

## Modeling bio-geomorphological influences for offshore sandwaves

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The coastal environment shows a wide range of bed patterns, for which sandwaves and sandbanks are the most common. Less known in this context is the high benthos diversity in the coastal environment, which gives rise to the question to what extent the benthos interacts with the shape of the seabed. This paper reviews field and flume experiments on bio-geomorphological influences between benthos and sediment and tests the hypothesis that both the occurrence and the dimensions of sandwaves and sandbanks are dependent on the benthos diversity in the North Sea. Mathematical inclusions to account for biological activity in idealized models reveal that biota is able to influence the wavelength of sandwave significantly, compared to the default case. More importantly, the models indicate that biota is able to induce bed patterns while the physical parameters suggest a stable flat bed and vice versa. Present model explorations indicate that future research should focus on the parameterization of subtidal biological activity on sediment dynamics and thereby on seabed patterns. Such knowledge will enable process based modeling of the spatial and temporal variation in biological activity on seabed morphodynamics and validate the proposed model with field measurements.

### Introduction

Coastal areas are highly important both from an ecological and economical perspective, as these areas serve both for a broad variety of human activities and form the habitat for a broad variety of benthic organisms. Many human activities such as offshore constructions, maintaining navigation channels, constructing pipelines and telecommunication cables depend on a good understanding of the sediment dynamics in these coastal waters (Németh et al., 2003). The conservation and management of the benthic biodiversity in the coastal zone also requires knowledge about spatial and temporal distribution of macrobenthic species and thus the sediment dynamics (Borja et al., 2000). Hence there is both from an ecological and economical perspective a growing interest in the biophysical interactions between benthos and their sedimentary environment. Studies from intertidal areas indicate that benthos can strongly influence local sediment composition and dynamics, by acting as either

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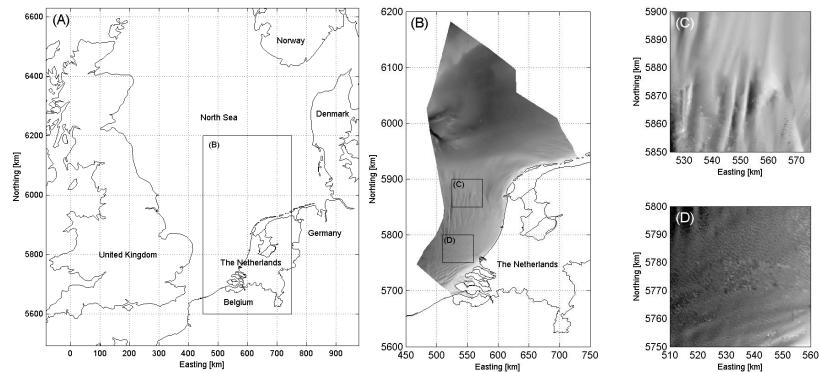
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stabilizers or destabilizers (e.g. Widdows and Brinsley, 2002). The subtidal seabed is neither flat nor static, and significant differences can be found in the benthic assemblage related to meso-scale bedforms at the subtidal seabed (e.g., Baptist et al. 2006). Nevertheless, the feedback effects from these assemblages to the characteristics of the subtidal bedforms have not yet been studied.

Nowadays, idealized models are often used to predict seabed dynamics (for an overview see Besio et al., 2008). However, the hydrodynamics and sediment dynamics in these models lacks correction for biological activity. Given the predictive power of the idealized models, extending the models with biological activity will give us a tool to manage the utilization and conservation of the seabed.

The aim of this paper is (1) to explore the influences between biota and bedforms in a subtidal environment and (2) to propose formulations to include bio-geomorphological influences in idealized models. We will achieve these objectives by reviewing the offshore environment both from a morphodynamic and benthic perspective (Section 2) and the known impact of some key benthic species in the subtidal environment on the hydrodynamics and sediment dynamics (Section 3). We subsequently focus on methods to model such bio-geomorphological influences between key benthic species and hydrodynamics plus sediment dynamics (Section 4), where after the main findings of this paper are discussed (Section 5), leading to important general conclusions (Section 6). In the present paper we use the Dutch part of the North Sea as example, as it has been relatively well described with respect to bedforms and organisms (detailed in next Sections).



**Figure 1. Seabed patterns in the Dutch part of the North Sea (A), in which sandbanks (C) and sandwave fields (D) can be distinguished. Grid size is 200 x 200 m.**

### OFFSHORE ENVIRONMENT OF THE DUTCH COAST

The Dutch part of the North Sea covers roughly 57,000 km<sup>2</sup> with a maximum water depth of 70 m (Figure 1a). Several bed forms are present at the offshore seabed (Figure 1b), distinguishable on their wavelength, height, orientation with respect to the tidal current and the capability to migrate. Sandbanks (Figure 1c) have wavelengths (distance between two crests) of a few kilometers and an amplitude of tens of meters. The orientation of the crests with respect to the principal direction of the tidal current is up to 40° anticlockwise in the Northern Hemisphere. There is no evidence that sandbanks move (Dyer and Huntley, 1999). Sandwaves (figure 1d) have much smaller wavelengths (of the order of hundreds of meters), while the heights are up to 5 m. Sandwaves migrate with a speed of tens of meters per year (McCave, 1971). Their orientation is almost perpendicular to the direction of the main current. Sandbanks are associated with relatively weak tidal currents, whereas sandwaves are related to strong tidal currents. As a result, sandbank and sandwave fields sometimes partly overlap.

The bottom of the North Sea is inhabited by a great number of benthic organisms that live in and on the bottom of the sea (Heip et al., 1992; Künitzer et al., 1992; Rabaut et al., 2007). By their activities these benthic organisms can modify their habitat, which is generally referred to as bio-geomorphological influences. The benthic communities composition on the seabed is generally related to physical parameters like median grain size, slope, mud content and water depth (e.g. Degraer et al., 2008).

In the present paper, we focus on three species that are (1) characteristic for benthos living in sandwaves and sandbanks, (2) can be found in large amounts in and on the bed and (3) have significant influences on the surrounding environment. The first one is the sea urchin *Echinocardium cordatum*, which is usually 40-50 mm in length, has a density distribution of around 20 individuals per m<sup>2</sup> and lives up to 200 mm deep into the sediment.

The second species is tube building worm *Lanice conchilega*. The worm can reach a length up to 150 mm, partly protruding from the sediment and its density distribution is locally extremely large (over 3000 ind. m<sup>-2</sup>). Finally, as third species we study the clam *Tellina fabula*, which has a maximum shell length of 20 mm, a slight smaller density distribution compared to *E. cordatum* of around 15 individuals per m<sup>2</sup> and lives up to 100 mm deep in the sediment.

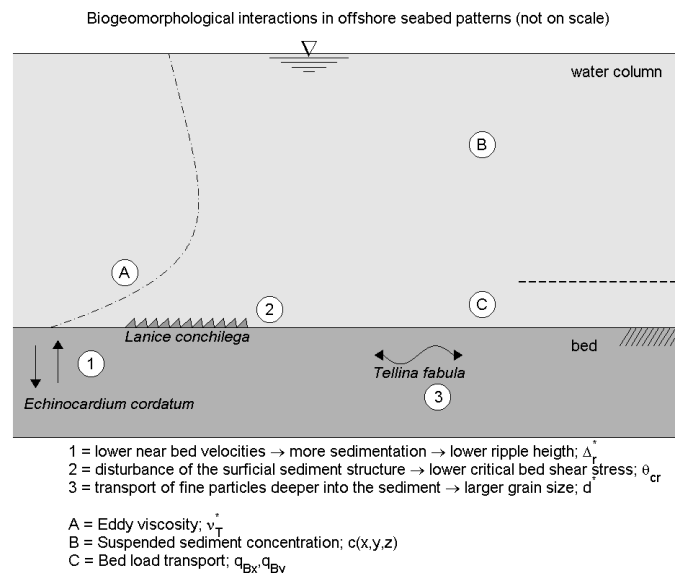
The influence of these three species on the sediment dynamics and hydrodynamics will be compared to the default case, which is defined as the situation in which no biological activity is present.

## IMPACT OF SUBTIDAL BIOTAL ON SEDIMENT DYNAMICS AND HYDRODYNAMICS

The interaction between biota and sediment dynamics has been well studied and clearly shown for the intertidal environment, in field studies (e.g. Austen et al., 1999), flume experiments (e.g. Widdows et al., 1998) and modeling studies (e.g. Borsje et al., 2008a). All these studies conclude that biota is able to influence both the sediment dynamics and hydrodynamics by several orders of magnitude and acts on a large spatial (tidal basin) and temporal (seasonal and inter-annual) scale. Compared to the benthos biomass in intertidal systems, the benthos biomass in subtidal areas in the North Sea area is much smaller. Nevertheless, some explorative studies already show that such relatively small benthic biomass still influences the sediment dynamics significantly (e.g., Borsje et al., 2008b). We will now review the available research for those three benthic species that are most relevant for subtidal sandbanks and sandwaves: *Echinocardium cordatum*, *Lanice conchilega*, and *Tellina fabula*.

The sea urchin *Echinocardium cordatum* has been shown to displace up to  $20,000 \text{ cm}^3 \text{ m}^{-2} \text{ d}^{-1}$ , causing the surface sediment to be reworked about once every 3-4 days (Lohrer et al., 2005). Moreover, field experiments in the Gullmar Fjord (Western Sweden) show that the reworking intensity was directly related to the biovolume of the *E. cordatum* individuals (Gilbert et al. 2007). Being a surface deposit feeder, *E. cordatum* may rapidly transport particles from the sediment surface deeper into the sediment (Osinga et al., 1997), which results in a heterogeneous sediment distribution in the top centimeters of the bed (Figure 2). Although *E. cordatum* is regarded as a non-selective deposit feeder (Lohrer et al., 2005), its feeding activity will for two reasons result in a top layer of the sediment that consists of relatively coarser particles, compared to the default case in the absence of benthos.

Firstly, *E. cordatum* feeds on organic matter. Given that fine sediment is richer in organic matter, compared to coarse sediment (Burenó et al., 2003), *E. cordatum* moves to a new spot after it has reworked all the fine sediment, leaving the coarser sediment particles that are not ingested at their original position on top of the sediment (Cramer et al., 1991). Secondly, the chance to get ingested and brought downward is larger for small particles relative to coarse particles, as finer particles have a relative larger surface area. A comparable non-selective deposit feeder (*Arenicola marina*), is able to double the grain size in the top five centimeters of the bed, compared to the case in which no *A. marina* was included, for an experiment with initially the same vertical sediment distribution (Baumfalk, 1979).



**Figure 2. Schematic overview of the bio-geomorphological influences (1-3) by *Echinocardium cordatum*, *Lanice conchilega* and *Tellina fabula*, and the consequences for the sediment dynamics and hydrodynamics (A-D).**

The tube building worm *Lanice conchilega*, is known to occur in high densities which have a decelerating effect on the near bottom flow, and thereby cause fine particles to deposit within such patches (Eckman et al., 1981; Rabaut et al., 2007). Given both the lower near-bottom flow velocity and a smaller medium grain size at the sediment surface compared to the default case in the absence of benthos, the ripples on top of the sediment surface are lower (Figure 2), as observed in the field by Featherstone and Risk (1977). Such effect is highly important, as ripples are the main origin of sea bed roughness and one of the main determinants of the amount of sediment transported (see discussion in Section 4.1). Given the maximum density of *L. conchilega* found in the North Sea (3,000 ind.  $m^{-2}$ ) the near bottom velocity will reduce to 30% of the near bottom flow, relative to the default case, according to flume experiment by Friedrichs et al. (2000). Such flow reduction will decrease the ripple height up to 70%, based on empirical relations given by O'Donoghue et al. (2006).

The bivalve *Tellina fabula* is a selective deposit feeder as well as a suspension feeder. Due to its burrowing and feeding activities, the surficial sediment structure is disturbed, making it more prone to erosion (Austen et al., 1999). Data on the bio-engineering capacity of the bivalve *T. fabula* are scarce, but the sediment modification by the bivalve *Macoma balthica* is much better known (e.g. Widdows et al., 2000). Whereas both bivalves have comparable feeding strategies, they occur in quite different sediment types. However, *M.*

*balthica* is mostly found in muddy sediments, while *T. fabula* prefers fine sediments. Therefore, the distribution of *M. balthica* is much more bordered close to the coast, in contrast to *T. fabula* which can be found in all other parts of the North Sea. Based on field measurements, Borsje et al., (2008a) constructed a parameterization of the relation between the biomass *M. balthica* and the critical bed shear stress. Small biomass grazers contribute to the largest modification of the critical bed shear stress, whereas larger biomass grazers will not further reduce the critical bed shear stress. In other words, for large biomass grazers, the critical bed shear stress will be 60% compared to the critical bed shear stress for the default case.

### **MODELING THE ROLE OF BIO-GEOMORPHOLOGICAL INFLUENCES FOR SEABED PATTERNS**

The model used in the present paper is based on the work by Besio et al., (2006) and later modified by Cherlet et al. (2007), whom modeled sandwave lengths along the Belgium Continental Shelf. By linking the relations described in Section 3 with the idealized model of Cherlet et al., (2007), a first insight can be obtained in the possible influence of benthos on the wave length and occurrence of offshore sandwaves.

The model is run for two different cases: using the default parameter settings without including biological activity (default case) and a case in which the transport parameters are modified by the presence of biological activity (biological case).

The results for the default case are in accordance with the results discussed by Borsje et al. (2008b), and are only discussed briefly hereafter. By increasing the waterdepth (left panels Figure 3), the wavelength for the sandwaves in the default case grow almost linearly. This observation is the result of a decrease in the Shields parameter for an increase of waterdepth, causing lower transport rates and resulting in longer sandwaves (Besio et al., 2006). By increasing the medium grain size (middle panels Figure 3) the default model results first in a shorter wavelength. This reduction in wavelength is caused by a decrease in suspended sediment concentrations for increasing grain sizes, since the presence of suspended sediment tends to increase the wavelength of sandwaves. However, once a critical grain size threshold is passed (i.e.,  $d_{50}$  around 0.45 mm), the wavelength of the sandwaves increase strongly with grain size, as sediment is only transported as bed load (middle panels Figure 3).

Finally, an increase in flow velocity (right panels Figure 3) causes a decrease in wavelength, indicating that stronger tidal currents tend to generate shorter sandwaves. However, the wavelength of the sandwaves does reach a minimum. The latter may be explained that in case of very strong tidal currents, the suspended sediment provides a stabilizing mechanism, resulting in sandwaves with an almost constant wavelength.

The results for the biological case shows a clear difference, compared to the default case. *E. cordatum* initiated longer sandwaves compared to the physical case. For almost all other model settings, less sediment is transported as both bed-load and suspended load in the case for which *E. cordatum* is included, resulting in longer sandwaves. The contradiction for small grain sizes is due to the fact that small grain sizes are related to high suspended sediment concentrations and therefore to longer sandwaves. However, due to the presence of *E. cordatum* the suspended sediment concentrations for small grain sizes are significantly lower, because the grain size at the bed-water interface is doubled. Consequently, the wavelength for this typical model settings is smaller, compared to the default case.

The influence of *L. conchilega* is clearly opposite to the effect of *E. cordatum*, as *L. conchilega* causes sandwaves to become shorter compared to the physical case (Figure 3). The main difference for the case in which *L. conchilega* is included relative to the case in which *E. cordatum* is included, is that the former species follows almost the same trend compared to the physical case, whereas the latter species is able to influence both the position and the trend of the line compared to the physical case.

The effect of *T. fabula* on the wavelength of the sandwaves is limited for current model parameter settings. As discussed before, *T. fabula* is only influencing the critical bed shear stress. Consequently, in the case where sediment transport is already present, as was the case for our model, *T. fabula* is hardly influencing the amount of bed-load or suspended load transport, and therefore of limited influence on the wavelength of the sandwaves (Figure 3). However, in those physical case where hardly any sediment transport is initiated, *T. fabula* is able to have a significant influence on the wavelength of sandwaves, as shown by Borsje et al. (2008b) for the Belgium Continental Shelf.

We subsequently modeled sandwaves at three locations in the North Sea, that were selected based on their contrasting process parameters. For every location, the model could give three distinctive outcomes. First, sandwaves are modeled with a certain wavelength (bars in Figure 4). Secondly, no sediment transport is initiated (squares in Figure 4). Finally, in some cases the bed turns out to be stable and flat due to the stabilizing effect of suspended sediment (triangles in Figure 4). Location 1 is characterized by a high flow velocity, small grain size and a moderate water depth. As a result, suspended sediment concentrations are high, resulting in a stable flat bed. However, due to presence of *E. cordatum* the grain size at the sediment water interface is larger, relatively to the default case. This higher grain size results in lower suspended sediment concentrations, and therefore a less destabilizing effect on the bed. Consequently the presence of *E. cordatum* allows the triggering of the formation of a wavy bed pattern, while in all other cases the bed is flat.

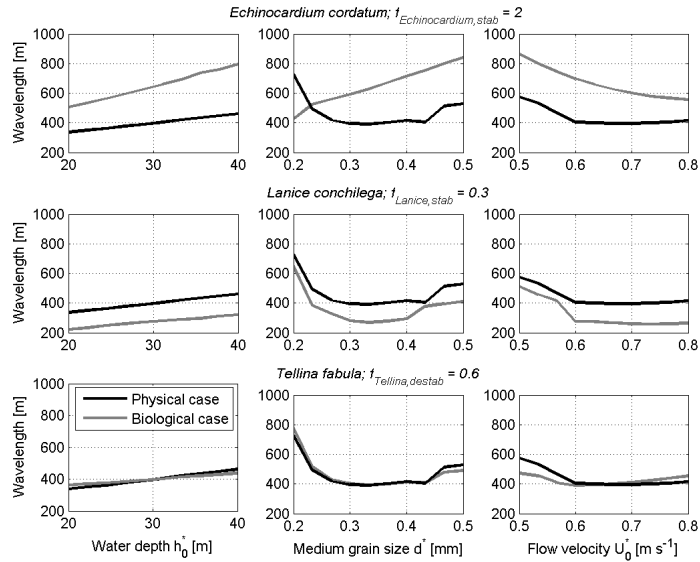


Figure 3. Model results for the physical case (black line) and biological case (gray line), for the three different bio-engineers (rows), and variation in the three different process parameters (columns).

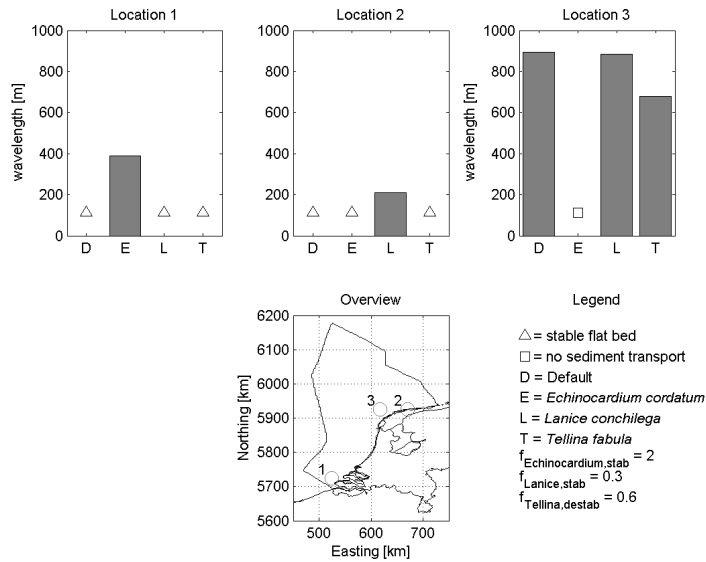


Figure 4. Model results for the occurrence of bedforms, for three different location on the Dutch part of the North Sea.



Location 2 only differs from location 1 by having a much smaller water depth and a slightly larger medium grain size. Similar to what we found for location 1, in most cases, the bed at location 2 also turns out to be a stable flat bed. The model however predicts that, *L. conchilega* is able to reduce the ripple height, and thereby preserving a wavy bed pattern. Finally, location 3 is characterized by a large water depth, and both a moderate flow velocity and grain size. In most cases, sediment is transported and sandwaves appear. However, the model indicates that at this location, *E. cordatum* will increase the grain size of the bed material and as a consequence, the sediment will not be transported.

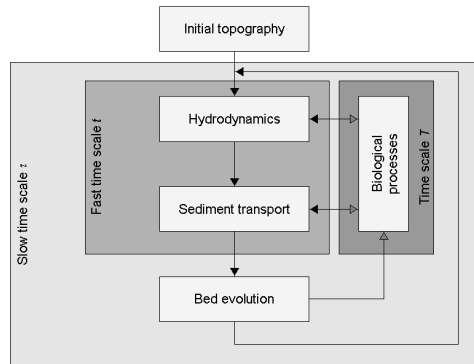
Based on these model simulations, we conclude that bio-engineers can influence both the wavelength and the presence of bedforms significantly.

## DISCUSSION

This paper explores the bio-geomorphological influences in offshore seabed patterns, using a model analysis of the interaction between hydrodynamics, geomorphodynamic and biological processes. From the bio-geomorphological loop (i.e., an extension of the morphological loop described by Roos and Hulscher, 2003) it is clear that each of these processes have different temporal and spatial scales (Figure 5). The separation in three timescales is essential, as the interaction between hydrodynamics, sediment transport and biological processes act within a tidal cycle (half a day) and the bed evolution acts on a much longer time  $\tau$  (decades to centuries).

The time scale on which the biological processes alter is seasonal. However, there are also strong indications that biological processes may differ on a much longer time and spatial scale. For example, due to a northerly shift in geographical distribution of key species as a result of global warming (Widdows and Brinsley, 2002).

Besides, there are also strong indications that a feedback exists from the bed evolution to the biological community and the processes they influence (e.g. Ryan et al., 2007). For example, Daniell et al., (2008) found a relation between the occurrence of seagrass beds on the one hand and dune migration and sand supply on the other hand. In the present model study, we explored a limited but important number of biological effects within the bio-geomorphological feedback loop (i.e., black arrows in Figure 5). It is an important challenge for the future, to extend these kind of explorations by including both temporal scales plus feedbacks from changes in hydrodynamics, sediment transport and bed evolution to the biological activity (white arrows in Figure 5). For this purpose, we first need a better parameterization of the biological activity to include in idealized models and good field sets for model validation.



**Figure 5.** The bio-morphological loop, which consist of the water movement (hydrodynamics), transport of sediment, biological processes and the bed evolution. Starting from a initial topography, the water movement initiates the transport of sediment. Both the hydrodynamics and sediment transport are influenced by biota. The fast time scale of the interaction between hydrodynamics, sediment transport and biological processes compared to the slow time scale of bed evolution, allows us to only focus on the tidal average sediment transport. The results is an updated topography, which is the input to start again the computation of the hydrodynamics and sediment transport rates.

## CONCLUSIONS

The Dutch part of the North Sea is not only characterized by different seabed patterns, but also by a diverse biological community. Some bio-engineering species within this benthic community are able to significantly influence the sediment transport processes and hydrodynamics in the North Sea area, and thereby have a direct relation to the morphodynamics of the seabed. Firstly, the sea urchin *Echinocardium cordatum* feeds from the surface sediment layer and brings fine sediment particles to the deeper sediment and consequently influences the vertical sediment distribution. Secondly, the clam *Tellina fabula* makes the top layer of the sediment more prone to erosion due to its burrowing and grazing activities. Accordingly, the critical bed shear stress for erosion reduces. Finally, the tube building worm *Lanice conchilega* reduces the near bottom flow and by this facilitates the deposition of fine material. As a result, the ripple height on top of the bed forms reduces.

By including the maximum modification of the transport parameters by these bio-engineers in an idealized sandwave model, a first insight is given in the bio-geomorphological interactions in offshore seabed patterns. First of all, the wavelength of the bed forms is significantly influenced and even more important: stabilizing bio-engineers are able to preserve a stable flat bed, while the physical conditions suggest bed patterns. Likewise the opposite effect is induced by destabilizing benthos.

Future research should focus on improving the parameterization of biological activity on the sediment transport parameters, and thereby generating a tool to extend current models with both temporal variation in biological activity and feedbacks from seabed evolution to the composition of the biological community. Moreover, gathering site specific field data both on physical parameters and biological activity will help to validate the proposed model.

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