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Storm Surges in the Elbe, Jade-Weser and Ems Estuaries

Elisabeth Rudolph

Summary

Storm surges in the estuaries along the German Bight of Elbe, Jade-Weser and Ems may cause severe damages and endanger the life of the inhabitants of these coastal areas. The results of a sensitivity study are analysed in order to arrive at a better understanding of the importance of the processes modifying the height of a storm surge along an estuary. Hydrodynamic-numerical models can be used to carry out separate investigations on the impact of the wind over the estuary, the sea level rise at the mouth of the estuary and the fresh water discharge into the estuary. Wind, fresh water discharge and sea level rise are varied systematically, in line with today's knowledge, within the range of expected changes in future climates. The results of this sensitivity study show a bandwidth of possible changes in water levels during storm surge. This study enables vulnerabilities along the estuaries due to climate change to be identified and adaptation strategies to be developed.

Keywords

Storm surge, storm surge scenario, hydrodynamic numerical model, estuary, sensitivity study, wind, sea level rise, fresh water discharge

Zusammenfassung

Sturmfluten in den Ästuaren von Elbe, Jade-Weser und Ems können große Schäden verursachen und das Leben der Bewohner dieser Küstengebiete gefährden. Um ein besseres Verständnis für die Bedeutung der Prozesse zu bekommen, die die Höhe einer Sturmflut entlang des Ästuars beeinflussen, werden die Ergebnisse einer Sensitivitätsstudie analysiert. Durch den Einsatz hydrodynamischer numerischer Modelle der Ästuare können die Auswirkungen des Windes über dem Ästuar, eines Meeresspiegelanstieges in der Mündung des Ästuars und einer Zunahme des Oberwasserzuflusses in das Ästuar getrennt untersucht werden. Wind, Abfluss und Meeresspiegelanstieg werden auf der Grundlage des heutigen Wissens über die möglichen Auswirkungen des Klimawandels systematisch verändert. Die Ergebnisse der Sensitivitätsstudie geben einen Hinweis auf die mögliche Bandbreite der durch den Klimawandel hervorgerufenen Veränderungen der Sturmflutabschwellwasserstände, ermöglichen Vulnerabilitäten zu identifizieren und Anpassungsmaßnahmen zu entwickeln.

Schlagwörter

Sturmflut, Sturmflutszenario, hydrodynamisch numerisches Modell, Ästuar, Sensitivitätsstudie, Wind, Meeresspiegelanstieg, Oberwasserzufluss

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1 Introduction

Numerical models of estuaries have been used for different purposes. OPTTEL showed that hydrodynamic-numerical models of the Elbe estuary can be used to produce a reliable forecast of water level, current velocity and salinity under ordinary and under storm surge conditions (BORK and MÜLLER-NAVARRA 2012; KREMP et al. 2012). In MUSE numerical models were used amongst others to hindcast historical storm surges in order to investigate what a historic storm surge would look like in today's topography (MÜLLER-NAVARRA et al. 2006). Hydrodynamic numerical models of estuaries can be useful in investigating the importance of the processes causing or modifying storm surges in estuaries.

Autumn and winter storms over the North Sea may cause storm surges in the estuaries in the German Bight of Elbe, Jade-Weser and Ems. Storm surges in these estuaries are not only influenced by the tidal dynamics and the wind set up in the German Bight, but also by processes in the actual estuaries, which reach up to 100 km into the North German Plain. Local wind effects over the estuaries, the bathymetry i.e. the flood plains connected to the estuary or the fresh water discharge into the estuary also influence water levels during storm surge.

Climate change may alter the bandwidth of values of these parameters. A sensitivity study is performed to investigate the influence of wind, fresh water discharge und sea level rise on the highest water levels during storm surge. Numerical models of the Elbe, Jade-Weser and Ems estuaries enable the impact of each process to be investigated separately. Wind, fresh water discharge and sea level rise are varied systematically in line with today's knowledge of expected changes in future climates.

The Elbe, Jade-Weser and Ems estuaries host the waterways to the ports of Hamburg (Elbe), Bremerhaven (Weser), Bremen (Weser) or Emden (Ems). As storm surges may cause severe damages along an estuary and endanger the life of the inhabitants of coastal areas, it is important to understand the processes that modify a storm surge along an estuary. This understanding can help in the development of adaptation measures to improve e.g. shore protection along the estuaries today and in times of climate change (SCHULTE-RENTROP and RUDOLPH 2012; SEIFFERT and HESSER 2014).

2 Numerical modelling of storm surges

The hydrodynamic numerical model UnTRIM (CASULLI and LANG 2004; CASULLI and WALTERS 2000) is used for the investigation presented here. UnTRIM is a 3-dimensional finite difference model. It solves the shallow water equations and the transport equations of salt on an unstructured orthogonal grid. UnTRIM is an adequate tool for applications in geometrical complex estuaries with large periodically wetting and drying tidal flats.

The models of the estuaries use bathymetries measured in 2003 (Elbe and Jade-Weser) and 2006 (Ems). The model domain covers the area of the estuary influenced by storm surges. During storm surges the weirs at Geesthacht (Elbe), Hemelingen (Weser) and Herbrum (Ems) are lowered. This means that the influence of the storm surge is also apparent in the riverine part of the Elbe, Weser and Ems. Fig. 1 shows a schematic map of the area. For the study presented here it is assumed that the storm surge barrier in the Ems at Gandersum is not in use (results of simulations with an operated barrier are shown in SEIFFERT and HESSER (2014)).

The model is forced at the boundaries with fresh water discharge at the upstream end of the estuary, with water level and salinity at the seaward open boundary and with wind over the estuary during the periods of interest. For the reference scenario (“today”) the wind fields are provided by the German Meteorological Agency (DWD), the water level at the boundary to the North Sea is generated from measurements and the measured fresh water discharge is used. The models of the estuaries will provide time series of e.g. water levels and current velocities at each grid point. For each estuary an individually calibrated model is used.

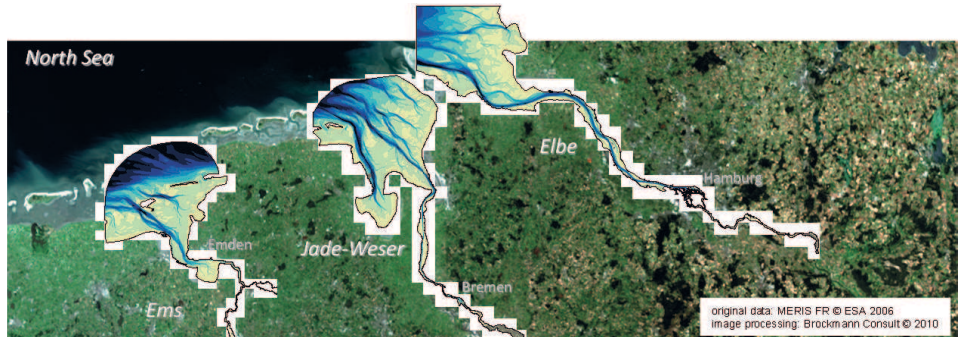


Figure 1: Schematic picture of the modelled area of the estuaries of Ems, Jade-Weser and Elbe in the German Bight. The distance from Cuxhaven at the mouth of the Elbe to Hamburg is about 100 km.

3 Sensitivity study

The height of a storm surge in an estuary is determined by the water level at the estuaries' boundary to the North Sea, the river run off into the estuary and the wind field over the estuary. A sensitivity study is used to investigate scenarios that highlight central elements of a possible future. Numerical models of the estuaries can be used to investigate the identical scenarios in all three estuaries. Common and different reactions to changes in the driving forces of storm surges in estuaries can be identified.

The scenarios are built on the basis of high historical storm surges: the storm surge of 3. January 1976 (SF76) in the Elbe and the Weser and the storm surge of 1. November 2006 (SF06) in the Ems estuary. The implied assumption here is that the basic storm characteristics over the German Bight will not change in response to climate change and that storm surges that occurred in the past are therefore just as likely to occur under future climate conditions. The sensitivity study investigates the influence of

- sea-level changes in the North Sea,
- increased fresh water discharge into the estuaries and
- increased local wind speed over the estuary

on the highest water level HW along the estuaries during storm surge. The parameters mentioned are varied systematically according to the knowledge of expected changes in a future climate (BECKER 2012; HEINRICH et al. 2012; HORSTEN et al. 2012). The reference storm surge scenario uses the measured development of the water level at the boundary to the North Sea, the measured wind speed over the estuary and the measured fresh water discharge.

The sea level changes are added to the boundary values at the estuaries boundary to the North Sea. Three different sea level rise scenarios - all three of which can be found in the literature (GÖNNERT et al. 2009) - are investigated: 25 cm, 80 cm and 115 cm. In order to investigate the influence of the local wind speed over the estuaries the wind speed is increased by 10 %.

Table 1: Measured fresh water discharges at Neu Darchau (Elbe), Intschede (Weser) and Versen (Ems) during historic storm surges and characteristic discharges (HPA HAMBURG PORT AUTHORITY 2012; NLWKN NIEDERSÄCHSISCHER LANDESBETRIEB FÜR WASSERWIRTSCHAFT, KÜSTEN- UND NATURSCHUTZ 2013).

	Elbe [m ³ /s]	Weser [m ³ /s]	Ems[m ³ /s]
3 January 1976	500	250	114
1 November 2006	299	147	33
MQ (mean discharge)	709	326	80
HHQ (highest discharge observed)	3620	3500	1200
Q _{design storm surge}	2200	2000	700

The fresh water discharge Q is provided for the numerical model at the upper end of the estuaries. The storm surge scenarios are modelled with the measured discharge as well as with three increased discharges, 2000 m³/s, 3000 m³/s and 4000 m³/s for the Elbe and Weser, 350 m³/s, 700 m³/s and 1200 m³/s for the Ems. For comparative purposes Tab. 1 shows characteristic measured discharge values.

4 Results

4.1 Sea level rise

Fig. 2 shows time series of the water level at Hamburg (Elbe-km 623N), Bremen (Weser-km 0) and Emden (Ems-km 40) for today's sea level and for a sea level rise of 25 cm, 80 cm and 115 cm at the mouth of the estuaries. The sea level rise increases the high and low water levels during the tides before the storm surge as well as on the day of

the storm surge. The highest water level during storm surge is higher and high water time occurs several minutes earlier due to a sea level rise. High water levels, e.g. water levels higher than NHN + 3.00 m last up to several hours longer due to a sea level rise.

The highest water level during the storm surge period (HW) is analysed for all scenarios on a profile along the estuaries from the mouth of the estuary to Bleckede (Elbe), Intschede (Weser) and Bollingerfähr (Ems). Fig. 3 shows the highest water levels during storm surge (HW) for the reference scenario and the three sea level rise scenarios investigated.

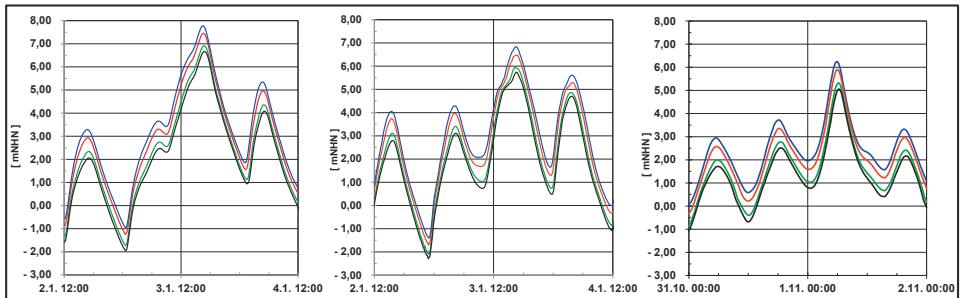


Figure 2: Sensitivity study sea level rise: time series of the water level at Hamburg (Elbe-km 623N, SF76, left), Bremen (Weser-km 0, SF76, center) and Emden (Ems-km 40, SF06, right). The reference scenario is indicated in black. The amount of sea level rise at the mouth of the estuary of 25 cm is indicated in green, 80 cm in red and 115 cm in blue.

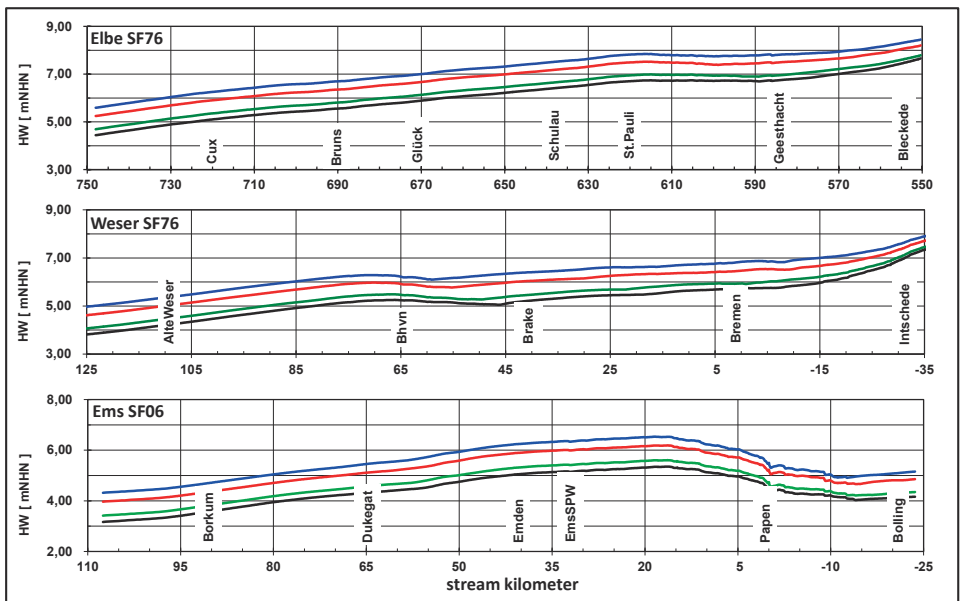


Figure 3: Sensitivity study sea level rise: Highest water level during storm surge HW along the estuaries of Elbe (top), Weser (middle) and Ems (bottom). The amount of sea level rise at the mouth of the estuary of 25 cm is indicated in green, 80 cm in red and 115 cm in blue.

A sea level rise at the mouth of the estuary raises the highest water levels during storm surge along the whole profile, which includes the whole area that is already being affected by storm surges today.

4.2 Local wind over the estuaries

A second sensitivity study investigates the influence of the local wind over the estuary during storm surges. For the purposes of this artificial sensitivity study it is assumed that the wind speed increases by 10 % over the estuaries during the period investigated. During the reference storm surge scenario SF76 wind speeds over the Elbe reach 29 m/s in the area of the mouth and 20 m/s in the area of Hamburg. Over the Weser wind speeds reach 25 m/s in the mouth area during reference scenario SF76 and 22 m/s in the area of Bremen. During the reference storm surge scenario SF06 the wind speeds over the Ems reach 25 m/s in the mouth area and 16 m/s in the area of Emden. Only low winds are observed over the three estuaries on the day prior to the reference storm surge scenarios.

Fig. 4 shows the influence of local wind on water levels during storm surge for today's mean sea level and for a sea level rise of 80 cm. As expected, increased wind speed has no influence on the water levels on the day before the storm surge, that is during periods with low wind speeds. On the day of the storm surge an increase in wind speed of 10 % causes an increase in water level of up to 30 cm for the scenario with today's mean sea level as well as for the scenario with a sea level rise of 80 cm.

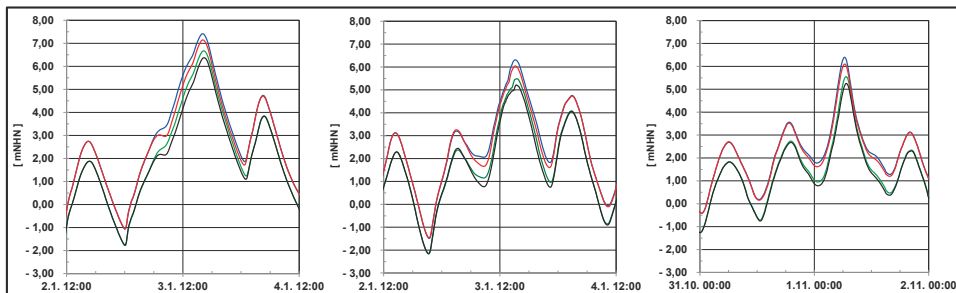


Figure 4: Sensitivity study wind and sensitivity study wind and sea level rise: time series of the water level at Schaulau (Elbe-km 640, SF76, left), Brake (Weser-km 40, SF76, center) and Terborg (Ems-km 25, SF06, right). Black: today's sea level, green: today's sea level and increase of local wind speed by 10 %, red: sea level rise of 80 cm, blue: sea level rise of 80 cm and increase of local wind speed by 10 %.

4.3 Fresh water discharge

The influence of the fresh water discharge on the highest water levels during storm surge in the Elbe estuary is described e.g. in LÄNDER-ARBEITSGRUPPE (1988). Measurements were analysed and the amount of increase in water level per 1000 m³/s of fresh water discharge for several places of interest was derived. A numerical model can be used to investigate a broader range of combinations of fresh water discharge and storm surge.

Fig. 5 shows how increased fresh water discharge (3000 m³/s in the Elbe and Weser, 700 m³/s in the Ems) influences water levels during storm surge for today's mean sea

level and for a sea level rise of 80 cm at the mouth of the estuaries for Hamburg (Elbe-623N), a central location in the Elbe estuary, for Bremen (Weser-km 0) in the upper part of the Weser estuary and for Emden (Ems-km 40) in a wide area of the Ems estuary.

An increase in fresh water discharge increases the high and low water levels on the day before the storm surge and reduces the tidal range, especially in the central and upper part of the estuaries today and in the scenario with additional sea level rise. The influence of the increased discharge on the highest water level during storm surge also depends on the location in the estuary. The highest water level in Bremen is increased by several decimetres during storm surge as a result of increased fresh water discharge, whereas in Emden only a very small increase can be found.

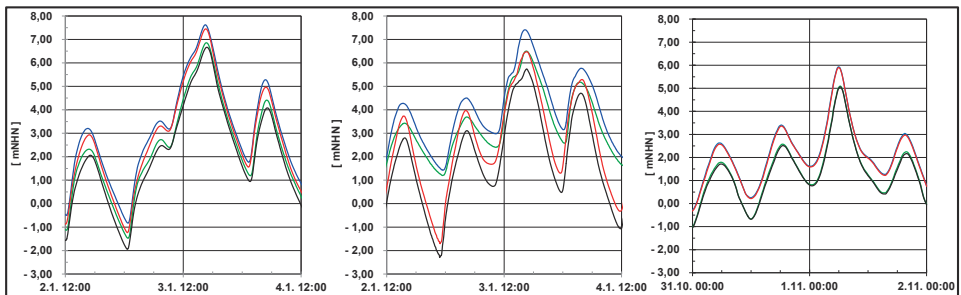


Figure 5: Sensitivity study fresh water discharge and sensitivity study fresh water discharge and sea level rise: time series of the water level at Hamburg (Elbe-km 623N, SF76, left), Bremen (Weser-km 0, SF76, center) and Emden (Ems-km 40, SF06, right). Black: today's sea level, green: today's sea level and discharge $3000 \text{ m}^3/\text{s}$ for Elbe and Weser and $700 \text{ m}^3/\text{s}$ for Ems, red: sea level rise of 80 cm, blue: sea level rise of 80 cm and discharge $3000 \text{ m}^3/\text{s}$ for Elbe and Weser and $700 \text{ m}^3/\text{s}$ for Ems.

The highest water level during the storm surge period (HW) is analysed for all fresh water discharge scenarios and combined fresh water discharge with sea level rise scenarios on a profile along the estuaries from the mouth of the estuary up to Bleckede (Elbe), Intschede (Weser) and Bollingerfähr (Ems). Fig. 6 shows the highest water levels during storm surge for the scenarios mentioned.

It shows that in the mouth of three estuaries investigated, the highest water level during storm surge HW is mainly modified by a sea level rise. HW increases here to an extent approximately equal to the rise in sea level. In these wide parts of the estuaries, with flood and ebb volumes which are much larger than the fresh water discharge, an increase in discharge has no significant influence on the water level. In the upper, narrow parts of the estuaries the highest water level during storm surge is modified by the fresh water discharge. Towards the riverine part upstream of the estuary the fresh water discharge is the single parameter determining the water level. In the central part of the three estuaries investigated the highest water level during storm surge is modified both by sea level rise and changes in fresh water discharge.

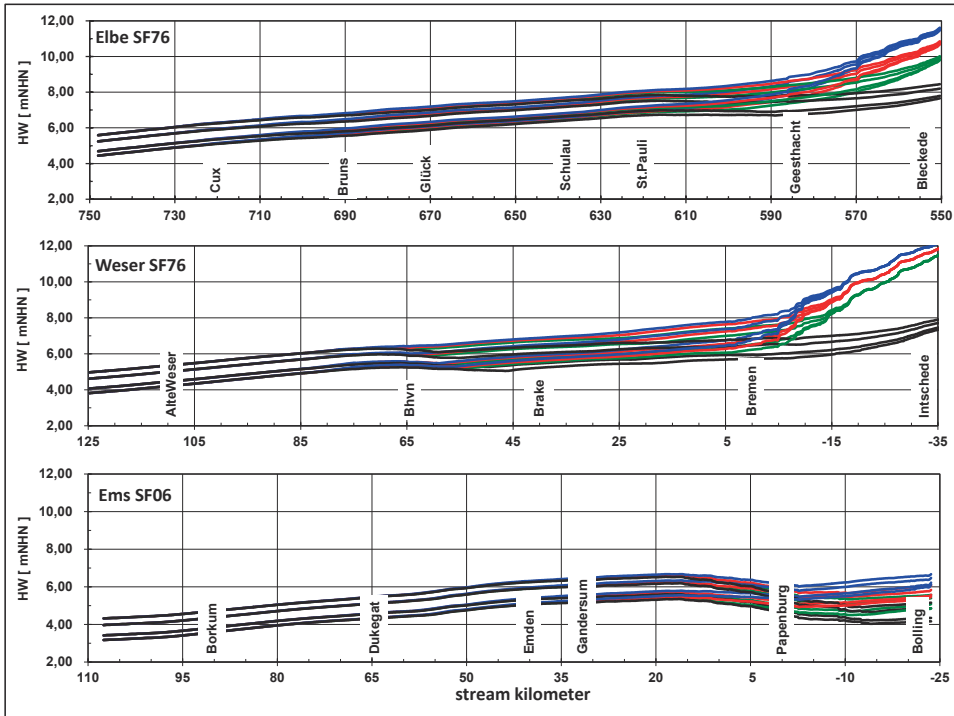


Figure 6: Sensitivity study fresh water discharge in combination with sea level rise: Highest water level during storm surge HW along the estuaries of Elbe (top), Weser (middle) and Ems (bottom) for a sea level rise at the mouth of the estuaries of 25 cm, 80 cm and 115 cm. The colours indicate the amount of fresh water discharge. Black Elbe 500 m³/s, Weser 250 m³/s, Ems 32 m³/s, green: Elbe and Weser 2000 m³/s and Ems 350 m³/s, red: Elbe and Weser 3000 m³/s and Ems 700 m³/s, blue: Elbe and Weser 4000 m³/s and Ems 1200 m³/s.

5 Conclusions

In order to develop a strategy for adaptation to climate change for the German estuaries it is important to understand today's situation and to analyse what developments climate change will bring about in the future. The impact of climate change on storm surges in the German estuaries of the Elbe, Jade-Weser and Ems is investigated using a sensitivity study. The study analyses the influence of sea level rise at the mouth of the estuary, wind over the estuary and fresh water discharge. Hydrodynamic numerical models of the Elbe, Jade-Weser and Ems estuaries can be used to investigate the impact of each process separately. Wind, fresh water discharge and sea level rise are varied systematically in line with today's knowledge of expected changes in future climates. The three estuaries examined show the same response to the scenarios investigated. The results of the study are summed up in Tab. 2.

In the mouth of the estuaries, the highest water level during storm surge is determined by conditions in the North Sea, i.e. storm surge and sea level rise (slr). In the central and landward reaches, the highest water level during storm surge is determined both by conditions in the North Sea and inland (fresh water discharge Q). An increase in local wind

over the estuary influences the highest water levels during storm surge along the whole estuary.

All the scenarios considered result in a rise in the highest water level during storm surge, earlier occurrence of the highest water level during storm surge and in a longer duration of high water levels.

Table 2: Changes in the highest water levels during storm surge in the estuaries of Elbe, Weser and Ems for the scenarios investigated in the sensitivity study.

	mouth of the estuary	central estuary	upper estuary
sea level rise slr	+ slr	+slr \pm 10 cm	+ slr \pm 10 cm
fresh water discharge	\pm 1 cm	5 cm to 30 cm	10 cm to 100 cm
combination Q & slr	+ slr	\leq (slr + Q)	\leq (slr + Q)
local wind	up to 10 cm	up to 30 cm	up to 30 cm
combination wind & slr	\sim (slr + wind)	\sim (slr + wind)	\sim (slr + wind)

The results of this sensitivity study are used by SEIFFERT and HESSER (2014) to investigate climate change impacts and to develop adaptation strategies in German estuaries.

6 Acknowledgement

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