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The effect of bedforms (crest and trough systems) on sediment erodibility on a back-barrier tidal flat of the East Frisian Wadden Sea, Germany

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Abstract

The erosion potential over bedforms in a tidal flat of the East Frisian Wadden Sea was studied by conducting erosion and physical and biological sediment property measurement on the crests and troughs of bedforms. Five stations along a cross-shore transect of 1.5 km length from immediately below the salt marsh to the mid tide-level of the tidal flat were visited during two field campaigns in June and September 2002. Measurements of sediment erodibility were made on both crests and troughs using an EROMES erosion device and quantified in terms of critical erosion shear stress and erosion rate. Surface sediment scrape samples (upper 1 mm layer) were taken from crests and troughs to determine various physical and biological properties of the sediment. The results show that crests are generally more stable (i.e. higher critical erosion shear stresses and lower erosion rates) than troughs. In general, crests contained more chlorophyll-a, colloidal carbohydrate, and EPS (extracellular polymeric substance) than troughs. Medium grain-size, water content and wet bulk density of the crests showed no statistically significant difference from those of the troughs with the exception at the most landward station

immediately below the salt marsh margin, where crests had significantly lower water content and higher wet bulk density than troughs.

Two different processes were identified for the difference in erodibility between crests and troughs in this study: (1) At stations with emersion times less than 6 hours, the higher benthic diatom biomass (measured as chlorophyll-a concentration) on the crests increases the amount of EPS, which is likely to stabilize the sediment surface of these features. (2) In a saltmarsh transition area (most landward station), physical processes such surface drying and compaction seem to enhance in a synergistic way the sediment stability on the crests.

1. Introduction

Bedforms of various sizes occur in most coastal sedimentary systems (Dyer, 1986). These can be broadly classified as (a) channels, creeks, and gullies; (b) ridge-runnel system; (c) ripples and other micro-topography; (d) cliffs (Dyer 1998). Structure and size of intertidal bedforms have a significant impact on the overall flow in an estuary by increasing the bottom roughness length (Ke *et al.*, 1994). Crests and troughs max redirect flows and wave propagation at very shallow water depths (Whitehouse *et al.*, 2000), cause localised near-bed concentrations of sediment (Roberts *et al.,* 2000) and control the drainage export of sediments from the flats (Le Hir *et al.*, 2000; Bassoullet *et al.*, 2000). For granular, non-cohesive bed materials, bedform generation, shape and size is generally understood as resulting from instability of bed-flow interaction, which may start from a plane seabed and horizontally uniform flow exceeding the threshold for sediment transport (Dronkers, 2005). Fine cohesive sediments, which prevail on intertidal flats, on the other hand, oppose this type of bedform generation as they are either highly mobile or highly consolidated and their formative mechanisms are less well understood (Whitehouse *et al.*, 2000). Ridge-runnel bedforms observed at the Skeffling mudflats (Humber estuary, UK) were considered to result from surface drainage and organised flows during ebb tide

(Christie *et al.*, 2000), while ridge-runnel bedforms observed at Paterstone Wentlooge mudflats (Severn Estuary, UK) appear to be caused by wave-induced induced erosion of the sediment (O'Brien *et al.*, 2000). Furthermore, biological processes can give rise to bed topography. The gently undulating seabed studied by Wheatcroft (1994), for example, was produced by bioturbation and ripple formation found to be induced by biogenic mounds (Fries *et al.* 1999).

For sandy intertidal flats, de Boer (1981) demonstrated the impact of benthic micro-algae in prevention and retardation of sediment grain transport and the migration of ripples in the field, and inferred, that due to binding activity of algae in the area, a limited amount of sand grains was available for transport during the experiment. In another study, Allen and Friend (1976) reported different hydrodynamic thresholds of sandy intertidal bedform migration over a tidal neap/spring cycle. They suggested that higher thresholds when going from neap to spring tide conditions were due to the formation of a thin protective crust of algae and mud over the sediment surface during neaps.

In the last years evidence has accumulated suggesting positive feedback mechanisms, which link initial ripple generation by waves (Amos *et al.*, 1988a.; O'Brian *et al.*, 2000) with emerging patterns of micrpohytobenthos and erosion resistance, are key elements in shaping mudflat morphologies (Christie *et al.*, 2000; Paterson *et al.*, 2000; van de Koppel *et al.*, 2001). Elongated parallel ridge-runnel systems present at the mid flats of macrotidal estuaries are the most prominent and well-studied bedforms of this type (O'Brian *et al.*, 2000, Bassoulet *et al.*, 2000, Whitehouse *et al.*, 2000). For a mudflat in a mesotidal estuary, the interplay between the development of diatom biofilms, the emergence of criss-cross bed structures or random depression patterns is conceptually explained by the connection of diatom growth, increased bed stability and silt accumulation (de Brower *et al.*, 2000). Van de Koppel *et al.* (2001) put forward a positive feedback mechanism between local silt accumulation, enhanced growth of diatoms and resulting increased

sediment surface stability to model the emerging patterns of higher and lower concentrations of silty sediments and diatoms. However, a model that predicts the development of crests and troughs by coupling the biological mechanism to intertidal flat flow dynamics is still lacking.

Guided by indirect observational evidence, crests of the bedforms have been assumed to be more stable than troughs due to drying effects and biostabilisation by benthic diatoms (Blanchard *et al.*, 2000; Christie *et al.*, 2000). Troughs of bedforms are usually considered to be associated with loose flocculated material, which is more easily eroded, although this is less supported by specific data. On the other hand, erosion resistance of cohesive sediments can not be directly predicted by physical or biological properties alone (Dyer, 1986). Erodibility of natural cohesive sediments on intertidal flats is influenced by a number of physical and biological factors including sediment grain-size, bulk density, water content, air exposure, consolidation, microphytobenthos and benthic macrofauna (Amos *et al.*, 1988b; Paterson *et al.*, 1990; Williamson & Ockenden, 1996; Widdows *et al.*, 1998). However, to date very few studies (Widdows *et al.*, 1998; Paterson *et al.*, 2000) have specifically examined and compared the erodibility of crests and troughs of intertidal bedforms.

Bedforms similar to the above mentioned prevail also on the intertidal flats of the East Frisian Wadden Sea that according to Dyer *et al.* (2000) can be characterised as sheltered and mesotidal. The crest and trough systems bear some similarity to the ridge-runnel system at the Skeffling mudflats, although the detailed characteristics and areas of coverage as well as their size are different. A comprehensive study of these bedforms remained to be undertaken in the Wadden Sea. In contrast to other areas (Whitehouse *et al.*, 2000), they also can be found in the upper tidal region, which is exposed to waves disturbance only during storm surges. In the study presented here, the sediment characteristics and microphytobenthic patterns of crests and troughs in relation to their

erodibility were consistently investigated along a transect ranging from the very upper to the middle tidal flats thus covering a broad range of benthic habitats. The aim of the study was to test whether the elsewhere observed sediment property patterns also exist under the conditions of backbarrier tidal flats of the Wadden Sea, and to assess which biological and or physical processes are main responsible for the generation and sustainability of the bedforms. The results also have the potential to contribute to the modelling of sediment transport rates over intertidal flats, mudflat development or estimation of sediment budgets by improving the formulation of bed roughness lengths or of erosion parameterisation considering also small-scale (sub-grid) variability in erodibility.

2. Material and methods

2.1. Study site

The study was conducted on the Dornumer Nacken, a back-barrier tidal flat located between the barrier island of Baltrum and the East-Frisian mainland coast, Germany (Figure 1). The mean tidal range at the study site is approximately 2.8 m and the tides are semi-diurnal. Depth-averaged tidal current velocities in the channels close to the inlet reach maximum values up to 70 cm s^{-1} and on the tidal flats up to 25 cm s^{-1} (Krögel & Flemming, 1998).

The Dornumer Nacken is a relatively protected tidal flat shielded by other tidal flats to the east and west, and by the barrier islands of Baltrum and Langeoog in the north. A sluice, which drains freshwater from agricultural areas, a dike, and a narrow salt marsh are situated to the south side of the tidal flat. The incoming tide enters the tidal flat from the north, mainly through a channel called "Accumersieler Balje". Sediment grain-sizes show a general increase of mud content towards the coastline, ranging from pure sand at the most outer parts to some 40 % at the mean high water line and about 50 % in the salt marsh region (Krögel & Flemming, 1998).

The sampling was carried out at five stations along a cross-shore transect approximately 1.5 km long from immediately below the salt marsh to the middle of the tidal flat (designated A - E seawards). The transect from station A to B is normal to the tide line, whereas stations C, D and E are arranged in parallel to the main channel "Accumersieler Balje". Station A was located close to the salt marsh edge. Under average conditions, this station is continuously exposed for up to 7 days between successive spring and neap tidal cycles. Station B was located approximately 130 m from the salt marsh edge and exposed for 6 h per tidal cycle. This inner zone of the Dornumer Nacken shows a predominantly homogeneous distribution of habitats. Macrobenthos at station A is characterized by small sessile polychaetes (e.g. *Heteromastus filiformis* and *Pygospio elegans*) and patches of the cockles *Cerastoderma edule* and *Macoma baltica* (van Bernem, 1999). At station B, the mud snail *Hydrobia ulvae* is most abundant on the sediment surface with densities of more than 15,000 individuals m^{-2} (Lanuru, 2004). Stations C, D and E (respectively 700, 1000, and 1500 meters from salt marsh edge) are located in the middle zone which exhibits a slight local depression in height compared to the inner and outer zone with emersion times of about 4 - 5h per tidal cycle. Here, habitat patterns show a higher heterogeneity including patches of changing density of the blue mussel (*Mytilus edulis*) and cockles (*Cerastoderma edule*) (van Bernem, 1999) and sessile polychaetes dominated benthic macrofauna. Blue mussel patches of about 5 m in diameter and 15 - 20 m apart characterized station E. Epipelic diatoms at all stations dominated microphytobenthos assemblages (Lanuru, 2004). The transect was not extended further out as the sediments are to sandy there (mud content less than 5 %), which does not allow erosion experiments to be conducted with the device employed in this study.

Irregular crest and trough systems (bedforms) were present at all the stations during the sampling periods and were also observed at other seasons. The bedforms were aligned more or less normal to the shoreline, with a wavelength of 50 - 100 cm and a height of 10 -

15 cm. The elevated crests emerged at low tide, whereas filaments of troughs contained trapped or slowly running water during most of the emersion period (Figure 2), thus feeding larger gullies, which drain the Dornumer Nacken eastwards towards the Dornumersieler Balje. The data presented here are result of two extensive sampling periods from June and September 2002, where sufficient samples were taken to systematically study differences in crest and trough erodibility.

2.2. Erosion measurements

Sediment cores for erosion measurements were taken from the tidal flats by means of 10 cm diameter perspex tubes about 1 h after the sampling stations were exposed. At each station, 4 to 10 cores were taken alternately upon the crests and within the troughs, resulting in 66 cores in all. To minimise sample surface disturbance during transport and to achieve reproducible conditions in the erosion experiments, sampling choice was biased to surfaces that were flat, visually undisturbed and free of surface water and macrobenthos. When the deepest parts of the troughs were covered by water, cores in the troughs were often placed on dry patches slightly above the water surface. The cores were immediately transported to a nearby mobile laboratory and carefully filled with seawater to a level of 20 cm and then allowed to rest between 2 and 8 hours. In this way, erosion experiments were started after several hours of submerged conditions.

Two identical EROMES (erosion devices) were used for the determination of critical erosion shear stresses and erosion rates (Schünemann & Kühl, 1991; Riethmüller et al., 1998). A detailed description and discussion of sampling, transportation and core preparation for the erosion measurements was previously published (Riethmüller et al., 2000; Tolhurst et al., 2000). The EROMES system uses artificially induced turbulence to erode the samples and to keep the eroded matter in suspension. The erosive force is induced by a rotating propeller 3 cm above the sediment surface. During each erosion experiment, the applied bed shear stress was initially started from 0.05 N m^{-2} and

increased in steps of 0.1 N m^{-2} every 5 min. The concentration of eroded material in the system was continuously determined by measuring the turbidity using an optical backscatter sensor (OBS). The experiment was stopped when the OBS was saturated. The turbidity was calibrated against water samples taken for gravimetric analysis, and calibration curves were produced for each erosion experiment. Incremental erosion rates were computed from the differences in the suspended sediment concentrations at beginning and the end of each bed shear interval.

The critical erosion shear stress was defined as the bed shear stress when the erosion rate exceeds a critical threshold of 0.01 g m^{-2} s^{-1}. Riethmüller *et al.* (1998; 2000) describe the computational procedure for critical erosion shear stresses in detail and claim an error in the determination of the critical erosion threshold of 0.05 N m^{-2}. The erosion rates reported in this study represent rates averaged between bed shear stresses of 1.0 and 2.0 N m^{-2} ("EROMES erosion rates"). The average over 1.0 to 2.0 N m^{-2} was chosen, as in the majority of cases, critical erosion shear stress has already been attained. On the other hand, the OBS was saturated in some cases already below bed shear stresses of 2.0 N m^{-2}. To allow for a consistent rate determination, a power law was fitted to the incremental erosion rates as a function of the excess shear stress. The correlation coefficient was found to be greater than 0.95 in all cases. The EROMES erosion rates were then computed by integrating the fitted functions. Details of the procedure are published elsewhere (Lanuru, 2004).

Comparative studies with another EROMES that operated in the field without core excavation (Andersen & Pejrup*,* 2001) and other in-situ operating erosion devices, revealed no detectable influence of coring, transport and differences in resting time on the critical erosion shear stresses (Tolhurst *et al.*, 2000; Lanuru, 2004). The erosion rates were compared with published results from the *in situ* annular flume device (Widdows *et al.*, 1998) operated at the Skeffling mudflat, Humber estuary (UK). For sediments with

comparable grain-size and critical erosion shear stress, the rates agree very well for excess shear stresses up to 1 N m^{-2} (Lanuru, 2004). This is somewhat surprising, as the EROMES device generates radially non-uniform bed shear stresses and, compared to a channel stream, large turbulence fluctuations (Gust & Müller, 1997). In this study, the EROMES erosion rates are only used to parameterise differences in the crest and trough erodibility. But their good agreement with the *in situ* annular flume device rates and their power law dependence may indicate their use also in terms of absolute numbers.

2.3. Sediment property measurements

Surface sediment scrape samples (upper 1 mm layer), about two times the erosion core area, were taken using a spatula from both crests and troughs in the perimeter of each erosion core. The samples were well mixed and sub-samples were taken to measure sediment grain-size distributions, wet bulk density, water content, organic content, chlorophyll-a concentration, colloidal carbohydrate and extracellular polymeric substance (EPS) concentration.

Sediment samples were freeze-dried prior to the determination of chlorophyll-a, carbohydrates, and grain-size. Chlorophyll-a concentrations were measured using the acetone extraction and reverse-phase column HPLC technique of Wright *et al.* (1991). Two different fractions of carbohydrate were determined: the colloidal fraction and EPS in the colloidal fraction (Underwood *et al.* 1995). In this procedure, 5 ml of saline water (25 ^{o}/oo) was added to 100 - 150 mg of dry sediment. The samples were then left for 15 min at 20 ^{o}C, followed by centrifugation for 15 min at 2500 rpm. 1 ml of the supernatant (from 5 ml extract) was used for the determination of the colloidal fraction. To obtain the EPS in the colloidal fraction, 7 ml of cold ethanol (2 - 4 ^{o}C) was added to 3 ml of the supernatant (from 5 ml extract) to a final concentration of 70%. The sample was incubated overnight at 5 ^{o}C, followed by centrifugation for 15 min at 2500 rpm. The supernatant was subsequently discarded and the pellet that contained EPS resuspended in 1 ml of distilled

water. The colloidal carbohydrate and EPS in the colloidal fraction were determined using the phenol-sulfuric acid assay with glucose as a reference (Dubois *et al.*, 1956).

Grain-size analyses were done on samples pre-treated with H_2O_2 to eliminate organic matter before being wet-sieved through a 300 µm mesh. Grain-size distributions of the fractions <300 µm were determined at size intervals of 1 µm by means of a Galai Cis-1 laser particle analyzer. Sieve analyses were also carried out on a number of selected samples for the comparison with the results of the CIS laser particle size analyzer. The data show that values obtained from CIS agree reasonably well with those obtained from the sieving method, and therefore only data obtained from CIS are presented in this paper. Median diameters were determined by taking the d_{50} (i.e., the size given by the 50th percentile) of the fractions < 300µm. Sieve analysis revealed that the amount of fractions > 300 µm were very small (on average less than 0.5% by weight). Hence, exclusion of the fraction > 300 µm should not significantly affect the determination of the median diameters. In the following, mud content is the fraction by weight of sediments < 63 µm.

The water content of the sediment was determined by drying to constant weight for 24 hours at a temperature of $105\ ^{O}C$. The organic content was measured by loss on ignition of the samples at $550\ ^{O}C$ in an oven for 1 h.

2.4. Statistical analysis

The significance of the difference in mean values between crests and troughs were statistically examined using the *t*-test (Fowler & Cohen, 1997). Differences were regarded as statistically significant when the probability of error was lower than 5 % (P < 0.05).

3. Results

3.1.   Critical erosion shear stress and erosion rate

The results of the study showed marked differences in the erodibility/stability of the sediments on the crests and in the troughs of the bedforms at the study sites. Sediments

on the crests were on the average always more stable (i. e. higher critical erosion shear stresses and lower erosion rates) than those in the troughs (Figure 3a, b). At some of the stations, high data variation together with the limited number of sample replicates, on the other hand, did not allow to regard all differences as statistically significant. For all stations, the results of the statistical significance tests between crests and troughs for critical erosion shear stresses, erosion rates and physical and biological sediment parameters are listed in Table 1: Crests had statistically significant higher critical erosion shear stresses than troughs at station A (crests 2.1 N m^{-2}, troughs 0.65 N m^{-2}; P < 0.05) and station D (crests 1.1 N m^{-2}, troughs 0.5 N m^{-2}; P < 0.05), but not at stations B, C and E; erosion rates were statistically significant lower on the crests than in the troughs at station A (crests 0.014 g m^{-2} s^{-1}, troughs 0.25 g m^{-2} s^{-1}; P < 0.05), D (crests 0.5 g m^{-2} s^{-1}, troughs 1.5 g m^{-2} s^{-1}; P < 0.05), and E (crests 0.05 g m^{-2} s^{-1}, troughs 0.17 g m^{-2} s^{-1}; P < 0.05), but no statistically significant differences were observed at station B and C. The average differences in crest/trough erodibility at all stations can nicely be seen when considering the mean erosion profiles of the crests and troughs (Figure 4 a-e). Prominently the trough cores at stations A and E show the strongest increase in the suspended sediment concentration with applied bed shear stress when compared to the crest cores. For station C, as a counter example, crest and trough erosion profiles overlap over the full range of the applied bed shear stresses.

3.2. Chlorophyll-a, colloidal carbohydrate, and EPS

Figure 5 shows the mean chlorophyll-a, colloidal carbohydrate and EPS concentrations on the crests and in the troughs at all stations. Crests contained significantly higher chlorophyll-a concentrations than troughs at station A (P< 0.05), B (P < 0.05), D (P < 0.01) and station E (P < 0.01) (Figure 5a and table 1). Station C showed the same pattern too, but the differences were minimal.

Both colloidal carbohydrate (Figure 5b) and EPS concentrations (Figure 5c) followed mainly the patterns found for the chlorophyll-a, but statistically significant crest and trough differences were only found for stations A ($P < 0.01$) and D ($P < 0.05$). Station B proved to be an exception of the rule: here both colloidal carbohydrate and EPS concentrations were slightly higher at the troughs than in the crests.

3.3. Sediment surface bulk parameters

As listed in table 2, the sediments at station A were the finest among the stations with mud contents varying between 46 and 69 % by weight. The sediments at stations B - D contained mud generally in fractions between 15 and 35 %. The sediments at station E showed the highest range of variation with mud contents between 18 and 79 %. Median grain-size (Figure 6a) increased from station A ($\approx$55 µm) to D ($\approx$125 µm), but was lower again at station E ($\approx$100µm). At the same time, no statistically significant differences in median grain-size between crest and trough, and also no unique trend from crest to trough were observed at stations A to D. Only at station E was the median grain-size found to be statistically significant lower at the crests ($P < 0.05$) (table 1).

At most stations, there was also no statistically significant crest and trough difference for mean water contents (Figure 6b), wet bulk densities (Figure 6c), and organic contents (Figure 6d). Only at the salt marsh margin at station A, crests exhibited significantly lower mean water contents ($P < 0.05$, table 1) and higher mean wet bulk densities ($P < 0.01$, table 1).

3.4. Correlations between sediment surface parameters

Table 3 lists the Pearson correlation coefficients (r) between all parameters mentioned above. The sediment surface bulk parameters are all highly correlated. EPS concentrations follow closely the colloidal carbohydrate concentrations ($r=0.92$, $P < 0.01$). The correlation coefficient between both parameters with chlorophyll-a is somewhat lower ($r=0.70$ and 0.77, resp., $P < 0.01$). Critical erosion shear stresses are well correlated with

EPS and colloidal carbohydrate concentrations (r >0.7, P < 0.01), but less with chlorophyll-a (r=0.59, P < 0.01). EROMES erosion rates correlate only weakly with all parameters (r < 0.4 in most cases), although the error probability is lower than 0.01.

4. Discussion

The results of these corroborate previous findings and indirect observations that surface sediments of crests have indeed a higher resistance against erosion forces than those of troughs: the mean critical erosion shear stresses were higher and the erosion rates lower (Figure 3a and b). As shown in Figure 4, average erosion profiles for the crests are lower than for the troughs, the patterns being particularly clear for the surface sediments of station A and E. This pattern was found at all stations along the transect, but this is statistically significant only on three out of five stations.

The discussion of the results is divided into four parts. First, artefacts caused by biased sampling are discussed. The next three parts consider the impact of physical sediment properties and of the presence of microphytobenthic organisms. As organic content is highly correlated with the physical sediment surface properties (table 3), it is not considered in the discussion. The results of station A, which has much longer exposure times than all the four stations, is given extra attention. Finally, the results are compared to those published for other tidal flats.

4.1 Impact of biased sampling

The crest surfaces had systematically longer emersion times than trough surfaces. As a result, drying of the surfaces may have additionally increased the surface stability of the biolfims, as observed by Paterson et al. (1990). At the same time part of the colloidal carbohydrates may have been washed out by the waters still running in the troughs after flat exposure, thereby weakening the biofilm (Blanchard et al., 2000). Both processes may have lead to the observed crest and trough patterns, which were possibly not present during the submerged periods. However, no statistically significant differences in the water

contents of crests and toughs were detected, at station D the water content in the troughs was even lower. Station A is an exception of this rule, but this station is exposed for most of the time and drying possibly played a greater role than at the other stations. Most likely the ability of surface diatom biofilms to retain water in order to avoid desiccation and to maintain diatom viability may substantially have reduced drying of the surface sediment on the crests (Christie *et al.*, 2000). Consistently, Blanchard *et al.* (2000) state that the water content of exposed sediments is often fairly constant. Finally, Patterson *et al.* (2000) did not observe any increase in critical erosion thresholds on the crests even over an exposure period of seven hours. Significantly lower concentrations of EPS in the upper sediment layers of the troughs were only observed at stations A and D. As EPS is generally closely related to chlorophyll-a (see table 3), changes in EPS concentrations are most likely causally related to the density of diatoms present. An exception to this is only found at station B where mucilage secreted by the high numbers of the mud snail *hydrobia ulvae* most probably contributed to the surficial EPS. One reason for the marginal differences in water content and, in part in the EPS, might be caused by the fact that the surfaces chosen for sampling had to be free of water. Hence with respect to exposure times, the conditions for the crest and trough cores were nearly comparable. By this sampling protocol, on the other hand, the conditions at the most depressed parts of the troughs were only rarely sensed. That may have contributed to the occasionally low differences in the crest and trough sediment parameters (see table 1). All in all, there is strong evidence that the observed crest and trough patterns in the sediment surface parameters are not caused by biased sampling or by different exposure times of crests and troughs.

4.2 Impact of physical sediment properties offshore the mean high water line

The different erodibility of crests and troughs may come first from variations in their physical properties, notably the water content: in some cases reduced water content was

observed to result in sediment with increased strength and hence greater resistance to erosion (Anderson & Howell, 1984; Amos *et al.*, 1988; Paterson *et al.*, 1990).

For the stations offshore the mean high water line (B to E), variation in physical sediment surface properties such as median grain-size or wet bulk density, cannot explain lower erodibilities on crests versus those on troughs, as the differences were never statistically significant. Furthermore, no strong correlation between these parameters and critical erosion shear stress or erosion rates showed up (table 3). Evidently, effects of drying or bed compaction can be ruled out as being associated with the higher sediment stability on the crests at stations B – E.

4.3 Impact of microphytobenthos

The higher degree of biostabilisation by benthic diatoms (Figure 5a) through secretion of mucopolysaccharides (Figure 5b and c) seems to play a more important role in stabilizing the sediment surface on the crests. For all stations, the occurrence of the crest and trough structure was correlated with higher erosion stability, higher densities of diatoms and higher concentrations of colloidal carbohydrates and EPS on the crests. However, this pattern was statistically significant only for stations A, D, E (table 1). In case of station B, high abundances of the grazer *Hydrobia ulvae* most probably erased the crest and trough pattern of the biofilms. Together with the specifically high critical erosion shear stresses at relatively low chlorophyll-a concentrations at station A, this process is responsible for the lower correlation coefficient between critical erosion shear stresses and chlorophyll-a concentrations (table 3). Overall, critical erosion shear stresses correlate most strongly with concentrations of colloidal carbohydrates and EPS in the upper sediment surfaces (table 3). The fact that also the erosion rates are generally lower on the crests than on the troughs can in part attributed to variations in critical erosion shear stresses: mean erosion rates between 1 and 2 N m^{-2} tend obviously to be lower when the critical erosion thresholds are higher. The low correlation coefficient of –0.33 between

critical erosion shear stresses and erosion rates however suggests that the high variation in the magnitudes of erosion rates (Figure 3b) and erosion profiles (Figure 4a-e) is also caused by other benthic parameters. Using typical values for the concentrations of the eroded material of 1000 mg dm^{-3} (at a bed shear stress of 2 N m^{-2}) in the 20 cm high EROMES sampling cylinder, water contents of 35 % and wet bulk densities of 1.7 g cm^{-3} (Figure 4 and 6), one can estimate that the thickness of the eroded material is in the order of 200 μm. On the other hand, observations of the sediment surface during the erosion experiments indicate that the sediment is rifled to depth of several millimetres. Hence the erosion rates should also be influenced by below-surface sediment properties, which may be reflected in the low, but statistically significant correlation coefficients with the averaged upper millimetre sediment surface parameters.

4.4 Impact of long exposure periods

Compared to stations B to E, station A exhibits quite different characteristics. Although benthic diatom biomass was relatively low, the critical shear stresses on the crests were the highest found among all stations. Also, the relative crest and trough differences observed at station A are much higher than at any of the other stations. The mean critical erosion shear stresses were more than three times higher on the crests and the EROMES erosion rates fifteen times lower (Figure 3a and b). At the same time, the crest and trough differences were also statistically highly significant for water content, wet bulk density, colloidal carbohydrates and EPS concentrations. The relatively long emersion times prevailing from mean to neap tide conditions probably favour sediment drying and consolidation and reduce physical disturbance. Compaction of these surface sediments relative to those at the outer stations can be qualitatively shown when the mud content and wet bulk densities of stations A and E are compared. The mean mud content at station A amounts to 58%, and at station E to 38 % (table 2). According to Flemming & Delafontaine (2000) and Riethmüller *et al.* (2000) wet bulk densities of intertidal sediments decrease

with increased mud content. Against this well documented trend, which predicts a lower surface sediment density at station A, wet bulk densities have a similar magnitude of 1.6 g cm^{-3} at both stations. It is quite likely that drying of sediment and dehydration of the mucopolysaccharide (EPS) matrix may synergistically act together to increase sediment stability as already observed by Paterson (1988).

4.5 Comparison with other mudflats

In the following, the results from the Dornumer Nacken are assessed against the macrotidal Skeffling flats (Humber estuary, UK) and the mesotidal mudflat of Biezelingse Ham (Westerschelde, NL), as for these areas a similarly comprehensive data set was published. The crest and trough patterns found at the Dornumer Nacken are to some extent similar, but less clear compared to the ridge and runnel structure of the Skeffling flats. Christie *et al.*, (2000) report that the ridges (crests) progressively dry out when emerged during low tide, whereas the runnels (troughs) are often covered with a thin layer of trapped or slowly running water. In contrast to the Dornumer Nacken, sand content of the surface sediments in the runnels were statistically significantly higher there. In parallel, Paterson *et al.* (2000) found statistically higher concentrations of colloidal carbohydrates on the ridges in the upper 200 μm of the sediment surfaces. Crest and trough erosion shear stresses were of similar magnitude as on the Dornumer Nacken, but statistically significant. Obviously, the spatial variability in critical erosion shear stresses was less than at the Dornumer Nacken stations.

Likewise the Dornumer Nacken situation, Christie *et al.* (2000) found at the Skeffling mudflats that the critical erosion shear stresses correlated, in contrast to the physical sediment parameters, only with colloidal carbohydrate concentrations present in the sediment surfaces. The authors put forward the hypothesis that the favoured growth of diatoms on crests, which were most probably initiated by waves, and the consequent higher sediment stability, promoted the formation of ridges and runnels. Blanchard *et al.*

(2000) and Paterson *et al.* (2000) put forward two explanations for the lower concentrations of both carbohydrate and chlorophyll-a in the runnels. First, the carbohydrate freshly excreted by microphytobenthos in the troughs is probably rapidly dissolved in the thin layer of trapped water and may be washed out with the slowly running water. Second, a decrease in light due to overlying turbid water as explicitly observed in the intertidal mudflat of Brouage (Baie de Marennes-Oléron, FR) by Bassoullet *et al.* (2000), probably results in a lower activity of microphytobenthos in the troughs. Rapid dissolution of carbohydrates, however, seems not to play an important role in the troughs of the Dornumer Nacken flat, as it would lead to a decoupling of the chlorophyll-a from the colloidal carbohydrate concentrations, which is was not detected. The second process was sometimes observed, but not explicitly measured at the Dornumer Nacken.

By analysing the spatial and temporal patterns of bedforms, biological and sediment properties on the mudflat of Biezelingse Ham (Westerschelde, NL), de Brouwer *et al.* (2000) found close connections between changes in the bed morphology from more homogeneous to criss-cross patterns, the development of diatom mats, increase in sediment stability and fixation of fine sediments in the diatom mats. These findings, the generally observed bed stabilisation by diatoms and favoured conditions for diatom growth in finer sediments, were the starting point of a positive feedback model (van de Koppel *et al.*, 2001) between diatom growth and silt accumulation. If short range facilitation between diatoms exists, this model might be extended to explain the development of regular patterns in diatom cover, sediment surface stability, sediment properties and bedforms on mudflats by self-organisation (van de Koppel, pers. comm.).

Thise positive feedback loop might also be applicable for the ridge and runnel systems on the Skeffling tidal flats where a correlation between higher mud contents and higher concentrations of carbohydrates was found. For the Dornumer Nacken flats that were the focus of this study, however, the correlation between mud accumulation and diatom

density was not detectable and such a positive feedback loop most probably does not exist. Here, other processes than described above may facilitate diatom growth on the crests and or hinder it in the runnels.

5. Conclusions

Erosion data from and intertidal flat in the East Frisian Wadden Sea presented in this study corroborate previous observations of a systematic spatial variation in sediment strength and hence erosion potential over bedforms. The sediments deposited on the crests of bedforms were found to be more stable than those in the troughs, but the differences were not found to be statistically significant at all instances. Two different processes were identified as being responsible for the differences in erodibility between crest and troughs: (1) at stations offshore the mean high water line (B – E), firmer films of mucilage fabricated by benthic diatoms are likely to stabilize the surfaces of crests more than the surrounding troughs; (2) at the lower salt marsh margin around the spring tide high water level (station A), where the tidal emersion period is longer, physical processes of drying and compaction seem to contribute in a synergistic manner to enhanced sediment stability on the crests. In contrast to previous findings, however, differences in physical sediment properties were negligible. Hence, a proposed positive feedback model (van de Koppel *et al.*, 2001) which, among others, links higher mud contents to higher diatom densities seems not to be applicable in this region. Considering the wide variety of benthic habitats covered in this investigation and the generally low differences in the crest and trough erosion potentials, it may be questioned whether diatoms alone play a central role in the growth and stability of intertidal bedforms and whether other or different types of positive feedback loops must be applied to explain the emergence of crest and trough bed forms. The role of drying and compaction on flats with long exposure times provide one example for this. The inclusion of biological processes might consider interactions with endobenthic meio- and/or macrofauna. A physical approach for example might consider

ballistic mediated bed shear stress by grains or shell debris (Amos *et al.*, 1998) transported along the troughs with the drained waters during the exposure times. On the other hand, the wide prevalence of intertidal bedforms even in the presence of versatile diatom grazers (Station B) and bedform reoccurrence even after significant wave disturbances (de Brouwer *et al.*, 2000) shows that such feedback loops must be a general feature and very efficient.

Acknowledgements

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Table 1. Level of significance of the difference between crests and troughs for critical erosion shear stress, erosion rate and physical and biological sediment parameters.

	Station A	Station B	Station C	Station D	Station E
Critical erosion stress	$P < 0.05$	ns	ns	$P < 0.05$	ns
Erosion rate	$P < 0.05$	ns	ns	$P < 0.05$	$P < 0.05$
Median grain-size	ns	ns	ns	ns	$P < 0.05$
Mud content	ns	ns	ns	ns	ns
Chlorophyll-a	$P < 0.05$	$P < 0.05$	ns	$P < 0.01$	$P < 0.01$
Colloidal carbohydrate	$P < 0.01$	ns	ns	$P < 0.05$	ns
EPS	$P < 0.01$	ns	ns	$P < 0.05$	ns
Wet bulk density	$P < 0.01$	ns	ns	ns	ns
Water content	$P < 0.05$	ns	ns	ns	ns
Organic content	ns	ns	ns	ns	ns

ns: not significant ($P > 0.05$)

Table 2. Median grain-size and mud content of the surface sediment at the sampling stations.

Station	Median grain-size (µm)	Mud content (%)
A	37 - 71	46 - 69
B	94 - 105	16 - 28
C	95 - 121	16 - 30
D	95 - 136	11 - 36
E	30 - 145	18 - 79

Table 3. Pearson correlation coefficients between critical erosion shear stress and physical and biological sediment properties.

Den. = wet bulk density, Mud = mud content, Median = median grain-size, Water = water content, Org. = organic content, Chl-a = chlorophyll-a concentration, Coll. car. = colloidal carbohydrate concentration, EPS = EPS concentration, τ_{cr} = critical erosion shear stress, and E. rate = EROMES erosion rate.

	Den.	Mud	Median	Water	Org.	Chl-a	Coll. car.	EPS	τ_{cr}
Mud	**-0.70**								
Median	**0.63**	**-0.95**							
Water	**-0.98**	**0.71**	**-0.64**						
Org.	**-0.89**	**0.73**	**-0.67**	**0.89**					
Chl-a	**-0.27**	0.15	-0.09	0.22	**0.37**				
Coll.car.	**-0.48**	0.14	-0.15	**0.44**	**0.53**	**0.77**			
EPS	**-0.55**	0.20	-0.18	**0.51**	**0.59**	**0.70**	**0.92**		
τ_{cr}	**-0.38**	**0.25**	-0.19	**0.36**	**0.48**	**0.59**	**0.71**	**0.73**	
E. rate	**0.37**	**-0.44**	**0.36**	**-0.37**	**-0.41**	**-0.38**	**-0.34**	**-0.31**	**-0.33**

Numbers in bold: significant at P < 0.01

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Figure 4. Average erosion profiles as defined by the suspended sediment concentration in the EROMES sampling cylinder versus the applied bed shear stress for sediments on the crests and troughs for station A (a), B (b), C (c), D (d), and E (e) (mean ± standard error, n = 4 - 10). The height of the water column above sediment bed was around 20 cm. The erosion profiles end at the bed shear stress interval where the OBS signal in the EROMES saturated.

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