Parametrization of bedform induced hydraulic flow resistance in coastal-scale numerical models – an evaluation of Van Rijn's empirical bedform roughness predictors

Gerald Herrling *Inst. of Geosciences, Kiel University, Germany – gerald.herrling@ifg.uni-kiel.de*
Knut Krämer *MARUM, University Bremen, Bremen, Germany – kkraemer@marum.de*
Marius Becker *Inst. of Geosciences, Kiel University, Germany – marius.becker@ifg.uni-kiel.de*
Alice Lefebvre *MARUM, University Bremen, Bremen, Germany – alefebvre@marum.de*
Christian Winter *Inst. of Geosciences, Kiel University, Germany – christian.winter@ifg.uni-kiel.de*

ABSTRACT: Bedforms (dunes and ripples) constitute a form roughness, i.e. hydraulic flow resistance, which has a large-scale effect on hydrodynamics and sediment transport of coastal environments. This hydraulic effect of bedforms needs to be parameterized in coastal-scale process-based models, since individual numerical grid cell sizes of typically 20 to 200 meters do not allow a proper discretization of bedform elements. State-of-the-art empirical bedform roughness predictors (Van Rijn 1984, 2007) are tested in numerical model simulations of both a simplified flume experiment and on the estuarine domain scale. A sensitivity analysis shows the performance of the bedform roughness predictors at variable water depths, flow velocities and mean grain-sizes. Predicted dune heights and lengths in a model of the Weser estuary are compared to dune dimensions observed by high-resolution multibeam measurements.

1. INTRODUCTION

Bedforms, such as ripples, megaripples or large dunes, cause a local hydraulic flow resistance which has a large-scale effect on hydrodynamics and sediment dynamics of rivers, estuaries and coastal seas. The resistance to the flow induced by bedforms, i.e. hydraulic bedform roughness, is associated with the flow expansion on their lee side resulting in kinetic energy loss, as exemplified for river dunes by Engelund and Fredsøe (1982). Additional turbulence generated in case of flow separation behind the bedform crest and recirculation on the downstream side greatly enhances this effect (e.g. Vanoni and Hwang, 1967). The expansion loss and the rate of velocity decrease downstream of the bedform crest can be related to the lee slope angle (Best and Kostaschuk, 2002; Motamedi et al., 2013; Paarlberg et al., 2007; Lefebvre and Winter, 2016).

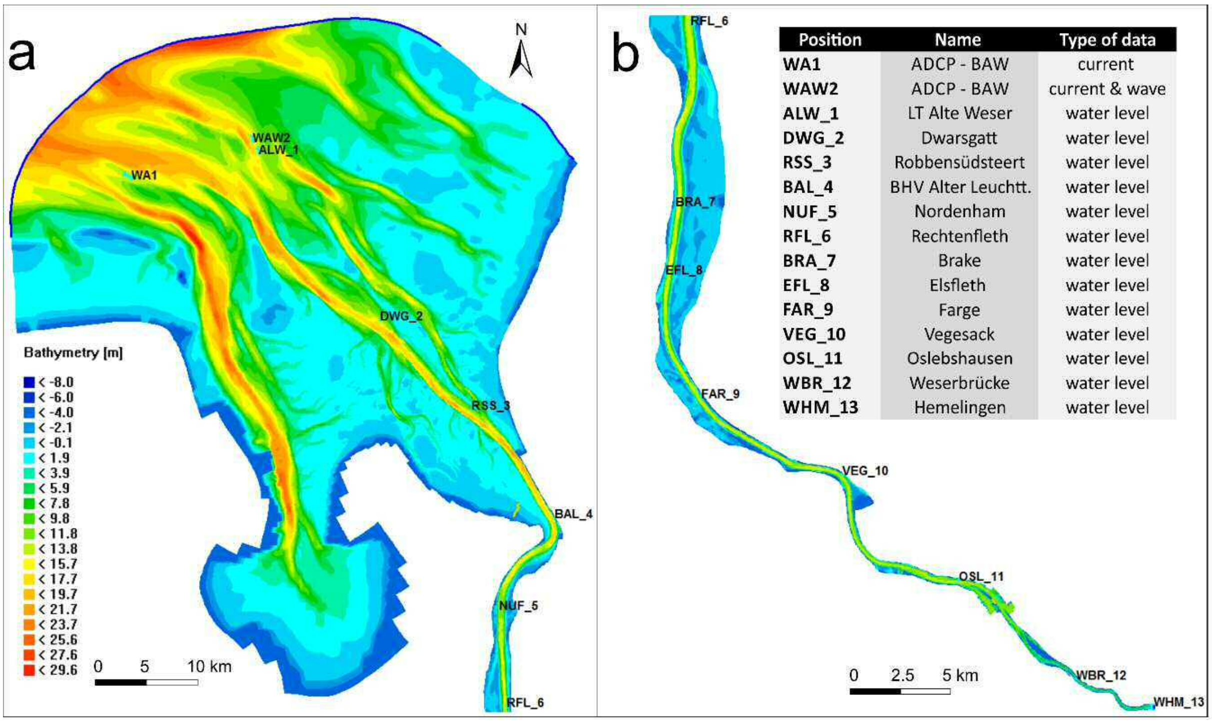

Figure 1. Bathymetry of the model domain and position of measurements (a) from the open sea boundary (blue line) to Rechtenfleth (RFL_6) and (b) from Rechtenfleth to the tidal barrier at Hemelingen, Bremen (WHM_13). Note the different spatial scales selected to improve the presentation of the outer and inner part of the estuary.

Energy loss above bedforms must be taken into account in numerical hydro- and morphodynamic model simulations in the form of bed friction coefficients that are associated with grain and form roughness. Particularly the applicability and performance of form roughness predictors has received little attention in large-scale model applications. Although computer power increases gradually, numerical coastal domain models are typically still restricted in horizontal and vertical grid resolutions to properly represent all topographical and morphological features; common grid cell sizes of process-based models are between 20 and 200 meters. This implies the parameterisation of the effect of bedform roughness elements that are of the length of a model grid cell or less. Thus bedforms are usually considered as of 'sub-grid-scale' (Sandbach et al., 2012). It should be noted that even at high spatial resolution and adequate 3-dimensional discretization of bedforms, their resistance to the flow may not be taken into account; flow separation and turbulence generation over bedforms requires simulations with a fully non-hydrostatic model configuration (Lefebvre et al., 2014, 2016).

Although common in fluvial studies, there are very few numerical model studies in coastal settings that apply bedform roughness predictors and deal with the effect of bedform roughness on the hydro- and morpho-dynamics. Van Rijn's bedform roughness predictor (2007), and particularly the dune roughness predictor, have primarily been developed for riverine conditions. The scheme has already been applied in a few large-scale coastal area models and appears to be robust (Davies and Robins, 2017; Herrling et al., 2017; Villaret et al., 2011; Wang et al., 2016).

Hydraulic bedform roughness predictors commonly are based on the ratio of height and length (i.e. steepness) of a bedform (e.g. Julien and Klaassen, 1995; Karim, 1999; van Rijn, 1984; Yalin, 1964) and thus require field data or a prediction of bedform geometries. Yet the predictor of van Rijn (2007) directly expresses the bedform roughness height depending on current velocity, surface sediment grain-size and water depth. Thus, in tidal environments, variations of current speed and water depth may result in variations of bedform roughness over a tidal cycle.

This study explores the parameterisation of bedform hydraulic roughness in a simple flume experiment (sensitivity study) and a model of the Weser estuary, Germany, using the Delft3D (Deltares, 2014) modelling system. Well-established bedform roughness predictors of van Rijn (1984, 2007) are evaluated and predicted bedform dimensions are compared to observations from high-resolution multi-beam bathymetry.

overall bedform roughness. The overall bedform roughness predicted by VR07 is known as a combination of the roughness from ripples, megaripples and dunes and may vary spatially in its composition and magnitude. In this study only the bedform roughness of dunes (VR07) is considered and is compared to the dune roughness predicted by VR84. For a detailed description of the formulae used in these predictors and the implementation into the modelling system, it is referred to the original publications (van Rijn 1984, 2007) and the manual of the model system Delft3D (Deltares, 2014).

Numerical flume experiment

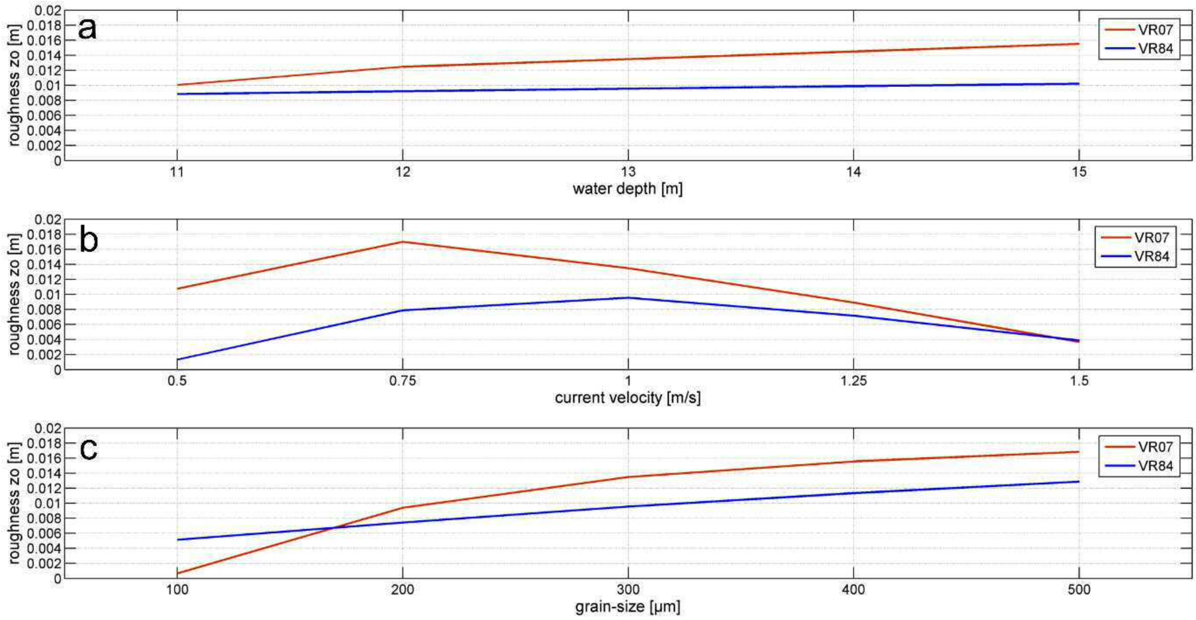

Figure 2. Bedform (dune) roughness height z_0 predicted by VR84 and VR07 for simulations with (a) variable water depths, (b) variable current velocities and (c) variable mean grain-sizes in a numerical flume experiment.

2. METHODS

Bedform roughness prediction

Predictors of bedform dimension (van Rijn, 1984) and bedform roughness (van Rijn 1984, 2007) were tested. While the predictor after van Rijn 2007 (VR07) directly estimates the bedform roughness height z_0, van Rijn 1984 (VR84) determines bedform dimensions (height and length) in an intermediate step before calculating the

Sensitivity tests were conducted in a simple numerical flume experiment with unidirectional flow to study the predicted bedform roughness (VR84 and VR07) as a response to variable water depths (11 to 15 m), current velocities (0.5 to 1.5 m/s) and mean grain-sizes (100 to 500 µm). These conditions are within typical ranges of the parameters found in the Lower Weser estuary. For each model run, only one parameter has been altered at a time; the reference condition is a water depth of 13 m, a flow velocity of 1 m/s and mean grain-size of 300 µm. The model domain has a width of 100 m and length of 5000 m, the simulations are performed in depth-averaged (two-dimensional horizontal, 2DH) and three-dimensional (3D) configurations applying velocity forcing at the upstream open boundary and a stationary water level at the downstream boundary. Bedform roughness heights are extracted at 1000 m downstream of the upstream end after a hydrodynamic spin-up of 12 hours.

model of the Weser estuary forced by real-time tidal flow and upstream discharge (Herrling et al., 2017).

Predicted bedform dimensions of VR84 and VR07 were compared to dune observations in the Lower Weser estuary. Predicted dune heights and lengths were determined from VR84. For VR07 a backward calculation based on Van Rijn (1984) determined bedform dimensions.

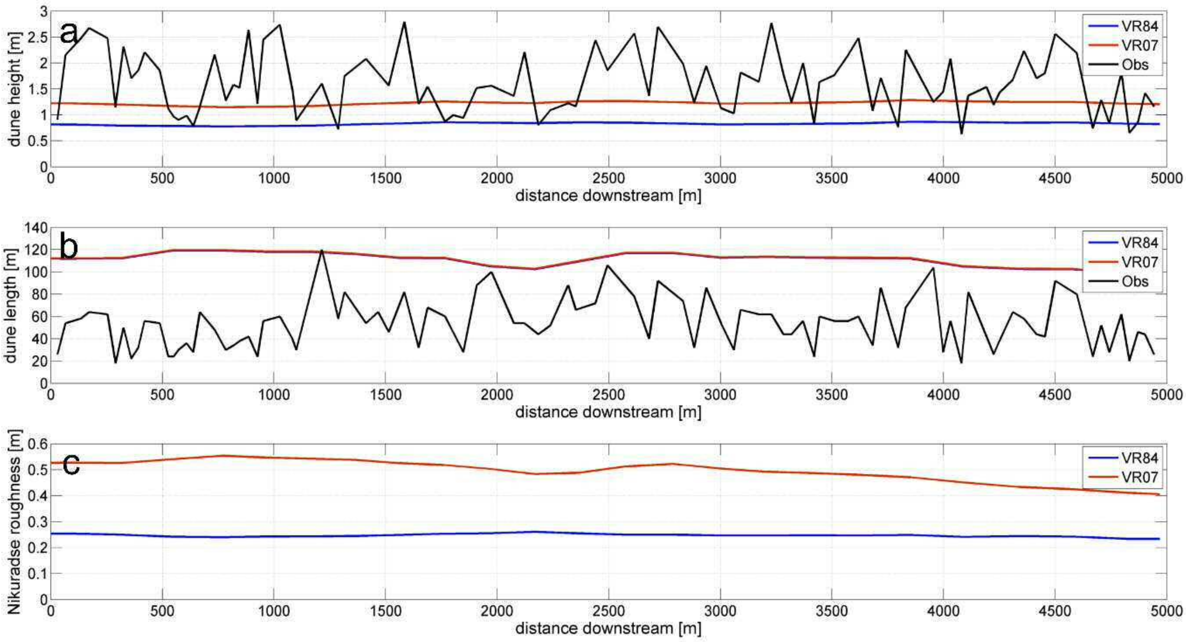

Figure 3. Predicted (at max. ebb flow, VR07, VR84) and observed (a) dune heights and (b) dune lengths along a section of 5 km downstream of Rechtenfleth in the Lower Weser estuary in Sept. 2012; (c) Predicted Nikuradse dune roughness.

As expected both formulae predict larger roughness with increasing water depth and/or grain-size with an order of magnitude range (Fig. 2). The case of variable current magnitudes shows that under Weser estuarine conditions the critical conditions occur, where bedform roughness has a maximum. It is noted that the application of VR07 results in significantly higher dune roughness values compared to VR84.

Evaluation of bedform roughness prediction in the estuarine domain model

The performance and effect of uncalibrated bedform predictors at estuarine scale is shown with a numerical morphodynamic

High-resolution multi-beam bathymetric data surveyed by local authorities (WSA Bremerhaven) in September 2012 resolve a bedform field at a section of 5 km downstream of Rechtenfleth in the Lower Weser (RFL_6, Fig. 1). Dune heights and lengths were determined by filtering and zero-upcrossing (Krämer et al., abstract MARID 2019).

3. PRELIMINARY RESULTS

Predicted dune height and length from the uncalibrated model simulations are compared to measured bedform dimensions. In September 2012, measured dune heights of the observed dune field are between 0.6 and 2.8 m with overall mean heights of 1.6 m. Mean dune lengths are 53 m with absolute lengths varying between 18 and 120 m.

Predictions of dune heights are consistent along the section with mean values of 0.83 and 1.23 m for VR84 and VR07, respectively; thus underestimating observations. Predicted dune lengths are very similar for both formulae and vary between 100 and 120 m. These values in turn are at the upper limit of observed values. From a physical understanding, results imply a possible underestimation of bedform roughness, as the underestimated heights and over-estimated lengths would result in lower steepness of the modelled dunes compared to the measured ones.

Nikuradse dune roughness heights are predicted to be significantly larger for VR07 compared to VR84.

Although maximal current magnitudes are simulated to be similar for ebb and flood, dune height and roughness are predicted to be larger during flood than ebb, particularly for VR07 (not shown here). It is noted that upstream discharges about 105 m^3/s are low in September 2012 in relation to long-time mean discharges of 323 m^3/s. Maximal ebb currents occur at late ebb when water levels are lower compared to maximal flood currents at late flood.

4. SUMMARY AND OUTLOOK

Dynamic dune roughness prediction has a significant effect on simulated hydrodynamics. In this study two empirical bedform roughness predictors, developed by Van Rijn (1984, 2007), primarily for riverine, unidirectional flow conditions, have been tested and evaluated.

Applied for tidal flow conditions, dune heights predicted by VR07 and VR84 underestimate observed mean dune heights by 23% and 48%, respectively. Predicted mean dune lengths are overestimated by both formulae by approximately 50% with respect to measurements. A smaller dune steepness is thus predicted compared to observations.

For a section of 5 km in the Lower Weser, predicted dune roughness and dimensions are consistent; however on the entire estuarine scale predictions vary spatially. An upcoming evaluation of predicted dune dimensions in relation to measurements of dune fields along the Outer and Lower Weser estuary will reveal the spatial performance of bedform roughness predictors. Variations of roughness height on annual time scales with seasonal and event-driven discharges will be evaluated against estimations of dune dimensions analysed from monthly bathymetric surveys.

5. ACKNOWLEDGEMENTS

This study was funded by the research projects MorphoWeser and FAUST being financed by the German Federal Waterways Engineering and Research Institute (BAW). We thank the relevant authorities (WSA Bremerhaven) for providing data on Weser bathymetry. AL is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), project number 345915838.

6. REFERENCES

Best, J., Kostaschuk, R.A., 2002. An experimental study of turbulent flow over a low-angle dune. J. Geophys. Res. 107, 3135. doi:10.1029/2000jc000294

Davies, A.G., Robins, P.E., 2017. Residual flow, bedforms and sediment transport in a tidal channel modelled with variable bed roughness. Geomorphology 295, 855–872. doi:10.1016/j.geomorph.2017.08.029

Deltares, 2014. Delft3D-FLOW, User Manual, Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. The Netherlands.

Engelund, F., Fredsoe, J., 1982. Hydraulic theory of alluvial rivers. Adv. Hydrosci. 13, 187–215. doi:http://dx.doi.org/10.1016/B978-0-12-021813-4.50009-3

Herrling, G., Benninghoff, M., Zorndt, A., Winter, C., 2017. Drivers of channel-shoal morphodynamics at the Outer Weser estuary, in: Coastal Dynamics Conference, Helsingoer, Denmark. Helsingoer, Denmark.

Julien, P.Y., Klaassen, G.J., 1995. Sand-dune geometry of large rivers during floods. J. Hydraul. Eng. doi:10.1061/(ASCE)0733-9429(1995)121:9 (657)

Karim, F., 1999. Bed-Form Geometry in Sand-Bed Flows. J. Hydraul. Eng. 125, 1253–1261. doi:10.1061/(ASCE)0733-9429(1999)125:12 (1253)

Lefebvre, A., Paarlberg, A.J., Ernstsen, V.B., Winter, C., 2014. Flow separation and roughness lengths over large bedforms in a tidal environment: A numerical investigation. Cont. Shelf Res. 91, 57–69. doi:10.1016/j.csr.2014.09.001

Lefebvre, A., Winter, C., 2016a. Predicting bed form roughness: the influence of lee side angle. Geo-Marine Letters 36:121-133. doi:10.1007/s00367-016-0436-8

Lefebvre, A., Paarlberg, A.J., Winter, C., 2016b. Characterising natural bedform morphology and its influence on flow. Geo-Marine Lett. 36, 379–393. doi:10.1007/s00367-016-0455-5

Motamedi, A., Afzalimehr, H., Gallichand, J., Fazel Najaf Abadi, E., 2013. Lee Angle Effects in Near Bed Turbulence: An Experimental Study on Low and Sharp Angle Dunes. Int. J. Hydraul. Eng. 1, 68–74. doi:10.5923/j.ijhe.20120106.02

Paarlberg, A.J., Dohmen-Janssen, C.M., Hulscher, S.J.M.H., Termes, P., 2007. A parameterization of flow separation over subaqueous dunes. Water Resour. Res. 43. doi:10.1029/2006WR005425

Sandbach, S.D., Lane, S.N., Hardy, R.J., Amsler, M.L., Ashworth, P.J., Best, J.L., Nicholas, A.P., Orfeo, O., Parsons, D.R., Reesink, A.J.H., Szupiany, R.N., 2012. Application of a roughness-length representation to parameterize energy loss in 3-D numerical simulations of large rivers. Water Resour. Res. 48. doi:10.1029/2011WR011284

van Rijn, L.C., 1984. Sediment Transport, Part III: Bed forms and Alluvial Roughness. J. Hydraul. Eng. 110, 1733–1754. doi:10.1061/(ASCE)0733-9429(1984)110:12(1733)

van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. J. Hydraul. Eng. 133, 649–667.

Vanoni, V.A., Hwang, L.-S., 1967. Bed forms and friction in streams. J. Hydraul. Div. Vol 93, 121–144.

Villaret, C., Huybrechts, N., Davies, A.G., Way, O., 2011. Effect of bed roughness prediction on morphodynamic modelling: Application to the Dee estuary (UK) and to the Gironde estuary (France), in: Proceedings of the 34th World Congress of the International Association for Hydro-Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering. Engineers Australia, p. 1149.

Wang, Y., Yu, Q., Jiao, J., Tonnon, P.K., Wang, Z.B., Gao, S., 2016. Coupling bedform roughness and sediment grain-size sorting in modelling of tidal inlet incision. Mar. Geol. 381, 128–141. doi:10.1016/J.MARGEO.2016.09.004

Yalin, M.S., 1964. Geometrical Properties of Sand Wave. J. Hydraul. Div. 90, 5105–119.