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Modelling the Morphodynamics of the Kwinte Bank, Subject to Sand Extraction

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ABSTRACT

The North Sea is, to an increasing degree, subject to human activities and interests; a particular example of a user function of this environment is sand extraction. In order to satisfy the demand for sand, tidal sandbanks in some sectors of the North Sea act as a source of sediment, this may lead to the creation of large-scale pits on these bedforms. Sandbanks, which provide protection to adjacent stretches of coastline, are therefore worthy of investigation, especially when their potential as a source of aggregates is taken into account.

To investigate seabed dynamics, in general, and to predict the long-term morphodynamics of tidal sandbanks subject to sand extraction, in particular, process-based modelling is a commonly-used method. Different approaches can be considered: (i) based on complex numerical simulations; (ii) or applying an idealised model, designed specifically to describe sandbank dynamics. Herein, the first approach is applied to a case study of the Kwinte Bank; this is a tidally-maintained sandbank, located on the Belgian continental shelf. The modelling is set up using the complex process-based model Delft 3D – Online, the waves were not taken into account.

Numerical results and experimental data from a field campaign (undertaken in March 2004) are compared and show good agreement. Analysis of residual currents indicates a predominance of ebb flow over the bank. However, the residual sediment transport pattern is flood-dominated. The predicted residual sediment transport pattern shows that the Kwinte Bank should be regarded as part of a system of swales and sandbanks.

Finally, the long-term evolution is discussed, considering complementary approaches that combine the benefits from the complex numerical modelling with the idealised one. The evolution of a tidal sandbank, after removing an amount of sand, is difficult to predict. No clear tendency is evident in the evolution of the depression area on the basis of the long-term full process-based modelling. However, on the basis of idealised modelling, the anticipated long-term trend of an excavated area is the recovery of the depression, resulting in an equilibrium of the sandbank, over a time-span of a few centuries.

ADDITIONAL INDEX WORDS: *sandbank dynamics, numerical modelling, Delft 3D, stability analysis.*

INTRODUCTION

The offshore seabed of shallow shelf seas, like the North Sea, is covered with a wide variety of rhythmic sedimentary features of different length scales. In the potential sand extraction areas, tidal sandbanks and sandwaves, even both are likely to occur (see e.g. Hulscher and Van den Brink, 2001). Tidal sandbanks are the largest of the offshore features; they have lengths of several kilometers, a spacing of up to 10 km and a height of several tens of meters (Dyer and Huntley, 1999). Sand waves are smaller, but are more dynamic and prominently present throughout the North Sea. Tidal sandbanks and sandwaves may act directly as sources of sand, this may lead to the creation of large-scale pits on these bedforms. Typical dimensions of such pits are several kilometers long and wide and several meters deep. Offshore sandbanks affect navigation, but provide protection to adjacent stretches of coastline. These structures, therefore, are worthy of investigation, especially when their potential as a source of aggregates is taken into account.

The formation of tidal sandbanks can be explained in terms of a morphodynamic instability of a flat seabed, subject to tidal flow and sediment transport (Huthnance, 1982). The underlying hydrodynamic mechanism, known as tidal rectification (Zimmerman, 1981), explains the formation and, usually, the counter-clockwise orientation of the bank's crest with respect to the tidal current in the Northern Hemisphere. However, little is known of the morphodynamic processes that shape and maintain tidal sandbanks in equilibrium. Besides, a large-scale intervention such as sand extraction can interfere with the complex hydrodynamic and morphodynamic processes; nonetheless, this impact is largely unknown. In particular, the long-term effects on time-scales of decades to centuries from

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such interaction are of interest to the aggregate industry and to coastal managers.

In order to investigate seabed dynamics, in general, and to predict the long-term evolution of tidal sandbanks subject to sand extraction, in particular, process-based modelling is an approach which has been used commonly. Different approaches can be considered: (i) based upon complex numerical simulations, with a full process-based model such as Delft3D – Online (Lesser *et al.*, 2004); or (ii) applying an idealised model, designed specifically to describe sandbank dynamics (Roos *et al.*, 2004). Although both approaches are based upon the underlying physical processes, they are essentially different; as such, they have different benefits and limitations.

The full process-based models combine different processes (e.g. wind- and wave-driven currents, density gradients, Coriolis force, sediment transport, etc …) within broad classes of problems, over different temporal and spatial scales; they are able to deal with complex geometries. The morphodynamic procedure consists of the coupling of a number of modules that simulate processes such as wave and current propagation, sediment transport and morphodynamic bed updating. In all of these models, the hydrodynamic module is usually the most computationally expensive, explaining why their applications are, in most cases, restricted to initial sedimentation/erosion modelling. This so-called morphostatic approach, which has been extensively and effectively used in comparative impact studies, does not enable the modeling of the long-term evolution of a system. Further disadvantage of these models is related to the uncertainties associated with the boundary conditions and with the inputs, such as wind stress, expressed as explicit forcing terms in the equations.

Alternatively, idealised models have been designed to study rhythmic bed forms (Dodd *et al.*, 2003). These models are based also upon the underlying physical processes and have been developed for particular applications (e.g. sandbank formation in Hulscher, De Swart and De Vriend, 1993; and Huthnance, 1982). Assuming a strongly simplified geometry, inputs and boundary conditions, they are much less computationally expensive. Therefore, they are more appropriate to study the long-term transient behaviour of sandbanks. In particular, they can be used to study the evolution of sandbanks subject to extraction (Roos, 2004). A different example is the study undertaken by De Swart and Calvete (2003), who developed an idealised model to investigate the non-linear response of shoreface-connected ridges, subject to sand extraction.

Comparing and combining the benefits of these two approaches has been the subject of an earlier study on tidal sandbanks (Idier and Astruc, 2003). In this contribution, the objectives are (i) to study the short-term morphodynamics of the Kwinte Bank, and (ii) to discuss the benefits of the idealised and full process-based modelling, to investigate the long-term evolution of the bank subject to sand extraction.

The text is organised as follows. In section 2, the geographical and physical characteristics of the site are presented. Subsequently, section 3 contains the results of the modelling of a field measurement programme. Comparison is undertaken between numerical results and observations, on the basis of statistical analysis. The flow and sediment transport patterns are described next, during the period of interest and focusing upon the depression area. As the long-term effects of sand extraction are of interest to coastal managers and policymakers, the fundamental difficulties of extrapolating short-term

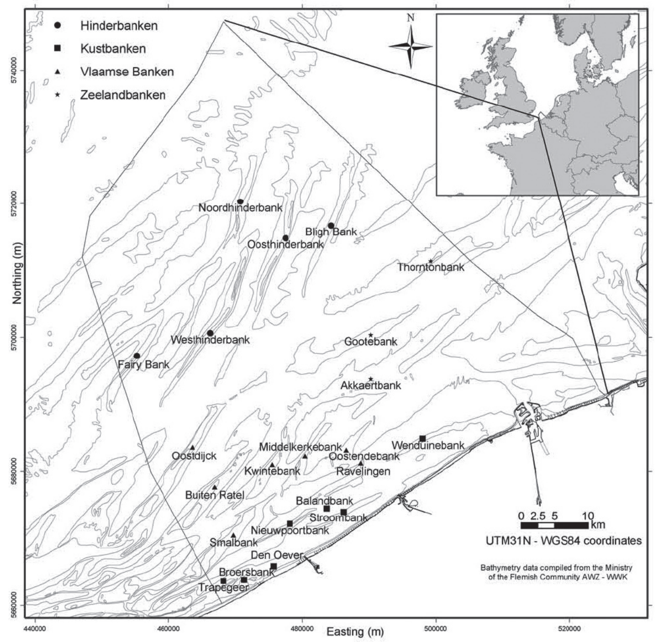

Figure 1. Sandbank patterns in the Belgian continental shelf.

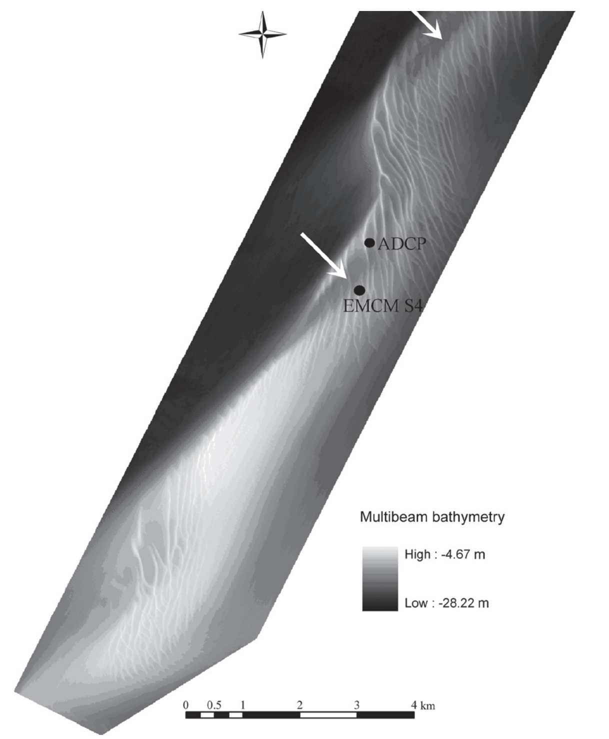

Figure 2. The Kwinte Bank at time of cessation of extraction, showing measurement locations used in the model assessment, and the two main areas of excavation dredging (indicated with arrows).

results to long-term prediction are finally discussed in section 4. Section 5 contains the conclusions.

STUDY AREA

Geographical and Physical Characteristics of the Kwinte Bank

The Kwinte Bank is a Southwest/Northeast oriented tidal sand bank which is located on the Belgian continental shelf and belonging to the Flemish Banks' system (Figure 1.). The sandbank itself has a length of 15 km and a width which varies from 2 km in its southern part, to 1 km in its northern part (Figure 2.). The minimum water depth is about – 5 m MLLWS (Mean Lowest Low Water Springs) in the southern part of the bank. The depth reaches – 22 m MLLWS in the swales around the bank. On the basis of its bathymetry, the estimated volume of the bank represents approximately 400 Mm^3 (Garel, this volume). In the northern part, the bedform is covered by large dunes with maximum height of about 8 m. Sand dunes are also present in the central part of the bank. The cross-section of the sandbank is asymmetrical, with a steeper side facing the northwest and a seabed slope reaching 3° (Van Lancker *et al.*, 2004).

In general, the hydrodynamics of the southern part of the North Sea are characterised by semi-diurnal progressive tides, dominated principally by M2, S2, N2 and M4 harmonic components (Williams *et al.*, 2000). Over the Kwinte Bank, the average tidal ellipse is elongated along a southwest/northeast axis, at about 6 ° in a clockwise direction from the bank's axis. The tidal currents rotate counter-clockwise, over 12 hours 25 mins (Lanckneus *et al.*, 1992), with the strongest peak currents, of about 1 m/s, being during the flood, towards the northeast (Van Cauwenberghe, 1971). Furthermore, numerical modelling and Waverider measurements undertaken on the adjacent Middelkerke Bank (Williams *et al.*, 2000) have shown that significant wave heights less than 3 m are unlikely to have any significant effect on the bed. On the other hand, observed residual currents in the same area were found to be correlated strongly with wind duration, speed and direction. Recent sediment sampling campaigns undertaken over the Kwinte Bank area have established a mean grain-size (d_{50}) distribution ranging from 0.25 to 0.55 mm (Bellec *et al.*, this volume).

Since 1979, sand has been extracted mainly from two distinct areas of the Kwinte Bank, located along the crest in the northern and central parts of the bank (Figures 2.). The latter location is the most excavated, with dimensions of about 700 m wide, 1 km long and 5 m deep, at time of cessation of extraction. Dredging here ceased in February 2003 to allow the monitoring of the evolution of the depression zone, and to improve the knowledge on the biological and physical impacts of aggregate extraction on the state and dynamics of the sandbank.

Field Experiment

Since 2003, field campaigns were carried out by Institutes involved in the MAREBASSE and EUMARSAND projects, focusing mainly upon the central depression (Van Lancker *et al.*, 2004). The objectives were to investigate the mechanisms of sandbank maintenance, as well as the impact of sand extraction on the benthos. Hydrodynamic measurements (Figure 2.) were obtained between the 2^{nd} and 12^{th} March 2004 (Garel, this volume), and are considered here. A 1200 kHz Acoustic Doppler Current Profiler (ADCP Teledyne RDI) was moored during 9 days (2-11/03/2004), at the northern extremity of the central depression; this recorded data every 50 cm, from 1.4 m up to 16.4 m above the seabed. An Electro-Magnetic Current Meter (EMCM S4) was moored at the bank crest during the same period and recorded, at 2 Hz frequency, the horizontal components of the currents at 0.75 m from the seabed.

The measurements obtained by the ADCP showed a good agreement (Garel, this volume) with a parametric velocity profile (Soulsby, 1997), which has been adopted for comparison between the depth-averaged numerical results and the S4 point measurements, near the bed:

$$U(z) = U_{avg}\left(\frac{z}{0.32h}\right)^{1/7} \qquad (1)$$

where U_{avg} is the depth-averaged velocity, z the sensor height above the seabed and h is the water depth.

METHODS

The characterisation of the flow and the sediment transport patterns on the Kwinte Bank is based upon the morphodynamic modelling of the field experiment of March 2004, using the complex process-based model Delft 3D – Online (Lesser *et al.*, 2004).

Model Schematisations

The hydrodynamics have been simulated in a depth-averaged 2D model, as a 2DH approach appears sufficient when focussing on the morphodynamics. Moreover, the choice is supported by the pragmatic reason of reducing the computational time.

The model solves the non-linear shallow-water equations using a finite differences formulation. The eddy viscosity included is a property of the flow, varying generally in space and in time. However, a constant viscosity value is used in the modelling undertaken here, as sensitivity tests showed that the model is not strongly sensitive to this particular parameter. Eddy diffusivity in the model is set at 0.5 m^2/s. On the other hand, numerical results are more sensitive to a change in the Chezy coefficient C, which appears in a quadratic bed friction law:

$$\vec{\tau} = \frac{\rho g}{C^2}\|\vec{u}\|\vec{u} \qquad (2)$$

where ρ is the density of water, g is the acceleration due to gravity and $\vec{u}$ is the depth-averaged velocity.

The best agreement between the numerical results and observations was obtained using a coefficient, C, of 65 $m^{1/2}/s$. The sediment transport formulation of TRANSPOR1993 (Van Rijn, 1989) is adopted to estimate the sediment transport rates. A constant grain-size is considered over the sandbank, with a mean grain-size (d_{50}) equal to 325 µm.

The bathymetric data were provided by the Ministry of the Flemish Community (Ministerie van de Vlaamse Gemeenschap; Afdeling Kust). The model set-up is based upon a grid covering the Belgian continental shelf, with the highest resolution associated with the Kwinte Bank area. For example, the averaged grid cell length is around 300 m in the area of the depression. The domain, of 4200 grid points, extends from the coastline to some 32 km offshore and over 40 km in the alongshore direction. Model boundaries are located sufficiently far from the Kwinte Bank to ensure that any potential spurious effects are maintained to be outside the area of interest. The hydrodynamic module is forced by time-dependent water levels, generated by the OPTOS-BCZ model (Luyten *et al.*, 1999). Wind stress upon the sea surface is taken into account within the simulations; these data were provided by the UK Met Office, Bracknell. A southwesterly wind component was observed over 35 % of the time, with a speed ranging from 5 to 8 m/s at 10 m above the mean sea water level.

Observations on the adjacent Middelkerke Bank (Williams *et al.*, 2000) demonstrate that no significant changes in the significant wave height and in the wave period occur across the bank when *Hs* < 3 m. Failure to detect significant loss in wave energy across the bank implies that interactions between waves and the bed are weak under "normal" conditions i.e., *Hs* < 3 m. By implication, enhanced mobilisation and suspension of bed sediments and modification to bed topography by wave action is likely to occur only in storm conditions. Therefore, in this study on the Kwinte Bank, the effect of waves on the seabed has not been included due to limited wave activity over the period of the observations (S4 records show significant wave heights of less than 1.3m, during the period 2-9/03/2004)

Model Performance Statistics

Comparing field measurements with numerical results requires the acquisition of a large amount of data, in order to incorporate the wide spectrum of spatial and temporal evolutions. Consequently, field measurements were undertaken over 11 days, the data being recorded at high-frequency. However, the extensive data set makes visual analysis difficult and, as such, statistical methods are used. Information on the statistics adopted for the present comparison, alternative statistics and examples of their use in the EU COAST3D Project, can be found in Sutherland, Peet and Soulsby (2004).

In order to quantify the performance of numerical models, the root-mean-squared error (*RMSE*) is used commonly, defined according to:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(Y_n - X_n)^2} \tag{3}$$

where *Xn* are the observed values, *Yn* are the computed values and *N* is the total number of observations.

However, the *RMSE* is appropriate for scalar quantities (e.g. water levels), but not for vector quantities (e.g. flow velocities). To this end, a mean absolute error *MAE* can also be used. Here, for a two-dimensional vector $\vec{X} = (X_1, X_2)$, the *MAE* is defined according to:

$$MAE = \left\langle \left| \vec{Y} - \vec{X} \right| \right\rangle = \frac{1}{N}\sum_{n=1}^{N}\sqrt{(Y_{1n} - X_{1n})^2 + (Y_{2n} - X_{2n})^2} \tag{4}$$

The use of the modulus makes the statistics more difficult to apply, than using a *RMSE* index. However, the *MAE* includes errors of magnitude and direction, in a single statistic. The quality of the modelling may be judged from the value of the mean absolute error, relative to the observations (*RMAE*):

$$RMAE = \frac{MAE}{\left\langle \left| \vec{X} \right| \right\rangle} \tag{5}$$

A *RMAE* value includes the contribution from the measurement error. Van Rijn, Grasmeijer and Ruessink (2000) have discussed the measurement errors associated with the COAST3D Project. They showed that the errors were related to the physical size of the instruments deployed, together with the measurement and conversion principles. On the basis of the equipment used and the conditions prevailing in the present experiment, an average value of the observed error (*OE* = 5 cm/s) is adopted, for comparison. An adjusted relative mean absolute error (*ARMAE*) is proposed then, reducing the influence of the observational errors (eq. 6):

$$ARMAE = \frac{\left\langle \left| \vec{Y} - \vec{X} \right| - OE \right\rangle}{\left\langle \left| \vec{X} \right| \right\rangle} \tag{6}$$

Statistical Analysis

During the data acquisition, we averaged ADCP records in order to provide values of the current velocity and direction over 5 minutes, every 15 minutes. The S4 was set up to provide an average of pressure and current fluctuations over 9 minutes, every 15 minutes. The depth-averaged values were extrapolated from measurements obtained near the bed, using the velocity profile expression (eq.1). Subsequently, the numerical results were analysed considering 861 and 838 samples at the S4 and ADCP locations, respectively.

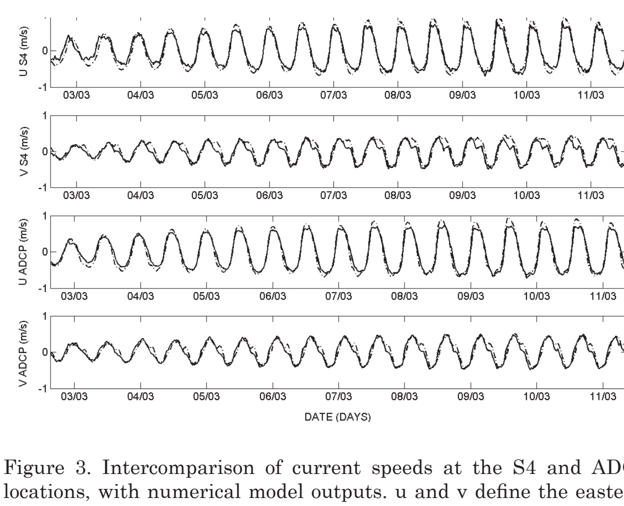

Figure 3. Intercomparison of current speeds at the S4 and ADCP locations, with numerical model outputs. u and v define the easterly and northerly components, respectively. Full and dotted lines display the experimental data and the numerical results, respectively.

Table 1. *Error statistics from DELFT 3D flow module.*

Sensors	Zc (m)	Zc /(*h*)	$\left\langle \left| \vec{Y} \right| \right\rangle$ (cm/s)	$\left\langle \left| \vec{X} \right| \right\rangle$ (cm/s)	RMSE (cm/s)	BIAS (cm/s)	STD (cm/s)	MAE (cm/s)	RMAE	ARMAE
S4 point	0.75	0.03	53.0	45.1	12.3	7.8	9.5	14.2	0.31	0.10
ADCP point			53.4	48.5	9.0	4.9	7.7	11.9	0.24	0.08

RESULTS

Validation Results

The water level statistics indicate that inputs at the boundaries are of good quality: data available from the S4 deployment show a *RMSE* error of 15 cm and a bias (numerical results, minus experimental data) of 1.5 cm.

Time-series of the current speeds are presented in Figure 3., in terms of the easterly (u) and northerly (v) components at the S4 and ADCP deployment sites. Good agreement is shown between the observations and the numerical model outputs. At the S4 location, the model reproduces the tidally-induced flow variation along the easterly axis, although a difference in amplitude can be noted. In contrast, the northerly component shows a slight difference in phase. The model overestimates the phenomenon of tidal rectification: the west northwest cross-bank component of the flow is accelerated, by continuity; whereas the along-bank component is decelerated, by the increased effect of bottom friction. Such flow deflection is noticeable particularly during the ebb tide, in the numerical results; in contrast, the experimental velocities are directed mainly towards the west southwest. At the S4 location, the measured maximum and mean (absolute time- averaged) current speeds are 81 cm/s and 45 cm/s, respectively. The numerical predictions are somewhat higher, at 92 cm/s and 53 cm/s, respectively. At the ADCP location, the maximum and mean velocities of the current are, respectively, 87 cm/s and 49 cm/s for the experimental data; the numerical predictions are higher, at 94 cm/s and 53 cm/s, respectively. The major tidal ellipse axes (not presented here for the sake of brevity, see GAREL, this volume; and VAN DEN EYNDE *et al.*, this volume) are rotated about 10° clockwise compared to the bank's axis, due to tidal rectification. The observations show that the mean orientation of the axes is similar at both the S4 and ADCP locations; in contrast, the stronger currents, obtained at the S4 location with the model, are directed more eastward than those obtained at the ADCP point. At both locations, the numerically predicted ellipses are more spherical in shape than the elongated experimental ellipses.

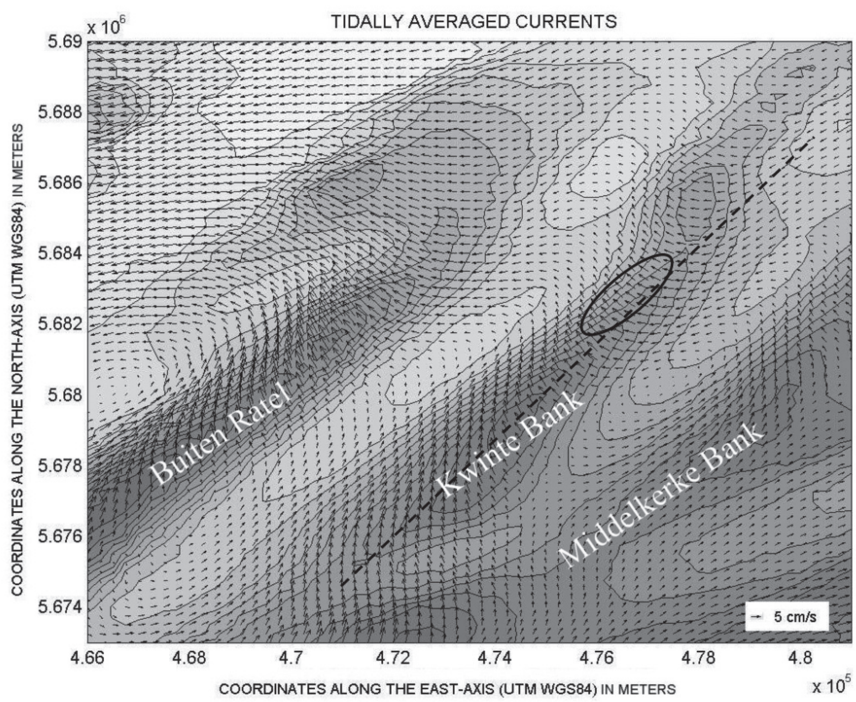

Figure 4. Residual currents over the Kwinte Bank area. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

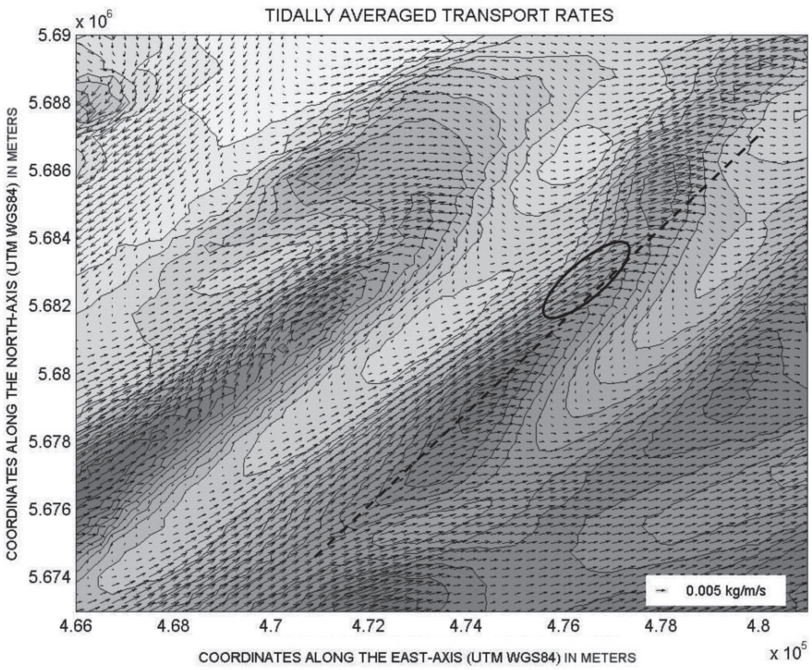

Figure 5. Residual sediment transport rates over the Kwinte Bank area. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

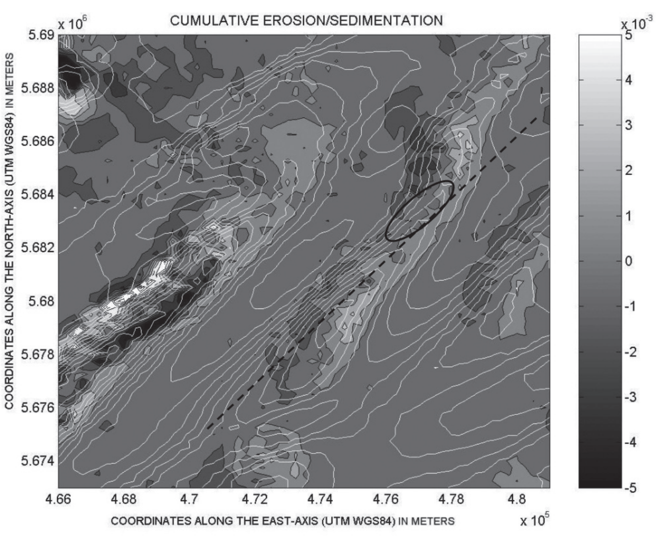

Figure 6. Cumulative erosion/accretion rate (m) over the Kwinte Bank area, over a 10 days period (02/03/2004 to 12/03/2004). Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

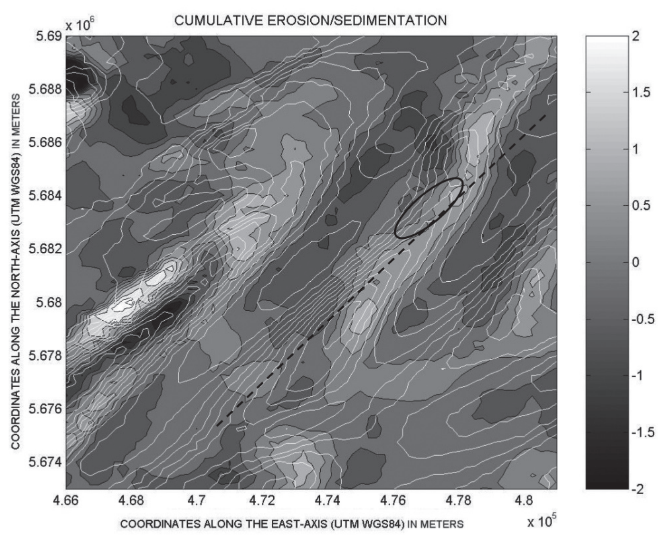

Figure 7. Tidal flow driven cumulative erosion/accretion rate (m) using an elongated tide, over the Kwinte Bank area, for a 30 years period. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

The mean (absolute time- averaged) current speeds, together with the *RMSE*, *MAE*, *RMAE* and *ARMAE* errors are summarised in Table 1. The mean current speed is overestimated, by 13 % and 9 % respectively, at the S4 and ADCP measurement locations. The maximum numerical velocities occur during the flood flow, which differs from the experimental results. However, the *MAE* indices are 14 cm/s (S4 location) and 12 cm/s (ADCP location); these are low considering the mean current speed. Thus, the *RMAE* indices are 0.31 and 0.24. Following SUTHERLAND, PEET and SOULSBY (2004), the results can be classified in terms of their *ARMAE* values. This classification shows that the DELFT 3D simulations, described here, have a level of performance with results in the "excellent" category (0.10 and 0.08, respectively, at the S4 and ADCP locations).

Short-term Modelling: Flow and Sediment Transport Patterns

On the basis of the numerical results obtained over an 11 days- period (2/03 to 12/03), the tidally-averaged currents have been obtained for each tidal cycle, and have been integrated over the period.

Figure 4. shows that the mean residual currents vary considerably over the domain, with the general pattern consisting of counter-clockwise gyres, centering over the swales. As such, the residual currents are higher on the top of the banks, than in the swales. Over the banks, the circulation is in the opposite direction, describing clockwise vortices. The flood and the ebb are dominant on the western and eastern flanks of the Kwinte Bank, respectively; this is in agreement with the observations of LANCKNEUS *et al.,* (1992) and of BELLEC *et al.* (this volume). Along the western part of the Kwinte Bank, the residual currents follow the depth contours towards the northeast. The flow pattern along the eastern flank is influenced by the gyre between the Middelkerke Bank and the Kwinte Bank. Consequently, the residual currents are directed to the southwest along the northern and central parts of the bank.

Conversely, the direction of the tidally-averaged currents is towards the north along the southern part of the flank. These results agree, qualitatively, with the numerical results obtained using the OPTOS model system (VAN DEN EYNDE *et al.*, this volume; and VAN LANCKER *et al.*, 2004).

Over the Kwinte Bank, the residual currents are directed mainly towards the west southwest in the northern part of the bank, and towards the north in the southern part. The depression area shows ebb-dominated residual currents, tending to be parallel to the bathymetric contours. However, on the basis of the tidally-averaged currents obtained for each tidal cycle, variability of the residual direction can be noted between 02/03 and 05/03, with an eastern dominance observed during a few tidal cycles. Such flood currents are related to the wind effect, as a 5 to 8 m/s southwesterly wind component was observed during the campaign. At both locations, the numerically-derived residual currents are around 5 cm/s; these are in agreement with the values obtained from the measurements.

Due to the non-linear character of sediment transport, residual sediment transport patterns may vary from the direction of the residual currents. In contrast with the flow pattern described previously, the residual sediment transport vectors describe a s-curve around the sand bank (Figure 5.), as shown previously by VAN LANCKER *et al.* (2004).

This pattern illustrates that the Kwinte Bank cannot be considered in isolation, but as part of a system of swales and sandbanks. Sand transport is directed towards the northeast along the western flank of the Kwinte Bank, whereas the eastern part is characterized by transports occurring in different directions (from southward to eastward). In the area of the central depression, the residual sediment transport vectors are opposed to the residual currents, i.e. directed towards the east. In contrast to the flow pattern (Figure 4.), the sediment transport vectors are more uniform over the study area with a constant rate of about 0.01 kg/m/s over the different tidal cycles. Sand can be expected to be eroded on the western side of the bank, but deposited on its eastern part (Figure 6.).

The erosion and sedimentation rates are of the same order of magnitude, at about 2.5 mm over an 11 days- period. These numerical predictions are in good agreement with those obtained by VAN LANCKER *et al.* (2004) and VAN DEN EYNDE *et al.* (this volume) using the OPTOS model system. They confirm also the results obtained by GAREL (this volume); these data showed a net transport towards the northeast on the western part of the bank (depression and west flank) and described an ebb-dominated pattern on the eastern side, confirming that sediment transport is related to a particular phase of the tide on each side of the bank (LANCKNEUS *et al.,* 1992).

The short-term modelling of the Kwinte Bank, undertaken here, reveals spatial and temporal variability in the flow, due to tidal asymmetry and wind-driven currents.

Besides, wind waves are likely to play an important role on the flow and the sediment transport patterns. When the waves are taken into account, the sediment transport rates are higher over the Kwinte Bank and the direction of the flux is also different, with dominance towards the west (VAN DEN EYNDE *et al.*, this volume).

Finally, it should be noted that the small-scale morphologies, such as such sand waves and dunes, are not taken into account in the present study. These features may also influence the variability of the flow (HULSCHER, DE SWART and DE VRIEND, 1993).

DISCUSSION ON LONG-TERM MODELLING

As sandbanks evolve on a large time-scale, the long-term effects of sand extraction are of interest to coastal managers and policymakers (PETERS and HULSCHER, 2006). Such long-term impact can be investigated through the use of long-term morphodynamic modelling (IDIER *et al.*, this volume).

Numerical Modelling

Practically, the complex full process-based models cannot be used straightforwardly for a long-term prediction, as they are too time-consuming in terms of computer time. Still, specific approximate methods have been developed to decrease their computational requirements (DE VRIEND *et al.*, 1993). To this end, representative wave, wind and tidal forcing are adopted commonly; this implies inherent predictability limits, as the morphodynamic process is stochastic. Regarding the tidal forcing, two methods are used widely (LATTEUX, 1995): (i) the continuity correction, and (ii) the lengthening of the tide. The first approach is based upon the input filtering: the morphodynamic change following a representative tide is extrapolated over *N* tides, using a continuity correction; this is as long as the bed changes do not exceed a critical value. The second approach is that of the lengthening of the tide, which is adequate to study propagative features as sandbanks (LATTEUX, 1995);

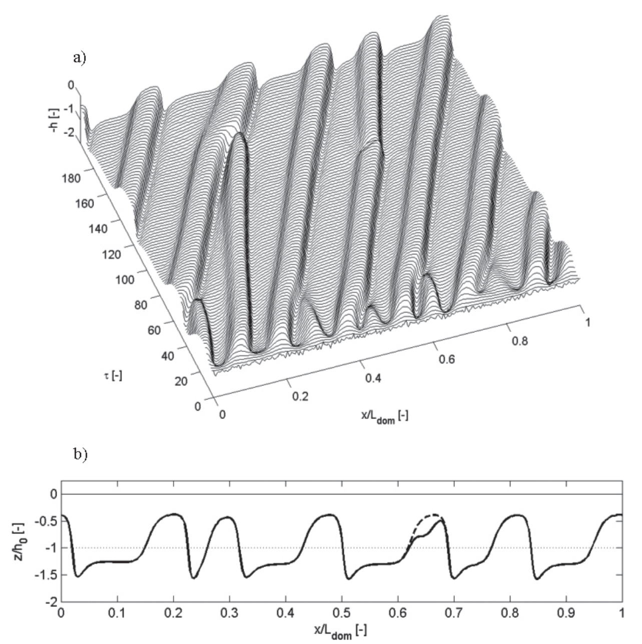

Figure 8. (a) Evolution of a sandpit, modeled as a local perturbation of a sequence of sandbanks (Roos, 2004; Roos and Hulscher, 2007). The x-axis describes the spatial dimension whereas the y-axis describes time (in units of 20 to 40 years) and the vertical axis the bed elevation (scaled against the mean water depth of about 30 m). The plot shows the autonomous dynamics of a sequence of sandbanks, as well as the response of a single bank to a local removal of sand (created in the crest at x/Ldom=0.65, tau=125). (b) The sandbank profile just before (dashed) and just after (solid) extraction. Note: the model geometry is one-dimensional, assuming uniformity in the along-bank direction, which implies that also the sand extraction is uniform in the along-bank direction. The extraction's cross-section has a Gaussian shape with a depth of 10 m implying an extraction of 4000 m3 per alongbank m. (Figure adapted after Roos and Hulscher, 2007).

this consists of increasing the morphological time-step by a so-called morphological factor (typically, N = 100 to 1000). This approach is implemented in the Delft 3D – Online modelling system. Nevertheless, we stress that these approximate methods are pragmatic and non-physical, in the sense that their main aim is to save computer time; caution is therefore required when applying large N-values.

A further disadvantage of the full process-based models is related to uncertainties associated with the boundary conditions. As such, the amplification of errors can have a large effect on the long-term behaviour of a small error in the hydrodynamics. However, full process-based models enable to study the dynamics of a complex geometry; for example, they provide an indication of the long-term evolution of the Kwinte Bank.

Hence, considering the spring tidal cycles observed during the field experiment of March 2004, and neglecting the wave and wind effects, the bed evolution has been computed over a 30 years period (Figure 7.).

The derived erosion/accretion rates suggest two patterns, depending upon location on the bank. Over its southern part, sand may be supplied from a bank located to the south of the Kwinte Bank, preventing the displacement of the feature. Over the northern and central parts, the bed is eroded on the western side of the bank and sediments are transported on the western flank. In this case, the crest may shift in an eastward (onshore) direction.

Besides, the Figure 7. shows that a supply from the swales can be also expected. De Moor (2002) discussed the stability of the Flemish Banks and of the swales. He concluded that sections of the swales might have provided sand for the regeneration of the dredged areas. However, Bellec *et al.* (this volume) noticed that there is only a limited Quaternary cover and that the Tertiary substratum is locally eroded, in the Kwinte Bank area; addressing consequently that there are no large amounts of sand available in the swales.

On the basis of the long-term full process-based modelling over 30 years, no clear tendency is evident in the evolution of the depression area, and no recovery of the depression can be anticipated.

Moreover, any interaction between the excavated area and the sandbank itself cannot be clearly discerned from Figure 7. Besides, any interpretation is limited by the fundamental problem of differentiating between anthropogenic and natural processes.

Idealised Modelling

As noted in the introduction, idealized process-based models provide an alternative to investigate the long-term dynamics of large-scale bed forms in the marine environment. A typical feature of these models is their strongly simplified geometry, the inclusion of only the essential physical mechanisms as well as the focus on the temporal scales of interest. These models are therefore suitable to obtain insight in the general physical mechanisms behind the morphodynamics. In the following we briefly describe and review how idealized models have been extended to study the system's response to sand extraction. However, owing to the idealized nature of the models, this should not be interpreted as a site-specific study of the Kwinte Bank case.

The formation stage of both tidal sandbanks (Hulscher, De Swart and De Vriend, 1993 ; and Huthnance, 1982) has been explained as inherent instabilities of a flat seabed subject to tidal flow and sediment transport. The underlying hydrodynamic mechanism, known as tidal rectification (Zimmerman, 1981), described the friction-topography and Coriolis-topography interactions of tidal flow over an uneven seabed. In particular, the stability analysis provides characteristics of a so-called fastest growing mode, i.e. preferred values of wavelength and orientation. Later on, Roos *et al.* (2004) investigated the finite-amplitude behaviour and found equilibrium profiles, expressing a tidally averaged balance between bank-building mechanisms associated with tidal rectification and the downslope sediment transport of (wind-wave stirred) material. The shape and height of the equilibrium profiles were found to depend on the tidal conditions, the mode of sediment transport, wave stirring as well as the relative importance of frictional and Coriolis effects. In each of the above approaches, a depth-averaged flow description has been employed, and Roos *et al.* (2004) accounted for wave effects in a parametric way, using a depth-dependent stirring factor in the sediment transport formulation. This approach relied on the formation theory, since the orientation and wavelength were fixed from the linear stability analysis.

Subsequently, Roos and Hulscher (2007) considered a larger domain in which a sequence of tidal sandbanks, uniform in the along-bank direction, was studied. This allowed for the investigation of both autonomous dynamics as well as the system's response to a local removal of sand. See Figure 8., where asymmetric tidal conditions were employed on a domain of about 130 km. From one of the banks, sand was extracted at tau=125, where *tau* is a dimensionless time, measured in units of roughly 20 to 40 years. It was concluded that on a time scale of several decades the bank tend to recover, but that the longer term fate of a bank is unknown.

Alternatively, De Swart and Calvete (2003) investigated the non-linear response of shore-face connected ridges, subject to sand extraction. The bed forms under consideration are of a similar size to tidal sandbanks, but they exist closer to the shoreface on the sloping bed of the inner continental shelf; as such, the physics of their formation is different. As shown by the model results, following the local removal of sand, the system tends to return to its original equilibrium state. This gradual process, taking place over several centuries, is attended with a supply of sand from both the outer shelf and the near-shore zone.

Clearly, this type of long-term behaviour cannot be investigated with the full process-based numerical simulation packages. One can further argue that, on such time scales, understanding the qualitative behaviour is more important than the quantitative details.

CONCLUSIONS

In order to satisfy the increasing demand of sand, tidal sandbanks of the North Sea act as a source of sediment; this may lead to the creation of large-scale pits, on these bedforms. Amongst others, the Kwinte Bank has been used to supply marine aggregates, resulting in the development of a large depression in the central part of the bank.

In this contribution, the dynamics of the bank and, in particular, the impact of sand extraction on its morphology, have been studied using morphodynamic modelling, using the full process-based model Delft 3D – Online.

Short-term modelling of the Kwinte Bank has been set up, on the basis of conditions measured during a field campaign, carried out in March 2004 (Garel, this volume). Comparison between the numerical results and the measurements showed good agreement (*ARMAE* values of about 0.1).

The derived flow pattern revealed that the flood and the ebb are dominant on the western and eastern flanks of the Kwinte Bank, respectively. Over the bank itself, the residual currents are directed mainly to the west southwest. The depression area is ebb-dominated, with currents tending to run parallel to the depth contours. Still, the residual sediment transport is flood-dominated. The derived residual sediment transport pattern has shown that the Kwinte Bank cannot be considered in isolation, but should be regarded as part of a system of swales and sandbanks. Sand transport is directed towards the northeast along the western flank of the bank, whereas the direction is generally southward along the eastern part. In the area of the depression, the predicted residual sediment transport pathways are opposed to the residual currents, i.e. directed to the east.

Long-term predictions are somewhat difficult to extrapolate from the short-term results. Thus, the long-term impact of sand extraction has been discussed, but considering complementary approaches, combining the benefits of complex numerical modelling with an idealised approach. The evolution of a tidal sandbank to equilibrium, following the removal of an amount of sand, is difficult to predict. No clear tendency is evident in the evolution of the depression area over 30 years, on the basis of the long-term full process-based modelling. However, on the basis of idealised modelling, the anticipated long-term trend of an excavated area is the recovery of the depression; this resulting in a new equilibrium of the sandbank, over a time-span of a few centuries.

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