INFLUENCE OF RETENTION AREAS ON THE PROPAGATION OF STORM SURGES IN THE WESER ESTUARY

Anna C. Zorndt[1][2], Nils Goseberg[1][3], Torsten Schlurmann[1]

The hydrodynamics of estuaries are forced by the tides from the open sea and the river runoff from the catchment area. The hinterland is often low-lying and densely populated and must therefore be protected by dikes. Anthropogenic climate change poses new challenges to the coastal protection. However, changes in the geometry of the estuaries can have equally severe impacts on the deformation of a storm surge wave form when it propagates through the estuary. This affects the peak water levels and hence the design water levels. This contribution focuses on the influence of retention areas or forelands seaside of the main dike lines, which are protected by summer dikes against the less severe but more frequently occurring storm surges. This is shown at the example of a retention area in the Weser estuary, which has historically been the cite of a soccer stadium and thus hosts high values which stand in sharp contrast against the low safety level against flooding. The investigation is conducted with a 3D hydrodynamic numerical model which has previously been validated for the simulation of storm surges. The results show that even very small changes in the geometry of the estuary can have effects on design levels. This is even the case when they only regard the summer dike crests heights around retention areas and not their volume. Another important finding is that the geometry changes may have their maximum impacts quite far away from the specific river reach in which they are carried out. The results underline that for designing safe and reliable storm surge infrastructure, storm events should be studied in high resolution models which are able to resolve even small scale features such as summer dike lines.

Keywords: Weser estuary; retention areas; storm surges; design water levels

INTRODUCTION

Motivation

The Weser estuary (Fig. 1, left) can be described as meso- to macro tidal. It has a tidal range of 2.8 m in the outer estuary, where salinity almost equals to seawater salinity. About 120 km upstream, the estuary ends at a tidal weir which cuts off the influence of the tides from the upstream river reaches. At the weir, the tidal range amounts to a maximum value of 4.2 m. This strong and almost continuous increase is due to the strong convergence of the funnel-shaped outer estuary and the narrow shape of the inner estuary which allows only little dissipation of the energy of the tidal wave.

The hinterland of the estuary is low-lying and therefore, coastal protection has historically always played an important role. According to Thorenz (2008), an area of 6.600 km^2 is located below mean tidal high water in the German Federal Land Lower Saxony. This area would be flooded daily twice without the coastal protection system which is in place today. The design levels (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz 2007) however are chosen in a way not only to protect from an average high tide, but from a much higher theoretical design event based on a deterministic design approach (German *Einzelwertverfahren*, e. g. Thorenz 2008). This approach considers the storm surge to be a combination of different components. At each location, the maximum values of all components ever observed at that location plus a secular trend setup are summed up to achieve the design level. Yet, in the upper estuary at locations potentially influenced by river runoff, this approach is not valid. Instead, the design levels are extracted from storm surge simulations of a "design event", mimicking the design values in the outer estuary (Niemeyer et al. 2003).

However, there are also areas excluded from the main protection line which are protected by summer dikes parallel to the main dikes. In the Weser estuary, many of the areas have historically been used for agricultural purposes and even host housing as well as valuable infrastructure. In order to protect the areas from the regular flooding by the semidiurnal tidal high water or frequently occurring small storm surge and flood events, the areas are protected by summer dikes. In contrast to the completely shielded areas behind the main dike line, those low lying areas serve as retention areas in case of storm events or floods during which water levels become higher than the summer dike crest levels.

One example of such an area is the Weser island Strohauser Plate (Fig. 1, right). It is protected by a summer dike of 3.20 m height, while the adjacent main protection line has a design level of 6.85 m. This illustrates that the purpose of those areas is to provide additional flooding capacity only in the case of severe storm surges while remaining a certain protection against smaller events. Another example for this is the area Pauliner Marsch in the city center of Bremen very close to the tidal weir (see Fig. 1, bottom). At this approximately 50 ha large area, the design level of the main protection line is 7.37 m and the summer dike crest, which surrounds the area, is about 5.50 m.

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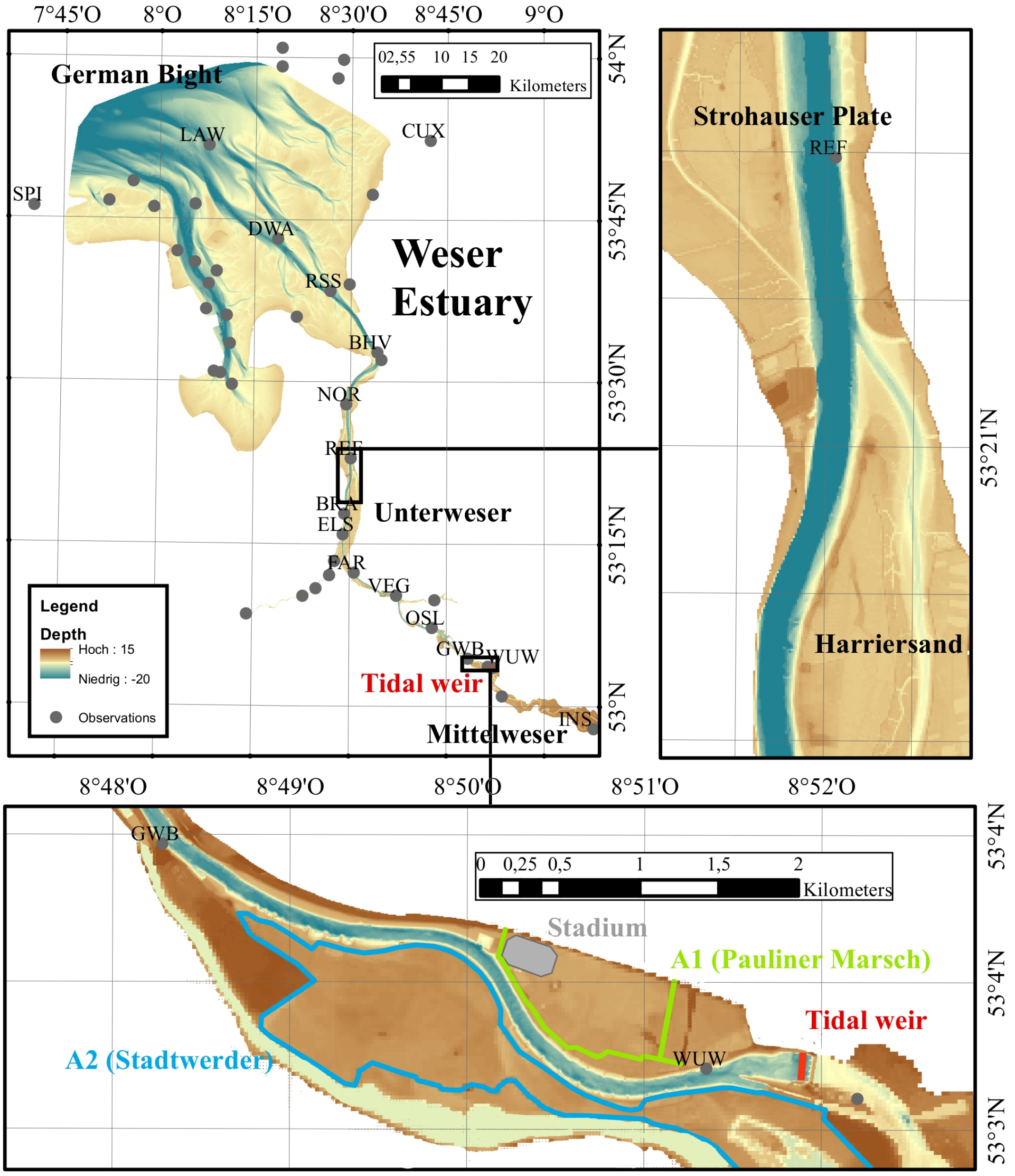


Figure 1. Model domain of the Weser estuary with gauge data base available for model calibration. Right inset illustrates the underlying data basis in a close up at the Weser islands Strohauser Plate and Harriersand. Bottom inset shows the upstream area where retention areas A1 (Pauliner Marsch, green) and A2 (Stadtwerder, cyan) are located.

The setup in this original foreland area is quite unique, as it is the site of the stadium of the local soccer club SV Werder Bremen. The stadium was first built in 1909 (Klingebiel 2006), when the tidal range in Bremen amounted to only about 1.50 m (Wetzel 1988). However, since then several river training and deepening campaigns were carried out to strengthen the economy of the city and to compete with the harbor in the city of Hamburg. These river training measures increased the tidal range of the river Weser substantially and nowadays it is almost three times higher than in 1909. At the same time, the stadium was renovated and rebuild several times and its capacity now yields approximately 42,000 seats. Thus, while the flood risk grew over the years, the monetary values in the area have been rising extraordinarily.

In this light, users and authorities more frequently requested a greater level of protection to properties situated in the area between the summer dikes and the main line of protection. Aside from the increasing values in the area, the discussion has also been facilitated by the increasing awareness in the public that climate change might increase water levels so that storm surge levels become higher. The existing risk for storm-surge induced flooding was well underpinned by the occurrence of the recent storm surge Xaver, which met the German Bight at December 6th. As shown in Fig. 2, the peak water level in the city of Bremen was about 5.30 m high, which was only 20 cm below the crest level of the summer dike. However, a change in the geometry of the estuary may have an impact on the deformation of the storm surge while it propagates through the estuary. Thus, each change in geometry needs to be evaluated against a potential impact on the design levels. Another aspect which needs evaluation is that an attempt to increase crest heights of a summer dike around one area may potentially increase flood risk for other adjacent retention areas. In the city of Bremen, this may apply to the area Stadtwerder which is located opposite the river from the area Pauliner Marsch (Fig. 1). This area has a size of about 200 ha and is occupied by small garden colonies.

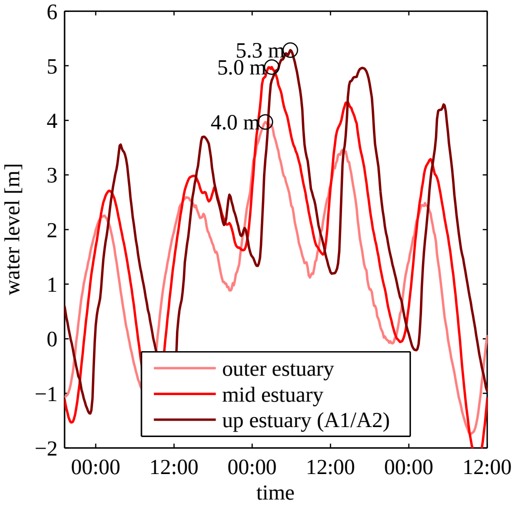


Figure 2. Time history of the water surface elevation during storm surge Xaver in the Weser estuary, from outer (pale) to inner estuary (red).

Objectives

With respect to the above outlined background, a study on potential changes in design water levels was carried out with the following two-step approach:

1. Investigation of the impact on the flooding of the retention area Stadtwerder (in the following depicted as area A2). This goal was primarily achieved by simulating a storm event which has the same maximum peak water level as the investigated summer dike crest at Pauliner Marsch (in the following depicted as area A1). This combination is considered the worst case for the area A2. To calculate the necessary height of the summer dike around A2 which, for a given summer dike around A1, is necessary to prevent an impairment at this site, several combinations of summer dike crest increases at both sites were simulated. The changes in respective flood volumes of the areas were calculated to quantify the impairment.

2. Investigation of the impact on the peak water levels along the main river channel: This was done by simulation of an event similar to the design event. In this case, the changes in peak water levels of the event can be interpreted as changes in design values.

This contribution highlights the necessity to carefully examine possible impacts from man-made changes in a reasonably large vicinity of the region of interest. From the Weser estuary, more general conclusions can be drawn as it may serve as a typical example for highly trained estuaries.

NUMERICAL METHODS

Modeling tool

The main modeling challenges in the Weser estuary are the vast tidal flats which make up about 30 % of the modeling domain, and the different spatial scales. While the wadden sea area and the deeper parts of the outer estuary need to be resolved as coarse as possible to remain computationally efficient, small geometrical features such as summer dikes need to be incorporated in the inner estuary. Therefore, an unstructured grid model was chosen (SELFE), which was developed by Zhang and Baptista (2008). This model solves the 3D shallow water wave equations along with transport equations for salt and temperature. To be more efficient, the model is run in barotropic mode in this study. Also, the parallelized version of the code is used for which good scalability and efficiency were achieved (Zhang et al. 2011).

Model domain

The bathymetry used in this study is a high resolution bathymetry dated around the year 2009 which was described in greater detail in Zorndt et al. (2012). The model domain has a size of about 2.000 km^2 and can be seen in Figure 1. It is similar to the one described by Zorndt and Schlurmann (2014), except for the following differences: For the sake of simplicity, all tributaries are cut off completely. The reason is that in case of storm surges, the storm surge barriers to the tributaries are closed to protect the hinterland from flooding. This simplified approach leads to a slight loss in model skill for the tides before and after the storm event. As this error is in the order of centimeters for high and low tides, a more complicated set-up with moving weirs was not considered necessary at this point. Another important difference is that the model domain does not end at the tidal weir in the city of Bremen, but extents it 20 km in the southern direction. This area of the river is usually not tidally influenced due to the tidal weir in Bremen. During average conditions, its five fishbelly flap gates are steered to keep a constant water level of 4.5 m upstream the weir. When the river discharge exceeds 1200 $\mathrm{m}^3\mathrm{s}^{-1}$ or when the water level gradient between up- and downstream the weir is less than 15 cm during storm surges, the gates are opened. This would be the case for the simulated events (see below). Thus, the weir is modeled as a fixed structure in the bathymetry with its bottom sill at a height of 1.5 m.

The meshing was described in Zorndt et al. (2012) and is based on a hybrid approach using geo-information software for construction of boundary and polygones, Triangle (Shewchuk 1996) for triangulation and Matlab as an interface (similar to Bilgili et al. (2006)). Special attention was paid to model the summer dike lines around the retention areas as shown in Figure 3. The resulting domain discretization contains 171.157 nodes and 336.026 elements.

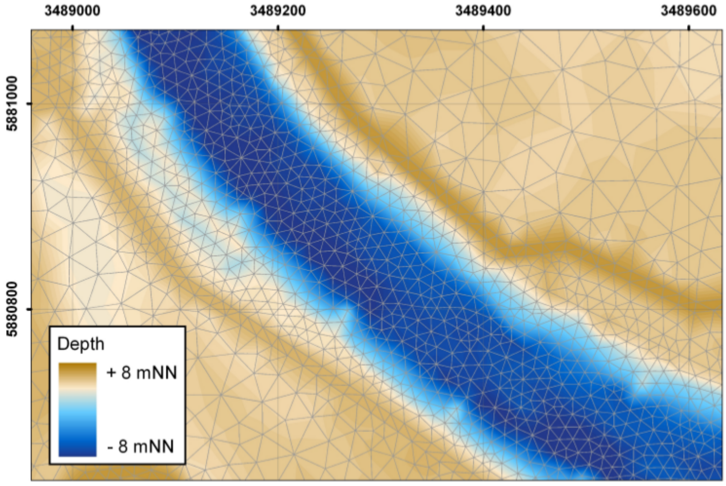


Figure 3. Detail of model discretization and bathymetry in the area of Bremen, indicating river main channel (blue) and summer dike lines of areas A1 and A2 (brown).

The parameters of the model are similar to those of the model version which was used in Zorndt and Schlurmann (2014). As described there, simulated water surface elevation, current velocity and salinity were compared to observations for different simulation periods. A skill assessment showed that the model is capable of reproducing the observations with mostly very good model skill. The values of this model version may differ slightly due to the different domain and neglection of baroclinic processes, but can be expected to be within similar ranges due to the comparable set-up of the model.

IMPACT ON FLOODING ON AN ADJACENT RETENTION AREA

Boundary conditions

The first step of the investigation was to calculate the necessary summer dike height around area Stadtwerder (A2) to prevent more severe flooding for a given summer dike increase around adjacent area Pauliner Marsch (A1). The worst case for A2 was assumed to be a scenario which has the same peak water level as the summer dike around A1.

The chosen scenarios S1 and S2 resemble the event considered in Section but with less strong wind speeds and no set-up for sea level rise. The runoff into the model domain at the upstream is assumed constant at a value of 1210 m^3s^{-1}. This is the longterm mean of the annual maximum (Spekker 2008). The peak water level of S1 is 5.99 m at the station Weserwehr Unterweser (WUW) close to the area A1. S1 is therefore suitable to investigate the impact of a summer dike increase of 0.5 m (from 5.50 m to 6.0 m) around A1 on the flooding of A2. The peak water level of S2 is 6.54 m which makes S2 suitable to investigate a summer dike increase of 1 m.

To quantify the impact of storm events on a coastal system, the amount of flooded area is a common choice as a metric. This measure is not suitable here, as the area is limited by the main dike line and comparatively small, so that it is 100 % wet after a comparatively short time. Instead, the maximum water volume V_{max} which has flooded into the retention area is used to quantify the impact.

Results

The investigated combinations of summer dike heights in area A1 and A2 are depicted in Table I and graphically illustrated by Figure 4. Figure 4 relates the maximum inflow volume into the retention areas A2 to the equivalent summer dike crest height changes at both river sides. Again, the considered scenario differs (S1, S2) and its peak water level is always at the same height as the summer dike crest heights of area A1. The volume presented in the graph depicts the maximum volume based on the water depth extracted from the numerical model in the retention area A2. Light blue and pink colored horizontal graphs indicate the volumes accumulated the retention area A2 in when no geometry change takes place (status quo volumes for S1 and S2, cf. Table I, row C10, C20). Further, the dark blue graph indicates the inflow volumes for scenario S1 with respective summer dike changes (row C11 ff.), whereas the dark red graph presents inflow volumes for the scenario S2 (row C21 ff.).

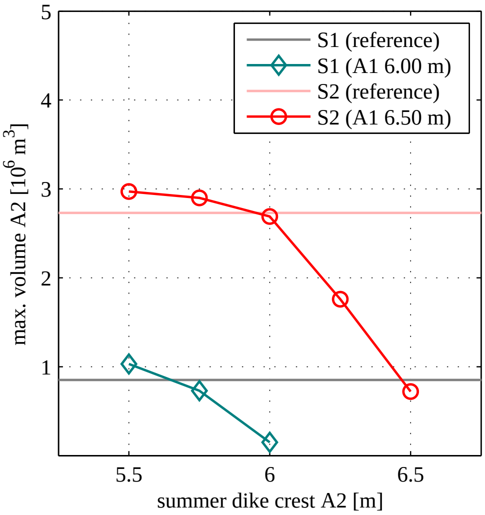


Figure 4. Determination of necessary summer dike height around area A2 to compensate for summer dike increase around A1.

The results show that the flooding of adjacent area A2 would be significantly increased if the summer dike around A1 was increased. With an increase to 6.00 m around A1, maximum water volume flooding into A2 would increase by 20 %. To completely prevent impairment for A2, the summer dike around

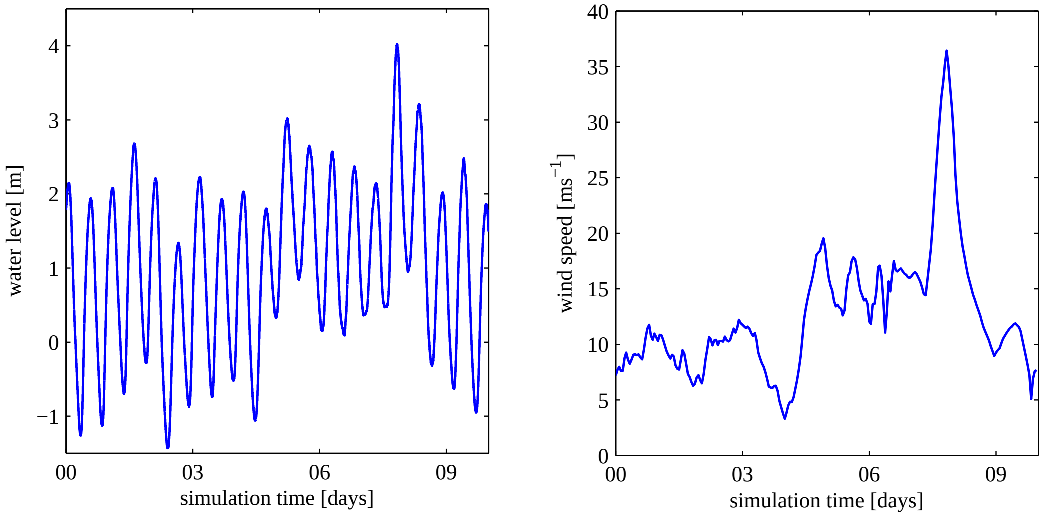
A2 would theoretically need to be increased to 5.65 m (linear interpolation). In case of a summer dike increase around area A1 to 6.50 m, the summer dike around area A2 would need to be increased to 5.96 m (linear interpolation) to prevent impairment in flooding for the area.

DETERMINATION OF THE IMPACT ON THE DESIGN LEVELS

The second step of the investigation was to calculate possible impacts of the summer dike crest increases on the design water levels. Therefore, a simulation with an event similar to the design event was carried out. By this means, changes in peak water levels due to the event can be interpreted as changes in design values and thus it can be judged whether a particular geometry change effects the surrounding main protection lines negatively by decreasing existing safety margins.

Boundary conditions

The boundary conditions of the established design event were chosen, which are a combination of a river flood, a severe storm surge and a mean sea level rise setup (Niemeyer et al. 2003). The river runoff, which is prescribed at the upstream open boundary, amounts to 2000 m^3s^{-1}. This value corresponds to a return period of approximately 11 years (Spekker 2008). The storm surge is modeled by prescribing external surge and tide at the North Sea open boundary (Fig. 5a) and wind over the model domain (Fig. 5b). In addition, the North Sea boundary condition and the initial water surface elevation of the model are increased by a setup for mean sea level rise of 50 cm (Niemeyer 2007).



(a) Water surface elevation at the open boundary to the German Bight

(b) Wind speed over the outer estuary domain

Figure 5. Boundary conditions of the simulated event, cf. Knaack et al. (2006).

To achieve similarity with the original design event, the wind field over the domain was manually adjusted aiming at the peak water levels of the event to match the design water levels along the main channel of the inner estuary. The results are presented in Figure 6 along centerline of the main river channel. The differences between design values and peak water levels are in the order of centimeters with maximum absolute differences of around 10 cm. It thus can be concluded that sufficiently good agreement between the design event and the peak water levels is achieved in order to interpret the changes in peak water levels as changes in design values.

To test the robustness of the results, additional studies were carried out. To investigate impact of model roughness on the results, some combinations were tested with different model roughness values. Also, alternative design events such as synthetic events with no manipulation of wind fields and higher external surge were tested. The results showed slightly different absolute deltas in peak water levels, but a strong consistency with the below described patterns described was found.

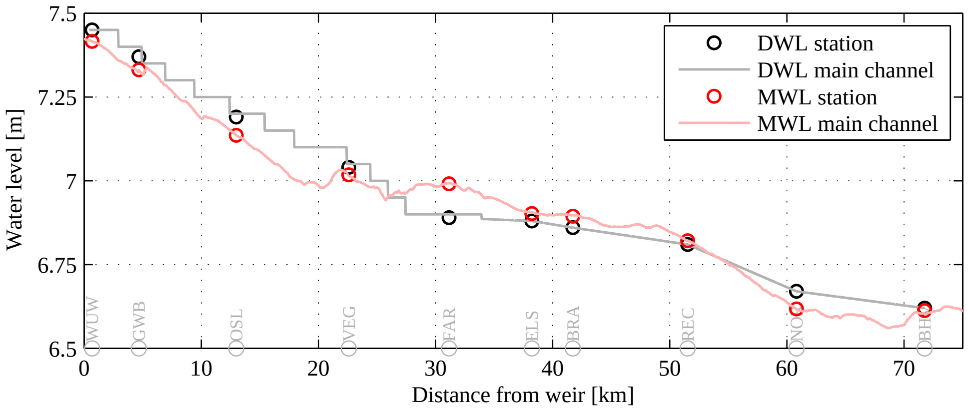


Figure 6. Comparison of established design water levels according to official bulletin (constant values for dike segments) (DWL) along the distance from the tidal weir and maximum water levels of the simulated event (MWL) with simulated water levels according to the boundary conditions described above. Abbreviations on the x-axis indicate available water level gauges.

Results for patterns along the main river channel

The changes in peak water levels along the main river channel are presented in Figure 7. Minimum and maximum differences for all tested combinations and their locations are also depicted in Table II.

As changes of estuarine geometry, be it changes in dike crest levels or deepening of navigation channel, may result in response of the flow, it is important to quantify this response. The impact of the tested summer dike crest heights on the status quo (in which summer dike heights of both retention areas A1 and A2 are kept at the actual level of 5.5 m) is thus investigated by means of difference plots along the centerline of the estuary.

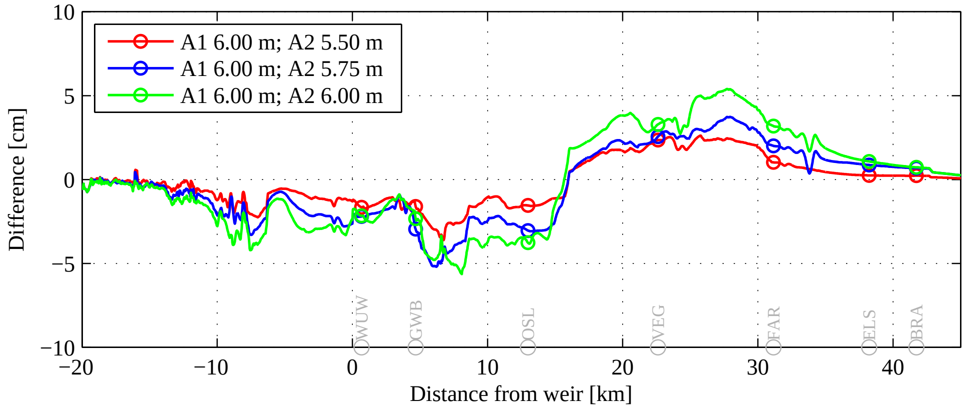
In Figure 7(a), the combinations of a summer dike increase around area A1 to 6.00 m with three summer dike increases of retention area A2 are depicted. The pattern of the changes in peak water levels are the same for all combinations. The deltas are significantly different from zero in the area between -15 km upstream and 45 km downstream of the tidal weir. Along the entire river stretch upstream of 15 km from the weir, there is a general decrease in peak water levels. The minimum is found just downstream of the retention areas. Along the river stretch 15 km from downstream the weir, peak water levels increase. Maximum values are up to 4.8 cm for the combination C13. As a general trend, increasing crest heights of retention area A2 result in increasing differences of peak water levels. It is particularly interesting to observe that the peak water levels do not start increasing before a distance as far as 15 km downstream of the disturbance caused by a rather small increase in summer dike crest heights.

Similarly, the system response to geometric changes is shown for combinations of a summer dike increase around A1 to 6.50 m with five summer dike increases around A2 in Figure 7(b). The general patterns are the same as in Figure 7(a), except for the following differences: The turning point between increase and decrease of peak water levels is located slightly closer to the weir, at a distance of 10 km. However, the distance at which the maximum differences in peak water levels occur is still remarkable. Also, the upstream patterns are slightly more complex and two local minima upstream and downstream the retention areas can be found. Same as before, increasing differences in peak water levels are correlated with increasing crest heights of the summer dikes. This is most possibly be caused by the time-lag in the flooding of those areas as discussed in the Summary chapter.

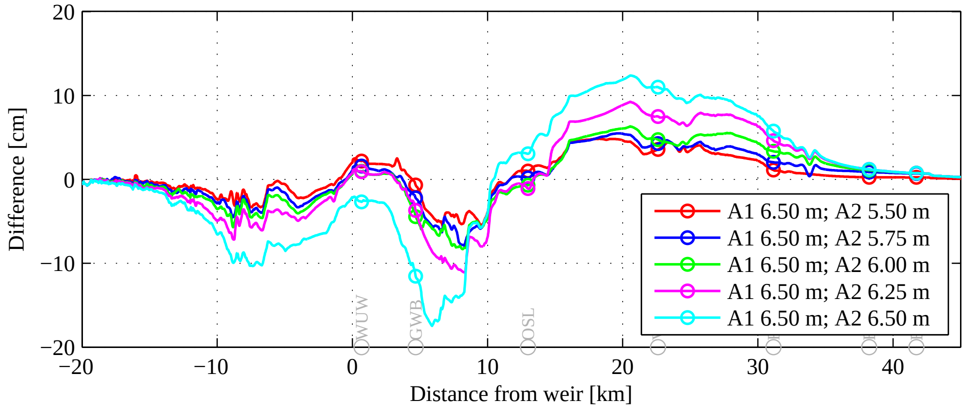
Results for maximum expected design water level increases

The maximum possible increases of design water levels (without consideration of where they occur) are compared in Figure 8 for all tested combinations. It should be stressed that in contrast to Figure 4, the combinations are all tested with the same scenario. The maximum differences in peak water levels are displayed with respect to the tested increase of summer dike crest heights of retention area A2 group according to the corresponding crest height increases of retention area A1.

It is clearly seen that the increase is not linearly correlated but grows over proportional for all grouped combinations. A reason for this behavior is the storm propagation pattern discussed in the Summary.



(a) Combinations with summer dike increase to 6.00 m around A1 and 5.50 m (C11), 5.75 m (C12) and 6.00 m (C13) around A2



(b) Combinations with summer dike increase to 6.50 m around A1 and 5.50 m (C21), 5.75 m (C22), 6.00 m (C23), 6.25 m (C24) and 6.50 m (C25) around A2

Figure 7. Differences in peak water levels between the status quo situation and the simulated combinations of crest height in increases, along the main river channel.

TECHNICAL IMPLICATIONS

Regarding the specific questions which were investigated here, two conclusions can be made:

1. As expected, increasing the summer dike around retention area A1 increased flooding in retention area A2. It is however possible to prevent this impairment by increasing the summer dike around retention area A2. To keep the present safety level, it would not be necessary to increase to the same dike crest as for retention area A1. Instead, minor increases would be sufficient.

2. Unexpectedly, increases of summer dike crests in the upper estuary close to the tidal weir may significantly impact the design water levels, although the volume in the retention areas remains unchanged (see Summary and Discussion). All tested combinations show maximum changes of design water levels higher than 2 cm. In particular combinations which increase safety of area A1 and at the same time ensure keeping the status quo in area A2, show high impacts on the design water levels.

When human interventions in the estuary have impacts on the design water levels, the main dike line needs to be adjusted to keep the present safety levels. As this is in practice complicated and extremely cost-intensive, it is important to avoid impacts on design water levels in the planning of interventions. Therefore, alternative measures have now been envisaged to increase the safety level for the stadium.

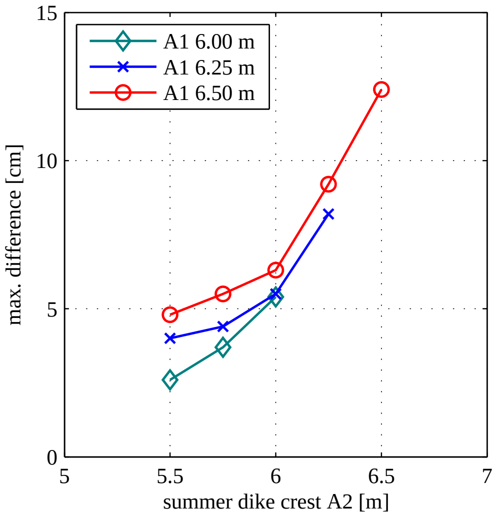


Figure 8. Maximum differences in peak water levels of all tested combinations.

Those include a higher protection line around a smaller portion of area A1, which has no impact on design water levels or flooding of adjacent area A2 (not shown here).

SUMMARY AND DISCUSSIONS

Summary

Small interventions in the geometry may have strong effects on the storm surge dynamics in an estuary. This was shown here at the example of retention areas of the Weser estuary, Germany.

Simulations with several estuary geometries were carried out which only differed by the height of summer dike crests around two particular retention areas close to the tidal weir. The overall volume of the estuary remained unchanged. An extreme event consisting of a combination of a storm surge with a river flood was tested. The changes of peak water levels may be interpreted as possible changes in design water levels. The results show that the increase of the summer dike crests have a significant impact on the peak water levels during the event, compared to the status quo geometry: Close to the retention areas, a decrease in peak water levels can be observed. Further downstream the estuary, peak water levels increase. The patterns of the differences are consistent between geometries, but the absolute values differ: In short, higher summer dike crest increases show stronger impacts on design water levels. The highest increases of peak water levels can be observed 18 to 28 km from the weir and mount up to 12 cm.

Discussion

It can be assumed, but needs to be further investigated, that this strong impact is due to the proximity of the retention areas to the tidal weir in the upstream reach of the estuary. Those areas are not flooded before the storm water level reaches the summer dike crest. An increase of summer dike crest therefore causes a time lag in the flooding of the areas. As a result, the water level increase is accelerated in the upstream reach during this early phase of the storm surge. This leads to a higher instantaneous water level gradient along the main channel, causing a pile-up effect. This effectively partly hinders the upstream propagation of the storm surge. Hence, the later occurring final peak storm surge water levels increase in the mid-estuary, while they decrease in the upstream reach.

Besides the relative location of the retention area, this behavior is a function of the retention area's volume and other characteristics. It may differ in other estuaries. All in all, the observed complex interactions between the different geometric features of the estuary in case of extreme events aim toward a more encompassing understanding of storm surge dynamics in estuaries. Also, they underline the need for a more elaborate approach for the determination of design levels in terms of storm intensity instead of a mere focus on the peak water levels.

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APPENDIX

Table I. Simulation results for the impact on flooding on the adjacent retention area A2

		Summer dike crest height		Maximum volume area A2	
Scenario	Combi-nation	Area A1	Area A2	absolute	change compared to C*0
S1	C10	5.50 mNN	5.50 mNN	0.85 10^6m^3	-
S1	C11	6.00 mNN	5.50 mNN	1.03 10^6m^3	+20 %
S1	C12	6.00 mNN	5.75 mNN	0.73 10^6m^3	-14 %
S1	C13	6.00 mNN	6.00 mNN	0.15 10^6m^3	-82 %
S2	C20	5.50 mNN	5.50 mNN	2.73 10^6m^3	-
S2	C21	6.50 mNN	5.50 mNN	2.97 10^6m^3	+9 %
S2	C22	6.50 mNN	5.75 mNN	2.90 10^6m^3	+6 %
S2	C23	6.50 mNN	6.00 mNN	2.69 10^6m^3	-1 %
S2	C24	6.50 mNN	6.25 mNN	1.76 10^6m^3	-35 %
S2	C25	6.50 mNN	6.50 mNN	0.72 10^6m^3	-74 %

Table II. Impact on peak water levels during design event

Summer dike crest height			Maximum difference		Minimum difference	
Combi-nation	Area A1	Area A2	Value	Dist. from weir	Value	Dist. from weir
C10	6.00 mNN	5.50 mNN	2.6 cm	25.8 km	-3.6 cm	6.7 km
C11	6.00 mNN	5.75 mNN	3.7 cm	27.9 km	-5.2 cm	6.2 km
C12	6.00 mNN	6.00 mNN	5.4 cm	27.7 km	-5.6 cm	8.1 km
C30	6.25 mNN	5.50 mNN	4.0 cm	23.5 km	-4.8 cm	13.2 km
C31	6.25 mNN	5.75 mNN	4.4 cm	19.8 km	-5.1 cm	6.3 km
C32	6.25 mNN	6.00 mNN	5.5 cm	27.7 km	-6.3 cm	11.1 km
C33	6.25 mNN	6.25 mNN	8.2 cm	20.6 km	-10.8 cm	7.3 km
C21	6.50 mNN	5.50 mNN	4.8 cm	18.3 km	-5.5 cm	9.5 km
C22	6.50 mNN	5.75 mNN	5.5 cm	19.8 km	-7.9 cm	8.3 km
C23	6.50 mNN	6.00 mNN	6.3 cm	20.6 km	-8.3 cm	8.1 km
C24	6.50 mNN	6.25 mNN	9.2 cm	20.6 km	-11.1 cm	8.4 km
C25	6.50 mNN	6.50 mNN	12.4 cm	20.6 km	-17.5 cm	5.9 km

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