MORPHODYNAMIC DEVELOPMENT OF TIDAL FLATS

by

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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.

1. 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.

Figure 1. Map of the German North Sea coast

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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.

2. 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 biogenious 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.

3. AREA UNDER INVESTIGATION

The field investigations take place 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 Neufelder Sand started to develop in the years after 1926 when a shallowness formed in the south of the Neufelder Watt. The ebb stream ran along the south banks of the Neufelder Watt. While the "Neufelder Channel" (= "Neufelder Rinne") deepened, the tidal flat area Neufelder Sand grew. Figure 2 shows to maps of the investigation area from 1864 and 1962.

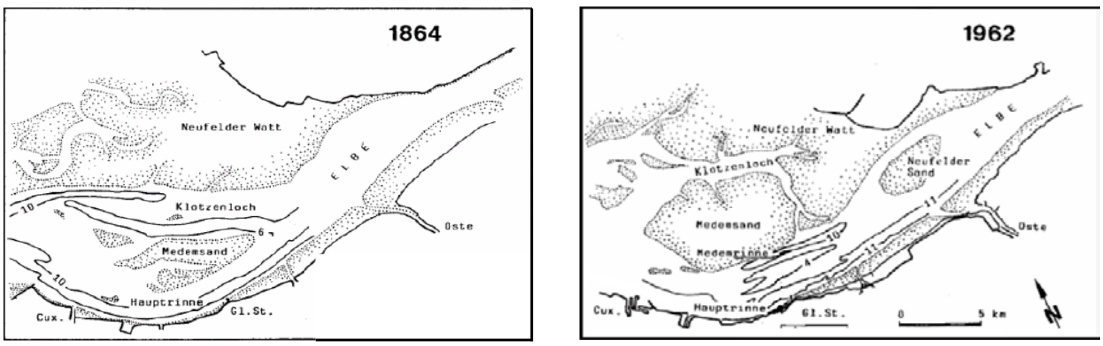

Figure 2. Maps of the investigation area of the years 1864 and 1962

After 1960 at the south bank of the Neufelder Watt a groin was build to stabilize the intertidal area. The ebb stream was refracted to the main channel and the Neufelder Rinne decreased in depth. In the following decades the area under investigation grew increasingly and the Neufelder Rinne changed to a creek with smaller depth. Yet it is still of high importance for a huge part of the Neufelder Watt due to its dominating role in flooding and dewatering of the tidal flat area.

In 2006 a cross section of the Neufelder Rinne was chosen to collect data. Figure 3 shows the position of the profile in the area under investigation. The average tidal range is about 3 meters. At the measuring profile the Neufelder Rinne was approximately 100 meters wide and the deepest point was at – 2.00 m NN. This leads to water levels from 0.50 m at mean low water to 3.50 m at mean high water at the deepest point. The surrounding tidal flats and the measuring equipment at the banks of the creek fall dry around low water.

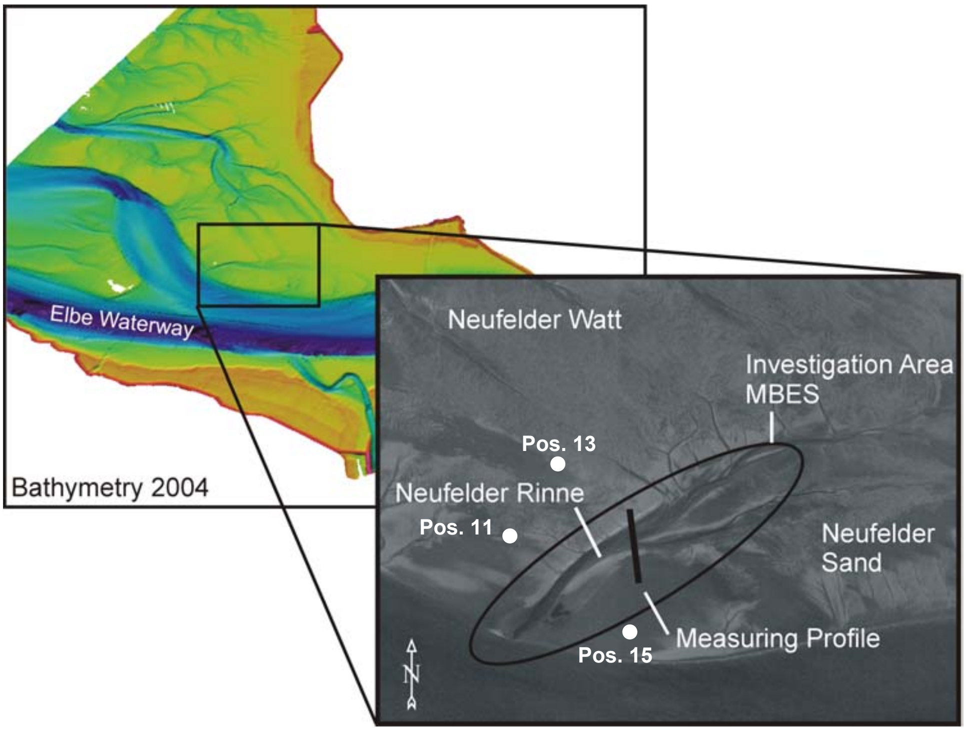

Figure 3. Investigation area and measurement positions in the mouth of the estuary Elbe

4. LONG-TERM DEVELOPMENT

By means of current and historical data the morphologic changes of the mouth of the estuary Elbe for large spatial and temporal scales were analyzed. To take all available topographic data into consideration and to quantify the changes, the elevation differences between all maps were determined. There it is advisable to examine limited areas, which morphological belong to one unit.

The evaluation of the elevation differences brings up two characteristic values describing the morphodynamic activity of the research area: a medial altitude change in form of a difference value (balance altitude) and the medial altitude as an absolute value (volume altitude) of sedimentation and erosion.

As a result of the research project MORAN (SIEFERT, 1987), the volume altitude h_u can be determined as a saturation function over a reference period a.

$$h_u = h_{ua}\left(1 - e^{a/a_0}\right) \qquad (1)$$

The variable *a* indicates a period under observation (time scale between two topographic records), but not a continuing period. The asymptotic volume altitude h_{ua} presents a median limit value for h_u. a_o stands for the time frame in which h_{ua} could be reached in case of a continuously, linear, changing topography. The gradient in the derivation is equal to h_{ua}/a_0 and therefore equal to the volume rate.

This method was applied on seven squares of the Neufelder Sand (Fig. 4) and it was tried to determine a saturation function. For instance for square III, 18 topographic records are available (from 1954 to 2004). Hence it is possible to compare 152 maps with each other, applied reference periods could be a = 1 year (i.e. 1983/1984), a = 2 years (i.e. 1977/1979) or even a = 50 years (1954/2004). The 152 volume values are drawn in a diagram, where the reference period describes the X-Axis. The diagram shows that there is no limit value; therefore, a saturation function cannot be determined.

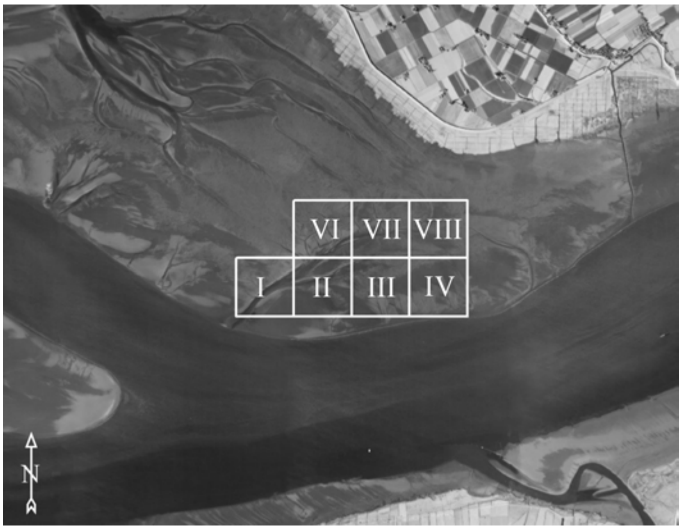

Figure 4. Positions of the investigated squares

A saturation function can only be determined, if the balance altitude h_b inclines towards zero or if it levels off a certain value. In case that h_b increases alongside a cumulative *a* (proportional to h_u) a secular elevation can be observed.

Figure 5 shows the balance heights of square III along the reference periods *a*. Most of the map comparisons show sedimentation, which means the researched area gained elevation and sediments over the reference period continuously. The largest balance altitudes can be found during large reference periods. To gain further information about the morphological changing rate within the researched area, the balance altitude was uniformly distributed over the duration of its associated reference period and afterwards applied on the reference period itself (Fig. 6).

The larger the reference period the more the change of the balance altitude levels off at approximately 0.04 m per year in square III. This means in a long term period the researched area within the Neufelder Sand increases by 0.04 m per year. Shorter reference periods show, that the changing rate can increase or decrease immensely. Based on this form of diagram, periods of large changes can be determined (i.e. 1984/1983). The evaluation of the other squares shows similar results, whereas the squares III and IV show the lowest balance heights and balance rates. Constant balance rates are reached within short periods. The squares II and VI show larger balance heights. Also the balance rates are larger and a constant value is reached after longer periods. The squares I and especially VII and VIII are strongly influenced by the sedimentation of the Neufelder Rinne. Very large balance heights can be assessed. Constant balance rates can only be found at very large comparison periods.

Overall on all considered areas an increase of heights takes place. This development is particularly strong affected by the sedimentation of the Neufelder Rinne. But also considered areas on the Neufelder Sand underlie a constant increase of heights. Over shorter or longer periods constant balance rates are reached. The described development of the investigated areas has to be assessed against the background of an anthropogenic change – the construction of the groin. Without this groin the area under investigation would have developed in another way.

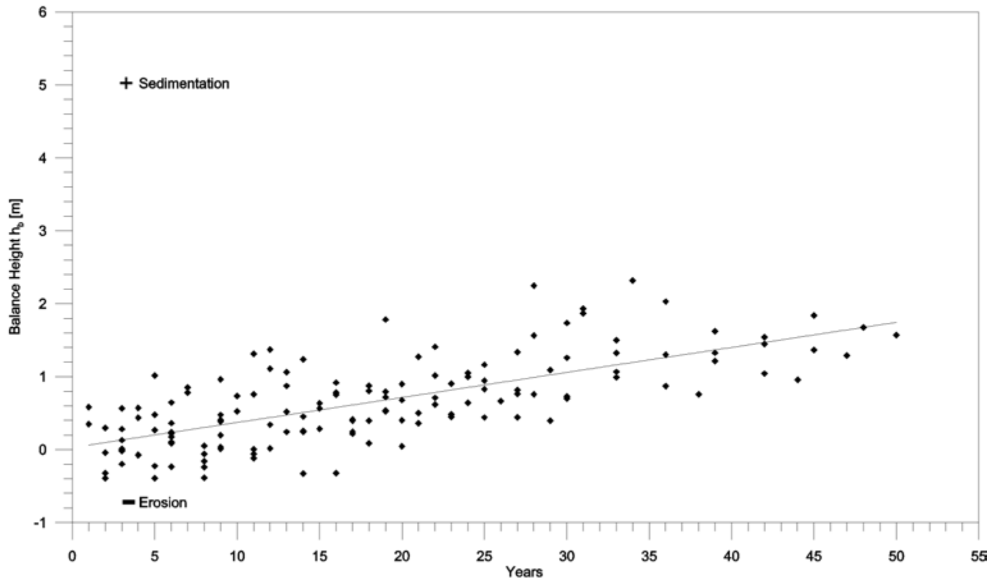

Figure 5. Balance heights of square III

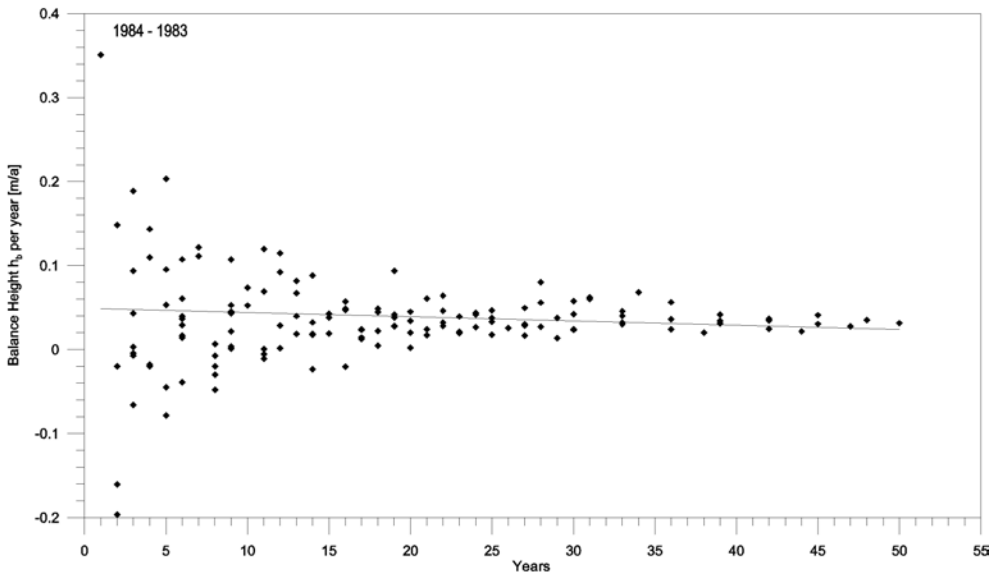

Figure 6. Balance rates of square III

5. FIELD MEASUREMENTS

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 morphodynamical 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 3 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.

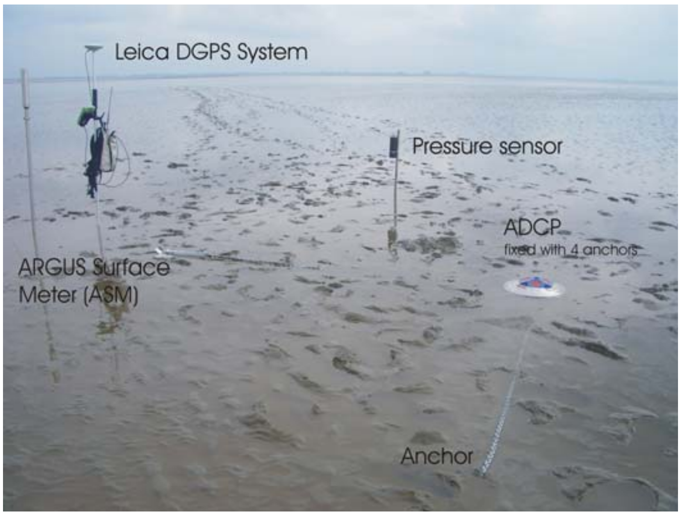

Figure 7. Installation of pressure sensor, ADCP, ASM; DGPS to level the devices

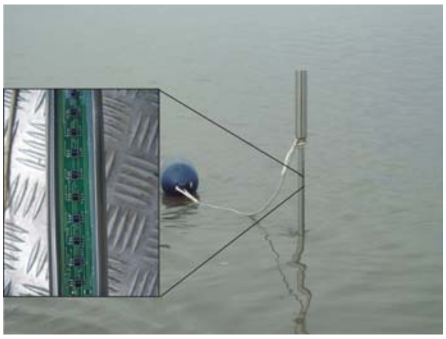

Figure 8. ARGUS Surface Meter (ASM) with optical backscatter sensors

The arrangement of the measuring devices in one position is shown in figure 7. Flow parameters were recorded continuously and in a high resolution from June 2006 until December 2006 and April 2007 until November 2007 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. 8). Therefore, 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 ± 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 analysed 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 9 were attempted after extreme events.

Figure 9. Research vessel “Nekton”

In April 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 and on the tidal flat areas in the northwest of the Neufelder Rinne. 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.

6. ANALYSIS OF THE FIELD DATA

6.1 Multi-beam echo soundings

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.

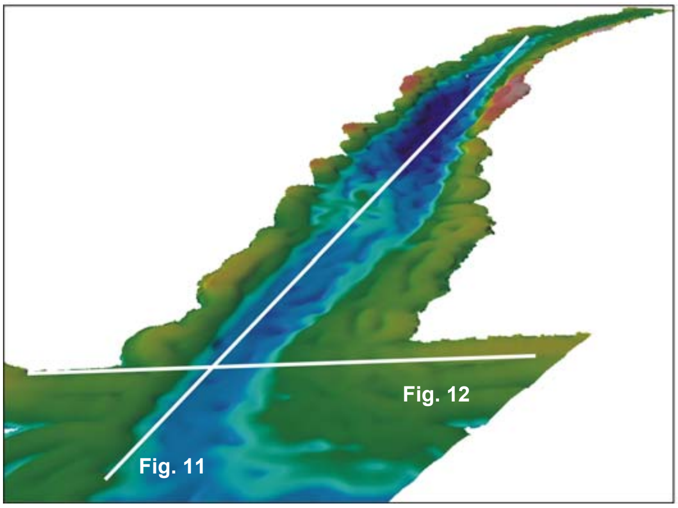

Figure 10. Results of MBES from June, 28th 2006 and position of the cross section and longitudinal section at the Neufelder Rinne

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. 10) at different times the vertical and horizontal displacement of the creek can be shown.

Figure 11 shows a longitudinal section of the creek from the entry to the measuring profile. The large 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. In the rear part of the creek the changes were marginal. There is no direct influence of a heavy storm surge visible that took place on November, 1st 2006. Between November 2006 and February 2007 the development continued, whereas in the middle and the rear part of the creek the elevations increased. Between February and October 2007 the shift of the creek axis continued. The elevation of the surrounding tidal flat areas increased. Due to the decreasing width of the creek, a deepening could be observed in the middle of the longitudinal section. Figure 12 shows a cross section at the entry of the creek at different times and therefore visualises the large relocation of the entry of the creek. An eastward directed movement of the entry could be recognized. Especially between February and October 2007 the tidal flats surrounding the entry of the creek increased in elevation.

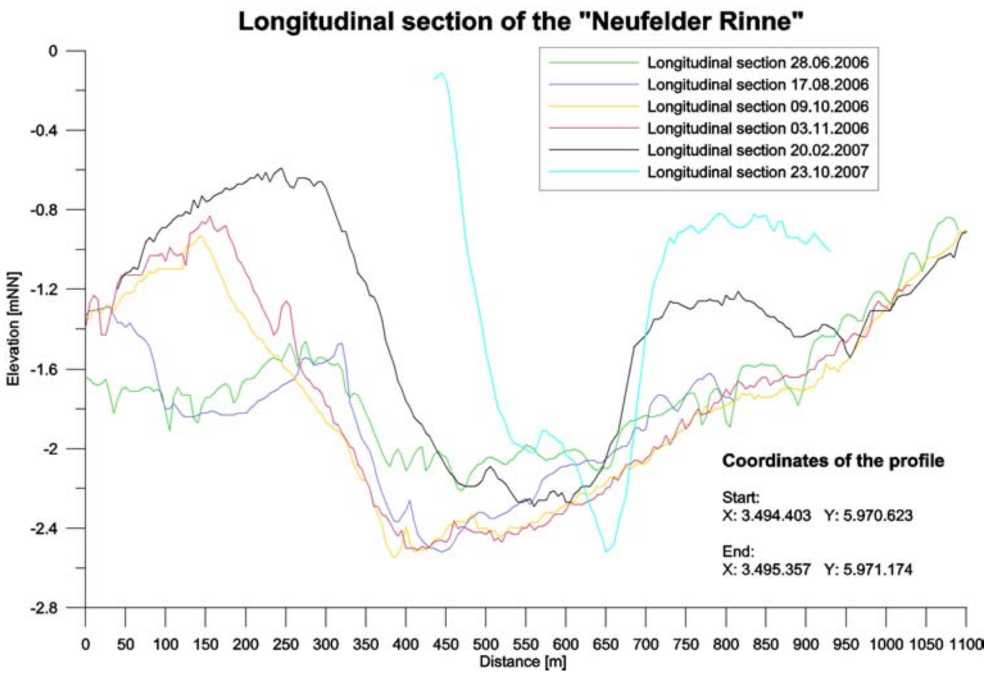

Figure 11. Longitudinal section of the Neufelder Rinne at different times

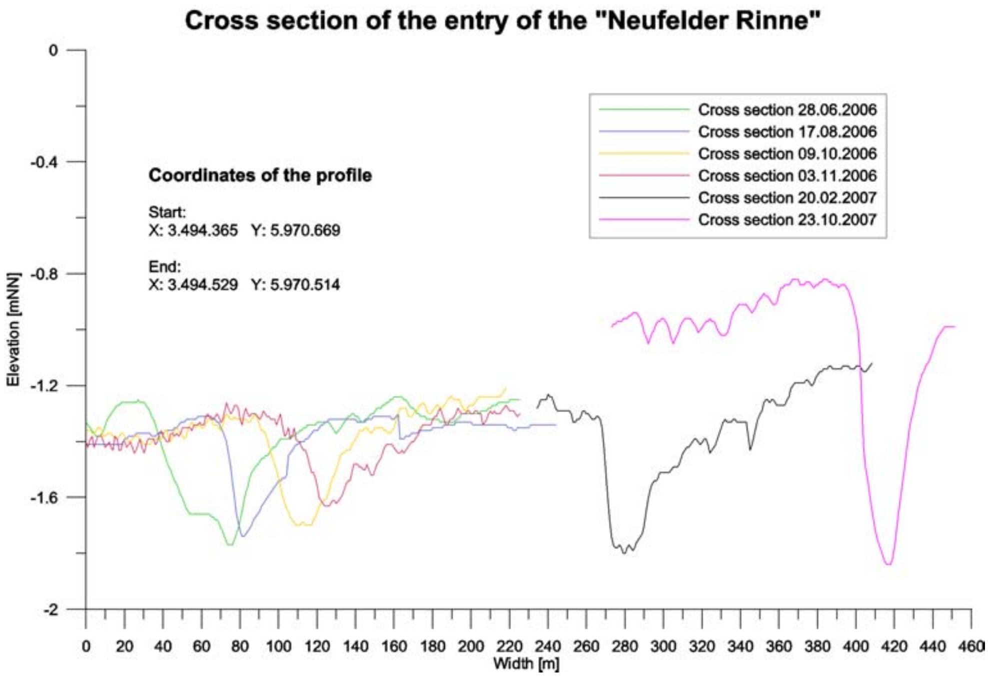

Figure 12. Cross section of the Neufelder Rinne at different times

The horizontal movement of the entry of the creek is of minor interest for the morphodynamics of the overall 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 except the shift of the entry the axis of the creek is comparatively stabile in position. The surrounding tidal flat areas gained height. The continuous change of the Neufelder Rinne took place during winter months as well as over summer months.

6.2 Flow parameters and sediment concentrations

In Figure 13 the recorded data from July, 3rd until 5th in the middle of the creek are shown. They are exemplary 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 to see. 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 larger variability. In general there are wide maxima following delayed the maxima of flow velocities. During the diagramed period the concentrations of suspended sediments are higher than during other periods. This could be observed repeatedly at normal water levels and a tide dominated situation.

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 and thus sediment was carried out of the creek and formed an ebb delta. The amount of transported material could vary strongly from tide to tide, however overall phases with high or little transport were counterbalanced.

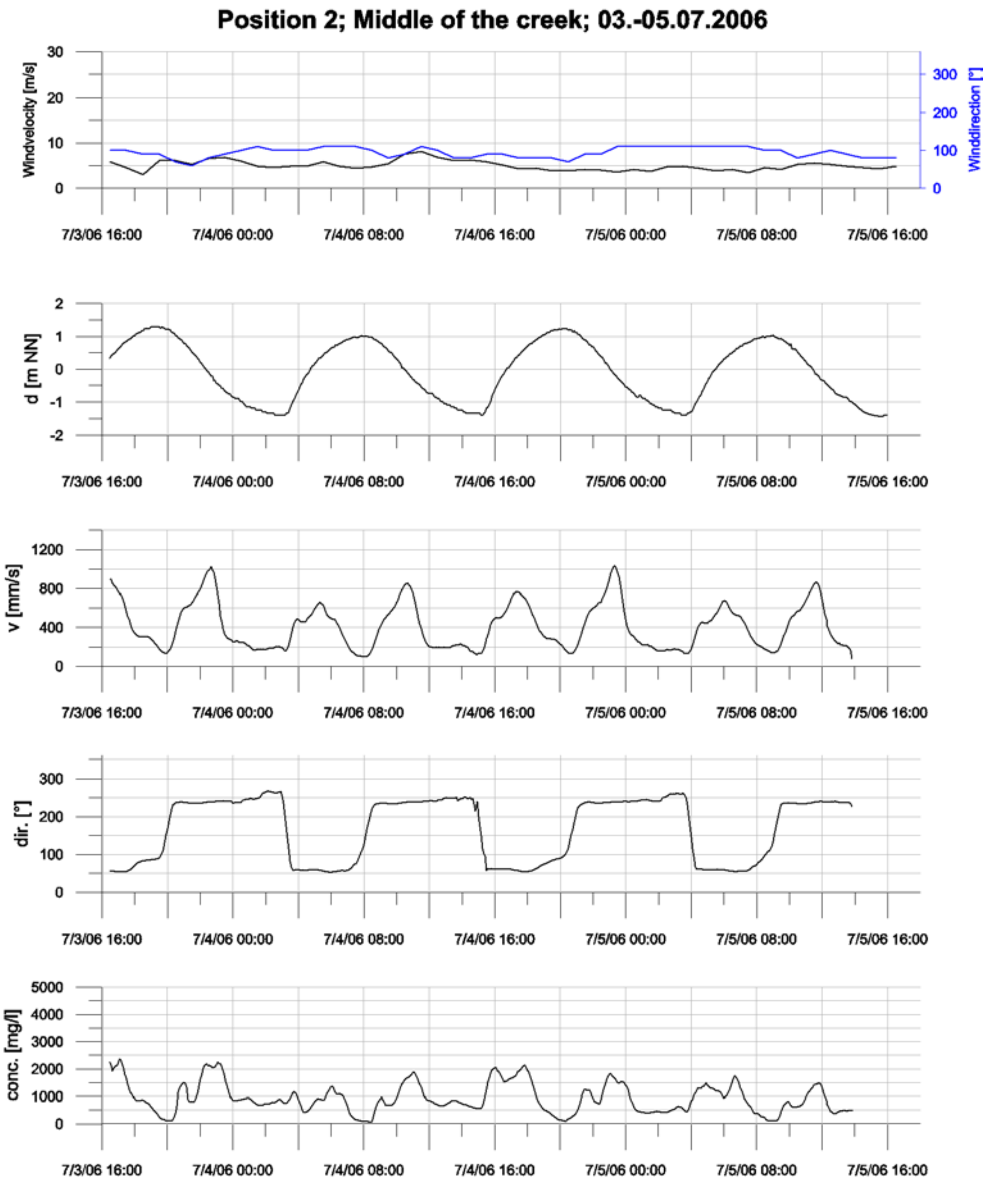

Figure 13. Field data from July, 3rd – 5th 2006 in the middle of the Neufelder Rinne

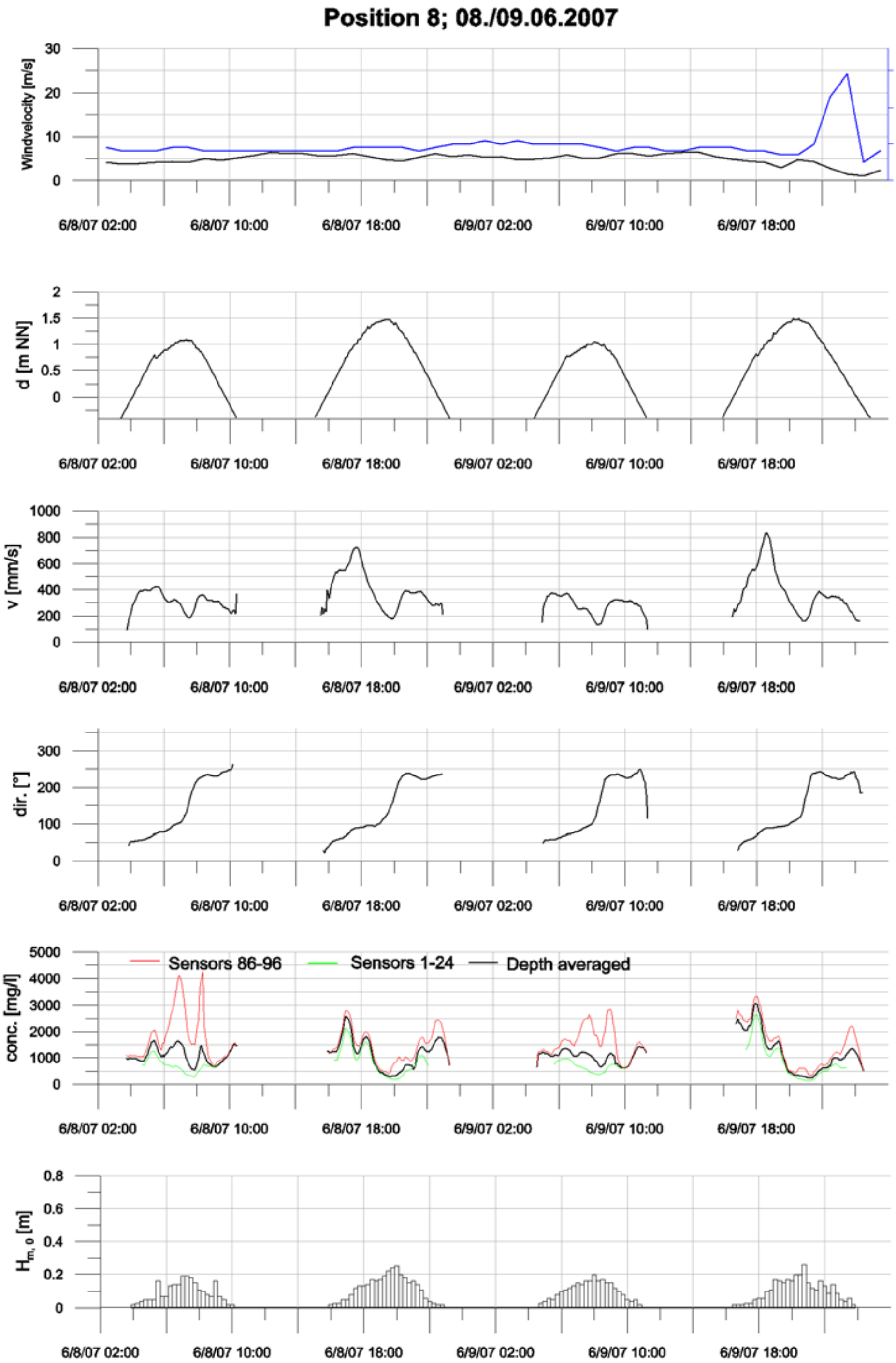

Figure 14. Field data from June, 8th – 9th 2007 at position 8

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 could be used to verify the deliverables from the Neufelder Watt.

Figure 14 shows the field data from June 8th and 9th 2007 measured at position 8, which is on the tidal flats at a relative high elevation. On this account the devices fall dry around low water and the data is not continuous. The flow velocity does not reach the peaks that were recorded in the creek. The diagram shows a comparatively calm weather situation with wind of 3 Beaufort from east-southeast, which leads to small waves with significant wave heights of maximum 0.20 meters. The displayed flow direction is characteristic for normal weather conditions. The depth averaged sediment concentration is marked in black. The red line shows the deepest 10 backscatter sensors near to the bottom, the green line shows the 10 sensors at the top of the device, one meter above the bottom. The concentration of suspended sediments (SSC) at the bottom is higher than one meter above the bottom. The course of the SSC is similar, if the course of the flow velocity is comparable (see 2nd and 3rd branch). Conspicuous is the occurrence of a peak in the SCC before the peak velocity is reached. The loosely bedded material left from the last ebb phase starts to move at lower flow velocities when water reaches the measuring positions again. These peaks are higher than the ones caused by the peak flow velocity. The influence of even small waves is visible at the 1st and the 2nd branch. At low flow velocities especially the concentration of the deepest sensors increases. This phenomenon only occurs if the water level at high water is lower than usual.

7. 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 overall region under investigation. A heavy storm surge did not affect the system, as it was observed, directly after the event. It was conspicuous that the surrounding tidal flat areas overall gained elevation.

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 through higher sediment concentrations at the creek banks.

The sediment transport in the creek 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.

To explain the transport of material from the tidal flats towards the creek, measurement devices were installed on the tidal flats. Sediment transport started before the peak flow velocity was reached, explained by the high SSC in the early flood phase especially at the deepest sensors. That way large amounts of sediments were transported on the tidal flats and towards the creek.

8. 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 and to improve the process knowledge of sediment transport on tidal flats.

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. On the tidal flats large amounts of material were transported at low water levels and low flow velocities. Even small waves had an influence on the sediment concentration. To identify seasonal effects the measurements are continued.

The results of the field measurements will contribute to the success of the next 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.

Regular echo sounder measurements of the creek and the surrounding areas 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 velocities, 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 the basis on the so far undertaken research it is sensible to install the devices in the creek and on the tidal flats northwest and southeast of it. The received information will provide information on the overall hydrodynamic and morphodynamic situation. 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.

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