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Investigating Climate Change Impacts and Adaptation Strategies in German Estuaries

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Summary

Due to sea level rise, estuaries are particularly affected by climate change. Besides sea level rise, changes in precipitation resulting in changing fresh water discharge and changes in storm activities can also have an impact on estuaries. 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. We need to know how climate change affects the estuaries in order to develop adaptation strategies. Generally, it is difficult to project climate change impacts on a local scale. The uncertainties involved can become very large. In this paper we describe an approach to determining the impacts of local climate change and to the investigation of adaptation measures without getting lost in the large range of uncertainty. First, we identify the main drivers which are assumed to be altered by climate change. In the next step we carry out sensitivity studies in which the main drivers are varied. For the sensitivity studies we use 3D-hydrodynamic numerical models. To test possible adaptation measures we repeat selected simulations which then include different adaptation measures. The results on local climate change impacts suggest that today's challenges are likely to become more acute. Higher salinities, increased upstream sediment transport, and higher water levels during storm surge must be expected. Adaptation measures can reduce these effects.

Keywords

hydrodynamic numerical model, uncertainties, sensitivity study, sea level rise, fresh water discharge, waterways, tidal dynamic, salt transport, sediment transport, storm surge

Zusammenfassung

Aufgrund des Meeresspiegelanstiegs sind Ästuare besonders durch den Klimawandel betroffen. Neben dem Meeresspiegelanstieg können auch Änderungen im Niederschlag, die den Oberwasserzufluss beeinflussen, und veränderte Sturmverhältnisse Auswirkungen auf die Ästuare haben. Die Ästuare Elbe, Jade-Weser und Ems werden als Wasserstraßen genutzt und bilden wichtige Ökosysteme. Voraussetzung für die Entwicklung von Anpassungsoptionen ist das Verständnis darüber, wie sich der Klimawandel auf die Ästuare auswirkt. Im Allgemeinen ist es schwierig die Folgen des Klimawandels auf lokaler Ebene abzuschätzen, da die Unsicherheiten groß werden können. In diesem Artikel beschreiben wir eine Herangehensweise, wie lokale Folgen des Klimawandels und Anpassungsoptionen trotz großer Unsicherheiten analysiert werden können. Im ersten Schritt identifizieren wir die Haupteinflussfaktoren, die voraussichtlich durch den Klimawandel beeinflusst werden. Anschließend führen wir Sensitivitätsstudien durch, in denen die Haupteinflussfaktoren variiert werden. Dafür verwenden wir 3D-hydrodynamisch-numerische Modelle. Um Anpassungsoptionen zu untersuchen, wiederholen wir ausgewählte Simulationen unter

Berücksichtigung verschiedener Anpassungsmaßnahmen. Die Ergebnisse zu den Folgen des Klimawandels deuten darauf hin, dass sich Herausforderungen, die schon heute bestehen, vergrößern werden. Es muss mit höheren Salzgehalten, einem verstärkten Transport von Sedimenten nach stromauf und höheren Sturmflutscheitelwasserständen gerechnet werden. Die untersuchten Anpassungsmaßnahmen zeigen, dass sie die Auswirkungen reduzieren können.

Schlagwörter

Hydrodynamisch-numerisches Modell, Unsicherheiten, Sensitivitätsstudien, Meeresspiegelanstieg, Oberwasserzufluss, Wasserstraße, Tidedynamik, Salztransport, Sedimenttransport, Sturmflut

Contents

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 important 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. Climate change may, for example, impact tidal dynamics, salt transport, transport of sediments, and extreme water levels in the event of storm surges.

To date, few studies have investigated the local impacts of climate change and adaptation strategies in the estuaries of Elbe, Jade-Weser or Ems. GRABEMANN et al. (2001) explore the impact of climate change 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 (see this volume). They also use a 3D-hydrodynamic numerical model. Their analyses focus on changes of characteristic numbers of water level and salinity. Other studies on climate change impacts and adaptation strategies in the German estuaries concentrate on storm surge protection (LIEBERMANN et al. 2005; GROSSMANN et al. 2006). Studies of climate change impacts in the Elbe, Jade-Weser, and Ems estuaries that focus specifically on the needs of navigation are not available.

Within the framework of the research project KLIWAS (Impacts of climate change on waterways and navigation - Searching for options of adaptation) we investigate potential climate change impacts on German estuaries and develop adaptation strategies with regard to the needs of navigation. The overall KLIWAS project considers both coastal and inland waterways in Germany. With a chain of models (e.g., global climate models, regional climate models, hydrological models, and hydrodynamic models) the global climate change signal is downscaled step by step to the local waterways.

The outcomes at the end of this downscaling process are in many cases difficult to interpret because the uncertainties attached to them are large. All models represent nature in a simplified way. Additionally, boundary conditions contain assumptions and are taken from other models or observations that do not represent nature in a perfect way either. For this reason the uncertainties become larger at each step of the downscaling process. At the end of the downscaling process the uncertainties attached to local climate change signals can be large (WILBY and DESSAI 2010; CARTER et al. 2007). Hence it is difficult to determine the local impacts of climate change on small regions such as estuaries.

LOWE et al. (2009) describe one way of dealing with these uncertainties. They develop adaptation strategies for storm surge protection in the Thames estuary in relation to sea level rise. A key idea of their approach is to define threshold levels of sea level rise up to which different adaptation strategies would work. Although they do not know how high sea level is rising, they prepare an adaptation plan for different potential scenarios. This adaptation plan must also include time horizons for planning and implementing the adaptation measures. KWADIJK et al. (2010) describe a similar approach. They introduce the concept of adaptation tipping points. Adaptation tipping points are points in time at which, in the face of climate change, existing measures will no longer be able to meet their objectives. The aim of applying the concept of adaptation tipping points is to determine the amount of climate change and rise in sea level an existing measure will be able to cope with. A sensitivity study is performed to identify adaptation tipping points.

We also carry out sensitivity studies. Whereas LOWE et al. (2009) and KWADIJK et al. (2010) mainly concentrate on the development of adaptation strategies, we combine the investigation of local impacts and the development of adaptation measures. This paper describes a method for using hydrodynamic numerical models to explore climate change impacts on small regions such as estuaries and for the development of adaptation strategies. We present the main findings of different sensitivity studies in the results section of this paper.

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 grid. SediMorph computes the sedimentological processes at the alluvial bed of the estuaries. We use it in a mode in which morphodynamic changes of water depths are not simulated. For each estuary we apply an individually calibrated model. The resolution in space and time, the size of the model domain, and the length of the time period simulated depend on the question focused on. The horizontal resolutions of the unstructured grids vary from a few metres to several hundreds of metres. The time periods simulated range from a few days to several months. 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.

To explore possible climate change impacts on the estuaries we carry out several sensitivity studies. In a first step we identify the main drivers that are presumably affected by climate change. The main drivers of the local system are the most important external parameters forcing the local processes. They affect the characteristics of water levels, current velocities, salt transport, and sediment transport. The main drivers are sea level and the tidal signal in the North Sea, fresh water discharge, and wind. The bathymetry of the estuary also determines the hydrodynamics, but future changes in bathymetry are difficult to estimate. Changes in bathymetry are inhomogeneous in space and determined by anthropogenic activities such as dredging and dumping of sediments as well as by natural processes. For this reason we keep the bathymetry constant. Sea level, fresh water discharge, and local wind are varied both separately and in combination. They are modified within the range of expected possible future climate values. Sea level is rising due to climate change. Long periods with little precipitation in the catchment area can result in long-lasting low fresh water discharge. On the other hand, extremely high precipitation can lead to very high fresh water discharge. Wind affects the estuary mainly during storm surges. Higher wind velocities would increase highest water levels.

A sensitivity study consists of the simulation of the reference state and of one or more scenarios in which the main drivers are varied. The comparison of the scenarios and the reference state reveals how water levels, currents, salinity, and sediment transports react to changed boundary conditions. Thresholds can be identified that cause increased vulnerability. In the next step we investigate the efficacy of different adaptation measures. We repeat selected simulations of the sensitivity studies. This time, however, we include adaptation measures in the numerical model (Fig. 1). This approach presents a direct way to test and compare the adaptation measures.

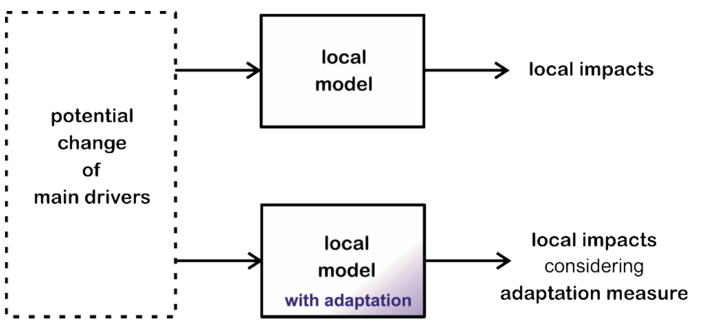

Figure 1: Schematic diagram of the investigation of local climate change impacts and adaptation measures, adapted from SEIFFERT et al. (2013).

3 Results of sensitivity studies

3.1 Local climate change impacts

In one of the sensitivity studies we vary sea level in the North Sea to investigate the impacts of sea level rise on tidal dynamics. We increase sea level in the North Sea by 80 cm. This value 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. A detailed description of the simulations carried out for this sensitivity study can be found in HOLZWARTH et al. (2011). The study shows that water levels in the interior of the estuaries do not just increase uniformly due to sea level rise. Tidal dynamics change. In most parts of the estuaries high water levels rise more than low water levels (Fig. 2). Thus the tidal range is larger in the model simulations that include sea level rise. The shape of the tidal curve is changed. Flood current velocities increase more strongly than ebb current velocities in many parts of the estuaries. There is an increase in the ratio of flood current velocity to ebb current velocity (Fig. 3). 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. In this part the ratio of flood current velocity to ebb current velocity decreases.

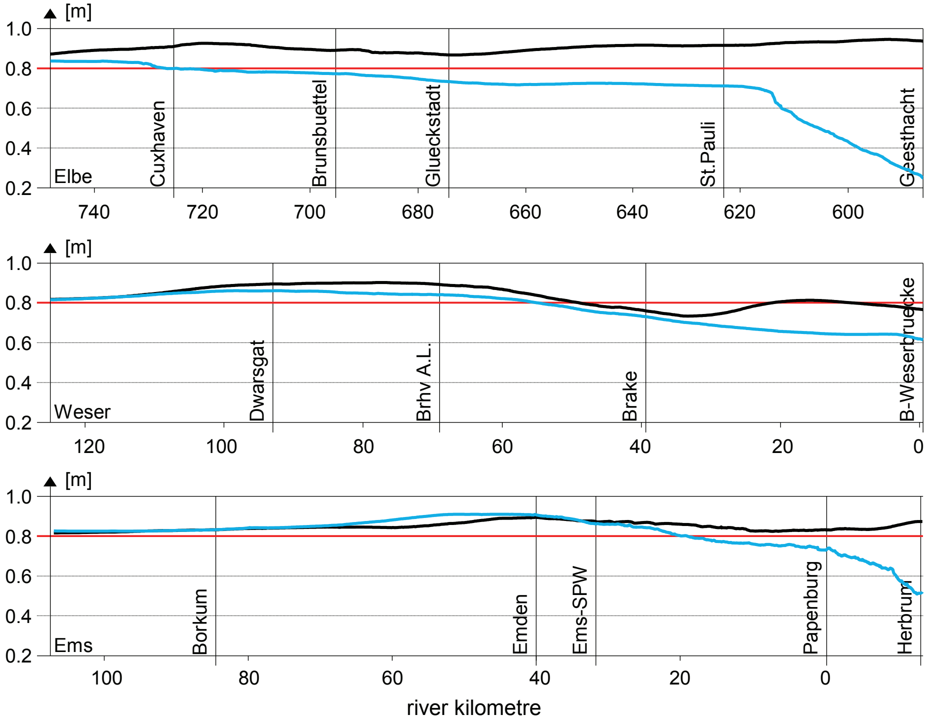

Figure 2: Change of mean high water levels (black) and mean low water levels (blue) due to a sea level rise of 80 cm along the fairways of the estuaries Elbe, Weser, and Ems.

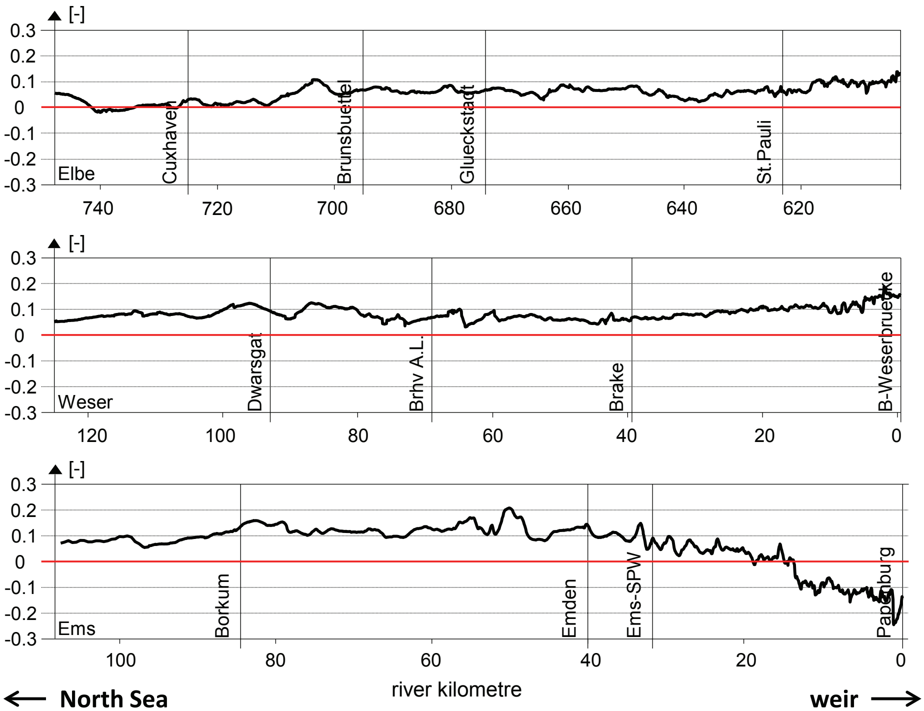

Figure 3: Change of the ratio flood current velocities (mean) to ebb current velocities (mean) due to a sea level rise of 80 cm along the fairways of the estuaries Elbe, Weser and Ems.

In another study we investigate the intrusion of salt into the estuaries in the event of long-lasting low fresh water discharge and sea level rise (SEIFFERT et al. 2012). Long-lasting low fresh water discharge is assumed, since periods with little precipitation in the catchment area can result in low fresh water discharge (NILSON et al. 2014). In different simulations with and without sea level rise fresh water discharge is held constant over several weeks, first at the mean measured freshwater discharge (MQ) and then at the mean of the lowest discharge measured per summer half-year (SoMNQ). The results of this study show that both low fresh water discharge and sea level rise generally lead to higher salinities in the inner estuary (Fig. 4). In comparison, long-lasting low fresh water discharge can have a much larger effect on salinities than a sea level rise of 80 cm. The combination of both results in the highest salinities. Changes in sea level and fresh water discharge, however, act and last on different time scales. Whereas fresh water discharge fluctuates on rather short time scales and leads to short term increases in salinity, mean sea level rises very slowly but leads to permanent changes.

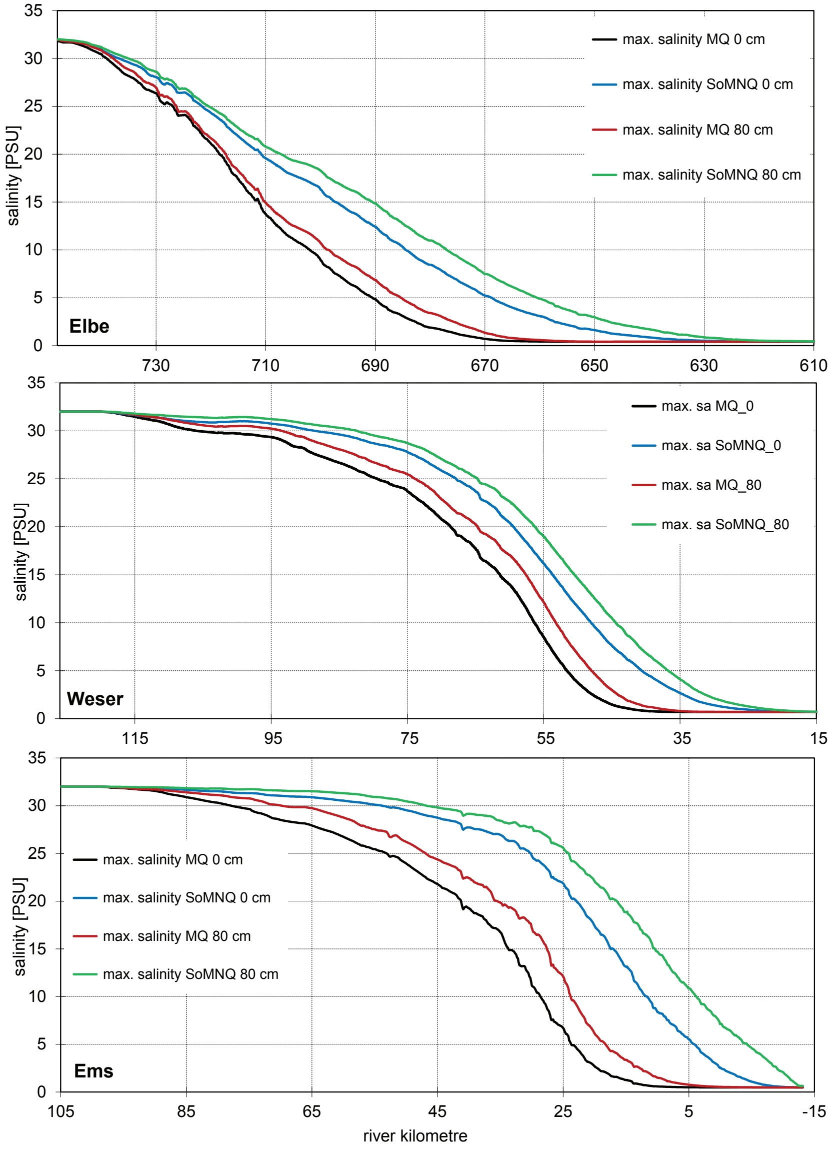

Figure 4: Maximum salinity (averaged over one spring-neap cycle) along the fairways. Black: mean fresh water discharge (MQ). Red: mean fresh water discharge and a sea level rise of 80 cm. Blue: low fresh water discharge (SoMNQ). Green: low fresh water discharge and a sea level rise of 80 cm.

The results of a sensitivity study on climate change impacts in the case of storm surges are shown in RUDOLPH (2014) in this volume. In this sensitivity study historical storm surges are simulated with different sea level rises, wind velocities, and high freshwater discharge. The study shows that the effects of sea level rise reach far into the interior of the estuaries. The highest water levels in the inner estuary are approximately increased by the sea level rise that is applied at the mouth of the estuary. Higher wind velocities would increase highest water levels, too. In the upper part of the estuary fresh water discharge dominates highest water levels.

3.2 Development of adaptation strategies

The sensitivity studies referred to above show that climate change is likely to amplify the challenges we are already facing today. Higher salinities, increased upstream sediment transport, and higher water levels during storm surge must be expected. The aim of investigating adaptation strategies is to check and improve existing measures as well as to develop new adaptation measures. An adaptation strategy can include different possibilities. With respect to the maintenance of waterways, for example, sediment management in the estuaries could be adapted. Hydraulic engineering structures are another potentially suitable adaptation response. We investigate exemplarily different measures.

In the Ems estuary a groundsill at the storm surge barrier near Gandersum is discussed. Numerical simulations suggest that a groundsill could decrease sediment import from the North Sea. This would then reduce the necessary dredging effort. Using the approach described above (Fig. 1) we test whether the groundsill would still work under climate change. We find that it is still effective when sea level rises and fresh water discharge is low (SEIFFERT et al. 2014).

Storm surge barriers provide protection against storm surges. Today the storm surge barrier in the Ems estuary near Gandersum protects the hinterland against the extreme water levels which occur during storm surge. To test how the storm surge barrier works under future climate conditions, we carry out a sensitivity study with different sea level rises and fresh water discharges (RUDOLPH et al. 2012). The results show that the barrier effectively protects the hinterland up to a certain level of sea level rise (Fig. 5).

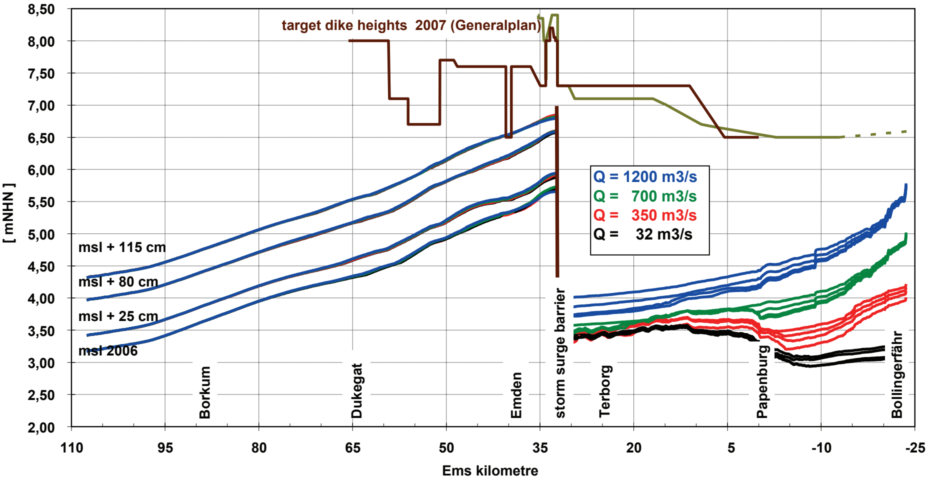

Figure 5: Highest water levels along the fairway of the Ems estuary for different mean sea level (msl) rises and fresh water discharges (Q). The storm surge barrier is closed when the water level reaches NHN +3.50 m at the barrier.

Similar to the barrier in the Ems estuary a storm surge barrier in the mouth of the Weser estuary can be an option. Our simulations with and without barrier and sea level rise show that a storm surge barrier near Bremerhaven would effectively protect the areas in the upstream direction of Bremerhaven (SEIFFERT et al. 2014). Sea level rise has no effect on water levels upstream of the barrier when the barrier is closed (Fig. 6). Coastal areas seaward of the barrier are still exposed to sea level rise. Additionally, the barrier itself can affect highest water levels on the seaward side. Depending on the closing time of the barrier a surge wave can be released. A surge wave develops if the closing time coincides with pronounced flood current velocities.

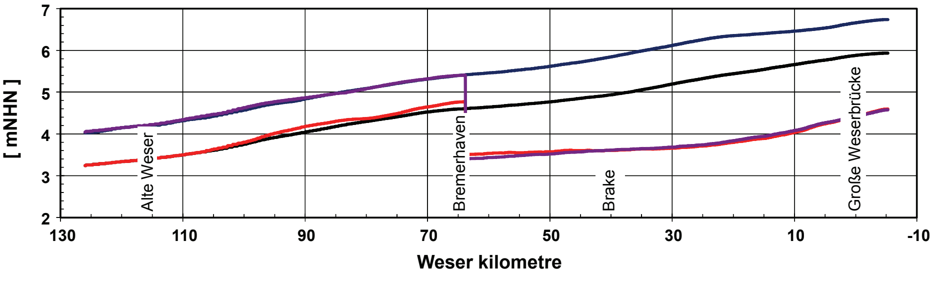

Figure 6: Highest water levels along the fairway of the Weser estuary of the simulated storm surge on 1 November 2006 (black), with 80 cm sea level rise (blue), with storm surge barrier (red), with 80 cm sea level rise and with storm surge barrier (purple).

Storm surge barriers completely block the entrance of estuaries during storm surges. Alternatively, measures could be taken to narrow the mouth of the estuary (SEIFFERT et al. 2014). This would dampen storm surges entering the estuary. Measures narrowing the mouth would have less impact on navigation. Furthermore they could also have positive effects on sediment transport under normal tidal conditions (KLÖPPER 2013). Fig. 7 shows two measures in the mouth of the Elbe estuary: an island located in the outer area of the mouth and a dam closer to the inner area of the mouth. The height of both measures is NHN +10 m.

Fig. 8 shows the results of simulations of the storm surge on 1 November 2006 with and without these two measures. The island has almost no effect on highest water levels. On the contrary, the dam reduces highest water levels along the whole estuary upstream of the measure by around 20 cm. The dam is more effective because the actual flow cross section is narrowed much more by the dam than it is by the island further out to sea. Generally, the more the measure narrows the cross section, the greater the reduction in highest water levels. Compared with a storm surge barrier, which blocks incoming storm surges completely, the dam only partly reduces the impact of sea level rise.

The measures also influence current velocities. In the area of the fairway near the dam current velocities are considerably increased. High current velocities can result in intensified erosion rates and affect navigation.

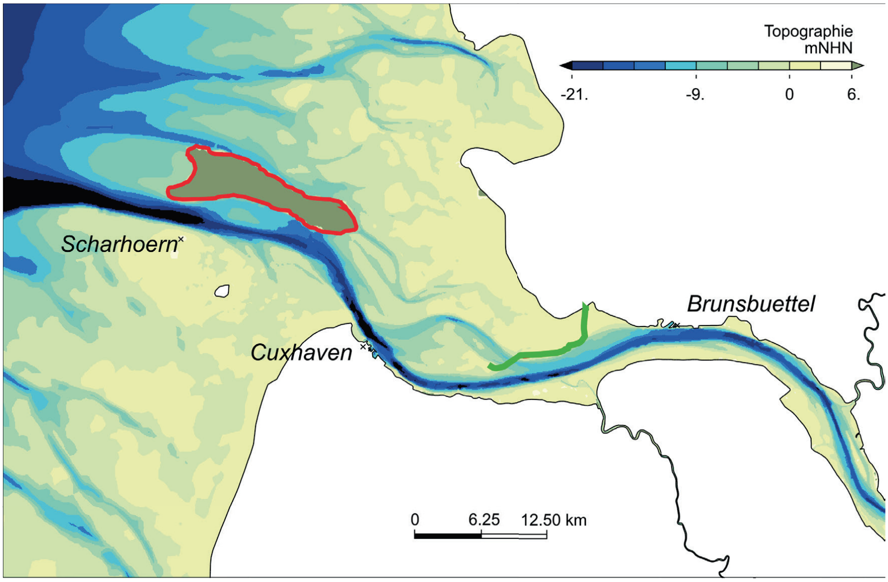

Figure 7: Mouth of the Elbe estuary with two different measures narrowing it: an island located in the outer area of the mouth (red) and a dam located closer to the inner area of the mouth (green).

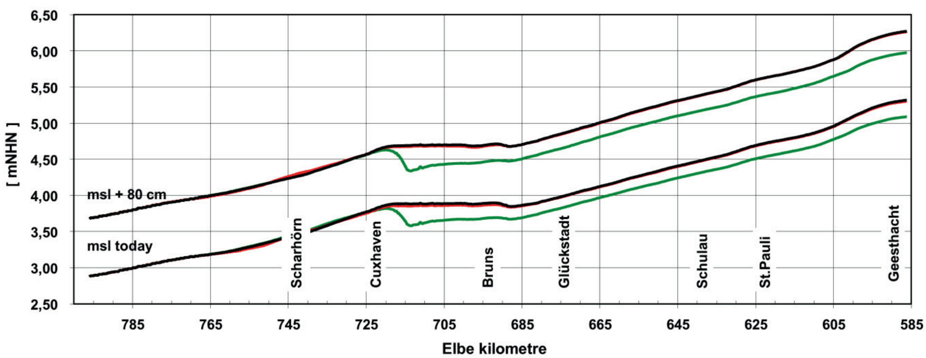

Figure 8: Highest water levels along the fairway of the Elbe estuary of the simulated storm surge on 1 November 2006 with and without sea level rise of 80 cm, black: no narrowing measures, red: with island, green: with dam.

4 Discussion and conclusions

In this paper we have shown how hydrodynamic numerical models can be used to investigate climate change impacts and adaptation strategies on a local scale. The challenge is to investigate climate change impacts in a specific local system without getting lost in the large range of uncertainties. Sensitivity studies help us to gain a better understanding of the processes involved. They produce clear if-then-statements which are easy to understand. Of course, uncertainties are not actually reduced by the formulation of if-then-statements. By definition, each if-then-statement is based on an assumption. Typically, no or little extra information about the likelihood of an assumption being correct is given. The probability of an assumption being correct is simply not known. For example, we do not know how far the sea level will have risen in the North Sea by the year 2100. Therefore, it is not possible to make a forecast, for example, about the increase of the tidal range by the value x at year 2100. Sensitivity studies reveal whether we should expect an increase or decrease and provide us with some idea about the order of magnitude of changes. Thus, it is not important what particular assumption we make for single simulations.

The length of numerical simulations carried out can be kept short since estuarine processes respond rapidly to changes in external conditions. The response time of morphodynamic processes is an exception. The simulation of long-term morphodynamic processes, however, is associated with a high degree of uncertainty. The models require further development in order to produce feasible results. This is one reason why we keep the bathymetry static in all simulations. This does mean, however, that we do not take account of the feedback processes connected to morphodynamic processes. For example, the sensitivity study that explores the effects of sea level rise implies an increased transport of sediments from the North Sea into the estuaries due to sea level rise. This means more sediment is deposited in the estuaries. To ensure safety and efficient navigation more dredging effort might be the consequence. Based on the assumption of no 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 associated with morphodynamic processes.

The adaptation measures presented in this paper are first suggestions about what such measures could be and how they can be tested using hydrodynamic numerical models and sensitivity studies. The results of this study lay the groundwork for further investigations. Such further investigations should not only include optimisation with regard to hydraulic effectiveness but should also consider impacts on other sectors, e.g. ecology. Generally, preference should be given to the development of cross-sectoral adaptation strategies. However, impacts on other sectors must be investigated and taken into account at the very latest as soon as serious consideration is given to applying an adaptation measure.

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