

Morphodynamics of Wadden Sea Areas – Field Measurements and Modeling

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Abstract

The Wadden Sea areas of the German North Sea coast are affected by intense morphodynamics. Especially in the mouths of the estuaries sedimentation and erosion occur on different temporal and spatial scales and therefore challenge the decision-makers. To satisfy the requirements, which modern maritime traffic demands, a sustainable concept for sediment management has to be developed to grant an economic and ecologic balanced system. To evaluate different actions and their effects, e.g. by means of numerical models, an improved knowledge of morphodynamic processes on tidal flats is required. The Institute of River and Coastal Engineering at the Hamburg University of Technology runs detailed measurements to collect hydrodynamic and morphodynamic data of tidal flats in the estuary Elbe, that is the approach to the port of Hamburg. Water levels, flow and wave parameters and concentrations of suspended sediments are recorded in high resolution. Furthermore, the bathymetry is determined in frequent intervals with a multi-beam echo sounder.

Keywords: Morphodynamics, Wadden Sea, Field Measurements, Coastal Sediments.

INTRODUCTION

The North Sea is an epeiric sea of the Atlantic Ocean. Thus, the tidal oscillation of the Atlantic affects the North Sea from the north and through the British Channel. Huge tidal flat areas, long tidal channels and creeks, ripples and dunes have an effect on the view of the German North Sea coast. Especially the areas of the Wadden Sea underlie sediment relocations on different spatial and temporal scales.

The most important waterways at the German coast are the estuaries Elbe, Weser and Ems. In spite of several measures, that stabilize the waterways, strong morphodynamic changes occur. Especially in the mouth of the estuary Elbe these permanent displacements challenge the stakeholders and decision-makers. The Elbe is the approach to the port of Hamburg and thus it may be called a lifeline of a whole region. The harbor of Hamburg is a turntable of the international container shipping, the largest port in Germany and the second largest in Europe. To live up to expectations of many different parties a holistic and innovative estuary management is necessary. A main issue of a new concept for a sustainable development of the tidal area of the Elbe estuary is to decrease the energy caused by tidal flow into the estuary (HPA and WSV 2006).

A broad process-knowledge is necessary to assess the resulting risks and to find an agreement between utilization demand and ecological meaning of the affected coastal zone. Due to its high sensitivity against hydro- and morphodynamic changes tidal flat areas, especially in the mouths of estuaries, move over to the center of scientific activities. Big challenges in this interrelation are the impacts of the climate change.

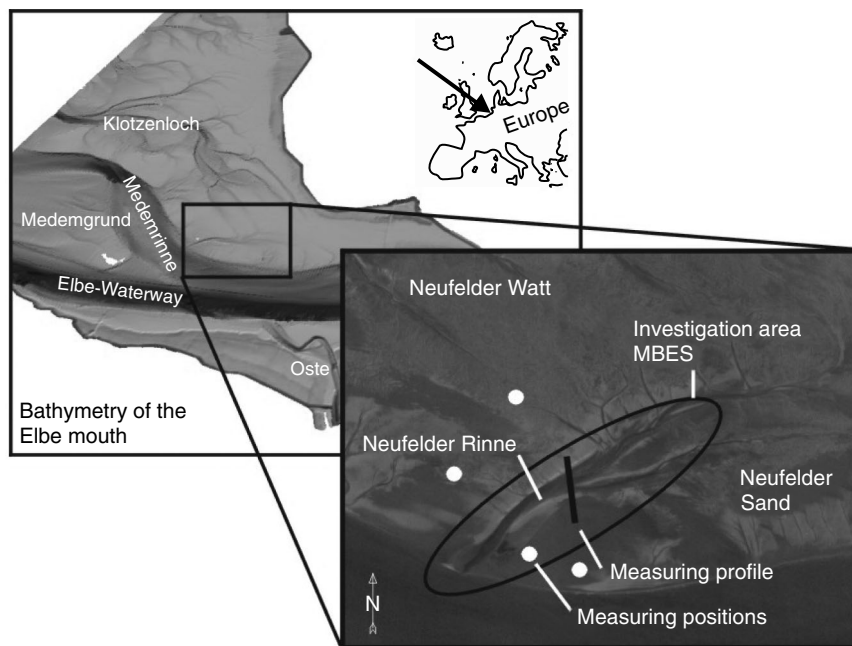


Figure 1. Investigation area and measurement positions in the mouth of the estuary Elbe

In spite of great successes in numerical modeling it was not possible to generate reliable forecasts of morphodynamic changes of tidal flats in consequence of short and long-term impacts. This is founded in both, the lacking resolution of the models and the insufficient process knowledge. For instance secure perceptions about the effect of Wadden Sea areas as a sediment reservoir of estuaries are missing. The function of wave-induced processes in tidal creeks and channels and of higher spring tides or lower storm surges is not yet completely understood. Frequently phases of sedimentation and erosion on tidal flat areas change patchwork-like over different seasons without any visible pattern.

The aim of the research project discussed in this paper is the analysis of hydrodynamic and morphodynamic changes in the investigation area “Neufelder Watt” in the mouth of the estuary Elbe (cf. Fig. 1). Supported by the Hamburg Port Authority (HPA) the Institute of River and Coastal Engineering of the Hamburg University of Technology (TUHH) runs comprehensive field measurements to improve the process knowledge on tidal flats. The results may provide a secure theoretical background for the mathematical multi-dimensional modeling of morphodynamic processes on tidal flats.

INVESTIGATION AREA

The field investigations are accomplished in the Neufelder Watt with the “Neufelder Sand” in the mouth of the estuary Elbe. The area under investigation is in close interaction with the main stream of the Elbe. The average tidal range in the investigation area is about 3 meters. The Wadden Sea areas around the “Neufelder Rinne” fall dry during a longer period around low tide. The water depths during an average tidal high water amount to 1.5 m northwest of the channel and 2 m southeast of the channel. The largest water depths in the main part of the channel add up to 4.5 m at mean high tide according to measurements in September 2008. The inlet was silted up highly at that time so that the water depths in that area are only a few centimeters at mean tidal low water.

Figure 1 shows the bathymetry in the mouth of the estuary Elbe with the Wadden Sea areas and the “Medemgrund” as the most important shallowness.

FIELD MEASUREMENTS

In summer 2006 at first a cross section in the Neufelder Rinne was selected to install the measurement devices (Fig. 1). The equipment was positioned in the middle of the creek as well as on both banks. Flow parameters, sediment concentrations and waves were measured permanently in a high resolution. In the following phases of the project the measuring positions were installed at areas of higher elevation northwest and southeast of the channel. In that process three Acoustic Doppler Current Profilers (ADCP) were used as well as six pressure sensors and three Optical Backscatter Profilers, which allowed an assessment of the suspended sediment concentration (SSC). Additional to the permanent installed instruments multi-beam echo sounder (MBES) measurements were performed in the channel and on the surrounding areas in frequent intervals of three to five weeks and after extreme events. Furthermore, soil samples were taken. They were completed to a sediment register of the area under investigation. The temporal changes of the top layer of certain positions were analyzed as well.

The arrangement of the measuring devices in one position is shown in figure 2. Flow parameters were recorded continuously and in a high resolution with three RDI ADCP Workhorse Sentinel. Over a period of 5 minutes an ensemble of 50 pings was collected, whereas the accuracy of the flow velocity is ± 0.3 cm/s and the one of the flow direction $\pm 2^\circ$. Suspended sediment concentrations were measured with three Argus Surface Meters (ASM) by ARGUS Environmental Instruments. In that innovative measuring instrument 100 optical backscatter sensors (OBS) mounted in a steal bar assessed the sediment concentration over a one-meter column above the sea bottom. Before the deployment the device was calibrated with the suspended matter occurring in the area under investigation. Every 5 minutes 5 samples were collected and averaged, whereas the accuracy is $\pm 10\%$. Regularly suspended matter samples were taken and compared with the results of the ASM. Six pressure sensors recorded waves with a measurement frequency of 10 Hz. Those sensors are a self-construction of the Institute. Data can be collected self-sustainingly over a period up to three months and is stored on a MMC memory card. All other devices work autarkic as well.

In regular intervals of three to five weeks the bathymetry of the marked investigation area was analyzed with a multi-beam echo sounder. Furthermore, measuring tours were attempted as soon as possible after extreme events. Therefore the research vessel "Nekton" of the Institute of River and Coastal Engineering comes into operation. To survey the bathymetry a built-in multi beam sonar Elac Nautik Seabeam 1185 with a frequency of 180 kHz is used. It is especially appropriate for

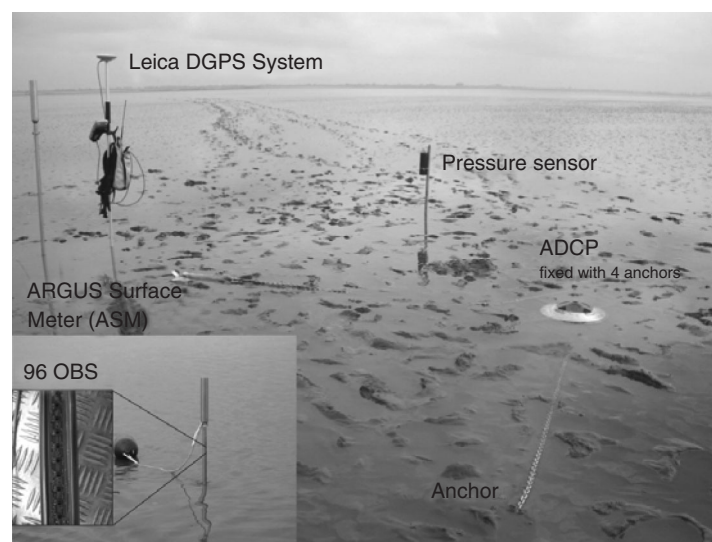


Figure 2. Measuring position with installed devices. DGPS-System to level the devices

surveys in shallow water but also applicable for water depths up to 300 m. The tide correction is done by Real Time Kinematics (RTK Tides) and the vessel's movements are compensated by an Octans gyrocompass.

RESULTS

Flow parameters and sediment concentration

In the course of the sediment concentration on the tidal flats over a tidal cycle a flow dependent pattern consisting of four maxima is constituted. The first maximum develops at increasing flow velocities at the beginning of the flood phase. A second maximum of the sediment concentration results afterwards from decreasing flow velocities, whereas the higher concentrations occur especially at the bottom sensors. After slack water the before deposited particles are re-mobilized at increasing flow velocities and cause a third maximum, which lies as a rule at the beginning of the saddle point of the flow velocity in the ebb phase. At the end of this saddle a fourth maximum of sediment concentration develops at decreasing flow velocities.

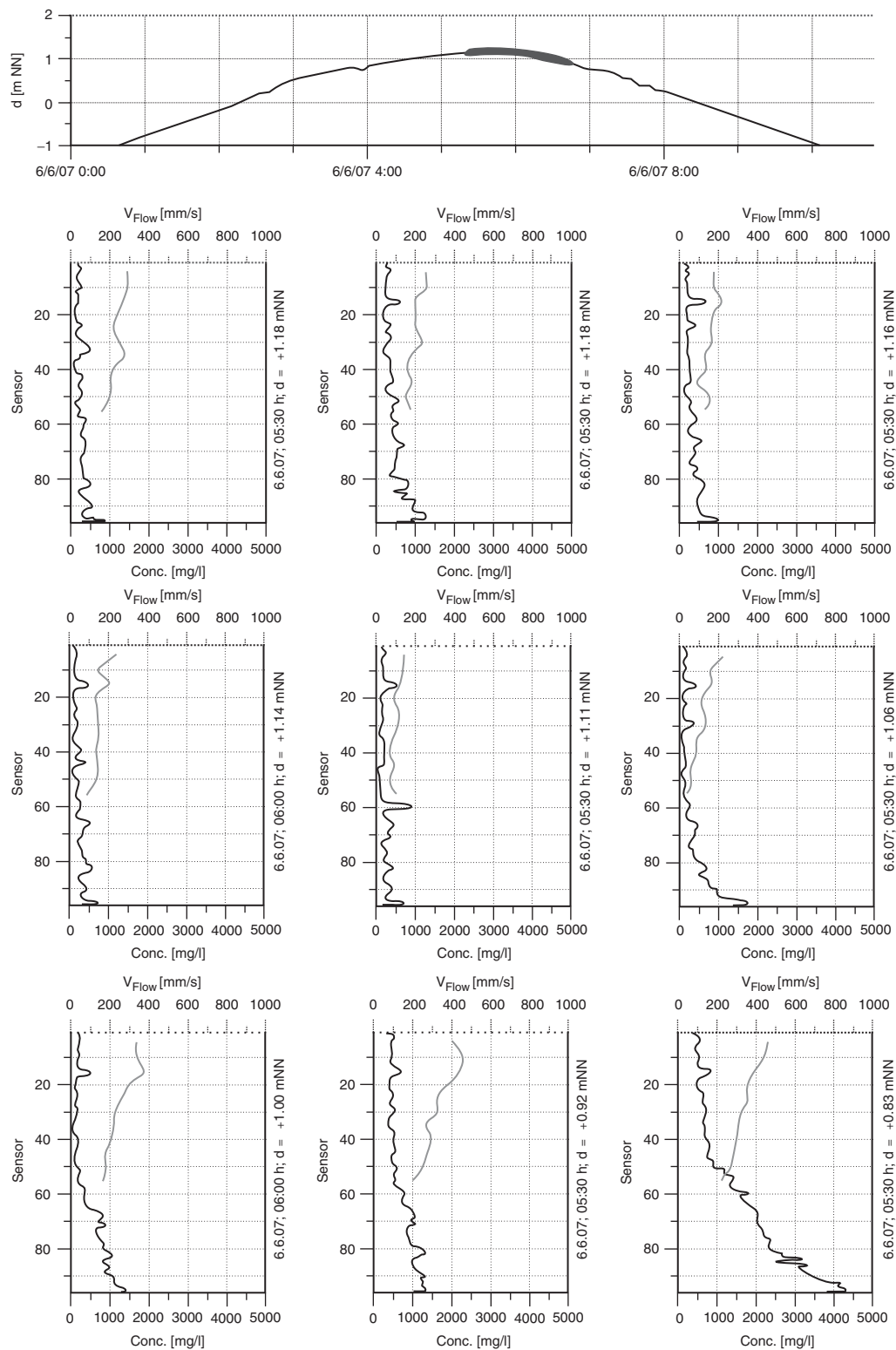
Figure 3 shows the field data from June 6th, 2007 measured at a position on the Neufelder Sand to the east of the inlet. The nine diagrams visualize the profiles of the flow velocity and the suspended sediment concentration (1st sensor up) in ten-minute intervals around slack water. After 06:10 a.m. the flow velocity increases during the ebb phase. The sediment concentration reacts at the bottom first where higher levels are reached. At 06:50 am values of more than 1000 mg/l were recorded at the 45 bottom sensors. This marks the third maximum described before. Due to the blanking of the ADCP the flow velocity plotted in grey could not be recorded near to the bottom.

The described pattern is more or less pronounced depending on the measuring position and the course of the corresponding tide. It is visible most clearly during tides with mean high tide water levels. During tides with lower or higher high water levels the peaks are damped. At certain measuring positions the maxima are essentially stronger developed and sediment plumes are flowing along the bottom sensors at recurring points in time. The sediment samples at those positions show a very heterogeneous grain size distribution with increased silt and coarse sand rates and a very low compactness of the packing.

During distinct east wind dominated weather conditions with low water levels the level of the sediment concentration is considerable above the concentrations during normal or increased tides. At that time there is no maximum, which can be constituted as dominant. In figure 4 the wind velocities and directions, water levels, flow velocities and directions and sediment concentrations are shown. Flow parameters and sediment concentrations are specified depth averaged. Due to the relative high elevation the devices fall dry around low water and the data is not continuous. The diagram shows a weather situation with increasing wind velocities up to 7 Beaufort (hourly averaged values) from east. The water is pushed out off the Elbe mouth and the water level decreases clearly on September 28th. Parallel the suspended sediment concentrations increase significantly up to values of approximately 2000 mg/l depth averaged over the sample length of 0.96 m. This phenomenon occurs basically only during tides with low high tide water levels, when the ratio between the significant wave height and the water depth increases.

Multi-beam sonar

Figure 5 shows profiles of the bathymetry at the inlet of the Neufelder Rinne derived from the results of different multi-beam echo soundings. Especially at the inlet strong dynamics are obvious. Essentially the inlet moves east, whereas the relocation can be up to one meter per tidal cycle (between February and April 2008). It continuous until the inlet branches off from the deeper main part of the channel, that relocates less, in a very acute angle. Then at the undercut slope of the ebb stream of the main part of the channel a new inlet is formed. For a short while two inlets exist (February 2008), until the older one is silted up. This reversible development is visible between April 23rd and August 21st 2008. Subsequent the process begins again.

Figure 3. Profile of flow velocity and SSC from June 6th 2007

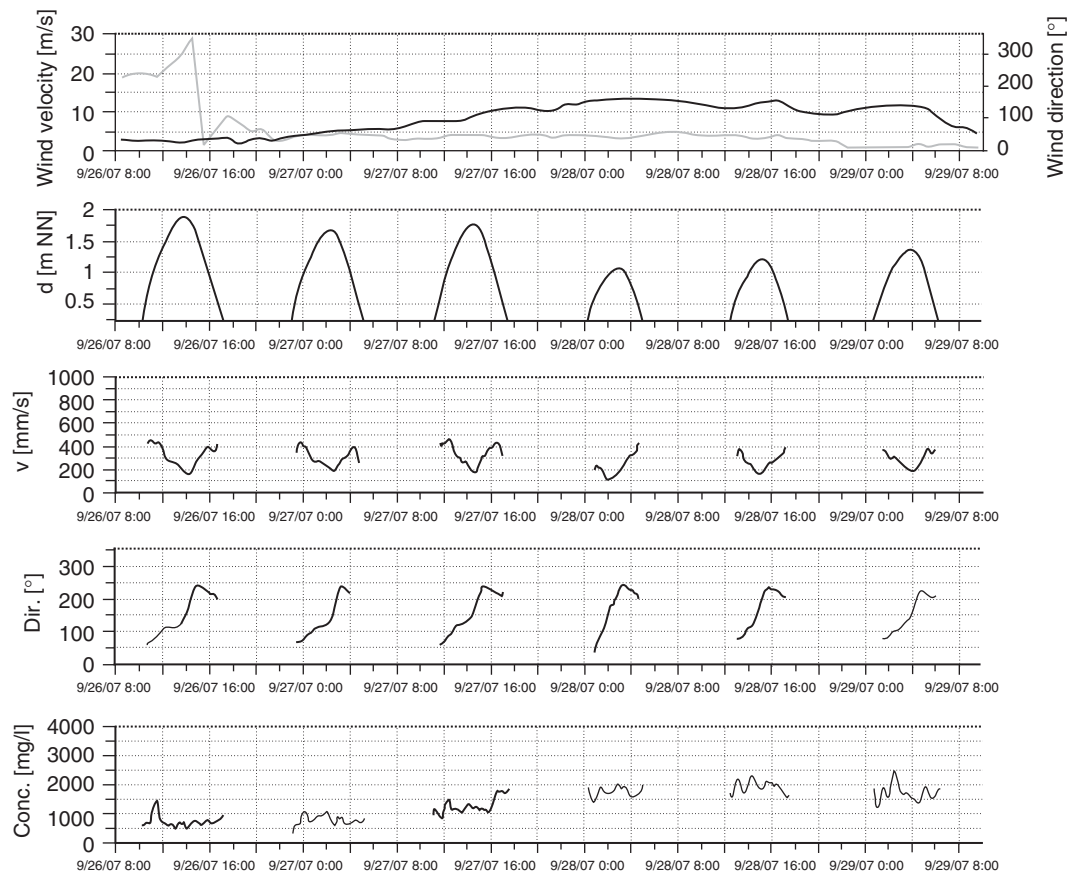
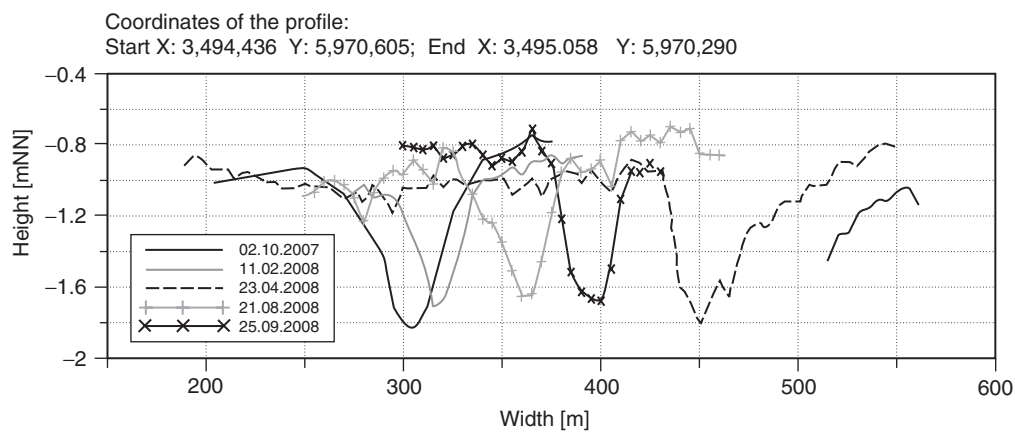
Figure 4. Field data from September 26th–29th 2007

Figure 5. Profiles at the inlet of the Neufelder Rinne

The horizontal displacement especially of smaller creeks was already discovered by EHLERS (1988). Different observations showed that those creeks may change their positions about a few decimeters per tide. These changes are reversible and do not lead to large medium-term changes.

The described and relatively continuous relocations occurred both, during summer and winter months. Direct impacts of two recorded heavy storm surges on the bathymetry could not be observed.

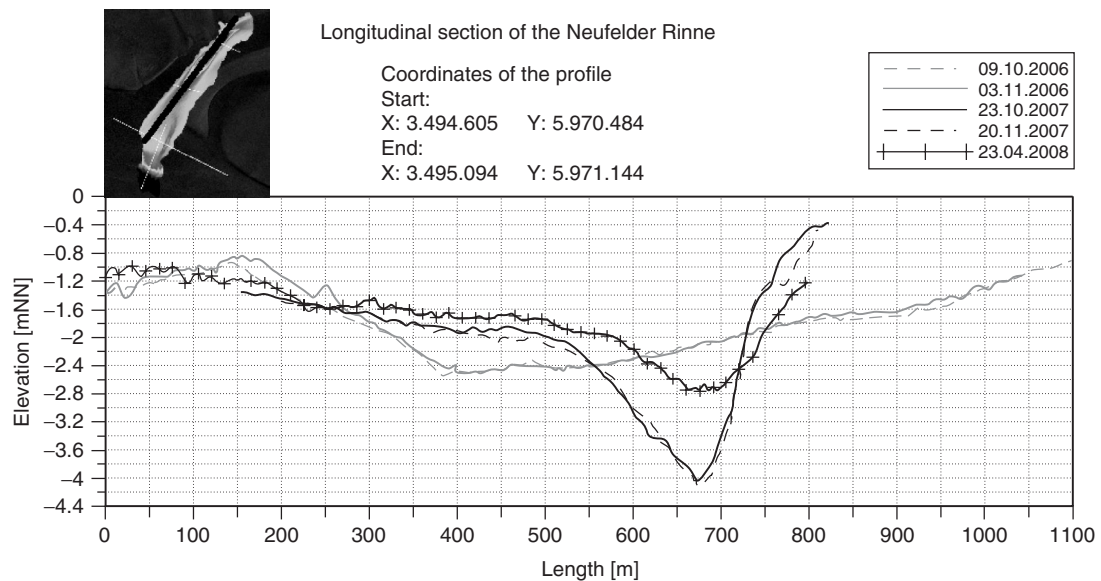


Figure 6. Longitudinal section of the Neufelder Rinne at different times

Figure 6 shows longitudinal sections of the Neufelder Rinne at different times. On November 1st 2006 a storm surge with water levels of approximately 3 meters above mean high tide occurred. Minor changes near the inlet are not due to that extreme event but due to the described continuous relocations. On November 9th 2007 another storm surge also with water levels of approximately 3 meters above mean high tide appeared. Direct – but minor – consequences of that event on the bathymetry are only visible at the northeast end of the creek, where parts of the slope were eroded. For comparison one profile from the year 2008 is plotted. Large changes within the creek are obvious in the rear part (600–750 m) where a scour formed due to a smaller creek discharging into the Neufelder Rinne from the north. In 2008 the development of that creek was regressive so that the scour began to disappear again.

NUMERICAL MODELING

The morphodynamic modeling is done with the multi-dimensional finite element model RMA-10S (KING, 2006), which is based on RMA2 (DONNELL et al., 2006). The further development of the model, leading to the version RMA•Kalypso, has been done by the Institute of River and Coastal Engineering of the Hamburg University of Technology. For this application, the two-dimensional depth averaged numerical model is used.

The model boundaries are defined by the existing tide gauges, so that the area to calculate is enlarged to approximately 220 km². It is inefficient to model the whole mouth of the Elbe morphodynamically when only the Neufelder Watt is the focused area. Therefore, two models are developed: a larger surrounding model creates the hydrodynamic boundary conditions for a detailed morphodynamic model of the focus area.

Firstly the larger surrounding model was set-up and calibrated. This model is controlled exclusively with water level boundary conditions from three tide gauges. The finite element network for the hydrodynamic calculation in RMA•Kalypso consists of 34,500 irregular triangular elements. The resolution is not only high in the investigation area but also in all areas that are of importance for the flooding and drainage of the Wadden Sea areas. The navigation channel on the other hand is discretized by larger elements.

The surrounding model passes water level and discharge boundary conditions to the detailed model, which covers the focused area around the Neufelder Rinne. Here the Wadden Sea structures are described with high resolution to be able to model the morphological changes as detailed as

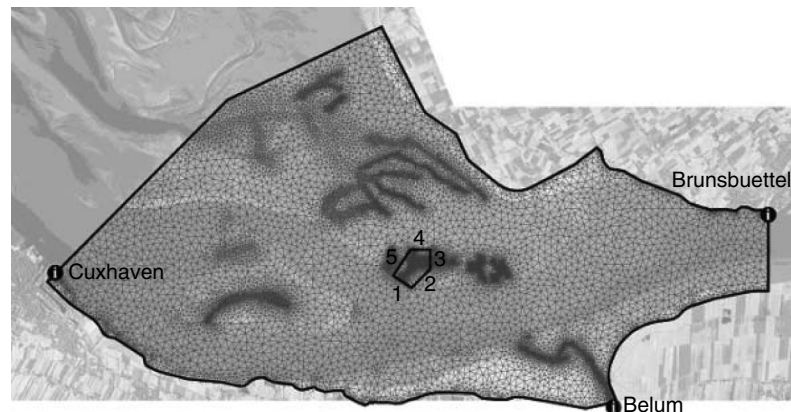


Figure 7. Modeling area and finite element network

possible. Approximately 13,000 quadratic finite elements with an edge length of 10 m define the network of the detailed model. The model is controlled by defining the water stage at boundary line 1 and four discharges at the boundary lines 2 to 5 (cf. Fig. 7).

The drying and rewetting of the finite elements of the Wadden Sea areas caused by the tide is modeled with the marsh porosity method, which is a form of the thin slot algorithms (NIELSEN & APELT, 2003, KING, 2006, DONNELL et al., 2006).

Up to now the larger surrounding model and the focused model are calibrated and validated. The morphodynamic calculation of the detailed model will be run with the computed discharge and water stage boundary conditions as well as with the measured sediment concentrations in the Neufelder Watt. The results will be compared with the field measurements.

Conceptually it is planned to simulate the sediment transport within firmly defined periods. The temporal boundaries of these scenarios result from the data of the echo soundings. Besides the input requirement of an existing start and end bathymetry hydrodynamic measurements and sediment concentrations of these periods are essential. The scenarios have a length of a couple of weeks.

CONCLUSIONS

From the recorded and analyzed sediment concentrations and flow parameters the residual transport was calculated by balancing the transported material (cf. Figure 8). On the tidal flats the sediment transport during flood phase overbalances and is directed southeast towards the Neufelder Rinne. The Neufelder Rinne interrupts this transport, material deposits at the western slope and pushes the creek's axis to the east. The highest sediment transport rates occur at the border of the tidal flats due the exposed position, where the transport is directed to the east. This explains the huge relocations of the inlet of the Neufelder Rinne. Furthermore, an interrelation of the morphodynamics with the spatial location of the considered structures exists. Largest changes occur if the creeks' course runs orthogonal to the main transport direction. The more the creeks' course follows the main transport direction, the smaller are the relocations. Inside the Neufelder Rinne the residual transport during ebb tide overbalances. A part of the suspended sediment, which is transported over the tidal flats into the creek, is carried out and forms an ebb delta at the border of the tidal flats, which is clearly visible on the sonar soundings.

The sediment transport is significantly influenced by tidal currents, which results in a clear distribution of peaks in the course of the sediment concentration. Superior and long-lasting weather and wind conditions have an impact on the level of the sediment concentrations. Pronounced east wind situations lead to relative high sediment concentrations due to lower water levels and a larger ration of wave heights to water levels. However, the transport rates during those situations are low and the resulting morphologic changes are of minor importance. During storm surges in the investigation area

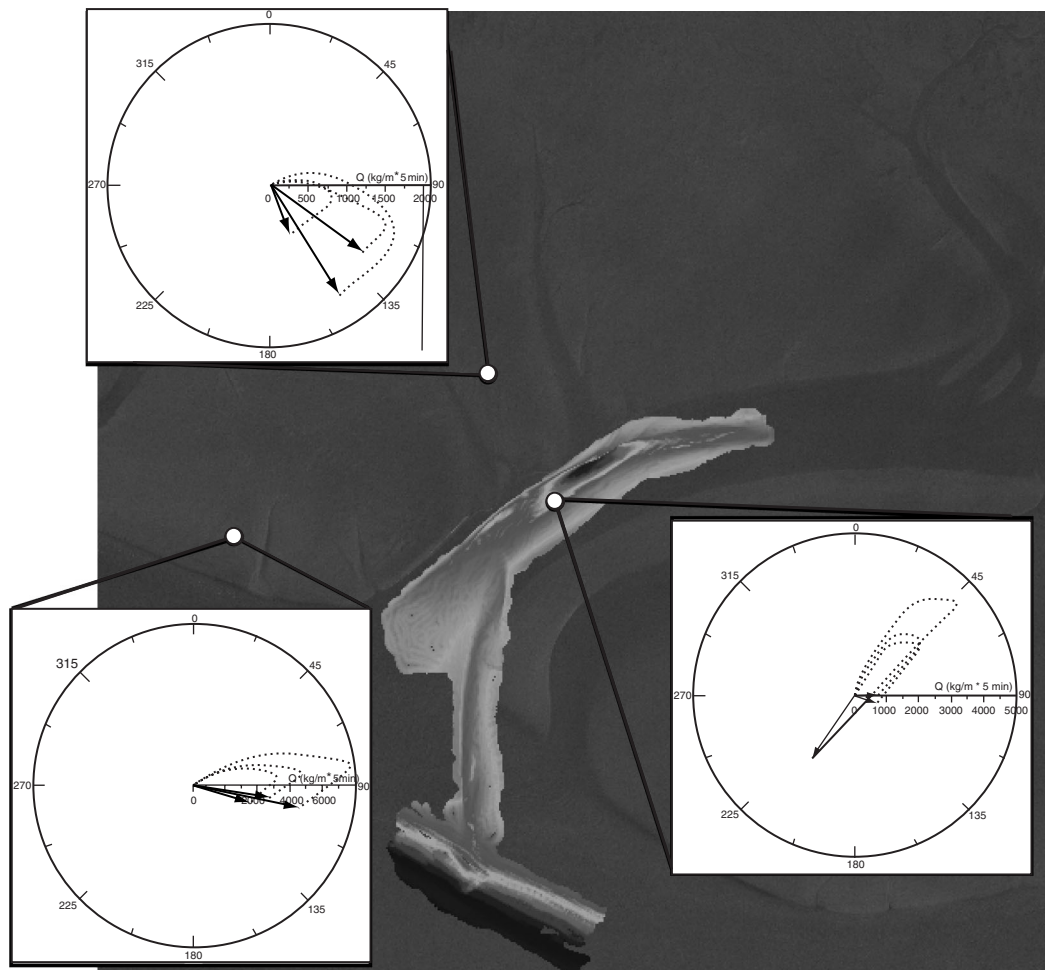


Figure 8. Residual transport in the investigation area during different tides in June 2008

the ratio of wave heights and water levels is lower and leads to sediment concentrations, which are comparatively little. Moreover, the duration of storm surges is limited, so that the morphologic changes in the investigation area during storm surges are negligible. Largest changes of the bathymetry occurred during long-lasting west wind situations with wind speeds of more the 10 m/s for several days. Here, relative high sediment concentrations appear together with higher current velocities and cause large sediment transport rates. These situations accelerate the velocity of the observed relocations.

SUMMARY AND OUTLOOK

Facing the high importance the free approach to the port of Hamburg means to the economic development of Northern Germany, a sustainable estuary management is required. In particular the knowledge about morphodynamic processes on tidal flats needs to be improved.

On the basis of comprehensive high-resolution field investigations the Institute of River and Coastal Engineering at the Hamburg University of Technology analyzed morphodynamic processes on a tidal flat area in the mouth of the estuary Elbe. It is the intention to implement the results in a detailed morphodynamic model and to improve the process knowledge of sediment transport on tidal flats.

Morphodynamic tendencies and displacements were recorded in the creek Neufelder Rinne and the nearer surroundings with a multi-beam echo sounder. During the complete observation period large dynamics – essentially an eastward directed movement – especially at the inlet of the creek could be determined. In the main part of the creek the displacement was articulately smaller. Two recorded heavy storm surges did not have any significant impact on the bathymetry of the investigated area.

The course of the sediment concentration over a tidal cycle is primarily related to the flow velocity. The level of the sediment concentration thereby is dominated by the tidal high water level and waves. During east wind dominated weather conditions with higher wind velocities the sediment concentrations increased compared with tides with mean high water levels. During tides with increased high water levels the sediment concentration level lies below the mean level. Largest sediment transport rates were recorded during long-lasting west wind situations with wind speeds of more the 10 m/s.

A calculation of the residual transport at different positions showed, that the sediment transport on the tidal flats during flood phase overbalances and therefore is eastward directed. The Neufelder Rinne interrupts this transport band. Inside the creek the sediment transport during ebb phase overbalances, transported matter deposits at the inlet and forms an ebb delta. The eastward directed transport causes the described relocation of the creek structure. The west wind situations mentioned above accelerate the morphologic changes.

The fixed field measurements are only punctual. Due to the shallow water in the investigation area even the multi-beam soundings only can cover limited areas. By the choice of the measuring positions information about spatial processes can be derived from the punctual information.

ACKNOWLEDGEMENT

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