Modelling grain size influence on sand wave predictions in the North Sea

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Abstract

The North Sea is a very dynamic area, where different morphological features appear, from small ripples to large tidal sand banks.

We extended the work of Hulscher and van den Brink (2001), who were the first to compare an idealized model, of large-scale seabed patterns with data of seabed patterns in the North Sea.

Firstly, the model is adapted by implementing a critical shear stress. Secondly, a variable viscosity profile based on Komarova and Hulscher (2000) is introduced in the model. And thirdly, the model is extended by including a grain size dependency.

The adaptations made to the model of Hulscher and van den Brink lead to more accurate predictions of large-scale bed forms that occur at the sea bed of the North Sea.

1 Introduction

The North Sea is a very dynamic area, which is reflected in several morphological features, ranging from small ripples to large tidal sand banks.

The southern bight of the North Sea is a shallow shelf sea, which is deeper in front of the British coast and becomes shallower towards the east. Prominent shoals are the Norfolk banks, the Texel spur and Dogger bank. The seabed of the North Sea consists mainly of fine to medium sands (125-500µm) but along the British coast and in the Strait of Dover large parts of the seabed are covered with gravel. The seabed sediments show a gradual fining towards the north-east (Van der Molen, 2002). The seabed of the North Sea is covered with all kinds of bed forms. In this research we only focus on the large-scale morphological features, namely the sand banks and sand waves. This means that we are looking at horizontal scales between about 500 meter (sand waves) and several kilometers (sand banks).

The largest bedforms are tidal sand banks, they can be either active or moribund, the latter being formed during periods of lower sea level. Banks often store large amounts of sediment, their length can be up to 55km, they can have a width up to 5km and their crests reach up to a few meters below the water level. Mostly the bank crests are aligned in an oblique angle to the main tidal current direction (Dyer and Huntley,1999; Collins et at., 1995).

Sand waves cover large parts of the North Sea seabed, they are much smaller than sand banks with a spacing varying between 100 and 800 meter and a height up to 5 meter. Their crests are aligned roughly perpendicular to the tidal current (Németh, 2003). Sand waves can be dynamically active and can migrate at rates up to tens of meters per year (Morelissen et al., 2003).

A lot of human activity is going on in the North Sea. User functions of the North Sea that interact with the large-scale morphology are shipping, oil and gas transportation (pipelines), telecommunication cables, gas and oil mining, sand mining, artificial islands and offshore wind parks. Because these functions interact with large-scale natural morphological features, it is important to know where large-scale morphological features occur, what their natural behaviour is and how they interact with human activities.

There are different models that describe the evolution, maintenance and occurrence of large-scale seabed features. These models can roughly be divided into two groups, analytical models and numerical models. Analytical models are mainly aimed at finding out which processes are important and how these processes influence the morphology, these models can give insight in the origin and occurrence of bed forms but are less suitable for practical applications. The other type of models are the numerical models like Delft3D and TELEMAC, these models exist of different modules (e.g. for the sediment transport) which are combined at a grid. These models are mostly used for specific well defined problems. At this moment the calculation time of these models is too large to produce results of the whole North Sea at a resolution that is needed for studying large-scale bed forms.

The goal of the project is to build a GIS of the North Sea in which data of the North Sea is gathered. This data can then be compared to the results of morphological models, so these can be calibrated and validated. By implementing the morphological models the GIS will be able to predict the integral consequences of human activities in the North Sea area. Therefore, it can be used to propose the most suitable locations for a certain activity in the North Sea area.

All data will be gathered in a GIS. GIS stands for Geographical Information System and is a digital map with extended possibilities to manipulate and analyze geographical data. A GIS is a computer system that uses geographical data to carry out various management and analysis tasks. There are two main data structures: raster and vector based. Raster data is stored in a grid (an array of equally sized square cells arranged in rows and columns). A vector based data source uses points, lines and areas to represent the real world. With a GIS one can combine several datasets with these structures to extract additional information (Heywood et al., 1998).

The GIS is used in this project in three ways. Firstly, it is used as a database which enables accessibility and analysis of data. Secondly, it is used to validate and calibrate the morphological models on a large scale, here the GIS is used to retrieve local parameters that are used as model input, therefore the models give location specific outcomes, which form a separate layer in the GIS. And thirdly, the GIS is used to present the effects of scenario's of human activities that are calculated by the morphological models. These scenario's are assembled based on current plans for the North Sea area.

An overview of the function of the GIS is given in figure 1.

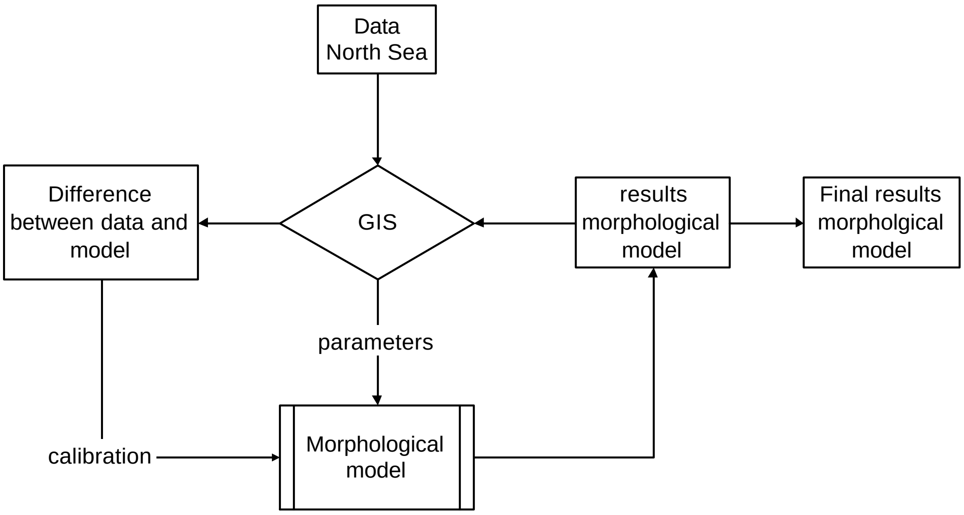

Figure 1: Function of the GIS in the project.

The data that are needed for the models are collected and imported into the GIS and the link between the GIS and the model will be set up. The results of the model are imported back into the GIS, where they can then be compared with data from the North Sea bathymetry (see also figure 2).

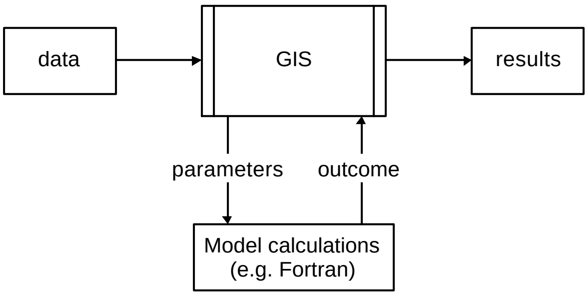

Figure 2: Communication between the GIS and the models.

The project is started by extending the work of Hulscher and van den Brink, who compared an idealized model of seabed patterns with North Sea data.

This model is implemented in a modern GIS environment, ARCGIS. Firstly, a critical shear stress is included in the model; this implies that below a certain threshold value of the tidal velocity, no sediment transport occurs. Secondly, a variable viscosity profile, as described by Komarova and Hulscher (2000) is implemented in the model. And thirdly, the model is adapted by including a grain size dependency in the model.

2 Model

2.1 Three dimensional shallow water Model of Hulscher (1996)

The three-dimensional model developed by Hulscher (1996) is used to study how tidal currents can form wavy bed patterns. The vertical flow structure that is included in this model is needed to describe the formation or absence of sand waves. When only the horizontal flow structure is taken into account, the formation of sand banks can be modelled. In the model the tide and seabed are seen as a coupled system, free instabilities of this system are investigated to study the dynamics of rhythmic bed patterns. To do this a linear stability analysis is performed, which means that only small perturbations can be investigated.

The model calculates growth rates for different wavelengths. When the growth rate is negative, the situation with a flat seabed is stable and no bed patterns occur. However, when the growth rate is positive, the situation with the flat bed is unstable and bed patterns can occur. The wavelength with the fastest growth rate is considered to represent the occurring bed form.

The model is based on the three-dimensional shallow water equations, which are applied to tidal flows:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-g\frac{\partial z}{\partial x}+\frac{\partial}{\partial z}\left(A_v\frac{\partial u}{\partial z}\right) \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-g\frac{\partial z}{\partial y}+\frac{\partial}{\partial z}\left(A_v\frac{\partial v}{\partial z}\right) \tag{2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

Here u, v and w are the velocity components in the x, y and z direction. $z=z$ denotes the free surface elevation, and h is the bottom level with respect to the undisturbed water depth H. The parameters f and g denote the Coriolis parameter and the acceleration of gravity.

The model for sediment transport only includes bedload, which is assumed to be dominant in tidal environments, also the equation includes a downhill gravitational component:

$$Q=a\left|t_b\right|^b\left\{\frac{t_b}{\left|t_b\right|}-l\nabla h\right\} \tag{4}$$

Where a is a bed load transport proportionality parameter, b expresses the non-linearity of transport in relation to the bed shear stress and t_b denotes the bottom shear stress:

$$t_b=A_v\left(\frac{\partial u}{\partial z},\frac{\partial v}{\partial z}\right)\Big|_{z=bottom} \tag{5}$$

Where A_v is the vertical (eddy) viscosity.

For different values of the Stokes number (E_v) and the resistance parameter ($\hat{S}$), different dominant modes are found, that can be identified as tidal sand banks, sand waves, tide parallel ridges, or flat beds (see also figure 3). The parameters E_v and $\hat{S}$ are defined as:

$$E_v=\frac{2A_v}{sH^2} \tag{6}$$

$$\hat{S}=\frac{2S}{sH} \tag{7}$$

In which s is the frequency of the tidal motion and S quantifies the ratio between the slip velocity at the bed and the shear stress.

The values of E_v and $\hat{S}$ cannot be measured directly, therefore a method has to be derived to estimate these parameters from available data.

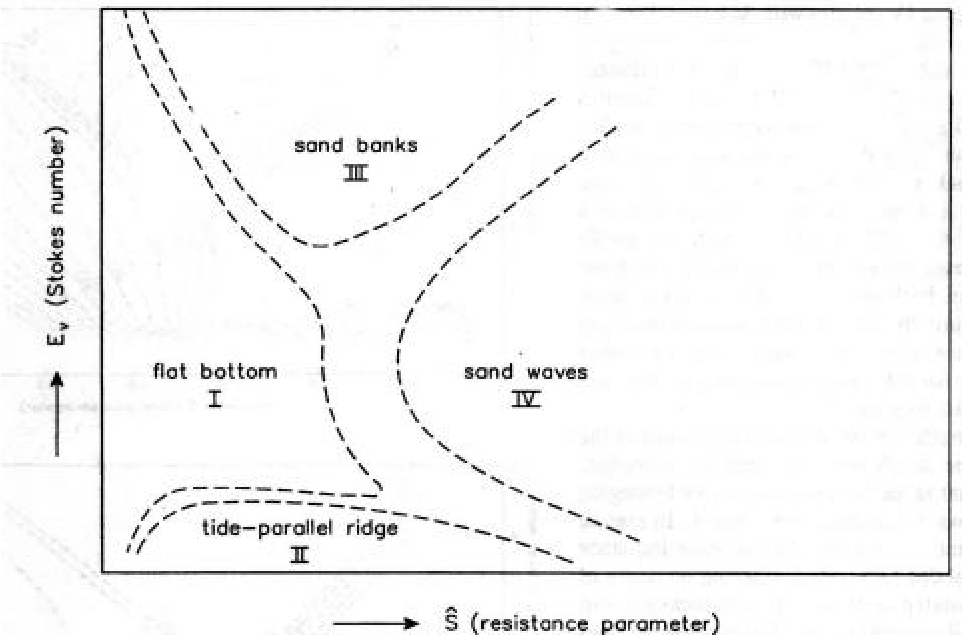

Figure 3: Characteristic bed forms predicted by the three dimensional shallow water model as a function of the resistance parameter ($\hat{S}$ *) and the Stokes number (* E_v *)(Hulscher(1996)).*

In the model of Hulscher (1996) the eddy viscosity (A_v) is assumed to be constant, this means that at the seabed a partial slip condition exists. Because of this partial slip condition it is straightforward to model the shear stress at the bottom, without explicitly including the difficult processes that occur in the boundary layer. The assumption is made that the top of the boundary layer can be interpreted as the physical sea bottom.

2.2 GIS Hulscher and Van den Brink

Hulscher and van den Brink (2001) used a GIS environment to test the model of Hulscher (1996) against observations of sand bank and sand wave occurrence in the North Sea. They used local parameters of the North Sea as model input, which results in local predictions for the occurrence of sand banks and sand waves. These results were then compared with data on the occurrence of large-scale bedforms.

The values of E_v and $\hat{S}$ are estimated by fitting the partial slip model to a more realistic turbulence model. This model has a no-slip condition at the bed and a parabolic Eddy viscosity. The conditions that have to be met are: the water discharge should be equal in both models, the models should produce the same shear stress and the depth average viscosity of the advanced turbulence model should equal the constant viscosity of the partial slip model. This leads to the following expressions for E_v and $\hat{S}$:

$$E_v = \frac{k^2 B}{A}\frac{3p}{4}\frac{u_m}{Hs} \qquad (8)$$

$$\hat{S} = \frac{k^2 B}{A(AB - \frac{1}{3})}\frac{3p}{4}\frac{u_m}{sH} \qquad (9)$$

In which, k is the Von Karman constant and u_m is the depth-averaged velocity amplitude at a particular location. A and B are denoted by:

$$A=\left[\ln\left(\frac{H}{z_0}\right)-\frac{1}{e}+\frac{1-e}{e}\ln\left(\frac{1-e}{1-e\frac{z_0}{H}}\right)+\frac{e-1}{e^2}\ln(1-e)\right] \tag{10}$$

$$B=\frac{3-2e}{6} \tag{11}$$

In which e denotes the viscosity variation parameter, which may range from 0.5 (maximum viscosity at the water surface) to 1.0 (zero viscosity at the water surface and maximum viscosity halfway up the water column).

Hulscher and van den Brink conclude that for the southern part of the North Sea the range of e and z_0 is large enough to be able to distinguish the different possible bed forms. The model can predict the contours of a sand wave area but is unable to explain the smaller-scale variation in the area. Hulscher and van den Brink conclude that there must be other factors, that are not included in the model, that influence the occurrence of sand waves. One of these factors may be the type of bed deposit. The work of Hulscher and van den Brink confirms the validity of the model of Hulscher (1996).

2.3 Adaptations

The work of Hulscher and van den Brink is adapted in three ways. Firstly in the model of Hulscher and van den Brink, a critical shear stress is included. The sediment transport in the model is denoted by equation (4). Where t_b is the bottom shear stress denoted by:

$$t_b=\frac{u^2}{C^2\Delta d_{50}} \tag{12}$$

In which C is the Chezy coefficient given by:

$$C=18\log\left(\frac{12H}{10d_{50}}\right) \tag{13}$$

When a critical shear stress is included in the model, the expression for sediment transport will have the shape:

$$t_b \le t_c \qquad ? \qquad Q=0$$

$$t_b > t_c \qquad ? \qquad Q=|t_b|^b\left\{\frac{t_b}{|t_b|}-l\nabla h\right\}$$

Where the critical shear stress is given by:

$$t_c=0.013D_*^{0.29} \tag{14}$$

With: $D_*=d_{50}\left(\frac{\Delta g}{n^2}\right)^{\frac{1}{3}}$ and $\Delta=\frac{r_s}{r}-1$

Here r_s stands for the density of the sediment, r for the density of water and n for the kinematic viscosity of water.

The second adaptation is the inclusion of a variable viscosity profile described by Komarova and Hulscher (2000). The turbulence closure scheme used in Hulscher and van den Brink is:

$$n_t=k\hat{u}_*z\left(1-e\frac{z}{H}\right) \tag{15}$$

Where $\hat{u}_*$ denotes the peak shear velocity.

Komarova and Hulscher (2000) discuss another viscosity parameterization. n_t defines the thickness of the boundary layer. For a simple unidirectional or harmonic flow over a flat bed the assumption that the boundary thickness is constant can be made. However when the water flows back and forth over bedforms, the amount of turbulence in the water is likely to have a horizontal structure. The time dependence of the flow also affects the distribution of the turbulent vortices. As long as the bed shapes are not too large, the viscosity changes are linear in h (Komarova and Hulscher (2000)), this is denoted by:

$$n_t = n_0 \left(1 + 2h\left[a_1(k)\cos ka + a_2(k)\sin kxu_0(h,t)\right]\right) \tag{16}$$

Where a_1 and a_2 are a function of the wavelength, n_0 is a constant eddy viscosity (corresponding to an unperturbed tidal flow over a flat bed), k is the wavenumber, and u_0 is the unperturbed tidal flow.
The third adaptation is the inclusion of a connection of the level of zero intercept (z_0) to the type of bed material. In the model of Hulscher and van den Brink, the level of zero intercept is defined as:

$$z_0 = z\Delta_r \left(\frac{\Delta_r}{l_r}\right)^{1.4} \qquad \text{(after Soulsby (1983))} \tag{17}$$

where $\Delta_r = bH$ and (after van Rijn (1993)) (18)

$l_r = gH$ (19)

in which b and g are coefficients which can be related to the megaripple regime.
Here the level of zero intercept is only dependent on the occurrence of small-scale ripples and the water depth, the model is adapted by connecting the level of zero intercept (z_0) to the type of bed material.

3 Results

As a result of the adaptations that are made to the model of Hulscher and van den Brink, the degrees of freedom of the model increase. Therefore, the model can predict more variations at a smaller length scale. Consequently, it then distinguishes scattered sand waves from continuous sand wave fields.
The inclusion of a grain size dependency, by means of a connection between the level of intercept and the type of bed material leads to more accurate predictions of large-scale bed pattern occurrence. In the model of Hulscher and van den Brink the level of intercept is only based on the water depth. Therefore, the model is not able to give accurate predictions for areas where the sediment is not mainly existing of sand, for example areas where gravel occurs (e.g. off the British coast). The adapted model is sensitive for the type of sediment, and will therefore give better predictions.
The inclusion of a critical shear stress mainly affects the time-scales at which the bed patterns evolve. The wave length is barely influenced by the presence of a critical shear stress and there is no effect on the occurrence of large-scale bed patterns.
The inclusion of the viscosity profile as discussed by Komarova and Hulscher only marginally affects the areas where bed forms are predicted.
It can be concluded that the adaptations made to the model of Hulscher and van den Brink lead to a better representation of the occurrence of bed forms that occur on the sea bed of the North Sea.

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