Conference Paper, Published Version

Seiffert, Rita; Hesser, Fred; Schulte-Rentrop, Annette; Seiß, Guntram

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10th International Conference on Hydroinformatics
HIC 2012, Hamburg, GERMANY

POTENTIAL EFFECTS OF CLIMATE CHANGE ON THE BRACKISH WATER ZONE IN GERMAN ESTUARIES

RITA SEIFFERT, FRED B. HESSER, ANNETTE SCHULTE-RENTROP, GUNTRAM SEIß

Hydraulic Engineering in Coastal Areas, Federal Waterways Engineering and Research Institute, Wedeler Landstr. 157, 22559 Hamburg, Germany

For the development of adaptation strategies we need to know how future climate change will affect hydrodynamic conditions in German estuaries. Climate change will have an impact on several parameters influencing the hydrodynamic conditions. Two important parameters are the freshwater discharge into the estuary and the mean sea level in the North Sea. Both parameters have a direct effect on the brackish water zone (region where sea water and fresh water mix). The aim of this study is to investigate how the position of the brackish water zone depends on the amount of freshwater discharge and sea level rise. We focus on the three main German estuaries Elbe, Weser and Ems. Using a 3D hydrodynamic numerical model we calculate water level, current and salt transport in several model simulations with different input parameters. In particular, we force the model with a low constant freshwater input at the weir and with a sea level rise of 80 cm in the North Sea. The analyses show that the brackish water zone is shifted by several kilometres in upstream direction if the freshwater discharge is low for a long period of time. The increase in sea level also results in a shift of the brackish water zone in upstream direction.

INTRODUCTION

Due to increasing atmospheric greenhouse gas concentrations climate will change. The results of the 4th Assessment Report of the International Panel on Climate Change (IPCC) suggest an increase of the globally averaged surface temperature for the next decades (IPCC [1]). Even if the greenhouse gas concentrations would be kept constant from today on a climate change could not be prevented. For the development of adaptation strategies we need to know how future climate will affect us. In this study we focus on the impacts of climate change on the hydrodynamics and the transport of salt in the three largest German estuaries Elbe, Weser and Ems.

In particular, we analyse how the position of the brackish water zone is affected in these estuaries. The term ‘brackish water zone’ denotes the region where saline sea water and fresh river water mix. Generally, it is characterised by a steep longitudinal gradient of salinity. The brackish water zone plays an important role for the ecosystem and the utilisation of the estuaries, e.g., agriculture, groundwater management and maintenance of coastal waterways.

The position of the brackish water zone depends to a large extent on the incoming tidal signal at the mouth of the estuary and the freshwater discharge at the weir. Both, the tidal signal and the freshwater discharge, are expected to change due to climate change.

According to IPCC [1] (Chapter 11: Regional Climate Projections) in southern and central Europe the risk of droughts is expected to rise. In the future long periods of little precipitation could lead to long periods with low freshwater discharge. Holzwarth et al. [2] show that a sea level rise at the boundary of the North Sea leads to changes in the tidal dynamics of the estuaries. For the Weser estuary Grabemann et al. [3] investigated the effects of a specific climate scenario with a mean sea level rise of 55 cm and a change in tidal range (+30 cm) for the year 2050. They found an average shift of the brackish water zone in upstream direction of about 2 km. How exactly low freshwater, sea level rise and the combination of both influence the position of the brackish water zone in Elbe, Weser and Ems is not clear and has not been comprehensively investigated.

The purpose of this paper is to systematically address the question of how possible future low freshwater discharge and sea level rise affect the position of the brackish water zone. Within a well-defined model-setup we are able to investigate the reaction of the estuaries to changed external conditions.

METHOD

Study region

The three estuaries Elbe, Weser and Ems are located in the German Bight in the North Sea. The hydrodynamic conditions in all three estuaries are strongly characterised by the tides entering the estuaries at the seaward boundary and by the freshwater discharge entering the estuaries at the weir. Table 1 lists the mean characteristic discharges at the respective gauging stations. The maximum tidal range inside the estuaries lies in the order of 3 - 4 m.

Table 1: Discharge characteristics of the three estuaries according to the hydrological yearbooks.

	Elbe Neu Darchau (1926-2006)	Weser Intschede (1941-2006)	Ems Versen (1941–2005)
MHQ (mean of highest discharge per year) [m³/s]	1940	1230	373
MQ (mean discharge) [m³/s]	710	325	80
MNQ (mean of lowest discharge per year) [m³/s]	277	117	16
SoMNQ (mean of lowest discharge per summer half-year) [m³/s]	304	127	16

Numerical model and model simulations

We use the hydrodynamic numerical model UnTRIM (Casulli and Walters [4]). This semi-implicit finite difference model solves the three-dimensional shallow water equations on an unstructured grid. At the Federal Waterways Engineering and Research Institute (BAW)

UnTRIM is frequently used in project-related studies for the preparation of expert reports for planning maintenance and upgrading work of German coastal waterways (e.g., BAW [5]).

Using UnTRIM we carried out four different simulations for each estuary: MQ_0, SoMNQ_0, MQ_80, and SoMNQ_80. First we generated a reference state (MQ_0) that represents today's conditions in an idealised way. At the seaward boundary we force the model with water levels extracted from a simulation with a North Sea model. The North Sea model was driven by the astronomic tidal signal during two spring neap cycles in the period 7 July 2006 till 4 August 2006 (period of simulation time). No external surge and no wind stress are included in the model simulations. Salinity at the seaward boundary is prescribed to the constant value of 32 PSU. The freshwater discharge at the weir is set constant to the mean measured freshwater discharge MQ (Table 1). To be independent of initial conditions the model simulation is repeated in loops over several periods of simulation time until the hydrodynamic conditions and the brackish water zone have reached a state of equilibrium.

To better understand the dependence of the salinity distribution on the freshwater discharge we carried out the model simulation SoMNQ_0. This simulation is identical to MQ_0 except that it is forced with the low freshwater discharge SoMNQ (mean of the lowest discharge measured per summer half-year) of each estuary. SoMNQ_0 starts from the state of equilibrium found in MQ_0.

To consider the effects of a possible sea level rise in the German Bight we carried out two more simulations in the same manner as described above but with an increase in sea level by 80 cm. The value of 80 cm lies within the range of sea level rise projected until 2100 for the North Sea (Gönnert et al. [6]). The sea level rise is added as a constant value to the mean water level at the boundaries of the North Sea model. First, the simulation MQ_80 with mean freshwater discharge is carried out. Second, the freshwater discharge is set to SoMNQ in the simulation SoMNQ_80. SoMNQ_80 starts from the state of equilibrium found in MQ_80.

RESULTS

Figure 1 illustrates the reference state in all three estuaries. Shown is the mean salinity per tide averaged over the last spring neap cycle of MQ_0. All estuaries are characterised by a well developed brackish water zone. Salinity decreases in upstream direction from values around 32 to values near zero.

The mean position of the brackish water zone depends mainly on two competing mechanisms. Through turbulent mixing mostly caused by tides but also, e.g. by wind, saline sea water penetrates from the mouth of the estuary further into the estuary. On the other hand the freshwater discharge flushes the saline water in downstream direction back towards the sea (Savenije [7]). In nature there are rarely times in which both mechanisms remain steady long enough to reach a state of equilibrium.

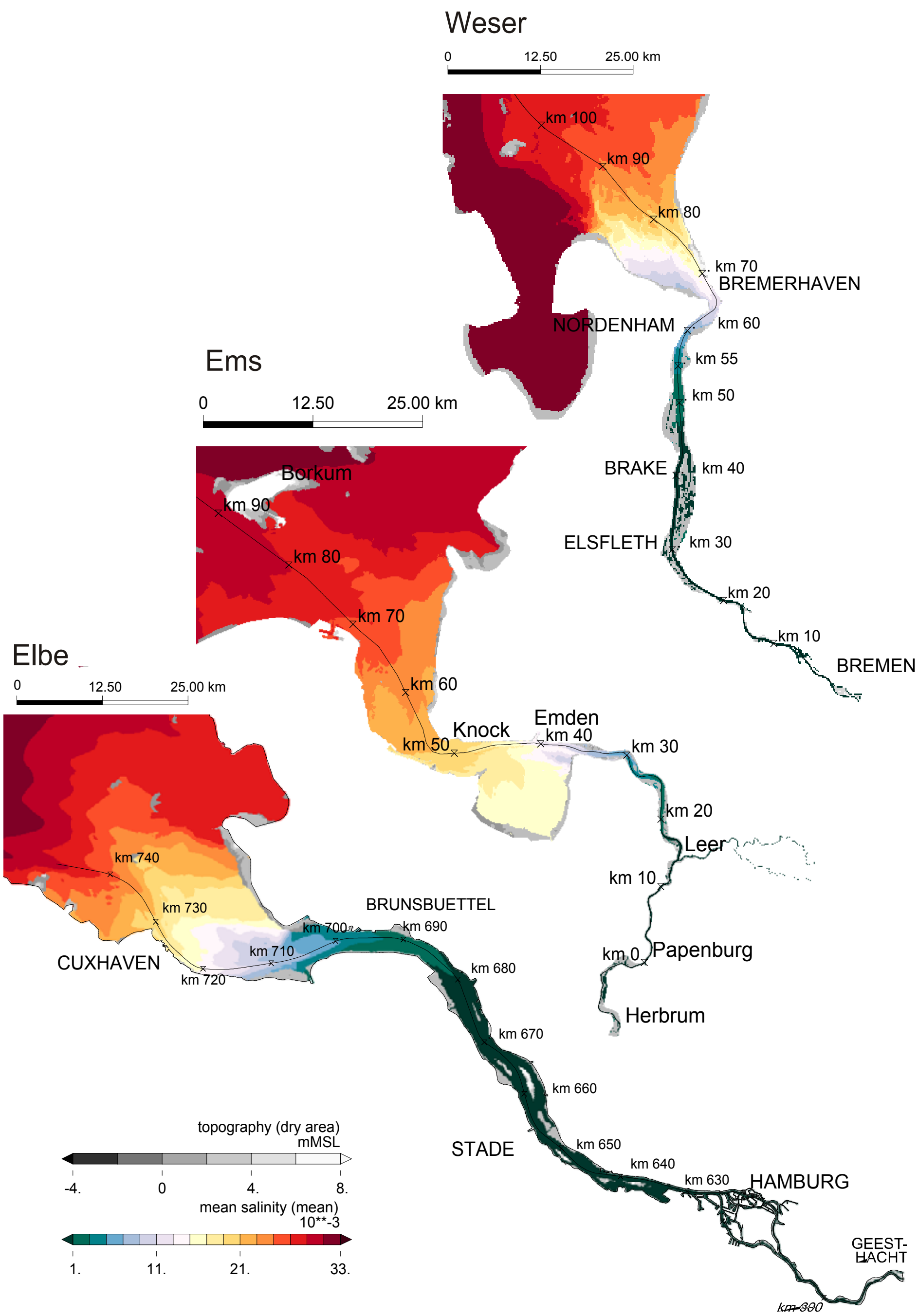

Figure 1: Mean salinity per tide averaged over the last spring neap cycle of the model simulation MQ_0. The black line marked with kilometre information depicts the fairway.

In our model simulations we control the relevant parameters (i.e., constant freshwater discharge, constant mean tide water, no wind). Figure 2 shows how the brackish water zone responds to a decreased freshwater discharge. Shown are time series of salinity at three locations within the Weser fairway of the simulation SoMNQ_0. Due to the low freshwater discharge mixing processes dominate pushing more salt into the estuary. At all three locations salinity first increases rapidly and then more slowly until reaching a maximum level. Even though the freshwater discharge remains at the low value of SoMNQ the brackish water zone stops penetrating further into the estuary. After a certain time the system reaches a new state of equilibrium. The time horizon until the system is equilibrated differs from estuary to estuary. In the Weser estuary it takes only about 30 d until the mean salinity does not increase further. In the Elbe the system is equilibrated after about 50 d (not shown). The Ems estuary needs longest. Even after 80 d the salinity in the fairway near Emden is still slightly increasing (not shown).

The position and extension of the brackish water zone in the equilibrated system is shown in Figure 3. For all four model simulations mean salinity per tide as well as maximum salinity per tide are displayed. All values are averages over the last spring neap cycle of the simulations. Thus we can assume that the values represent the state of equilibrium in each simulation. This Figure illustrates how far the brackish water zone penetrates in upstream direction when the freshwater discharge is for a long time low (blue lines) in comparison to the simulation with mean freshwater discharge (black lines). For numbers (in kilometres) of the shift of the 1 PSU- and 10 PSU-isohaline see Table 2.

Figure 3 and Table 2 show also the results for the two simulations, MQ_80 and SoMNQ_80, with a sea level rise of 80 cm. The rise of sea level leads also to a shift of the brackish water zone in upstream direction. The reason are changes in mixing processes

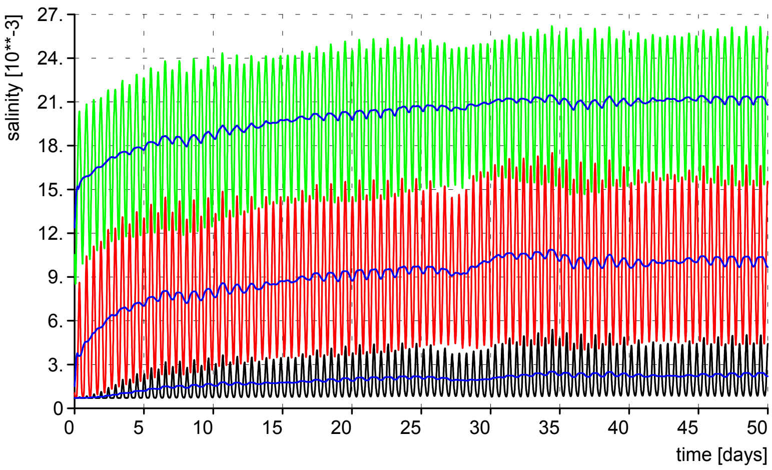

Figure 2: Time series of salinity in the Weser fairway at km 40 (black), km 55 (red) and km 70 (green) of the model simulation SoMNQ_0. The blue lines show the moving average over the period of 12.42 h (that is the period of M_2).

caused by tides. The sea level rise influences the tidal dynamics. It raises the mean tide water and alters the form of the tidal curve (Holzwarth et al. [2]). Due to the raise of mean water the flood volume increases. More saline sea water is mixed into the estuary. The ratio of saline water to fresh water in the estuary is increased.

Note that in all three estuaries the shift of the brackish water zone due to sea level rise in MQ_80 (red lines) is less than the shift caused by long-lasting low freshwater discharge in SoMNQ_0 (blue lines). The combination of both, sea level rise and low freshwater discharge, leads to the highest values of salinity in the estuaries. In the Ems estuary in this extreme scenario the brackish water zone extends almost up to the weir near Herbrum, where the model domain ends. The effects of low freshwater discharge and sea level rise seem to add linearly in the Weser estuary. However, this is not the case in the other two estuaries. The shift of, e.g., the 10 PSU-isohaline from MQ_80 to SoMNQ_80 is larger than the shift from MQ_0 to SoMNQ_0 in Elbe and Ems.

Table 2: Shift of the 10 PSU- and 1 PSU-isohaline of the mean salinity (first number) and the maximum salinity (second number).

	Elbe shift of [km]		Weser shift of [km]		Ems shift of [km]	
	10 PSU	1 PSU	10 PSU	1 PSU	10 PSU	1 PSU
MQ_0 → SoMNQ_0	17 / 18	31 / 31	9 / 8	15 / 16	17 / 17	20 / 19
MQ_0 → MQ_80	3 / 6	7 / 6	3 / 3	4 / 5	4 / 5	6 / 7
MQ_0 → SoMNQ_80	23 / 25	41 / 41	12 / 12	19 / 20	24 / 25	28 / 26
MQ_80 → SoMNQ_80	20 / 21	34 / 35	9 / 9	15 / 15	20 / 20	22 / 19

DISCUSSION AND CONCLUSIONS

In this study we have investigated how the position of the brackish water zone changes when freshwater discharge is low for a very long period of time and sea level rises. Both scenarios and the combination of them could occur as a consequence of climate change. We carried out this study within an idealised framework. In nature, the estuaries, e.g., rarely experience a freshwater discharge of MQ for a very long time. Despite the idealised character our results can act as a basis for further research and for the development of adaptation strategies.

The time frame in which the estuaries adjust to the change in freshwater discharge (Figure 2) is of interest for potential adaptation strategies. It is valuable to know that even if we experience a very long dry period, i.e., the freshwater discharge is low for a very long period of time, the brackish water zone is not moving further and further in upstream direction. After a certain time the salinity stops to increase. The system reaches a new state of equilibrium. For the development of adaptation strategies this result implies, we can focus on worst-case scenarios represented by the new states of equilibrium.

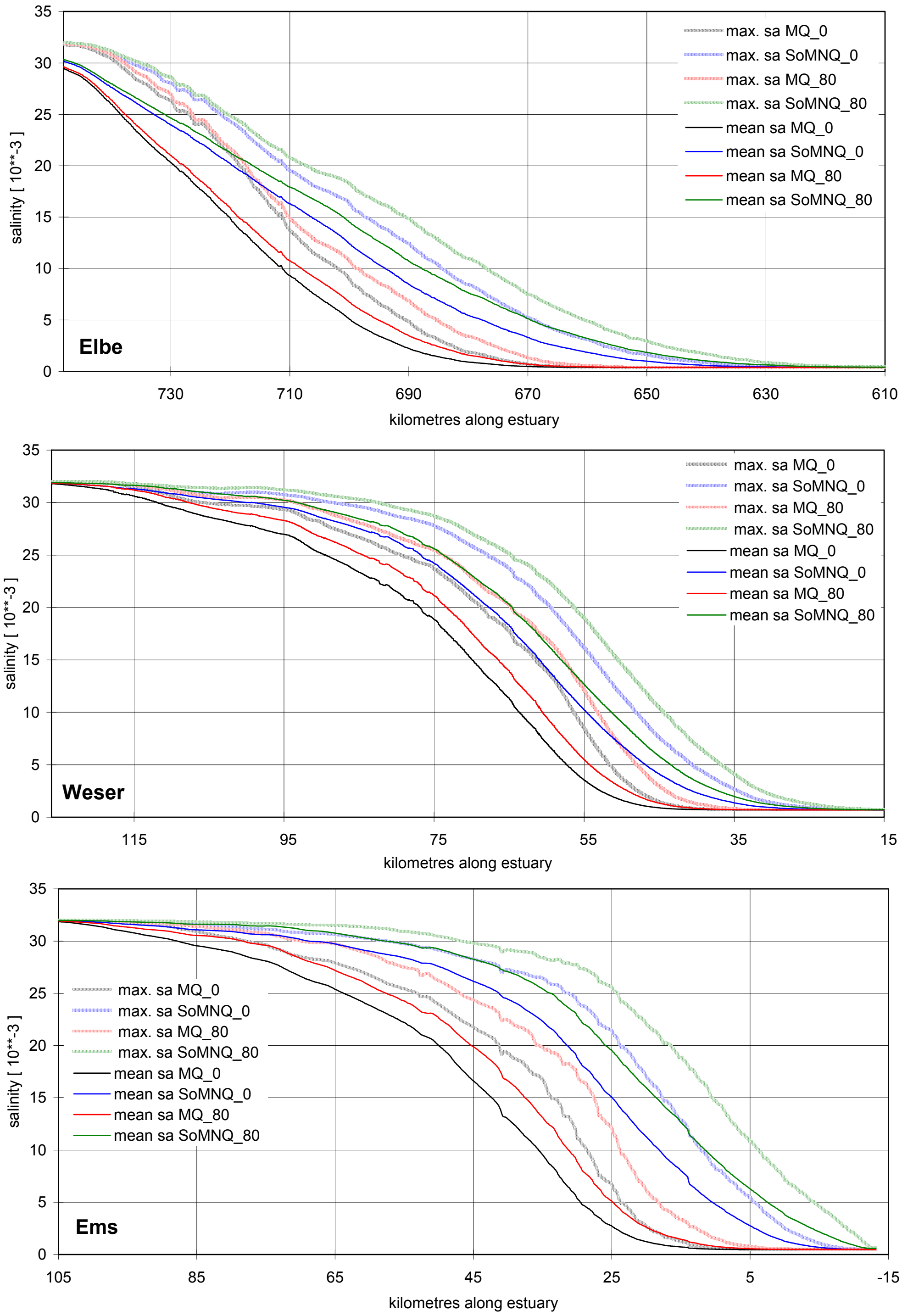

Figure 3: Salinity along the longitudinal profile defined by the fairway. The position of the fairway is marked in Figure 1.

It seems that in the near future sea level rise has not such a large effect on the brackish water zone. In comparison to the model simulation with low freshwater discharge the shift of the brackish water zone caused by a mean sea level rise of 80 cm is much smaller (Figure 3). Furthermore the rise of sea level is a rather slow process. The value of 80 cm is an estimation for the year 2100. The changes due to sea level rise will, however, be continuous and permanent. In contrast the variation of freshwater discharge is larger and much faster. Effects caused by varying freshwater discharge will have a discontinuous and temporary character.

ACKNOWLEDGMENTS

We thank Frank Kösters for providing the North Sea data of simulations he carried out within the KFKI-Project AufMod. We thank Ingrid Holzwarth, Elisabeth Rudolph and Norbert Winkel for useful discussions. This study has been carried out within the research programme 'KLIWAS-Impact of climate change on waterways and navigation' and KLIMZUG-Nord 'Regional strategies concerning climate changes in the metropolitan area of Hamburg'. KLIWAS is financed by the German Federal Ministry of Transport, Building and Urban Development; KLIMZUG-Nord is supported by the German Federal Ministry of Education and Research, the city of Hamburg and the metropolitan area of Hamburg.

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