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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 measurements 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. Median 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: (1) At stations with emersion times less than 6 h, 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 as surface drying and compaction seem to enhance in a synergistic way the sediment stability on the crests.

Keywords: tidal flat; erodibility; erosion rate; bedforms; microphytobenthos; biostabilisation; Wadden Sea; Germany

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 (Bassoullet et al., 2000; Le Hir 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

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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'Brien et al., 2000) with emerging patterns of microphytobenthos and erosion resistance, 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 (Bassoullet et al., 2000; O'Brien 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 Brouwer 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 and 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 (subgrid) variability in erodibility.

2. Material and methods

2.1. Study site

The study was conducted on the Dornumer Nacken, a backbarrier tidal flat located between the barrier island of Baltrum and the East-Frisian mainland coast, Germany (Fig. 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 and 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