Organisms influence fine sediment dynamics on basin scale

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ABSTRACT
The amount of fine sediment in the water phase and in the bed is an important factor influencing the functioning of the ecosystem. Therefore, man-made and natural changes in the amount and distribution of fine sediment will affect the functioning of the ecosystem. Many bottom dwelling organisms engineer the temporal and spatial distribution of fine sediment in the bed by actively changing settling and erosion processes. In this way organisms influence local habitat quality to their own advantage. Impact on settling and erosion processes will through changes in the bed force changes in the fine sediment availability in the water column. This study elaborates the effect of such local ecosystem-engineers on sediment budget and suspended sediment concentrations at the scale of whole tidal basins. In the Wadden Sea yearly average settling and erosion fluxes are roughly known on the basis of long term monitoring of suspended sediment concentrations. It is shown that the effect of ecosystem engineers, occurring predominantly on shallow areas (less then 3m water depth), causes erosion fluxes and suspended sediment concentrations to change significantly due to the seasonality of biomass variations. The effect could explain the seasonal variation in suspended sediment concentrations measured in the Wadden Sea. Absolute biomediated fluxes are comparable to exchange of fine sediment between North Sea and Wadden Sea. Biomediated fluxes are an order of magnitude larger than the multi-year averaged nett import flux of fine sediment into the Wadden Sea. The study results are in agreement with field data and it is shown that the effect of ecosystem engineers on erosion fluxes and on suspended sediment concentrations is quite large and will result in lower turbidity in the summer and higher turbidity in the winter on basin scale.

Introduction
Research on estuary scale is relevant for society because emergent ecological processes -such as ecosystem self design and human induced ecosystem engineering- act on this scale (Odum, 1996), and therefore, by definition, both must be interacting dynamically. Also, de Jonge (2000) argued that, for the Wadden Sea ecosystem, relevant temporal and spatial scales for management are both annual and basin wide, emphasizing the need for research on that scale.
In tidal basins, fine sediment availability (defined as mixture of cohesive and non-cohesive minerals, smaller then 64 μm diameter)I is associated with the occurrence and the distribution of many species living on and in the bed. The distribution of fine sediment suspended in the water phase and deposited on the estuary bed is therefore an important factor governing the functioning of the estuarine ecosystem. It is clear from many studies that bottom dwelling ecosystem-engineering species can change sediment properties in their habitats, on the sub-mudflat scale. The objective of this study is to clarify the influences of bottom dwelling species on the basin scale fine sediment budget.

Study area
This study is focused on the Western part of the Dutch Wadden Sea, located in the North-West of the Netherlands (Figure 1). The study area, the Dutch Western Wadden Sea (WWS) is bounded by the Afsluitdijk, sandy barrier islands and the watershed between Schiermonnikoog island and the mainland (Figure 1). The area of the WWS covers about 2178 km^2 which is made up of 1050 km^2 intertidal, 502 km^2 subtidal (defined here to lie between 1.5 m and 3 m average water depth) and 626 km^2 gullies (more than 3 m water depth). The area is characterized by a diurnal tide, ranging from 1 to 2 m in amplitude.

The bed sediment consists of sands with a median diameter between 170-190 microns, with an average concentration of 1% of mud in the top 10 cm of the drying areas. About 270 km^2 of intertidal area is considered muddy with a mud content averaging 5.8%. Due to the lack of a large local river, mud in the Wadden Sea originates mainly from sources in the North Sea. The physical processes governing the import of mud into the Wadden Sea have been studied extensively. The work of Postma (1961, 1981) and later Dronkers (1984) established a firm base to understand the driving forces behind the transport of fine sediment. Borsje et al. (2008) elaborated the spatial distribution of (de)stabilizing ecosystem engineers in the Wadden Sea, based on biomass and bathymetry, resulting in a spatial zoning presented in Figure 1.

Quantification of basin scale fine sediment budget

Postma (1981) quantified fine sediment transport from North Sea to the Wadden Sea. If we apply his approach to the study area, it can be estimated that the quantity of North Sea water entering the WWS with each flood tide through the various inlets is about 2.2 km^3. With a yearly average concentration of about 10 mg/l of fine-grained suspended matter, this gives an input of about 21 000 ton per tide or $16 \cdot 10^6$ tons each year. The permanent deposition is estimated at 3-5% of the input by various authors (Postma, 1961; Eisma, 1979). This means that each ebb tide must on average leave about 1000 ton behind. In addition to loading from the North Sea, some mud arrives in the WWS from rivers through the Afsluitdijk and the Lauwersmeer. The total riverine input is less than 4% of the total input. Gross fluxes within the Wadden Sea basins, especially the exchange between the bed and the water phase, are almost two orders of magnitude higher, due to shallow depths and sensitivity to wave impact. Almost all of this material has to settle each tide within the basin to maintain the observed net balance. If we assume with Postma (1981) that 85% (the remainder has too low settling speeds) of the material can settle in one slack tide, this gives 182 000 ton of settled sediment per tide on the intertidal and subtidal areas of the WWS combined. This calculation is based on an average depth of 3 meter and the multi-year average of suspended sediment concentration data from many stations inside the Wadden Sea, including Zoutkamperlaag and Dantziggat (stations are indicated in Figure 1; see Figure 2 (left panel) for field data of these two stations from the long term monitoring program of Rijkswaterstaat, Waterbase (2008)). Both Postma (1981) and Dronkers (1984) considered biological influences on settling and erosion to be possible important factors for the residual sediment transport between the North Sea and the Wadden Sea. Black et al. (2002) stated that there is no sediment without organisms and cites Paterson (1997), that the biomass and activity of sediment-inhabiting organisms, ranging from bacteria to worms and shrimps, act as important regulatory controls on natural sediment stability, according to many earlier authors. Therefore field data presented in Figure 2 (left panel) must include the effects of ecosystem engineers.

Quantification of ecosystem engineered effects on fine sediment budget

Main ***stabilizing*** species are benthic primary producers such as diatoms and cyano-bacteria (MPB) that rapidly colonize freshly deposited layers and stick them together, sometimes resulting in layered tidal deposits (Grant & Gust, 1987; Austen, 1999; De Brouwer, 2000; Paterson et al., 2000; De Deckere et al., 2001). Bed ***destabilization*** -and therefore increased capacity for erosion- is mainly caused by key surface deposit feeding species such as the surface grazing mud snail *Hydrobia ulvae,* the mudshrimp *Corophium volutator* and Baltic tellin *Macoma balthica*. Although many other species are present in the Wadden Sea, quantitative and seasonal effects of MPB and surface deposit feeding (SDF) macrobenthic ecosystem engineers *Macoma balthica* and *Hydrobia ulvae* are well documented (Widdows et al. 2000a & 2000b; Andersen et al. 2004). Borsje et al. (2008) have analyzed the effect of seasonal biomass variation of (de)stabilizing ecosystem engineers on bed strength and erosion rate. On the basis of the quantifications presented by Borsje et al. (2008) in combination with known gross sediment fluxes presented above, an attempt was made to quantify the effect of ecosystem engineers on whole basin fluxes of fine sediment. Table 1 shows the data used for the analysis.

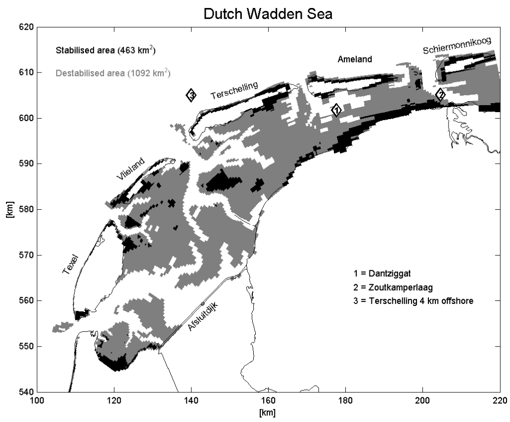

Table 1 Overview of input parameters for quantitative analysis of sediment budget

Parameter	Value
Area of WS (km^2)	2178
Average depth of WS (m)	3
Volume of WS (km^3)	6.5
Sandy area of WS < -3m (km^2)	1550
Mud content of sandy area <-3m (fraction) [2]	0.01
Stabilized area in WS with mud (km^2) [1]	463
Mud content of MPB patches in stabilized area (fraction) [2]	0.1
Patchiness factor MPB[1]	0.25
Average depth stabilized area (m)	1
Biomass dependent erosion coefficient MPB (min<>max)[1]	0.37<>0.99
Biomass dependent erosion coefficient SDF (min<>max)[1]	2.8<>3.2
Average settling flux WS (ton/tide)[3]	183 000
Average erosion flux WS (ton/tide)[3]	182 000
Average burial flux (ton/tide)[3]	1000

[1] Values derived from Borsje et al. (2008)
[2] Sedimentatlas (1998)
[3] Postma (1981)

Figure 1 Study area Western Wadden Sea with zones of stabilized and destabilized bed.

Results: Ecosystem engineered influence on sediment budget

The influence of ecosystem engineers on erosion in the Wadden Sea is quantified on the basis of the known average erosion flux. An estimate of (de)stabilizing coefficients (Table 1) was derived from Borsje et al. (2008) and is used to influence the average erosion flux. Destabilizing SDF have a significant impact on increase of the erosion flux in the sandy areas. The stabilizing effect of MPB is reducing the erosion flux on the MPB patches in the muddy intertidal areas. Figure 2 gives an overview of the resulting suspended matter concentration (SPM) and settling and erosion fluxes, exclusively based on biomass trends of MPB and SDF throughout the year, assuming complete and instantaneous mixing in the water column. When compared to SPM measured in stations within the Wadden Sea (left panel of Figure 2) the seasonal patterns are strikingly similar. It becomes clear that ecosystem engineers (stabilizers and destabilizers combined) cause a significant 'bio-mediation' of erosion flux and therefore of SPM. The fluxes must be doubled when compared to a situation without biological activity, in order to maintain the observed average erosion flux. The variation of SPM is comparable to what is measured in the field. Driven by biomass cycles throughout the year, maximum influence of stabilizing MPB is seen in spring and summer, leading to lower SPM, while maximum influence of destabilizing SDF is seen in autumn and winter, gradually compensating stabilizing activity, resulting in increasing SPM. MPB reduces erosion flux with a magnitude comparable to the average import of fine sediment of North Sea to Wadden Sea. SDF increases erosion flux at least five times over the level of average import from North Sea.

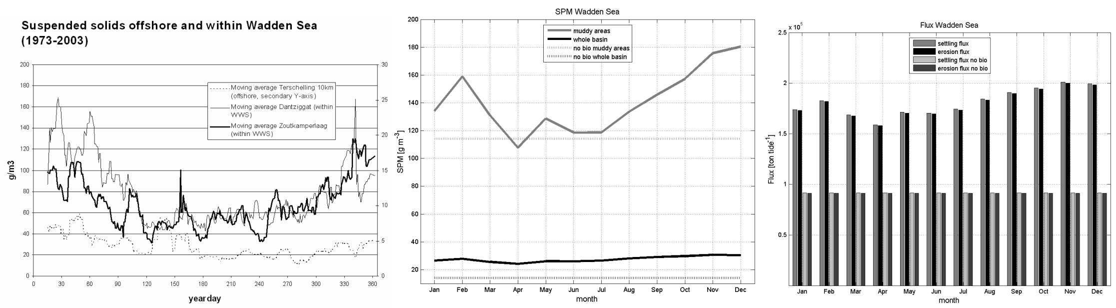

Figure 2. Suspended sediment concentrations measured in Western Wadden Sea (left panel), SPM calculated from biologically influenced erosion flux (middle). Settling and erosion fluxes influenced by biological activity (right panel).

Conclusions

This study demonstrates the influence of biota on the fine sediment transport on estuary scale. From this study a picture of ecosystem-engineers has arisen, that indicates that on basin scale, dynamic bio-physical interactions indeed emerge, influencing sediment transport. Sediment transport fluxes inside the Wadden Sea are affected following seasonal trends in biomass. The quantity of these effects is larger than the fine sediment exchange between Wadden Sea and North Sea and at least an order of magnitude larger than estimated nett import flux. The sediment destabilizing processes are stronger than the stabilizing processes and are occurring on larger areas, caused by the influence of basin shape on zoning of habitats. Strong effect on turbidity is observed, indicating a link between basin shape, activity of ecosystem engineers and water quality. Ecosystem engineering species might influence the balance between import and export of fine material between Wadden Sea and North Sea. The results emphasize the need of incorporating biological activity in the physical models to help formulate recommendations for the management and conservation of high biomass mesotidal tidal basins.

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