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Impact of Sea Level Rise on Estuarine Hydrodynamics

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ABSTRACT: The Elbe, Jade-Weser, and Ems estuaries located in the German Bight (North Sea) are not only important ecosystems, they are also used as waterways. The hydrodynamic conditions in these estuaries are influenced by several factors. One of them is the sea level in the North Sea. Future climate change leads to an accelerated increase of mean sea level in the North Sea. We need to know how this affects the hydrodynamic conditions in order to develop adaptation strategies. The objective of this work is to investigate how sea level rise changes tidal dynamics in the interior of the estuaries. Using 3D-hydrodynamic numerical models we simulate estuarine hydrodynamic conditions. We carry out different model simulations with and without sea level rise. The analyses show that in most parts of the estuaries high water levels rise more than low water levels. Hence tidal range is larger in the model simulations that include sea level rise. As a result of sea level rise the shape of the tidal curve is changed. In many parts of the estuaries flood current velocities increase more strongly than ebb current velocities. Due to the larger ratio of flood current velocity to ebb current velocity upstream sediment transport increases.

Keywords: Sea level rise, Tidal dynamics, German Bight, Sensitivity study, Hydrodynamic numerical model

1 INTRODUCTION

Increasing atmospheric greenhouse gas concentrations lead to changes in climate. Climate change affects people and wildlife almost everywhere. Due to global sea level rise, coastal areas in particular are affected. The Elbe, Jade-Weser, and Ems estuaries, located in the German Bight (North Sea), form important ecosystems which provide unique conditions for wildlife. They are also used as waterways and represent relevant economic factors. Climate change might restrict estuaries in their function as waterways. For the development of adaptation strategies we need to know how climate change will affect the estuaries. In this paper we focus on the effects of sea level rise.

To date, few studies have investigated the impact of sea level rise on the hydrodynamics in the estuaries of Elbe, Jade-Weser or Ems. Grabemann et al. (2001) explore the impact of sea level rise on the hydrography and water quality of the Weser estuary. They simulate one climate scenario using a 1-dimensional water quality and transport model. Plüß (2004) studies the effects of sea level rise on tidal dynamics in the Elbe estuary. He carries out simulations with different sea level rises using a 3D-hydrodynamic numerical model. His analysis concentrates on water levels. Zorndt and Schlurmann (2014) investigate the effects of sea level rise in the Weser estuary. They also use a 3D-hydrodynamic numerical model. Their analyses focus on changes of characteristic numbers of water level and salinity. Studies of climate change impacts in the Elbe, Jade-Weser, and Ems estuaries that focus specifically on the needs of navigation are not available.

Due to upstream sediment transport in many parts of the estuaries good sediment management strategies are needed to ensure safety and efficient navigation. Sediment transport strongly depends on tidal dynamics. Tidal dynamics, in turn, depend on water depth, among others. Hence the question arises how sea level rise, which increases the water depth, affects tidal dynamics and with it sediment transport. In this paper we investigate how sea level rise influences the tidal dynamics in the estuaries of Elbe, Jade-

Weser, and Ems. Using 3D-hydrodynamic numerical models we carry out different model simulations with and without sea level rise and compare important tidal characteristic numbers such as tidal high water levels, tidal low water levels, and the ratio of flood current velocity to ebb current velocity.

2 METHOD

For the simulation of hydrodynamic processes we use the hydrodynamic numerical model UnTRIM (Casulli and Walters 2000; Casulli and Lang 2004) in the version of UnTRIM2007 coupled with the morphological model SediMorph (Malcherek et al. 2005). UnTRIM is a semi-implicit finite difference model. It solves the three-dimensional shallow water equations and the transport equations of salt, heat, and suspended sediments on an unstructured orthogonal grid. SediMorph computes the sedimentological processes at the alluvial bed of the estuaries. We use it in a morphostatic mode.

For each estuary we apply an individually calibrated model. Figure 1 shows the model domains. The horizontal resolutions of the unstructured grids vary from a few metres to several hundreds of metres. At the seaward boundary we force the models with water levels and salinities extracted from a simulation with a North Sea model. The North Sea model is forced at the open boundary towards the North Atlantic by water levels composed of partial tides and constant salinities varying between 33 and 35 PSU along the boundary. For the period of simulation time we choose a period in summer 2006 which is characterised by low wind velocities and rather low fresh water discharges. We apply observed values for the freshwater discharge entering the estuaries at the weirs. In the Elbe estuary fresh water discharge varies between 250 m^3/s and 460 m^3/s, in the Weser estuary it ranges from 126 m^3/s to 159 m^3/s, and in the Ems estuary freshwater discharge lies between 25 m^3/s and 50 m^3/s in the period analysed. The length of the simulations is at least two spring neap cycles. For the analyses only the last spring neap cycle simulated (20 July 2006 till 3 August 2006) is used. Compared with climate simulations, which usually simulate several decades, our simulation time periods are rather short. These short simulation time periods are possible, because the modelled processes respond rapidly to changes of external drivers.

For each estuary we carry out two simulations. The first simulation without sea level rise represents today's state. The second simulation incorporates a sea level rise of 80 cm. This sea level rise is added as a constant value to the water levels at the North Atlantic boundary of the North Sea model. The value of 80 cm lies within the range of estimates for sea level rise in the North Sea up to the end of this century (Gönnert et al. 2009). The choice of 80 cm does not imply that this value is more likely than other values. It is well suited for our purpose of investigating the main processes involved when sea level rises.

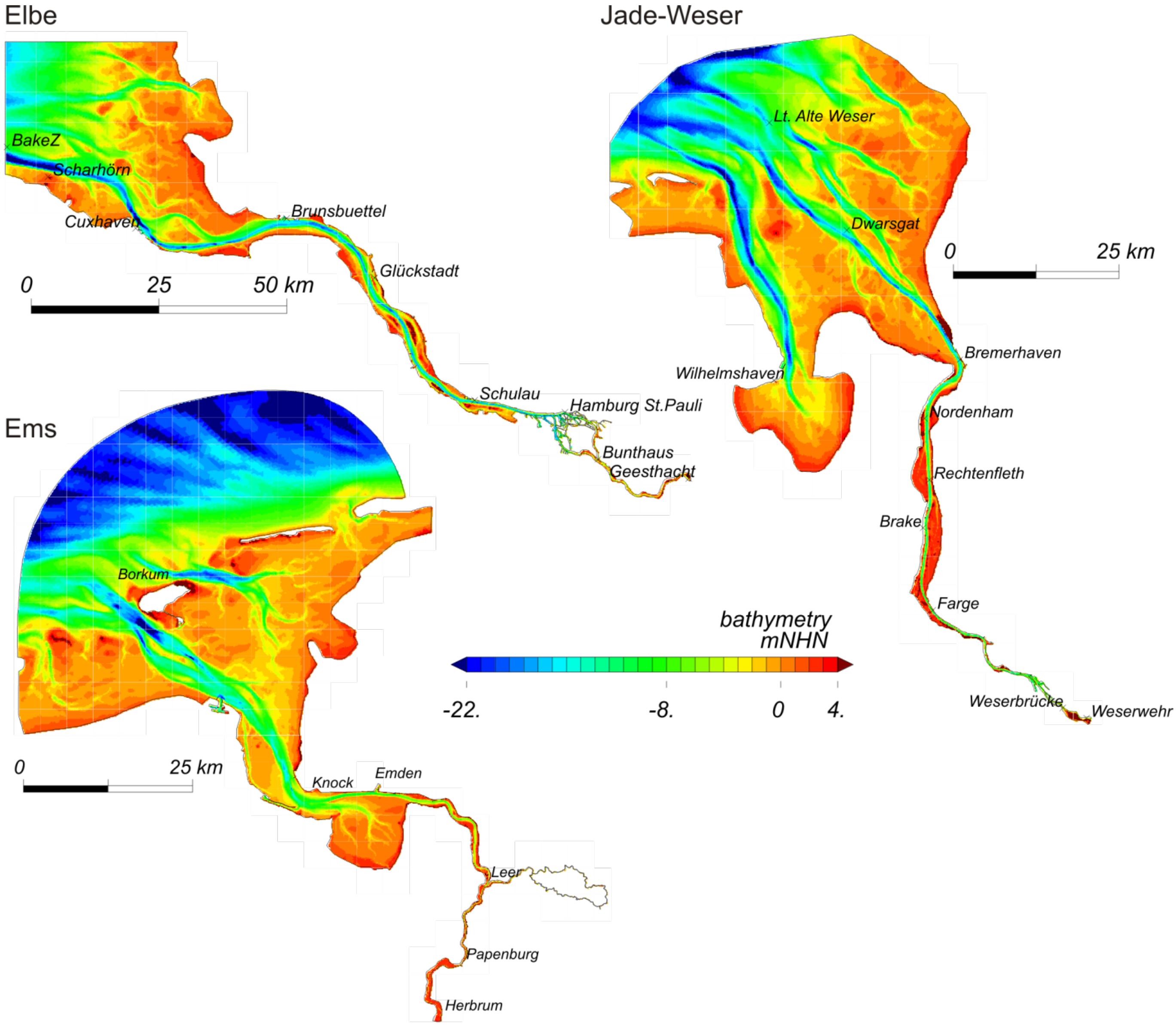

Figure 1. Domains of the 3D-hydrodynamic numerical models.

3 RESULTS

Figure 2 shows time series of the water level and the magnitude of the depth-averaged current velocity at three stations in the three estuaries. The water levels are generally increased due to sea level rise. The curves with sea level rise (dashed) are, however, not parallel translations to the curves without sea level rise (solid). The tidal curve is deformed. At the station Schulau (Elbe), for example, tidal high waters occur earlier in the simulations with sea level rise than in the simulation without sea level rise and high water levels rise more than low water levels.

Current velocities also change. Sea level rise affects current velocities differently at the station. At the stations Schulau (Elbe) and Brake (Weser) flood current velocities increase more strongly than ebb current velocities. This is associated with a shift of slack water times of flood current leading to a shortening of the flood current duration. At the station Papenburg (Ems) we see a different picture. Here, ebb current velocities increase more strongly than flood current velocities.

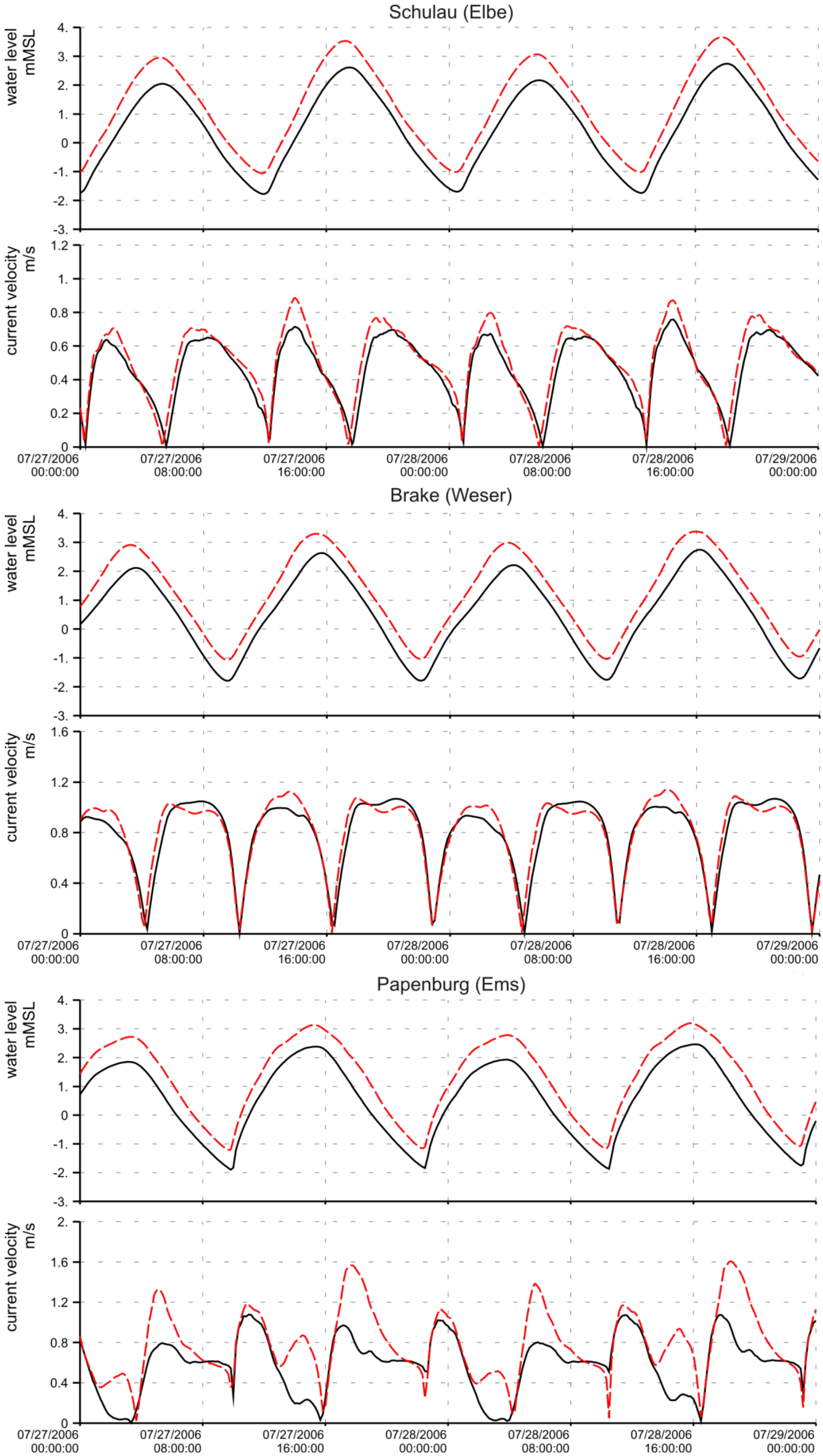

Figure 2. Time series of water level and the magnitude of the depth averaged current velocity at three stations. Solid: without sea level rise, dashed: with a sea level rise of 80 cm.

Figure 3 shows the changes in mean high water levels and mean low water levels due to sea level rise along the fairways of the three estuaries. If the changes were everywhere equal to 80 cm the increase in water levels would be equal to the imposed sea level rise. In most parts of the estuaries this is not the case. In many parts high water levels rise more than low water levels. Hence the tidal range is larger in the model simulations that include sea level rise.

Next, we look at the ratio of flood current velocity to ebb current velocity to estimate the potential impact on sediment transport in the estuaries. The ratio of flood current velocity to ebb current velocity plays a crucial role for the sediment transport. If the ratio is larger than 1 flood current velocity dominates indicating a net upstream transport of sediments. Figure 4 shows the ratio of the maximum flood current velocity to the maximum ebb current velocity in the simulations with and without sea level rise. In many parts of the estuaries flood current velocities increase more strongly than ebb current velocities. Thus the ratio of flood current velocity to ebb current velocity increases. Due to the larger ratio of flood current velocity to ebb current velocity more sediment is transported in the upstream direction. An exception is the upper part of the Lower Ems. The ratio of flood current velocity to ebb current velocity decreases. As seen from Figure 2 at the station Papenburg, ebb current velocities increase considerably in this part. The reason for this is the bathymetry of the Ems estuary. Upstream of Papenburg larger areas of river foreland are flooded in the simulation with sea level rise. During flood flow a larger volume is filled with water. During ebb flow this additional water leaves these areas through a bottleneck near Papenburg.

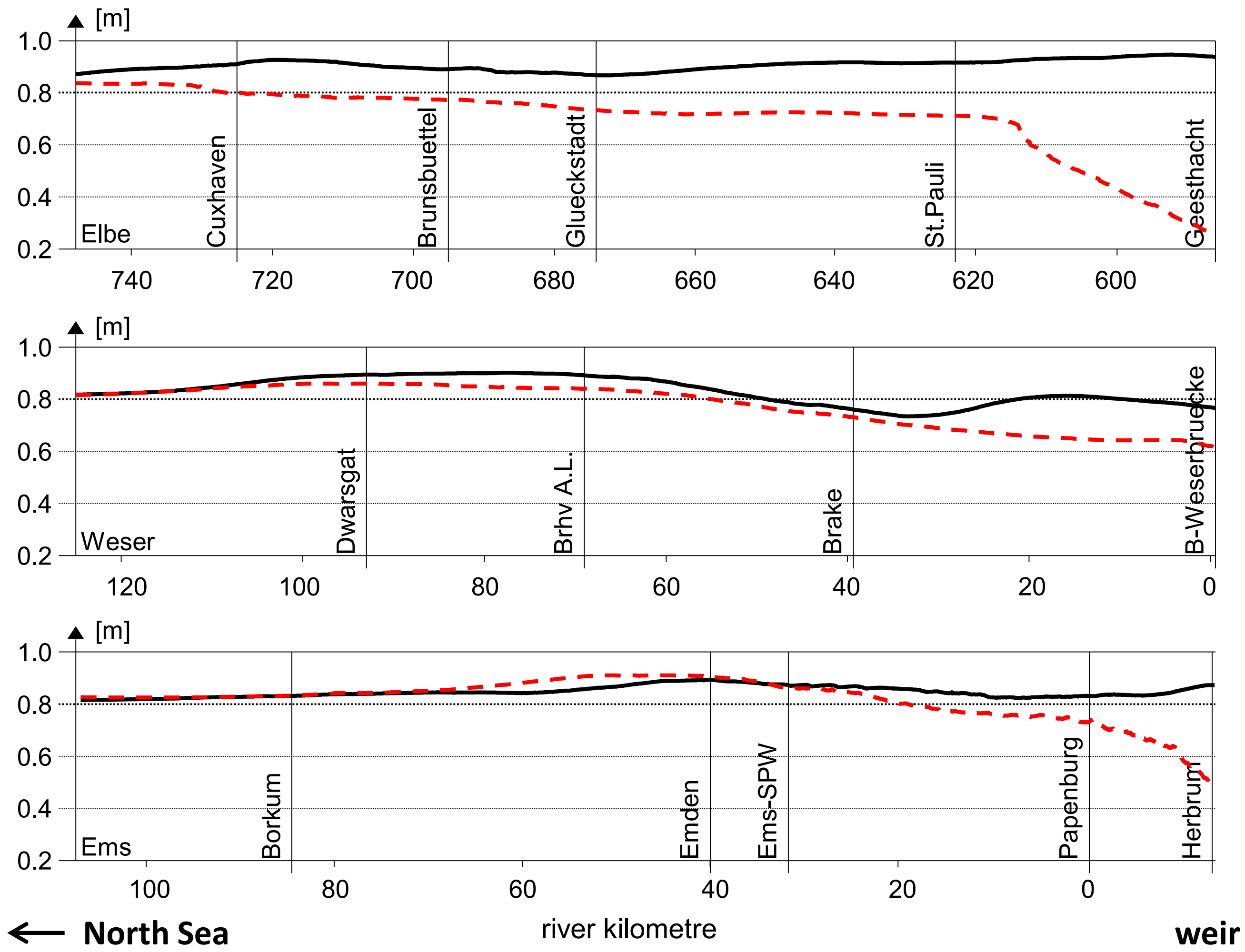

Figure 3. Change of mean high water levels (solid) and mean low water levels (dashed) due to a sea level rise of 80 cm along the fairways of the estuaries Elbe, Weser, and Ems.

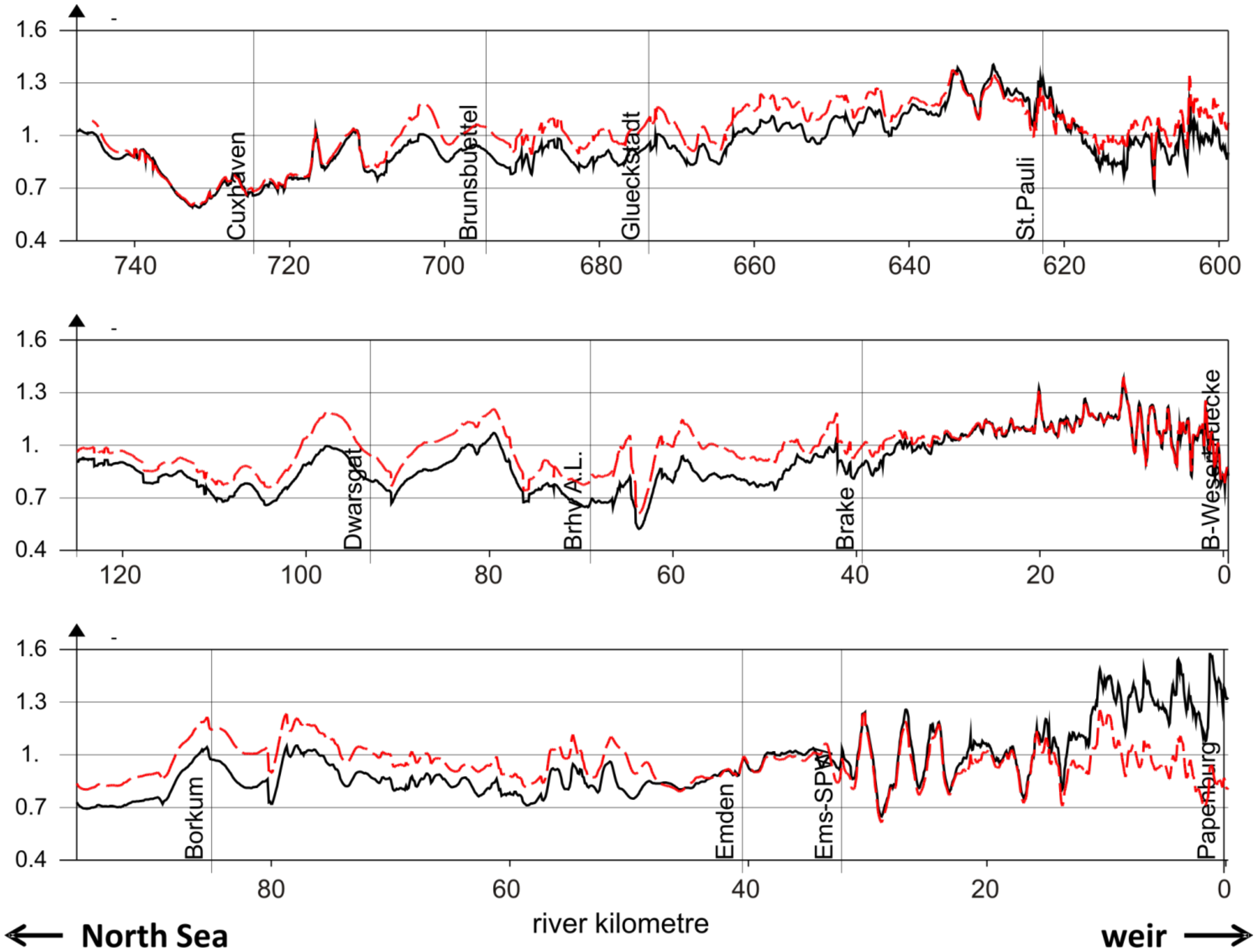

Figure 4. Ratio of the maximum flood current velocity to the maximum ebb current velocity along the fairways of the estuaries Elbe, Weser, and Ems. Solid: without sea level rise, dashed: with a sea level rise of 80 cm.

4 DISCUSSION AND CONCLUSION

In this paper we show how sea level rise changes tidal dynamics in the Elbe, Jade-Weser, and Ems estuaries. The detailed changes depend on the characteristics of each estuary. In general, all three estuaries show common features. In many parts of the estuaries we find an increased tidal range, which is consistent with the results of other studies (Plüß, 2004; Zorndt and Schlurmann, 2014). Furthermore, we see in our simulations a larger ratio of flood current velocity to ebb current velocity. This is an indicator for an increased upstream sediment transport due to sea level rise. To ensure safety and efficient navigation more dredging effort might be the consequence.

Since our simulations do not take account of morphodynamic changes, it is not clear how an increased upstream sediment transport could cause feedback processes. An increased upstream sediment transport can results in more deposition of sediments in the estuary. Based on the assumption of no additional dredging activities, more deposition would lead to shallower water depths. The water depth, in turn, influences tidal dynamics and thereby sediment transport. Long-term morphodynamic simulations will be needed in future studies in order to include the feedback processes connected with morphodynamic processes. The simulation of morphodynamic processes, however, is associated with a high degree of unvertainty. In particular, the simulation of long-term natural morphodynamic processes poses a challenge and need further development (Heyer, 2013).

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