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Numerical Modeling of Shoreface Nourishments in the Schleswig-Holstein Wadden Sea

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Abstract: Soft coastal protection measures can play an important role in reducing and mitigating the sediment loss at the coastline due to erosion. One example are sand nourishments to strengthen eroding beaches or natural reef systems in front of the coast. These softer approaches have the advantage that they are easier to adapt to future change and interfere more mildly in coastal ecosystems than classical coastal protection measures. As part of the Interreg North Sea Region project "Building with Nature" we examine the development of a shoreface nourishment done by the Agency for Coastal Defense, National Park and Marine Conservation Schleswig-Holstein (LKN.SH) in front of the coast of the island Sylt by using a numerical model to simulate the hydro- and morphodynamic processes of the focus area. The goal is to better understand local sediment transport processes and the responsible driving forces behind them to then evaluate the effects of nourishments in the area.

Keywords: Building with Nature, sand nourishments, numerical modelling, morphodynamics, coastal protection, current-wave interactions

1 Introduction

In many coastal areas the erosion of the coastlines is a major problem coastal protection plans have to address. While dykes are a reliable measure for protection from high water levels during storm surges, minimizing the sediment loss at beaches and dune systems is far more complicated. Regular sediment transport characteristics of a region can be greatly disturbed by extreme wave events. Classical protection measures like wave breakers or similar hard protection structures strongly influence the natural coastal sediment dynamics, which can even have detrimental effects on the sediment budget along the coast lines. Climate Change and an increasing sea level rise pose an additional challenge because adapting existing structures to changing conditions can be quite expensive and complex.

Softer measures can be a good alternative. They have found some spread over the last decades under the name "Building with Nature". One example are sand nourishments to strengthen eroding beaches or natural reef systems in front of the coast. These softer approaches have the advantage that they are easier to adapt to future change and interfere more mildly in coastal ecosystems than classical coastal protection measures. A more natural appearance of the coasts also has a positive effect on tourism and recreational land use in general.

To better understand the effects and optimize the application of such measures, additional research is necessary. The Interreg North Sea Region project "Building with Nature" has the goal to improve the understanding of the effects of sand nourishments at different locations along the North Sea coastline (Wilmink et al., 2017). As a project partner of the Agency for Coastal Defense, National Park and Marine Conservation Schleswig-Holstein (LKN.SH) we focus on modeling hydro- and morphodynamic processes in the Schleswig-Holstein Wadden Sea and more precisely the area around the southern part of Sylt and the Hörnum tidal basin. The goal is to better understand local sediment transport processes and the responsible driving forces behind them and to identify the effects of nourishments in the area. A shoreface nourishment at the western coast of Sylt is simulated and the transport pathways of the nourished sediment are examined.

The distribution is of importance because climate change and the rising sea levels put a lot of stress on the tidal flats. So far it is not clear if they can grow fast enough to keep up with the sea level. It would be helpful if nourishments can provide additional sediment that, while also strengthening the coast line, is over time transported into the tidal basin and ends up on the tidal flats to accelerate their growth.

2 History and Setup

2.1 Description and history of Sylt and the surrounding area

The focus area of this project includes the southern part of Sylt as well as the adjacent islands Amrum and Föhr, which are separated from Sylt by the main tidal inlet called the Vortrapptief. The western shoreface of Sylt is characterized by a reef barrier that nearly stretches along the whole coast at water depths of around 6 - 7 m. Southwest of Sylt lies Theeknobs, a shallow area with depths of around 2-3 m, which falls off starkly into the Vortrapptief with depths of up to 20 m. The Vortrapptief passes into the Hörnumtief which leads deeply into the tidal basin and then branches into smaller channels that lead onto the tidal flats (Fig. 1).

While the coastal region is heavily influenced by waves, the Vortrapptief has strong tidal currents with velocities of over 1.5 m/s. The exposed position of especially Sylt makes the area susceptible to coastal erosion by waves. This is especially problematic since the major wave direction of strong wave events with a wave height greater than 2.5 m lies between southwest and northwest. The eroding effect can best be seen at Hörnum-Odde where heavy erosion is occurring and the coast line is receding at a high rate. Storm Surges and their ability to mobilize large amounts of sediment play an important role in this process. Hard measures that were built in the past to dissipate the wave energy and protect the Odde instead interrupted the longshore sediment transport and reduced the sediment supply for the southern part of Sylt.

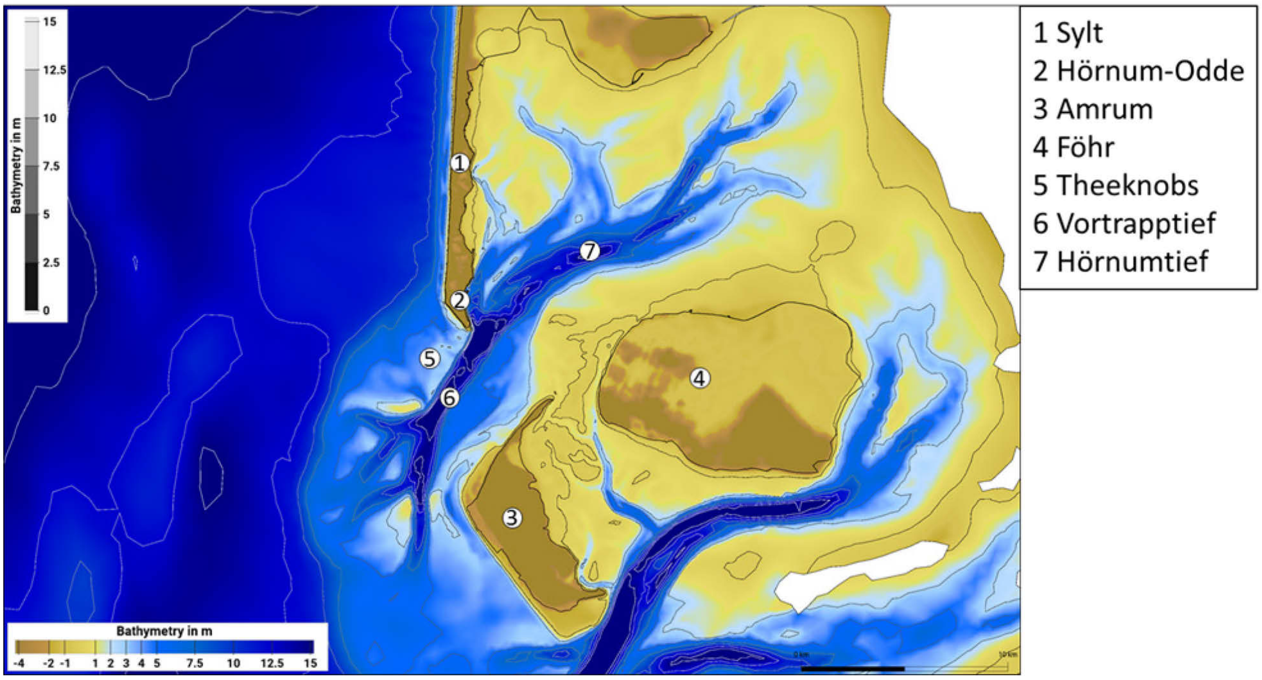

Fig. 1. Bathymetry of the focus area with the position of the main structures in the area.

To maintain the western coast line of Sylt, the LKN.SH started doing mainly beach nourishments with sand from an area a few km in front of the coast. A yearly volume of around 0.9 Mio m³ of sand is moved onto the beach as well as around 0.2 Mio m³ in the foreshore area (LKN.SH, 2015). As part of the Basewad project ("Balancing Sediment budgets in the Wadden Sea") additional foreshore nourishments are tested to strengthen the reef system. The desired effect is to increase the dissipative effect of the reef on the incoming waves and that the mobilized sediment is transported on the beach or with the longshore transport in the Vortrapptief and from there into the tidal basin or the ebb delta. 400.000 m³ of sediment are nourished on an area of the reef system of about 600.000 m². More sediment is put in the areas further away from the coast, leading to maximum depth changes of about 1 m.

The specific success of this nourishment is hard to quantify since it is part of the larger nourishment strategy for Sylt and during the same time frame regular nourishments at different areas of the beach of Sylt were performed. To increase the signal and better understand its effect on additional nourishment is planned for this year at the same site with another 400.000 m³ of sand. The long-term effects of nourishments along the western coastline of Sylt are positive. The erosion of the beaches was greatly reduced.

2.2 Model setup

For these simulations the hydrodynamic model UnTrim (Casulli and Walters, 2000) coupled with the morphodynamic model SediMorph (Malcherek et al., 2005) and the spectral wave model K-model (Schneggenburger, 1998) are being used. UnTrim is a semi-implicit finite difference (-volume) model based on the three-dimensional shallow water equations as well as on the three-dimensional transport equation for salt, heat and suspended sediments and works on an unstructured grid. SediMorph simulates the physical processes in the soil under surface waters. To do this the mass movements of different grain classes according to bed load and suspended load transport are balanced. It tracks the variation of the grain size distribution in space and time and computes bed roughness, bed shear stress and the transport rates for bedload and erosion fluxes for suspension. The K-Model computes the development, propagation and dissipation of waves, sea and swell in the ocean and coastal waters. It uses a source function which describes dissipation by wave turbulence interaction.

The model domain covers the whole German Bight with a higher grid resolution in the focus area around the southern part of Sylt to accurately display small scale topographical elements like the foreshore structures. With regards to this, special attention has been paid to the effects of grid resolution on interaction of waves, currents and the sediment transport. One important factor here is the grid resolution of the wave model. It has the greatest effect on the radiation stresses, which are calculated by the wave model and act as an impulse source on the velocities in the hydrodynamic model. In areas with a diverse topography and a strong wave impact a horizontal resolution of at least 100 m or finer is necessary to model the effects in a satisfactory way. Additionally the wave energy factors into the calculation of the bed shear stress and is able to move and mobilize sediment in areas with otherwise low tidal currents.

The initial sediment distribution for the model is taken from the project Aufmod (Bundesanstalt für Wasserbau, 2014) and consists of ten discrete sediment fractions ranging from very fine silt to gravel in accordance with the Udden-Wentworth scale. The dataset merged about 80.000 grain distributions of surface sediments for the whole North Sea region from various institutes and organizations. In the focus area around Sylt the two dominant sediment fractions are medium and fine sand. Along the coastline of Sylt and on Theeknobs the sediment tends to be a little bit coarser with more coarse sand occurring. In the offshore areas where the sediment for the nourishment is taken from, very fine sand is more common.

The hydro- and morphodynamic models use a time step of 1 min while the wave model uses a time step of 10 sec. The hydrodynamic model will solve some processes iteratively while the wave model will reduce the time step automatically if certain stability criteria are not fulfilled. As a result the model setup runs very stable. Computation time for the general simulation with a time frame of one year was roughly five weeks.

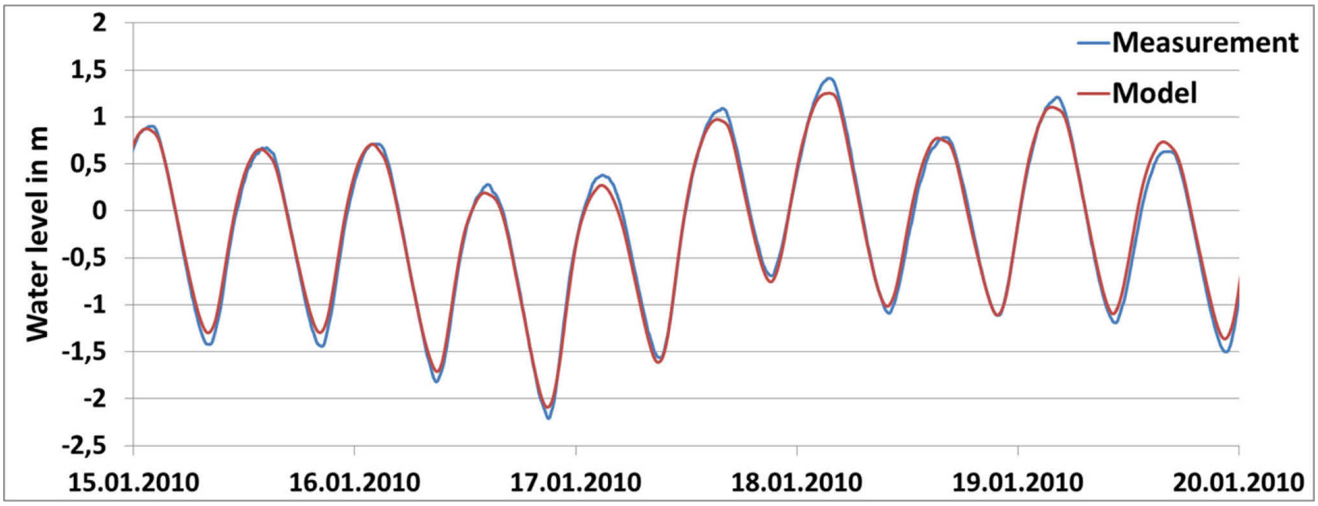

Fig. 2. Comparison of model results (red) of the water level with measurements (blue) at the gauge Hörnum-Hafen for a period of five days.

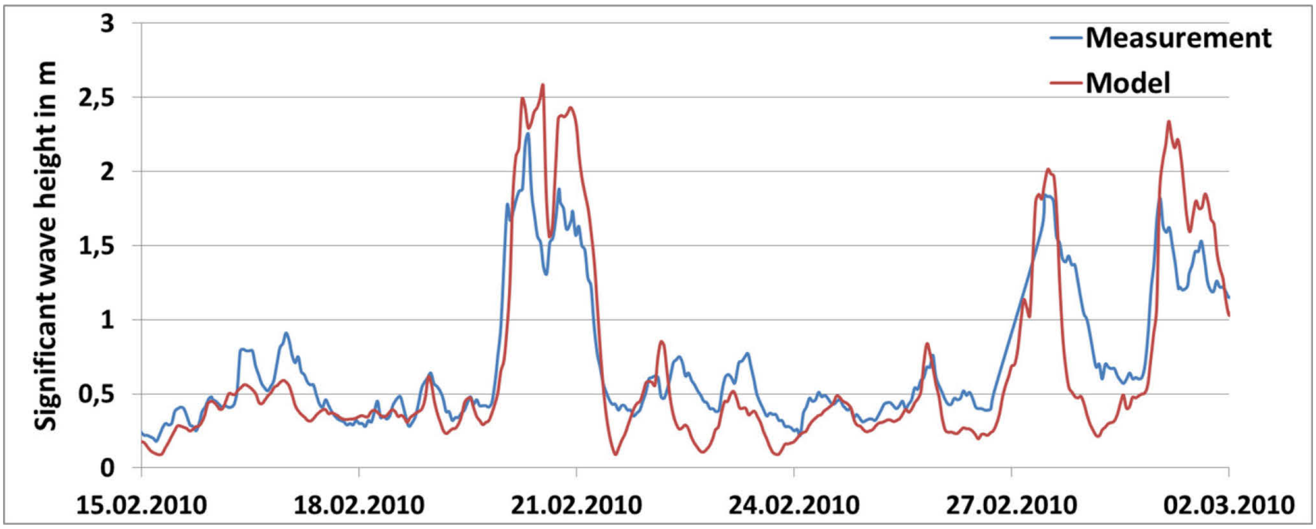

Fig. 3. Comparison of model results (red) of the significant wave height with measurements (blue) at the gauge Westerland for a period of two weeks.

3 Results

3.1 Model Performance

To prove the validity of the model setup, model results were compared to measurements along the German Bight. For the hydrodynamics the main focus were on the water levels and for the wave model on the wave height. Exemplary shown are the water level at the gauge Hörnum-Hafen (Fig. 2) and the significant wave height at the gauge Westerland (Fig.3). Both show good agreement with the measurements. The general forcing for the sediment transport through currents and waves is satisfactory.

Since a direct comparison of morphodynamic results with measurements can be difficult, as a first step to get a better understanding about the dominant influences on the sediment transport processes in this region, different analyses of the forces acting on the sediment were performed (Fig. 4). Tidal characteristic numbers for the current velocities for a neap-spring cycle include average velocities during the ebb and flood phases of a tide. The ratio of these shows a slight ebb dominance of the main inlet while the foreshore area of Sylt and the shallower areas surrounding the Vortrapptief are flood dominated.

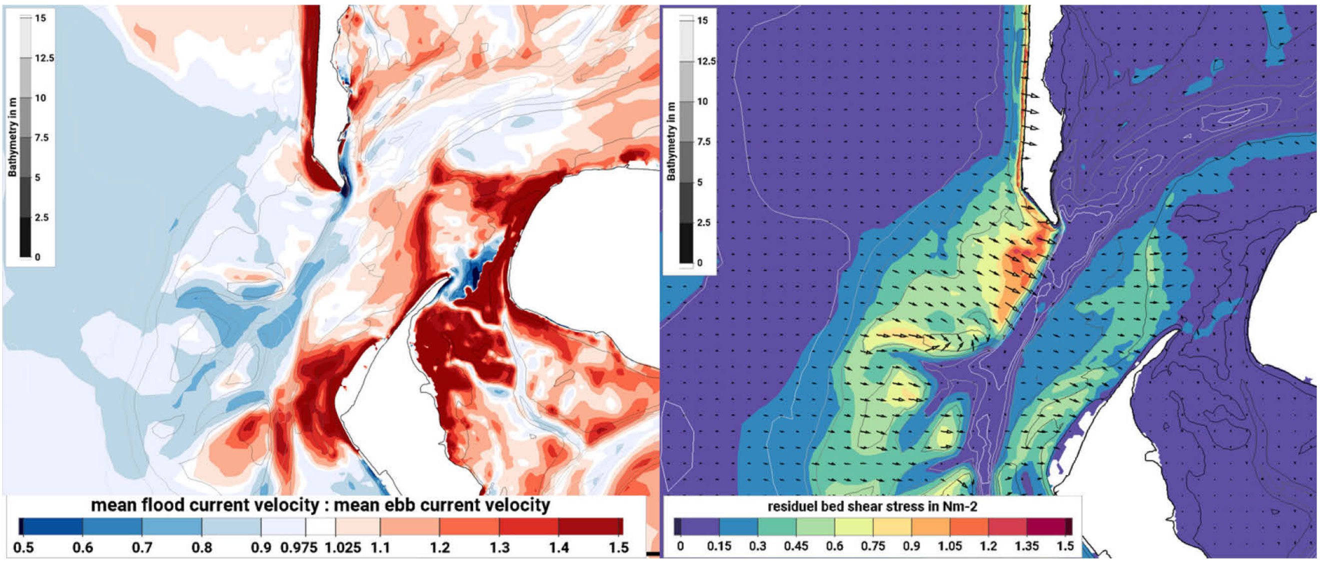

Fig. 4. Left: Ratio of the mean flood velocity to the mean ebb velocity during one neap-spring cycle. Blue areas indicate an ebb dominance while in red areas higher current velocities during the flood phase of a tide. Right: Residual bed shear stress for one month. Higher values occur along the coast line and in shallower areas. Vectors show the direction of the bed shear stress.

When looking at the residuals of the bed shear stress over a longer time period, the influence of the wave energy becomes visible and obvious. The highest values occur along the western coast of Sylt and Amrum as well as on the shallow area of Theeknobs and around the sandbanks of the ebb delta. These are the areas where the waves, which most commonly come from a westward direction, first get in contact with the ground and the dissipating wave energy acts as an eroding force. The potential for a longshore sediment transport in a southward direction along the coastline of Sylt and into the Vortrapptief is visible. The majority of the wave energy is already dissipated when entering the tidal inlet. This can be seen in the significant wave height in the tidal inlet, which falls off to about one third of the values in the near shore areas west of Sylt. This leads to markedly lower morphodynamic activities inside the tidal inlet (Fig. 5).

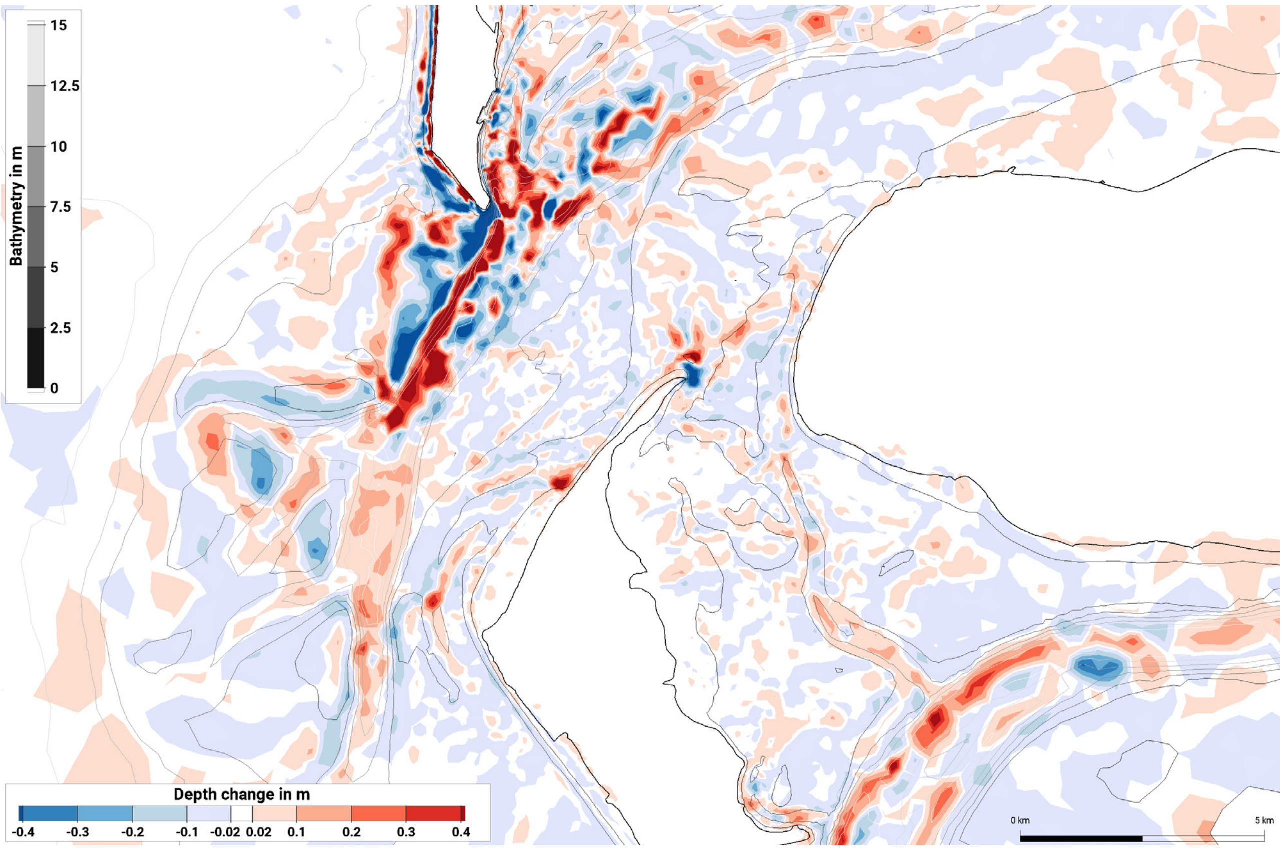

Fig. 5. Simulated erosion (blue) and sedimentation (red) patterns for the focus area after one year.

Morphodynamic simulations of one year show general large scale trends in bathymetry changes that are in accordance with observed trends. Erosion occurs along the western coast of Sylt and on parts of Theeknobs. The sediment is partly transported into the Vortrapptief, where as a result the western slope is growing while the eastern slope is eroding. At Amrum, sediment is transported along the coastline in northern direction into the tidal basin. Over the whole year around 1.8 Mio t of sediments are moved into the tidal basin Hörnumbecken. Heavy storm events play an important role in mobilizing the sediment in the ebb delta. For the simulated year 2010, three events make up for a large part of the increase of sediment in the tidal inlet.

3.2 Simulation of a foreshore nourishment

Based on this model setup, simulations for a shoreface nourishment were conducted based on a real nourishment conducted in the summer of 2017. The sediment for the nourishment is admitted into the water column as a source term with a constant inflow over the period of one week. The deposited amount of sediment varies spatially in accordance with data from the real measures and totals a volume of 400.000 m³ for the whole area (Fig. 6). The nourished sediment is modeled as one sediment fraction with a diameter of 180 µm and a settling velocity of 2 mm/s. It can be transported on the ground as bedload as well as in suspension provided the occurring bed shear stresses are high enough to mobilize it.

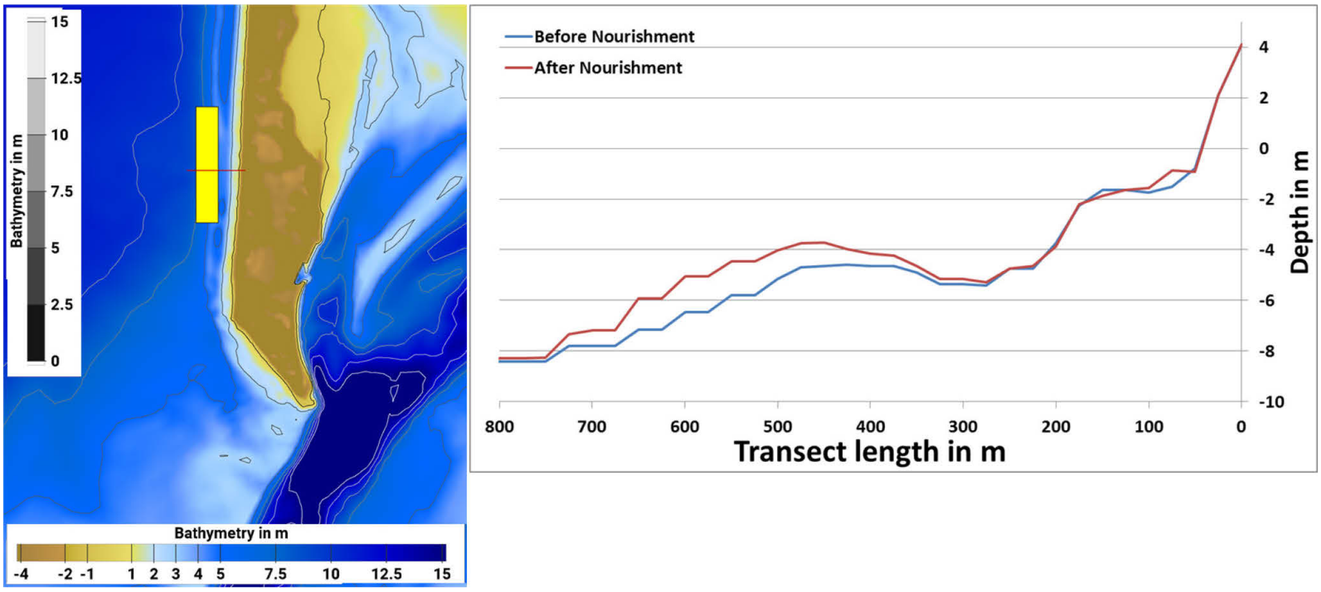

Fig. 6. Left: Location of the shoreface nourishment in front of the western coast of Sylt (yellow rectangle). Right: Transect from the beach across the reef system (red line in the left figure) showing the depth changes in the model due to the nourishment.

Although some initial drifting occurs when the sediment is admitted into the water column, most of the sediment settles in the area of the nourishment. Over a simulation period of two and a half months the sediment is then transported along the coast mostly a southward direction with the long shore transport and into the main tidal inlet. From there it is further moved into the tidal basin (Fig. 7).

Since no hydrological boundary values were available for the time frame in which the nourishment was conducted, a direct comparison with measurements is difficult. The measurements show some erosion of the nourishment and movement of the sediment towards the coastline and mostly in a southward direction. This trend can also be observed in the model. Evaluating further spreading of the nourished sediment from measurements is harder since the signal gets lost in the normal sediment movement in that area. Different indicators like volume balances for defined areas and the orientation of dunes point towards a general movement of sediment along the coast into the Vortrapptief from where it is distributed by the tidal currents along the western slope and in parts back onto Theeknobs and into the tidal basin. These trends are reproduced in the model although the model seems to underestimate the mobility of the sediment especially once it has reached the main channel.

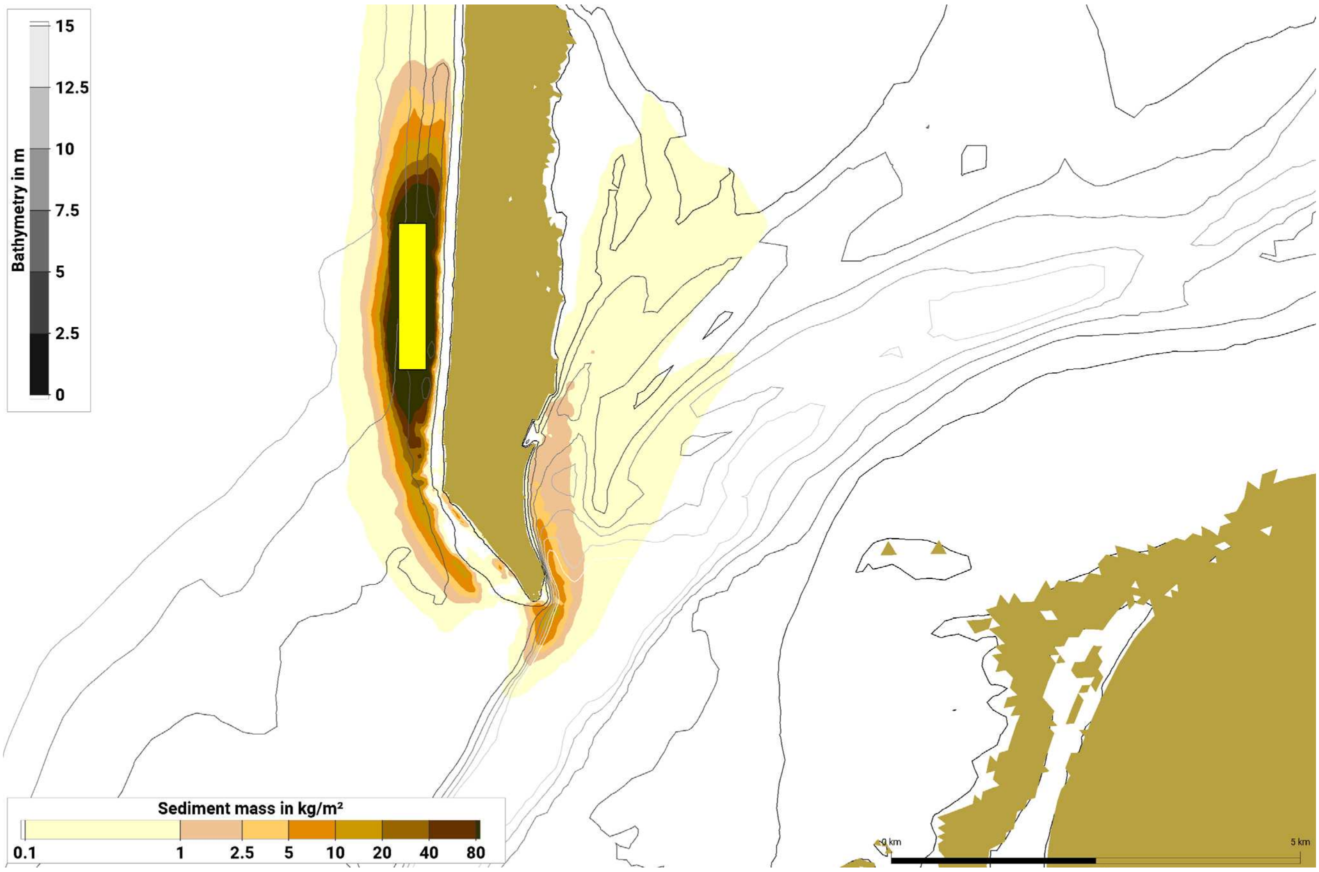

Fig. 7. Simulated distribution of the nourished sediment across the focus area after 2 ½ months with a logarithmic scale. Sediment mass at and closely around the nourishment site (yellow area) is a lot higher than the upper limit of the scale of 80 kg/m².

The properties of the nourished sediment play a very large role in the spread of the sediment. Settling velocity and the ratio between bedload and suspended transport are the main drivers of how far the sediment is transported into the tidal basin and especially how fast it, if at all, reaches the tidal flats. The chosen parameters for the presented simulation are more conservative and favor the bedload transport, so that only during situations with high wave energy a significant amount goes into suspension. As a result once the nourished sediment reaches the deeper parts of the area like the Vortrapptief, the majority of the sediment remains there and is not transported onto the tidal flats. Additional parameter studies are necessary to improve the model performance.

The impact of the wave forcing can be clearly seen in the aggregated mass balances for larger areas. The focus area has been divided into six control volumes for which the mass of the nourished sediment has been aggregated. A look at the development over time shows only light exchanges between the control volumes for most of the time, while single events make up for most of the change. These jumps coincide with situations of high wave energy during which the sediment is mobilized and then transported with the currents (Fig. 8).

4 Conclusions

A numerical model was successfully set up to simulate the general morphodynamic processes under the influence of tidal currents and waves in the area of Sylt and the Hörnum tidal inlet. The validity of the model with regards to reproducing measurements for hydrodynamic and wave parameters was shown and the main forces on and resulting pathways of the sediment transport were identified.

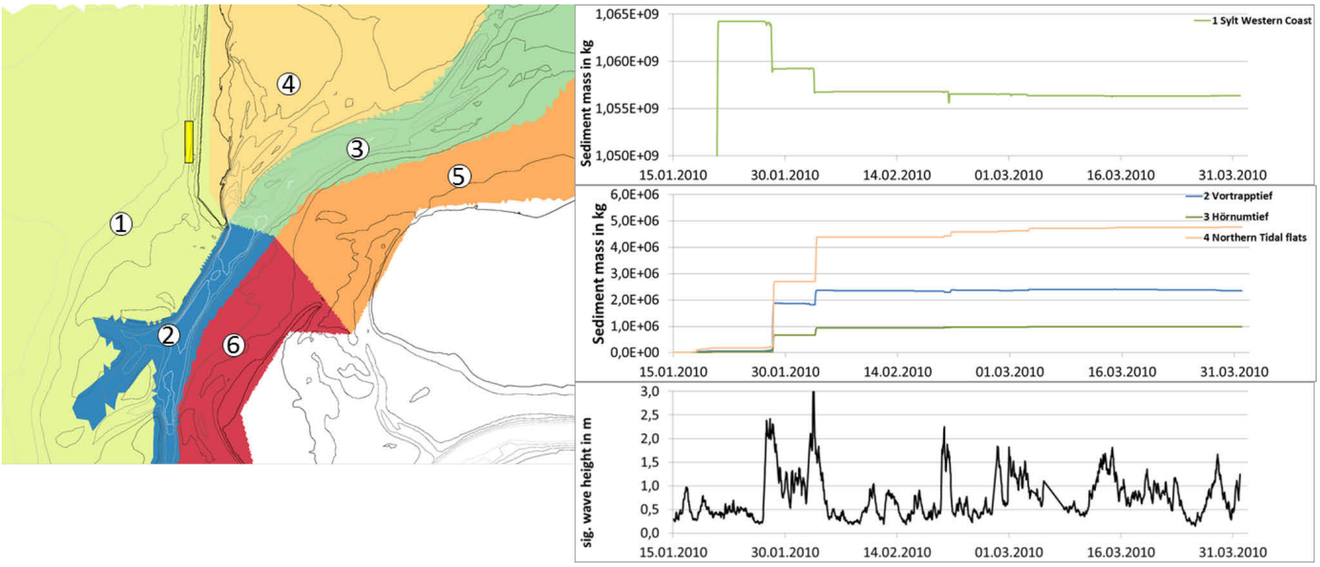

Fig. 8. Left: Outlines of the control volumes for the aggregated mass balances. Right: Development over time of the mass of the nourished sediment in kg for the four most important control volumes and the wave height for the same time period. Abrupt changes in sediment mass are due to strong wave events.

The simulations of the nourishment in front of the western coast of Sylt show a clear trend of movement of the nourished sediment in a southward direction into the main tidal inlet and the northern parts of the basin. The results show the large influence that waves have on mobilizing sediment in this area. Single events often lead to bigger changes than those taking place gradually over a longer time frame.

Further research needs to be done with regards to the transport properties of the nourished sediment fraction since those have a big impact on how far the sediment is transported. The main problem here is a lack of possible ways to validate this because the signal of the nourishment on the tidal flats is not strong enough to differentiate the effect of the nourishment from the normally occurring sediment transport.

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