Potential drivers for primary dune growth in the Outer Jade

Leon Scheiber *Ludwig-Franzius-Institute, Hannover, Germany – scheiberleon@gmail.com*
Oliver Lojek *Ludwig-Franzius-Institute, Hannover, Germany – lojek@lufi.uni-hannover.de*
Jan Visscher *Ludwig-Franzius-Institute, Hannover, Germany – visscher@lufi.uni-hannover.de*
Gregor Melling *Federal Waterways Engineering and Research Institute, Hamburg, Germany – gregor.melling@baw.de*

ABSTRACT: This study examines 47 navigational safety surveys of the Outer Jade. The bathymetric data is utilized for an analysis of local bedforms and a volume balancing study. The obtained cumulative volume differences from consecutive surveys are used to test for correlations with metocean influences and documented maintenance activities. For the relationship between bathymetric changes and maintenance works a statistically significant connection is found indicating a recirculation of dredge spoil as suggested in previous studies. However, additional research has to be undertaken, especially in terms of a coupled numerical simulation, to facilitate a verification of the described hypothesis.

1 INTRODUCTION

The Jade Bight is a tidal bay cutting deep into the marshland of northern Germany with no notable freshwater discharge and a tidal range of up to 3.69 m in Wilhelmshaven. Stretches of the Jade navigational channel, specifically along fairway kilometers (fkm) 14.8 - 23.6 and fkm 28.7 - 41.6, are characterized by compound subaqueous dunes. The aforementioned bedforms are of particular interest to the Federal Waterways and Shipping Administration (WSV), as dune crests tend to reduce the navigational depth of the fairway and thereby impede safe navigation towards the transshipment complex of Wilhelmshaven (Götschenberg & Kahlfeld 2008). The navigational depth along the Outer and Inner Jade is maintained at - 18.5 m below chart datum (CD). Dunes with crest heights reaching - 17.6 mCD jeopardize maritime traffic and are dredged by the local Waterways and Shipping Office (WSA). To enhance the understanding of the underlying morphodynamic processes, areas of increased morphological activity have been successfully identified by Kubicki & Bartholomä (2011). In 2017, subsequent investigations revealed the existence of a dune field of some 20 km² in the Outer Jade comprising a remarkable zone of dune convergence that indicated a potential recirculation of dredging spoils dumped nearby (Kubicki et al. 2017). Numerical simulations conducted by the Federal Waterways Engineering and Research Institute (BAW) further substantiated the hypothesis of a recirculation relating to hydrodynamics and transport capacities (Melling & Kösters 2017). Based on regular navigational safety surveys, the present study tests the hypothesis of a dune convergence zone by means of an analysis of bedform asymmetries and migration directions. Moreover, potential causes for the formation and growth of the respective bedforms are investigated. To this end, all echo-sounding data, sampled within the area of interest between 2012 and 2016, is analyzed and tested for correlations between the observed morphological changes on the one hand and metocean and/or operational factors on the other.

2 METHODS

2.1 Study area

The focus area of the present study is delineated by the intersection of all analyzed echo-sounding surveys and the domain specified by the previous investigations of Kubicki et al. (2017). It is situated in the Outer Jade fairway between the islands of Oldeoog/ Minsener Oog in the west and the lighthouse of Mellumplate in the east.

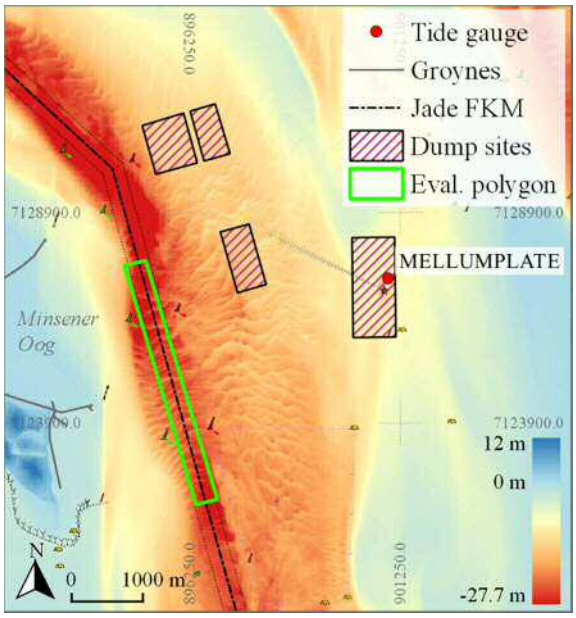

Figure 1. Location of the study area in the Jade navigational channel between the islands of Oldeoog/ Minsener Oog in the west and the lighthouse of Mellumplate in the east.

As depicted in Figure 1 the intersection polygon stretches roughly from fkm 29 to 32.5 of the Jade navigational channel and has a width of about 300 m. To allow for the analysis of longitudinal geodetic profiles, an intersection line is defined along the central axis of the fairway.

2.2 Data sources

At regular intervals of about one month, the Jade fairway bathymetry is monitored by the responsible German authority, namely the WSA Wilhelmshaven (Götschenberg & Kahlfeld 2008). For this purpose, the whole navigational channel is surveyed in distinct sections using a ship-mounted *Atlas Fansweep 20-200* multibeam echosounder (Kubicki et al. 2017). For the present study, 47 echo-sounding datasets, composed of gridded coordinate-elevation pairs at a horizontal resolution of 2 x 2 m, were provided by the WSA. This data is utilized to investigate the temporal morphodynamic evolution of primary dunes forming along the bottom of the fairway.

For subsequent examinations of potential correlations, comprehensive information on the conducted maintenance works, i.e. dredging and dumping activities in the vicinity of the study area, was available from the federal maintenance monitoring database *MoNa*. The unfortunate fact, that maintenance volumes moved by private companies were not quantified, is addressed by estimating these values to be of similar magnitude as the overall mean volume.

Furthermore, metocean data was collected from various adjacent measuring stations. In detail, information on current velocities and directions was obtained from an official monitoring station located at fkm 21. Wind and wave conditions are constantly measured by the National Meteorological Service of Germany (DWD) at the lighthouse of Alte Weser and can be downloaded from a public database. Finally, tidal water level data is readily available from the measuring station at Mellumplate (fkm 31.1) about 3 km east of the study area.

2.3 Data processing

In the course of this study, various bathymetric analyses of the survey domain are conducted. In a first step, geodetic profiles along the intersection line are assessed, identifying distinct bedforms according to an automated approach presented by Zorndt et al. (2011). After detecting dune crests and troughs on the basis of local extrema, the bedform dimensions, specifically the heights and lengths of large to very large dunes as defined by Ashley (1990), are computed. Asymmetries, as a proxy for migration directions, are calculated from the relative upstream dune side lengths (cf. Zorndt et al. 2011) and migration rates are derived from the horizontal displacement of dune crests between the individual echo-soundings.

Thereafter, the morphological changes between consecutive echo-soundings are computed by means of a volume balancing study and the temporal course of observed volume differences inside the survey domain is used as one variable of the correlation analysis. In detail, the bathymetric changes are examined for linear and cross correlations with the cumulative maintenance volume and with data on the local metocean conditions, respectively.

3 RESULTS

3.1 Bedform characteristics

The examination of monthly geodetic profiles shows an average number of 83 primary dunes along the 3.5 km fairway axis adding up to a total of 3885 analyzed bedforms for the four-year period between 2012 and 2016. The corresponding dune dimensions vary between 0.8 m and 7.6 m of height, and between 17.7 m and 336.7 m of length, respectively. Figure 2 illustrates the relative frequency of observed dune dimensions and reveals an average dune height of 2.5 m and an average dune length of 67.0 m inside the study area. As previously suggested by van der Mark et al. (2008), the distribution of dune dimensions can be adequately described by a Weibull function.

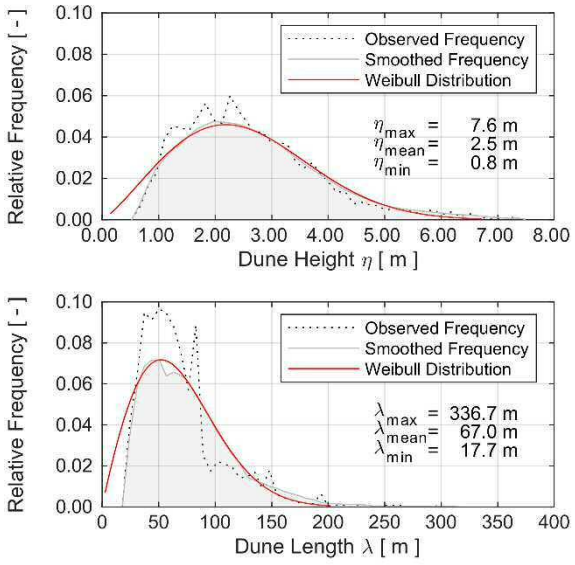

Figure 2. Observed and smoothed frequency of prevailing dune dimensions inside the fairway segment and the corresponding Weibull distribution.

Investigations of the spatial distribution of bedform characteristics, in particular of dune asymmetries and migration rates, indicate a distinct segmentation of the analyzed domain. Whereas primary dunes in the southern half of the survey area (fkm 29.0 - 30.7) mainly show northward directed migration at an average rate of u_{mig} = 8.7 cm/d and a mean asymmetry of A = 0.576, dunes between fkm 31.1 and 32.5 are characterized by southward migration (u_{mig} = - 9.1 cm/d) and a mean asymmetry of A = 0.408. The average migration rate and asymmetry of the fairway segment between fkm 30.7 and 31.1 are of a minor order of magnitude (u_{mig} = - 0.1 cm/d, A = 0.498) and, thus, support the hypothesis of a dune convergence zone in this area.

3.2 Bathymetric changes

In a second step, the morphological changes between consecutive echo-sounding surveys are analyzed by assessing the gridded elevation data of the defined fairway segment cell-by-cell and comparing the respective sediment volumes. This volume balancing study results in a list of consecutive volume differences documenting both erosive periods with sediment losses, such as 53,400 m³ in September 2013, and intervals of intense sediment deposition of up to 107,600 m³ in March 2015. However, in general the morphological situation of the study site can be characterized as depositional with an overall sediment accretion of 883,700 m³ implying a reduction of the average depth by Δh = 0.84 m within 47 months.

3.3 Investigation of causes

The temporal course of sediment volume changes is used, subsequently, to check for potential correlations with the corresponding metocean data, i.e. prevailing wind, wave and current conditions. In this context, the coefficient of determination R^2 varies between 0.00 and 0.33 for the available parameters (see Table 1) and, hence, no significant correlation is evident, neither linear nor phase-shifted.

Table 1. Achieved coefficients of determination R^2

	2012	2013	2014	2015
Max. wind speed [m/s]	0.05	0.03	n.a.	n.a.
Max. wave height [cm]	0.00	0.00	n.a.	n.a.
Max. ebb current [m/s]	0.09	0.03	n.a.	n.a.
Max. flood current [m/s]	0.06	0.33	n.a.	n.a.
Maintenance volume [m³]	0.09	0.76	0.67	0.62

Concerning a relationship between the observed bathymetric changes in the fairway segment and the documented maintenance activities, no evidence for a distinct phase-shifted dependency could be obtained from the cross-correlation analysis. However, investigations regarding a linear correlation indicate a significant similarity between cumulated mean elevation changes and maintenance volumes; the corresponding coefficient of determination reaches a value of $R^2 = 0.96$ for the complete analyzed period (see Figure 3).

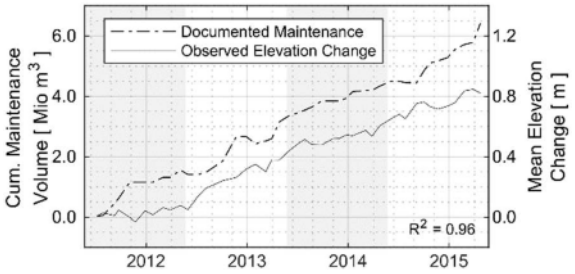

Figure 3. Temporal course of the cumulated maintenance volume and the cumulated mean elevation change inside the fairway segment, respectively; the coefficient of determination reaches $R^2 = 0.96$ for the period between 2012 and 2016.

4 DISCUSSION

After comparing the computed dune characteristics with historical data on bedform dimension ratios (Flemming 1988), the present results are considered plausible. Moreover, the observed dune dimensions meet the codomain of the bedforms reported by Kubicki et al. (2017) fairly well, likewise implying that the automated approach applied in this study renders feasible.

With respect to metocean causes for the evolution of primary dunes, no correlation could be established from the available point measurements. However, it is obvious that extreme events, such as storm surges, have an impact on the hydrodynamic processes in the Outer Jade and, thus, on the transport regime inside the survey domain as well. Preliminary results on the temporal variation of dune migration rates indicate that the horizontal movement of large bedforms may be influenced by the storm season. Further investigations will clarify, whether metocean factors may also influence the net sediment transport in this area, e.g. in combination with longshore transport.

With regard to the positive correlation between cumulated maintenance volumes and morphological changes, the present results suggest a causal connection, namely the hypothesized recirculation of dredge spoil from the dump sites close to the fairway segment. However, the purely mathematical correlation between the two time-series is not tantamount to a causal nexus. And although previous numerical model simulations indicate a zone of recirculation relating to hydrodynamics and transport capacities (Melling & Kösters 2017), the behavior of the dumped sediment volumes should be further investigated by simulations respecting the specific dynamics of dredge dispersion at the adjacent spoil grounds. As prior studies concluded before (e.g. Kubicki et al. 2017), a high-resolution model coupling hydrodynamic and sediment transport processes seems essential for the understanding of the fate of dumped sediments. Nevertheless, if the recirculation hypothesis holds, significant changes have to be applied regarding the official sediment management strategy and especially concerning the location of spoil grounds.

5 CONCLUSIONS

Within the scope of this study echosounding datasets of 47 consecutive navigational safety surveys in the Outer Jade are examined. The obtained bathymetric information is utilized for an analysis of local

bedforms and a volume balancing study. The temporal variation of sediment volume differences from consecutive bathymetric surveys inside a predefined fairway segment is used to test for potential correlations with the corresponding metocean time-series and with documented maintenance activities, respectively. In this context, significant correlations are observed for the linear relationship between bathymetric changes and reported maintenance works, yielding a high coefficient of determination of $R^2 = 0.96$. This finding indicates a recirculation of dredge spoil dumped in the vicinity of the navigational channel as previously suggested by other authors. However, further research has to be undertaken on this topic, especially in terms of numerical simulations, to facilitate a verification of the described hypothesis.

6 ACKNOWLEDGEMENT

The described investigations were undertaken in the course of a Master's Thesis at the Gottfried Wilhelm Leibniz University. The joint project was supervised by associates of the Ludwig-Franzius-Institute in Hannover and the Federal Waterways Engineering and Research Institute of Germany, Hamburg. Therefore, sincere thanks are given to these competent supporters of the present paper. Moreover, special thanks go to the experts of the Waterways and Shipping Office of Wilhelmshaven who generously shared their "digital treasure", i.e. navigational safety surveys and MoNa reports, with us.

7 REFERENCES

Ashley, G.M. (1990): Classification of large-scale subaqueous bedforms; A new look at an old problem. In: Journal of Sedimentary Research 60 (1), S. 160–172. doi:10.2110/JSR.60.160

Flemming, B.W. (1988): Zur Klassifikation subaquatischer, strömungstransversaler Transportkörper. In: Bochumer geologische und geotechnische Arbeiten 29 (93-97).

Götschenberg, A.; Kahlfeld, A. (2008): The Jade. In: Die Küste, 74 ICCE (74), S. 263–274.

Kubicki, A.; Bartholomä, A. (2011): Sediment dynamics in the Jade tidal channel prior to port construction, southeastern North Sea. In: Journal of Coastal Research SI 64, S. 771–775. ISSN 0749-0208

Kubicki, A.; Kösters, F.; Bartholomä, A. (2017): Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. In: Geo-Marine Letters 37 (1), S. 47–58. doi:10.1007/s00367-016-0470-6

Melling, G.; Kösters, F. (2017): Voruntersuchungen zum Sedimentmanagement in der Jade. Internal Report. Federal Waterways Engineering and Research Institute (BAW), Germany.

Van der Mark, C.F.; Blom, A.; Hulscher, S.J.M.H. (2008): Quantification of variability in bedform geometry. In: Journal of Geophysical Research (Earth Surface) 113. doi: 10.1029/2007JF000940

Zorndt, A. C.; Wurpts, A.; Schlurmann, T. (2011): The influence of hydrodynamic boundary conditions on characteristics, migration, and associated sand transport of sand dunes in a tidal environment. In: Ocean Dynamics 61 (10), S. 1629–1644. doi:10.1007/s10236-011-0452-1