimated from the regime analyses, is assumed to settle in the areas of net deposition. In this way long term trends can be estimated without resorting to very long model tests.

The methodology to extrapolate the short term predictions is summarised below.

(i) Calculate flow conditions for a representative spring tide (very little motion takes place on neap tides). The effect of wave orbital motions, derived from local wind records, is superimposed onto the tidal flow pattern so that wave stirring is represented in the model.

(ii) Look at the existing flow condition and analyse the relationship between the cross sectional areas and peak tidal discharges under the existing bridges.

(iii) Run the mud transport model to predict the main areas of accretion and erosion over this single spring tide.

(iv) Run the flow model for the proposed new bridge embankment.

(v) Use the regime analysis to estimate the likely scour in the bridge opening.

(vi) Redistribute this mud, according to the relative proportions, in the areas of net deposition predicted by the mud transport model.

The following assumptions were made:

(i) There is sufficient data to define a relationship between peak tidal discharge and cross-sectional area in the bay which can be applied to the potential area of erosion.

(ii) Spring tides move the mud.

(iii) The bed changes are not sufficient to alter the flow pattern appreciably.

The engineering works included a reclamation and a dredged marina, and the main purpose of the model was to predict the area where the eroded mud would settle. The total amount of erosion in the bridge opening was determined from the regime relationship. The model predicted the extent of the area of erosion. The model could have been rerun with the modified bathymetry to check that no further erosion was taking place.

## 3.6 Area models

Area models are required to describe morphological evolution of the sea bed where assumptions of long-shore (or cross-shore) uniformity are invalid. Reviews of such models and their application to estuaries are given by Dennis (1990) and Hydraulics Research (1990). Numerous studies with tidal models utilize some kind of reduction in inputs to reduce the run-time. Some studies also include waves, although area models combining waves, tides, sediment transport and morphology are still in an early stage of development.

Parametric models are also under development, which attempt to model long-term evolution only.

### 3.6.1 Mud siltation in an artificial tidal lagoon

As part of the Cardiff Barrage Scheme (HR, 1988a) it was required that a suitable alternative feeding area for overwintering birds be found or developed. This study used a 2-D model to predict long term siltation of an artificial lagoon made by dredging an area of land close to the sea. The lagoon was assumed to be flooded by either breaching the sea wall or by using a more elaborate system of pipes in order to maintain the water inside the lagoon at a particular level. The lagoon was designed to dry out at each tide in order to give adequate feeding grounds for the birds.

The methodology to extrapolate short term predictions is summarised below.

(i) Run a single representative spring tide to assess the depth-averaged tidal flows in the lagoon.

(ii) Run a mud transport model for one tide based on the tidal flows. Calculate the amount of mud erosion/accretion from a knowledge of the difference between the predicted bed shear stress and estimated critical stresses for erosion and deposition.

(iii) Use an estimated bed density to derive bed level changes from the mud erosion/accretion in the lagoon.

(iv) Extrapolate the bed changes for tide over a number of tides until it is deemed necessary to rerun the flow model because the flow depths have changed appreciably.

(v) Continue the above process until the simulation period is reached.

The following assumptions apply:

(i) Spring tides move most of the sediment and so cause most siltation in the lagoon. Wave effects were assumed to be negligible.

(ii) The long term siltation of the lagoon can be represented by considering the effect of spring tides and then assuming that spring tides represent one third of all tides. In order to simulate a full year of change a total of 233 tides was extrapolated.

(iii) The bed is divided into two types; the old, stiff, consolidated mud and the newer, lower density, more-easily-eroded deposits.

(iv) Various mud transport assumptions were required to simplify bed exchange processes - single values of erosion strength, erosion rate, and deposition stress.

(v) The suspended sediment at the mouth of the lagoon during the flood is assumed constant and is based on observations near the entrance to the proposed lagoon.

The results showed a general silting up of the lagoon by 0.4m over a period of 6½ years. It was also found that, despite the 2-D model showing significant eddies around the sea breach, similar long term siltation results could be obtained by using a 1-D sector model. Comparison with observations is not possible, as the lagoon does not yet exist, but the results appear sensible. The model was used to make a number of predictive tests to assess the effect of varying the connections to the sea.

A variety of problems and limitations were encountered, as summarised below

(i) Strong, localised erosion at the mouth of the lagoon at the start of the simulation meant that the extrapolation for a number of tides was not representative, as this would lead to overprediction of the scour in this region. This meant that the flow model had to be rerun for a number of tides at the start of the simulation until the scour had settled down. The maximum extrapolation period was 1 year (233 tides).

(ii) The model requires, and seems to be quite sensitive to, the specified suspended sediment concentration on the incoming tide.

(iii) The model excludes the effects of waves, which are severely limited in size by the dimensions of the artificial tidal basin.

The application relies on good judgement of how far the bed level should be allowed to change before the flow should be recalculated. The effect of such judgements should be tested by carrying out sensitivity tests. The method could be applied to predict the effect of tidal barrages, provided care was taken to prescribe realistic suspended mud concentrations on the incoming tide at the seaward boundary of the model. These concentrations should not be affected by the proposed engineering works. The use of representative spring tides means that the method ignores any consolidation or strengthening of surface mud deposits during neap tides. The method could be modified to include wave effects.

### 3.6.2 Sandy siltation in a bay with a dredged channel

As part of a study for the development of the Port of Poole, 2-D models were used to predict the impact and cost of maintenance of a dredged channel (called Swash Channel) at the entrance to Poole Harbour (HR, 1988b). It was recognised that the dredging of the channel would lead to enhanced orbital velocities either side of the channel, as a result of internal reflection of the waves, and this study combined the effect of waves and spring tides to assess the changes in the accretion/erosion in the area as a result of the work. The bed comprised sand and gravel, and distinction between the two was made in the bed roughness and sediment mobility. Sand was allowed to move across, and lie on, exposed gravel at the bottom of the channel. Representative spring tidal current fields were calculated using a two-dimensional, depth-averaged model.

A 2-D field of orbital velocities was calculated for typical and storm wave conditions, with two representative spectral peak periods and heights, by taking the average orbital velocities from three directional bands, each 20 degrees wide.

Allowance was made for diffraction round headlands and waves breaking on the shallow sand banks adjacent to the dredged channel. Net sand (0.17mm) transport was predicted for a representative spring tide in calm conditions, typical waves and storm waves. A large proportion of the transport occurred during periods of typical wave action (30% of the time), as compared to calm conditions or storm conditions. A weighted average net siltation and erosion was then evaluated, taking into account the frequency of occurrence of spring tides and various wave conditions. The initial net sand transport rates were then extrapolated to predict bed level changes over a 6 month period. To avoid the creation of unrealistically steep slopes, the extrapolated bed levels were smoothed. The maximum bed level change on the shoals adjacent to the channel was 0.6m.

Maintenance dredging was assumed to remove all the sediment within the base width. The tidal currents, orbital velocities and sand transport were recalculated, and showed a reduced rate of siltation on the east side of the shoals compared to the initial six month period, indicating that they would remain stable after a period of initial adjustment.

The methodology of extrapolating the short term predictions is summarised below.

(i) Simulate a representative tidal flow regime.

(ii) Simulate orbital velocities for several representative wave conditions on the same grid as the flow model.

(iii) Calculate the net sand transport for a number of combinations of tide and wave conditions.

(iv) Evaluate a total net sand transport by weighting the contributions according to their combined frequency and duration.

(v) Evaluate the changes in bed levels over a prescribed period by extrapolation allowing for maintenance dredging in the channel if necessary.

(vi) Repeat procedure.

The following assumptions apply

(i) Negligible sand transport occurs on neap tides.

(ii) No interaction exists between waves and tidal currents.

(iii) The method self-corrects overshooting due to the extrapolation.

The method was applied to a model with about 13,000 cells, using a uniform 44m grid. If necessary, more than one tidal cycle could have been considered. The formula for the transport of sand by the combined effects of waves and tidal currents is very sensitive, as it includes high powers of both the tidal current (4th power), the wave bed orbital velocity (3rd power) and sand grain size (2nd power). The method can allow for more than one wave condition. The computed bed level changes tend to have exaggerated peaks and troughs, as a result of the extreme sensitivity of the sand transport formula. The linearly extrapolated bed levels were, therefore, smoothed before starting the next cycle of predictions.

### 3.6.3 Sand siltation in a coastal seawater intake

The Danish Hydraulic Institute (DHI) have developed a long term siltation model (Anderson et al, 1988), which was applied to predict the sand siltation in a cooling water intake (300m x 300m) formed by an alignment of jetties from the coast. This model calculates the sand transport mechanism under waves and steady currents. The model is designed to simulate transport outside the surf zone, so that the combination (coupling) of the waves and currents is not considered. The bedform equation also caters for the effect of the slope of the bed, as well as differentiating between flow over a presumed rippled or plane bed (depending on the strength of the near-bed orbital motion).

The methodology for extrapolating short term predictions is summarised below.

The bed changes result from integrating the sediment transport over period of time, $\Delta t$, and then recalculating the new flows, before back-tracking and recalculating the sediment movement and bed level changes. The bed changes are assumed to occur as a result of, not only the 'old' flow conditions, but the 'new' - in short, a "predictor-corrector" method. The detailed procedure is as follows:-

(i) calculate flow over bed (waves plus steady inflow in the quoted case)
(ii) calculate sediment transport
(iii) calculate new bed
(iv) calculate new flow
(v) go back to old bed and compute new bed changes given 'old' and 'new' flow field
(iv) recompute 'new' flow field
(vii) repeat procedure, or extrapolate changes in flow, and hence sediment movement and bathymetry.

(i) The morphological time step is large compared to the typical duration of a single wave and current situation, so stationary wave and current fields are assumed. In this way, a number of different wave climates and currents are simulated, and a weighted average method is used, according to the required simulation. The sediment transport at the open boundary is calculated by a choice of either specifying that the bed level be fixed or by inputting a suspended sediment time series.

(ii) At the outlet boundaries, the bed level is interpolated along a line of characteristics according to the assumption that the bed locally acts as a sand wave.

(iii) The sand is single grain sized.

(iv) There is no coupling between the waves and currents.

(v) Both wave and flow fields change with time.

(vi) Currents are caused by steady discharge, so that tidal effects are excluded.

Sand transport rates are very sensitive to tidal currents and wave effects in shallow water. The "predictor-corrector" method helps prevent bed level predictions overshooting, because it allows rapid feedback from changes in the bathymetry to the rate and pattern of sand transport. This should mean that the time step can be increased, compared to methods which predict bed level changes by extrapolating forward using old velocity fields. The method of combining extrapolation with the predictor-corrector method is not clear. The method should be applicable to tidal regimes and to larger areas.

### 3.6.4 Long-term morphological evolution of tidal lagoons

Di Silvio and Gambolati (1990) describe a numerical finite element model of the evolution of tidal flats, shoals and channels due to a change in the dominant physical factors (eg tidal flow, fluvial sediment transport, sea waves, internal land subsistence, etc). The model is an extension of the zero dimensional one presented by Di Silvio (1989) and described in Section 3.2.3. The major difference is that the long-term sediment balance is written for an elementary portion of the lagoon having an infinitesimial horizontal surface, rather than for a cell of finite volume.

An example is given in which the sediment concentration of the sea at the inlet of a schematic lagoon is reduced by 15%. As a consequence, a progressive depth increase of both shoals and channels follows until a new equilibrium concentration is achieved. The initial peturbulation gives rise to the typical in-relief edges between channels and shoals, called 'veluce' in the Lagoon of Venice. These increase and then decrease in size but can take centuries before disappearing.

As with any other parameterized model, considerable data is required for proper validation and calibration of the model. However, some success has been achieved in reproducing the physical features of lagoon systems and the model is capable of being run for hundreds of years, so far impossible with any alternative approach.

## 4. CONCLUSIONS

A number of formulae for sediment transport under currents and waves have been developed. These can be broadly grouped into empirically based relations and more formal derivations based on physical agreements.

The empirically based relations comprise adaptions of existing uni-directional formulae with a stirring term which is modified by the presence of waves. However, they all appear unreliable except when the effect of currents dominate that of waves.

Profile models favour sediment transport predictions based on an energetics approach because the results are less sensitive to small deviations in the velocity and concentration profiles.

A wide variety of morphodynamic models are available for predicting coastal and estuarine evolution. In order to separate out the variety of timescales and prohibitively large computer run times two techniques have been developed:

(i) Input filtering. The number of wave and tide conditions is reduced whilst maintaining a realistic representation of the wave/current climate.

(ii) Process filtering. A simplified model is used that can be run for a full chronological series of inputs.

A number of case studies are presented in which the main features were described and any conclusions drawn were noted.

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