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Influence of Hydrodynamic Boundary Conditions on Dune Migration and Associated Sand Transport Rates in the Elbe Estuary

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SUMMARY

Large parts of the tidal estuary of river Elbe (Germany) are characterized by regular patterns of sand dunes. They evolve due to complex sand transport mechanisms and show multi-faceted migration patterns, which are influenced by hydrodynamic boundary conditions such as runoff and tidal forces. This contribution aims at increasing the understanding of the way hydrodynamic boundary conditions influence dune migration. This is the basis of an effective sediment management as well as an important requirement for planning offshore structures. From a unique data set of up to six annual bathymetrical multibeam soundings between 1995 and 2010, bed-form characteristics and migration rates have been processed and analysed autonomously. The influence of river runoff, water levels, tidal range and river depth on characteristics and migration was tested statistically. The results show that migration is mainly influenced by the incoming flood tide, while rates and directions depend on the amount of runoff originating from the inland catchment.

1. INTRODUCTION

Under special sedimentological and hydrodynamic conditions [9], complex sediment movements on the river bed can lead to the formation of different sizes of bed forms. The same factors which influence their formation can also cause a migration of bed forms, which results into a residual sand transport. Many studies have been undertaken to describe and characterize the forms [cf. 4,2,1] and to determine the influences of grain size, current velocity, water depth as well as form characteristics on the migration in both flume experiments and in nature [cf. 9,4,6].

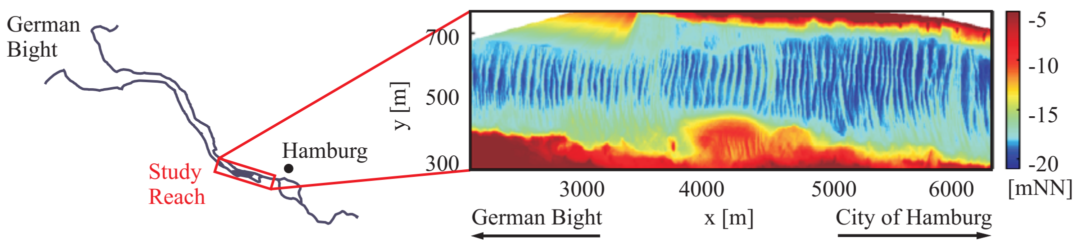


Figure 1: Study reach located in tidal river Elbe with detailed bathymetry (August 2008)

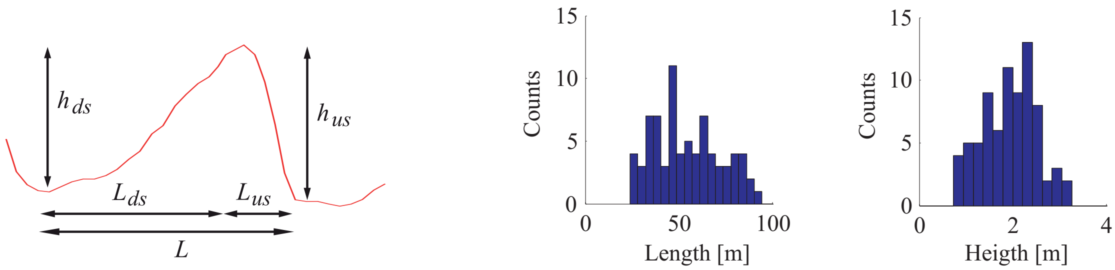
This study focuses on evaluating the influence of different boundary conditions such as runoff, tidal range and water depth on the bed form migration on-site. For this purpose, a study reach in the Elbe Estuary was chosen in which a strong formation and migration of bed forms had been observed. Despite the fact that the area shows a superposition of bed forms of different sizes, this study focuses on the dominating forms which have a length of up to 100 m and will be referred to as sand dunes. The study reach is located approximately 100 km south-east from the Germany Bight close to Hamburg as shown in Figure 1. As the formation of sand dunes seemed most pronounced in the deep navigation channel, the study focuses on this part of the river. The average tidal range in the study reach is $tr = 3.40$ m. The mean water depth is $h = 18$ m, while the average runoff from the inland river catchment mounts to

$Q = 700$ m^3/s. The bathymetry of the area has been regularly measured for monitoring purposes by Hamburg Port Authority (HPA) by multibeam echo-sounders with a frequency of 240 kHz. HPA provided a unique data basis of up to six sounding per year since 1995 for this study, as well as data from different gauges nearby to account for the boundary conditions.

2. METHODS

2.1. Computation of Dune Characteristics, Migration Rates and Associated Sand Transport

To evaluate the influence of hydrodynamic boundary conditions on the dunes, their characteristics and migration rates as well as associated sand transport rates have to be described.
For the computation of form characteristics, an automated dune tracking algorithm was implemented. It detects crests and troughs in a longitudinal profile from local minima and maxima. This approach was validated by the results of a manual dune tracking of exemplary data. From the troughs and crests in the longitudinal section, dune height h, length L and asymmetry A were calculated and averaged for every measurement (see Fig. 2a). Asymmetry A ranges from $-1 < A < 1$ with positive values for dunes with their steeper slope in headwater direction and vice versa as described by Knaapen [6]. To calculate dune migration, different approaches were compared and validated by comparison to the results of manual dune-tracking of two preceding longitudinal sections. The best results could be obtained with a cross-correlation method similar to the approach described by Duffy and Hughes-Clarke [3]. This method is based on finding the best statistic correlation between a section of one bathymetry measured at time t_i with any section of the following bathymetry measured at time t_{i+1}. From the distance of the two corresponding sections, migration rates $u_{i,i+1}$ can be derived. Applying this method to every point of a bathymetry results in a vector field, from which, after filtering outliers, the average migration is calculated.



a) Sketch of dune characteristics b) Results of dune height h and length L (August 2008)

Figure 2: Dune characteristics computed with automated dune tracking approach

In order to compute the associated bed-load transport q_b, the commonly used 1D approach [cf. 8, 5] was expanded to define 2D transport rates as calculated by the cross-correlation method. For a more detailed description of the methodology see Zorndt et al. [10].

2.2. Evaluating the Influence of Hydrodynamic Boundary Conditions

The data basis for testing the relationships between computed dune characteristics and migration rates and hydrodynamic boundary conditions consisted of different river gauges close to the study reach. Runoff Q was given in daily values and water levels t in intervals of 10 minutes. Moreover, daily times and water levels of high and low tide were available so that the tidal range tr could be calculated. To find correlations between the dune characteristics h_i, L_i and A_i with the time series data, a number of averages was computed for a sounding at time t_i, such as $Q_{i,10d}$ as the runoff averaged over time t_i and the 10 preceding days. In total, for every boundary condition B, 19 averages ranging from $B_{i,1d}$ to $B_{i,2a}$ were tested upon their correlation with the specific characteristic. Migration rates $u_{i,i+1}$ between two soundings at times t_i and t_{i+1} were correlated with the average of the boundary condition $B_{i,i+1}$ between the two soundings.
Apart from that, the average depth below reference datum d of the study reach was tested. This takes into account that in order to adapt to a new navigation channel depth standard, the study reach was deepened from approx. $d = 17.3$ m to $d = 18.0$ m below reference datum between 1999 to 2000.

3. RESULTS

3.1. Dune Characteristics, Dune Migration Rates and Associated Sand Transport Rates

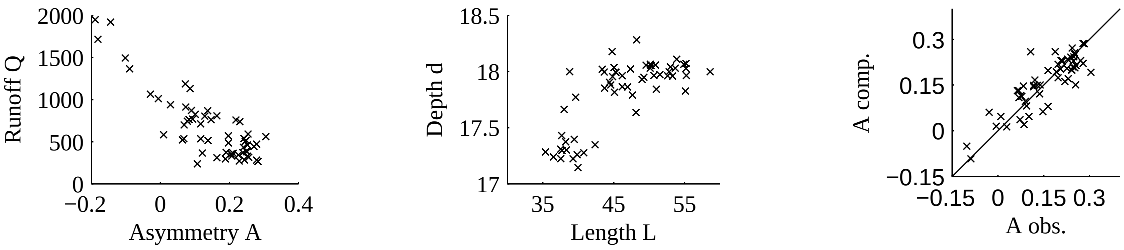
Taking the full set of bathymetry echo-soundings within the study area into account, an overall averaged dune height of $h = 1.70$ m and length of $L = 46.47$ m were observed. Figure 2b shows exemplary results for a bathymetry in August 2008. Showing strong asymmetry in shape, the dunes can be best characterised as *megaripples type 1* according to the definition of Dalrymple et al. [2]. Averaged over all soundings, 72.7 % of all upstream-lying slopes were shorter and thus steeper than the ones facing seawards, showing an average asymmetry of $A = 0.14$. As dunes are known to migrate in the direction of their steeper slope [6], this already indicates a residual upstream migration. This was confirmed by the results of the cross-correlation approach which showed an average dune migration of $u = 0.05$ m/d in headwater direction. Applying these results to the bed-load transport formula, this leads to a daily bed-load transport of $q_b = 0.07$ m³/(dm), i. e. over one year, a sand volume of approximately $q_b \approx 5000$ m³/a is transported towards Hamburg.

3.2. Influence of Hydrodynamic Boundary Conditions on Dune Characteristics

To test the influence of boundary conditions such as tide and runoff one by one, a correlation study was carried out. The asymmetry A shows the strongest correlations with the chosen boundary conditions, correlating with runoff Q_{30d} with $\rho = -0.86$ as shown in Figure 3a. Stronger tidal ranges tend to lead to higher dunes, but only after a period of several months (highest correlation of $\rho = 0.58$ for tr_{240d}). Larger depths below reference datum d result in increasing dune lengths L with a correlation coefficient of $\rho = 0.44$. This correlation could be improved to $\rho = 0.77$ as shown in Figure 3b, excluding one out of $n = 58$ soundings with an untypical bathymetry altered by dredging activities. On the basis of those and other relationships, functions for predicting dune characteristics were derived. Among others, the asymmetry can be predicted with equation

$$A_i = -2.19497 - 0.000239613 * Q_{i,30d} + 0.0657763 * d_i + 0.00366443 * tr_{i,240d}\,, \qquad (1)$$

which explains $R^2 = 81.23$ of the total variance of the observed values as shown in Figure 3c.



a) Asymmetry A [-] and runoff Q_{30d} [m³/s]

b) Length L [m] and depth below reference datum d [m]

c) Observed vs. computed Asymmetry A [-]

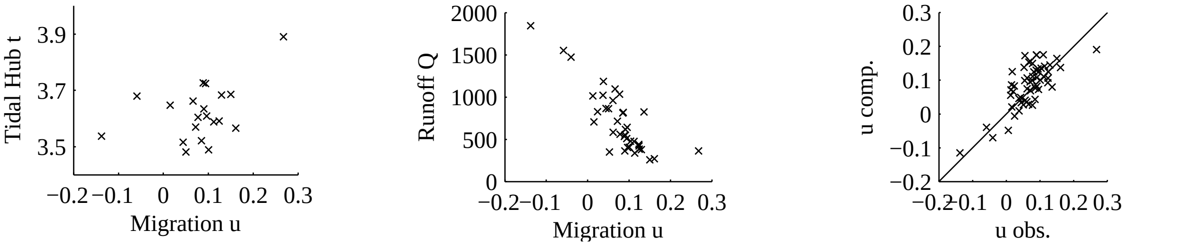
Figure 3: Correlations of hydrodynamic boundary conditions and dune characteristics

3.3. Influence of Hydrodynamic Boundary Conditions on Dune Migration

Furthermore, correlations between boundary conditions and migration rates were tested in order to predict dune migration. The influence of runoff Q on migration was tested with a significant correlation coefficient of $\rho = -0.76$ ($n = 57$). Under the assumption that the results for dune migration deteriorate for longer intervals between the two preceding soundings, the correlation could be improved to $\rho = -0.82$ by taking into account only the migration rates computed for soundings with a time interval no longer than $\Delta t = 90$ d ($n = 38$, Fig. 4a). As an indicator for the energy of the inflowing tidal wave, the tidal range tr was chosen. Yet, there is no significant correlation between dune migration and tidal range for the whole set of $n = 57$ pairs of bathymetries. However, a significant coefficient of $\rho = 0.44$ could be obtained by including only migration rates for intervals of $\Delta t < 65$ d ($n = 20$) as shown in Figure 4b. This indicates a tendency for a stronger tidal range to increase dune migration in headwater direction. Furthermore, the influences of water levels *t* as well as depth below datum *d* were tested but did not show high influence on dune migration. Thus, dune migration is best predicted via

$$u_{i,i+1} = -0.567723 - 0.000156496 * Q_{i,i+1} + 0.00209622 * tr_{i,i+1}, \quad (2)$$

for migration rates with intervals $\Delta t < 65$ d ($n = 20$) with $R^2 = 79.05$ as shown in Figure 4c. However, having few samples available for this relation, the equation can only be seen as a rough approximation.



a) Migration *u* [m/s] and tidal range *t* [m] for $\Delta t < 65$ d

b) Migration *u* [m/s] and runoff *Q* [m³/s] for $\Delta t < 90$ d

c) Observed vs. computed migration rate *u* [m/d]

Figure 4: Correlations of hydrodynamic boundary conditions and dune migration rates

4. DISCUSSION

An average dune migration of $u = 0.05$ m/d in headwater direction of river Elbe indicates that the migration is mainly induced by sediment movements during flood tide, which, due to tidal asymmetry, exerts greater shear stress on the river bed than ebb tide or runoff. Runoff on the other hand can modulate direction and rate of dune migration. Under low and average runoff conditions, migration is directed in headwater direction, while runoffs above a threshold value of $Q_{thr} = 1300\ m^3/s$ cause a change of migration then being directed towards the German Bight. This demonstrates the strong influence of tidal asymmetry for bed-load transport.

Migration rates as well as some dune characteristics at the study reach can be fairly well predicted by river runoff, tidal range and water depth. For sites closer to the German Bight, it is expected that the influence of runoff decreases. Together with a decreasing tidal asymmetry, this should lead to more stable dunes and reduced migration rates which should be examined in further research.

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References

[1] Amos, C. L. & King, E. L. (1984). Bedforms of the Canadian Eastern Seabord: A comparison with global occurances. *Marine Geology*, 57, pp. 167-208.
[2] Dalrymple, R., Knight, R. & Lambiase, J. (1978). Bedforms and their hydraulic stability relationships in a tidal environment, Bay of Fundy, Canada. *Nature*, 275 (5676), pp. 100-104.
[3] Duffy, G. P. & Hughes-Clarke, J. E. (2005). Application of spatial cross correlation to detection of migration of submarine sand dunes. *Journal of Geophysical Research*, 110, F04S12.
[4] Führböter, A. (1967). Zur Mechanik der Strömungsriffel. *Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen der Technischen Universität Hannover*, 29.
[5] Gaeumann, D. & Jacobson, R. B. (2007). Field Assessment of Alternative Bed-Load Transport Estimators. *Journal of Hydraulic Engineering*, pp. 1319-1328.
[6] Knaapen, M. A. F. (2005). Sandwave migration predictor based on shape. *Journal of Geophysical Research*, 110, FS0411.
[7] Van der Mark, C. F. & Blom, A. (2007). *A new and widely applicable tool for determining the geometric properties of bedforms* (Tech. Rep.). University of Twente.
[8] Simons, D. B., Richardson, E. V. & Nordin, C. F. (1965). Bedload equations for ripples and dunes. *U. S. Geol. Surv. Prof. Pap.*, 462-H.
[9] Zanke, U. (1982). *Grundlagen der Sedimentbewegung*. Springer-Verlag.
[10] Zorndt, A., Wurpts, A., Schlurmann, T., Ohle, N., Strotmann, T. (2010). Dune Migration and Sand Transport in Tidal Estuaries - The Example of the River Elbe. *32nd International Conference on Coastal Engineering* (in press).