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Modeling large scale cohesive sediment transport by including biological activity

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ABSTRACT: Biological activity 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 biological activity. These large scale effects could be of great importance for the conservation and management schemes of different estuaries.

Hereto, effects of biology are quantitatively incorporated in the process-based model Delft3D in order to form the BAS-model (Biological Activity Simulated). This model is used to study cohesive sediment transport patterns in the Western Wadden Sea for a year.

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

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). First of all, stabilisation 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 destabilise the top layer of the bed during their burrowing and feeding activities (e.g. de Deckere et al., 2001).

Much research on biogeomorphology is executed on a small spatial scale, like individual mudflats in the Western Scheldt estuary (Widdows et al. 1998, 2000a,b; Knaapen et al., 2003; Paarlberg et al., 2005) and the Humber estuary (De Deckere et al., 2001; Widdows & Brinsley, 2002) 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 significant influence on sediment transport and bed composition.

However, the large scale effects of biological activity on the cohesive sediment dynamics are not known, and are of particular interest for the management and conservation of estuaries.

The main objective of this study is to determine the influence of biology on cohesive sediment transport and bed composition during one year on a large scale, i.e. the scale of a basin.

The content of this paper is as follows. Section 2 introduces the study area. Next, in Section 3 we present the used model and the parameterisation of the biological activity. In Section 4, the set-up of the model is described, and the biological activity in the study area is determined. In Section 5, the results of the model, in which the cohesive sediment dynamics over a period of a year are calculated, are discussed. Section 6 gives a discussion on the main findings of this paper. We end with some conclusion in the final section.

2 STUDY AREA

The Dutch Western Wadden Sea is a shallow coastal sea (Fig. 1) located along the South-East coast of the North Sea. The study area covers about 2287 km^2. The Dutch Western Wadden Sea is bounded by the Afsluitdijk, the watershed of the island Schiermonnikoog and five islands. Tides are semi-diurnal, ranging from 1 to 2 m amplitude. The average quantity of water entering the area through the various inlets is estimated at $2200 \times 10^6\,m^3$ (Ridderinkhof, 1990). The current velocities in the area vary, with the highest speeds in excess of $2\,m\,s^{-1}$ in the different tidal inlets, where waterdepths are up to 50 m.

The mud content in the bed is low (<10%) for almost 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). Fresh water is discharged through two sluices in the Afsluitdijk (Den Oever and Kornwerderzand).

Based on an analytical model described by Winterwerp & Van Kesteren (2004), it is determined that the concentration profile in the Western Wadden Sea is relatively uniform, due to the relative low suspended sediment concentrations and the high turbulent shear stresses.

In the study area, diatoms and the clam *Macoma balthica* and the mud snail *Hydrobia ulvae* are representative organisms with bio-stabilising and bio-destabilising effects respectively (Wijsman, 2004).

3 MODEL

3.1 *Description of the BAS-model*

A first successful step in the issue of aggregation of smaller estuarine process scales to larger ones is derived with the so called process-based models, as stated by Hibma et al. (2004) and Elias et al. (2006). These models consist of modules that describe the waves, currents and sediment transport. Delft3D is an example of a process-based model, in which the process knowledge is applied to the physical system by mathematical representations.

In this study, the numerical modeling system Delft3D is used, to set up the BAS-model (Biological Activity Simulated). The BAS-model calculates the sediment dynamics for the Western Wadden Sea for the period of January 1, 1998 to December 31, 1998. The biological influences on the sediment strength, are incorporated in the model by means of a parameterisation.

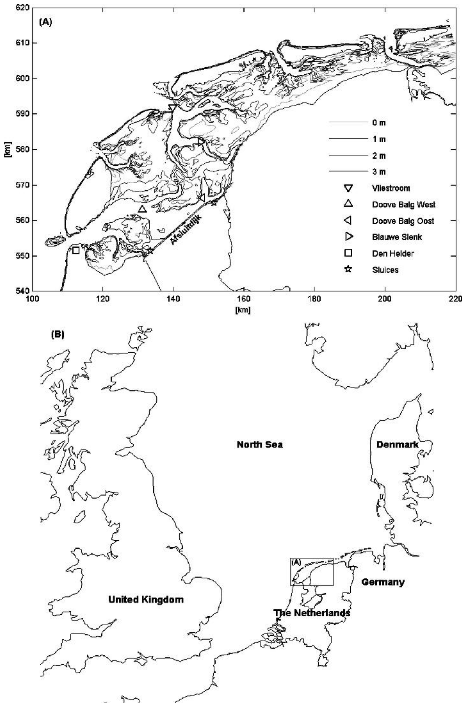

Figure 1. Location of the Western Wadden Sea (A) in The Netherlands (B). Depth with respect to Mean Sea Level (MSL) and co-ordinates are based on the Paris co-ordinate system.

The 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:

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

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 waterdepth (m), D_X and D_Y are dispersion coefficients ($m^2\,s^{-1}$) and S_i is the source/sink term ($g\,m^{-2}\,s^{-1}$). The latter describes the vertical fluxes between the bed and the water column. These fluxes are caused by erosion and deposition, which are calculated in Equation 2 and 3 respectively.

For erosion, the formula proposed by Hayter & Mehta (1986) for dense and consolidated beds is used:

$$S_E = \varepsilon\left(\frac{\tau_b}{\tau_e} - 1\right)H(\tau_b - \tau_e) \tag{2}$$

where S_E is the erosion rate ($g\,m^{-2}\,s^{-1}$), ε is the erosion coefficient ($g\,m^{-2}\,s^{-1}$), τ_b is the bed shear stress ($N\,m^{-2}$) and τ_e is the critical bed shear stress for erosion ($N\,m^{-2}$). 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):

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

where S_D is the deposition rate ($g\,m^{-2}\,s^{-1}$), w_s is the settling velocity ($m\,s^{-1}$) and τ_d is the critical bed shear stress for deposition ($N\,m^{-2}$).

The bed shear stress is calculated with respect to currents and waves:

$$\tau_b = \frac{\rho_w g V^2}{C^2} + \frac{1}{4}\rho_w f_w U_b^2 \tag{4}$$

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 ($m^{1/2}\,s^{-1}$), 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 & Dorrestein (2003), by which equilibrium waves are calculated. As a consequence, the wave height, length and period are only dependent on the wind speed and waterdepth. The processes of shoaling, refraction and wave breaking are not included in calculating the wave dynamics.

3.2 *Parameterisation of the biological activity*

The stabilising and destabilising effects of benthic organisms on the bed are brought to expression in the model by means of modification of the formulations for the critical bed shear stress for erosion and the erosion rate (Knaapen et al., 2003).

Bio-stabilisation by diatoms is represented by the chlorophyll-α content, which is an indicator for microphytobenthos biomass (Staats et al., 2001). Bio-destabilising 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:

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

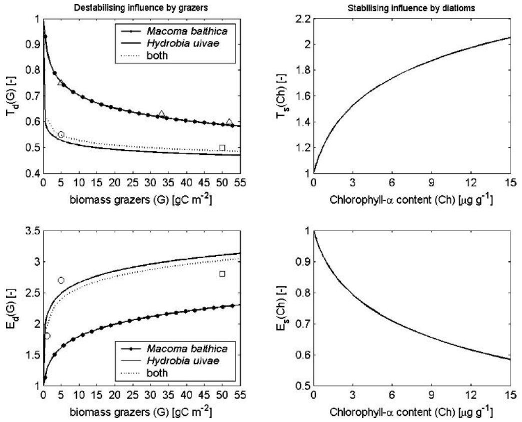

Figure 2. Parameterisation of the biological influence on the critical bed shear stress for erosion (upper) and erosion coefficient (under) based on data provided by Austen et al. (1999) (Δ), Andersen et al. (2002) (○) and Lumborg et al. (2006) (□).

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

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

The parameterisation for the critical shear stress for erosion and the erosion coefficient is given in Figure 2. The maximum biomass of grazers and the maximum chlorophyll-α content reflect the maximum values found in the Western Wadden Sea, as will be discussed in Section 4.2.

The destabilisation functions are corrected for the contribution of the individual biomass grazers to the total biomass, as suggested by Wijsman (2004), showing the much larger influence of *Hydrobia ulvae* on the destabilisation 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) is used. The data given by Lumborg et al. (2006) are used in a modeling study on the influence of *Hydrobia ulvae* on cohesive sediment dynamics, based on measurements executed at the Kongsmark tidal flat in the Danish Wadden Sea. The relationships for bio-stabilisation show strong similarity with the relationship found by Lanuru (2004), which are deduced from experimental data of an intertidal flat located in the German Wadden Sea.

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

4 MODELING SET-UP

4.1 *Cohesive sediment transport*

The substance included in the model is characterized as inorganic, cohesive fine sediment. The settling velocity for this substance is set at 5.10^{-4} m s^{-1}. This value is within the range of values measured by Andersen and Pejrub (2002) in the Danish Wadden Sea for disaggregated cohesive sediments eroded from a mud flat. 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 mud concentration in the water column (e.g. Winterwerp, 2002). Based on time scale analysis executed by Van Ledden (2003), 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 N m^{-2} and the erosion coefficient is set at 0.1 g m^{-2} s^{-1}. These values are in accordance with measurements for non-biological influenced mud flats in the Danish Wadden Sea (Andersen, 2001). A critical bed shear stress for deposition does not exist (Winterwerp & Van Kesteren, 2004). By using a large critical shear stress for deposition, continuous sedimentation is allowed, while the heaviside function in Equation 3 is always larger than zero. Bottom roughness is prescribed by a global Chézy coefficient of 62 m$^{1/2}$s^{-1}, which is the result of the calibration of the water level and currents. The wind fetch is set variable in time between 1500 and 9500 m, and is set uniform for the modeling area. A wind fetch of 1500 m correspondents to a wind direction of 130° (south-east), while a wind direction of 315° (north-west) correspondents to a wind fetch of 9500 m. Based on the wind fetch and wind speed, the wave height and the wave length are calculated. The wind speed and wind direction are measured by the Dutch Meteorological Institute (KNMI) with 1 h intervals on Den Helder (Fig. 1).

At the North Sea open boundaries of the model, the suspended sediment concentration are imposed based on data provided by the Dutch National Institute for Coastal and Marine Management (RIKZ). The boundary suspended sediment concentrations show a temporal variation, especially close to the coast, with the highest values occurring in February and the lowest values in Augustus.

Flow simulations show a good agreement with observed water levels and currents (not shown in this paper).

Table 1. Average biomass biota (gC m^{-2}), classified in different depth zones (MSL), based on field measurements.

Biota	Depth zone 1 (0–1 m)	Depth zone 2 (1–2 m)	Depth zone 3 (2–3 m)
Macoma	1.6	0.2	0.2
Hydrobia	–	38.3	38.3
Diatoms*	4	–	–

* Diatoms are also present at a waterdepth < 0 MSL.

4.2 *Biological activity*

The biomass grazers are based on field measurements executed 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-September) at two areas in the Western Wadden Sea. At these locations, nine transects are located. The height of these transects are between +0.2 and −4.9 m MSL. At each transect, 15 to 20 samples are taken. For the intertidal area, the clam *Macoma balthica* appeared to be the dominant surface deposit feeder. In the sub-tidal area, the mudsnail *Hydrobia ulvae* is the dominant surface deposit feeder. However, *Macoma balthica* is also present in the sub-tidal area.

The biomass found at the two measurement locations for the two grazers are assigned to the whole Western Wadden Sea.

Diatoms are restricted to depth, due to 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 microphytobenthos is determined.

The spatial variation in biological activity is shown in Table 1. No biological activity is assigned for a waterdepth larger than 3 m MSL, and no grazers are present at a waterdepth smaller than 0 m MSL.

The variation in biomass biota in the different depth zones results in a spatial varying critical bed shear stress for erosion and erosion coefficient; Figure 3. Consequently, the destabilised area in the Western Wadden Sea is much larger (1092 km^2) compared to the stabilised area (463 km^2).

The temporal variation in the biomass grazers and microphytobenthos is shown in Figure 4. This variation is based on the bi-annual field measurements for grazers (Dekker & De Bruin, 1999) and the monthly field measurements for microphytobenthos (Cadée and Hegeman, 1974).

The largest biomass grazers are observed in October, while microphytobenthos have 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.

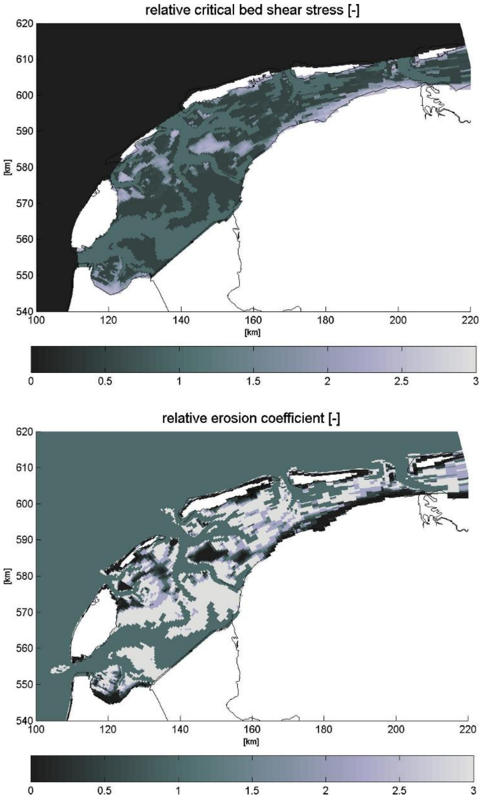

Figure 3. Influence of biological activity on the critical bed shear stress for erosion (upper) and erosion coefficient (under), based on average biomass biota. A value of 1 correspondents to no influence on the default transport parameters.

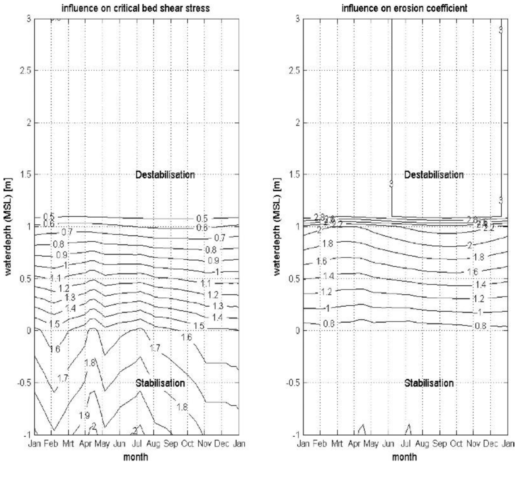

Figure 4. Spatial and temporal variation in the relatieve critical shear stress for erosion (left) and erosion coefficient (right) along a transect in the Western Wadden Sea. Biological activity is limited to a waterdepth of 3 m MSL.

At places where both *Macoma balthica* and *Hydrobia ulvae* (total biomass varying between 22 and 55 gC m^{-2}) are present (depth zone 2 and 3), the critical bed shear stress and erosion coefficient show not a clear temporal variation (Fig. 4). However, at places where only *Macoma balthica* is present (depth zone 1) also microphytobenthos is present, leading to a variable effect throughout the year. In this area 44 km^2 is both stabilised and destabilised, depending on the period of the year.

Moreover, at places where only microphytobenthos is present (waterdepth $<$ 0 m MSL; Table 1), 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 stabilisers.

A second bottom layer will account for the fact that sediment is buried downward by grazers (bioturbation). By using a second bottom layer, biological influence is limited to the upper bottom layer, and the second bottom layer serves as buffering during calm weather. The porosity for the two bed layers is different. Due to bioturbation, the porosity increases, especially in the top centimeters of the bed, as proven by e.g. Widdows & Brinsley (2002) and Orvain et al. (2006).

Based on the porosity, the flux of sediment to the second bottom layer is calculated. Transport of sediment between the two sediment layers is only possible, when the thickness of the upper bottom layer exceeds 10 cm. This value represents the depth in the bed, where biological activity is limited. Resuspension from the second bottom layer is only possible when the upper bottom layer is completely eroded.

Data on wind speed and wind direction show that 1998 was not a representative year. The number of hard winds ($>$13.9 m/s) were the largest since 1979 measured at Den Helder. Due to the large number of hard winds, this year enables us to study the interaction between biological and physical processes in an extreme case. The biological activity in the study area showed no clear deviancy compared to other years (Beukema et al., 2001).

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

5 RESULTS

Data to evaluate the model results are obtained from the DONAR-database. This database contains measurements of suspended sediment concentrations at a depth of 1 m below the water surface. The database

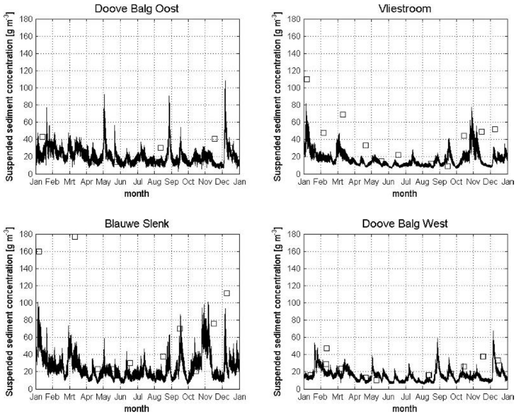

Figure 5. The modeled suspended sediment concentrations [g m^{-3}] and measured concentrations (☐) for four different locations in the Western Wadden Sea.

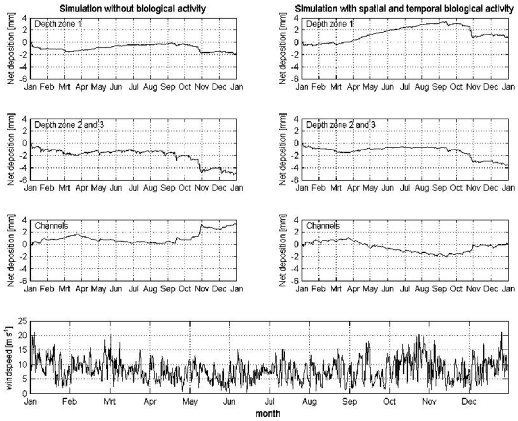

Figure 6. Modeled net deposition (mm) in the different depth zones for the situation without biological activity included (left) and the situation in which biological activity is varied spatial and temporal (right) and the wind speed (m s^{-1}) measured at Den Helder (under).

is owned by the Dutch Ministry of Public Works (Rijkswaterstaat).

For the year of interest, 1998, and for the model domain, all measuring stations with suspended sediment concentrations are the four stations shown in Figure 1 (triangles).

The modeled seasonal pattern of suspended sediment concentration shows good agreement with the measurements (Fig. 5). However, the suspended sediment concentrations are mostly underestimated (on average 30% compared to the measured suspended sediment concentrations). This underestimation is probably caused by the overestimation in the measurements from the DONAR-database (containing both inorganic and organic matter).

The net deposition of cohesive sediment is shown in Figure 6. The net deposition is averaged over the total area of the different depth zones. Distinction is made between the default parameter settings (left) and the simulation in which biological processes are included (right).

In general, the bed level in depth zone 1 gradually increases during calm weather. During rough weather, severe erosion occurs. The sedimentation 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 to be eroded form this area during high biomass microphytobenthos (March-September). For depth zone 2 and 3, the net deposition of sediment is comparable for both simulations. This observation is reasonable, while the transport parameters for the simulation with biological activity show no clear temporal variation (Fig. 4).

The bed level changes in the channels show an opposite trend, compared to the bed level changes in the higher areas. Apparently, sediment eroded during rough weather conditions is stored in the deeper areas, where wave action is less dominant. During calm weather, sediment is transported to the higher 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 1. Based on the model simulations, the biological processes influence the bed composition on an estuarine scale, and are even responsible for the difference in net annual deposition or erosion of the bed in the different depth zones.

6 DISCUSSION

This paper describes the influence of biota on the cohesive sediment transport on a large scale. In reality, the biological influence shows much more spatial variation, than modeled in this study (e.g. Andersen et al., 2002). The stabilising influence for microphytobenthos is much lower, compared to values found in the field (up to a critical bed shear stress of 3 N m^{-2}) (Austen et al., 1999). In this study, the stabilising factor is corrected for the patchy distribution of microphytobenthos (Seuront & Spilmont, 2002) and the often very thin layer (∼3 mm) of micro algae (Andersen, 2001).

The modeled net deposition of sediment in depth zone 1 (Fig. 6) is comparable to observations discussed by Andersen et al. (2005) for a mudflat in the Danish Wadden Sea, showing a net sea-ward transport during winter and a net land-ward transport during summer. The model results also suggest that the sediment is stored in winter and autumn on the channel banks.

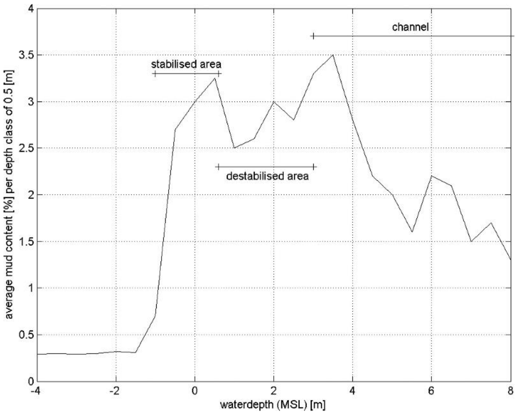

Figure 7. Relation between the measured amount of cohesive sediment in the bed and waterdepth (MSL) for the Western Wadden Sea.

As a consequence, the sediment content in the mudflats and the channel banks is much larger compared to the sediment content in the destabilised area (depth zone 2 and 3). This idea is supported by measurements presented in Figure 7, which are based on field data provided by the National Institute of Coastal and Marine Management (RIKZ) for the Dutch Western Wadden Sea.

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

Based on a sensitivity analysis, in which the biological influence on the critical bed shear stress and erosion coefficient is varied in a realistic range, a different 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. 7). This influence is also caused by the much larger area bio-destabilisers in the Western Wadden Sea.

However, the spatial variation in biomass 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. 4).

Based on the results of the model, we found that there is a dynamic interaction between physical and biological processes for 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 are boundary condition or noise. In future, climate change will not only change the physical system (increase storminess and sea level rise) but also the biological processes (change in zonation of biota and increase of water temperature). The outcome of the dynamic interaction of both processes is of great interest for the management and conservation scheme of 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 influence on the sediment balance between the North Sea and the Western Wadden Sea.

7 CONCLUSIONS

The presented study demonstrates the influence of biology activity on the cohesive sediment transport on an estuarine scale. Moreover, the seasonal variation in the suspended sediment concentrations and bed composition is caused by the combined effect of wind, suspended sediment concentrations at the North Sea and biological processes. The results show the importance to incorporate biological activity in the present models to bring up recommendations for the management and conservation of different estuaries with large biological activities.

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