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# Modeling the influence of a young mussel bed on fine sediment dynamics on an intertidal flat in the Wadden Sea

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ABSTRACT

Mussel beds are known to affect fine sediment dynamics and morphology on mudflat scale, a clear example of ecosystem engineering. Current research into possible ecological engineering applications of mussel beds makes quantitative modeling desirable. In this study a process-based model of the interaction between a young mussel bed and fine sediment was set up for use in the hydrodynamic and morphological model Delft3D-FLOW. The model encompasses the hydraulic roughness of the mussel bed, active capture of suspended sediment by filter feeding and changed bed properties due to biodeposited matter. The mussel bed implementation in Delft3D-FLOW was applied in a test case: a Wadden Sea intertidal mudflat model. It was concluded that a combination of active deposition via filtration and slow down of the flow due to increased roughness leads to high net deposition in the mussel bed. In addition, the ability of young mussels to quickly climb on top of deposited material results in rapid trapping of large amounts of fine sediment. In the wake of the mussel bed, deposition is also high because of reduced flow velocities. The effects of different existing mussel bed patterns were also evaluated. Patchiness and specifically striped patterns cause mussel beds to experience less sedimentation than uniformly covered beds of the same size and may therefore be favorable to mussels.

## 1. Introduction

Large aggregations of mussels (*Mytilus edulis*), so called mussel beds, are found in many shallow marine environments, including the Dutch Wadden Sea. Mussel beds range in size from small clumps to large beds of several hectares (Dankers et al., 2001). Mussels are strong ecosystem-engineers, implying that they exert substantial effects on their surroundings (Jones et al., 1994). Potentially important influences of mussels on their environment are active filtration of sediment and the subsequent formation of biodeposits (Flemming and Delafontaine, 1994; Oost, 1995) and passive influence of the rough and sediment retaining mussel bed (Widdows and Brinsley, 2002).

Currently, the feasibility of using the biogeomorphological impact of mussel beds for ecological engineering purposes (Odum and Odum, 2003), is under investigation. Examples include the use of mussels to reduce turbidity (Beukema and Cadée, 1996), which is thought to be beneficial for the reintroduction of sea grasses in the Wadden Sea (Van Katwijk, 2003). Furthermore, mussel beds (or other shell fish reefs) could be used to dissipate wave energy and thereby protect valuable salt marshes from erosion (De Vries et al., 2007; Piazza et al., 2005), in a similar fashion to sediment fences experimented with by Scarton et al. (2000) and Boumans et al. (1997). Extra deposition of fine sediments in these areas by a reduction of flow velocities or fixation as (pseudo-) fecal matter is also thought to increase the resilience of salt marshes. Modeling the influence of mussel beds on fine sediment dynamics will be a useful tool in predicting the effectiveness of these measures. At this moment such a model implementation does not exist.

The objective of the research presented in this paper is to model mussel-sediment interactions for a young mussel bed during a calm summer period in order to study the net retention and the spatial distribution of fine sediment on a Wadden Sea intertidal flat. This might allow us to predict the influence of mussel beds on fine sediment dynamics on local and large estuarine scales. The Wadden Sea has been chosen as a research area because it is both a natural habitat for mussels and a proposed location for use of mussels as bio-tools.

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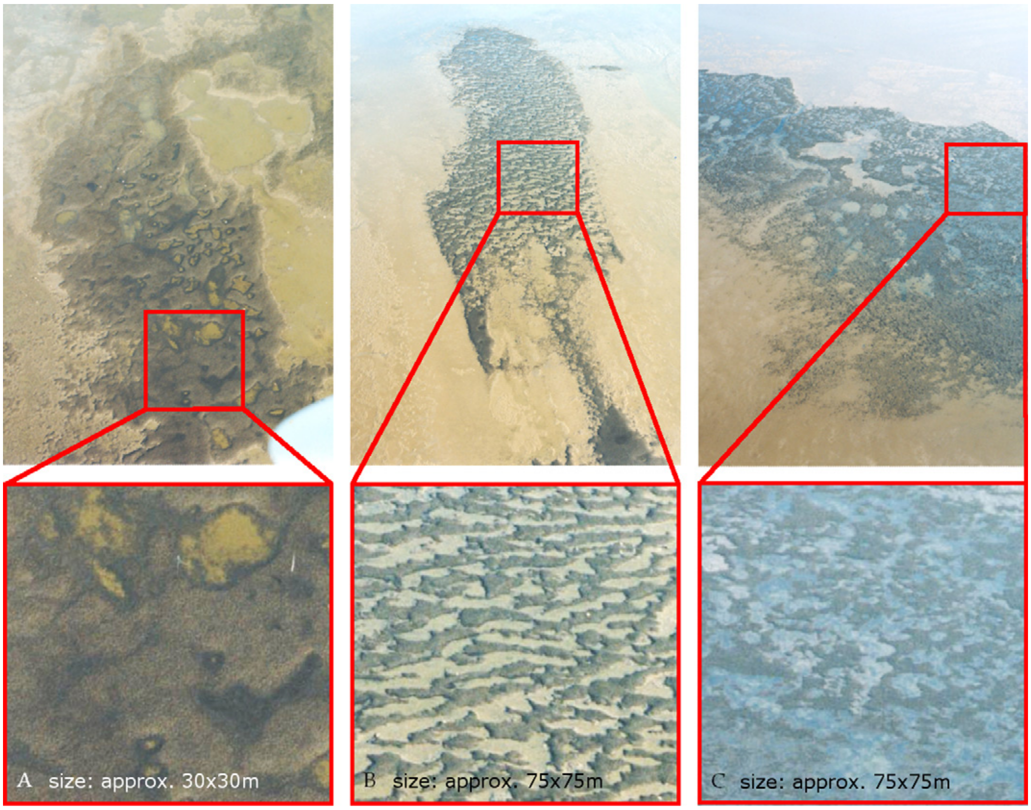

**Fig. 1.** Patterns in young mussel beds: (A) (nearly) uniformly covered, (B) striped pattern and (C) random patchy pattern. Photographs provided by Norbert Dankers.

## 2. Mussel beds and fine sediment interaction

Mussels experience sedimentation inside the bed. This sedimentation is the result of passive settling of sediment during slack tide and active filtration of suspended sediment. The latter process is due to the fact that mussels are filter feeders. Large amounts of water are inhaled by mussels to filter algae for food. Together with algae, fine sediments are also taken out of suspension. These indigestible particles are excreted and deposited as (pseudo-)fecal pellets. Young mussels are highly mobile and respond to sedimentation by climbing on top of the sediment and covering it. It has been observed that mussels buried by sediment can climb as much as 6 cm in a day (Widdows et al., 2002). In this way young mussel beds can accumulate large quantities of sediment. It has been reported that young mussel beds can rise up to 30–40 cm in the first half year of existence (Dankers et al., 2004). Older mussels gradually lose the ability to move and may be buried by sediment or younger mussels. The maximum growth of mussel beds is restricted by submergence (i.e. feeding) time and will hardly ever exceed mean sea level.

The combination of high density coverage and the ability of young mussels to quickly climb on deposited sediment, means that young mussel beds can capture a lot of sediment. About half of the young mussel beds are lost due to storms in the first winter after colonization. In consecutive years the amount of sedimentation in mussel beds is reduced, as a result of lower coverage and a lesser ability to move. However, over the years, mussel beds accumulate coarse sediment and shells, and the mud consolidates. The resulting harder foundation is less susceptible to erosion. In summary, young mussel beds are important with regard to the capture of fine sediment, whereas more mature mussels mainly retain sediment that has already been deposited. The focus of the research presented here is on young mussels in the first summer of their existence.

Young mussel beds quickly develop from an initial uniform coverage to non-uniform coverages as depicted in Fig. 1, a phenomenon that has recently been replicated in the laboratory (Van de Koppel et al., 2008). In the Wadden Sea three patterns can be discerned: uniform, irregularly patchy and striped patterns. Most mussel beds appear to have irregular patchiness, about 25% of the beds display a striped pattern transverse to the dominant current (Van de Koppel et al., 2005).

## 3. Modified Delft3D-FLOW

In order to model the interaction between fine sediment and a young mussel bed the process-based hydrodynamic and morphological model Delft3D-FLOW was used. The standard equations of this modeling tool have been modified to allow for the implementation of a young mussel bed. A depth-averaged implementation of DELFT3D has been used as a starting point in the modeling effort. The model used is thus a two- rather than a three-dimensional model, this implies the assumption that suspended fine sediment is distributed uniformly over the vertical. It has been shown in previous model studies that assuming well-mixed conditions with regard to the distribution of fine sediment over the vertical is a reasonable assumption for the Wadden Sea (Van Loon, 2005).

### *3.1. Hydrodynamic equations*

The two-dimensional depth-averaged implementation of the process-based Delft3D-FLOW module (for an extensive description, see WL|Delft Hydraulics (2006)) was used. This model solves the shallow water equations, which for this application reduce to:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial^2_{\mathrm{hyd}}h}+\frac{g|U|u}{C^2_{\mathrm{hyd}}h}-\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+\underbrace{u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}}_{\text{advection}}-\underbrace{g\frac{\partial \zeta}{\partial y}}_{\text{surface slope}}+\underbrace{\frac{g|U|v}{C^2_{\mathrm{hyd}}h}}_{\text{bed friction}}\underbrace{-\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)}_{\text{diffusion}}=0 \tag{2}$$

where $u$ = depth-averaged velocity in $x$-direction (m s$^{-1}$); $v$ = depth-averaged velocity in $y$-direction (m s$^{-1}$); $\zeta$ = water level (m); $|U|$ = absolute velocity magnitude = $(u^2+v^2)^{0.5}$ (m s$^{-1}$); $h$ = water depth (m); $g$ = gravitational acceleration (m$^2$ s$^{-1}$); $C_{\mathrm{hyd}}$ = Chézy coefficient for hydrodynamic roughness (m$^{1/2}$ s$^{-1}$); $\upsilon$ = horizontal eddy viscosity (m$^2$ s$^{-1}$)

Combined with the continuity equation:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hu}{\partial y}=0 \tag{3}$$

this yields a system of equations that can be implicitly solved by Delft3D-FLOW for structured grids.

### 3.2. Fine sediment transport

Based on the computed flow velocities, fine (cohesive) suspended sediment transport can be calculated using the advection–diffusion equation. This equation has been extended with a biodeposition term, $D_{\mathrm{bio}}$:

$$\frac{\partial hc}{\partial t}+\underbrace{u\frac{\partial hc}{\partial x}+v\frac{\partial hc}{\partial y}}_{\text{advection}}-\underbrace{\varepsilon_{\mathrm{s}}\frac{\partial^2 hc}{\partial x^2}+\varepsilon\frac{\partial^2 hc}{\partial y^2}}_{\text{diffusion}}=E-D-D_{\mathrm{bio}} \tag{4}$$

where $c$ = suspended sediment concentration (kg m$^{-3}$); $\varepsilon_{\mathrm{s}}$ = eddy diffusivity (m$^2$ s$^{-1}$); $E$ = erosion source term (kg m$^{-2}$ s$^{-1}$); $D$ = deposition sink term (kg m$^{-2}$ s$^{-1}$); $D_{\mathrm{bio}}$ = biodeposition sink term (kg m$^{-2}$ s$^{-1}$).

Erosion is incorporated by the source term $E$, which describes a flux from the bed to the water column. The method to describe erosion of sediment is based on Partheniades (1965):

$$E=M\cdot\max\left(0,\frac{\tau_{\mathrm{b}}}{\tau_{\mathrm{crit}}}-1\right) \tag{5}$$

where $M$ = erosion rate (kg m$^{-2}$ s$^{-1}$); $\tau_{\mathrm{b}}$ = bed shear stress (N m$^{-2}$); $\tau_{\mathrm{crit}}$ = critical shear stress for erosion (N m$^{-2}$).

Thus, erosion is a function of bed shear stress. Bed shear stress is the force exerted on the bed by the flow and is expressed as:

$$\tau_{\mathrm{b}}=\frac{\rho g|U|^2}{C^2_{\mathrm{mor}}} \tag{6}$$

where $\rho$ = density of water (kg m$^{-3}$); $C_{\mathrm{mor}}$ = Chézy coefficient for morphological roughness (m$^{1/2}$ s$^{-1}$).

Note the distinction between the morphological roughness, $C_{\mathrm{mor}}$, and the earlier introduced hydrodynamic roughness, $C_{\mathrm{hyd}}$. The former is used to compute the forces available for erosion, whereas the latter computes the forces exerted on the flow by the bed. The distinction between the two roughness parameters is implemented to model roughness elements that exert forces on the flow, but are not erodible sediment. In this case these elements are mussel shells.

Two deposition sink terms are included in Eq. (4), the simplified conventional deposition term derived by Krone (1962), $D$, and the newly introduced biodeposition term, $D_{\mathrm{bio}}$:

$$D=w_{\mathrm{s}}\cdot c \tag{7}$$

$$D_{\mathrm{bio}}=fr\cdot c \tag{8}$$

where $w_{\mathrm{s}}$ = settling velocity (m s$^{-1}$); $fr$ = filtration rate (m s$^{-1}$).

Because both deposition terms have the same form, the settling velocity and filtration rate can be added together. In effect, biodeposition is modeled as a local increase in the settling velocity.

Processes of erosion and deposition alter the amount of sediment in the bed. After a given amount of computational time steps this is translated into an updated bathymetry. It is possible to multiply any changes in the bed by a morphological scale factor ($f_{\mathrm{mor}}$), allowing accelerated bed level changes to be dynamically coupled with the flow computations (Roelvink, 2006).

## 4. Mussel bed implementation

The introduction of a biodeposition term and the distinction between a hydrodynamic and morphological roughness allows the implementation of a young mussel bed. This implementation consists of three features: (1) an increased roughness due to the mussel shells, (2) a value for the filtration rate and (3) an adjustment of the sediment properties within the bed. Thus, the mussel bed is not modeled as a separate entity, but its effect on fine sediment is simulated by changes in the hydrodynamic and morphological processes.

### 4.1. Shell roughness

Hydrodynamics are forcing fine sediment dynamics, as is represented in Eq. (4). Hence, any influence on the hydrodynamics will also affect fine sediment dynamics. A rough mussel bed poses an obstruction to flow, causing a slow down in flow velocities and consequently an increase in sedimentation. The roughness of the mussel bed is implemented by setting a value for $C_{\mathrm{hyd}}$.

The hydraulic roughness is estimated based on the size of the roughness elements in a mussel bed. Young mussels vary in size from 5 mm to 30 mm depending on their age (Dankers et al., 1989). When the mussels are still small, the mussel bed roughness is determined by the form in which they organize more than by the size of individual shells. For example, it is known that mussels often settle on old shells, cockle grounds or fields of tube building organisms (sand mason). As such, a roughness element size of 30 mm is considered a good estimation in this uncertain and variable case. The roughness length ($z_0$, which is a measure for roughness) can be estimated from the height of roughness elements using an empirical relation for the roughness of stones (Hofland, 2005):

$$z_0=\frac{d}{10} \tag{9}$$

where $z_0$ = roughness length (m); $d$ = height of roughness elements (m).

Using this equation $z_0$ of 3 mm is found. This corresponds to experimentally derived roughness lengths for flow over a mussel bed in a flume set-up (Van Duren et al., 2006). The roughness length $z_0$ can be translated into the Nikuradse roughness length, $k_{\mathrm{s}}$ (m):

$$k_{\mathrm{s}}=30\cdot z_0 \tag{10}$$

It follows that $k_{\mathrm{s\_hyd}}$ = 0.09 m. The Nikuradse roughness length is used because it is independent of depth ($h$), unlike the Chézy parameter which is related to $k_{\mathrm{s}}$ via:

$$C=18\log\left(\frac{12h}{k_{\mathrm{s}}}\right) \tag{11}$$

Delft3D-FLOW computes both the hydraulic ($C_{\mathrm{hyd}}$) and the morphological ($C_{\mathrm{mor}}$) roughness based on Eq. (11) from the input variables $k_{\mathrm{s\_hyd}}$ and $k_{\mathrm{s\_mor}}$, respectively. Note that the high roughness ($k_{\mathrm{s\_hyd}}$ = 0.09 m) would lead to high shear stresses on the sediment had not a distinction been made between a hydrodynamic roughness and a morphological roughness. For the morphological roughness the same value as for bare sediment ($k_{s\_mor} = 0.005$ m) will be used, for there is no reason to assume that the sediment between mussels is either rougher or smoother.

### *4.2. Filtration rate*

Mussels feed by pumping and filtering large amounts of water. The sediment suspended in this water is excreted as feces (ingested) or pseudo-feces (rejected before ingestion). If the filtration rate is known, the biodeposition rates are known as well, because all the suspended material in the inhaled fluid is bound in (pseudo-)fecal pellets.

The filtration rate is estimated based on a more mature mussel bed with known properties. This can be considered a conservative estimation, as young mussels are known to filter more water per unit area (Dankers et al., 1989). Filtration rate highly depends on quantities of suspended matter and is inversely related with suspended sediment concentration (Widdows et al., 1979). At low to intermediate suspended sediment concentrations, the filtration rate can be approximated by a constant value. Based on Widdows et al. (1979) and assuming a suspended sediment concentration range of 0–100 mg $l^{-1}$, it is found that a single mussel (5 cm in length) filters 2.0 l $h^{-1}$ $ind^{-1}$. According to the data of Widdows et al. (1979), this value introduces a maximum error of 20% for given concentration range; this error is deemed acceptable in relation to other parameter uncertainties. It should be noted that using a constant filtration rate limits the applicability of the model to conditions with low to intermediate suspended sediment concentrations. Assuming a mussel bed with density of 1800 ind $m^{-2}$ (as used in the experiments by Van Duren et al. (2006)), a filtration rate of 3600 l $h^{-1}$ $m^{-2}$ or 1 mm $s^{-1}$ is found. Assuming further that half of the water will be refiltered (because mussels are stacked close together), the effective filtration rate (*fr*) is set to 0.5 mm $s^{-1}$. This value is similar to settling velocities used for fine sediment in the Wadden Sea (Van Ledden, 2003), which corresponds to the observations by Ten Brinke et al. (1995) that passive settling and biodeposition contribute equally to total deposition.

It should be noted that in this depth-averaged model, the filtration rate is applied over the entire water column. Such an approach would only be accurate if velocities and fine sediment concentrations are more or less uniformly distributed over the water column. In reality this is not the case. Also, mussels influence this distribution by consuming suspended matter from the water phase near the mussel bed. During slack tide this can even lead to depletion of algae (food) near the mussel bed (Fréchette et al., 1989; Tweddle et al., 2005). However, in contrast to algae, fine sediment is vertically distributed with higher concentrations near the bed, and fresh sediment is continuously supplied due to the relatively high turbulence in the shallow Wadden Sea waters. Moreover, additional mixing caused by turbulence from the rough mussel bed and exhalent jets from filter feeding also contributes to well-mixed conditions. As such, although a depth average assumption does not account for all dynamics known to be present over mussels, it is assumed that it provides a reasonable approximation of the sediment source available for retention by mussel beds.

### *4.3. Sediment properties*

The properties of the sediment in between mussels are influenced by biodeposition. The biodeposited material consists of pseudo-fecal matter, which is light and easily erodible, and fecal pellets, which are denser and thus more difficult to erode. Quantitatively, little is known about the properties of these materials. Considering the qualitative properties as described, it cannot be argued that an aggregate of normal sediment, pseudo-fecal matter and fecal pellets is either quicker or slower to initiate erosion. Hence, the critical bed shear stress ($\tau_{crit}$) is maintained at the level of sediment without (pseudo-)fecal content. However, once erosion has started, the large entities of biodeposited matter (in the order of mm) generate larger quantities of eroded material. The erosion rate ($M$) has therefore been increased by a factor four relative to sediment without (pseudo-)fecal content.

Besides the sediment properties, the amount of force available between the mussels plays an equally important role in the erosion process. Computing flow velocities and turbulence between mussels cannot be done in a depth-averaged model but requires a more detailed modeling tool. This means that results regarding the erosion are rather uncertain. A sensitivity analysis is performed in order to investigate the influence of the uncertainty in the parameter settings. Variation in the values of the sediment properties can also be seen to incorporate uncertainties in the acting forces, i.e. a higher bed shear stress is equivalent to a lower critical bed shear stress, see Eq. (5). The need for a sensitivity analysis is not limited to the sediment properties, as uncertainty and variability in the two other parameters ($k_{s\_hyd}$ and *fr*) are also significant.

## 5. Model set-up

There are no field data to validate the mussel bed implementation described above. Instead the mussel bed implementation is applied in a test case model, which represents a typical mussel inhabited mud flat in the Wadden Sea. Also, the model should be sufficiently simple to facilitate the evaluation of the mussel bed implementation in a sensitivity analysis. The latter requirement suggests the use of an idealized model. As an example area for the model domain, a rectangular area bordering a channel south of the island Ameland is chosen. This area is historically richly inhabited with mussels, as can be seen in Fig. 2. Based on the actual bathymetry of the area, a profile (Fig. 3(B)) including a tidal flat (slope 1:1000) and a channel (slope 1:50) have been set-up and applied uniformly to form the bathymetry presented in Fig. 3(A). The model domain is divided into 8631 rectangular computational cells, varying in size from 2 m × 2 m in the mussel bed area and direct vicinity to 10 m × 100 m near the boundaries. The northern boundary is closed; the other boundaries (west, east and channel)

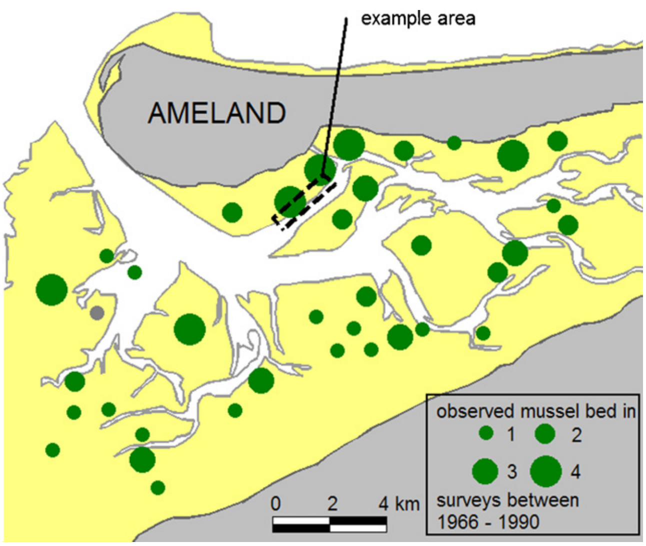

**Fig. 2.** Example area with known mussel bed locations adapted from Brinkman et al. (2002).

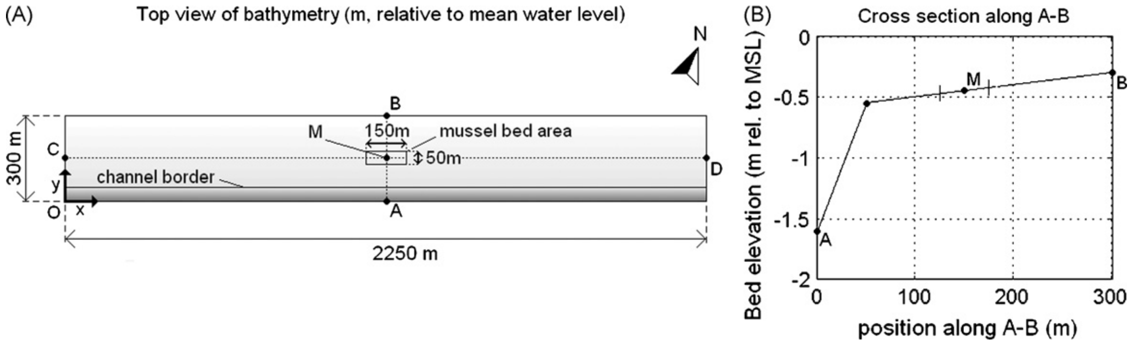

**Fig. 3.** (A) Top: overview of model area with channel to the south. The rectangle in the middle specifies the mussel bed location. The *x*-direction is from C to D, the *y*-direction from A to B. (B) Cross section along AB, with channel to the left.

are open. In this research sixty calm summer days will be modeled. As currents are dominant during the summer (Janssen-Stelder, 2000), no waves will be taken into consideration.

It has been established by Brinkman et al. (2002) that optimum mussel habitats exist where maximum flow velocities are 0.5 m $s^{-1}$ and emergence time is 40%. These values are used as guidelines in setting up the model conditions. A harmonic tide with an amplitude of 1.5 m and a period of 12 h has been imposed, which is an idealization of the actual tidal forcing in the Wadden Sea. The tidal phase difference between the west and the east boundary is calibrated to achieve maximum flow velocities of 0.5 m $s^{-1}$. Fine sediment is brought into the model domain from the west and east boundary at respectively incoming and outgoing tide. The tide comes in from the west and this will carry most sediment (40 mg $l^{-1}$), more than the outgoing tide which has a reduced suspended sediment concentration as sediment has settled during slack tide (30 mg $l^{-1}$ on the eastern boundary, which is realistic for the Wadden Sea (Postma, 1981)). A single cohesive fine sediment fraction is used, with settling velocity $w_s = 0.5$ mm $s^{-1}$ and critical bed shear stress $\tau_{crit} = 0.5$ N $m^{-2}$ (these values are used in earlier studies of fine sediment dynamics in the Wadden Sea (Van Ledden, 2003)). To shorten computation time, a morphological scale factor of 10 was applied. Consequently, six days of hydrodynamic simulations were actually performed, translating to sixty days of morphological developments. The parameter settings are listed in Table 1.

Finally, the effect of mussel bed patterns on the influence of mussel beds on fine sediment retention was studied. The patterns in mussel beds are implemented by varying the coverage and extent of the mussel bed. The mussel bed patterns presented in Fig. 4 are applied to the mussel bed location indicated in Fig. 3(A). Patches have cross sections of 10 m, corresponding to observed mussel bed patterns. It should be noted that coverage refers, from here on, to the percentage of surface covered by a certain pattern relative to the standard mussel bed (U 100%). The number of individuals per unit area is assumed constant in all simulations.

## 6. Results and discussion

### 6.1. Reference situation

All mussel bed simulation runs were compared to a reference simulation without a mussel bed. Conditions for this reference simulation at location M (see Fig. 3(A)) have been displayed in Fig. 5. Conditions closely follow the imposed boundary conditions and thus suit the habitat requirements introduced in Section 5. More water flows through the channel boundary at outgoing tide (going with the bathymetry slope) than at incoming tide. The same amount of water travels less distance westwards and hence flow velocities are slightly less prolonged in that direction. This, combined with the asymmetry in the imposed sediment concentration, explains the different heights of the peaks in the suspended sediment concentrations.

The effect of these conditions on the cumulative erosion/deposition after sixty days for the entire and part of the model domain is displayed in Fig. 6. It becomes clear that there is no sedimentation in the channel. Flow velocities there are too high for fine sediment to settle. Roughly 1.4 cm of fine sediment has accumulated, corresponding to an accretion rate in the order of a few mm $month^{-1}$ which is normal for mudflats during summer (Andersen, 2005). Accretion is highest near the east and west boundaries as a result of boundary effects. These effects were anticipated and are the reason for the elongated design of the model domain which makes that the boundary effects hardly affect the area of interest.

### 6.2. Uniform mussel bed

If the same simulation is made with the mussel bed present, a very different result is obtained. The area of interest has been displayed in Fig. 7. It can be seen that the mussel bed elevates itself by around 10 cm, which is in agreement with the observation that young mussel beds heighten to around 30–40 cm in the

**Table 1**
Parameter settings. Default values are used throughout the model domain, unless a value is specified for the mussel bed. The mussel bed parameter settings are applied locally where the mussel bed exists.

| Parameter | Symbol | Value | | Unit |
|---|---|---|---|---|
| | | Default | Mussel bed | |
| Hydrodynamic roughness | $k_{s\_hyd}$ | 0.005 | 0.09 | m |
| Morphological roughness | $k_{s\_mor}$ | 0.005 | | m |
| Critical bed shear stress | $\tau_{crit}$ | 0.5 | | N $m^{-2}$ |
| Erosion rate | $M$ | $1 \times 10^{-4}$ | $4 \times 10^{-4}$ | kg $m^{-2}$ $s^{-1}$ |
| Filtration rate | $fr$ | 0 | 0.5 | mm $s^{-1}$ |
| Settling velocity | $w_s$ | 0.5 | | mm $s^{-1}$ |
| Sediment density | $\rho_s$ | 2650 | | kg $m^{-3}$ |
| Bed porosity | $s$ | 0.18 | | – |
| Morphological scale factor | $f_{mor}$ | 10 | | – |

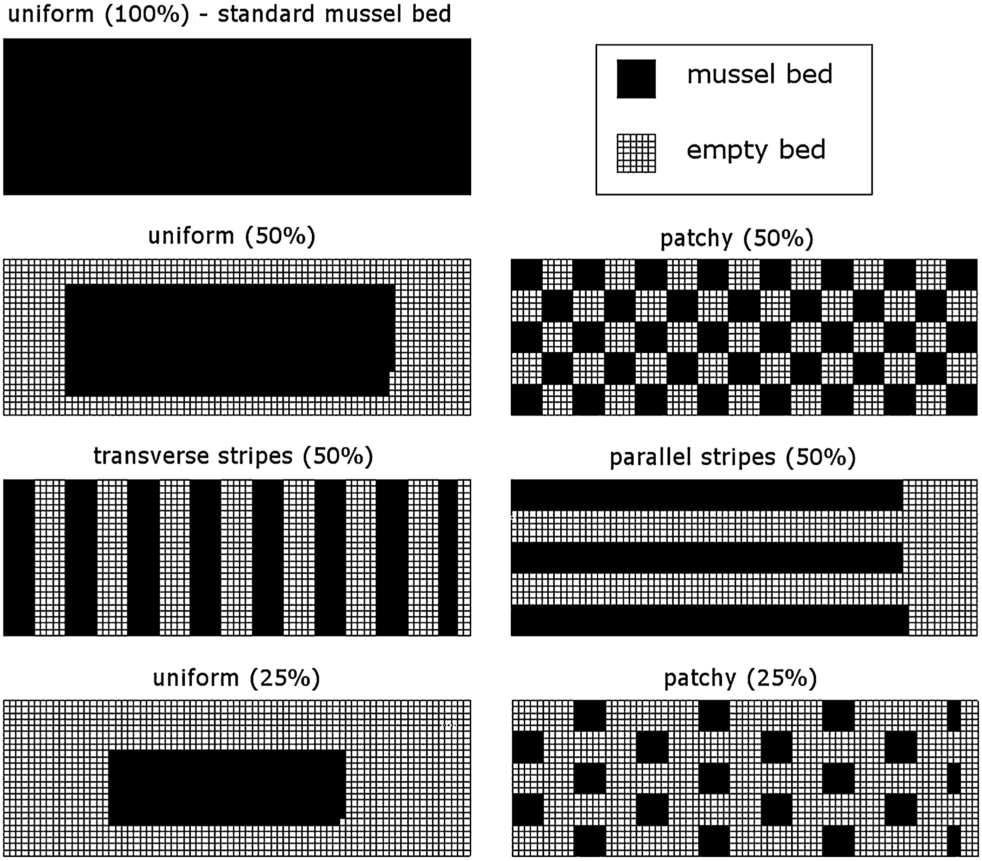

**Fig. 4.** Mussel bed area with the coverage configurations applied in this study. The surface of the 100% uniform mussel bed is 7500 m$^2$, which implies 3750 m$^2$ for 50% and 1875 m$^2$ for 25% coverage. Note that some of the configurations have been adjusted to keep the surface area constant.

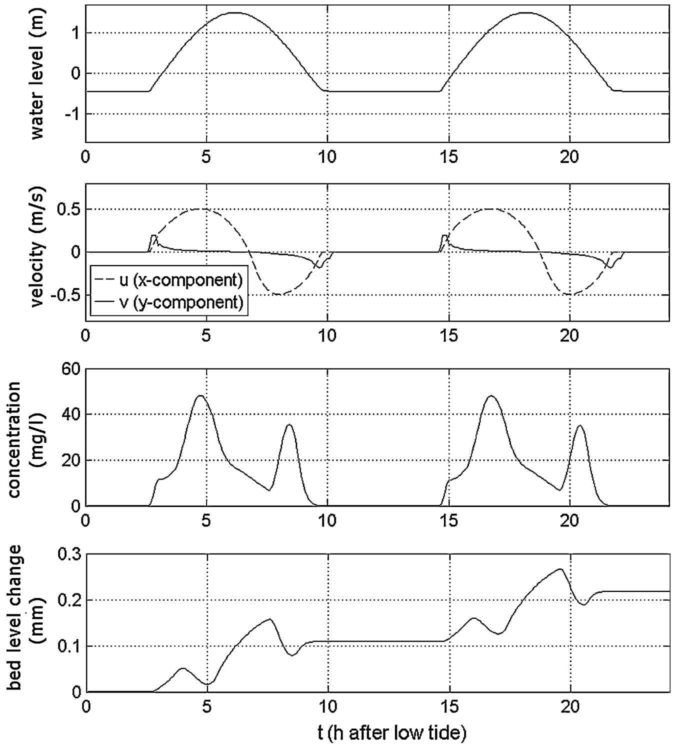

**Fig. 5.** Water level relative to mean water level, flow velocity, suspended sediment concentration and bed level change in M for the reference simulation during a double tidal cycle following low tide. Note that the change in bed level has been divided by 10 to compensate for the morphological scale factor.

first half year of existence (Dankers et al., 2004). The deposition pattern outside the mussel bed area shows that accretion occurs in the wake of the mussel bed, during both incoming and outgoing tide. Flow has accelerated north and south of the mussel bed, increasing erosion and decreasing deposition, hence relatively little net deposition has occurred there. In comparison with the reference case 390 ton more sediment has been captured by the mussel bed, and 565 ton more sediment has accumulated outside the mussel bed.

### 6.3. *Sensitivity analysis*

All parameters relating to the mussel bed implementation ($k_{\text{s\_hyd}}$, $fr$, $M$, $\tau_{\text{crit}}$) have been varied. It is found that the amount of sediment captured in the bed is mainly related to the filtration rate, whereas the amount of deposition around the bed is especially sensitive to the hydraulic roughness. Results become clearly unrealistic if the sediment in the mussel bed was modeled to be more erodible, independent of whether this was achieved by increasing the erosion rate or lowering the critical bed shear stress. In the standard case, as presented in the previous section, erosion from the mussel bed is negligible. If erosion becomes substantial, the mussel bed does no longer reach realistic elevations and sometimes becomes even lower than the surrounding sediment. Based on this result it can be concluded that erosion cannot play an important role in young mussel beds during calm weather conditions, as we know that these beds actually accumulate a large amount of sediment. Apparently mussels protect the sediment significantly by climbing on top and covering it.

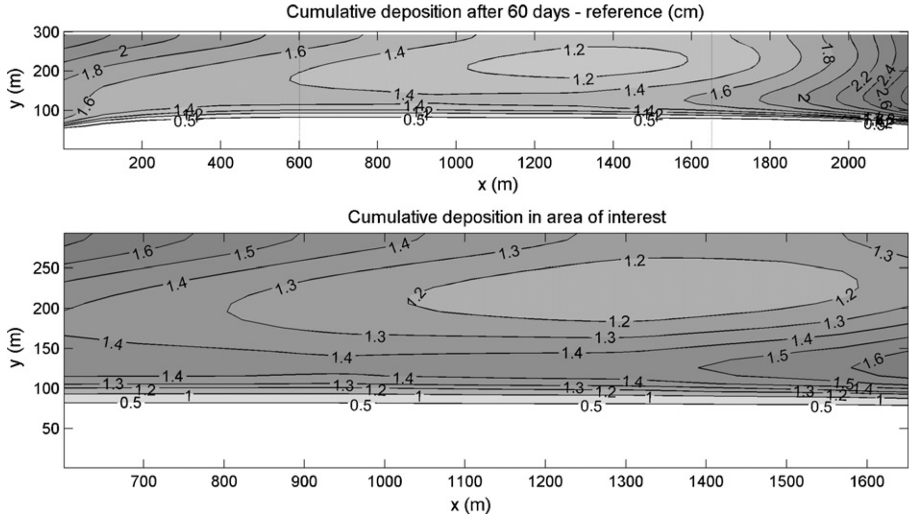

**Fig. 6.** Cumulative deposition/erosion after 60 days in cm for the reference situation, without mussel bed. The upper figure displays the entire domain. The lower figure focuses on the area of interest located between the dotted lines in the top figure.

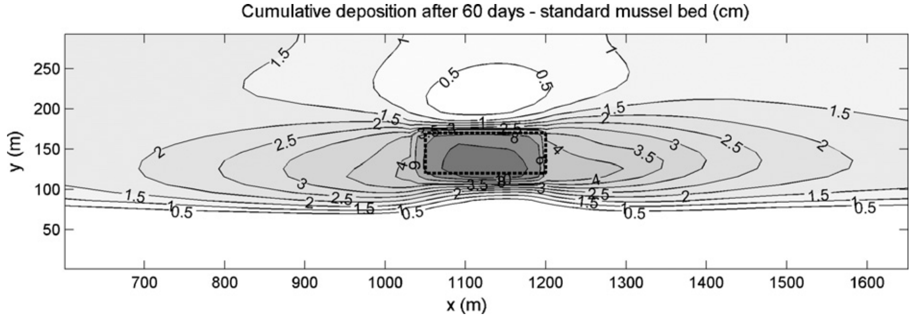

**Fig. 7.** Accretion in case of a standard mussel bed. Notice the change in shading scale in comparison with Fig. 6. The mussel bed area is depicted by the thick dotted line.

### 6.4. *Mussel bed patterns*

The patterns presented in Fig. 4 have been implemented in the model. The net deposition for mussel beds with coverage of 50% has been displayed in Fig. 8. It is apparent that the uniform pattern is elevated more than the other patterns. The non-uniform patterns show much lower maxima in accretion. Fig. 9 aggregates the effects of different patterns on the cumulative erosion/deposition

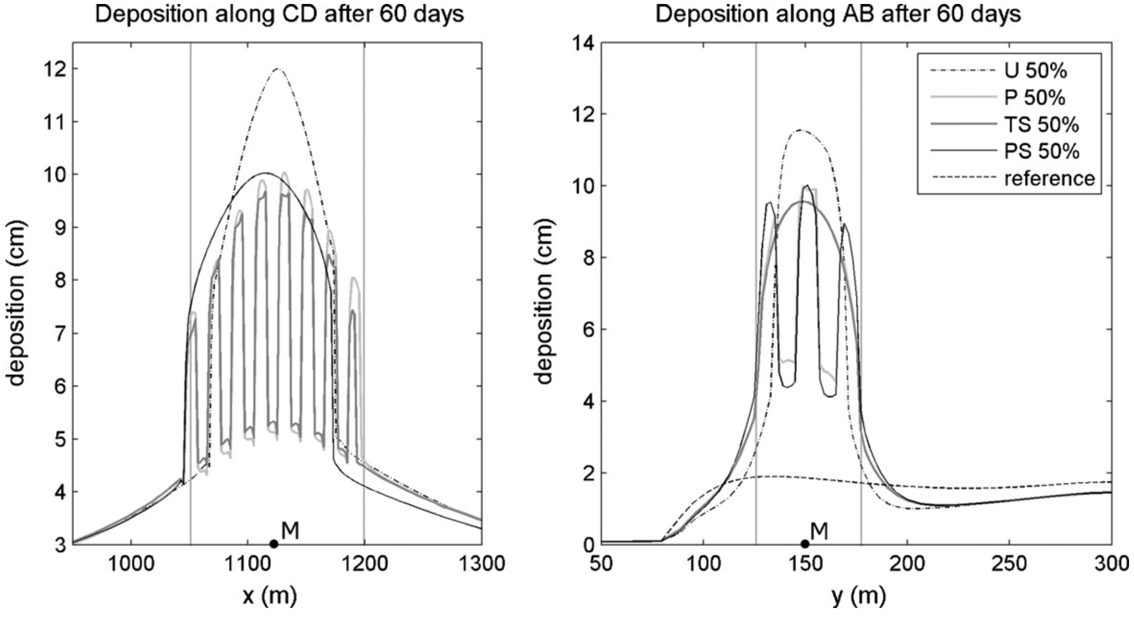

**Fig. 8.** Cross sections of cumulative deposition in case of mussel bed patterns covering 50% of the surface of the standard mussel bed. Cross sections are defined in Fig. 3(A). Two vertical grey lines mark the mussel bed location. U = uniform, P = checkerboard, TS = striped transverse to channel and PS = striped parallel to channel, see Fig. 4.

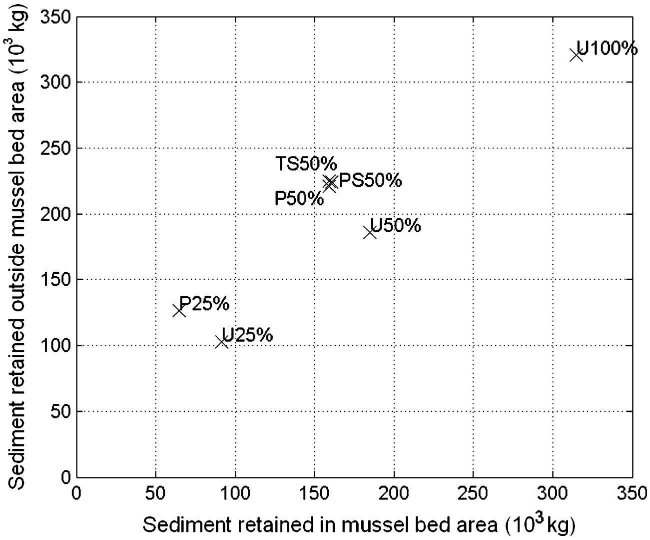

**Fig. 9.** Influence of patterning on deposition inside and outside the mussel bed area. Abbreviations refer to imposed mussel bed patterns as presented in Fig. 4. Note that the mussel bed area is taken to be the same for all simulations, i.e. only in U 100% is the mussel bed area fully covered with mussels.

relative to the reference situation. A distinction is made between the amount of sediment retained inside and outside the mussel bed. It is clear that the striped and patchy patterns capture less sediment inside the mussel bed and more in the wake of the mussel bed, as compared with a uniform mussel bed of the same size. This effect can be explained by considering that an open structure will allow higher flow velocities than a dense uniform mussel bed. Higher velocities mean more erosion and less deposition. However, the higher velocities also mean that the flow as a whole loses more energy (see Eqs. (1) and (2), momentum due to bed roughness is proportional to the square of the velocity), resulting in an overall lower flow velocity. This means that the wake of the mussel bed on average experiences lower velocities and thus higher deposition/lower erosion.

It is interesting to see that patchy and striped beds, which are common in the Wadden Sea, reduce the amount of captured sediment. There are reasons to believe that elevating its surroundings can be advantageous to mussels: it puts the entire bed out of reach of predators such as crabs (Brinkman et al., 2002) and being higher in the flow can offer an advantage in feeding for individual mussels. However, the high sedimentation associated with this elevation can also have negative effects. It has been shown that mussel beds can actually be smothered as a result of sedimentation (Ten Brinke et al., 1995). Even if not fatal, constantly having to crawl out of the sediment and having to reattach to other mussels will be a drain on mussel energy levels. Finally, quick deposition will result in highly unconsolidated sediment, making it easier for the entire bed (including mussels) to erode. Therefore it can well be argued that it is advantageous for mussels to rise up slowly, which is achieved when the waste products such as (pseudo-)fecal pellets are resuspended as much as possible. It can be seen in Fig. 9 that the transverse striped pattern accumulates the least amount of sediment, although only slightly. Apparently this pattern is most efficient in allowing the flow to take away the excess in waste products. If rising slowly is indeed advantageous to mussels, this study shows that mussel survival benefits from self-organizing into striped patterns oriented transverse to the flow. This finding is supplemental to earlier research which showed in a modeling study that self-organization of mussel beds in patches or stripes optimize availability of algae (Van de Koppel et al., 2005). The relatively high flow velocities that are associated with patchy organization are better able to both replenish the food supply and carry away unwanted sediment. Thus, there are several benefits for mussels to prefer self-organization in patchy or striped patterns above forming a homogeneous bed with an equal density.

## 7. Conclusions and recommendations

We showed that modeling mussel bed influence on fine sediment dynamics is indeed possible. Young mussels protect precipitated sediment from erosion by climbing on top and covering it. Comparable amounts of sediment are deposited inside the mussel bed (mainly determined by the filtration rate) and in the wake of the mussel bed (mainly determined by the hydraulic roughness of the mussel bed). This knowledge can assist in applying mussel beds as an engineering tool. Finally, patchiness has been shown to reduce the amount of sediment depositing inside the mussel bed. This gives another reason that self-organization of mussel beds into patchy or striped patterned beds, as observed in the Wadden Sea, is beneficial to mussel survival.

This study takes a first step in predicting the impact of mussel beds on the fine sediment balance. The presented modeling approach offers insight in patterns of sedimentation on a mudflat scale within a calm summer period for low to intermediate concentrations of fine sediment, its validity is limited to those conditions. It would be particularly interesting to adapt the mussel bed implementation so that waves (and thus winter conditions) can be modeled, thus enabling the simulation of (and validation for) development over a full year. Mussel beds form both a seasonal and a longer term storage of fine sediment. The seasonal storage is due to young mussel beds capturing large amounts of fine sediment in summer, as simulated in this research. In winter, around half of these mussel beds are eroded and the captured sediment is resuspended (Dankers et al., 2004). This seasonal effect of stabilization in summer and re-exposure in winter is comparable to another biogeomorphological stabilizer: microphytobenthos, which forms protective algal mats during summer (Andersen, 2005). Additionally, mussel beds which survive the first winter become more erosion resistant and as such form a stable storage of sediment which can remain for many years. For future use, adequate monitoring of a developing mussel bed will be important to validate the presented model approach.

Another valuable direction for future research will be to investigate the effect on basin scale of mussel beds to decrease turbidity of channel-flat-marsh systems and to redistribute fine sediment deposits. Quantification of these effects can be used to extend model studies of biological influence on fine sediment dynamics on the Wadden Sea scale (Borsje et al., 2008). Only then will it become clear whether mussel beds are a significant factor, influencing turbidity and possibly long term morphological processes in the Wadden Sea. These insights could result in adaptation of management of mussel fishery and protection schemes of mussel beds in the Wadden Sea and other coastal areas.

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