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Meso-Scale Morphodynamics of the Eider Estuary: Analysis and Numerical Modelling

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ABSTRACT

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In order to improve the understanding of relevant processes in the meso-scale (years to decades) morphological evolution of an estuary and thus help in the management of the area a numerical model has been set-up. The large amount of field data of the hydrographical and morphological well monitored domain allows the calibration and validation of the model. Common modelling techniques for meso-scale morphodynamics (input filtering, model reduction) are discussed. A method for the definition of a representative tide is proposed in which the reference computation is replaced by observed morphodynamics. Hence a representative tide can be chosen that produces best correlations to natural dynamics. Model simulations of two year and eleven year evolutions show satisfactory results in terms of vertical accumulation and erosion patterns. However the main driving force for the rapid horizontal displacement of a tidal channel is not induced by the representative boundary condition as defined here.

ADDITIONAL INDEX WORDS: *Representative boundary condition, morphological tide, input filtering.*

INTRODUCTION

In the course of time the estuary of the river Eider on the German North Sea coast (N54.3/E8.9) has been undergone numerous morphological transformations caused by civil works. The construction of the Eider-Canal in the 1770s, the Kiel-Canal in the 1890s and Nordfeld-Dam in the 1930s changed the hydrography and morphology of the river. At last the main channel which had been free to meander across the 4km wide tidal flats at the river mouth was restrained to the 200m gate openings of a storm surge barrier built in the early 1970s. However the morphological activity of the river bed continued seaward and landward of the barrier with an annual displacement of several hundred meters.

A continuous hydrographical and bathymetrical monitoring by the relevant authorities qualifies this domain as a study area for the application of morphodynamic numerical models. The large amount of field data enhances the set-up and calibration of numerical models and vice-versa the numerical model is to help in an assessment of future morphological development.

STUDY AREA

This study focuses on the tidally influenced part of the estuary from Nordfeld-Dam (35km upstream) to the Eider storm surge barrier. For 21km the river runs in a narrow, channel-like bed. Downstream the city Toenning the banks extend to the tidal flats of the Katinger Watt (see Figure 2) which are submerged during high water. The partly mixed estuary's tidal volume is about 15Mm³ and the mean discharge from the 1739km² catchment area is around 1Mm³ per tide. Stratifications only develop in times when the gates of the barrier are closed, e.g. during storm flood events. A tidal range of about 2.6m characterises the mainly semi-diurnal estuary as a meso-tidal environment. Maximum current velocities are below 1.5m/s throughout the domain but up to 4m/s at the barrier gates. Mean grain sizes of bed sediments range from 80 to 120µm in the main tidal channel, on the tidal flats much finer sediments dominate. Suspended sediment varies from a background-concentration of about 50mg/l to maxima of 500mg/l at maximum flood velocities and about three hours after maximum ebb velocities. Suspended sediments show mean grain sizes of 10-50µm partly in agglomerated structures. Bed forms only occur in very limited areas (WINTER, 2002).

The development of the main channel after the construction of the barrier in the early 1970s until the early 1990s is shown in Figure 2. Since the construction of the weir (1967-1972) until the mid-eighties the north-western part (labelled A) propagated south some hundred meters per year. The north-southerly oriented branch (B) remained stable during that period. Right after the construction of the barrier the development of a small flood channel (C) was initiated, which attached to the main channel around 1980. In the mid-eighties the protection works of the southern banks stopped a further southward migration of the upper part A. While this part now came to a rest, the main channel started to move south, with temporal separations into several minor channels. The flood channel B silted up in the following years. This large scale migration seems to have come to an end at the beginning of the nineties. The further evolution mainly comprises a deepening of the channels and the steepening of the channel banks.

MORPHODYNAMIC MODELLING

Dynamic, process-oriented models map the physical processes of the morphodynamic system on mathematical formulations which then are numerically solved on a discrete grid.

The natural system is fully coupled in a sense that climatological, hydrodynamic, transport and morphological processes interact in all spatial and temporal scales. A perfect model therefore would require a continuous feed-back of all simulated processes in elaborate time and space discretisation. As for computational reasons the natural dynamics cannot be fully resolved a reduction and filtering at different stages of model development and application has to be carried out.

Model reduction is performed by limiting the simulation to (case-specific) significant processes. A differentiation in time scale between the hydrodynamic and the morphodynamic processes leads to further reduction options: Assuming that the morphological evolution takes place on much larger timescales than the underlying hydrodynamic processes the bed level can be considered invariant throughout a hydrodynamic event. This allows a successive computation of the hydrodynamics, the

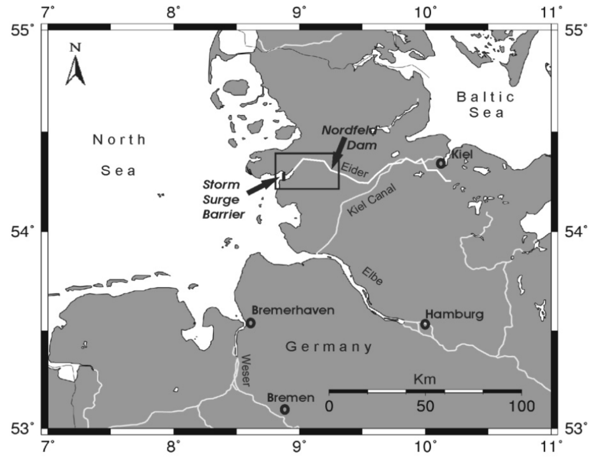

Figure 1. Eider estuary study area.

sediment transport and the bottom evolution in single computational modules. The repeated feed back of the new bottom topography (*morphological time step*) into the hydrodynamic and transport computations results in a dynamic evolution of the bed. Further model reduction then is achieved by increasing the morphological time step (*lengthening of the tide*) either by an extrapolation of the computed bottom evolution (*morphological factor*) or by methods to avoid the time-consuming re-computation of the hydrodynamics after every transport and bed-evolution step (*continuity correction*) (DE VRIEND *et al.*, 1993).

The separation of time-scales also leads to the assumption that long-term morphological effects are based on short-term processes. Thus long-term dynamics e.g. during a neap-spring cycle or an annual cycle - can be represented by a single or a few tides, if their cumulative effect on the morphology is close enough to the effect of the whole period (STEIJN, 1992, LATTEUX, 1995). This input filtering procedure typically involves a *reference simulation* of the morphodynamic effect of a long term cycle and several simulations of the cumulative morphodynamic effect of single or few tides (STEIJN, 1992). The specific single tide that -if continuously applied- produces similar morphological effects as the reference computation is taken as representative (*morphological tide*).

Several authors describe different strategies to set-up the *reference simulation*: E.g. CAYOCCA (2001) or MASON and GARG (2001) apply a method introduced by LATTEUX (1995) in which the long term cycle is differentiated into several classes of tidal conditions and their corresponding proportion of occurrence. For each tidal class a residual transport field is computed. The reference simulation then is composed of the individual transport fields, weighted upon their frequency of occurrence. HIRSCHHAEUSER *and* ZANKE (1999) also follow this procedure but use volumetric differences instead of transport fields. ROELVINK (2000) proposes a straightforward averaging of a one month transport simulation. All authors then find single or double representative tides that reproduce the morphodynamic effect of the reference simulation with acceptable accuracy. Typically these morphological tides are in the order of 2 to 10% higher than the mean tidal range.

These common methods base the representative tide on a more or less parameterised reference computation of transport or morphology. Furthermore the reference computations rarely use more than the pure harmonic tidal signals without the inclusion of climatological events which also trigger the morphodynamic evolution. Therefore the chosen representative tide may not necessarily produce best results in terms of similarity to nature.

For this study the application of a method has been tested in which the reference computation is replaced by observed morphodynamics. Hence a representative tide can be chosen which produces best correlations to natural dynamics. In addition extreme events can be excluded here as the domain of interest is located behind the storm surge barrier, which acts as a wave breaker and is kept closed during extreme storm flood events.

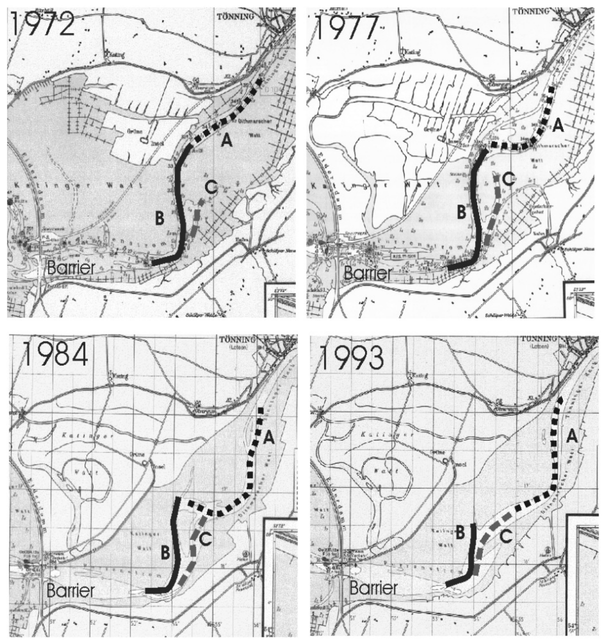

Figure 2. Observed evolution of the Eider estuary after the construction of the storm surge barrier.

SOFTWARE

The dynamic process-based modelling system Delft2d-MOR has been applied, comprising modules for the simulation of hydrodynamics, sediment transport and morphological evolution (ROELVINK *et al*., 1994). The finite difference system simulates the physical processes on a curvilinear grid. In this study the 2DH (two-dimensional, depth averaged) mode is applied, neglecting density differences, which should hold for the well-mixed environment. The hydrodynamic module solves the depth averaged equations for the conservation of momentum in both horizontal dimensions and the depth averaged continuity equation (STELLING *and* LEENDERTSE, 1991).

The transport model computes the bed- and suspended sediment load. The entrainment, deposition, advection and diffusion of the suspended sediment are determined by a numerical solution of an advection-diffusion equation.

$$\frac{\partial c_s}{\partial t}+\frac{\partial u c_s}{\partial x}+\frac{\partial v c_s}{\partial y}-\frac{\partial}{\partial x}\left(\varepsilon\frac{\partial c_s}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon\frac{\partial c_s}{\partial y}\right)\quad\frac{c_{se}-c_s}{T_s}\qquad(01)$$

In which u, v=current velocity components and ε =horizontal dispersion coefficient. The dimensionless adaptation time for the vertical sediment concentration profile T_S is a function of h and the settling velocity of suspended sediment w_S. The equation is solved for the depth-integrated suspended sediment concentration c_s. Here a quasi-3D approach is applied where the distribution along the vertical of the current velocity and suspended sediment concentration are described using shape-functions (GALAPPATTI, 1985). The local equilibrium concentration c_{se} (=S_{se}/uh) is derived from the equilibrium suspended sediment transport rate S_{Se}, as modelled by an algebraic sediment transport formula (eg. van Rijn, Bijker, Ribberink-Van Rijn, etc.).

The sediment balance module solves the bottom evolution equation:

$$(1-\varepsilon_{por})\frac{\partial z_b}{\partial t}+\frac{\partial S_X}{\partial x}+\frac{\partial S_Y}{\partial y}+\frac{\partial S_{Sx}}{\partial x}+\frac{\partial S_{Sy}}{\partial y}=0\qquad(02)$$

In which ε_{por}=bed porosity, z_b the bed level and S_x, S_y the bed load sediment transport components derived from the algebraic derived from:

$$S_{Sx} = q_x c_s - h\varepsilon \frac{\partial c_s}{\partial x} \qquad S_{Sy} = q_y c_s - h\varepsilon \frac{\partial c_s}{\partial y} \qquad (03)$$

In which q_x,q_y=local discharge. The modules are coupled through a morphodynamic time-stepping mechanism that allows a feedback of a generated morphological change into the hydrodynamic module (*continuity update*). If morphological changes are small, a new flow velocity field can be directly calculated from the discharge field and the new morphology (*continuity correction*).

MODEL SET-UP

The model area covered by the curvi-linear computational grid comprises the estuary of the river Eider from a dam in Nordfeld 35km downstream to the Eider storm surge barrier at the river mouth (Figure 3). The grid lines more or less follow the isobaths to reduce numerical diffusion. Element sizes vary from 8m in the vicinity of the barrier and morphologically active regions to 150m in areas of minor interest. Bathymetrical data - obtained from echo-soundings of the relevant authorities and digitized topographical charts- were linearly interpolated on the numerical grid. The lateral open boundaries are set-up at the locations of the five gates of the storm surge barrier downstream and Nordfeld dam upstream. The computational modules were calibrated and validated independently before morphodynamic computations were carried out.

The hydrodynamic model is forced by measured water level time series at the seaward open boundaries and parameterised discharge at the upstream open boundary. In theory the implicit numerical scheme is unconditionally stable. For accuracy reasons the Courant condition is kept below 42 here, which implies a computational time step of 3 seconds. Sensitivity studies show that for mean conditions the wind does not significantly influence water levels and velocities. For further simulations wind forcing was therefore not included. Differences between measured and hindcasted water levels stay below some centimetres (~1%) at high water and 20cm (<8%) at low water throughout the model domain. The phase and characteristics of measured velocities at single locations (shorter and faster flood currents vs. longer and slower ebb currents) are captured by the model simulations. Due to the depth-averaged model hydrodynamics, the computed velocity magnitudes are higher than the observed, which were measured approximately 0.5m above ground. Cross-sectional discharges measured with Acoustic Doppler Current Profilers were computed with high accuracy.

Due to the scarcity of field data, the sediment transport model at first has been subject to sensitivity and calibration studies on flume data by FRANZIUS INSTITUT (1986). The stationary experiments on the initiation of motion and suspension of Eider bed material were hindcasted with a numerical model of the experimental flume. As a result it was decided to apply the VAN RIJN (1984) formula for the computation of equilibrium suspended sediment (see above) as it correctly reproduces the observed initiation of motion at 0.35m/s. The model is able to simulate the observed suspended sediment concentrations for mean current velocities in the range of 0.35 to 0.45m/s and 0.8 to 1m/s. In between it slightly underestimates the suspended sediment concentration.

The sediment transport model of the estuary uses the same computational grid as the hydrodynamic module. Commonly open boundaries preferably are located as far as possible from the area of interest, thus parameterised conditions (e.g. equilibrium or zero transport) can be prescribed which do not influence the required results. As in the present model set-up the seaward open boundaries are in the vicinity of the investigation area, time-series of suspended sediment concentration conditions computed by a numerical model of a part of the German Bight (DELFT HYDRAULICS,1997) were used. Outcropping bed sediments are represented by a homogenous fine sand (D_{50}=80µm, D_{90}=110µm). A deeper layer of consolidated fine grained sediment has been implemented as a rigid, non-erodible layer in the model. Sensitivity studies show the strong dependency of the computed sediment concentrations on the bottom roughness, which varies from flat bed to some decimetres at the barrier bed protection. The bottom roughness was locally adapted to the geographical settings as much as field data was available. A direct validation of the sediment transport model had to be restricted to a short period (November 1996): Figure 4 shows observed vs. computed suspended sediment concentrations during two tides at a position near the barrier gates. The computed values are in the order of magnitude of measured data, however the model underpredicts concentrations during the ebb and overpredicts concentrations during the flood. Regarding the somewhat non-representative positioning of the measurements a further calibration has not been performed. The mean error for this position and period is below 10mg/l, 51% (90%) of the computed concentration values are within a factor 2 (6) of observed values.

The morphodynamic coupling of the modules has been structured in a successive computation of the hydrodynamics, the sediment transport, and the bed-evolution. The computed bathymetry is fed back into the sediment transport model in a sub-loop twice before a full re-computation of the hydrodynamics. The model was forced by a representative tidal cycle as described in the next section. Sensitivity studies show that a uniform change of parameters in the transport model (e.g. Bottom roughness) mainly alters the scale of computed morphodynamics but does not influence the resulting characteristics as the proportion and location of erosional and depositional areas.

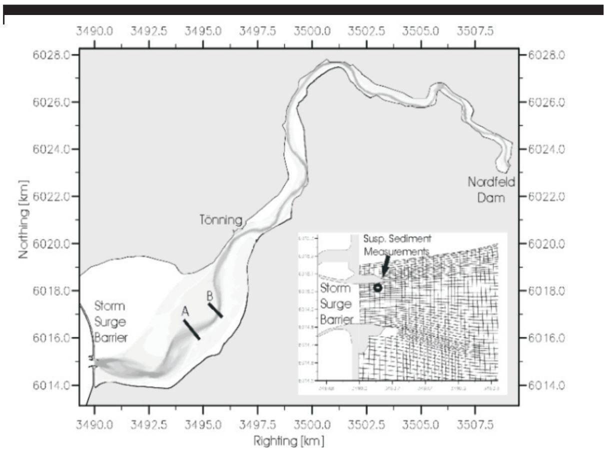

Figure 3. Bathymetry and a detail of the computational grid near the storm surge barrier of the Eider Estuary model.

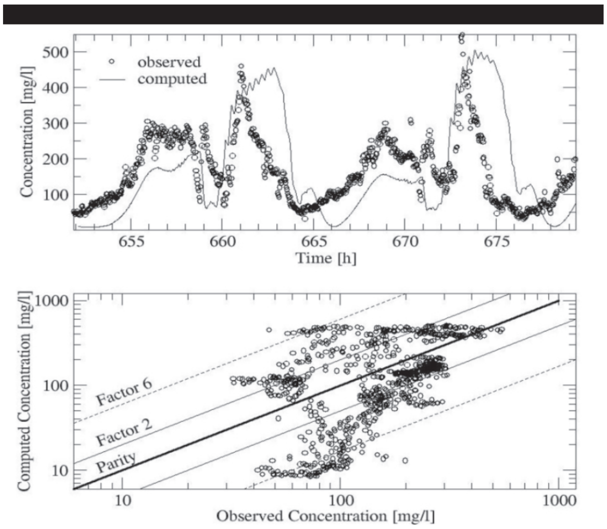

Figure 4. Transport model validation (see location on Figure 3): Observed and calculated suspended sediment concentration time-series (upper plot) and correlation (lower plot).

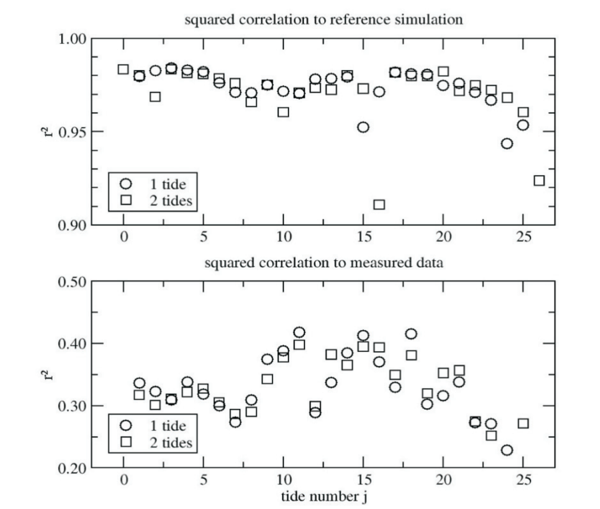

Figure 5. Squared correlation of single and double tide simulations to reference simulation (upper plot) and to field data (lower plot).

REPRESENTATIVE BOUNDARY CONDITION

As stated above the choice of a morphologically representative tide involves the reference dataset (e.g. the difference between the initial and the end bathymetry) and a number of prospect datasets which have to be ranked according to their goodness of fit to the reference set of data. Here the straightforward squared correlation r^2 of two sets of morphological differences has been chosen as a skill score:

$$r^2 = \frac{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2} \qquad (04)$$

In which x_i is the morphological difference of the reference dataset at the position i, y_i is the morphological difference produced by a single or double tide at position i. are the averaged morphological differences of all positions of the according datasets. The squared correlation as the percentage of variance in common between the two datasets is sensitive to differences in characteristic, which is the wanted quality criterion but less sensitive to errors in scale.

Initially the common procedure for the definition of a morphodynamic tide has been applied as follows: A full neap-spring tidal cycle (27 *M2* cycles $\approx$14 days) was simulated. At 17 cross-sections covering the morphologically dynamic part of the estuary the resulting bathymetry was subtracted from the initial bathymetry. These differences form the reference dataset x_i. Then 27 simulations were performed each repeating one single tide for 14 days. The resulting morphodynamics y_{ij} ($j=1\ldots27$) of these simulations were correlated to the reference dataset. Then 27 simulations were carried out each repeating a double tide (25h) for 14 days. Squared correlations of single and double tide simulations to the reference simulation range between 90 and 98% (see Figure 5). In contrast to results from the cited literature, numbers here do not indicate an advantage of double tides. The highest skill was achieved by a tide with 5% increased tidal amplitude compared to the mean (of the 27 cycles). The low water level of that particular tide is similar to the mean low water level.

For the second approach observed morphodynamics are taken into account for the reference dataset x_i. This is composed of the differences of (gridded) bathymetrical data of two consecutive years. Figure 5 shows the resulting squared correlations. As expected the similarity between the (field data) reference dataset and (modelled) morphodynamic effect of individual tides is much lower: Here values range between 18 and 40%. Again results for single and double tides do not differ much. This approach favours a single tide with different characteristics: Its tidal amplitude is 2% smaller than the average. The low water level of this tide is 10cm higher than the mean.

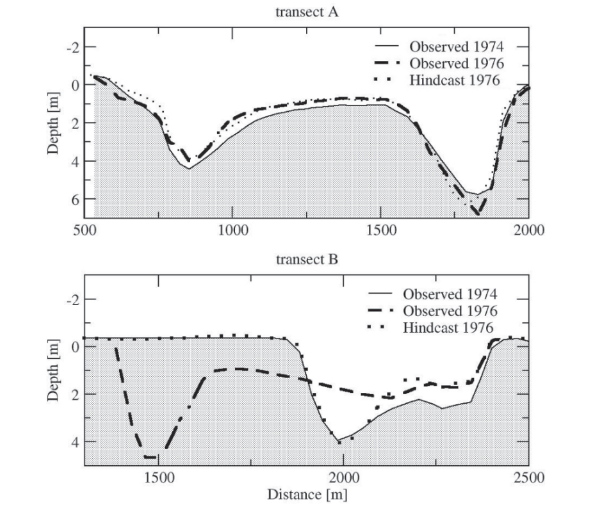

Figure 6. Observed and hindcasted two year evolution at two transects (see Figure 3 for location).

No linear correlation could be detected between the squared correlation and parameters as the tidal range, the minimum or maximum water level, or the tidal asymmetry of the concerning tide. However the tidal cycle derived by the second approach has been chosen for the further application in morphodynamic simulations.

MORPHODYNAMIC SIMULATION

Using the above defined morphological tide, the model performance first was tested on a two year evolution: Starting with the 1974 bathymetry a two year simulation was carried out. The resulting bathymetry then was compared to the 1976 observations. The morphological development in this period is dominated by the above mentioned southerly migration the main channel. The channels deepen and shallow parts tend to fill.

The model generally reproduces the observed morphodynamics in the same order of magnitude. Figure 6 shows results exemplarily at two transects: Transect A is located at the (during this time) morphologically stable middle part of the estuary (see Figure 2). Here the accumulation of the southern (left) channel and the shallow parts are calculated with acceptable accuracy. Also an erosion of the northern channel is captured by the model. Transect B crosses the highly dynamic north-eastern part of the estuary. Here the accumulation of the northern part is calculated well enough, but the migration of the main channel (500m to the south) is not captured at all by the model.

Secondly the morphological evolution of the Eider estuary from 1982 to 1993 was simulated. During this period measurements reveal the relocation and the local deepening of the middle part of the main channel (see Figure 7b). Model results are shown in Figure 7c. The model simulates that the former eastern flood trench is extended to form the new main channel. Also the observed deepening and a steepening of the river banks are captured. The shown result state after 11 years of simulation time remains stable in the shown channel-like morphology and may be considered as the equilibrium state.

DISCUSSION

The common concept of using a single or small number of representative tides to drive morphodynamic computations has been applied to the estuary of the river Eider. The proposed choice of a suitable tidal forcing may be based on observation

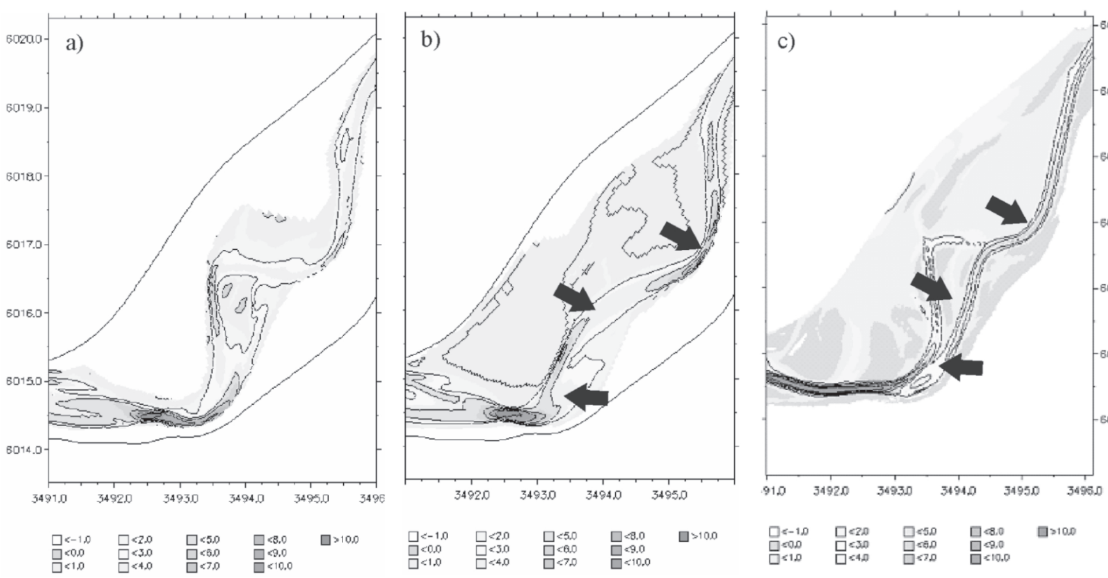

Figure 7. Observed and simulated 11 year evolution of the Eider estuary: 1982 state (a), 1993 observed (b), 1993 simulated (c).

data if available. Resulting morphodynamics show realistic tendencies as depositional and erosive areas are captured with acceptable accuracy. However the model shows its limitations as e.g. the rapid horizontal migration of the main channel is not hindcasted: This raises the question whether the model physics (reduced model) or the model forcing (input-filtering) are responsible for this shortcoming. As stated above computed morphodynamic characteristics (in contrast to rates) are less dependent on inherent transport model parameters as on the driving hydrodynamic forces. On the other hand no clear correlation could be detected between tidal characteristics of the analysed single tides and the quality of model results. As the 27 single and double tides which were taken into account here could only contain a small number of possible conditions, a more detailed study of different combinations of climatological conditions, runoff from the hinterland and tidal forcing will follow. However it is expected that rather the variation in tidal forcing than special characteristics of single tides leads to natural-like evolution, which will be accounted for by a combined set of boundary conditions.

CONCLUSIONS

A numerical model of the Eider estuary at the German North Sea coast has been validated for hydro- and sediment-dynamic processes. For the simulation of meso-scale dynamics (years to decades) a representative tide based on observed bathymetrical changes is proposed. Model simulations of two year and eleven year morphodynamics show satisfactory results in terms of vertical accumulation and erosion patterns. The model thus may serve as a decision support tool for short scale hydro- and morphodynamic studies.

However the main driving force for the large scale horizontal displacement of a tidal channel is not induced by the representative boundary condition as defined here. Although a more sophisticated transport model (space and time varying roughness, 3D, multi-fraction and multi-layered sediments) is expected to enhance results, further research should focus on the definition of differently combined sets of boundary conditions.

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