

Modeling large-scale cohesive sediment transport affected by small-scale biological activity

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Received 19 July 2007; accepted 19 January 2008

Available online 1 February 2008

Abstract

Biological activity on the bottom of the seabed is known to have significant influence on the dynamics of cohesive sediment on a small spatial and temporal scale. In this study, we aim to understand the large-scale effects of small-scale biological activity. Hereto, effects of biology are quantitatively incorporated into the process-based sediment transport module of Delft3D. This Bio-mud model is used to study cohesive sediment transport and deposition patterns in the Western Wadden Sea for a period of 1 year to capture seasonal changes.

The modeling results suggest that the seasonal variation in the sediment concentration is caused by the combined effect of the suspended sediment concentrations at the North Sea, wind and biological activity. Moreover, the stabilizing organisms are mainly responsible for the seasonal variation in suspended sediment concentrations, while the destabilizing organisms are mainly responsible for the spatial variation in fine sediment on the bed.

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Keywords: cohesive sediment transport; destabilizing grazers; stabilizing microphytobenthos; numerical modeling; Delft3D; Dutch Wadden Sea

1. Introduction

Biogeomorphology is the study of the interactions between sediment dynamics and biota. Biota are known to strongly affect the stability of the bed in two opposite modes (Rhoads, 1974; Nowell et al., 1981). Firstly, stabilization of the bed is induced by the secretion of extracellular polymeric substances (EPS) by locomotion of microphytobenthos (e.g. Riethmüller et al., 2000). On the other hand, surface deposit feeders destabilize the top layer of the bed during their burrowing and feeding activities (e.g. De Deckere et al., 2001).

Much research on biogeomorphology has been executed on a small spatial scale, such as individual mudflats in the Western Scheldt (Widdows et al., 1998, 2000a,b; Knaapen et al., 2003; Paarlberg et al., 2005), the Humber estuary (De Deckere et al., 2001; Widdows and Brinsley, 2002) and the Bay of Fundy (Faas et al., 1993) and individual tidal basins in the Wadden Sea (Austen et al., 1999; Andersen et al., 2002, 2005). All these studies have shown that biological activity has a significant influence on the cohesive sediment transport and bed composition.

To our knowledge, the effect of small-scale biological activity on large-scale cohesive sediment dynamics has never been quantified. However, such knowledge is of particular interest for the management and conservation of tidal basins (Thrush et al., 1997). Although direct experiments or large-scale field studies are the preferred way to investigate this lack of knowledge, large-scale field studies are logistically very difficult to employ (Widdows and Brinsley, 2002), and

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List of symbols

ε	Erosion coefficient [$\text{g m}^{-2} \text{s}^{-1}$]
ρ_w	Density of water [kg m^{-3}]
τ_b	Shear stress at the bed [Pa]
τ_d	Critical shear stress for deposition [Pa]
τ_e	Critical shear stress for erosion [Pa]
c	Suspended sediment concentration [g m^{-3}]
C	Chézy coefficient [$\text{m}^{1/2} \text{s}^{-1}$]
Ch	Chlorophyll- α content on the bed [$\mu\text{g g}^{-1}$ sediment]
$D_{X,Y}$	Dispersion coefficient in X and Y direction [$\text{m}^2 \text{s}^{-1}$]
E_s	Stabilizing factor for the erosion coefficient [–]
E_d	Destabilizing factor for the erosion coefficient [–]
f_w	Wave friction factor [–]
g	Gravity acceleration [m s^{-2}]
G	Biomass of grazers [gC m^{-2}]
h	Water depth [m]
H	Heavyside function
S_E	Erosion rate [$\text{g m}^{-2} \text{s}^{-1}$]
S_D	Deposition rate [$\text{g m}^{-2} \text{s}^{-1}$]
T_s	Stabilizing factor for the critical bed shear stress [–]
T_d	Destabilizing factor for the critical bed shear stress [–]
$V_{X,Y}$	Depth-averaged flow velocities in X and Y direction [m s^{-1}]
w_s	Settling velocity of sediment [m s^{-1}]

rather expensive as well. In absence of sufficient data on the interactions between sediment and biology, an appropriate modeling system incorporating all relevant biological and physical processes might prove a fair substitute. In this study we try to assess the influence of biology on cohesive sediment transport and fine sediment distribution on the bed adopting such a modeling system. We consider a period of 1 year to cover the dominant seasonal biological variation. We use the Western Wadden Sea as our test site. It should be noted that even in a modeling study not all the biological activity and the transport parameters can be prescribed in detail for the entire study area. Therefore, only trends and orders of magnitude of the biological influence on suspended sediment concentrations and fine sediment distribution can be calculated. Therefore, our aim is to corroborate, quantitatively, that small-scale biological processes are indeed able to have basin wide effects on sediment transport and deposition. Precise calibration of the different biotic model parameters both in time and space is outside the scope of this study. First, the data required for a proper calibration process are not available. But more importantly, our main aim is to show that inclusion of average but well-documented settings of small-scale biological parameters is already sufficient to yield basin wide effects on fine sediment dynamics.

The structure of this paper is as follows. In Section 2 the study area is introduced. Next, in Section 3 we present the model and the parameterization of the biological activity. In Section 4, the set-up of the model is described, and the biological activity in the study area is quantified. Section 5 discusses the results of the model, in which the cohesive sediment dynamics over a 1-year period are calculated. Section 6 presents a discussion about the main findings of this paper. We end by drawing some conclusion in Section 7.

2. Study area

The Western Wadden Sea is a shallow series of interconnected tidal basins (Fig. 1) located along the south-east coast of the North Sea. It covers about 2287 km². The study area is bounded by the Afsluitdijk, by the tidal watershed between Schiermonnikoog Island and the main land and by five islands. Tides are predominantly semi-diurnal, ranging from 1 to 2 m amplitude. The average quantity of water entering the area through the various inlets during one tidal cycle is estimated at $2200 \times 10^6 \text{ m}^3$ (Ridderinkhof et al., 1990). Current velocities in the area vary, with the highest speeds in excess of 2 m s^{-1} in the various tidal inlets, where water depths are up to 50 m. Fresh water is discharged through two sluices in the Afsluitdijk (Den Oever and Kornwerderzand; Fig. 1). Typical fresh water inflows for the two individual sluices are $500 \text{ m}^3 \text{ s}^{-1}$.

Typical suspended sediment concentrations at the North Sea are 3 g m^{-3} , while typical suspended sediment concentrations in the Western Wadden Sea are 30 g m^{-3} (Postma, 1981). Based on an analytical model described by Winterwerp and Van Kesteren (2004), it is determined that the concentration profile in the Western Wadden Sea is highly uniform, due to the low suspended sediment concentrations and the high turbulent shear stresses. The mud content in the bed is low (<10%) for most of the entire basin, although high values (>50%) are found near the borders and the watersheds of the different tidal basins (Van Ledden et al., 2004).

In the study area, diatoms (bio-stabilizing) and the clam *Macoma balthica* and the mud snail *Hydrobia ulvae* (both bio-destabilizing) are the dominant organisms (Wijsman, 2004).

3. Description of the Bio-mud model

3.1. Hydrodynamics, waves and sediment

A first step in the issue of aggregation of smaller estuarine process scales to larger ones is achieved with the so-called process-based models, as shown by Hibma et al. (2004) and Elias et al. (2006). These model systems typically consist of modules that describe the waves, currents and sediment transport. In this study, the Delft3D numerical modeling system is used to set-up the Bio-mud model. The Bio-mud model calculates the sediment dynamics for the Western Wadden Sea for the period of 1 January 1998 to 31 December 1998.

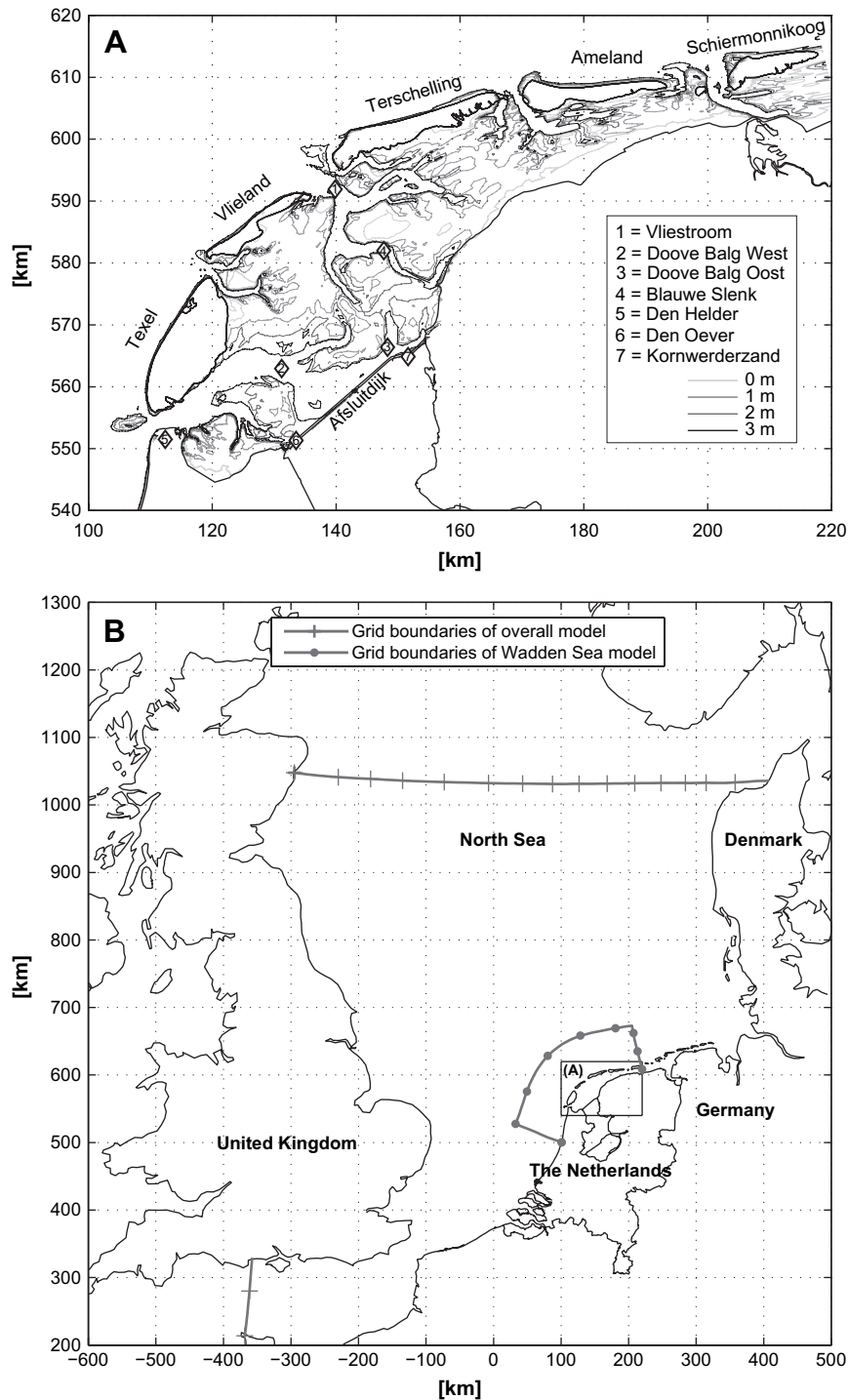


Fig. 1. Location of the Western Wadden Sea (A) in the north of The Netherlands (B). Depth with respect to Mean Sea Level (MSL). Locations and grid boundaries are included for later reference.

The flow conditions are simulated with the Delft3D-Flow module (Stelling, 1984; Stelling and van Kester, 1994; WL|Delft Hydraulics, 2006). The Delft3D-Flow module is a multidimensional (2D or 3D) hydrodynamic simulation program, which calculates non-steady flow resulting from tidal and meteorological forcing at the boundaries, wind stress at the surface and pressure gradients due to free surface gradients and density gradients.

Waves and sediment dynamics are calculated within the Delft3D-WAQ module (Postma and Hervouet, 2008). Biological influences on the sediment strength are incorporated into the model by means of parameterizations. Transport of fine suspended sediment in the model is based on the advection–diffusion equation as described by, e.g., Teisson (1991), in which advection is determined by the velocity field and diffusion by the dispersion coefficient:

$$\frac{\partial \bar{c}}{\partial t} + V_X \frac{\partial \bar{c}}{\partial x} + V_Y \frac{\partial \bar{c}}{\partial y} = \frac{1}{h} \frac{\partial}{\partial x} \left(h D_X \frac{\partial \bar{c}}{\partial x} \right) + \frac{1}{h} \frac{\partial}{\partial y} \left(h D_Y \frac{\partial \bar{c}}{\partial y} \right) + \sum_{i=1}^n \frac{S_i}{h} \quad (1)$$

where c is the suspended sediment concentration (g m^{-3}), V_X and V_Y are depth-averaged flow velocities (m s^{-1}), h is water depth (m), D_X and D_Y are dispersion coefficients ($\text{m}^2 \text{s}^{-1}$) and S_i are the source/sink terms ($\text{g m}^{-2} \text{s}^{-1}$). The latter describe the vertical fluxes between the bed and the water column. These fluxes are the result of erosion and deposition, which are calculated in Eqs. (2) and (3), respectively.

To calculate the erosion rate, the formula proposed by Hayter and Mehta (1986) for dense and consolidated beds is used:

$$S_E = \varepsilon \left(\frac{\tau_b}{\tau_e} - 1 \right) H(\tau_b - \tau_e); \quad H(\tau_b > \tau_e) = 1, \quad H(\tau_b < \tau_e) = 0 \quad (2)$$

where S_E is the erosion rate ($\text{g m}^{-2} \text{s}^{-1}$), ε is the erosion coefficient ($\text{g m}^{-2} \text{s}^{-1}$), τ_b is the bed shear stress (Pa) and τ_e is the critical bed shear stress for erosion (Pa). The Heaviside function H is equal to zero for negative arguments and is equal to 1 for positive arguments.

Deposition is calculated using the settling flux formulation (Krone, 1962):

$$S_D = w_s \bar{c} \left(1 - \frac{\tau_b}{\tau_d} \right) H(\tau_d - \tau_b) \quad (3)$$

where S_D is the deposition rate ($\text{g m}^{-2} \text{s}^{-1}$), w_s is the settling velocity (m s^{-1}) and τ_d is the critical bed shear stress for deposition (Pa). Bed shear stress is calculated with respect to currents and waves (Lesser et al., 2004):

$$\tau_b = \frac{\rho_w g (V_X^2 + V_Y^2)}{C^2} + \frac{1}{4} \rho_w f_w U_b^2 \quad (4)$$

where ρ_w is the density of water (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), V is the depth-averaged flow velocity (m s^{-1}), C is the Chézy coefficient ($\text{m}^{1/2} \text{s}^{-1}$), U_b is the horizontal mean wave orbital velocity at the bed (m s^{-1}) and f_w is a dimensionless wave friction factor. Wave characteristics are based on equations proposed by Groen and Dorrestein which are described by, e.g., Tamminga (1992), by which equilibrium waves are calculated. Consequently, wave height, wavelength and wave period are only dependent on wind speed and water depth. The processes of shoaling, refraction and wave breaking are not included in the calculation of the wave dynamics.

3.2. Parameterization of the biological activity

Both the stabilizing and destabilizing effects of benthic organisms on the stability of the bed are incorporated into the model by means of modification of the formulations for

the critical bed shear stress for erosion and the erosion rate, as proposed by Knaapen et al. (2003) and discussed by Borsje et al. (2007).

Bio-stabilization by diatoms is represented by the chlorophyll- α content, which is an indicator for microphytobenthos biomass (Staats et al., 2001). Bio-destabilizing organisms are represented by the abundance of surface deposit feeders (Austen et al., 1999). The influence of biological activity on the sediment strength is represented in:

$$\tau_e = \tau_e^0 T_s(\text{Ch}) T_d(G) \quad (5)$$

$$\varepsilon = \varepsilon^0 E_s(\text{Ch}) E_d(G) \quad (6)$$

where T_s and T_d are the stabilizing and destabilizing factors, respectively, for the critical bed shear stress for erosion, and E_s and E_d are the stabilizing and destabilizing factors, respectively, for the erosion coefficient (see Eq. (2)). The superscript '0' for the critical shear stress and erosion coefficient represents the values without the influence of biological activity. Ch is the chlorophyll- α content in the sediment ($\mu\text{g g}^{-1}$) and G is the biomass of grazers (gC m^{-2}).

The parameterization for the critical shear stress for erosion and the erosion coefficient is given in Fig. 2. The maximum biomass of grazers and the maximum chlorophyll- α content reflect the maximum values found in the Western Wadden Sea, as is discussed in Section 4.3.

The destabilization functions are corrected for the combined reworking of the sediment by the two species at a certain location, based on the contribution of the individual biomass to the total biomass of grazers, showing the much larger influence of *Hydrobia ulvae* on the destabilization of the bed.

The data given by Austen et al. (1999) are based on measurements in the Danish Wadden Sea for *Macoma balthica*. Andersen et al. (2002) executed a laboratory experiment on *Hydrobia ulvae* in which sediment from the Lister Dyb tidal basin (Danish Wadden Sea) was used. The data given by Lumborg et al. (2006) are used in a modeling study on the influence of *H. ulvae* on cohesive sediment dynamics, based on measurements made at the Kongsmark tidal flat in the Danish Wadden Sea. The relationships for bio-stabilization show a strong similarity with the relationships found by Lanuru et al. (2006), which are deduced from experimental data of an intertidal flat located in the German Wadden Sea.

In this parameterization, the effects of sediment transport and bed composition changes on biological activity are not taken into account.

4. Modeling set-up

4.1. Hydrodynamic conditions

The hydrodynamic module consists of a 3D simulation with 10 vertical sigma layers. The water level boundary conditions for the Wadden Sea model are obtained by nesting into a 3D well-calibrated North Sea model, a variant of which is

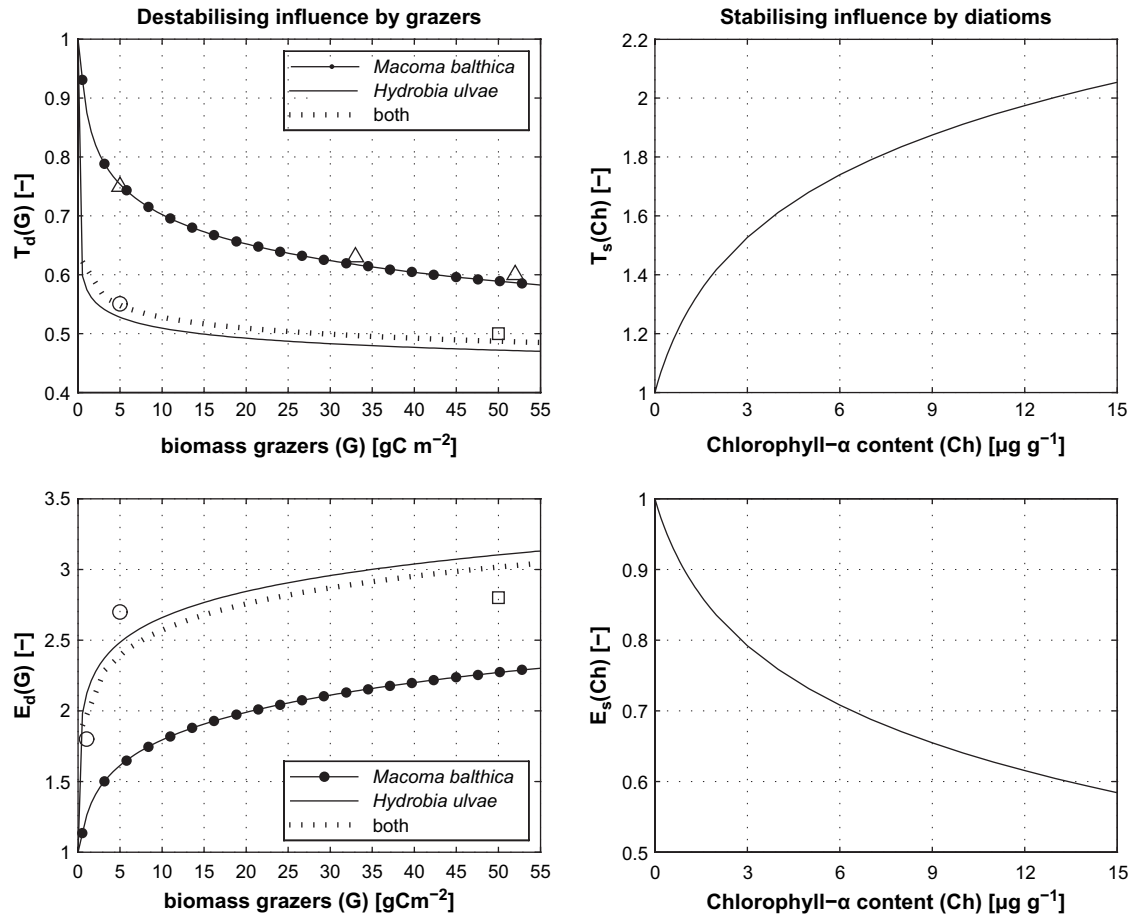


Fig. 2. Parameterization of the biological influence on the critical bed shear stress for erosion (upper) and erosion coefficient (under) based on data provided by Austen et al. (1999) (Δ), Andersen et al. (2002) (\circ) and Lumborg et al. (2006) (\square).

described in Gerritsen et al. (2000, 2001). The overall model has a grid size of about 2 km in the continental coastal zone from Belgium to the German Bight. Towards the boundaries (Fig. 1) the resolution goes down to order 25 km. The nested Wadden Sea model has a resolution of 200 m in all the Wadden Sea tidal inlets. Towards the shallower zones the cells become more elongated where the short sides have a length of 200–800 m whereas the long sides have a length of 600–800 m. Fifty kilometer offshore in the North Sea the resolution goes down to 4 km. Bottom roughness is prescribed by a uniform Chézy coefficient of $62 \text{ m}^{1/2} \text{ s}^{-1}$, which is the result of the calibration of the hydrodynamic module. Both the nested and the overall model are forced with 6-hourly spatially varying wind fields obtained from the Dutch Meteorological Institute (KNMI).

The modeled net discharge through Texel inlet shows similar results $O(1000) \text{ m}^3 \text{ s}^{-1}$ compared to the measured net discharge with a ferry-mounted ADCP (Buijsman and Ridderinkhof, 2007).

The tides have been validated with tidal components on all 12 water level stations that are available. The maps for the M2 and M4 tidal components show reasonable similarity for all stations (Fig. 3). The M4 component is only significantly off at the stations Vlieland haven and Nes. The inaccuracy here

is probably due to fact that these stations are small harbours where the tide enters through narrow gullies for which the resolution of the model is not sufficient to describe them. The M2 component is accurate on all stations near the North Sea. However, further into the basin the model tends to underestimate the tidal amplitude. The model is usually capable of predicting high water correctly, but the model typically overestimates low water. We hypothesize these inaccuracies are due to the absence of small gullies in the model. In reality the tidal flats are easily drained through the fine branches of the gully system. Due to the limited resolution of the model this gully system cannot be modeled in the digital elevation model, only the wider channels are present. Hence, in the model the water has to leave the shallows by flowing over the shallow flats themselves. Due to the roughness of the shallows the water tends to be trapped on the flats too long. Therefore, generally, further into the basins the model therefore has a tendency to underestimate the M2 component, and to overestimate the duration of the wetting of the flats. In general we believe the modeling of wetting and drying of tidal flats on a grid with a limited resolution will continue to be a challenge.

For one central station the performance of more tidal constituents is displayed in Fig. 4, showing the slight underestimation of the M2 component. However, most other tidal components

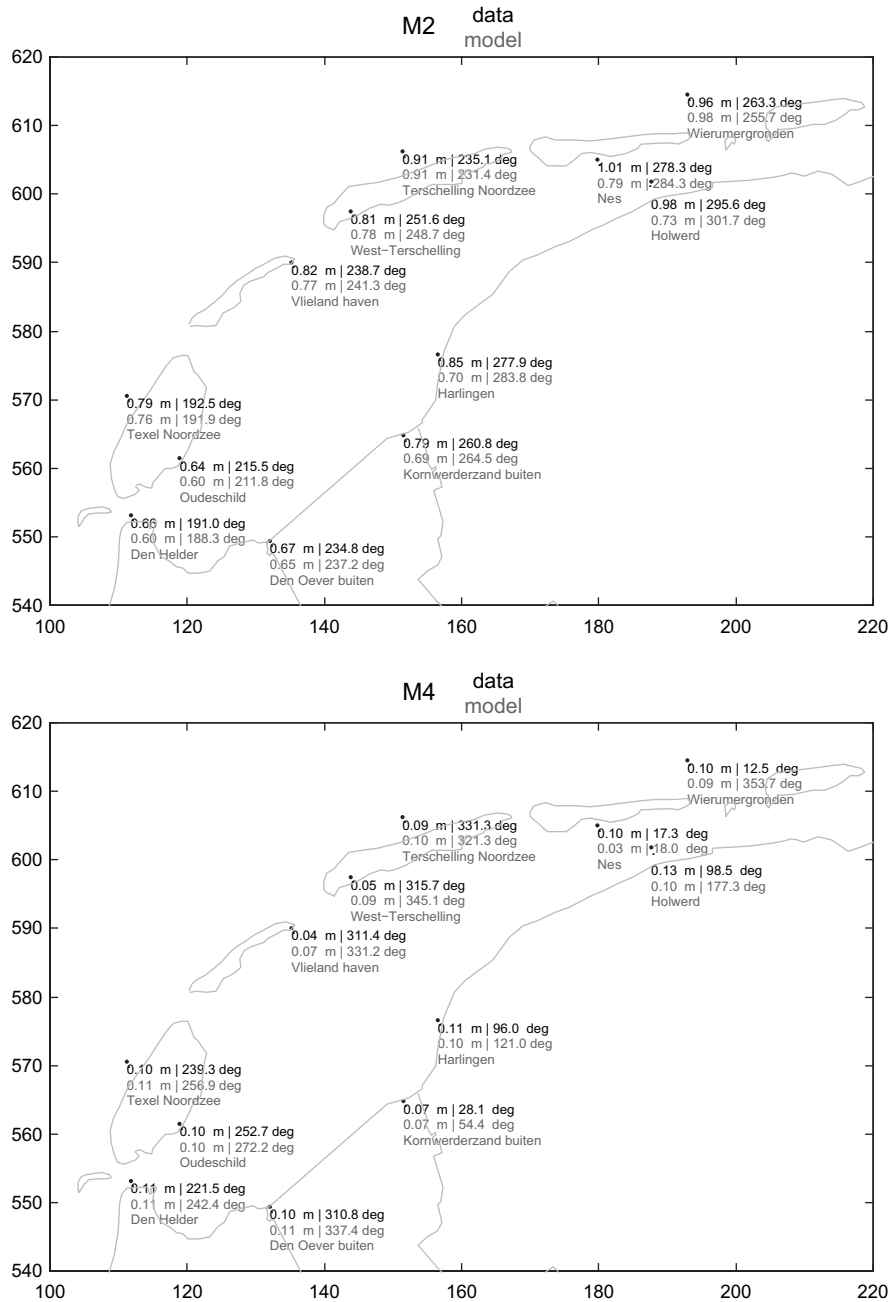


Fig. 3. Comparison between the measured and modeled tidal amplitude and phase of the M2 tidal component (top) and the M4 tidal component (bottom) in the Western Wadden Sea.

have a good performance, only the 4-hourly components (M6, etc.) are much too low in the model. The amplitude and hence the absolute error at these components is small though.

The 3D hydrodynamic model results are aggregated to 2DH (two-dimensional depth-averaged) and stored every 20 min, resulting in a manageable hydrodynamic database for the 2DH Bio-mud model.

4.2. Waves

Wave characteristics are calculated based on water depth, wind speed and wind fetch. The wind fetch is related to the

wind direction and is set to be variable over time between 1500 and 9500 m. A wind fetch of 1500 m corresponds to a wind direction of 130° (south-east), while a wind direction of 315° (north-west) corresponds to a wind fetch of 9500 m. Wind speed and wind direction are measured by the Dutch Meteorological Institute (KNMI) at hourly intervals on Den Helder (Fig. 1).

Data on wind speed and wind direction show that 1998 was not a representative year. The number of storms ($>13.9 \text{ m s}^{-1}$) was the greatest since 1979 measured at Den Helder. Due to the high number of hard winds in 1998, this year enables us to study the interaction between biological and physical processes in an extreme case.

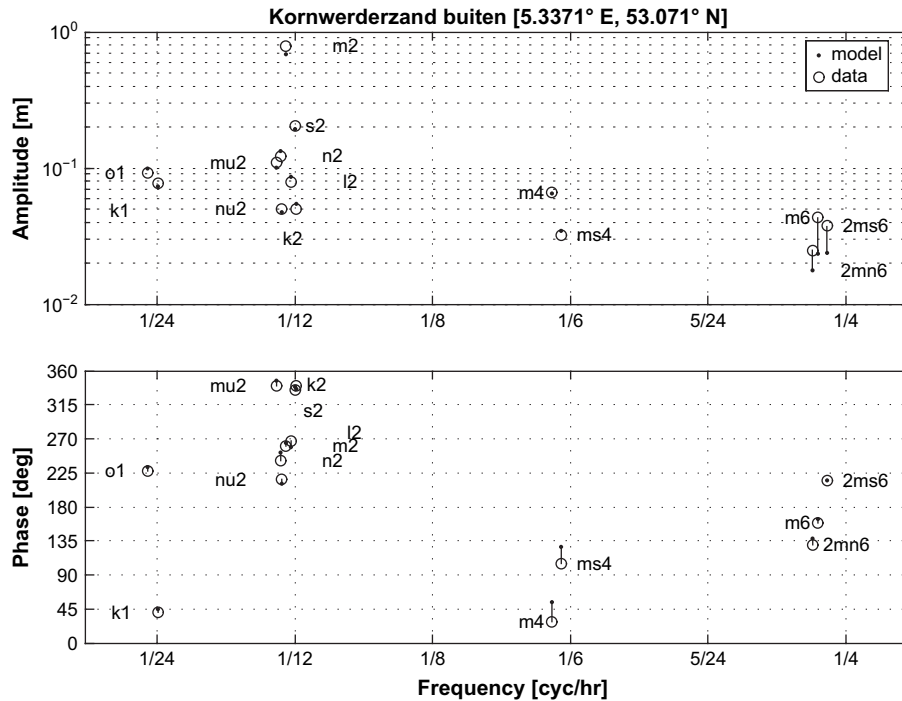


Fig. 4. The 14 most important tidal components at the station Kornwerderzand (for location see Figs. 1 and 3). The tidal components are calculated with τ_{TIDE} (Pawlowicz et al., 2002) from the modeled and measured time series of entire 1998 at 10-min intervals.

4.3. Cohesive sediment transport

The sediment in the model is characterized as inorganic, cohesive, fine sediment, with a settling velocity of $5 \times 10^{-4} \text{ m s}^{-1}$. This value is within the range of values measured by Andersen and Pejrup (2002) in the Danish Wadden Sea for disaggregated cohesive sediments eroded from a mudflat. In general, the settling velocity for mud is not constant in time and space, because of the possibility of floc formation, and it strongly depends on turbulent intensity and the fine sediment concentration in the water column (e.g. Winterwerp, 2002; Baugh and Manning, 2007). However, based on time scale analysis performed by Van Ledden et al. (2004), strong variations in settling velocity are not expected during a tidal period for the study area.

The critical shear stress for erosion free of biological activity is set at 0.4 Pa and the erosion coefficient is set at $0.1 \text{ g m}^{-2} \text{ s}^{-1}$. These values are in accordance with measurements for non-biologically influenced mudflats in the Danish Wadden Sea (Andersen, 2001). By setting the critical shear stress for deposition equal to the largest bed shear stress occurring during the year (73 Pa), continuous sedimentation is allowed (Winterwerp and Van Kesteren, 2004), because the Heaviside function in Eq. (3) is always larger than zero (Table 1).

At the North Sea open boundaries of the model, temporally varying suspended sediment concentrations are imposed based on data provided by the Dutch National Institute for Coastal and Marine Management (RIKZ). The imposed suspended sediment concentrations exhibit the highest seasonal variation near the coast, with maximum values occurring in February and minimum values in August.

The spin-up time of the model is 1 year and starts with an empty bed. In this run-up year, the forcing functions for 1998 are used. At the end of the spin-up year, the fine sediment is distributed over the area. We assume that no physical feedback exists from the sediment transport processes to the hydrodynamic conditions.

4.4. Biological activity

The spatial variation in biological activity is shown in Table 2 and Fig. 5a. No biological activity is ascribed to a water depth greater than 3 m MSL, and no grazers are present at a water depth smaller than 0 m MSL. The variation in biomass of biota in the different depth zones results in a spatially varying critical bed shear stress for erosion and erosion coefficient (Fig. 5b and c). Consequently, the destabilized area in the Western Wadden Sea is much larger (1092 km^2) than the stabilized area (463 km^2).

The biomass of grazers is based on field measurements performed by Dekker and De Bruin (1999) for the Western Wadden Sea in 1998. Sampling is executed in late winter (February–April) and at the end of the summer (August–

Table 1
Process parameters for the situation free of biological activity

Description of variable	Symbol	Value	Unit
Critical shear stress for erosion	τ_e	0.4	Pa
Critical shear stress for deposition	τ_d	73	Pa
Erosion coefficient	ε	0.1	$\text{g m}^{-2} \text{ s}^{-1}$
Settling velocity	w_s	5×10^{-4}	m s^{-1}
Chézy coefficient	C	62	$\text{m}^{1/2} \text{ s}^{-1}$

Table 2

Average biomass biota [gC m^{-2}], classified in different depth zones (Fig. 5a), based on field measurements

Biota	Depth zone I	Depth zone II
Depth (MSL, m)	0–1	1–3
<i>Macoma balthica</i>	1.6	0.2
<i>Hydrobia ulvae</i>	–	38.3
Diatoms ^a	4	–

^a Diatoms are also present at a water depth <0 MSL.

September) at two areas in the Western Wadden Sea. At these sites, nine transects are located (Dekker and De Bruin, 1999). The height of these transects is between +0.2 and –4.9 m Mean Sea Level (MSL). At each transect, 15–20 samples were taken. For the intertidal area, the clam *Macoma balthica* appeared to be the dominant surface deposit feeder. In the subtidal area, the mud snail *Hydrobia ulvae* is the dominant surface deposit feeder. However, *M. balthica* is also present in the subtidal area. The biomass found at the two measurement sites for the two grazers is assigned to the whole Western Wadden Sea. The resulting spatial pattern is displayed in Fig. 5.

Diatoms are restricted to depth, due to the lack of light available for photosynthesis in deeper water. Based on measurements at six different tidal flats in the Western Wadden Sea described by Cadée and Hegeman (1974), the biomass of microphytobenthos has been determined (Fig. 5).

Fig. 6 shows the temporal variation in the biomass of grazers and microphytobenthos. This variation is based on the field measurements for grazers in the five individual months (Dekker and De Bruin, 1999) and monthly field measurements for microphytobenthos (Cadée and Hegeman, 1974). In October, the largest biomass of grazers is observed, while microphytobenthos has their largest biomass in April and July. This pattern is comparable to temporal variations discussed by Beukema (1974) for grazers and Cadée and Hegeman (2002) for microphytobenthos, based on long-term measurements in the Dutch Wadden Sea.

At places where both *Macoma balthica* and *Hydrobia ulvae* (total biomass varying between 22 and 55 gC m^{-2}) are present (depth zone II), the critical bed shear stress and erosion coefficient do not show a clear temporal variation (Fig. 6). However, in the more shallow areas where only *M. balthica* is present (depth zone I) microphytobenthos is also present, leading to a variable effect throughout the year. In this area, 44 km^2 can become either stabilized or destabilized, depending on the time of year. Moreover, at places where neither *Macoma* nor *Hydrobia* are found (water depth <0 m MSL; Table 2), the modification of the critical bed shear stress for erosion is the largest. Consequently, the seasonal variation in the critical bed shear stress and the erosion coefficient is mostly determined by the variation in the biomass of stabilizers.

A second bed layer accounts for the fact that sediment is buried downward by grazers (bioturbation). By using a second bed layer, the biological influence is limited to the upper bed layer, and the lower bed layer serves as buffer during calm weather (Orvain et al., 2006). The porosity for the two bed

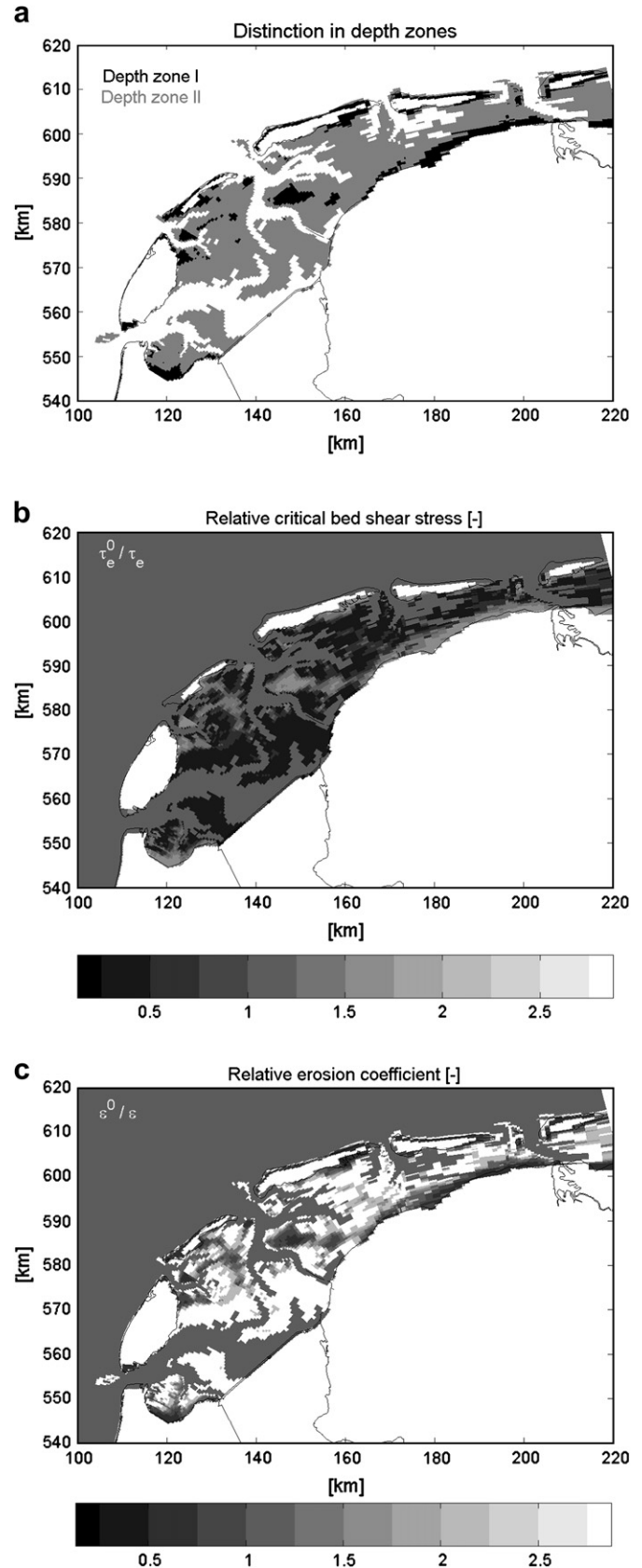


Fig. 5. Influence of biological activity on the critical bed shear stress for erosion (middle) and erosion coefficient (under), based on average biomass biota prescribed in the different depth zones (top) (Table 2). A value of 1 corresponds to no influence on the default transport parameters.

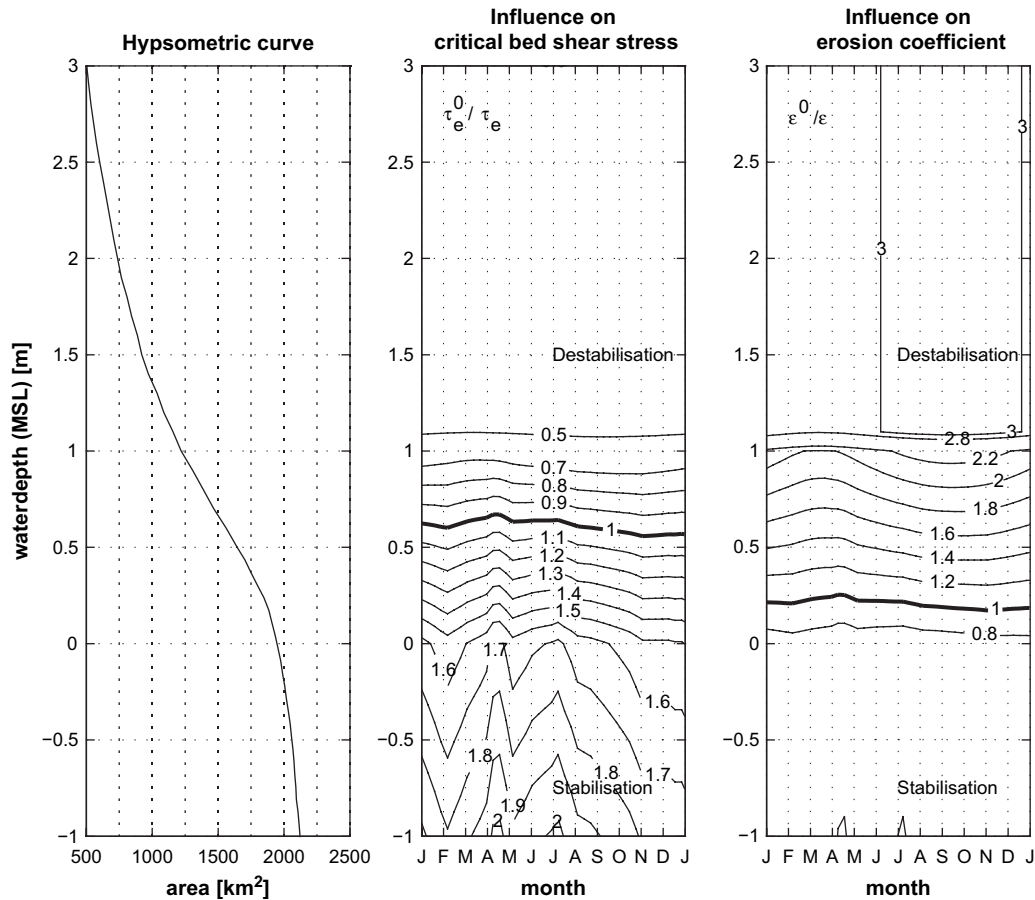


Fig. 6. Spatial and temporal variations in the relative critical shear stress for erosion (middle) and erosion coefficient (right) along a transect in the Western Wadden Sea, with corresponding area (left). Biological activity is limited to a water depth of 3 m MSL.

layers is different. Due to bioturbation, the porosity increases, especially in the top centimeters of the bed, as shown by, e.g., Widdows and Brinsley (2002). Based on the porosity and the amount of sediment in the upper bed layer, the flux of sediment to the second bed layer is calculated. Transport of sediment between the two sediment layers is only possible when the thickness of the upper bed layer exceeds 10 cm. This value represents the depth in the bed within which biological activity of surface deposit feeders is limited (Le Hir et al., 2007). Re-suspension from the lower bed layer is only possible when the upper bed layer is completely eroded. The transport parameters for the upper bed layer are dependent on the location and the time, as shown in Fig. 6. The transport parameters for the lower bed layer are the default parameter settings, which are not variable throughout the year, and are the same as the simulation in which no biological activity is included (see Section 5).

The biological activity in the study area shows no clear deviation from other years according to Beukema et al. (2001).

5. Results

The model is run for two different cases: the default parameter settings (case I) and a case in which the transport

parameters are modified by the presence of biological activity (case II). Evaluation of the model results is based on the suspended sediment concentration and the fine sediment distribution on the bed.

Data to evaluate the modeled suspended sediment concentrations are obtained from the DONAR-database. This database contains concentrations of suspended solids at a depth of 1 m below the water surface. The database is owned by the Dutch Ministry of Public Works (Rijkswaterstaat). For the year of interest, 1998, and for the model domain, the measuring stations with suspended sediment concentrations are the four stations shown in Fig. 1 by triangles.

The modeled seasonal pattern of suspended sediment concentrations shows good agreement with the measurements for the four monitoring stations (Fig. 7). However, the suspended sediment concentrations are mostly underestimated. This underestimation is probably at least partly caused by the analysis technique utilized in the DONAR-database (measurement values are based on the sum of both inorganic and organic matters). On the other hand, the suspended sediment concentrations for the case in which biological activity is included show more seasonal variation, compared to suspended sediment concentrations for the default case. All the four monitoring stations shown in Fig. 7 are located in large channels, which demonstrate that the biological influence on the suspended

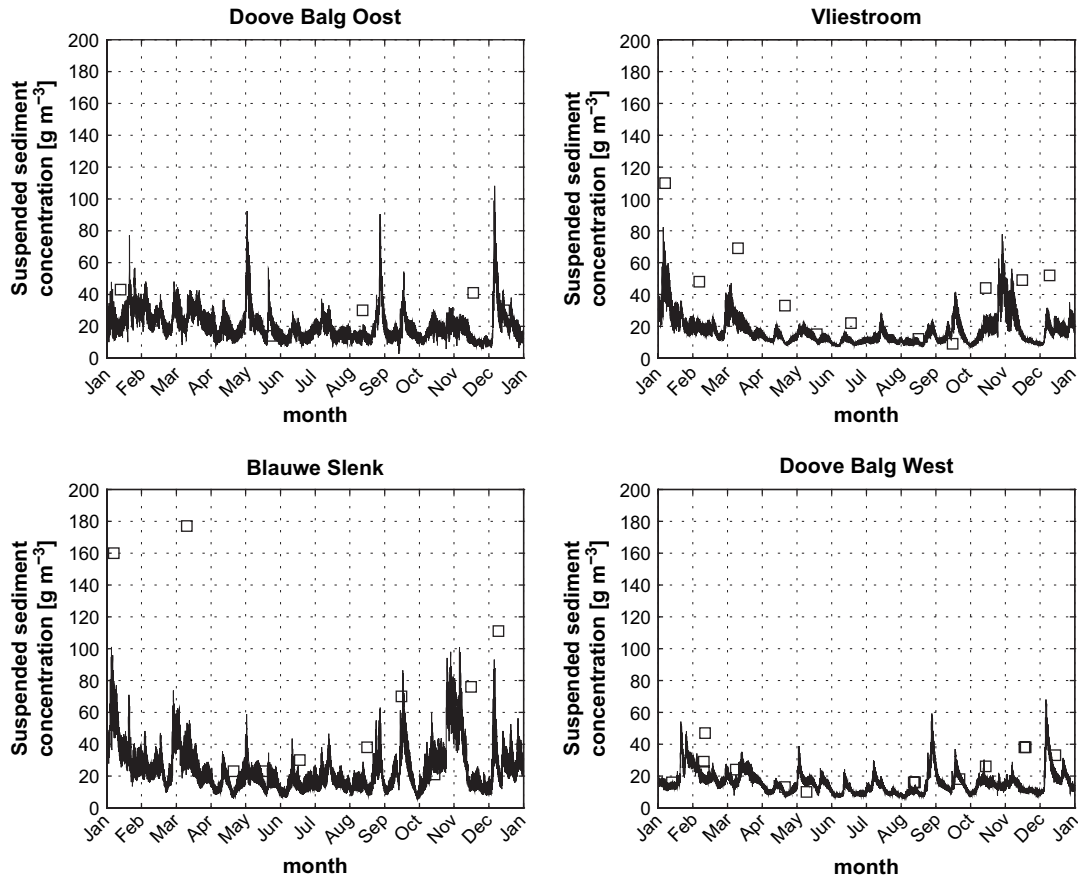


Fig. 7. Modeled suspended sediment concentrations [g m^{-3}] and measured concentrations (\square) for four different locations in the Western Wadden Sea (case II).

sediment concentrations is not only limited to the shallow areas in depth zones I and II, but extends to the whole tidal basin.

Fig. 8 shows the net deposition of fine sediment. The net deposition is averaged over the total area of the different depth zones (Table 2). In general, the bed level in depth zone I gradually increases during low wind speeds. However, during high wind speeds, severe erosion occurs. The sedimentation in depth zone I for the simulation in which biological activity is included is much larger compared to the simulation without biological activity. This difference is caused by the biological influence on the transport parameters, preventing the deposited material from being eroded from this area during high biomass of microphytobenthos (March–September). Combined with almost the same availability of fine sediment from depth zone II for both cases (Fig. 8; depth zone II), the resulting sedimentation for case II is larger compared to the resulting sedimentation for case I.

For depth zone II, the net seasonal deposition pattern of fine sediment is comparable for both cases. This observation is reasonable, because the transport parameters for the simulation with biological activity show no clear temporal variation in depth zone II (Fig. 6), and the transport parameters for the default case also show no temporal variation.

The bed level changes in the channels show a trend opposite of the trend in the shallower areas. It appears that sediment eroded during rough weather conditions (March and October)

is stored in the deeper areas, where wave action is less dominant. During calm weather with low wind speeds (April–September), sediment is transported to the shallower areas as a consequence of settling and scour lag and tidal asymmetry. However, for the simulation with biological activity, the bed level decreases, while sediment is trapped in depth zone I. Based on the model simulations, we can state that the biological processes influence the fine sediment distribution on a tidal basin scale. Moreover, the biological processes are responsible for the difference in net annual deposition or erosion of the bed for depth zone I and the channels.

6. Discussion

This paper describes the influence of biota on the cohesive sediment transport for a period of 1 year on a large-scale. The modeled maximum stabilizing influence for microphytobenthos is much lower, compared to values found in the field (up to a critical bed shear stress of 3 Pa) (Austen et al., 1999). In this study, the density microphytobenthos is corrected for the patchy distribution of microphytobenthos (Seuront and Spilmont, 2002). The biomass microphytobenthos is divided by factor 4, following the results of a field experiment on two tidal mudflats in The Netherlands (Jesus et al., 2005), where the area covered by microphytobenthos was linked to the total measured area. As a result, 25% of each grid cell in depth zone I is covered by microphytobenthos.

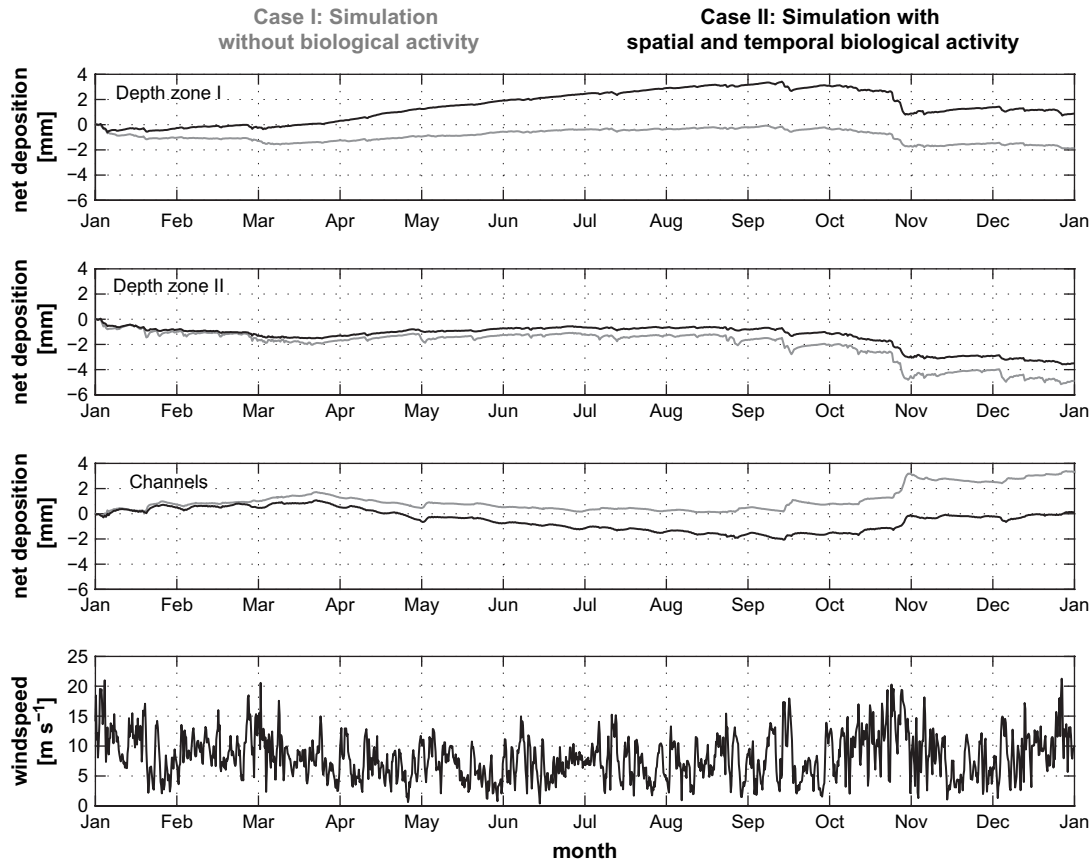


Fig. 8. Modeled net deposition [mm] in the different depth zones for the situation without biological activity included (case I; gray) and the situation in which biological activity is varied: spatial and temporal (case II; black). The box underneath gives hourly wind speeds measured at Den Helder, used for predicting hourly actual wave heights in the Bio-mud model.

The modeled net deposition of sediment in depth zone I (Fig. 8) is comparable to observations discussed by Andersen et al. (2005) for a mudflat in the Danish Wadden Sea, showing net seaward transport during winter and net landward transport during summer. The model results also suggest that the sediment is stored on the channel banks both in winter and autumn. As a consequence, the sediment content in the mudflats and the channel banks is much larger compared to the sediment content in the destabilized area (depth zone II). This idea is supported by measurements presented in Fig. 9, which are based on field data.

The decrease in the amount of cohesive sediment in the bed for a water depth between 1 and 3 m MSL must be attributed to the destabilizing influence of grazers on the bed in this area.

Based on a sensitivity analysis, in which the biological influence on the critical bed shear stress and erosion coefficient is varied over a realistic range, a difference in the influence of biota on the dynamics of cohesive sediment is found. The grazers are mainly responsible for the fine sediment distribution on the bed (Fig. 9). This influence is also caused by the much larger area occupied by bio-destabilizers in the Western Wadden Sea.

However, the spatial variation in biomass of grazers is limited, leading to hardly any temporal variation in the stability of the bed. The temporal variation in the suspended sediment

concentrations must mainly be attributed to the seasonal variation in microphytobenthos (Fig. 6).

The importance of including both the temporal and spatial variations in biological activity in bio-geomorphological

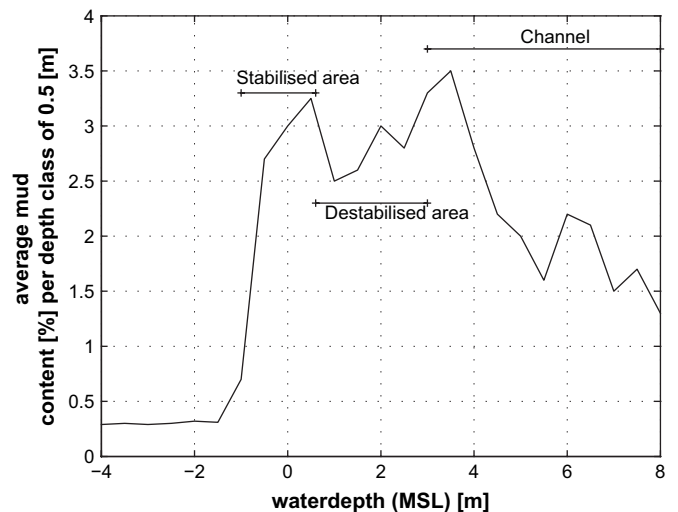


Fig. 9. Relation between the measured amount of cohesive sediment in the bed [%] and water depth [m] (MSL) for the Western Wadden Sea based upon sediment sieve samples of (Rijkswaterstaat, 1998) and mud relations by (Rijkswaterstaat, 2004).

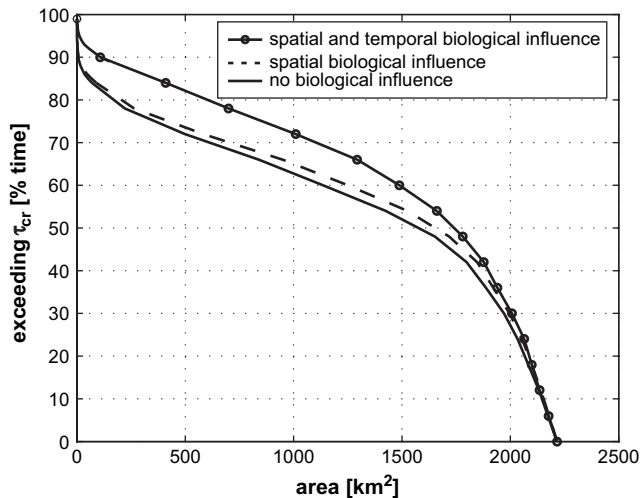


Fig. 10. Area of the Western Wadden Sea [km²] in which the critical shear stress for erosion (τ_{cr}) is exceeded [% time].

models is shown in Fig. 10. The exceeding time of the critical bed shear stress for erosion with only spatial varying biological activity is almost similar to the simulations without biological influences. By including both spatial and temporal variations in biological activity, the amount of time that the critical shear stress is exceeded deviates strong from the default model simulations.

The present model is based on a limited amount of data, especially the biomass represented by the species introduced into the model-approach is significantly less than the total biomass of benthos found in the system. However, too little is known about the bioengineering effects of these other species to allow inclusion into the study.

Based on the results of the model, we found that there is a dynamic interaction between physical and biological processes within the Western Wadden Sea. Following the scale concept introduced by De Vriend (1991), a dynamic interaction is only possible if processes act on the same temporal and spatial scale, otherwise processes act either as boundary conditions or as noise. In future, climate change is expected not only to change the physical system (increase storminess and sea level rise) but also the biological processes (change in zonation of biota, invasions of exotic species and increase of water temperature). The result of the dynamic interaction of both processes is of great interest for the management and conservation schemes for the Western Wadden Sea. It will be a challenge to investigate the future changes in both the physical system and biological processes on the cohesive sediment dynamics in the Western Wadden Sea and the indirect effect on the sediment balance between the North Sea and the Western Wadden Sea.

7. Conclusions

This study demonstrates the influence of biological activity on the cohesive sediment transport on a basin scale. Moreover, it argues that the seasonal variation in the suspended sediment

concentrations and fine sediment distribution on the bed is caused by the combined effect of wind, suspended sediment concentrations at the North Sea and biological activity on the bed. Biomass bio-stabilizers show a clear temporal variation throughout the year, inducing the temporal variation in the suspended sediment concentrations on a basin scale. The spatial variation in the fine sediment distribution on the bed must be attributed to the large modification of the transport parameters in the subtidal area where the bio-destabilizers are present.

The results show the importance of incorporating biological activity in models to help to formulate recommendations for the management and conservation of various tidal basins with large biological activities.

Acknowledgements

This research is supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Dutch Ministry of Economic Affairs. WL|Delft Hydraulics funded part of the research and made its Delft3D software available.

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