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Verfügbar unter/Available at: <https://hdl.handle.net/20.500.11970/99484>

Vorgeschlagene Zitierweise/Suggested citation:

Nasermoaddeli, Mohammad Hassan; Kösters, Frank; Hofmeister, Richard; Lemmen, Carsten; Wirtz, Kai (2014): First Results of Modelling Benthos Influence on Sediment Entrainment Using a Generic Approach within the MOSSCO Framework. In: Lehfeldt, Rainer; Kopmann, Rebekka (Hg.): ICHE 2014. Proceedings of the 11th International Conference on Hydroscience & Engineering. Karlsruhe: Bundesanstalt für Wasserbau. S. 625-632.

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# First Results of Modelling Benthos Influence on Sediment Entrainment Using a Generic Approach within the MOSSCO Framework

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**ABSTRACT:** Flow and sediment transport in coastal areas and shelves can be affected by the presence of benthic organisms. Depending on their feeding, sheltering and locomotion behavior, they may stabilize or destabilize the sediment by altering the erodibility, the critical bed shear stress, roughness, mud content, sediment aggregation and settling velocity. Near bed flow velocity and thereby bed shear stress can be further affected by the shape of benthic organism, tracks, burrows and tubes. Biodeposition and resuspension as well as fecal pellet production affect sediment concentration in the water column. Such biological effects have been often ignored in coastal and shelf-sea models or partly included only, i.e. in a very specific setup of a model or limited to only few different organisms. To overcome these limitations a generic platform has been developed here, which allows formulation of biological effects of an unlimited number of benthic organism provided that these effects have been already parameterized. This generic benthic geocology model (GBGM) was coupled to the MOSSCO (MODular System for Shelves and Coasts) framework to study the biological effects of the bivalve *Abra alba* and microphytobenthos in the North Sea. The coupled model was finally applied to a case study in the North Sea to evaluate the plausibility of the model and of the framework. The first simulation results are successful: they show the expected amplification and attenuation of the sediment concentration in the water column caused by the benthos biological effect.

*Keywords: Biological effects, Sediment transport, Abra alba, Microphytobenthos, MOSSCO*

## 1 INTRODUCTION

Organisms living on or within the sea floor ranging from plants to animals are referred to as benthos (Lalli and Parsons 1997). Benthic animals living wholly or partly within the substrate are called “infauna”, which include for example many clams and polychaetes. They are mostly abundant in subtidal regions with soft substrates. “Epifauna” refers to animals living on or attached to the seafloor, including corals, mussels, many starfishes and sponges. They are mainly present on hard substrates. In- and epifauna organisms larger than 1mm are referred to as “macrofauna” (Lalli und Parsons 1997). “Microphytobenthos” refers to a group of microscopic plants; including diatoms, cyanobacteria, blue and green algae and dinoflagellates. All these benthos groups either by their presence or activity shape their physical micro-environments.

Benthos in particular significantly affects hydrodynamics and sediment transport. Benthic organisms can either stabilize or destabilize sediments, depending on their feeding, sheltering and locomotion behavior. The erodibility of sediment can be notably modified by the mucus produced by benthic organisms such as extracellular polymeric substances (EPS) secreted by microphytobenthos (Paterson 1997).

Erodibility can be affected by macrofauna, either through the modification of roughness, or by bioturbation. Bioturbation represents “all processes implying sediment particles displacements generated by benthic organism in order to satisfy their vital needs (motion, protection from predators, feeding and excretion)” (Le Hir et al. 2007). Protrusion of benthic animals and macrophytes in the boundary layer changes the bed roughness and thus bed shear stress (BSS). Roughness increases due to the organisms themselves, or their tubes, tracks or burrows: protruding organisms can this way double the roughness of

the sea bed (Nowell et al. 1981). In case of motile animals, the density of roughness elements from tracks at the sea floor might be higher than the animals' roughness (e.g. *Hydrobia ulvae*, Orvain 2002). Increase of bed roughness from biogenic structures (e.g. body shape, tubes, or tracks) enhances bed shear stress and potentially bed erosion. Wave and currents may be strongly damped due to dense occupation of biota (Le Hir et al. 2007).

Moreover, feeding and locomotion of macrofauna alter sediment aggregation (Andersen and Pejrup 2011), but these effects can be highly seasonal (Le Hir et al. 2007). Production of fecal pellets and pseudo-feces by macrofauna results in aggregation of suspended particles, changing the settling velocity. Graf and Rosenberg (1997) have shown that physical properties of marine sediments, such as porosity and permeability can also be modified by benthic infauna.

For example, *Macoma balthica* is a bioturbating bivalve (clam) that lives a few centimeters below the sediment surface while feeding on the sediment surface or suspended sediment in the water column above. These bivalves inhabit generally intertidal areas with fine sediment (median particle diameter less than 0.2 mm) and occur up to a water depth of 20 m in coastal areas in Europe and North America (Bachelet 1980; Kamermans et al. 1999, in Montserrat Trotsenburg 2011). Bioturbation is the consequence of burrowing in sediment and deposit feeding (Andersen and Pejrup 2011). According to Widdows et al. (1998, 2000, 2000), *M. balthica* causes an increase of the erosion rate of mudflats because of its bioturbation of surface sediments, the rate of which depends primarily on their density. They probably indirectly affect erodibility by grazing on benthic diatoms, which otherwise would have a stabilizing effect on the bed (Andersen and Pejrup 2011). *Abra alba* is a bivalve similar to *M. balthica*, which modifies sediment aggregation by production of fecal pellets.

In this study, we propose a new model framework that enables to represent benthic biota effect within sediment transport models. We here focus on stabilizing and destabilizing effects of benthic fauna on sediment erodibility. Using a novel coupling approach we investigate the effects of those two key species on sediment dynamics in shallow marine waters.

## 2 MATHEMATICAL APPROACH

In the last 15 years, many process-based models have been developed, in which biological effects on the sediment transport have been parameterized as forcing variables (e.g. Wood et al. 2002, Knaapen et al. 2003, Paarlberg et al. 2005) or biological processes have been modeled using differential equations (François et al. 1997, 2002, Orvain et al. 2003, Orvain 2005, Montserrat Trotsenburg 2011, Orvain et al. 2012). According to Le Hir et al. (2007), however, mathematical models for a direct coupling of physical and biological processes, which include two-way feedbacks between biology and physics, do not exist yet.

While the effect of microphytobenthos on the erosion threshold is correlated with Chl a, EPS or colloidal carbohydrates in the literature, such a relation could rarely be established for macrofauna. Hence, there are different approaches available to model specific biological effects of individual species on particulate sediment transport parameters.

Knaapen et al. (2003) proposed a simple concept to include biological effects in morphological models. Bioturbation and biostabilization cause a reduction and increase of critical bed shear stress, respectively. To model these effects, the following relation is taken

$$\tau_c = \tau_{c0} \cdot f_d(M) \cdot f_s(c_p) \quad (1)$$

where  $\tau_{c0}$  and  $\tau_c$  are the critical bed shear stress without and with biological influence. The stabilization function  $f_s$  increases with increase in concentration of microphytobenthos  $c_p$ , leading to higher critical bed shear stress. The perturbation function  $f_d$  decreases with increase of the abundance of organism,  $M$ , resulting in a lower critical bed shear stress. This approach assumes that the biological effect of each species can be parameterized separately and used as a multiplication factor in the above equation. Based on the Widdows et al. (2000) parametrization of the biostabilisation of microphytobenthos and the relation between bed stability and the density of *M. balthica* in the Humber estuary the following equations were derived for  $f_s$  and  $f_d$  by (Knaapen et al. 2003):

$$f_s(c_p) = 1 + 0.08 \cdot c_p \quad (2)$$

$$f_d(M) = 0.0016 \cdot \ln(M^2) - 0.085 \cdot \ln(M) + 1 \quad (3)$$

in which  $c_p$  is the chlorophyll a concentration within the sediment ( $\mu\text{g}\cdot\text{g}^{-1}$ ), and  $M$  is the dimensionless density ( $\text{ind.}/\text{m}^2$ ) of the *bivalve*. However, the validity range of the empirical equation of  $f_s$  is likely rather small because of a relatively small number of underlying observations.

Paarlberg et al. (2005) followed a similar approach as Knaapen et al. (2003), but included additionally modification factors for erosion and bioturbation coefficients.

$$\varepsilon^{bio} = \varepsilon^0 \cdot g_d(M) \cdot g_s(c_p) \quad (4)$$

$$g_s(c_p) = 1 - 0.018 \cdot c_p \quad (5)$$

$$g_d(M) = \frac{b_2 \gamma}{(b_2 + \gamma \cdot b_1^M) I} \quad (6)$$

where  $\varepsilon^{bio}$  is the erosion coefficient for cohesive sediment in the Partheniades (1965) equation including biological effects. The superscript 0 represents values without biological activities.  $g_s$  and  $g_d$  are stabilizing and destabilizing factors for the erosion coefficient, respectively. The latter factor was derived based on data presented by Widdows et al. (2000). The data has been interpreted in the light of Eq. 1 and the statistical relationships given Eq. 2, Eq. 3 and Eq. 5. The derivation of Eq. 6 is based on the assumption that the biological effect reaches a maximum with increasing  $M$ , after which it remains constant. The maximum biological erosion coefficient of  $\gamma = 6 \times 10^{-7} \text{ms}^{-1}$  was estimated from data presented by Widdows and Brinsley (2002). In Eq. 6, the erosion coefficient without biological influence ( $I$ ) is equal to  $4.68 \times 10^{-8} \text{ms}^{-1}$  to scale the relationship, which is derived from Widdows et al. (2000).  $b_1 = 0.995$  and  $b_2 = 5.08 \times 10^{-8} \text{ms}^{-1}$  are both regression coefficient of an S-shaped fitting curve. It should be noted that few data were applied to generate Eq. 5 and Eq. 6, thus the level of confidence is low. In the above-mentioned model, feed-back interactions among organisms as well as sediment transport and bed level changes on benthos community (i.e. abundance of species) have been neglected. Furthermore, direct biodeposition and bioresuspension are not taken into account. It was deduced from the simulation results that biological activities have a significant effect on the sediment transport and morphology.

### 3 CONCEPTUAL MODEL

The interaction of macrofauna and sediment transport is complex as described in the introduction. Interaction of different physical time scales from tidal to diurnal with various biological time scales make it difficult to model biological effects on erodibility (Le Hir et al. 2007). Moreover, it has to be kept in mind that the erodibility of natural sediments is variable in space and time. Benthic biota is distributed non-uniformly, e.g. as patches. The effects of individual species on sediment erodibility may interact nonlinearly, which makes it very difficult to account for in sediment transport modeling. In addition to the spatial variability, biological components undergo temporal (seasonal) variation.

As a starting point a uniform distribution of organisms with no interaction among individuals has been considered in the present approach. It is assumed that the resultant biological effect of a benthos community on a specific sediment transport parameter, for example erodibility, can be either calculated by multiplication of the biological factor of each individual species according to Eq. 1 to Eq. 6 or for a community of species with similar functional traits. The so-calculated biological factor is then included in the corresponding equations such as Eq. 1 and Eq. 4. So far temporal variations of macrofauna communities have not been included.

An object-oriented programming approach was applied to develop a flexible platform for the inclusion of different species and their corresponding biological effects. To describe the biological effects of species within this platform, an object is first created from any of the three available generic classes, macrofauna, microphytobenthos and macrophytes. The desired biological effects are then included in the object structure as an object method (function). In this way an arbitrary number of species and biological effects can be added to the platform by extending each of the above-mentioned generic classes with the desired organism. A generic interface for macrofauna allows the superposition of individual macrofauna organisms or the overall community effect on each sediment transport parameter, as shown in Fig. 1. For example, *A.alba* is a subclass of macrofauna having two methods for calculating its effect on the critical bed shear stress and erodibility according to Eq. 3 to Eq. 6. Other macrofauna species are generated in a similar way and their effects are superimposed within the generic interface for macrofauna, provided that proper parameterizations are available for individual species or ideally for a functional group of macrofauna community. The above mentioned platform is neither limited to the number of species nor to the number of sediment transport parameters.

To account for benthos effects on the sediment transport, the above mentioned program was coupled to the geological (bed) model of Delft3D (abridged version) via the modular coupling framework of MOSSCO. This innovative modular framework integrates diverse models across physical domains from benthic to atmospheric components and diverse processes within each domain (Lemmen et al., 2013; Lemmen et al. 2014; Hofmeister et al. 2014). In the current 1D setup of MOSSCO, the hydrodynamic model GOTM and sediment transport driver within FABM (Framework for Aquatic Biogeochemical Models) were applied to model flow and sediment transport in addition to the Delft3D (abridged) and the above-mentioned benthos model.

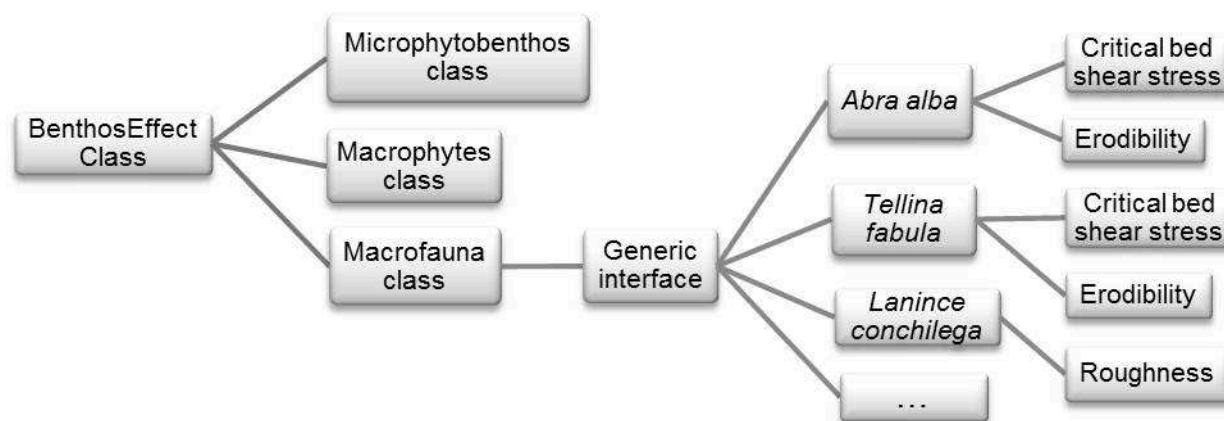


Figure 1. Structure of the generic modular benthic geocology model within the MOSSCO framework

#### 4 SIMULATION RESULTS - 1D CASE STUDY

The first case-study results of the model are presented in the following, which illustrates the contrasting effects of sediment stabilization and destabilization by means of biological effects. The 1D test case allows verifying the functionality of the MOSSCO framework and more specifically to evaluate the plausibility of the generic benthic geocological model. The 1D set-up represents hydrological and biological conditions at a station about 15 km southeast of Helgoland in the German Bight on March 2013. The 1D-setup includes the measured velocity profile, water level, macrofauna distribution and grain size analysis of the bottom sediments. As atmospheric forcing data from Helgoland station were applied. According to the measurements, the seabed comprises 30% cohesive sediment with a mean diameter of 27  $\mu\text{m}$  and 70% non-cohesive sand of 350  $\mu\text{m}$ . The parameters used for the simulation of sediment transport are given in table 1 (mean diameter, erosion parameters, settling velocity). The averaged water depth at the tidally influenced station has been measured to be about 26 m. Velocities range from 0 m/s to 1 m/s.

Table 1. Sediment parameterization

Sediment	Cohesive	non-cohesive
Critical bed shear stress (Pa)	0.,17	0.19
Erodibility ( $\text{kgm}^{-1}\text{s}^{-1}$ )	2.0e-5	-
Settling velocity( $\text{ms}^{-1}$ )	0.0003	0.013
Critical shear stress for mud deposition *(Pa)	1000	-

\* High value allows for permanent deposition

As can be seen from Fig. 2, the flow velocity follows the tidal sea level fluctuations during both ebb and flood phases. The velocity range corresponds well to measured velocities, although differences of the location of maximum velocities occur. Measured velocities were used as initial values and depth-averaged values as boundary condition.

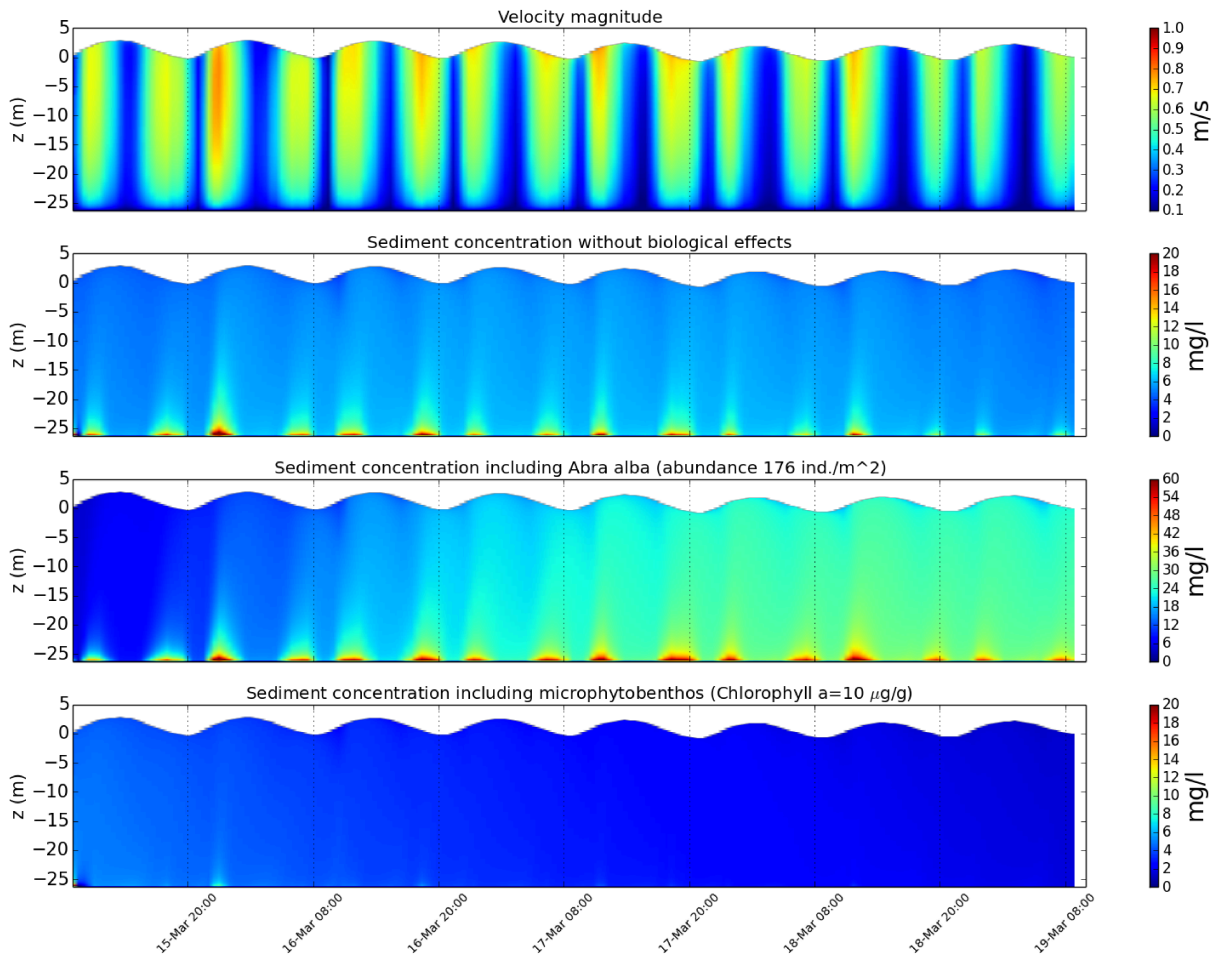


Figure 2. Simulation results of 1D-setup for 15 km southeast of Helgoland in the North Sea.

Based on calculated velocities, the total sediment concentration has been simulated with and without biological effects. Note that the first day of simulation is affected by initial conditions and should therefore not be interpreted. As can be seen from Fig. 2, the sediment concentration in the water column changes in phase with current velocities, presenting a plausible trend in case of no biological effects. The peak SPM concentrations in the water column correspond to the peak velocity magnitudes. Due to a lack of calibrated suspended particulate matter (SPM) measurements, the magnitude of SPM concentration cannot be justified. But a proper sediment concentration trend can be observed from the simulation. As already mentioned above, the purpose of the simulation has been a plausibility analysis of MOSSCO and the newly developed benthic geocology model.

Typically the destabilizing effect should be observed as an increase of SPM in the water column. This can be observed in case of setting the abundance of *A. alba* to 176 ind./m<sup>2</sup> (based on probes on March 2013) in the 1D-setup as seen in Fig. 2. Furthermore, the fluctuation of SPM concentration matches well those of tidal flow velocity. However, this high destabilizing impact on the sediment concentration (2-3 times increase of SPM concentration) is subject to large uncertainties. Neither a direct parameterization for the biological effect of this species on the sediment transport is available nor sediment concentration data for the station, therefore a reliable validation of simulation results is hardly feasible. However, the general trend of an increase in SPM concentration by an order of magnitude has been reported as a consequence of biological destabilization as explained in the introduction.

The availability of microphytobenthos is often measured by Chlorophyll a biomass content in the sea bed sediment mass. By setting this value to 10 µg g<sup>-1</sup>, bed sediment erosion is almost prohibited for current velocities considered here. Since the source of sediment in the water column is the vertical flux from bed, the initial SPM concentration reduces gradually due to the settling of the (cohesive) sediment particles so that the simulated SPM concentration approaches almost to zero. This result also confirms the plausibility of the GBGM and MOSSCO platform. It should be noted that more research is required to parameterize different biological effects of individual species or a community.

## 5 CONCLUSION

We developed a generic module for implementing biological effects of benthic biota (microphytes and macrofauna) on sediment transport. A deliberate number of organisms or functional groups within a community and their biological effects can be generated from generic objects, provided that parameterizations for individual sediment transport parameters are available for each organism or functional group. Therefore, our approach can be used as a library for biological effects on sediment transport. Coupling this generic benthic geoecological model (GBGM) with the arising MOSSCO framework allowed us to study the biological effects of a bivalve (*Abra alba*) and microphytobenthos on sediment dynamics. The MOSSCO configuration comprised the coupling of GBGM with atmospheric, pelagic and benthic domains. Our first results in a 1D-setup applied to a site southeast of Helgoland (North Sea) reveal an overall qualitative consistency. The simulations in particular represent plausible results for water current and sediment transport. Expected biological effects on sediment concentration could be produced reasonably for both organisms, confirming the sound functionality of GBGM and the coupling framework (MOSSCO). Future model verification requires simultaneous measurements of sediment fluxes, water physics (turbulent), and activity of benthic biota.

## ACKNOWLEDGEMENT

The MOSSCO project was funded by the German BMBF as part of the Coastal Research Agenda for the North Sea and Baltic Sea. This work results from joint efforts of the MOSSCO partners (grants 03F0668A, 03F0667A). Contributions of the NOAH project (C. Winter, Marum and I. Kröncke, Senckenberg Institute) and Deltares are thankfully acknowledged.

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