Modelling of Sediment Transport and Morphodynamics

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Summary

This article summarizes general concepts for morphodynamic modelling and sediment transport in the coastal zone. Firstly, basic concepts with respect to non-cohesive sediments are introduced. The following sections describe techniques to model fractionated sediment transport and to predict bed forms, as well as the related bed roughness. The last section is devoted to the simulation of dredging and dumping activities in the context of long term morphodynamic simulations.

Keywords

Zusammenfassung

Es werden die grundlegenden Konzepte der Sohlevolution und des Sedimenttransports nicht-kohäsiver Sedimente eingeführt. Anhand von Beispielen werden Ansätze zur Behandlung von Sedimentklassen und zur Prädiktion von Sohlformen vorgestellt. Der Einfluss von Unterhaltungsmaßnahmen in Seeschifffahrtsstraßen auf die langfristige Sohlentwicklung wird im Rahmen eines Langfristmodells aufgezeigt.

Schlagwörter

Contents

1   Introduction

Even today, modelling of the continuous changes in the elevation of the hydrographic bottom and the structure of the corresponding subsurface of coastal waters is a tremendous scientific challenge. Primary cause is the large number of processes involved. These range from the different scales of the currents involved, like turbulences, swell, tides and long-range currents (MALCHEREK 2010a), via the composition of the present sediments and biological processes, right up to anthropogenic encroachment like, for instance, dredging and dumping as maintenance measures or resource extraction.

This article aims to introduce the approaches established today and implemented in most current sediment transport models. Emphasis is placed on non-cohesive sediments, which, in coastal regions, are primarily represented through sandy sediment distribution. The multitude of empirical formulations and dedicated models regarding individual processes can and will not be covered. Rather, the emphasis is placed on outlining the premises pertaining to the various process models and their associated problems, limitations and knowledge deficits.

The mechanisms that apply to cohesive sediments are different than those applying to sandy sediments. An introduction to this topic and further research is given by MALCHEREK (2010b), MALCHEREK and CHA (2011), as well as WEHR and MALCHEREK (2012), in which an isopycnic numerical model for the simulation of cohesive transport processes in tidal regions was presented. Sediment mixtures constitute a further field of research. For an introduction to modelling of the interaction of cohesive and non-cohesive beds see DONG (2007) and JACOBS et al. (2010).

2   Fundamental Concepts of Natural Sediment Transport

As a rule, the beds of natural channels consist of a mixture of grains of sediment with varying properties, as well as miscellaneous biological components. They form a framework whose cavities are filled with in-situ water and whose structural cohesiveness may be influenced by chemical as well as biological processes. Separation processes and the geological history of the substratum lead to horizontal as well as vertical structuring.

This complex structure cannot be precisely described in a deterministic manner. Therefore, within the numerical model the mobile sediment of the bed and the adjoining bodies of water will be considered as a continuum (Fig. 1) and its physics described

through mathematical models. Particularly size, shape and the properties of the sediment particles, as well as the water content, apply to its specific classification.

The most basic case occurs with uniform sediment distribution of spherical sediment particles with a diameter of no more than 64 µm. This presumes a case of non-cohesive sediment, where the electro-chemical forces in relation to the weight force per grain are negligible. This concept forms the basis for the subsequent comments in this paragraph. Sediment particles with varying diameters represent an enlargement on the basic scenario. Sediment fractions can then be developed according to the grain distribution curve and models for the physical processes of inhomogeneous sediment distribution can be established. These approaches will be discussed in paragraph 3.
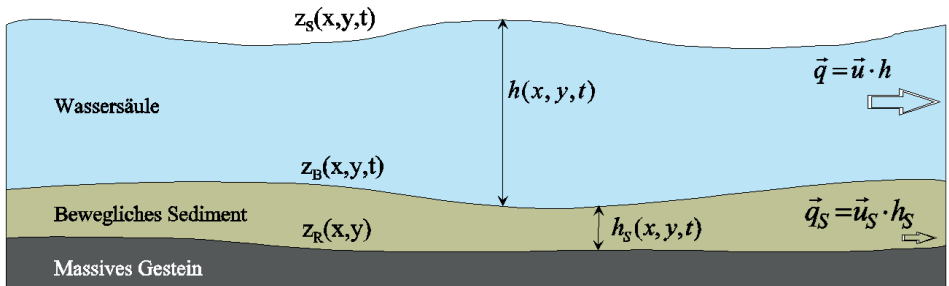

Figure 1: Conceptual design of a body of water with mobile bed.

2.1 The Bed-Evolution Equation

Almost all morphodynamic numerical models utilize the Bed-Evolution or Exner-equation as a basis for conceptual modelling. It describes the changes in the geodetic location of the bed z_B in dependence of the time t through the transport of bed and suspended load:

$$(1-n)\frac{\partial z_B}{\partial t} = -\mathrm{div}\vec{q}_S + \frac{\Phi_S}{\rho_S} \tag{1}$$

In this equation the dimensionless parameter n represents the porosity, $\vec{q}_S = \left(q_{Sx}, q_{Sy}\right)^T$ the horizontal volumetric bed load transport in [m²/s], Φ_S in [kg/m²s] the vertical sediment flow of suspended sediment and ρ_S in [kg/m³] the sediment density. The porosity represents the relation between water volume and the total volume of water and sediment and carries an approximate value of 0.3 for sandy sediment. A prediction of this parameter was presented in MALCHEREK and PIECHOTTA (2004). The dry density of the sediment is generally given as $\rho_S = 2650$ kg/m³.

As has been described, the movement of sediment can be differentiated as bed load transport and suspended sediment transport. In the former, sediment particles move along the bed in a rolling or skipping motion. Suspended sediment transport is achieved when turbulences near the bed are high enough to prevent the particles from settling. Particles are detached from the bed and transported within the current.

To interpret the bed evolution equation, both transport types will be considered separately in a one-dimensional scenario. For bed load transport in direction x the right side

of the equation is reduced to $-\partial q_{Sx} / \partial x$. Accordingly, the bed does not undergo any changes assuming the bed load transport rate also remains at a constant volume. An equilibrium exists. If, however, q_{Sx} increases in the x-vector, less sediment is introduced than discharged. The bed is degraded. Correspondingly, a deposition scenario results when the bed load transport is decreased and, thus, $\partial q_{Sx} / \partial x$ is negative. In the case of suspended sediment, the exchange of sediment between the water column and the bed is decisive. If the sediment flow is balanced, $\Phi_S = 0$ applies and the bed is not affected. In the case of a negative balance more sediment is discharged than being supplied to the bed. It deepens. The deposition scenario is reinstated when the sediment flow is positive.

These observations show that the gradient of sediment transport and the balance of the vertical exchange are decisive for bed evolution. In addition, sediment transport can take place, even without changes in the bed. Therefore, it has to be determined as of which current load sediment is transported and how it may be quantified in terms of bed load transport and suspended sediment transport.

2.2 Bottom Shear Stress and Transport Initiation

The interaction between current and the bed is modelled via the bottom shear stress $\overrightarrow{\tau_B}$ in [N/m²]. Assuming a logarithmic velocity profile and the equivalent bed roughness k_S in [m] for hydraulically rough beds, it is formulated as follows:

$$\overrightarrow{\tau_B} = \rho \frac{\kappa^2}{\left(\ln \dfrac{12h}{k_S}\right)^2} \|\vec{u}\| \vec{u} \qquad (2)$$

These are the water density ρ in [kg/m³], the dimensionless von-Karmann constant κ, the mean flow velocity $\vec{u} = \left(u_x, u_y\right)^T$ in [m/s] and the water depth h in [m]. According to Nikuradse, the equivalent bed roughness k_S can be set in relation to the in-situ sediment. A multitude of formulae exist in regard to their calculation, which essentially depends on a characteristic grain diameter, as well as a scaling factor. One example is the correlation $k_S = 3d_{90}$. To achieve three-dimensional current modelling, the bottom shear stress needs to be inserted in place of equation 2.

Natural channels often exhibit bed forms which dissipate additional flow energies. According to VAN RIJN (1993), the bed roughness may in this case be considered as the sum of grain coarseness k_S^g and bed form k_S^f. This will be discussed in more detail in paragraph 4. The stresses acting on the sediment particles are of importance regarding sediment transport. These can be calculated through inserting the grain roughness in place of the bed roughness in equation 2. Accordingly, the variable for the effective bottom shear stress can be expressed as:

$$\overrightarrow{\tau_B} = \rho \frac{\kappa^2}{\left(\ln \dfrac{12h}{k_S^g}\right)^2} \|\vec{u}\| \vec{u} \qquad (3)$$

It represents the morphologically active bottom shear stress and is of essential importance for the calculation of sediment transport.

The central question concerning transport calculations is, as at what level of bottom shear stress transport of mobile sediment is initiated. A popular approach in morphodynamic modelling is based on research by Shields regarding critical bottom shear stress. It assumes that sediment only becomes mobile after a critical value, the dimensionless Shields-Parameter $\theta_{cr,}$, has been exceeded. Shields does not supply a functional correlation, presenting his findings graphically in dependence of dimensionless parameters instead. In follow-up articles, this data was supported by curves. A number of functional correlations for the calculation of $\theta_{cr,}$ can be found in the appropriate technical literature. One example, the approach by BROWNLIE (1981), is shown in Fig. 2.

The course of the curve or, rather, the Shields diagram is commonly known and has been adequately discussed (BUFFINGTON and MONTGOMERY 1997; VAN RIJN 2007). It should be mentioned that this curve fit naturally represents Shields' data, but is intended to overestimate $\theta_{cr,}$, particularly for coarse sediment. Therefore, Figure 2 plots the approach according to PARKER et al. (2003), scaling the approach by BROWNLIE (1981) to 0.5. This should better represent the initiation of sediment transport. These two formulae alone demonstrate the range necessary to calculate the critical bottom shear stress. In addition, turbulent currents, which can be assumed in natural bodies of water, represent a stochastic process (ZANKE 2002). Stress peaks on single grains caused by turbulent fluctuations are not represented by the functional sequences shown in Figure 2. The approach using θ_{cr} has nevertheless been proven successful, as it represents a critical value whose exceedance points out that significant amounts of sediment are transported and not only scant particles.
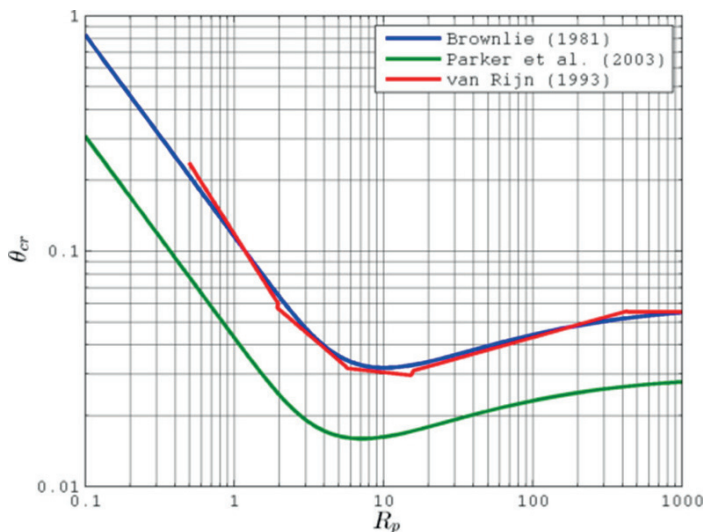

Figure 2: Critical bottom shear stress θ_{cr} of the transport initiation in dependence of the Grain-Reynolds-Number.

Fig. 2 displays a further curve. Shown is the partial parameterization according to VAN RIJN (1993), which is frequently used in numerical models. It should be noted, that it is a

good reflection of the critical bottom shear stress, while showing discontinuities along the transitions, though. These could lead to numerical instabilities and should not be applied, according to its authors. Approaches like those by BROWNLIE (1981), PARKER et al. (2003) or ZANKE (2001) are to be preferred.

2.3 Bed Load Transport

Calculating sediment transport along the bottom is a decisive step toward morphodynamic simulation. Technical literature offers a nearly overwhelming number of more or less empirically derived formulae, which have been previously examined extensively, for instance in ZANKE (1982). These have a certain validity based on the data applied, so that new approaches regarding different problems are still being published today, for instance regarding wave and tide influenced transport (CAMENEN and LARSON 2005; MALCHEREK and KNOCH 2005; VAN DER A et al. 2013).

The majority of bed load transport formulae can be divided into two classes. There are the marginal value formulae, in which sediment is not transported until the critical bottom shear stress has been exceeded. In general terms, many of these approaches can be described as

$$q_S = m\left(\theta' - \theta_{cr}\right)^n a \tag{4}$$

Here q_S represents the amount of the bed load transport capacity in [m²/s], m and n are formula-dependent parameters and $\theta' = \tau'_B / \left(\left(\rho_S - \rho\right) g d_{50}\right)$ is the effective dimensionless bottom shear stress with the gravitation acceleration g in [m/s²] and the grain diameter d_{50} in [m]. Furthermore, $a = \left(\left(s-1\right) g d_{50}^3\right)^{1.5}$ in [m²/s] with the specific density $s = \rho_S / \rho$. The vector transport rate is derived from the flow field along the x and y axes. The classic transport formula according to MEYER-PETER and MÜLLER (1948) is equally relevant as is, for instance, a formula based on data re-analysis by NIELSEN (1992). In addition, other formulae were developed that did not factor in this critical value, like the probabilistic approach by EINSTEIN (1950), or BIJKER's (1968) formula for coastal longitudinal transport.

In the case of large bed gradients, gravitation exercises a considerable effect on the amount and direction of bed load transport. To be able to consider this effect, a number of approaches have been developed, which modify the transport vector, the critical bottom shear stress or the entire transport formula (for instance SOULSBY 1997; CHENG et al. 2010). Is the bed gradient higher than the inner angle of friction, slope slides will occur, which have to be treated separately.

To characterize coastal bed load transport, a simulation result using the formula according to Meyer-Peter and Müller (with m=8 and n=1.5 in equation 4) for the flood-tide current is shown in Fig. 3 as an example. Only the tide was factored in as a load factor and fine sand assigned for the sediment. The results show large-scale mobilization of sediments within the German Bight. However, the transport rates are lower by several magnitudes in relation to the peak values. These occur in the inlets and estuaries, where bottom shear stresses are high. Therefore, large-scale bed load transports can be expected in these areas. The transport rate decreases markedly in the shallower areas. Within the

Wadden areas the model does not simulate any substantial transport due to the tidal load alone.

The example shown can merely give a general overview into the bed load dynamics of coastal regions, as the simulated results depend strongly on the applied transport formula and further sediment characteristics, as well as the applied loads. Depending on the selected approach, the bed load transport rates can vary by several magnitudes and may, therefore, lead to a different bed evolution. In addition, the simulation presumes the availability of a constant and sufficient quantity of sediment for the predicted transport capacity according to equation 4 and that this quantity is directly introduced into the bed evolution equation as the actual bed load transport rate. Numerically, limited sediment transport is much more difficult to model (MALCHEREK 1997).
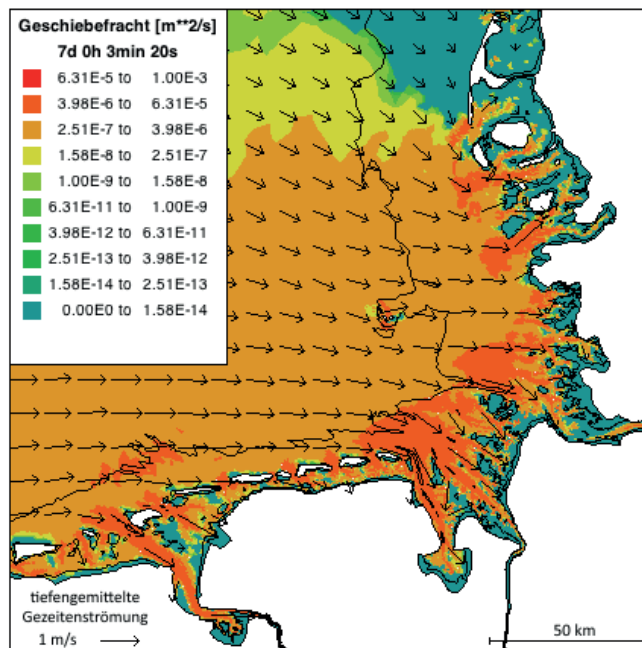

Figure 3: Example of bed load transport rate in the German Bight during incoming tide according to the Meyer-Peter-and- Müller formula.

2.4 Suspended Sediment Transport

The three-dimensional transport of suspended sediment can be described with the following scalar advection/ diffusion equation:

$$\frac{\partial c}{\partial t} + \mathrm{div}\left(c\vec{u_S}\right) = \mathrm{div}\left(\varepsilon_S \mathrm{grad} c\right) \tag{5}$$

Here c is the volumetric sediment concentration in the water in [m³/m³], $\vec{u_S} = \left(u, v, w - w_S\right)^T$ is the velocity vector with which sediment is carried, w_S the sink rate

in [m/s] and ε_S the sediment diffusivity in m²/s (JULIEN 2010). The sink rate can be calculated through formulae like, for instance, VAN RIJN (1993). It must be noted, however, that, especially in coastal zones, effects like flocculation (MALCHEREK 1994) or sediment mixtures exacerbate precise determination of sink rates considerably.

It is assumed as a marginal condition along the water surface that no sediment passes through the surface. Close to the bed, however, a vertical sediment flow between the body of water and its bed may occur. It is defined in a definite height above the bed, which represents the strength of the load-carrying layer. The sediment flow depends on the qualities of the sediment, the bed characteristics and the effective bottom shear stress. It is further divided into an erosion and a deposit flow. Several different approaches exist for its modelling. The erosion flow is commonly described in terms of a power law in dependence of the excess bottom shear stress $\max\left(0, \tau_B' - \tau_{cr}\right)$ (for instance according to Partheniades), while the deposit flow, in the simplest case, is dependent on the concentration close to the bed and the sink rate.

When determining the mean of the three-dimensional suspended particle transport equation (equation 5), the two-dimensional transport equation is achieved. It displays the erosion and deposit flows as source and sink terms. The definition of the deposit flow is problematic, as it technically depends on the sediment concentration near the bed. One possibility is the assumption that an equilibrium concentration will occur, during which the erosion and deposit flows cancel each other out. This is the basis upon which the necessary net flow for achieving this condition is calculated in the numerical model.

The result of a mean suspended particle transport equation is shown in Fig. 4. For comparison with the bed load transport rate, the suspended particle transport rate was calculated from the sediment concentration. Fine sand was defined as the mobile sediment for the entire modelling area and only the tidal currents were simulated. Furthermore, an equilibrium concentration was assumed in order to model the erosion and deposit flows. This transportation mode, too, incurs large-scale mobilization of sediment due to the floodtide current. The highest suspended sediment transport rates are generated in the estuaries and channels, where the current produces an elevated bottom shear stress and large quantities of sediment are transported in the water column. In the Wadden areas, however, only a limited mobilization of sediments can be detected for the generated current condition. Part of the suspended sediment transported by the tide is deposited here.

Decisive in both, the three-dimensional and two-dimensional, transport equations is the amount of sediment introduced into or discharged from the body of water along its bed. The net flow appears in the bed evolution equation and may possibly lead to a change in the bed. The formulations used for the deposit and erosion flows, as well as for the sink rate, are essential factors, which may alter the morphodynamic results considerably. It is interesting to note that the transported amounts can be higher by several magnitudes than during bed load transport and play a critical role in the overall sediment dynamics. Particular attention should therefore be paid to the modelling of suspended sediment transport.
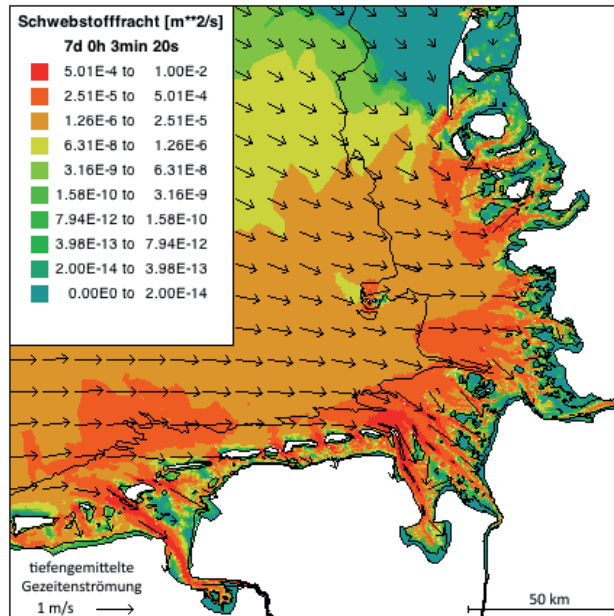
Figure 4: Example of mean suspended sediment transport during incoming tide.

3 Fractionated Sediment Transport

The bottom of natural channels generally consists of a mixture of different sediments. Since bottom shear stress, transport initiation and sediment transport are influenced by grain size, more advanced concepts than those already discussed are required. The composition of the bed can be discretized by way of sediment classes, to which a characteristic grain diameter will be assigned, saved as an initial sediment configuration. Another possibility would be to presume a lognormal distribution of the sediment classes. The statistical parameters for the description of the function profile would be saved and may change during the course of the simulation. This concept will not be discussed further here.

3.1 Vertical Discretization of the Hydrographic Bed

Grain size-dependent sediment transport leads to a separation within the uppermost sediment layer bordering on the body of water.

A modelling concept for this phenomenon is the Active-Layer-Concept. The hydrographic bed is divided into an active layer (the layer bordering on the body of water) and an underlying inactive layer. Further layers may follow up to a non-erodible soil horizon. Horizontal sediment transport and the exchange of sediments with the water column only take place within the active layer. Its strength is defined by the user or calculated, for instance dependent on grain diameter or the bottom shear stress.

Fractionated bed load transport can, for example, be modeled by calculating transport initiation and bed load transport rate with a grain diameter characteristic for the sediment mixture. The transport rate is then proportionally distributed on the existing sediment fractions and the bed evolution equation is solved. For suspended sediment transport, the calculated erosion and deposit flows can be determined similarly. Through fractionation of the sediment, effects like Hiding/Exposure can be considered.

Both in the active layer as well as all potential substratum layers, an initial sediment distribution has to be provided. Due to bed load and suspended sediment transport in the sediment classes, not only the composition but also the position of the bed changes over the course of the simulation.

3.2   Sediment Separation in a Tide-affected Bight

Fig. 5 shows an abstract of a separation study for the Jadebusen Bay by MALCHEREK and KNOCH (2004), utilizing seven different sediment fractions ranging from medium silt to very coarse sand. It incorporates bottom shear stress from tides as well as from wave effects. Fine sand was assigned as the initial sediment load. It was generated through the interpolation of measurement data and shows distinct artifacts. The actual water body structure, which is characterized by a multitude of tidal gullies and channels, is only superficially represented.
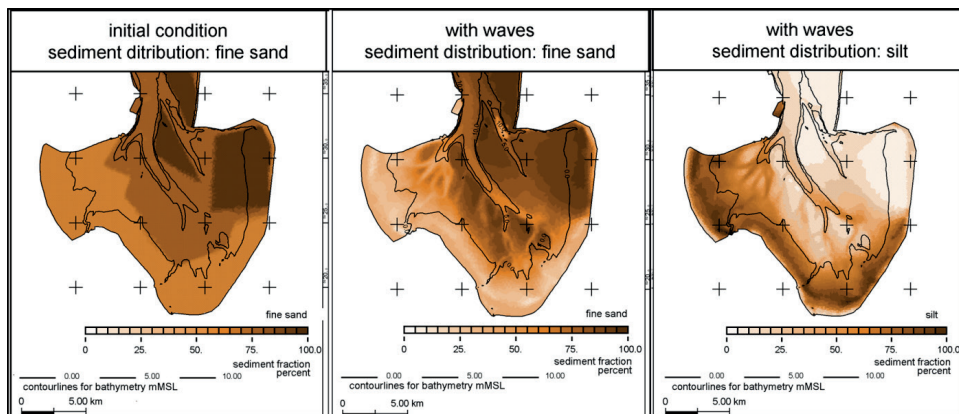

Figure 5: Initial distribution of fine sand, as well as fine sand and silt after 9 simulated days.

After a period of 9 days, a distinct transformation in the sediment composition can be detected. A structuring corresponding to the morphological structure can be recognized. The prevailing Westerly wind direction results in a lower wave load in the West and a higher wave load in the East of the bay. This leads to a higher percentage of fine sediment in the tidal change zone in the Western part of the Jadebusen, as outlined by the silt example. In contrast, the percentage of fine sand is reduced at the same location. The bottom shear stress in the Eastern part is so high that the sediment primarily consists of fine sand.

The results emphatically demonstrate the performance capabilities of morphodynamic modelling. The disadvantage of the Active-Layer-Concept, though, is the fact that data concerning the layering of sediment are lost during the simulation run. New developments attempt to correct this via a bookkeeping algorithm (MERKEL and KOPMANN 2012).

4 Prediction of Dunes and Ripples

If the bottom consists of mobile sediment, bed forms such as dunes and ripples may develop under certain current conditions and with the appropriate bottom substrate (YALIN 1992). In relation to the bed load stress, we need to distinguish between different stages of development, current status and decay. In coastal regions, roughness-induced bed forms can be classically divided into dunes and ripples. The latter may be generated through either tidal currents or wave load. In addition, dunes and ripples can occur simultaneously and may be superimposed.

4.1 Grain and Bed Roughness

If bottom forms are present, the roughness of the bottom increases significantly in relation to the pure grain roughness. In this case, a distinction must be made between the roughness of the grains, which have been selected for the calculation of sediment transport, and the current-related roughness. According to VAN RIJN (1993), the equivalent bed roughness can be partitioned as follows:

$$k_S = k_S^g + k_S^f \tag{6}$$

Accordingly, k_S is made up of the sediment-related grain roughness k_S^g and the bed form k_S^f, which is dependent on the extent of shaping of the bottom. The bed form can be further subdivided into ripple form k_S^r and dune form k_S^d. According to van Rijn, the individual form can be calculated as:

- The grain roughness: $k_S^g = 3d_{90}$
- The bed form due to ripples: $k_S^r = a_r \gamma_r \Delta_r^2 / \lambda_r$
- The bed form due to dunes: $k_S^d = 1.1 \gamma_d \Delta_d (1 - \exp(-25\Delta_d / \lambda_d))$

Here, a_r and γ_r are weighting factors. For a_r, literature indicates values between 8.0 (VAN RIJN 1993), 20.0 (NIELSEN 1992) and up to 27.7 (GRANT and MADSEN 1982). For superimposed ripples and dunes or sand waves, VAN RIJN (1993) gives a value of $\gamma_r = 0.7$, otherwise 1. Furthermore, Δ_r is the ripple height, λ_r the ripple length, Δ_d the dune height and λ_d the dune length. For natural conditions, a value of 0.7 needs to be applied for γ_d.

Thus, the definition of the bed form can be traced back to the prediction of length and height of the sediment bodies. For a detailed study on the prediction of dunes and ripples see MALCHEREK and PUTZAR (2004), as well as PUTZAR and MALCHEREK (2010). The methods described therein not only consider flow conditions and the in-situ sediment, but also include modelling of the temporal development.

4.2 Predicted Heights of Bed Forms and Resulting Roughness

In the following, the results of a morphodynamic simulation with fractionated sediment transport, tidal load, waves and wind is presented, that also considered the roughness of dunes and ripples. This simulation is based on the long-term model of the German Bight (in HEYER and SCHROTTKE 2012).

Fig. 6 shows the time-dependent ripple height. In comparison with the sediment distribution from HEYER and SCHROTTKE (2012), which is the basis of the simulation, it becomes apparent that these bed forms do not appear (or at least only negligibly) in areas with primarily cohesive sediment. Examples for this are the silt lens at Heligoland and the Dollart. On sandy soils, however, ripple heights of up to a maximum of 2 cm can be observed. But here too, there are areas in which ripples do not occur. Here the bottom shear stress of tides and waves is so high that the critical value of ripple existence is exceeded and the ripples disappear. Equally, there are areas in which the bed load is insufficient to generate ripples. The predicted dune height (Fig. 7), on the other hand, demonstrates a different spatial distribution. These bed forms can be found in channels and estuaries with sandy sediment. The predicted dune height also varies from only a few centimeters up to approximately 2 m. This results in the bed form k_S according to equation 4, as shown in Fig. 8. Not only is it significantly higher, as compared to the grain roughness k_S^d, but also demonstrates a larger spatial and temporal variability.
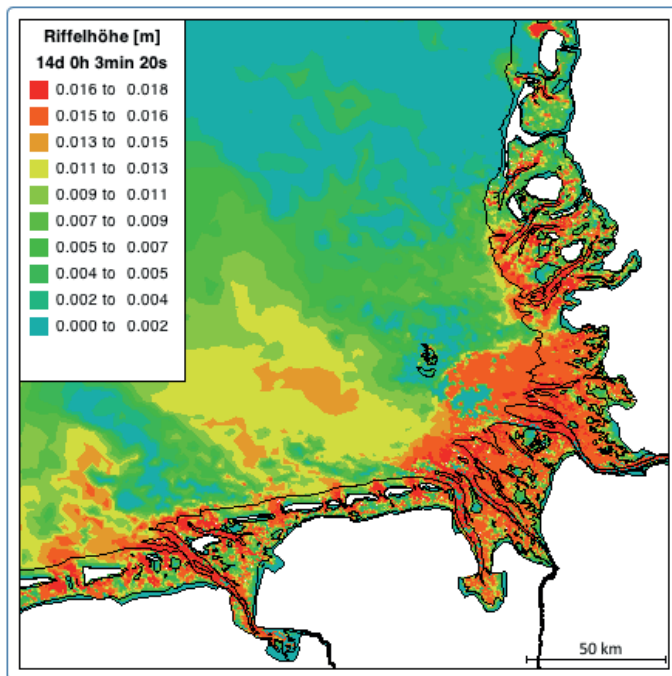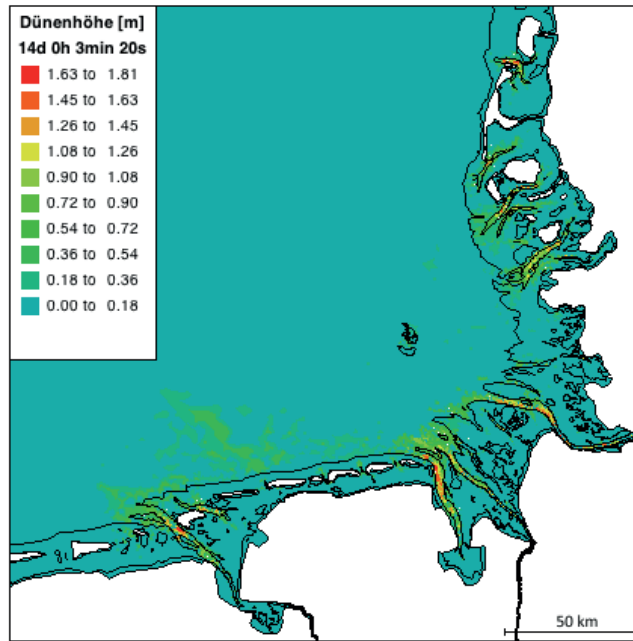

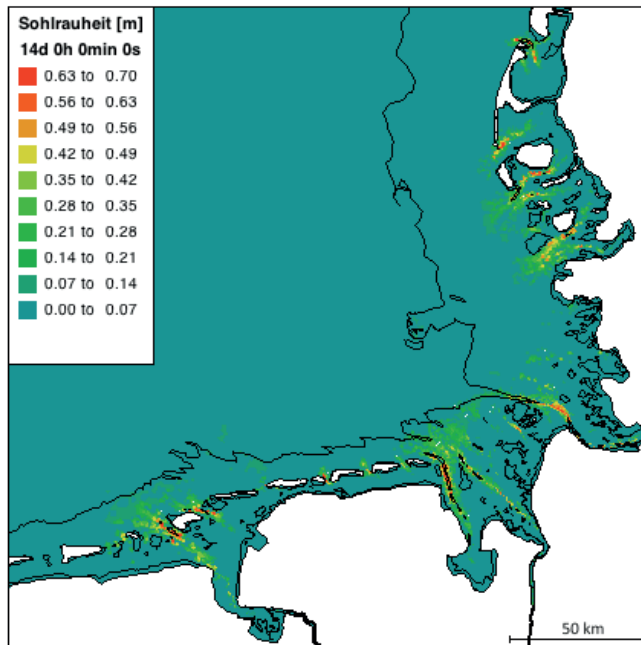Figure 6: Predicted ripple height.

Figure 7: Predicted dune height.

Figure 8: Bed roughness calculated from ripple and dune measurements.

The simulation results shown represent initial results towards a large-scale prognosis of bed forms and are still being actively researched. The results of the dune and ripple predictions depend on the hydrodynamic and sedimentological input data. In principle, the predictors need to be calibrated in order to attain naturalistic results. In particular, it must be noted that the predicted bed forms need to be assessed critically in regard to the effect of their roughness. VAN RIJN (1993) refers to the fact that a value $k_s^f = 0$ applies to symmetrical sediment waves. Future challenges will lie in the reliable prognosis of actual profile-related bed geometries.

5   Effect of Maintenance Measures on Bed Evolution

Whereas the previous paragraphs were dedicated to natural sediment transport, the following outlines the anthropogenic influences by example of maintenance measures on waterways. Through the extraction and dumping of dredged material, they can play a decisive role in sediment dynamics.

5.1   Modelling of Maintenance Measures

Dredging and dumping can be realistically modeled with the DredgeSim module (MAERKER and MALCHEREK 2010), which was developed by the German Federal Waterways and Research Institute in Karlsruhe in cooperation with the University of the German Federal Armed Forces in Munich, Institute of Hydrosciences. It is coupled with a morphodynamic-numerical model, for instance into the TELEMAC simulation system (HERVOUET and BATES 2000), and offers the option of optimizing sediment management and to make its planning more efficient.

   As part of the AufMod project/sub-project 4 (HEYER and SCHROTTKE 2012), dredging criteria were developed for the three major German estuaries, the Elbe, Weser and Ems rivers. All of these contained maintenance strategies and were incorporated into a long-term model of the German Bight (PUTZAR and MALCHEREK 2012; HEYER and SCHROTTKE 2012). Essentially, a minimum required depth for the navigation channel was determined, whose exceedance would ensue the extraction of sediment. The minimum depth is checked at intervals of one year and dredging operations are initiated as required. The extracted sediment can then be dumped in closely defined areas or removed entirely from the simulation model. A detailed description of the sub-project 4 can be found in HEYER and SCHROTTKE (2012).

5.2   Long-term Bed Evolution in the Elbe Estuary

As an example for the analysis of the effects of maintenance measures, two simulations are outlined, each with a simulated run-time of 100 years, one with, the other without sediment extraction within the Elbe estuary. For both simulation runs a grain diameter of 0.375 mm was used and the sole load on the bed was the tidal current. The maintenance measures on the tidal Elbe were considered by way of a defined minimum required depth. Dumping of the extracted sediment was dispensed with.

The effect of the maintenance measure on the simulated morphodynamics can be demonstrated particularly well in the area of the Elbe mouth. Without maintenance measures, the navigation channel of the Outer Elbe between the banks of Großer Vogelsand and the Gelbsand would shift toward the Northeast, as shown in Fig. 9. For the sake of orientation, the dredging areas are represented as yellow polygons. The navigable channel would fill in on a length of 14 km, making it impossible to guarantee the consistency and safety of the waterway.
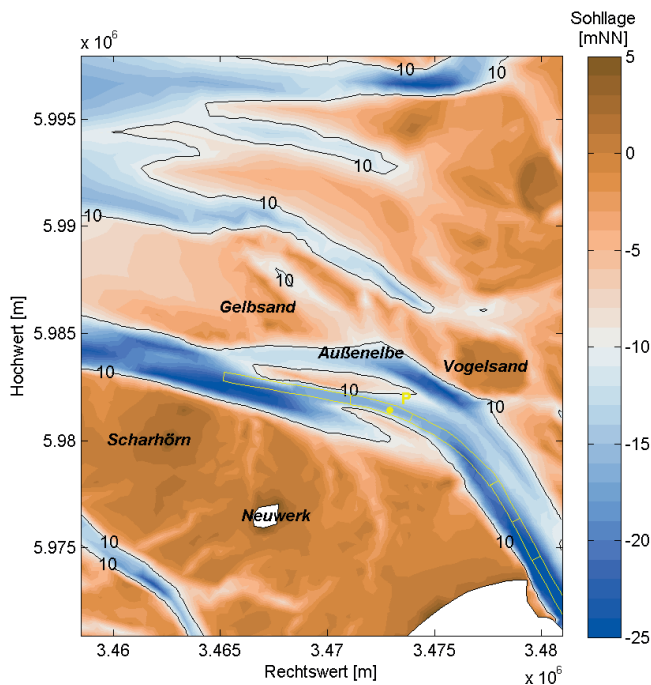

Figure 9: Simulated bed geometry, without dredging, after 100 years, in the Elbe estuary in the German Bight. Those areas of the shipping channel on which maintenance measures were carried out in the simulation, are marked yellow and are intended to ease comparison of the two simulations.

If dredging is to be simulated, the bed elevation is corrected in accordance with the minimum required depth and sediment is extracted from the shipping channel (Fig. 10), thereby creating a massive influence on the morphodynamic development. Even though sediment is still transported towards the Northeast in this simulation, it can be extracted from the navigation channel once the minimum required depth is undercut. The natural tendency of the navigation channel to drift towards the Northeast is reduced, as simulated in the model. The resulting differences in bed elevation from both simulations amount to up to 17 m.
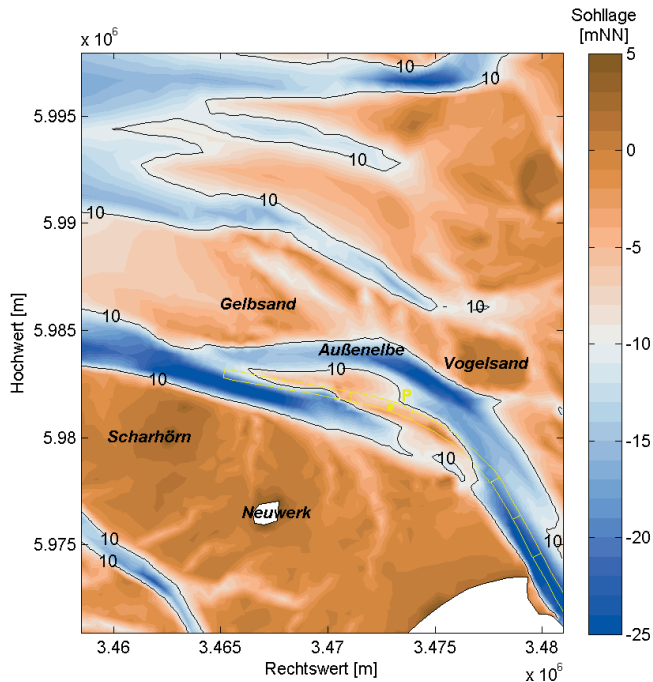
Figure 10: Simulated bed geometry, including dredging, after 100 years, in the Elbe estuary in the German Bight. The regions of sediment extraction in the navigation channel are marked yellow.

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