Monitoring of hydrodynamics and morphodynamics in a tidal flat area

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Abstract
The tidal flats 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 and stakeholders. To satisfy the requirements, which modern cargo ship industry demands, a 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 momentarily extensive measurements to collect hydrodynamic and morphodynamic data of tidal flats in the estuary Elbe that is the approach to the harbour of Hamburg. Water levels, flow and wave parameters and the concentration of suspended sediments are recorded in high resolution. Furthermore, the bathymetry is determined in frequent intervals with a multi-beam echo sounder.

Introduction
The North Sea is a border sea of the Atlantic Ocean. Thus, the 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. It underlies sediment relocations on different scales.

The most important waterways are the estuaries Elbe, Weser, Ems and Jade (fig. 1). 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 harbour of Hamburg and thus it may be called a lifeline of a whole region. The harbour 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 sustainable and innovative estuary management is necessary. The Hamburg Port Authority (HPA) and the Federal Waterway Administration (WSV) recently presented a new concept for a sustainable development of the tidal area of the Elbe River (HPA & WSV, 2006). A main issue is to decrease the energy caused by tidal flow in the estuary.

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 centre of scientific activities. Big challenges in this interrelation are the impacts of the climate change.
In spite of great successes in numerical modelling 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 tidal flats 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 are not yet completely understood. Frequently phases of sedimentation and erosion in tidal flat areas change patchwork-like over different seasons without any visible pattern.

**Aim**

The main goal of this research project is to analyse morphodynamic and hydrodynamic changes in the research area “Neufelder Watt” in the mouth of the Elbe estuary, to obtain an improved understanding of those processes. Thus the influence of man-made and climatic changes is going to be considered in a model to achieve a better prediction of sediment transport. The shear stresses caused by waves and the change in the state of stress in the transition area between mainstream and tidal creeks are of special interest. These stresses shall give a conclusion to relevant flow conditions for morphodynamics and their relationship to soil physics, geohydraulic and biogenous structures.

In general the impact of waves on shallow coastal areas is high and results in a high concentration of suspended matter in the water body. In comparison the influence of tidal currents at tidal flats is small. Tidal currents occur regularly with specific time intervals in which the variations happen. By contrast the wave impact is highly variable during small time scales, varies seasonally and depends also on tidal elevation (Malcherek & Knoch, 2006).

As part of a project supported by the Hamburg Port Authority (HPA) the Institute of River and Coastal Engineering of the Hamburg University of Technology aims to improve the process knowledge on tidal flats on the basis of extensive field measurements in the “Neufelder Watt” in the mouth of the estuary Elbe. The results may provide a secure
theoretical background for the mathematical multi-dimensional modelling of morphodynamic processes on tidal flats.

Methods

The field research takes place at the “Neufelder Watt” including a sand bank called “Neufelder Sand”. The research area is located within the Elbe estuary, therefore, hydro- and morphodynamically influenced by the mainstream of the Elbe estuary. Besides the requested results, the analysis of this area is going to add important data to short and long-term relocation processes of sediments in this special area as well as further information about environmental issues.

A cross section was selected to install measurement devices to collect data. The chosen section shown in figure 2 is located within the “Neufelder Rinne”, a tidal creek of special interest due to its enormous sediment relocations in the recent decades. 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. Three Acoustic Doppler Current Profilers (ADCP) were used as well as five pressure gauges and three Optical Backscatter Profilers. Additional to the permanent installed instruments multi-beam echo sounder (MBES) measurements were performed in frequent intervals of three to four weeks and after extreme events. Furthermore, soil samples were taken. They build a foundation for a sediment register of the area under investigation that will be completed in the course of the further research.

![Figure 2. Position of the area under investigation in the mouth of the estuary Elbe.](image)

The arrangement of the measuring devices in one position is shown in figure 3. Flow parameters were recorded continuously and in a high resolution from June 2006 until December 2006 with three RDI ADCP Workhorse Sentinel. Every 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 ± 2°. Suspended sediment concentrations were measured with three Argus Surface Meters by ARGUS Environmental Instruments. In that innovative measuring instrument 100 optical backscatter sensors mounted in a steal bar assessed the sediment concentration over a one-meter column above the sea bottom (fig. 4). Therefore, the device
Figure 3. Installation of pressure sensor, ADCP, ASM. DGPS to level the measuring devices.

Figure 4. ARGUS Surface Meter (ASM) with optical backscatter sensors 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 ± 10 %. Five pressure sensors recorded the sea state with a measurement frequency of 5 Hz. In the chosen profile in the Neufelder Rinne all relevant parameters were measured in the middle of the creek and on both banks. In addition waves were recorded at two points above and below the measuring profile. In regular intervals of three to four weeks the bathymetry of the marked
investigation area was analyzed with a multi-beam echo sounder. Furthermore, measuring tours with the research vessel of the Institute of River and Coastal Engineering that is shown in figure 5 were attempted after extreme events.

In May 2007 the field measurements were continued. In the current phase of the project the focus was set on the south banks of the Neufelder Watt at the boundary to deeper water. Again in one position the devices were placed closed to each other so that all relevant parameters were recorded punctually. Every time when the measuring equipment is maintained and data is collected the positions of all devices, especially the height coordinates, are quantified with a Differential GPS System.

Results

When assessing the results of the field study one has to consider unavoidable uncertainties. The record of the bathymetry contains an interaction of various devices, such as Differential GPS, motion sensor, gyrocompass and multi-beam echo sounder. All in all the accuracy of the system is approximately 5 to 10 cm. Although the bathymetry is assessed in regular intervals, in between some developments may be missed. The determination of the suspended sediment concentration via optical backscatter sensors is an indirect measuring method. Thus it contains uncertainties, which can be reduced by taking water samples to verify the records of the ASM. Even though a lot of measuring equipment is in use, due to the size of the investigation area it provides punctiform information. By changing the positions of the devices laminar information may be achieved.

Due to the low water depths and the high sediment concentrations in the area under investigation the clearing of the data collected by the multi-beam echo sounder is very important. After the post processing a digital terrain model of the Neufelder Rinne was created. Conspicuous is an ebb delta at the mouth of the creek. By means of the marked cross sections and longitudinal section (fig. 6) at different times the vertical and horizontal displacement of the creek can be shown.

Figure 7 shows a cross section at the entry of the creek at different times. An eastward directed movement of the entry could be recognized. At the same time the bottom elevation of the creek increased. Figure 8 shows a longitudinal section of the creek from the entry to the measuring profile. The changes at the entry result from the relocation of the axis of the creek in this area. In the course of the longitudinal section the bathymetric changes decrease. Merely in the middle of the section a deepening can be detected after June, 28th (fig. 9). In the
rear part of the creek the changes are marginal. There is no direct influence of a heavy storm surge visible that took place on November, 1\textsuperscript{st} 2006.

The horizontal movement of the entry of the creek is of minor interest for the morphodynamics of the area under investigation. Different measurements have demonstrated that minor creeks may alter their position by a few decimetres between tidal cycles but the changes are reversible. Over long time periods, the tidal creek positions displayed no significant shifts (Ehlers, 1988).

A comparison between different digital terrain models can be done by generating the differences of the elevations. From all multi-beam echo soundings can be concluded that in spite of spatial limited relocations and the shift of the entry the creek is stable in position. After evaluating the second phase of the project, which started in February 2006, one will know whether the results received from June to November 2006 were due to seasonal effects or proof a constant long-term movement.

Figure 6. Results of MBES from June, 28\textsuperscript{th} 2006 and position of the cross sections and longitudinal section at the Neufelder Rinne.

Figure 7. Cross section at the entry of the Neufelder Rinne at different times.
In figure 10 a the recorded data from July, 4th in the middle of the creek is shown. The set stands for a predominant part of the data from summer 2006 without important wind- or wave-induced currents. Displayed are the wind velocity and direction, water level, flow velocity and direction and sediment concentration. The last three values are depth averaged. The maxima of flow velocities during flood and ebb tide are clearly visible. The course of the tide can be withdrawn from the plotted flow directions, which follow exactly the axis of the creek even at higher water levels when the complete area is flooded. The shorter duration of the flood tide is conspicuous. The signal of the suspended sediment concentration underlies a lar-
ger variability. In general their maxima are following delayed the maxima of flow velocities. During the diagramed period the concentrations of suspended sediments are higher than during other periods. This was observed repeatedly at normal water levels and at tide dominated situations.

Figure 10b shows the measured values during the heavy storm surge from November, 1st 2006. The maximum water level rises up to 3 meters above mean high water. The maxima in the flow velocity are more expanded in comparison to a normal tide. The flow direction does not match with the direction of the creek axis anymore. The sediment concentration lies at a normal level and clearly under the ones from figure 10a.

From the recorded and analysed sediment concentrations and flow parameters the residual transport was calculated by balancing the transported material. The residual transport during ebb tide overbalanced, thus sediment was carried out of the creek. The amount of transported material can vary strongly from tide to tide, however overall phases with high or little transport were counterbalanced.

Within the framework of the research project PROMORPH, done by several research institutes in Germany in the years 2000 to 2002, field measurements were performed in tidal channels of the central Dithmarscher Bight at the west coast of the federal state Schleswig-Holstein. The measurements covered a wide range of tidal conditions whereas the widths of the surveyed tidal channels were up to ten times larger than the Neufelder Rinne and the water depths were up to 18 meters (Poerbandono & Mayerle, 2005). Although the areas under investigation have different hydrological and morphodynamic characteristics, a comparison between the results of the current project described in this article and the results of PROMORPH can be used to verify the deliverables from the Neufelder Watt.

Conclusions

Conclusions about morphodynamic processes in the wadden sea area Neufelder Watt can be drawn based on the so far undertaken research in the natural environment. Data from both, stationary measurement points and a mobile multi-beam echo sounder system were considered in the analysis and evaluation. The results are introduced in the numerical modeling and help to improve the process knowledge on the hydro- and morphodynamics in the area under investigation.

Morphodynamic tendencies and displacements of the surveyed creek were recorded with the multi-beam echo sounder. The Neufelder Rinne did not show significant signs of instability during the research duration. Merely in the entry of the creek a horizontal shift of the axis was observed. This movement is of minor interest for the morphodynamics in the region under investigation. Within the creek some relocations of sediment took place, but overall the situation is balanced. A heavy storm surge did not affect the system, as it was observed, directly after the event.

The analysis of the flow data showed the importance of the creek Neufelder Rinne for the flooding and dewatering of the area under investigation. The tide-induced flow directions follow the longitudinal axis of the creek. This was observed by the instruments installed over the whole width of the creek. Even at water levels above the upper edge of the creek the flow streams along the creek axis. During normal tides the concentration of suspended sediment reaches its maximum time delayed to the maximum of the flow velocity.

An estimation of the residual transport showed, that the amount of moved sediments during ebb tide outweighs. The eroded material deposits at the entry of the creek and builds up an ebb delta. The moved material seems to come from the surrounding tidal flat area, explained
Figure 10. Field data from July, 4th 2006 (a) and November, 1st 2006 (b).

through higher sediment concentrations at the creek banks.

The sediment transport is, therefore, primary related to the tidal currents. Drift- or wave-induced currents affected the currents only during or directly after extreme weather conditions. In case of a storm surge the amount of water above the bottom decreases the energy that would cause stresses, which would lead to erosion.

Summary and Outlook

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

On the basis of extensive high-resolution field investigations the Institute of River and Coastal Engineering at the Hamburg University of Technology analysed morphodynamic processes in a tidal flat area in the mouth of the estuary Elbe. It is the intention to implement the results in a detailed morphodynamic model.
During the first period of the project, important data and information about morphodynamic processes in the research area were gained. It is necessary to neglect certain effects, which are of minor meaning for the overall problem (e.g. the shift of the inlet). The Neufelder Rinne is a control element for the area under investigation. Higher sediment concentrations and larger transport rates occurred during “normal” weather conditions not during extreme events. These conditions have to be quantified. To identify seasonal effects the measurements are continued and extended to the tidal flat areas with higher elevations.

The results of the field measurements will contribute to the success of the second phase of the project, which consist of designing a hydro-numeric morphodynamic model. Later on, the model will help to design and to evaluate estuary management actions.

For the design of the model, a detailed model is going to be placed in a larger surrounding model. The surrounding model contributes the boundary conditions for the detail model. Latter is going to be modified by a wave model and validated with the help of the research data collected in the area under investigation. A two dimensional model matches the requirements of the hydrological and morphodynamic situation satisfyingly. For the simulation the model RMA-10S will be used.

Regular echo sounder measurements of the creek are planned further on. These are required to track the future development of the bathymetry and to estimate sediment balances. Furthermore, more measurements of flow velocity, suspended sediment concentrations etc. are required to support the design of the model. Especially to determine the boundary conditions several sets of data must be collected with the help of the research vessel provided by the Institute of River and Coastal Engineering. Along the boundaries of the model flow parameters and sediment concentrations must be recorded. On account of this along the boundaries successively in each case two ADCP’s and ASM’s are going to be installed to achieve line shaped information. The linear data incorporates directly in the model. Additionally, mobile flow measurements with an ADCP mounted on the research vessel will be performed at the south and east boundary of the model.

Wave measurements will be operated at various locations along the edge of the tidal flat area (southern edge of the model) as well as on the area of the embankment Neufelder Sand. Furthermore, to receive a detailed grid of information about the in-situ sediment, more soil samples will be taken. These data are also going to be an input for the model. Additional information about the sea bottom is going to be provided by hydro acoustic methods performed by the multi-beam echo sounder.

**References**


