Littoral Processes at Micro-Tidal Coasts of the Southern Baltic Sea

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A systematic study is presented to gain general understanding of sediment transport along a micro-tidal coast. A holistic numerical model is used to study the morphodynamic processes in the Gellen Bay. Based on long-term statistics, a period of 9 days corresponding to a severe storm in January 2000 is selected for morphodynamic simulations. The results show very good agreement with observed morphological activity and bathymetric structures.

Introduction

The knowledge of local littoral processes is of utmost importance for any coastal zone management with regard to coastal protection and maintenance of navigation channels. The German coastal regions of the southern Baltic Sea can be characterized as micro-tidal regimes where shorelines are formed by wind-generated waves and currents. In recent years, two dimensional numerical models have been developed to simulate the morphodynamic changes of large coastal areas.

The interaction of hydrodynamic and morphodynamic processes is particularly strong in near shore regions. Modifications of the local wave field immediately changes the flow patterns which in turn can lead to local depth changes along beaches of fine-grained sand. This dynamic system behavior needs to be reflected in simulation tools used for diagnostic and prognostic purposes. A new holistic numerical model is presented, which models the interaction between currents, waves and morphodynamic directly. This numerical model is used to investigate the morphodynamic processes in the Gellen Bay and its near shore zones.

Study Area

The Gellen Bay is located at the micro-tidal coast of the southwestern Baltic Sea. Its coastal boundaries are the Darss-Zingst peninsula in the South, the island of Hiddensee in the East and include the Gellen inlet which connects an extended lagoon system to the Baltic Sea (Figure 1). The open boundaries in the Baltic Sea are chosen about 40 km offshore to the North at Darss Sill along a 20m depth contour, and at Darss spit in the West. The model area is characterized by flat ridges which reach far into the Baltic Sea and partly date back to the last ice-age. These are essentially shaped by waves.

Systems of sand bars build up in the near shore area. The sand flat „Bock” shown in Figure 2 is located in the inner part of this bay and is a reservoir where sand masses accumulate which were transported southward along the island of Hiddensee and eastward along the Zingst coast.

Morphodynamically significant events in this coastal region depend on the local wave and flow conditions and also on the filling state of the southern Baltic Sea. Incoming waves from the West and the North propagate straight to the beaches of Gellen Bay without significant damping. Particularly the near shore regions undergo strong morphologic changes under such conditions.

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Correct and adequate consideration of the interaction of waves, currents and sediment transport processes and the subsequent change of the bathymetry is a prerequisite for the correct evaluation of morphodynamic processes.

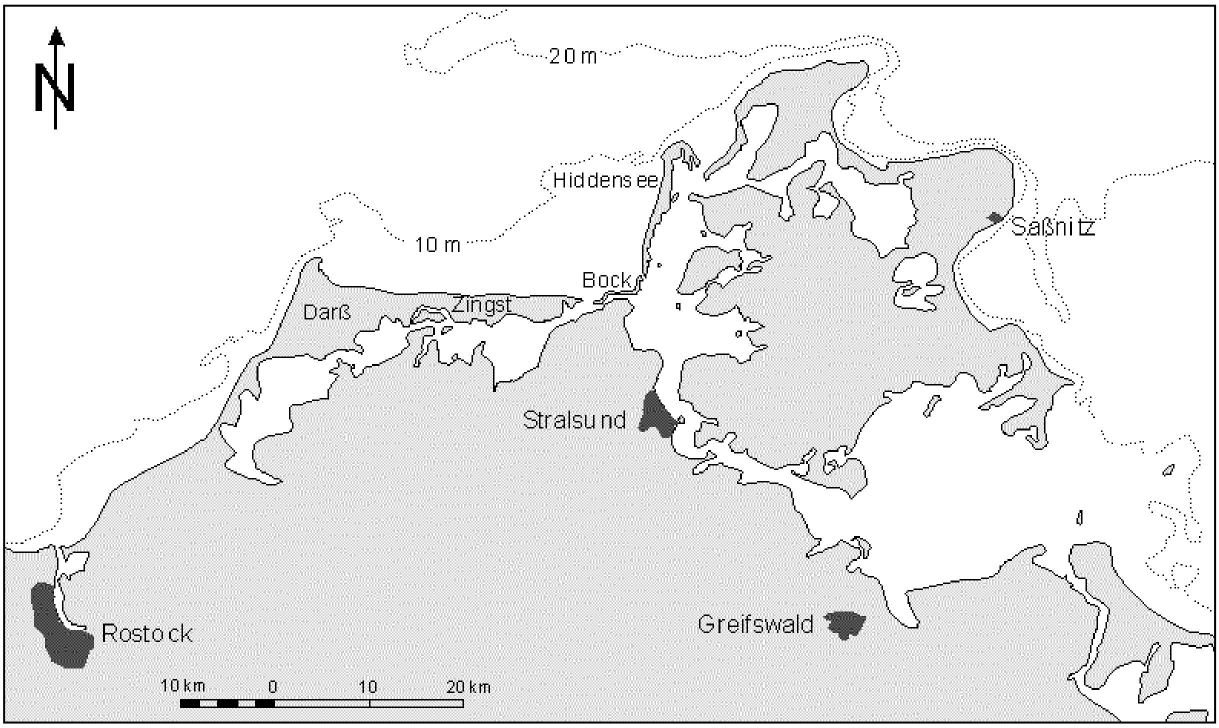


Figure 1: Costal area at Baltic Sea in Germany

Figure 2: Sand flat Bock, Southern Baltic Sea

Computational Model

A holistic numerical model based on nine partial differential equations is used to simulate the hydrodynamic and the morphological changes.

$$\frac{\partial K_i}{\partial t} = -\frac{\partial \sigma_a}{\partial x_i} + C_g \frac{K_j}{k}\left(\frac{\partial K_j}{\partial x_i} - \frac{\partial K_i}{\partial x_j}\right) \qquad \text{waves}$$

$$\frac{\partial \sigma}{\partial t} = -\left(U_i + C_{g_i}\right)\frac{\partial \sigma}{\partial x_i} - k_{x_i}\frac{\partial u_i}{\partial t} + f\frac{\partial h}{\partial t}$$

$$\frac{\partial a}{\partial t} = -\frac{1}{2a}\frac{\partial}{\partial x_i}\left(U_i + C_{E_i}\right)a^2 - \frac{S_{ij}}{\rho g a}\frac{\partial U_i}{\partial x_i} + \frac{U_i\left(T_i - T_i^B\right)}{\rho g a} + \frac{\varepsilon_B}{\rho g a}$$

$$\frac{\partial \overline{\eta}}{\partial t} = -\frac{\partial U_j d}{\partial x_j} \qquad \text{currents}$$

$$\frac{\partial U_i}{\partial t} = -U_j\frac{\partial U_i}{\partial x_j} - g\frac{\partial \overline{\eta}}{\partial x_i} - \frac{1}{\rho d}\frac{\partial S_{ij}}{\partial x_i} + \frac{1}{\rho d}\left(T_i - T_i^B\right)$$

$$\frac{\partial C}{\partial t} = -U_i\frac{\partial C}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\tau_i \frac{\partial C}{\partial x_i}\right) + S \qquad \text{sediment-transport}$$

$$q_i = \int_{-h}^{n} U_i C dz + q_b$$

$$\frac{\partial h}{\partial t} = -\frac{1}{1-n}\frac{\partial q_i}{\partial x_i}$$

Hyperbolic wave module

The first four equations describe the evolution of wind waves, using the wave number vector *K*, the angular frequency σ and the wave amplitude *a*. The propagation speed *C*, the group velocity C_g and the wave energy transport velocity C_E are obtained using linear wave theory. The wave model accounts for depth refraction as well as for current refraction. The input of turbulent energy in the water body due to wave breaking is realized by different breaking criteria. To describe the interaction between currents the concept of radiation stresses S_{ij} are used.

Shallow water flow module

The second block represents the shallow water equations with the vertically integrated velocity vector *U* and the mean water evaluation η. They account for the effects of wind shear stress at the surface, the Coriolis forces, and the wave radiation stresses.

Morphodynamic module

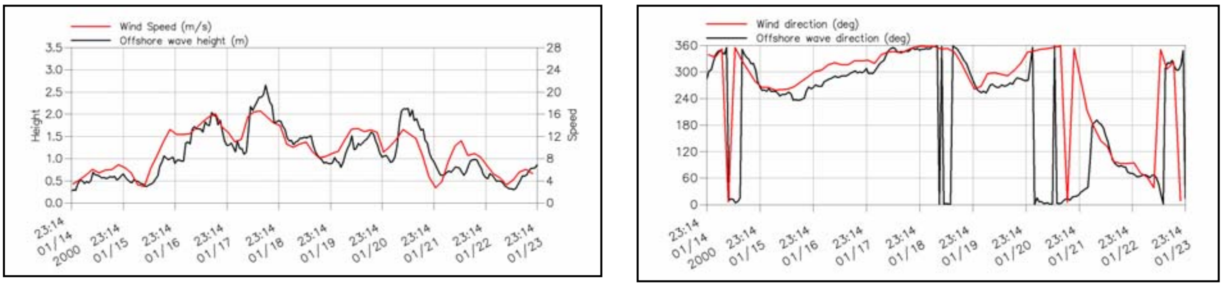
The last equation is the bottom-evolution equation which is used in order to calculate the morphodynamic changes. Bed-load transport can be calculated by different formulations. In the simulations presented here, the formula of van Rijn (van Rijn, 1994) is used. The suspended sediment transport is solved by a depth integrated transport equation. For the source and sink term *S*, different formulations are possible. The maximum suspended sediment concentration is calculated by Rossinsy and Debolsky (Rossinsy, 1980) in the simulation presented here.

Finite Element Approximation

The system of nine time-dependent partial differential equations is solved with stabilised finite elements (Milbradt, 2002). Triangular grids are used with linear interpolation functions in space for the state variables. Higher order terms are removed by partial integration. The stabilisation parameter corresponds to the largest absolute eigenvalues of the transport matrices in the above system of partial differential equations. The time integration is performed in the usual step by step manner.

Case study

Significant sediment transport is caused in Gellen bay by waves induced by winds from W-NW-N directions. This has been studied for a 5-year period with littoral transport models. Recently, data of a high water event lasting for 1 week in January 2000 have been recorded with wind velocities of 10 to 15 m/s and directions slowly changing from West to North directions. Figure 3 shows the strong correlation in the recorded time series of wind speed and offshore wave height (panel a), the directions of wind and wave propagation (panel b), and the water level at Zingst.



a) Wind speed and offshore wave height

b) directions of wind and wave propagation

c) Water level at Zingst

Figure 3: Field data for winter storm in January 2000

The measurements of significant wave heights near Bock inlet imply considerable sediment dynamics during this period of time. The simulation of this winter storm event starts from a regional model, which provides the necessary boundary conditions for high resolution local near shore models. Such nested models can be introduced at any region of interest. In this study it is used to describe the near shore morphodynamic processes in the inner Gellen bay.

Regional model

A regional coastal area model has been set up between Darsser Ort on the Darss-Zingst peninsula and Greifswalder Bodden. As shown in Figure 4, it also covers the entire lagoon system of the access channels to the port of Stralsund.

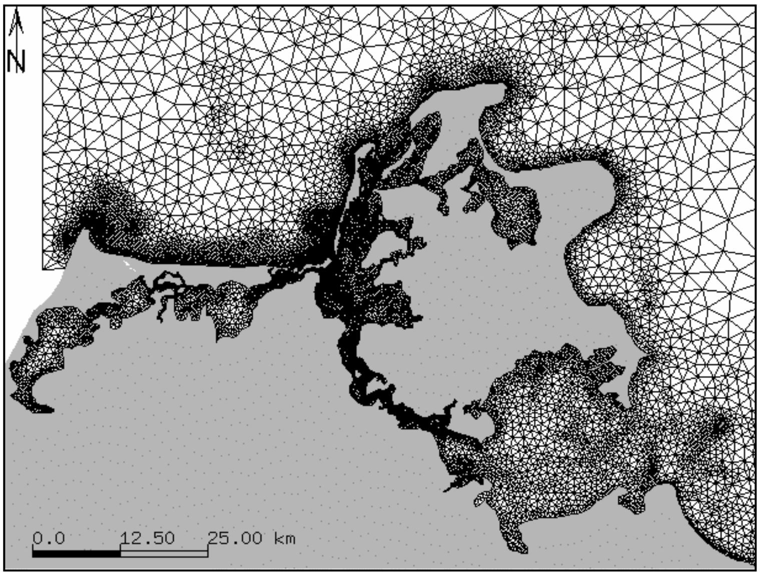


Figure 4: Finite Element Mesh of the regional model

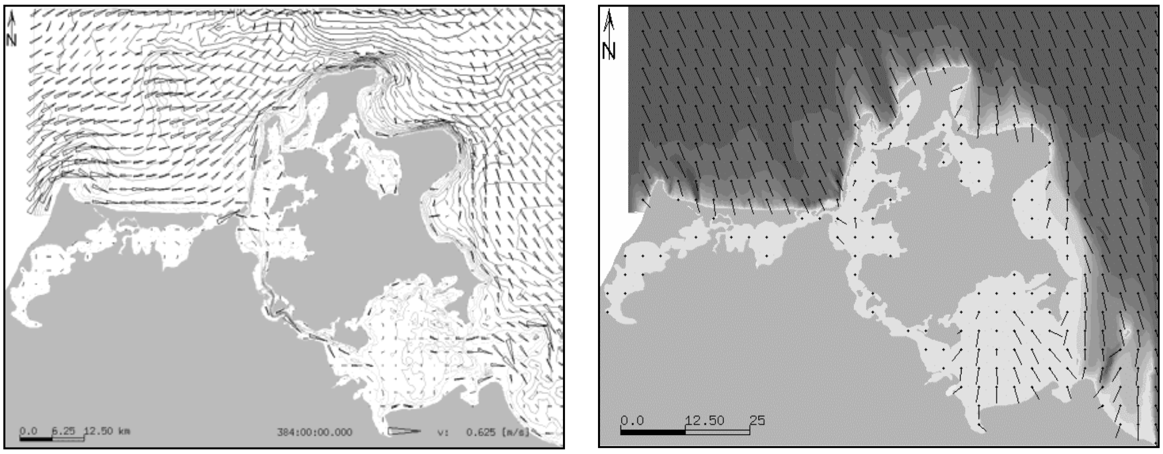


Figure 5: Large scale flow and wave pattern in regional model

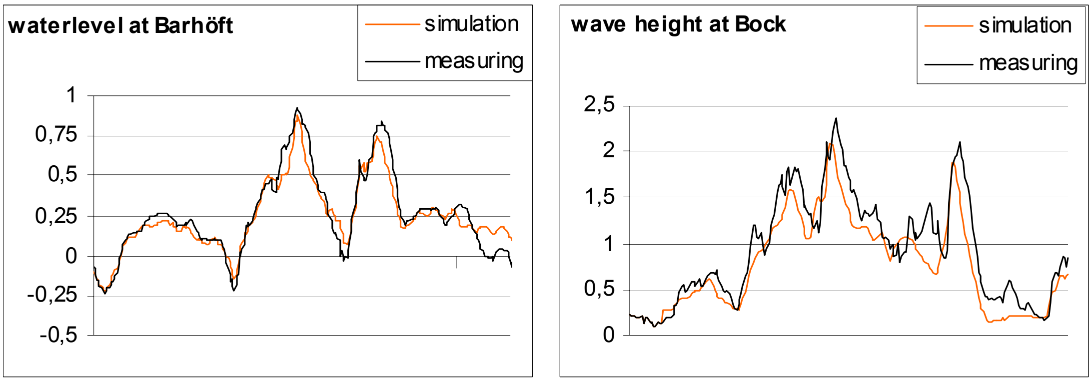


Figure 6: Time series of simulated and measured water levels and wave height in January 2000

The regional model serves to provide the large area flow and swell conditions and is used for downscaling transient hydrodynamic and meterological conditions obtained from the global circulation model of the Baltic Sea (Kleine, 1994). The model is validated with water level time series of 10 gauges along the coast and within the lagoon system as well as with time series of wave parameters measured with two stationary wave rider buoys and at three additional temporary positions.

Figure 5 shows flow and wave patterns for a typical North - West wind situation. The comparison of simulated flow and wave fields with field observations shows very good agreement in capturing the significant extreme events as can be concluded from the time series in Figure 6 for water levels at Barhöft and significant wave heights at the sand flat Bock.

Local Model (Nested Model)

Due to the computational expense of morphodynamic modeling, it is impossible to run the entire domain in full morphodynamic simulation mode. The computational grid applied when focussing e.g. on the immediate vicinity of an inlet needs high resolution in order to satisfy numerical requirements posed by the physical processes modeled.

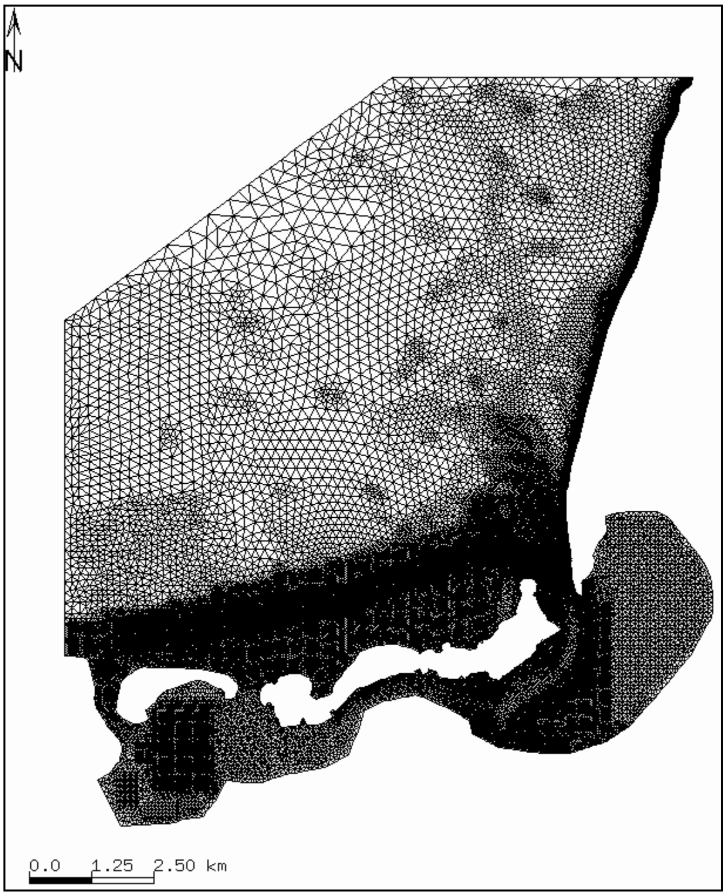


Figure 6: Grid for the local (nested) model

The computational grid consists of 40 thousand nodes and has a node distance of approximately 10 m in the near shore zone.

In the near shore zone, the waves break and generate strong long shore currents responsible for the majority of the long shore sediment transport. All wave directions between North and

West will lead to eastward transport along Zingst (in Figure 7 transport from left to right). Along the island of Hiddensee, the westerly waves may cause some northward transport and the north-west to northerly waves will cause southward transport (Figure 7, transport along Hiddensee towards the inlet).

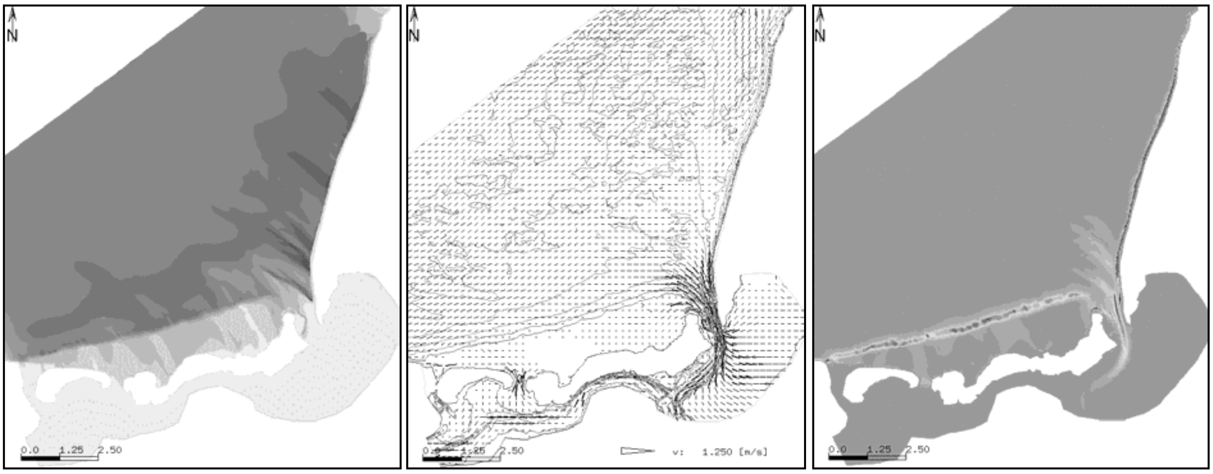


Figure 7: Wave amplitude distribution, flow feld, sediment concentration

An analysis of the sediment transport fields corresponding to Figure 7 shows significant onshore transport rates over flat areas that are flooded during events of high water levels and strong wave action. The resulting depth changes are shown in the following Figure 8.

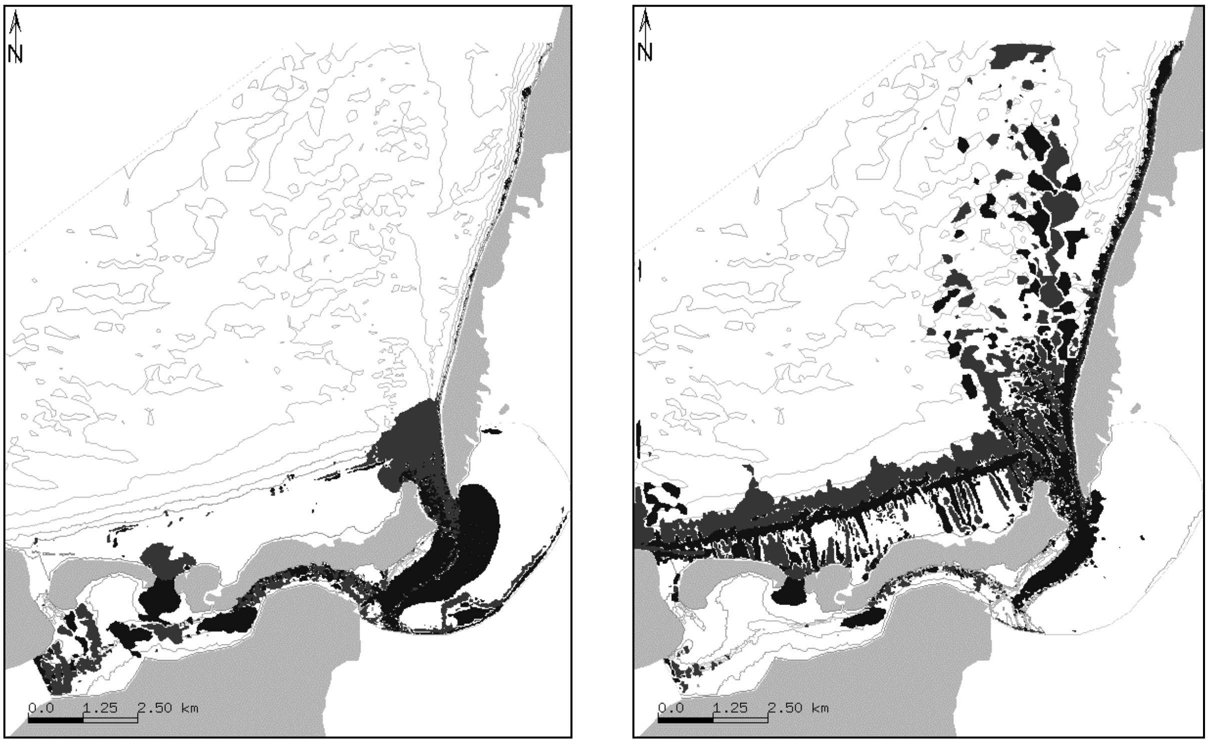


Figure 8: Computed sedimentation and erosion without and with wave action

The left panel shows results of a simulation without consideration of wave action which indicates massive erosion in the Gellen inlet at the Southern tip of Hiddensee island. The eroded material will be deposited in the inner regions of the lagoon system.

The right panel shows results for identical boundary conditions but with waves interacting with the currents during the numerical simulation. Here, the predicted tendencies are in part contrary to the former model run. Accounting for wave–current interaction strongly reduces erosion effects in the inlet which in turn means less deposition in the navigation channels.
Also, a much larger area of the study domain is affected by morphodynamic changes in this scenario which corresponds to the patchy bathymetry as can be seen from the depth contours in Figure 8. In addition, there is indication of formation of a beach ridge on the Bock sand flat which is clearly observable on the aerial view in Figure 2.
Both features are missing in the results obtained from simulations without waves. Figure 8 impressively indicates that waves must not be neglected in coastal morphodynamic simulation studies. Similar results are obtained for tidally influenced coastal areas of the North Sea.

Conclusions

The presented case study of a micro-tidal shore demonstrates that morphodynamics in wave dominated regions can successfully be simulated by numerical models. The recently developed holistic approach for modeling hydrodynamic and morphodynamic processes

- is free of data passing between conventional numerical process models,
- uses one single computational grid for all processes,
- is validated for currents and waves in the micro-tidal region of the Southern Baltic Sea,
- shows good agreement with observations regarding the formation of beach ridges.

Waves in this study domain could successfully and sufficiently be modeled by an instationary hyperbolic wave model. The holistic model can be used as a predictive tool for morphodynamic studies in the coastal zone.

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References

Kleine, E., 1994. Das operationelle Modell des BSH für die Nordsee und Ostsee. Bundesamt für Seeschifffahrt und Hydrographie, Hamburg

Milbradt, P., 2002. Holistic modeling of morphodynamic processes with stabilized finite elements, Hydroinformatics 2002, Cardiff

Rossinsy, K.I., Debolsky, V.K., 1980, Riverine load, Nauka (Moscow), 216 p. (in Russian)

van Rijn, Sediment Pick-Up-Function, 1994, Journal of Hydraulic Engineering, Vol 110, No.10