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Morphodynamic Models Used to Study the Impact of Offshore Aggregate Extraction: a Review

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ABSTRACT

This review highlights three morphodynamics modelling approaches, used for offshore marine aggregate extraction impact assessment. These approaches are based upon examples of (1) full process-based models; (2) idealised process-based models; and (3) conceptual models. Illustrated also is the way in which these models, applied for extractions on flat bed or sandbanks, can complement each other, towards the estimation of Coastal State Indicators (CSIs). This review leads to the conclusion that, for an optimal environment assessment, there are two main approaches: (1) either combine and couple the models, in order to simulate the full morphodynamics of the system over a long time-scale, taking into account also short-term events, or (2) use a set of existing models, knowing precisely their applicability to the CSI's and the reliability of their predictions, rather than using only the best model, available presently.

ADDITIONAL INDEX WORDS: *aggregate extraction, impact, morphodynamics, modelling, sandbanks, coastal state indicator*

INTRODUCTION

Marine aggregates have become recently a strategic mineral resource. Indeed, terrestrial aggregate resources are decreasing, such that large marine aggregate extraction is now being considered, or is already in progress. Thus, it is necessary to assess the impact of offshore marine aggregate extraction on offshore morphology; this can be undertaken by estimating the future trends of coastal systems, due to these extractions. The formulation of so-called Coastal State Indicators (CSIs) can assist in addressing these coastal management questions. The CSIs are a reduced set of parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of a coastal system (Van Koningsveld, Davidson, and Huntley, 2005).

Within the EUMARSAND project (2002-2005, Bonne, this volume), marine aggregate exploitation issues were addressed through the application of a wide range of scientific approaches (based upon geology, sedimentology, physics, ecology and engineering). The integration of these approaches can improve significantly both resource management and the knowledge of the impacts of aggregate extraction, on the state and dynamics of the inner continental shelf and coastal environments. In particular, morphodynamic modelling can contribute to increasing this knowledge, e.g., in terms of near-field modelling of the physical and ecological impacts of offshore sand and gravel mining; improvement in the understanding of 'bed regeneration' processes; and the far-field modelling of the effects of dredging on adjacent coastlines). Within the framework of the EUMARSAND Project, the morphodynamic modelling of experimental sites was set up with models which are based upon the description of small-scale processes (Brière *et al.*, this volume; Van Den Eynde *et al.*, this volume). The model calibration and the validation of the numerical results were performed against high-quality field observations. For this reason, fieldwork was undertaken in the North Sea and the Baltic Sea. The Kwintebank (located within a tidal environment) was selected as the field investigation site in the North Sea, whilst the area Tromper Wiek (non-tidal environment) was examined in the Baltic Sea (Garel and Lefebvre, this volume).

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Over the last decade, several other European projects have been concerned with the modelling of the impact of aggregate extraction, as outlined below.

- The SANDPIT project (Van Rijn *et al.*, 2005) was the most recent European project (2002-2004), whose overall objective was to develop reliable prediction techniques and guidelines, to better understand, simulate and predict the morphological behaviour of large-scale sand mining pits/areas, likewise, to understand the associated sand transport processes at the middle and lower (offshore) shoreface, together with the surrounding coastal zone.

- HUMOR (Besio *et al.*, 2008; Dodd *et al.*, 2008) was a European project (2001-2004), with the aim to develop reliable assessment and forecasting techniques, to better understand, model and predict the physical and geomorphological processes governing medium- and long-term natural changes of the coastal zone, including the impact of anthropogenic activities. The emphasis was on the role that large-scale morphological features play, in long-term coastal evolution.
- CSTAB was a European project (1992-1995), which focused on Circulation and Sediment Transport around Banks, based upon *in-situ* measurement and numerical modelling (O'Connor *et al.*, 1994).

In this contribution, we focus upon the offshore impacts of offshore aggregate extraction, with the offshore area being the portion of the beach profile that extends seaward from the breaker zone, to the edge of the continental shelf.

One approach for assessing the impact of aggregate extraction, quantitatively, is based upon morphodynamic modelling. Several types of morphodynamic models have been developed. Each approach has its own advantages and disadvantages.

This paper deals with the two following questions: (1) which model concepts are available to assess the aggregate offshore extraction impact?; and (2) how are these models to be used and, possibly, combined for an optimal environmental assessment of offshore marine aggregate extraction in tidal seas?

We focus upon a tidally-dominated environment, paying particular attention to the dynamics of regular sea-bed morphological patterns. Such patterns, such as sandbanks, are potential resources of marine aggregate.

This paper is organised as follows: section 2 incorporates an overview of available morphodynamic modelling approaches in tidally-dominated environments, to address the research question (1) above; Section 3 includes a discussion on how to use and combine the models, with the perspective of estimating coastal state indicators; and, finally, the conclusions are presented in Section 4.

MORPHODYNAMIC MODELS FOR OFFSHORE EXTRACTION IMPACT ASSESSMENT IN A TIDALLY-DOMINATED ENVIRONMENT (QUESTION I)

Model Approaches

Coastal characteristics result generally from many physical processes, which interact at various temporal and spatial scales. The concept of scales is important in modelling processes and in the selection of a model, or type of model. Here, three main classes have been distinguished:

- The full process-based models (FPBM), which describe small-scale processes and resolve physical equations in the physical space (x,y,z,time);
- The idealised process-based models (IPBM), which take into account processes relevant to the scale of interest and resolve physical equations partly in the spectral space (wave vector, time), partly in the physical space;
- The conceptual models (CM), which aim to describe the general behaviour of a phenomenon, without describing the details of the underlying physical processes.

Here, this particular model classification is preferred, instead of the commonly used temporal- or spatial-scale classification (e.g. short-term model, medium-term model and long-term model). Indeed, it is worthwhile to note that some approaches are more applicable over different time scales.

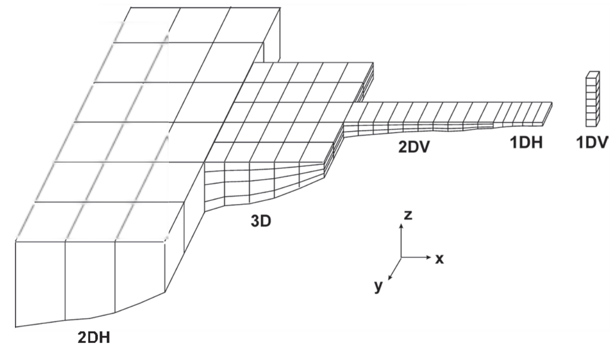

Figure 1. Discretisation levels for full process-based models. Note: the horizontal plane is (x,y). (Idier et al., present paper).

For instance, the stability analysis concept, which falls in the IPBM class, can be applied for long-term morphodynamics studies (e.g. sandbank dynamics (Huthnance, 1982)), as well as for short-term morphodynamics studies (e.g. ripple dynamics (Blondeaux, 1990)).

It may be noted that, within the process-based models, several aspects can be distinguished:

- Spatial dimensions of the model geometry (Figure 1): 1DV (V for the vertical, 0 the horizontal dimension); 1DH (H for horizontal, 1 horizontal dimension. The variables are integrated over the water depth); 2DV (V for vertical); 2DH (H for horizontal, 2 horizontal dimensions. The variables are integrated over the water depth); and 3D (three-dimensional. For instance, the velocity components are computed in the three directions x,y,z, at any location in the x,y,z space);
- Hydrodynamic processes: waves, tidal currents, wind-induced currents, and wave-current interactions;
- Sedimentary processes: suspension, bedload, and heterogeneous sediment mixtures;
- Bed evolution, related to (divergent) sediment transport.

Full process-based models (FPBM)

Theoretically, full process-based models rely upon processes alone which, in principle, should enhance their generic applicability. These models start commonly, from a number of more or less standard models of the constituent processes (waves, current, sediment transport); these are coupled through a bottom evolution equation.

De Vriend and Bakker (1993) have identified two types of full process-based models: initial sedimentation erosion (ISE) models; and medium-term morphodynamic (MTM) models. ISE models assume a fixed bed level whereas, in MTM models, the bed level is updated, on a time-scale which cannot be substantially larger than the hydrodynamic time-scale. MTM model applications are used regularly, nowadays, on time-scales of 5-20 years; this is due, not only to enhanced computer power and model robustness improvement, but also because of more reliable input reduction techniques (see, for example, Latteux (1995), for tides, and Chesher and Miles (1992), for waves). Application of these models at longer time-scales is still hampered by the fact that inaccuracies accumulate within a long-term morphological prediction; this is because of the approximations of the implemented physics, inaccuracies of the numerical schemes and schematised boundary forcing (input reduction). When these inaccuracies become of a similar order of magnitude as the physical phenomena being studied, it is not appropriate to extend further (in time) a process-based simulation.

Morphostatic models (ISE) permit the investigation of the initial response of system, to a perturbation/human intervention, i.e. not to determine towards which equilibrium, or instability, the system will develop. The solution to these limitations is to utilise morphodynamic models. However, in practice, there is often a need to interpret the results of initial transport computations, without having to resort to full morphodynamic simulations. One approach is to investigate the initial sedimentation/erosion rates; however, this method is flawed, in many respects: initial disturbances of the bathymetry have led to a very scattered pattern. For example, De Vriend *et al.*, (1993) have studied the morphodynamics of a 'sandy bump', subjected to a steady current. These investigations have shown that sedimentation/erosion patterns tend to migrate in the direction of transport; this is a behaviour which is not represented in the initial sedimentation/erosion patterns. Thus, several methods have been developed, to extend the time-scale towards a longer morphodynamic time-scale. Latteux (1995) has proposed several methods, such as tide-lengthening. This approach, which is adequate to study propagative features such as sandbanks (Latteux, 1995), consists of increasing the morphological time-step, by a so-called morphological factor (typically, N = 100 to 1000); this is such that full process-based morphodynamic models can now be applied, at time-scales of ~5 to 10 years (medium-term models). Such methods are implemented in many morphodynamical models. Roelvink (2006) developed another method, which assumes that the overall flow and wave patterns do not change for small bed level changes. This assumption is used also in the "continuity correction" of many morphological models. The tidally-averaged transport rate is a function of the flow and wave patterns (which do not vary on a morphological time-scale), and the local water depth (which varies on a morphological time-scale). Thus, given a certain set of current and wave conditions, transport at a particular location is only a function of water depth ($\left|\vec{S}\right| = A(x,y)h^{-b}$); here, h denotes water depth and b is a constant. In this case, the value of A at each horizontal point (x,y) can be derived directly from the local water depth and the initial transport rate, which may be computed using a sophisticated transport model. This approach means that the downslope preference of bedload (within the initial transport rate), as well as wind-driven current effects (within the transport rate, averaged over a tidal cycle) is included. A combination of the sediment balance equation, together with the equation cited, requires very little computational effort (this method has been implemented in Delft3D-RAM, Rapid Assessment Module). Within morphodynamically active areas, such as estuaries and outer deltas, the RAM method may still work well enough to be applied as a rapid updating scheme. As soon as the seabed change becomes too large, full simulation of the hydrodynamics and sediment transport is carried out for a number of input conditions. A weighted-average sediment transport field is then determined, which is the basis for the next RAM computation over, for example, a year. An important observation can be made that (costly) computations, to update wave, flow and transport fields, can be carried out in parallel; this, in addition to the simplified updating scheme, leads to a significant reduction in the simulation time (compared to a FPBM approach). With this approach, i.e. the coupling of the hydrodynamic FPBM Delft3D and the RAM module, morphodynamic simulations (covering decades to centuries) are feasible, in terms of computational effort. However, experience of applying such a process-based model, on time-scales longer than 50 years, is limited.

Finally, all of these models suffer from variability in, and errors associated with, the input and the boundary conditions.

Idealised process-based models (IPBM)

Idealised process-based models are morphodynamic models, intended especially to describe the dynamics (generation, growth, maintenance) of regular sea-bed patterns. Such models are based also upon physical equations, such that they have almost the same limits as the full process-based models, in relation to lack of knowledge (or parameterised incorporation) of small-scale processes. However, the models are developed and used for well-defined applications, to isolate certain phenomena, e.g. sandbank generation. Compared to the full process-based models, idealised models assume simplified geometry, inputs and boundary conditions; and such, IPBM are generally much less expensive, computationally. The simplified inputs imply that the hydrodynamic forcing is quite simplified, and that, at least untill now, the extreme events are not described explicitly. As inputs are simplified, this implies they have been designed mainly to provide information (preferred wavelength, orientation, saturation height, or shape for certain conditions) on the free behaviour (natural evolution without any temporal change in the forcing) of the system (e.g., sandbank generation over a flat bed).

The IPBM models assume an initial sea-bed perturbation which is, mathematically, infinitesimal with, for instance, the amplitude being several orders of magnitude less than the water depth. Subsequently, the aim of these models is to determine whether this seabed perturbation will grow, or decay, with time; likewise how it will evolve. Hereinafter, as a starting point of a stability analysis, a physically-relevant and exact solution of the constituent equations is required. For example, for an application to offshore bedforms, the basic state (the solution of the zeroth-order equations) is that of a flat bed. Therefore, the hydrodynamic and bed evolution equations are solved for an initial flat bed, leading to horizontally-uniform solutions. This basic state is perturbed by arbitrary small periodic bed waves, denoted by a 2D wave-vector (the module is inversely proportional to the wavelength and the direction is perpendicular to the bedform crests), allowing for all combinations of bed wavelengths and orientation. For some wave-vectors, these perturbations decay with time; for others, the basic state becomes unstable and some of the disturbances will grow. Thus, evolving into a regular pattern of finite amplitude. An important aspect of the idealised process-based models is that the equations are solved partly in spectral space (the space of wavelength and the orientation of bedforms) and partly in the physical space, instead of in the physical space of the full process-based models (e.g., Delft3D). For cases of uniformity in both horizontal directions, the equations are even solved fully in the spectral space. (Dodd *et al.* (2003) have undertaken a review of the different types of stability analysis). The two main classes are the linear and the non-linear stability models. The first approach yields information on the initial stage of formation (linear interactions only): for instance, for bedform generation, the assumption of a bedform amplitude much smaller than the water depth is related directly to this linear approach. If larger bedforms are considered, non-linear interactions occur and higher-order terms in the bed amplitude have to be taken into account.

Conceptual models (CM)

The conceptual models, also referred to as behaviour-oriented models, attempt to describe the general behaviour of a phenomenon, without entering into details of the underlying physical processes. The derivation of these models is based often upon both measurements and physical conservation (for instance the sediment-mass balance). HANSON *et al.* (2003) have provided an overview of these methods, for use in coastal regions.

A typical conceptual model focussing upon offshore dredging has been developed by KNAAPEN and HULSCHER (2002). These investigators developed a model describing the regeneration of sand waves, following their removal, to increase the water depth for navigation. Based upon the stability model of HULSCHER (1996), together with the knowledge that sand waves reach equilibrium with a finite height, KNAAPEN and HULSCHER (2002) assumed that the sand wave amplitude A follows the equation:

$$\frac{\partial A}{\partial t} = a_1 A - a_2 A^3$$

Where A is the bedform amplitude, coefficient a_1 is related to the linear growth and a_2 to the equilibrium height. This generic equation, referred usually to as the Landau equation, appears in many weakly non-linear stability analyses (DODD *et al.*, 2003), in which the coefficient a_2 can be derived from the (mathematical) weakly non-linear analysis. KNAAPEN and HULSCHER (2002) showed how the coefficients a_1 and a_2 can be derived, using data and the linear model. The coefficient a1 could be deduced from the stability model of HULSCHER (1996). Alternatively, the coefficients a_1 and a_2 could be estimated by fitting this model to the results of any other model. This remark is important, if there is only limited information available on the regeneration of larger sand patterns, for which the time-scales are even larger.

ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast; STIVE and WANG, 2003) provided another example of a behaviour-oriented model. This model describes the evolution of a tidal inlet, towards a new equilibrium forced by external conditions or geometric interventions. This concept was applied firstly to the Wadden Sea by EYSINK (1990), who derived an analytical expression for the morphological evolution of a disturbance, from the equilibrium state for a single element. ASMITA is an extension and aggregation of the ESTMORF model (STIVE et al., 1998). Aggregation is related to the fact that each morphological element is characterised by only one variable, i.e. its equilibrium volume. The underlying principle is that each element (delta, channel, flat) attempts to reach a new equilibrium state. Although ASMITA was originally not designed to investigate the effects of sand extraction, the concepts can be applied also to this problem. Instead of identifying morphological units, the schematisation can be based also upon a computational grid. The exchange between the cell-interfaces is determined by advection and diffusion of the sediment. The advective sediment exchange can be estimated from the residual tidal motion predicted by a process model (e.g., Delft3D or Telemac). Sediment diffusion is based upon an estimate of the equilibrium sediment concentrations, which depends upon the ratio between the actual water depth and an equilibrium depth (typically, the undisturbed ambient water depth).

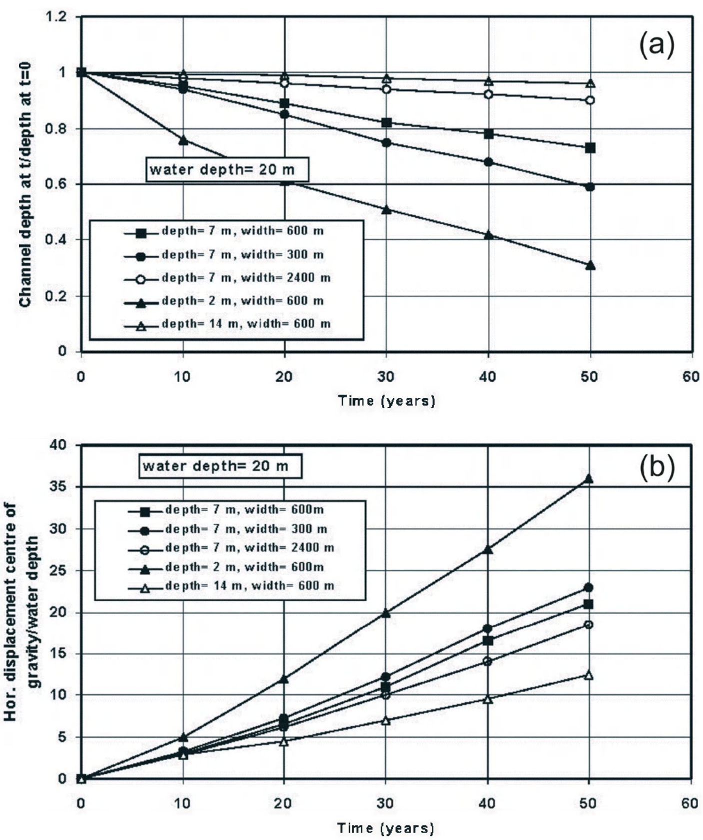

Figure 2. Influence of channel dimension on sedimentation and horizontal displacement of channel, after 50 years (Van Rijn and Walstra, 2002). Note: results obtained with SUTRENCH.

All of these conceptual models are based upon a number of assumptions, such as, for instance, that a dredged sandwave will recover its original amplitude; these have to be checked carefully, independently when, using these models.

Offshore Impact of Offshore Extraction

Offshore extraction on a flat bed

The offshore impact of offshore extraction, on a flat bed, has been studied using the two types of models: full process-based and idealised process-based models. For conceptual models, indications on possible future use are provided.

Full process-based models (2DV, 2DH and 3D). Several levels of complexity of full process-based models have been applied to, then compared with similar cases. VAN RIJN *et al.* (1999), studied the morphodynamics of a trench, using SUTRENCH; this is a 2DV model, based upon advection-diffusion equations for computing the bed sedimentation in channels under varying wave and flow conditions. The model calculates, in a time-dependent mode, sediment transport in response to currents and waves, as well as changes in bed levels. Using this model, the influence of the channel dimension on sedimentation and the induced horizontal displacement of the channel, over 50 years, has been studied (Figure 2). The study predicts that the water depth outside the mining pit has the greatest influence on its morphological evolution (Figure 2,

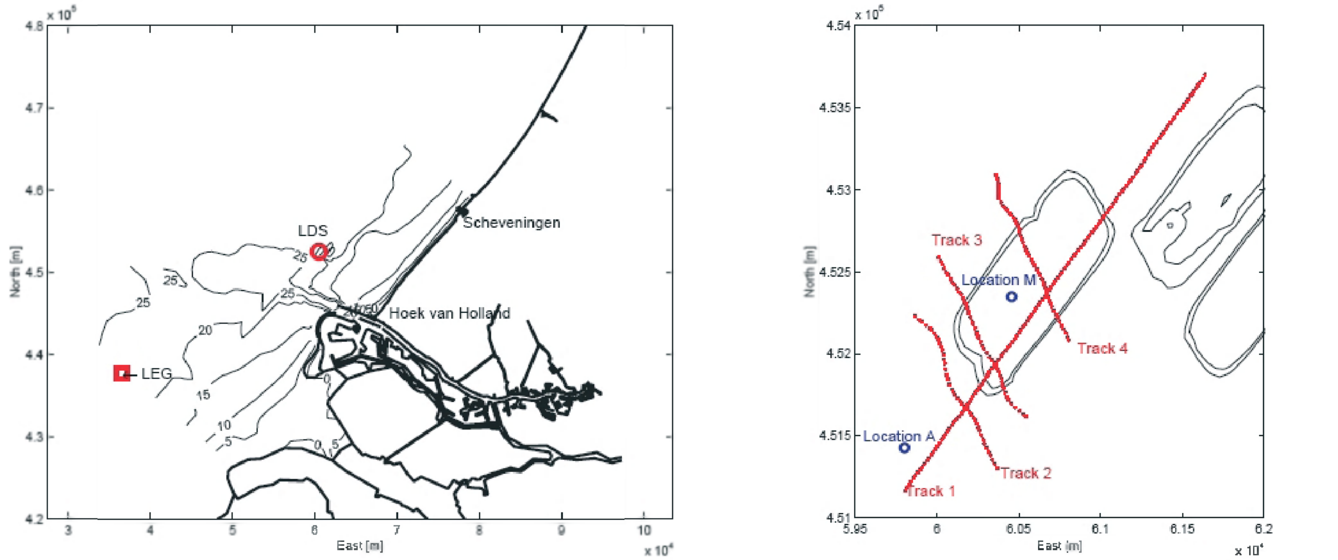

Figure 3. Plan view of LDS (LDS is the pit location), measurement locations and measured tracks.(a) : overview of pit location (LDS is pit location; LEG is the offshore wave station); (b) : plan view of LDS, with measurement locations (blue) and tracks (red). (from Walstra *et al.*, 2002).

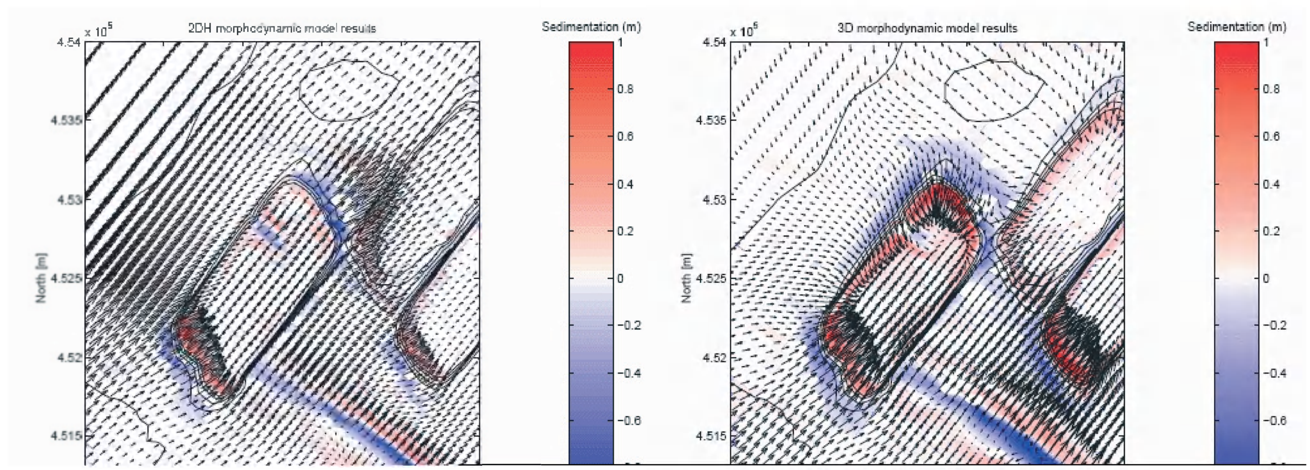

Figure 4. Sedimentation-erosion and yearly residual transport calculated in 2DH (a) and 3D (b). (from Van Rijn *et al.,* 2003).

upper panel); this is in response to the effect of water depth on the sediment transport capacity. In contrast, the pit geometry and its dimensions have much less effect on the morphological evolution of the pit. Figure 2 (lower panel) shows also that wide pits have a larger morphological time-scale than deep pits, which have also a smaller migration rate; this is "favourable" as it minimises the impact on the coastline. However, comparison with 2DH models shows the importance in reproducing the flow contraction that occurs in the trench, which was not included in the SUTRENCH simulations.

Walstra *et al.* (2003) validated the Delft3D model in both depth-averaged (2DH) and 3D-mode. In the sediment transport module, the model takes into account bedload, suspension and wave effects. The 2DH model has been used to study the sedimentation-erosion, as well as the annual residual transport, in an offshore pit in the North Sea; this was located 10 km off the Dutch coast, near the Hoek van Holland (Figure 3). These results (Figure 4a) have been compared to the results obtained with the 3D model, Delft3D (Figure 4b). Both models predict that most changes occur in the immediate vicinity of the pit, with erosion just outside the pit and sedimentation mainly on the pit slopes. However, the 3D simulation resulted in significant larger changes in the morphology. In particular, sedimentation on the longshore pit slopes is more pronounced in the 3D results; this is caused mainly by secondary cross-shore flows, related to the presence of the pit and density-driven flows (visible clearly in the residual transports patterns). The 2DH simulation predicts northeasterly transport, parallel to the main tidal direction; this leads to morphological changes occurring mostly on the pit slopes, perpendicular to the

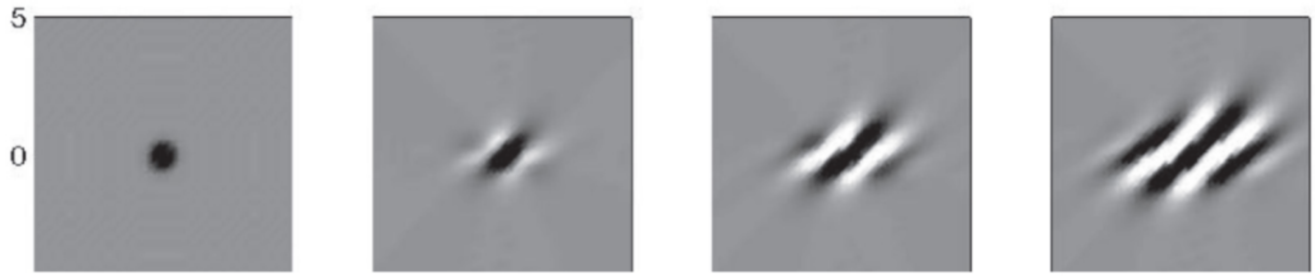

Figure 5. Plan view of the evolution of a sandpit, created on a flat bed, subject to tidal flow (M2 and M4). The deeper parts are shown in black, with the shallower parts white, the undisturbed seabed is grey. Domain size: approximately 70 x 70 km². (Roos and Hulscher, 2003).

main tidal direction, related to the acceleration and deceleration of the flow. However, the 3D simulation predicts that the pit location LDS attracts sediment from all directions, which results in southward transport over the northern part of the pit. Based upon surveys of the pit area, WALSTRA *et al.* (1997) concluded that the 3D morphodynamic simulations provided a more accurate prediction. However, such a conclusion cannot be validated definitively, because of the absence of reliable measured seabed changes (i.e. the observed bed changes were of the same order as the measurement error). Moreover, the relative small time-scale considered (one year) was too short to draw any definite conclusions.

Idealised process-based models. Using an idealised process-based modelling approach, ROOS and HULSCHER (2004) investigated the morphodynamic effects of creating a large-scale sandpit (2m deep, 15km length, and width of 1km), in a flat region of the offshore seabed (in a water depth of 20m). The results show that flow contraction occurs, increasing the water flux inside the pit. Such convergence of the streamlines of the depth-averaged flow, inside the pit, can be explained by: the continuity law of the flow entering and leaving the pit, the reduced friction inside the pit, due to the increased depth, and the adaptation length.

The morphodynamic implication of this phenomenon is a gradual deformation of the sandpit in the preferred direction of sandbank formation, together with the appearance of additional humps next to the pit (Figure 5).This morphodynamic response is related directly to the inherent instability of an initially flat seabed, which develops into a pattern of tidal sandbanks over a time scale of about 1000 years (HUTHNANCE,

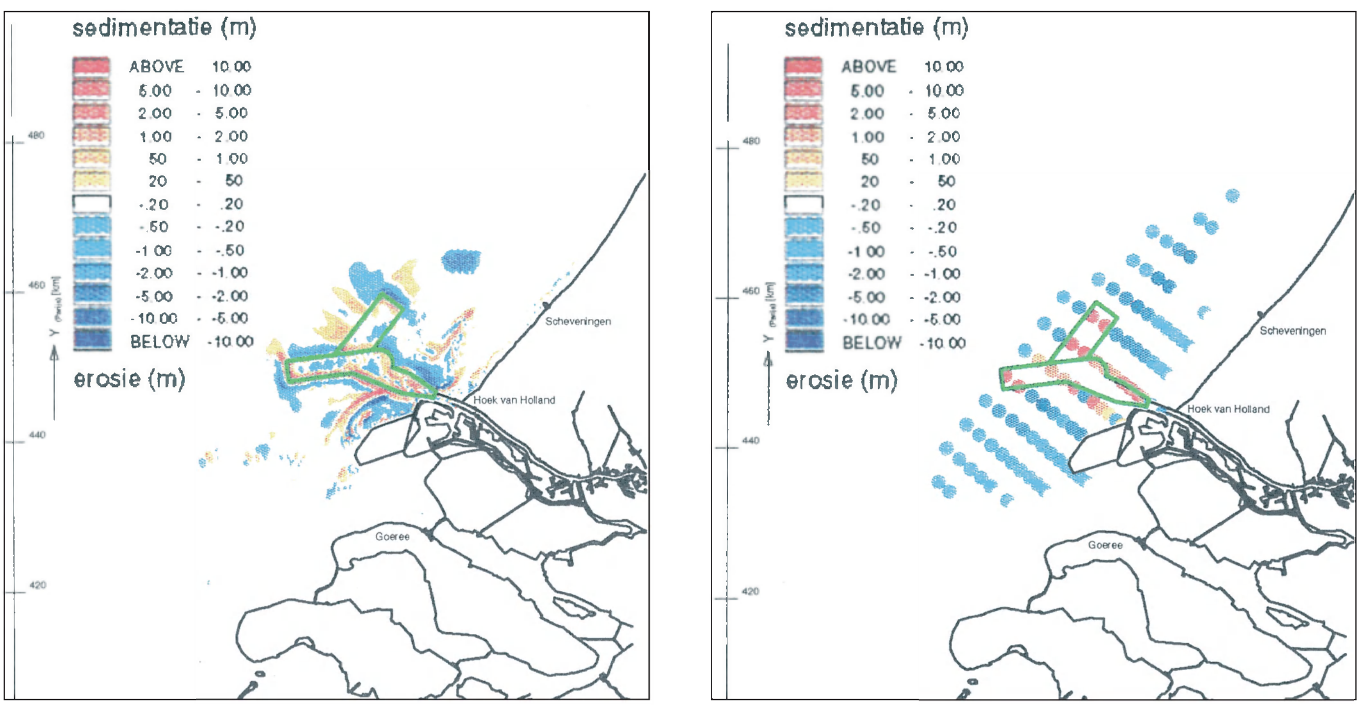

Figure 6. Predicted relative bottom changes due to sand extraction (bottom changes of the land reclamation are ignored, extraction area indicated by green polygon): (a) plot of the predicted changes, after 50 years, with Delft3D-RAM; (b) plot of the predicted changes, after 300 years, with ASMITA.

1982). The results display also pit migration in the direction of the tidal asymmetry with the response depending upon the pit geometry. Futhermore, the inclusion of sandwave formation processes leads to higher rates of pit migration (Roos *et al.*, 2005).

Conceptual model. To date, conceptual models relating to an offshore sand pit have still to be published. The lack of measured data makes it difficult to validate such models. Some conceptual models have been applied to study seabed dynamics, in the case of sand pit extraction (see the ASMITA model (next paragraph on combined models)), but they are not designed to reproduce the dynamics of the pit itself. A possible approach could be to examine a sand pit resulting from mining, as an initial perturbation from the equilibrium flat bed. Assuming that the interference effects (Figure 5) of Roos and Hulscher (2004) are avoided, relaxation theory assumes then that the infilling of the pit will be:

$$\frac{\partial D}{\partial t} = a_1 D$$

In the case of a negative growth parameter (a_1<0), the depth *D* of the pit will decrease, exponentially to zero. The value of this growth parameter has to be estimated; presently, this can not be determined from measurements. As the seabed dynamics on the length scales being examined will take place on very long time-scales (over decades), a reliable calibration would require surveys spanning decades. Nevertheless, process-based models reveal that the dynamics of such a pit depends strongly on the shape, size and orientation of the pit (Roos and Hulscher, 2004; Van Rijn *et al.*, 1999, Walstra *et al.*, 2003). This conclusion implies that calibration of the conceptual model should be applied to a wide range of pit sizes, shapes and orientations. It will be a long time before such measurements, on a wide range of pits, would be available, i.e. regarding the number of all possible pit size, shapes and orientation to span, as well as the long morphological time-scale associated to pit dynamics. Alternatively, the conceptual model could be fitted against a combination of outputs from process-based models. Once the conceptual model is tuned against results of various process-based models runs, it could be a rapid, yet reliable, and therefore a useful decision-making tool for seabed mining management.

Combined models. In Walstra *et al.* (1997), Delft3D (a full process-based model) and ASMITA (a conceptual model) were applied simultaneously, to investigate the large-scale extraction of 1 billion cubic meters of sand for land reclamation (Maasvlakte-2), at the Rotterdam harbour in the Netherlands (Figure 6). Delft3D-RAM simulations, over 50 years, predicted that the effects of the sand extraction (a lowering of 10 m, inside the green box in Figure 6) were confined to the immediate surroundings of the extraction area. The ASMITA simulation, covering a 300 year period, reveals that the morphological effects are present over a significantly larger area (the effects on the coast were not included). An important advantage in using the ASMITA conceptual model was the possibility to perform a sensitivity analysis, over the 300 year period. The sensitivity analysis concluded that the model predictions were robust, i.e. parameter variation resulted in linear, or almost linear, effects on the model output.

Offshore extraction on sandbanks

Sandbanks are characteristic of continental shelves with a high supply of sand and sufficiently strong tidal currents. The Belgian continental shelf, in the southern part of the North Sea, is covered abundantly with these large structures and has been studied extensively (Lanckneus *et al.*, 2001). All three model types (full process-based, idealised process-based, and conceptual models) have been used for studying the offshore extraction from sandbanks.

Full process-based models (2DH). FPBM models are used often for investigating the behaviour of the sea bed; their application to sandbank morphodynamics is not straightforward

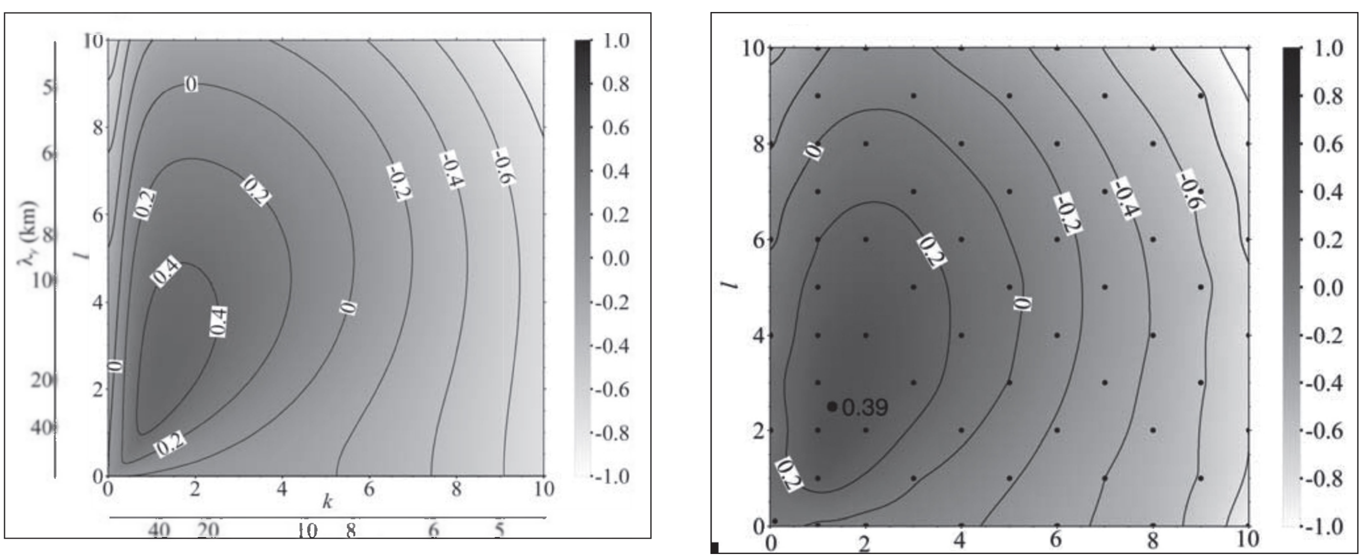

Figure 7. Dimensionless growth rate: (a) idealized process-based model (linear stability analysis); (b) full process-based model (Telemac). Note: on the Figure, wave number k is in the direction of the tidal current, whereas wave number l is perpendicular. Water depth=30 m. Grain size=0.5 mm. Strikler coefficient=55 m1/3s-1. Depth integrated velocity=1 m/s. Morphological time-scale=303 years. (from Idier and Astruc,2003).

and only limited applications have been undertaken, especially on the influence of sand extraction from sandbanks. However, part of the dynamics has been studied; for instance, the ability of a FPBM to reproduce sandbank generation (Idier and Astruc, 2003). Hydro-sedimentary patterns of dredged sandbanks have also been modelled (Deleu *et al.*, 2004); these studies as described below.

Based upon idealised process-based model results (linear 2DH stability analysis), together with those of a full process-based model (Telemac), Idier and Astruc (2003) have studied the linear and non-linear behaviour of large-scale underwater bedform patterns, such as sandbanks. The model is based upon depth-integrated hydrodynamic equations, with a quadratic bottom friction law (Telemac2D), together with a bed load sediment transport model including a bottom slope effect (Sisyphe, a module of the Telemac package). Firstly, the stability of a flat sand bed subject to a simple tidal current was computed, using the Telemac model. Small amplitude sinusoidal bedforms are superimposed upon the flat bed. They are characterised by a single wavelength and orientation, relative to the current. The growth rate of this eigenmode has been defined as:

$$\frac{\partial h}{\partial t} + \vec{\omega}_a . \vec{\nabla} h = \omega_g h$$

with h the bedform amplitude, ω_g the growth rate and $\vec{\omega}_a$ the migration rate. Good agreement with the linear stability results was found (Figure 7). Secondly, the Telemac model was used to investigate the non-linear behaviour of the instability, for a simple tidal current; more specifically, to estimate the saturation height of the theoretically most-amplified mode. Thirdly, a Landau equation, whose coefficients are computed from the previous results, was used to predict the temporal evolution of the bedform amplitude from its initial infinitesimal amplitude to saturation. A comparison with the characteristics of continental shelf sandbanks shows that the model provides a reasonable estimation of the temporal dynamics of these large-scale bedforms. The saturation height appears to be slightly overestimated, which is due to the study hypothesis (the study is focused on the temporal variations of one mode, assuming that the "linearly most amplified" mode will be the dominant mode in the non-linear regime). However, this study has shown that full process-based models are able to reproduce the generation of bedforms, whose characteristics are close to those of the sandbanks; it has shown also a part of the sandbank height saturation processes, since for large enough amplitudes, the model is able to provide negative growth rate for modes which were amplified initially. Furthermore, this publication provides an example of how to combine various approaches (here, full process-based model (Telemac), idealised process-based model (linear stability analysis), and conceptual model (Landau equation)).

The Hinder Banks (lying to the North Sea) and the Flemish Banks are non-idealised sandbanks studied within the framework of the CSTAB project (and also the BUDGET -Lankneus *et al.*, 2001- MAREBASSE -Van Lancker *et al.*, 2007- or EU-MARSAND projects). Within the CSTAB project, Williams *et al.* (2000) applied a three-dimensional model to the Middelkerke Bank. The model included tidal currents, wind waves and sediment transport. The results reveal the presence of a clockwise residual circulation of water around the bank, which is consistent with theory. Further, all of the studies undertaken showed that the sandbanks are areas of a changing spatial depositional budget, due to complex hydrodynamic forcing. Likewise, sandbanks should be seen as part of a system of swales and sandbanks. Such results assist in understanding the temporal and spatial evolution of tidal sandbanks.

Another example of a full process-based model applied to sandbanks is a study undertaken by Deleu *et al.* (2004) in which the Westhinder Bank (Belgian continental shelf) has been modelled using a morphostatic model; this consists of an hydrodynamic module, mu-HAB, and a sedimentary module, mu-SEDIM. These investigations provided information on current pattern and sediment circulation around the bank.

Idealised process-based model. In the field, two types of sandbanks are found: tidal sandbanks (sandbanks oriented counter-clockwise to the main current in the Northern Hemisphere) and shoreface-connected ridges (sandbanks lying closer to coastline and oriented clockwise to the main storm induced current). The extraction of marine aggregate has been studied for both of these features.

The stability model presented above (Section 2.3.1) considers a flat bed and, as such, is thus not suitable for studying the impact of sand extraction from tidal sandbanks. For this

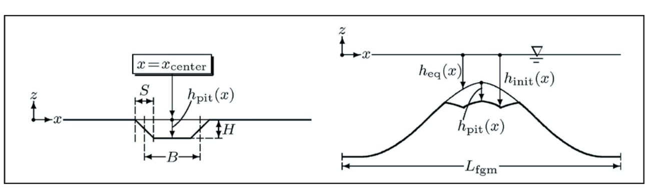

Figure 8. Definition sketch of a sandpit, as created in a one-dimensional equilibrium profile of a tidal sandbank (after Roos, 2004): (a) pit geometry h_pit(x), showing width B, depth H (and slope length S), (b) the same pit, now created at the crest of a tidal sandbank in morphodynamic equilibrium h_eq(x). Notes: (i) the pit location relative, to the bank profile, is an additional characteristic of sand extraction (compared to the flat-bed case) and (ii) the model assumes alongbank uniformity, i.e. the banks and pits are infinitely long.

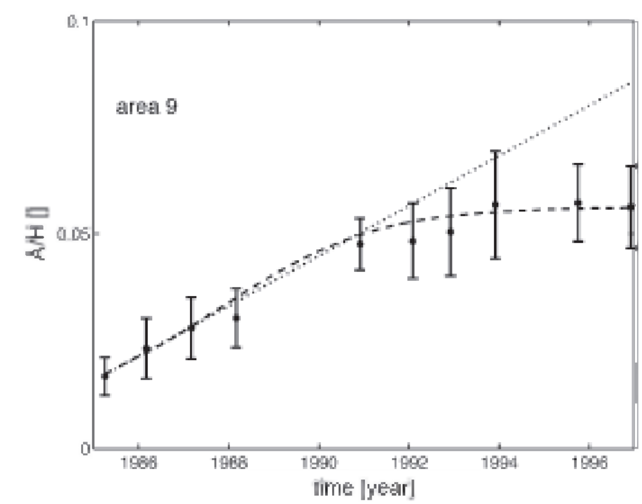

Figure 9. Prediction of the sand wave growth in Bisanseto Channel (Japan). The model is based upon the Landau equation (dashed line) and the linear trend analysis (dotted line), both based upon a model parameter tunning on the first three measurements (before 1968). (from Knaapen and Hulscher, 2002).

purpose, the finite amplitude equilibrium profiles were obtained, with the non-linear sandbank model provided by ROOS *et al.* (2005). Sand extraction from a tidal sandbank can be seen as a local perturbation of such a profile (Figure 8). ROOS (2004) showed that, after creating such a pit, the system shifts to a new equilibrium state. The corresponding time-scales are of the order of a century; they are shortest for deep and narrow pits created in the crests of the banks. It is important to realise that the above model approach considers sand extraction from each individual bank, within a periodic profile; thus, all of the banks are considered to be identical. As a result, the potential interaction between a sandbank, with a pit and surrounding banks (without a pit), cannot be studied. Such a limitation (lack of localisation) is inherent in such an idealised model.

Elsewhere, a stability analysis approach has been used by DE SWART and CALVETE (2003) to study the impact of extraction on shoreface-connected ridges. The model is based upon non-linear stability analysis. The main processes taken into account were: storm-driven currents; 2DH shallow-water equations; bedload and suspended sediment transport; the action of waves; net currents; and seabed slopes. In particular, these investigations have shown that, following the local removal of sand, the system tends to return to its original equilibrium state. This gradual process, occurring over several centuries, is associated with a supply of sand, from both the outer shelf and the nearshore zone. Thus, extraction of sand from the shelf (shoreface-connected ridges), together with the dredging of navigation channels, may have negative implications for the stability of the adjacent beach.

Conceptual models. To the knowledge of the authors, there is only one conceptual model which has been proposed, in relation to offshore dredged sandbanks (HOMMES, HULSCHER, and STOLK, submitted). Previously, KNAAPEN and HULSCHER (2002) applied a conceptual model to dredged sandwaves, assuming that they will recover their initial amplitude, after dredging. The growth of such tidal sandwaves followed a logistic equation, as illustrated in Figure 9:

$$\frac{\partial A}{\partial T} = a_1 A - a_2 A^3$$

In HOMMES, HULSCHER, and STOLK, submitted, this model is adjusted to predict the regeneration of 'sand ridges' (technically, the same as sandbanks), following dredging (Figure 10). Parameter settings have been estimated from the sandbank study of HULSCHER (1996). A value for the linear growth parameter a1 was estimated, based upon the physical processes and for typical North Sea conditions. The non-linear damping parameter a2 was estimated from bathymetric data available for sandbanks. Assuming that the sandbanks are in equilibrium with prevailing current conditions, i.e. no temporal change, the equation reduces to:

$$a_2 = \frac{a_1}{A^2}$$

The coefficient a_2 was estimated by assuming an equilibrium sandbank height of 15 m, this is a typical height for the Zeeland ridges. The model gives the recovery period, which is the time taken for the dredged bedform to reach its former height. The influence of the dredging depth on the recovery period was investigated, e.g., assuming that the crest of the sandbank will be lowered by 2 m and, using these coefficients, the recovery period would be about 400 years. After tuning the model against a combination of field measurements, idealised process-based models and full process-based models, the model's simplicity makes it a very useful tool for designing optimal sandbank mining strategies.

This approach, based upon a logistic equation, assumes a lowering of the complete sand bank. The dependency on horizontal pit size (shown in Figure 2) can be incorporated only by pit-size dependent model coefficients; likewise, the effect of pit migration needs to be negligible.

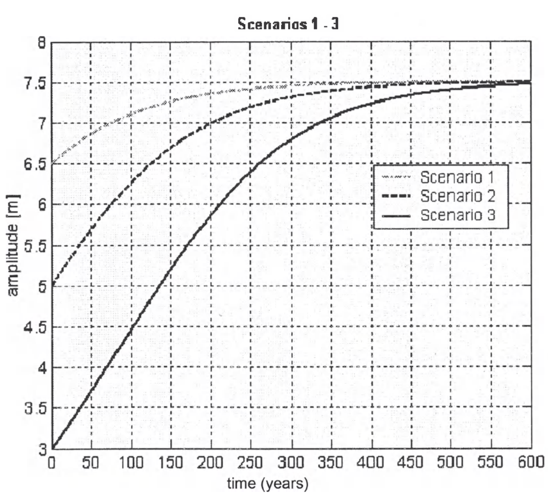

Figure 10. Results obtained from an amplitude-evolution model. In the model runs, the amplitude before dredging (A0) was taken as 7.5 m, which is similar to the amplitude of the Zeeland ridges (see text). The scenarios shown are: scenario 1 (dredging depth=2m); scenario 2 (dredging depth=5m); and scenario 3 (dredging depth=9m). (from Hommes, Hulscher, and Stolk, submitted).

Discussion on nearshore impact of offshore extraction

The influence of waves on sediment transport is stronger, generally, in the nearshore area. However, not all of the available offshore models integrate such wave-induced sediment transport processes. However, the offshore models can assist also in the evaluation of coastal dynamics, as they are able to explain how mining activities influence sediment transport patterns towards the shore. One impact of a bed depression on the adjacent coastline is the modification of the induced wave propagation. Such modification could have a drastic effect on the shoreline. The study of the relationship between the nearshore area and offshore sand extraction is still under investigation, e.g., using field measurements, it is difficult to relate properly offshore sand extraction and beach evolution.

Full process-based modelling has been used previously within the CSTAB project (MACDONALD and O´CONNOR, 1996). The project included modelling and field experiments undertaken on the Middelkerke Bank (the Belgian continental shelf) and the adjacent Nieuwpoort beaches. On the basis of field observations, these investigations concluded that sandbanks afford substantial protection to the coast and that this effect may be reduced by rising mean sea level and dredging activities.

The relationship between sandbanks and the shoreline was investigated also in the project "Understanding the Behaviour

Table 1. *Synthesis on the long-term approaches.*

	Advantage	Drawback	Outputs	Time/space scale
LESSER *et al.* (2004), with Delft2D/3D (full process-based)	Quite reliable results, on the short- or mid-term (VAN RIJN *et al.*, 1999; TONNON *et al.*, 2007; SUTHERLAND *et al.*, 2004; NICHOLAS *et al.*, 2004)	Highly sensitive to quality of local boundary and initial conditions Time-consuming, for sensitivity analysis	Current Wave Sediment flux Bed evolution	Few meters to hundreds km Minutes to decades
ROOS and HULSCHER (2004) (idealised process-based)	Process analysis (geared to describe an isolated phenomenon, in an idealized case, eg, sandbank dynamics)	Hard to set up a stability analysis model. Problem of validation of this approach (PETERS and HULSCHER, 2006). cannot be used in site-specific situations, e.g. the Kwinte Bank.	Current Sediment flux Bed evolution	Few meters to hundreds km Decades to century
HOMMES *et al.* (submitted) (conceptual)	Not time-consuming. Easy to use	Field data required Require qualitative support from process-based model results, or from field experience (check if the model is appropriated for the considered configuration ?)	pit/sandbanks amplitude	Event scale, or long-term

and Engineering Significance of Offshore and Coastal Sand Banks" (WHITEHOUSE, 2001). The influence of bank changes, on coastal sediment transport and morphodynamics was assessed using numerical coastal process-based models (SOUTHGATE and BRAMPTON, 2001), which showed that the beach generally supplies the banks, if the sand is exchanged between the beach and the bank. Other field studies have confirmed this behaviour: beach-bank exchange occurs, for example, at Donna Nook on the Lincolnshire Coast (UK).

Idealised process-based models, not specifically nearshore models, can also be used. For example, a stability analysis has been performed on shoreface-connected sand ridges by de Swart and Calvete (2003). In addition to the offshore impact, this study provides information on the nearshore impact of offshore extraction on the ridge.

HANSON *et al.* (2003) have provided an overview of nearshore models (especially, conceptual models), to study the impact on the shoreline, including waves.

Main characteristics of the three approaches: examples

Examples show how the three approaches complement each other. Table 1 lists some of their characteristics: advantages, disadvantages, outputs, and time/space scales; the latter are somewhat related. This relationship can be shown using linear stability analysis, where the morphological time-scale is related to the spatial scaling. For instance, in Idier and Astruc (2003), the morphological time-scale (hundreds of years) is related to the tidal excursion length (hundreds of kilometres).

In general, engineering studies use FPBM to analyse morphodynamic changes; they appear more reliable, because they

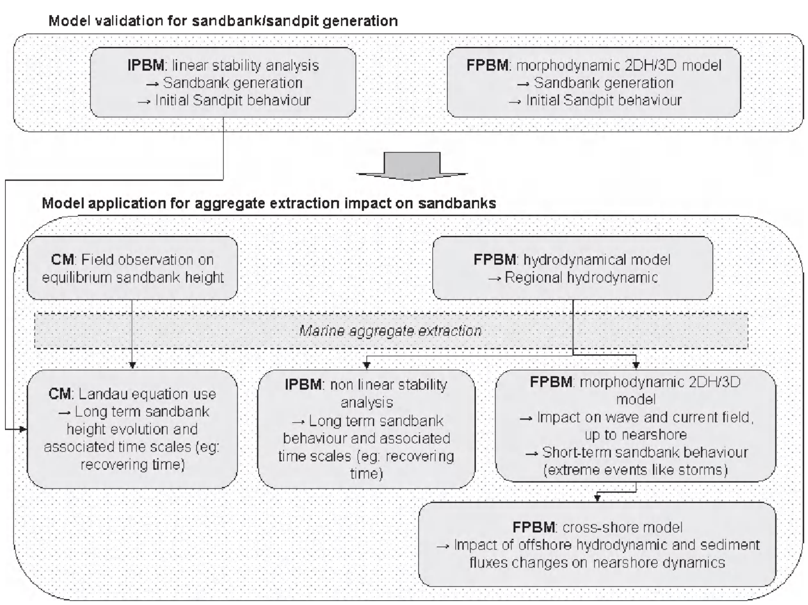

Figure 11. Schema example of model coupling for the impact study of offshore aggregate extraction, in a sandbank area. Terms: IPBM - Idealized process-based model ; FPBM - Full process-based model; and CM - Conceptual model.

contain descriptions of all the processes. Occasionally, a CM is used: ASMITA for problems around tidal inlets (Kragtwijk *et al.*, 2004), and the one-Line model (Demir *et al.*, 2004) for coastal changes. The IPBM has so far been used only rarely; these models are a combination of the CM (which is intuitive and easy to understand) and the complete FPBM. The models contain most, but not all, of the processes; they are difficult to understand (less intuitive), especially if non-linear effects are incorporated. However, they can provide relevant information (to orders of magnitude) on long-term temporal and spatial scales (Peters and Hulscher, 2006).

Each of these model approaches is dependent upon location and the hydro-sedimentary conditions of the surroundings. For instance, FPBM models need sufficiently refined bathymetric data, in order to establish relevant computational grids. IBPM can require also a range of regional data, in case it is applied "point by point", as in Van der Veen *et al.* (2006). Here, a stability analysis model is applied to the whole of the North Sea, using GIS data for input parameters. For example, CM models require sedimentary data (ASMITA), or the temporal evolution of the bathymetry (the Landau approach).

Upon the model being set up, a general problem with them is their validation: in the absence of long-period time-series, it is difficult to ascertain the model accuracy.

DISCUSSION ON THE USE OF MODELS TOWARDS COASTAL STATE INDICATORS

Coastal State Indicators

From a Coastal Zone Management (CZM) perspective, the possibility of sand extraction is determined by physical, socio-economic and administrative contexts. Rational CZM will be based upon an integrated analysis of the various components. A coastal manager will require a rational decision-making process,that is both transparent and reproducible. Strategic CZM objectives that are sometimes vague need to be translated into (specific) operational objectives. An important component of this process is the definition of a set of Coastal State Indicators (CSIs). Each indicator is related to a specific coastal-user function, e.g. coastal safety, navigation, offshore infrastructure.

The first question on the use of the models is: which model or approach is the most appropriate for estimating coastal state indicators?

For example, a number of indicators are listed below, together with examples of models which could be used to estimate the indicator.

- Sand budget in the offshore, extending to the nearshore zone: numerical morphodynamic model (Delft3D) (Class: FPBM)
- Wave height: numerical wave model (SWAN, REF-DIF) (Class: FPBM)
- Tidal current: numerical current model (Delft3D) (Class: FPBM)
- Sandbank height: non-linear stability analysis (Roos *et al.*, 2004) (Class: IPBM)
- Recovering time, after extraction: Landau equation (Class: CM)
- Short-term sandbank height variability (extreme events): numerical morphodynamic model (Delft3D) (Class: FPBM)

These offshore models can be used also as boundary conditions for engineering cross-shore models, to estimate Coastal State Indicators:

- beach profile : cross-shore model UNIBEST-TC, SBEACH, CROSMOR (class: FPBM);
- coastline accretion/erosion: longshore model GENESIS, UNIBEST-CL+, LITPACK (class: FPBM).

Discussion on Model Use

This review has presented several types of established models, for assisting in the assessment of the impact of marine aggregate extraction, on either a flat bed or within sandbanks. The approaches followed are: full process-based; idealised process-based; and conceptual modelling. On the basis of these studies, the main physical processes to take into account appear to be: tidally-, wind-driven flows and flow contraction phenomena, requiring a 2DH description; bedload transport (including the bed slope effect); and the wave-stirring effect, in the case of extraction on finite amplitude bedforms. All of these models are dependent, in a more or less detailed way, upon location and hydro-sedimentary conditions of the surroundings.

Each of these model approaches provides relevant information, on different aspects of the problem: time-scales; seabed stability; and hydrodynamic modification. Thus, it appears worthwhile to couple these models, to establish a broader view of the system behaviour, e.g. from aggregate extraction to the equilibrium return of the system. Full process-based sandbank models were designed initially for short- and mid-term applications, whereas idealised process-based, together with conceptual sandbank/sand spit models, are designed for long-term forecasts. Thus, combining these different model approaches would lead to a temporal and spatial continuity in coastal dynamics. For instance, this could help to better assess long-term morphodynamics, taking into account threshold effects associated with extreme events (e.g. breaching generation).

An example of how to use and couple each of the three approaches, to study aggregate extraction impact, is shown in Figure 11. The full-process model could be calibrated using available short-period survey data. The idealised process model might be calibrated against the same data or, if required, against a combination of the data and some short-period runs of the full process-based model. These models should then be able to provide some preliminary forecasts of the impact of the sand mining. However, both models take a long time to run, so it is impractical to analyse the consequences of all possible sizes of pits, together with their shapes and orientations. It would be more efficient to fit a conceptual model to the process-based models, to analyse the wide range of possible pit dimensions. Subsequently, the most suitable pit could be analysed, using the process-based models, to ensure that the results are reliable. Running different models, associated with varying the model parameters within realistic boundaries, will result in an estimate of the accuracy of the predictions.

However, it should be noted that morphodynamic model validation is often hampered by a lack of reliable measurements of long-term bathymetrical changes and associated hydrodynamical parameters (primarily, waves and wind). Thus, there is a need also to acquire and provide such datasets. Peters and Hulscher (2006) have shown also that, without full validation, models can still assist in the decision-making process, concerning large-scale sand mining. Indeed, focussing on the use of a new model (IPBM, stability analysis) in decision-making for offshore large-scale sand extraction, these investigations have attempted to: (1) evaluate whether model validation assists the decision-makers; and (2) explore how to improve the model and its use. It appears that validation will reduce only one component of the uncertainties; as such, it is insufficient to assist decision-makers. Even if they are not validated, models can still provide "early warnings". This observation is confirmed by the willingness of one of the decision-makers involved in large-scale sand extraction to use a new model approach (based upon stability analysis) that is not fully validated (PETERS and HULSCHER, 2006). Such a study has identified how to improve the model, together with its use, by decision-makers, based upon the Constructive Technology Assessment (CTA) method. This approach modulates the interaction between the model design process and the decision-making process. Starting with a new model and interacting with managers, leads to feedbacks between model design and the decision-making process, to demonstrate how the new model can be improved. Such an improvement has led to the modelling study performed by ROOS and HULSCHER (2003).

To estimate as many CSIs as are presently available, it is possible to use a set of existing models. HOMMES, HULSCHER, and STOLK, submitted, have investigated whether using such a set of models is more helpful in addressing management questions, than using only the best model within this set. The selected models were assessed in terms of: (1) their applicability to the CSIs; and (2) the reliability of their predictions. HOMMES, HULSCHER, and STOLK, submitted, quantified the prediction skill of the models, based upon these two parameters. These investigations concluded that, by using a set of models, it is possible to address more management questions effectively; this is compared to using only the best model available. Using this set of models increases substantially the prediction capability.

CONCLUSIONS

This review provides an overview of: (1) the model concepts available to assess the impact of aggregate offshore extraction; (2) how to utilise these models, to obtain an optimal environmental assessment of offshore marine aggregate extraction, in tidal seas.

Three main concepts have been identified: the full process-based models; the idealised process– based models; and the conceptual models. Until now, the idealised process-based model has been the approach which has been applied most, for investigating the morphodynamics of a dredged flat bed or sandbanks. Full process-based models have been used mainly to study the morphodynamics of a pit, sandbank generation and the influence of the dredging of sandbanks on hydro-sedimentary patterns. Only a limited number of dredging studies have been undertaken using conceptual models. One exception is a study concerned with the recovery time of dredged sandbanks. The main conclusion of this review is that none of the models have been validated, to provide reliable predictions of the impact of large-scale mining, on the morphodynamic stability of the region. However, the different approaches complement each other, supplying the end-user with a range of 'tools' for investigating the impact. As validation over (long) periods of interest is not yet possible, the only way to obtain a reliable insight into the future impacts is to combine the different modelling approaches and, concurrently, deal with the uncertainty of the forecasts. A suite of models or coupled models appears to provide the most complete description of the system behaviour (flat bed or sandbanks), following extraction. All of these models are still dependent upon location and the hydro-sedimentary conditions of the surroundings.

For an optimal environmental assessment, two main approaches are: (1) either combine and couple the models, in order to simulate the full morphodynamics of the system over a long time-scale, taking into account also short-term event; or (2) use a set of *existing* models, knowing precisely their applicability to the CSIs and the reliability of their predictions, rather than using only the best model, available presently.

Each of the models presented in this contribution, classified into one of the (3) approaches, can still be improved and benefit from on-going research, e.g. on sediment transport. In particular, the full process-based and the idealised based-model, would benefit from such an improvement. However, the conclusions drawn here would not be modified significantly.

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