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Modelling the Effect of an Ebb-Tidal Delta Nourishment on Local Grain Size Distribution Patterns

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Abstract

The ebb-tidal delta of the Ameland Inlet system is of great ecological importance since it hosts a variety of benthic habitats. In a pilot project, a (mega)nourishment of 5 million cubic meters of sand was carried out on the outer ebb-tidal delta. Since the strong correlation between habitat preference and sediment characteristics on the ebb-tidal delta, it is crucial to gain insight in the mechanisms governing sediment sorting in this area. To study the initial response of grain size distribution patterns, and subsequently potential changes to benthic habitats, process-based models are useful tools. Here, we present a hydro- morphodynamic model of the Ameland Inlet which is able to simulate grain size sorting patterns. Building upon previous modelling efforts, we specifically focus on the inclusion of graded sediment transport and bed stratigraphy. The simulations, here with the nourishment excluded, reveal that the model results on grain size distribution can be related well to the forcing in combination with the local depth. Particularly, it turns out that tidal motion is responsible for the sorting pattern in the deeper parts of the ebb-tidal delta, whereas the grain size distribution in the shallower, offshore parts is particularly shaped by wind and wave processes. Model sensitivity to several numerical parameters (thickness transport layer, MORFAC) is also investigated and seems relatively small, although further investigation is needed here. A preliminary comparison reveals that the model results compare qualitatively well to field data, although the shallower offshore areas seem to be predicted too coarse in the model.

Keywords: Sediment sorting, ebb-tidal delta, process-based modelling, benthic organisms, Delft3D

1. INTRODUCTION

An important part of coastal inlet systems, such as the Wadden Sea, is the ebb-tidal delta. This shallow sandy environment connects the back-barrier basin with the open sea. Since it is located on the seaward side of the barrier islands, it is prone to relatively high energetic hydrodynamic forcing. Wind and wave processes lead to a net sand transport in the direction of the basin, whereas sand is transported seaward by tidal currents. Sediments are deposited on the ebb-tidal delta due to decreasing flow velocities after passing through the narrow tidal inlet (Elias, 2006). Altogether, these processes lead to a remarkably complex bathymetric system (Figure 1). Moreover, this also results in a rich coastal ecosystem, with many different benthic organisms and habitat structures (Holzhauer et al, 2022), which makes this environment of high ecological value.

Erosion of the sandy coasts of barrier islands is often managed by applying beach and shoreface nourishments. As a pilot project, recently a new type of (mega)nourishment was carried out near the Ameland Inlet of the Wadden Sea (Figure 1), where a nourishment of 5 million cubic metres of sand was placed on the outer ebb-tidal delta, roughly 2 km northwest of the Kroftmansbult. As this area is characterized by its complex hydro- and morphodynamics, it is unclear how this nourishment will evolve in both the short and long term. Moreover, as this area is of great ecological importance, the stresses to the ecological environment should be minimized. One of the issues is that the sediment composition of the nourishment is different to that of the target area. Potentially, a change in sediment characteristics may significantly alter benthic habitats, since often there is a close relation between grain size and habitat preference (Reiss et al, 2014). This also holds for the Ameland ebb-tidal delta, where it was recently demonstrated that the degree of sorting increases with increased exposure to wave processes (Holzhauer et al, 2022).

Hence, there is a need to start understanding the sediment sorting processes on the ebb-tidal delta and thereby to make a first step in understanding and predicting the benthic species distribution. Specifically, the goal of this work is to gain insight in the initial changes of the sediment composition when the ebb-tidal delta is exposed to a short period of a mixed current-wave climate. To this end, we focus on the development of a hydro- and morphodynamic model which allows for graded sediment transport, including an arbitrary number of sediment grain size fractions, bed stratigraphy and typical processes such as hiding-exposure. Using this model we analyse the role of different types of forcing, and the sensitivity to several numerical model parameters on the resulting grain size patterns.

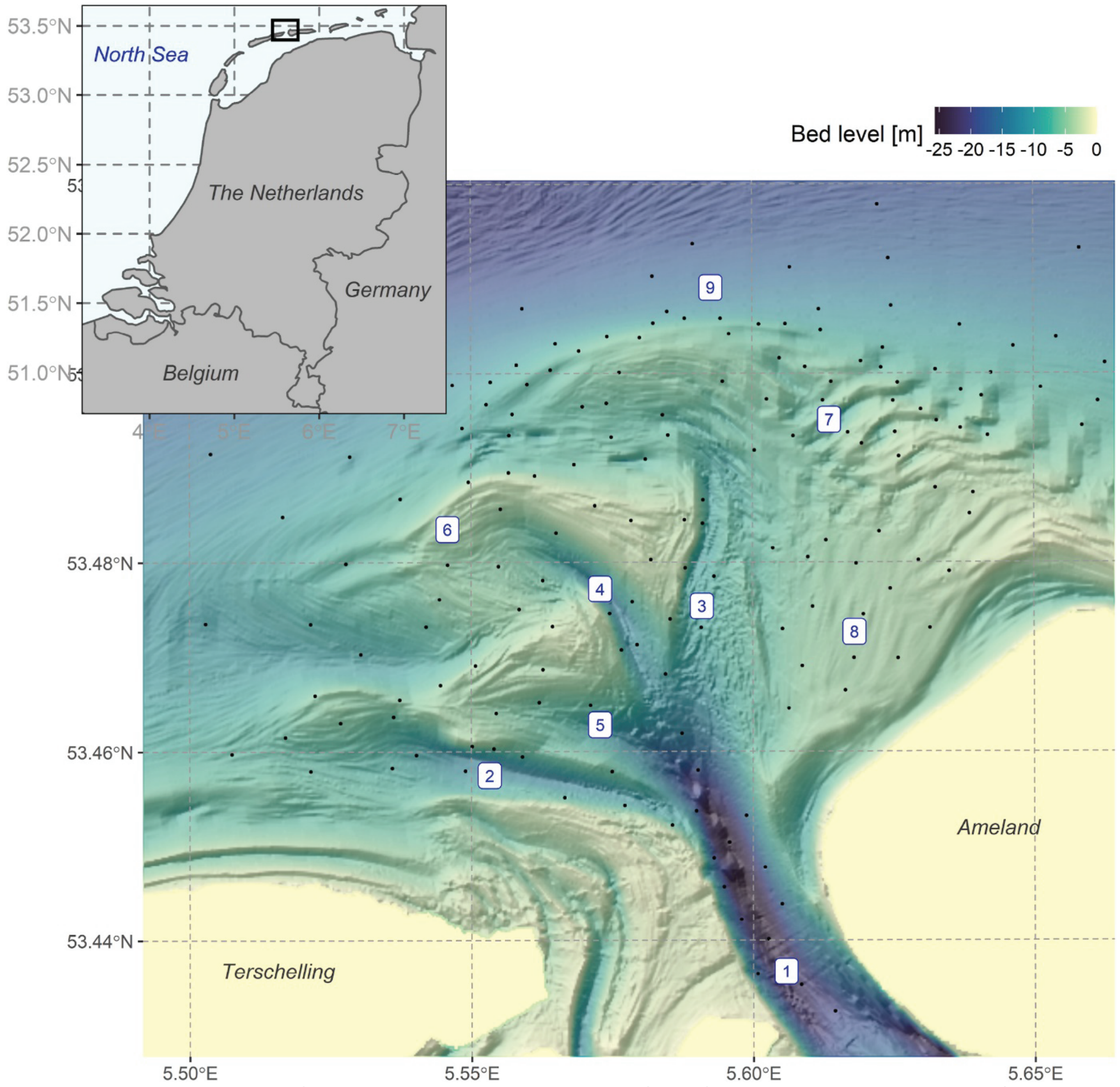

Figure 1. Bathymetric chart of the Ameland ebb-tidal delta. Specific locations on the map: 1) Borndiep, 2) Westgat, 3) Akkepollegat, 4) ebb chute-1, 5) ebb chute-2, 6) Kroftmansbult 7), Bornrif platform, 8) Shallow centre of the Bornrif platform, 9) Vlakte van Ameland bordering the terminal lobe. Reprint from Holzhauer et al (2022).

2. MODEL DESCRIPTION

We built upon earlier work from Nederhoff et al (2019), and Brakenhoff et al (2020a), who developed a morphodynamic model of the Ameland Inlet in Delft3D (Lesser et al, 2004). For an extensive description of the model setup, boundary conditions and forcing, we refer the interested reader to the abovementioned references, and we present a summary below.

The depth-averaged (2DH) hydro- morphodynamic model simulates waves, wind, water levels and atmospheric pressure. For the water levels on the boundaries, the larger continental shelf model DCSMv4ZUNOv6 (Zijl et al, 2013) was used, which provides information on tidal motion and meteorological data. Wave conditions at the model boundaries were derived from two measuring stations near the west and east boundary.

The computational grid extends from the island of Vlieland to the island of Schiermonnikoog, whereas the seaward boundary is located roughly 30 km offshore of the ebb-tidal delta. Neumann boundary conditions are applied in the back-barrier basin. Grid sizes in the area of interest are typically 50-150 m, which assures that hydrodynamic processes are represented appropriately (Nederhoff et al, 2019).

The bathymetry of the Ameland Inlet was measured in 2017 by Rijkswaterstaat and was combined with bathymetric data from earlier years for the wider model domain. In 2017, also another measuring campaign was carried out (as part of the SEAWAD research program, see van Prooijen et al (2020)), which provided detailed hydrodynamic data used for model calibration. Validation of the hydrodynamics was done using velocity data obtained from several ADCPs in 2002, 2011, 2017 and 2018.

The main novelty of this work is the application of the bed stratification module in Delft3D, which is able to simulate graded sediment transport (see e.g., Damveld et al, 2020). The module consists of an active layer, in which the exchange of sediments between the bed and water column takes place, and multiple underlayers, which are used to 'store' the history of erosion and deposition. Further beneath, a base layer completes the total sediment thickness. Following field measurements (see Prooijen et al, 2020), four equal fractions of cohesionless sediment were chosen, which roughly represents the soil composition of the area (D50 = 0.21 mm). The initial distribution of sediments in the model domain is considered well-mixed, i.e., fully homogeneous. In Table 1 the settings associated to the here presented simulations are given.

Table 1. Overview of the relevant model parameters. Underlined values refer to the base run.

DESCRIPTION	VALUES	UNIT
Grain size fractions	0.1, 0.2, 0.3, 0.4	mm
Underlayer thickness (excluding base layer)	1	m
Number of underlayers (excluding base layer)	4	-
Total initial layer thickness	20	m
Active layer thickness	0.1, <u>0.25</u>, 0.4	m
MORFAC	<u>1</u>, 50, 100	-

The model was run for six weeks, which exactly covers the period of the above mentioned SEAWAD field campaign of 30 August–8 October 2017. Noteworthy is a short period of stormy conditions halfway the model simulation, with velocity currents up to two times higher than during calm conditions (Brakenhoff et al, 2020a). To study the initial response of sorting patterns to the hydrodynamic forcing, only the soil composition (i.e., no bed level changes) in the model was allowed to be updated as a result of graded sediment transport. Importantly, for some simulations a morphological acceleration factor (MORFAC) has been applied, which also speeds up grain size sorting patterns.

3. RESULTS AND DISCUSSION

3.1 Grain size distribution patterns

Figure 2abc present the grain size distribution after two, four and six weeks of simulation, respectively, forced by both tides and waves. In general, the sediment distribution relates well to the depth contours. In the deeper parts of the main channels, the grain size is coarser due to the higher currents here. Also, the shallower parts of the outer delta appear to be coarser than the adjacent ebb-chutes. A small area of fine sediments stands out just north of Ameland, which is a relatively deep area compared to the shallow Bornrif platform. Moreover, the rhythmic bed pattern of the Bornrif platform can be distinguished well in the grain size map. A first visual comparison to field measurements of the ebb-tidal delta (see e.g., Holzhauer et al, 2022) reveals that especially the deeper channels are reasonably well predicted. However, the shallow areas in the area of the Bornrif platform are much coarser in the model than in the field measurements. Further analysis is needed here to explain these differences.

Figures 2def and 2ghi present the contributions of the tide and wind/wave motion, respectively, to the overall grain size pattern (again for two, four and six weeks of simulation). It should be noted here that the wave contribution is obtained by subtracting the tidal contribution from the base run in panels abc). Here it is visible that for the deeper channels, particularly the tide is responsible for the coarsening process. On the outer delta, wind and waves have much more influence and leads to an overall coarsening of the area. Specifically, the shallower areas are more prone to waves, which leads to strong coarsening. Interestingly, in the ebb-chutes tidal motion leads to a coarsening, whereas wave motion leads to a strong fining, resulting in an overall fine-grained spot. Finally, it is visible that the abovementioned grain size patterns on the Bornrif platform is mostly shaped by wind and wave forcing.

The results also show that for the overall sorting pattern to occur it is not needed to simulate the full six weeks of the field survey, as shown in the different columns. Already after two weeks, the sorting pattern closely resembles the pattern after six weeks. When viewing the individual forcing components, it appears that this is particularly the case for the wind and wave forcing, whereas the tidal component keeps changing slowly over time. Surprisingly, the period with stormy conditions is not visible in the results. Since this period is in the third week, a change in pattern would have been expected from week two to week four. This suggests that the sorting patterns is more sensitive to milder wind/wave conditions over a longer period of time, than to short, energetic forcing episodes.

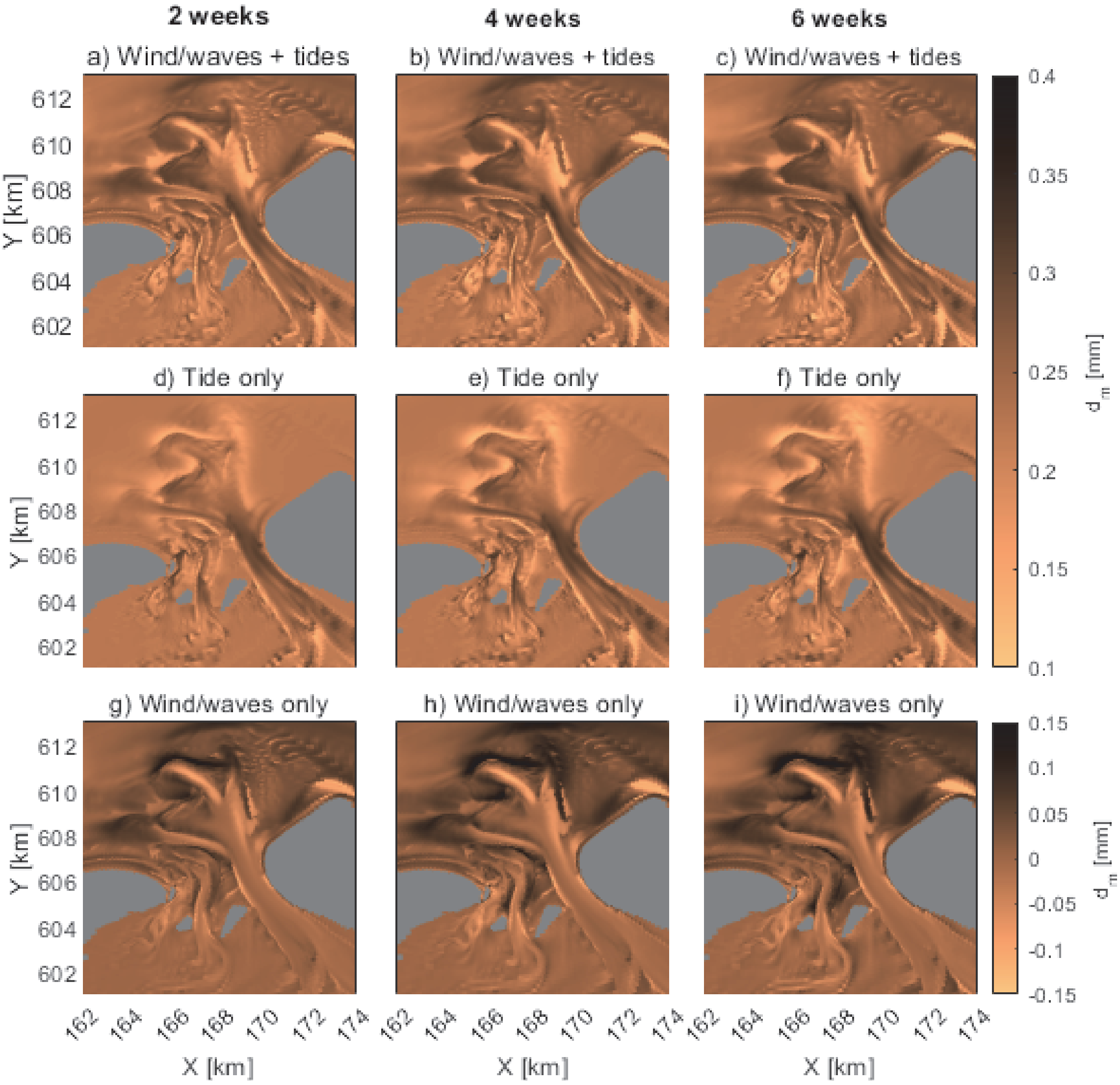

Figure 2. Grain size distribution d_m in the active layer. In abc) the result for the full simulation including wind/waves and tides, in def) the result with tidal motion only, and ghi) the result with wind and wave motion only. The columns differ in the actual time of the simulation, showing the result after two, four and six weeks, respectively. Note that in the lower row (wind/waves only) the result is obtained by subtracting the second row from the upper row.

3.2 Sensitivity analysis

To test the sensitivity of the morphodynamic model we have performed simulations for both the active layer thickness and the MORFAC. In Figure 3 the sensitivity to the active layer thickness is shown, with the tide-only reference simulation (Figure 2c) presented in panel a). From these results it appears that the thickness of the active layer is affecting the results only to a minor extent, as the overall grain size distribution patterns hardly change with increasing thickness. Further analysis should reveal its sensitivity when wave and wind processes are included. As was discussed in Damveld et al (2020), the sorting process slows down with increasing active layer thickness. They explained that the thickness of the active layer acts as a sort of sorting timescale, where a thicker layer means longer timescale. However, as the active layer thickness represents a physical process, i.e., it represents the height of the superimposed bedforms, its value should be chosen to closely mimic to field conditions. Since field observations have shown a great diversity of small-scale bedforms in the outer delta (Brakenhoff et al, 2020b), the model could be improved further with a spatially varying active layer thickness, which is closely related to the work by Brakenhoff et al (2020a) on modelling spatially varying bed roughness.

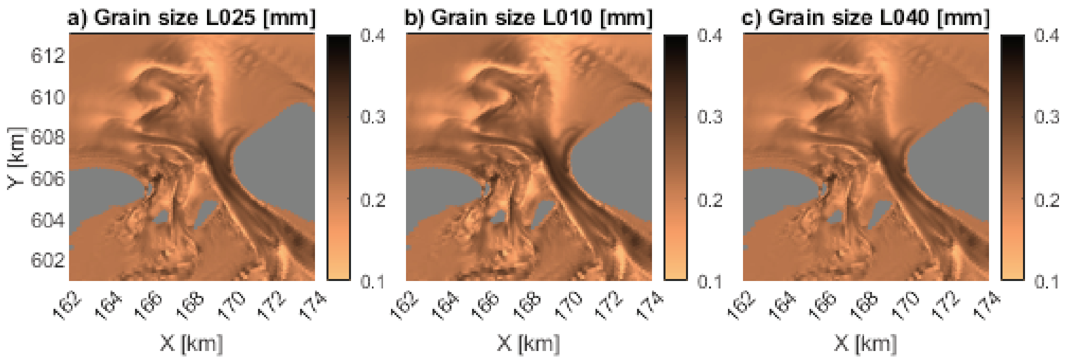

Figure 3. Sensitivity to a varying active layer thickness. In a) the reference run with a thickness of 25 cm. Panel b) and c) show the result for a thickness of 10 and 40 cm, respectively.

Due to the large computational effort this model requires (the base run takes approximately 21 days on 8 computational cores), a MORFAC could be considered. To see to what extent a MORFAC is influencing the results, we have performed some sensitivity simulations, presented in Figure 4. It can be seen that (again in case of tide only forcing) the grain size distribution pattern is strengthened with increasing MORFAC. However, the overall pattern remains the same. Moreover, the strengthening seems to reach an equilibrium as the increase from 50 to 100 is nearly unnoticeable. Similar to the active layer runs, the question is how this will perform when including wind and wave effects. In particular since, compared to the reference run, the MORFAC leads to a fining of the outer delta.

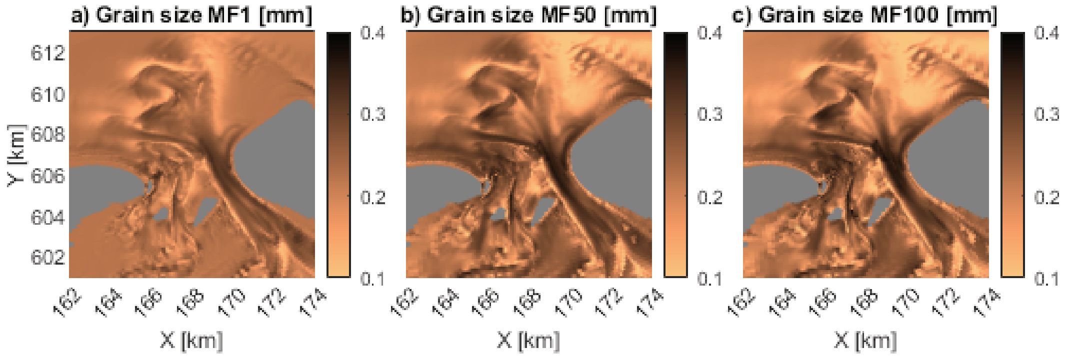

Figure 4. Sensitivity to an increasing MORFAC. In a) the reference run with a MORFAC of 1. Panel b) and c) show the result for a MORFAC of 50 and 100, respectively.

Also, other parameters involved in the stratification module of the model are potentially influencing the results and should therefore be investigated further. The number and thickness of the underlayers act as a history mechanism. Particularly in depositional areas this is a parameter which should be studied well. Without this history mechanism the excess sediment from the active layer would be added to a thick, general base layer, which is always fully mixed. Since the ratio of the excess sediment from the active layer with respect to the base layer thickness and is small, the grain size distribution of the base layer would only change to a small extent.

4. CONCLUSIONS AND OUTLOOK

We have presented a morphodynamic model of the Ameland Inlet, which is able to simulate grain size sorting patterns. The results show that the initial distribution pattern relates strongly to the local depth contours. Moreover, the type of forcing can be distinguished well in the results. It is particularly clear that inclusion of wind and wave motion leads to important variations of both fining and coarsening on the outer delta compared to merely tidal forcing. The sensitivity of the model to the active layer and morphological acceleration factor seems small, although further analysis is required here.

The next step is to compare the results to field measurements in order to reveal the actual predictive capacity of the model. To this end, the initial sediment fractions should be chosen to mimic the conditions in the area more closely. Also, a spatially varying active layer thickness may improve the predicted capacity of the model. Once the model is able to simulate field measurements it can be applied for coastal management efforts. Examples are the analysis of the effect of nourishments on the ebb-tidal delta or providing isotope information for ecological distribution models.

5. ACKNOWLEDGEMENTS

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