Properties of active tidal bedforms.

C. Winter, A. Lefebvre, M. Becker, Y. Ferret *Center for Marine Environmental Sciences, MARUM, Bremen, Germany* – cwinter@marum.de

V.B. Ernstsen, J. Bartholdy *Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark*

E. Kwoll *Department of Geography, Simon Fraser University, Burnaby BC, Canada*

B. Flemming *Senckenberg am Meer, Wilhelmshaven, Germany*

ABSTRACT: Bedforms of various shapes and sizes are ubiquitous in tidal channels, inlets and estuaries. They constitute a form roughness which has a large scale effect on the hydrodynamics and sediment transport of coastal environments. It has been shown that this form roughness can be expressed in terms of the lee side slope of bedforms. This study compiles data on the topography and hydraulics of compound dunes from different settings in the German Bight to discuss implications of a critical lee slope in tidal environments with reversing flow. Data from the Weser estuary is used to exemplify and quantify these effects.

1. INTRODUCTION

The German Bight is a prominent example for the dynamic interaction of different coastal ocean elements such as the shallow shelf sea, estuaries, tidal channels, barrier islands and tidal flats under a wide range of forcing conditions. This zone features extensive human uses (shipping lanes, ports, windparks, constructions, fishing, etc.) in close proximity of precious ecosystems as in the natural World heritage Wadden Sea (Winter & Bartholomä, 2006; Reise et al., 2010). Large scale morphodynamics of this area have been described by the annual bed elevation range (Winter, 2011), and respective drivers were differentiated into wave, wind and tidal forcing (Kösters & Winter, 2014). The highest morphodynamic activity is observed in the outer estuaries and tidal inlets of the Wadden Sea (Herrling & Winter, 2014; 2015). Predominately at these locations which are characterized by strong tidal currents a variety of mainly flow transverse subaqueous bedforms, are found (Ulrich, 1971; Winter et al., 2016). These morphological elements have been explored for long times (e.g. Flemming, 1988; Nasner, 1978, Davis & Flemming, 1991; Flemming & Davies 1992), and the availability of observation techniques like multibeam echosounders (MBES) with precise positioning and correction for ship motion (Ernstsen et al., 2006), has triggered a multitude of process-based studies on the stunning complexity of these bedforms (Ernstsen et al., 2005, 2006b), their formation and development (Ernstsen et al., 2005, 2006b, 2008, 2010, 2011; Svenson et al., 2008), and their interaction with the hydrodynamics (Lefebvre et al., 2011), suspended sediments (Kwoll et al., 2013), micro-biology (Ahmerkamp et al., 2015), bed fauna and flora, and coastal constructions (Noormets et al., 2006).

Besides their aesthetic nature, their role as prominent transport agents, their frequently addressed hazard for coastal constructions and navigation, it is the bedforms cross-scale impact that make them a prominent field of applied and fundamental research: These (individually) small scale elements of short term dynamics have a large scale and long term effect on whole coastal systems. The hydraulic effect of bedforms needs to be considered in the development, set-up and application of numerical models on coastal settings. Bedforms are ubiquitous and thus their effect on flow and transport patterns acts on large spatial scales, i.e. they constitute a hydraulic roughness influencing the overlying current structure, and thus the transport of sediments, and other biogeochemical properties throughout the whole coastal domain (Bartholdy et al, 2010).

Compound dunes in the outer tidal channels and estuaries of the German Bight are bedform assemblages of large (length O(100 meters), heights O(meters)) primary dunes which are superimposed by smaller (lengths O(10m), height O(dm)) secondary dunes, and occasionally by small scale ripples, which however often are below the resolution of ship mounted MBES observations and out of the scope of this study.

In this contribution *active bedforms* are defined as subaqueous flow transverse features which significantly influence the flow field and in turn develop (grow, migrate, decay) as an effect of the governing flow conditions.

2. RELEVANCE OF SCALES

The superimposed primary and secondary dunes dynamics feature different temporal behavior and can be separated by spectral methods into components of high and low celerity (Winter & Ernstsen, 2008). Secondary bedforms share geometric properties of dunes known from common laboratory flume experiments (Guy et al., 1966) and tend to adjust to the oscillating tidal currents, thus changing their asymmetric shape and migration according to the instantaneous flow direction. Reported secondary bedform celerity can be up to several meters per tide, although residual migration over a tidal cycle may be very low (Ernstsen et al., 2011). Primary bedforms develop at larger timescales, and follow in shape and migration the direction of residual tidal forcing, thus do not adapt to the reversing tidal directions. Recognition of individual bedforms in successive annual measurements have revealed slow migration celerities in the order of 10-20m per year in a tidal inlet (Ernstsen, 2006) 25 m in the estuaries of Weser (Nasner, 1974) and Elbe (Zorndt et al., 2010).

3. SUSPENDED SEDIMENTS

Bedforms interact with the flow in that turbulent wakes and coherent flow structures behind the crests of bedforms are formed, which depend in size and characteristics on the direction of the flow (Best, 2005; Kwoll et al., 2014). In estuarine tidal environments two separate transport regimes may be observed: Fine, cohesive sediments settle predominately in the troughs of dunes at slack water, with subsequent erosion and resuspension at rising tidal currents. The dunes are formed in coarser sediments and develop and migrate at higher flow stages, until the next slack water, when dune migration comes to a halt, and subsequently fines subsequently settle out at the next slack water, forming distinct mud deposits in the troughs of the dunes (Becker et al., 2013, Kwoll et al., 2013).

4. HYDRAULIC RELEVANCE

Double averaging of measured velocity profiles along dunes had revealed how the hydraulic effect of large asymmetric compound dunes differs according to the tidal stage. Lefebvre et al. (2011), calculated that the hydraulic effect of primary dunes can be an order of magnitude larger when the flow and bedform shape (gentle stoss side, steep lee side) are in line, thus the large bedforms may be called active or hydraulically relevant only if the flow is in the direction of dominant currents. The effect of secondary bedforms does not vary much over the tidal cycle, which is explained by the fast adaptation of bedform shape according to the instantaneous flow. The hydraulic effect of bedforms is mainly depending on the turbulent characteristics and energy turnover behind bedforms. The latter is highly dependent on the lee slope of bedforms (Best & Kostaschuk, 2002; Kwoll et al., 2016) at which flow separation may or may not occur, a simple descriptor can be found, which reduces common bedform descriptors depending on the lee slope (Lefebvre & Winter, 2016).

5. OBSERVATIONS

A compilation of MBES data from the Jade Bay, and the Weser and Elbe estuaries has produced about 40,000 individual datasets on bedform geometry. These bedforms range in heights from 0.05 to 8.9m and lengths from 4 to 490m. Only 4.2% of all identified bedforms meet the criterion of being active, or hydraulically relevant (here simplified to a lee slope >10°). These scale with $H=0.1665\ L^{0.6672}$ ($R^2=0.53$) when taking into account weighted bedform heights (generalized extreme value method). The majority of this subset falls in between predicted mean and maximum H/L relationship by Flemming (1988).

Classic bedform predictors reveal very limited skill in reproducing bedform shapes based on sedimentary and flow conditions. An adjusted polynomial model fit on all active bedform data results in a goodness of fit $R^2=0.66$.

For different areas of the Weser estuary the evolution of bedform geometry and migration is related to different drivers. Significant correlations to Weser fresh water discharge are shown.

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