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On the Prediction of Dunes in Estuarine Morphological Models

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ABSTRACT

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The prediction of dunes in coastal waterways is of great importance for at least two reasons. On the one hand the crests impose a lot of dredging problems and on the other hand dunes contribute to the hydraulic resistance of the system and to the damping of the tidal wave. Therefore it is a mayor research aim to simulate the development of dunes in morphological numerical models. In this paper a new algorithm is developed to simulate the evolution of dune heights and lengths. In the first step the dune parameters are calculated using empirical relations (i.e. here van Rijn) for every hydrodynamical time step. The values obtained in that way are not the actual dune heights and lengths because they would grow during ebb and flood tide and they would disappear during slack water. Instead of this they are regarded as asymptotical values reached theoretically after a certain time. The actual dune height and length are calculated applying a relaxation method using the empirical values as asymptotical values. This algorithm gives good results for the location of dunes in the Weser estuary at the North sea coast of Germany.

ADDITIONAL INDEX WORDS: *Relaxation methods, dune height, dune length, weser estuary.*

INTRODUCTION

The prediction of dunes in estuarine simulation systems is important for several reasons. A practical one is the maintenance of the navigation channels depth. Because dunes are generated more likely in deep waters they can be found especially in the navigation channels. Here their crests are the locations where dredging problems occur although the spatially averaged water depth fulfills the navigation channel standards.

Dunes are also important because of their effect on the flow itself. They increase the bed roughness significantly. This is usually be taken into account by dividing the effective bed roughness according to Nikuradse into grain and form roughness whereby the latter one is connected to the presence of ripples and dunes. While the grain roughness lies in the range of a millimeter, the dune roughness scales with the dune height i.e. meters. Therefore in the presence of dunes the bed roughness is dominated by them.

The bed roughness affects the kinetic energy dissipation and the tidal wave height can decrease significantly over dune fields. Therefore estuarine hydrodynamic models can not be calibrated without knowing the locations of dune fields. Obviously direct measurements can be used for the calibration of the model. But in case of bathymetric changes due to construction measurements the question has to be answered whether the characteristics of the dune systems and their spatial extension will change, too. Therefore a method to predict the occurence of dunes in numerical simulation models is needed.

Theories on the formation of dunes in steady flows i.e. flumes or rivers have a long tradition starting with EXNER in 1925. He derived a formulation for the dune celerity but did not succeed to explain the generation of dunes by stability analysis. KENNEDY (1963, 1969) used the linear Airy wave theory to describe the flow field over dunes. In his approach the free surface has a wave profile. Therefore good results are obtained for high Froude numbers as in the case of antidunes but bottom structures at very low Froude numbers can not be explained. This is also the case for the theories of ENGELUND and FREDSOE (1982), who used the stream line function theory to describe the flow over dunes.

On the other hand a lot of empirical relationships have been developed to predict the dunes described by their height and length. Some of these dune height formulas are more or less only relations between water depth and dune height, e.g. ALLEN (1986), YALIN (1964), i.e. they do not contain information about the flow velocity or the actual bottom shear stress. Although such formulas correspond quite well to natural conditions they can not be used for the prediction of dunes in numerical simulation models because they would predict the same kind of dunes in deep lakes and rivers.

Therefore only formulas depending on the bed shear stress or the water depth and flow velocity can be used to predict the dune characteristics under natural water bodies.

Using such dune height and length formulas in an estuarine simulation model, they would perhaps do a good job at high flood or ebb velocities. But at slack water the dunes would disappear, because they depend simultaneously on the hydrodynamic conditions. Therefore in this paper a relaxation algorithm is presented which preserves the dune characteristics at slack waters.

DUNE SYSTEMS IN THE OUTER WESER ESTUARY

The Weser estuary disembogues into the North Sea at its southern coast. Its mouth is located at Bremerhaven (km 63, 73). A satellite view of its outer parts indicating the shipping channel kilometers is shown in figure 1. In the center of the lower part of the picture the Jade bay can be seen. It is connected

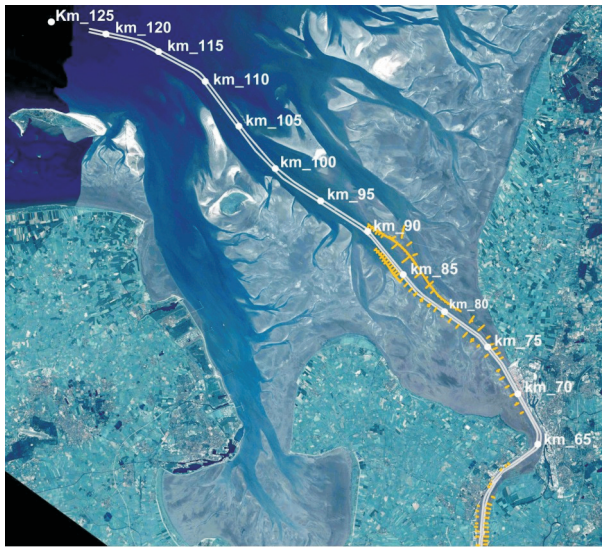

Figure 1. The outer Weser estuary at low tide.

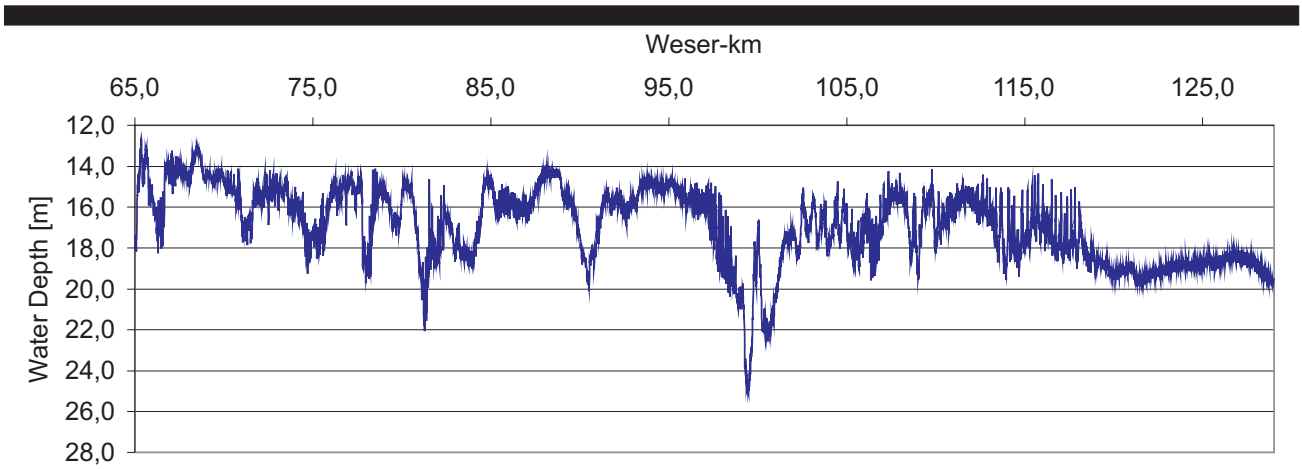

Figure 2. Bathymetry in the navigation channel

to the North Sea by a gorge, named the inner Jade followed by a wide natural inlet channel, the outer Jade.

Figure 2 shows the bathymetry on a cross section through the navigation channel of the Weser estuary. Coming from the sea the largest dune system can be found between km 133 118. A very pronounced dune system is located at the trailing edge between km 97 99. Other dune systems can be seen between km 105 107, km 85 87 and km 71 75. In figure 3 an enlarged view on the bottom structures between km 116.4 and 118.0 is shown. Large dunes with lengths of about 200 m can be seen. Smaller structures of about 20 m length are superimposed on them.

The dune parameters are determined by the following algorithm. First a short scale spatial floating averaging $\bar{z}_B$ is calculated using an averaging interval of 43 m. As it can be seen in figure 3 the resulting curve does not represent the dune heights any more but the dunes length information is conserved. Therefore a second long scale floating average using an averaging interval of 200 m gives the gross trend of the bottom co-ordinate . Summarizing the original bottom co-ordinate $\bar{\bar{z}}_B$ is split by the two averaging procedures as follows.

$$z_B = \bar{z}_B + z_B^{'} = \bar{\bar{z}}_B + z_B^{'} + z_B^{''} \qquad (1)$$

The dune length is determind by the zero down crossing method. Wherever the dune signal $z_B^{''}$ passes from positive to negative values a new dune is defined to begin. The dune height on the other hand is determined as the difference between the maximum and the minimum value of the original bottom co-ordinate z_B over the dunes' length.

COMPARISON WITH EXISTING DUNE FORMULAS

The resulting dune heights are compared in figure 4 to several dune formulas. The water depth, bed shear stress, Froude number and sedimentological input data for such formulas are obtained from a calibrated numerical model at maximum ebb tide.

YALIN (1964) proposed the formula:

$$\frac{\Delta_d}{h} = \frac{1}{6}\left(1 - \frac{\tau_c}{\tau_B}\right) \qquad (2)$$

Here Δ_d is the dune height, h is the water depth, τ_c the critical bed shear stress for the initiation of sediment motion according to Shields and the effective bed shear stress acting on the sediment grains. The formula maximizes the dune height to one sixth of the water depth. As a matter of fact the Weser dunes are everywhere smaller than this limiting value.

GILL (1971) presented the theoretical formula:

$$\frac{\Delta_d}{h} = \frac{1}{2n\alpha}\left(1 - \frac{\tau_c}{\tau_B}\right)\left(1 - Fr^2\right) \qquad (3)$$

He assumes n=3 for the power to which the bed load transport rate increases with the bed shear stress. This is actually too high, when the transport formulas of e.g. MEYER-PETER and MÜLLER or VAN RIJN are regarded. α is a shape factor having the value 0.5 for triangular and $2/\pi$ for sinusoidal dunes. In the Weser the dunes seem to have more a triangular than a sinusoidal shape. In contrary to YALIN, GILL takes into account the disappearance of dunes for critical flow conditions. As it can be seen in figure 4, Gills formula overestimates the dune height significantly.

The disappearance of dunes under higher shear stress conditions is much more pronounced in the formula proposed by YALIN in 1980 (see YALIN (1992)):

$$\frac{\Delta_d}{h} = 0.023\left(\frac{\tau_B}{\tau_c} - 1\right)\exp\left(1 - \frac{\tau_B/\tau_c - 1}{12.84}\right) \qquad (4)$$

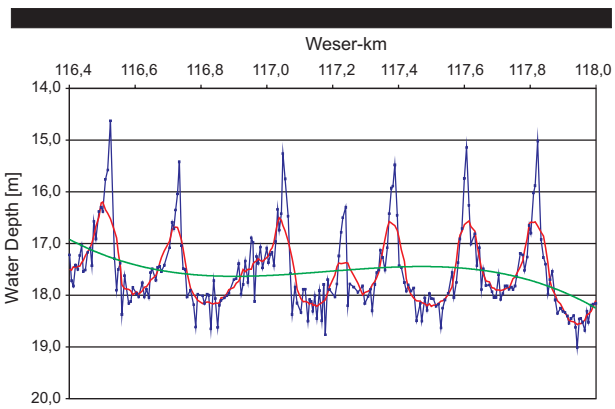

Figure 3. Determination of the dune parameters in the range of Weser-km 116,4 118 by double averaging. Blue line: original vertical co-ordinate of the bottom, red line: short scale averaging, green line: long scale averaging.

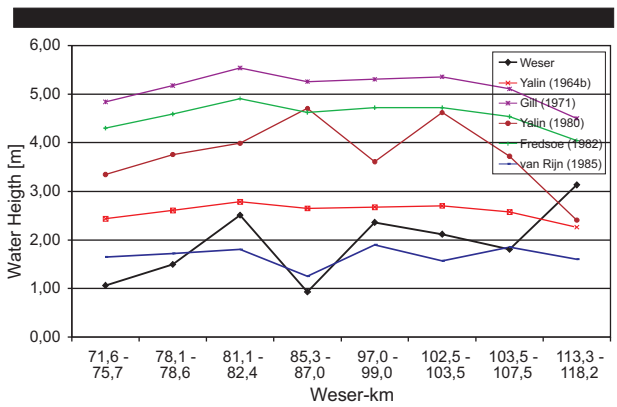

Figure 4. Comparison of the dune heights in the outer Weser with several formulas.

The comparison with the Weser dunes is poor. The formula predicts increasing dune heights where the actual height decreases and vice versa.

ENGELUND and FREDSOE (1982) derived the formula

$$\frac{\Delta_d}{h} = \frac{\left(1-\frac{\tau_c}{\tau_B}\right)}{3+\frac{1}{2}\left(1-\frac{\tau_c}{\tau_B}\right)} \qquad (5)$$

using a mathematical model. It overestimates the height of the Weser dunes about a factor of two or more.

VAN RIJN (1985) developed the empirical formula

$$\frac{\Delta_d}{h} = 0.11\left(\frac{d_{50}}{h}\right)^{0.3}\left\{1-\exp\left(-0.5\left(\frac{\tau_B}{\tau_c}-1\right)\right)\right\}\left(26-\frac{\tau_B}{\tau_c}\right) \qquad (6)$$

Taking into account a lot of data sets for natural dunes. Due to the last term his formula his formula predicts the disappearance of dunes at quite low bottom shear stresses when compared to the other formulas. For the Weser estuary his formula fits the dune heights quite well with respect to the absolute values and the course along the navigation channel.

None of the formulas can predict the large dunes in the range of Weser km 113 118.

The second important dune parameter is the dune length λ_d. Here a lot of empirical formulations do exists which all state that dune length and height are proportional to each other. In figure 5 the relations obtained from the Weser dunes are compared with the approach of FLEMMING (1988):

$$\lambda_d = 27.87\Delta_d^{1.23} \qquad (7)$$

and that of YALIN (2001)

$$\lambda_d = 6h = 36\Delta_d \qquad (8)$$

Both formula show a reasonable agreement, whereby the Weser dune heights seem to be too small with respect to their length.

THE SEDIMORPH MODEL

The *SediMorph* model is a three-dimensional morphological and fractionated sediment transport model. *SediMorph* is implemented in that way that it can be coupled with different hydrodynamic models by well defined interfaces. The programming language is FORTRAN 90.

It works on a sediment classification defined by the user through a sediment classification file. This file contains the specification of the sediment classes by specifying their grain diameters and grain densities. In this way *SediMorph* can work on every kind of sediment classification. This could be the Udden-Wentworth scale but any other classification is possible too.

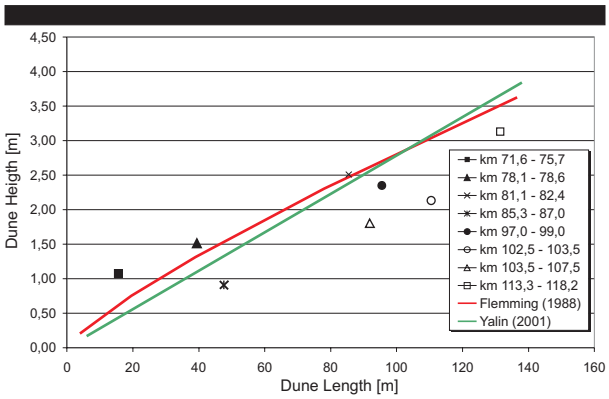

Figure 5. Comparison of the dune lengths in the outer Weser with two formulas.

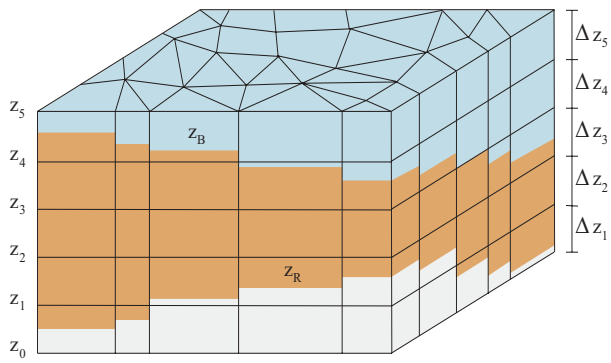

Figure 6. Structure of the morpological data set in *SediMorph*.

For this sediment classification the three dimensional morphological data set for the simulation area has to be constructed. It consists of a two dimensional unstructured mesh with several vertical layers. In this way a mesh of volume cells is defined. For every cell the volume fractions of every sediment class in the sediment classification file has to be specified.

During the simulation the HN model passes a water height and the average velocity related to this water height to SediMorph. In this way SediMorph can be coupled to a 3D as well as a 2D HN model, because this water height can either be the total or the water depth of the first cell over the bed.

SediMorph is now able to calculate the critical shear stresses for the initiation of motion, the transport rates and the bed evolution from the sedimentological data.

The dune parameters are simulated by the following algorithm: For every new time t^{n+1} the equilibrium dune heights Δ_{eq}^{n+1} are calculated according the formula of van Rijn. This height would be achieved when the flow conditions would not change for a certain relaxation time T. Therefore the actual dune height at the time tn+1 is calculated using a simple relaxation strategy:

$$\Delta_d^{n+1} = \Delta_d^n + (\Delta_{eq}^{n+1} - \Delta_d^n)\frac{\Delta t}{T} \qquad (9)$$

Starting from the dune heights Δ^n_d at the previous time the gap between the equilibrium and the actual dune heights is added. This gap is weighted by the ratio of the numerical time step and the relaxation time T. Afterwards the dune length is calculated according to Flemmings formula.

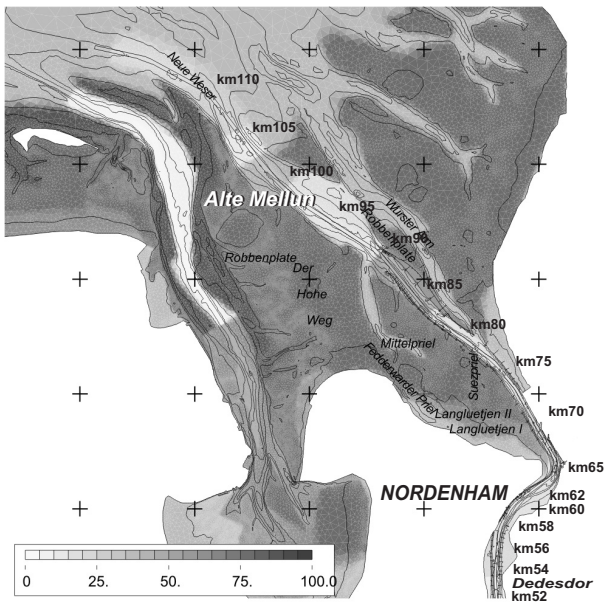

Figure 7. Assumed fine sand percentages in the morphological data set for the Jade-Weser estuary.

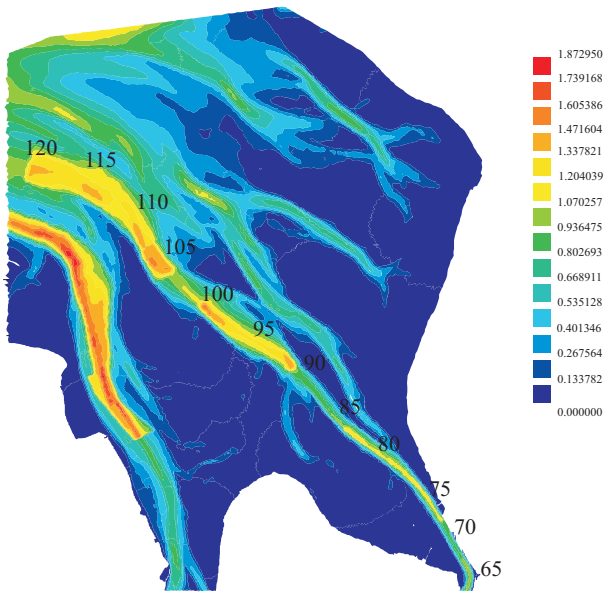

Figure 8. Synoptic View on the simulated dune heights in the outer Weser estuary.

RESULTS OF THE NUMERICAL SIMULATION

For the numerical simulation of the Jade-Weser estuary SediMorph was coupled with the depth averaged two-dimensional hydrodynamic model Telemac-2D (HERVOUET and BATES, 2000). The horizontal mesh consists of 90375 nodes forming 174197 triangular elements. The sediment bottom is discretized by one vertical layer. The sediment itself is discretized by six classes: silt, fine sand, medium sand, coarse sand and gravel. The overall percentages are constructed combining data from different sources. Nor synoptic measurements are available for the whole area. The assumed resulting fine sand percentages are shown in figure 7.

A period of five days was simulated. Because this is too short for the full generation of dunes, two relaxation times were distinguished. The relaxation time for the generation ($\Delta_{eq}^{n+1} - \Delta_d^n > 0$) was set to one hour, and for the destruction ($\Delta_{eq}^{n+1} - \Delta_d^n < 0$) to one week.

In figure 8 a synoptic view on the simulated dune heights is shown. Nor dunes were generated in shallow areas as it is in reality. Otherwise everywhere in the deeper channels dunes are predicted. The dunes are strongly dependent as it can be seen in the outer Jade. On the medium sand bed of the outer Jade large dunes are generated. This ends immediately over the fine sand bottom of the inner Jade which is the gorge to the Jade bay. Actually the dune heights in the outer Jade are as high as predicted by the numerical model.

In figure 9 the simulated results are compared to the

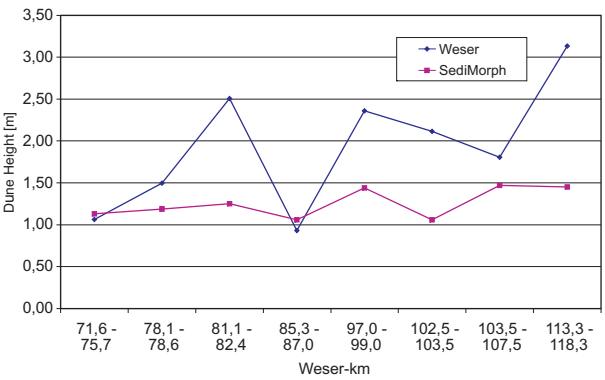

Figure 9. Comparison of measured and simulated dune heights in the shipping channel of the outer Weser estuary.

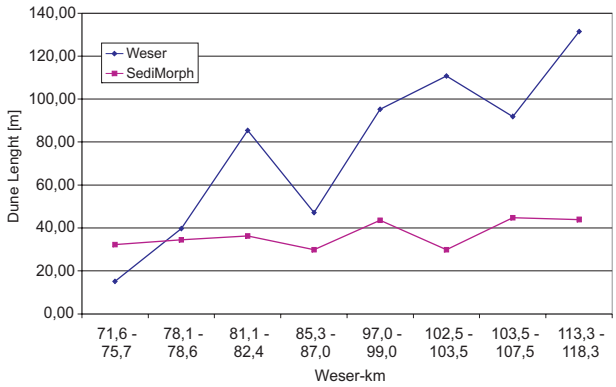

Figure 10. Comparison of the measured and simulated dune lengths in the shipping channel of the outer Weser estuary.

Measurements. In principal the simulations indicate the trends of the measurements but the maximum values are not reached.

Finally in figure 10 the measured and simulated dune lengths are compared. There is a seaward trend to longer dunes in the measurements which is not predicted by the numerical model.

ANALYSIS AND DISCUSSION

A comparison of figures 7 and 8 shows that the results are very sensitive on the composition of the bottom sediments e.g. the d50 and the critical bed shear stress for the initiation of motion. As mentioned before this can be seen in the outer Jade, where the dunes immediately disappear when the sediment conditions change. The dunes are mainly located where the fine sand content is low and the medium and coarse sands dominate. Therefore the sediment composition of the bed has to be known quite good which is not the case for the whole estuarine system.

A comparison between figures 9 and 4 shows that the numerical simulation including the tidal cycle and the relaxation strategy produces quite the same dune heights as the a priory estimation using the conditions at maximum ebb flow. This means that the discrepancies lying between measurements and simulations originate from the sediment input data or the van Rijn formula but not from the numerical algorithm.

As a matter of fact the relaxation times used in the simulation were chosen very pragmatically. As an improvement the generation times found in some dredging experiments could be taken. These range from weeks to months Unfortunately in this approach the simulation periods should then be much longer than the relaxation times which is related to very high computational costs. Theoretical approaches for the relaxation times can be obtained from stability theories. Here the relaxation time is directly related to the imaginary part of the complex wave frequency.

Summarizing further improvements should concentrate by the setup of the initial sediment data before judging the dune formula.

CONCLUSIONS

A simple dune predictor basing on empirical relations for the dune heights and lengths is presented. These relations are taken as equilibrium values which would achieved in a stationary flow. The inertness of the dune parameters in tidal flows is represented by a linear relaxation method which accelerates the growth and retards the destruction of the dunes during slack water.

The results are reasonable with respect to the empirical dune prediction formula and the lack of sedimentological input data.

Improvements of the modeling approach should be done in the calculation of the equilibrium dune parameters as well as in the determination of the relaxation times.

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