Efficiency of artificial sandbanks in the mouth of the Elbe Estuary for damping the tidal energy

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Abstract

The tidal system of the Elbe Estuary has changed significantly in the past. Due to anthropogenic interventions and natural changes flood plains were reduced and the friction of the Elbe Estuary decreased. As a result tidal range and sediment transport increased upstream. Furthermore the tidal wave propagates faster through the estuary and produces an increased tidal range in Hamburg. This leads to a heightening of the flooding risk along the Elbe Estuary. In the framework of the European Project THESEUS the efficiency of five different artificial sandbank scenarios in the mouth of the Elbe Estuary for attenuating the incoming tidal energy by reflection itself or by increasing the friction is investigated by means of a hydrodynamical numerical model. The results show that the effect of sandbanks above mean sea level on the currents and water elevations is rather local, the sandbanks are only relevant during flood-tide, and will not change the hydrodynamics along the Estuary significantly. Another option, the introduction of underwater sandbanks in tidal creeks, seems to be more effective.

Keywords: coastal defence, artificial sandbanks, THESEUS, numerical modelling, damping tidal energy

I. Introduction

Coastal zones play a vital role in terms of settlement, industry, trade, agriculture and tourism to mention some key sectors. Even though they make up only a small part of the world's land area they are among the most densely populated zones. Since the concentration of people in coastal areas is expected to grow fast in the next decades and economies continue to develop the asset base of risk will increase. Furthermore global climate change will raise the likelihood of extreme events, as well as accelerate habitat decline. The combination of increasing economic and social values and the impacts of climate change will lead to a growing pressure on coastal systems [6].

The EU-Project THESEUS will investigate the applicability of innovative combined coastal mitigation and adaption technologies. Besides technical aspects, social, economic and environmental factors are included. The main aim is to deliver both a low-risk coast for human use and healthy habitats for evolving coastal zones subject to multiple change factors [10]. European Estuaries, like the Elbe Estuary, are under special investigation. The Elbe Estuary has undergone in the past several natural and anthropogenic changes. They led amongst others to a reduction of the friction of the Elbe Estuary and to an increase in tidal range. As a result the tidal wave propagates through

the estuary with more energy and the risk of flooding is heightened. In the framework of the THESEUS project the Helmholtz-Zentrum Geesthacht and the Hamburg Port Authority are investigating how artificial sandbanks in the mouth of the Elbe Estuary could be used to attenuate the tidal energy along the Elbe Estuary. In the following text the investigation area is introduced first and in a second step the simulated hydrodynamic measures and their effectiveness are presented.

II. Area under investigation

A. Characteristics

The Elbe River reaches from the Giant Mountains in the Czech Republic to the German Bight, North Sea. With a length of about 1094 km and a catchment area of 148,268 km^2 the Elbe River is one of the important rivers of Europe. The tidally influenced part, the Elbe Estuary, extends from the tidal weir in Geesthacht to the North Sea and has a length of about 142 km [7].

The tidal system of the Elbe Estuary is influenced by the tidal wave entering the Elbe from the North Sea, the freshwater inflow from the catchment area of the Elbe and the characteristics of the Elbe River itself [1]. The mean low water discharge of the Elbe River is about 145 m^3s^{-1}, the mean fresh water run-off about 708 m^3s^{-1} and the mean high water discharge about 3620 m^3s^{-1} [4]. The tidal dynamic in the German Bight has a great influence on the hydrodynamic and morphodynamic processes in the Elbe Estuary. The tidal regime in the North Sea is characterized by a semidiurnal astronomical signal with two main constituents, the M2 and the S2 tide [8]. The amplitudes and phases of the tides are heavily modified by the basin bathymetry and already get deformed by the reflection in the German Bight. The tide in the Elbe Estuary has a mean period of 12 hours and 25 minutes and the tidal regime is characterized by a diurnal asymmetry. As the tidal wave is getting steeper during its way through the Estuary the duration of the flood is shorter than the duration of the ebb tide. The tidally influenced part of the Elbe River has an artificial border at the weir of Geesthacht. Except in the case of storm surges the tidal weir is closed and the tidal wave is reflected [3]. The tidal wave is reflected at two further locations in the region of Hamburg, where the depth of the Elbe River decreases to -11.40 m below German datum and to -6.40 m below German datum, respectively [3].

B. Anthropogenic interventions

In the past the whole Elbe River has undergone a couple of anthropogenic changes. There have been several deepening events of the navigation channel. The outer and lower Elbe River was dredged between 1936 and 1950 up to -10 m and between 1957 and 1962 up to -11 m below Chart datum. Few years later, between 1964 and 1969, the channel was deepened up to -12 m and between 1974 and 1978 up to -13.50 m. Since 1999 the shipping channel reaches a maintained depth of -14.50 m below Chart datum [1]. Further anthropogenic changes are the construction of the longitudinal dikes Kugelbake and Pagensand Nord, several extensions of the harbour of Hamburg, the building of underwater deposition areas or measures for flood protection [1].

Especially due to the construction of river barriers as flood protection measures, the foreshore areas of the tributaries are no longer available as flood plains. Although some measures within the mouth of the estuary helped to restrict storm surges, analyses by Siefert et al. [9] showed that the total of the diking and poldering measures led to an increase of the maximum peak water level of almost half a meter in Hamburg during storm surges.

Moreover these anthropogenic interventions in combination with natural changes in hydrodynamics led to a reduction of the friction of the Elbe Estuary. As a result not only the storm surge levels, but also the tidal range, sediment transport and siltation rate increased upstream. The tidal range of the monitoring station St. Pauli for example augmented in the last century from 160 cm to 360 cm [4].

C. Model area

For the model simulations an area was chosen which is large enough to simulate the physical processes in the Elbe Estuary (Fig. 1). The model area reaches from the weir of Geesthacht in the southeast to the German Bight in the northwest.

III. Scenario simulations

A. Positions and characteristics of the different sandbank scenarios

In the framework of this paper five different sandbank scenarios are simulated. Form and positions of the sandbank scenarios are shown in Fig. 1. All sandbanks have a maximum height of 4 m above German datum and are placed in regions which are considered as morphological relatively stable. Sandbank scenario 1 consists of two sandbanks in the west and east of the Medemrinne. Together they have a volume of about 3.62 Mio m^3. Sandbank scenario 2 is made up by one sandbank on the south coast of the Elbe River on the opposite of Brunsbüttel (volume of about 2.06 Mio m^3) and scenario 3 by one sandbank in the opening mouth near Cuxhaven (volume of about 3.32 Mio m^3). Sandbank scenario 4 combines all artificial sandbanks of scenario 1-3. This simulation is carried out to show whether there is a cumulative effect or not. The fifth scenario, a hypothetical one, is an extension of scenario 1 and has a volume of about 21.7 Mio m^3.

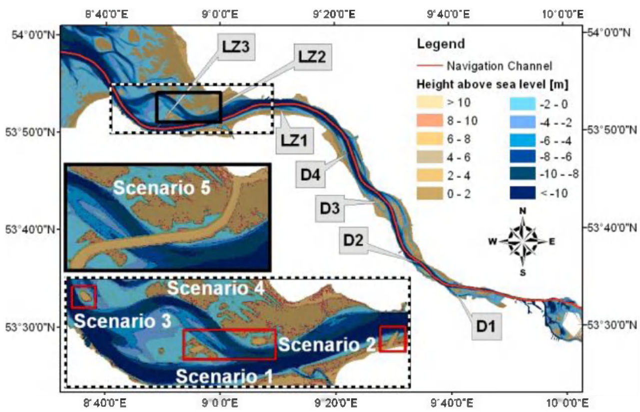

Figure 1. Form and position of the investigated artificial sandbanks. Monitoring stations D1-D4, LZ1-LZ3 (Reference: authors design).

B. Monitoring Stations

To investigate the effects of the different scenarios on water level and current velocity seven monitoring stations along the Elbe Estuary are considered (D1-D4 and LZ1-LZ3). Monitoring station D1 is situated close to the Port of Hamburg and LZ3 is placed in the outer Estuary (Fig. 1). At the positions of the stations the modelled time-series of water level and current velocity are compared to the reference situation (no sandbanks) and the recorded current velocity data.

IV. Numerical simulations

A. Hydrodynamic model TRIMNP

For numerical simulations an extension of the hydrodynamic model TRIM (Tidal, Residual, Intertidal Mudflat Model), called TRIMNP (Nested Parallel Processing), is applied. Because the main interest is on the influence of the sandbanks on water elevation, the model is run in the depth averaged 2-dimensional mode.

BThe hydrodynamic model calculates the water level and current velocity on a rectangular horizontal grid. To solve the depth averaged shallow water equations a semi-implicit, time-stepping, finite-difference method is used [2]. As most tidal hydrodynamic processes are convection dominated, the advection terms in the momentum equations are solved by an Eulerian–Lagrangian method (ELM). The model is also able to treat flooding and drying of computational cells. The governing equations include the conservation equations of mass, momentum, conservative scalar variables, and an equation of state [2].

To allow the investigation of the effects of the artificial sandbanks on water level and currents in the inner estuary a spatial resolution of 50 m and a temporal resolution of 15 minutes is used. The time domain of the simulations is the year 2006. As Cheng et al. [2] figured out the numerical method is “unconditionally stable” if the baroclinic forcing is ignored. For this reason and out of time restrictions the barotropic version was applied.

The model is driven on the north western open boundary by the model outputs water level and current velocity of the operational circulation model of the German Federal Maritime Office (BSH). This 3-dimensional model is daily run on two spherical grid nets. For this purpose the results of the grid including the German Bight and the western Baltic Sea are applied. The model calculates currents, water levels, water temperatures, salinity and ice cover. Grid spacing in the German Bight and the western Baltic Sea is 1.8 km. Model inputs are current meteorological conditions, tides and river runoff as well as external surges which enter the North Sea from the Atlantic.

Another forcing parameter is the freshwater inflow from upstream. These data are daily values measured 53 km upstream of the weir Geesthacht at the village Neu Darchau. A further boundary condition is the wind over the model area. Wind data are model outputs of the regional climate model REMO for the year 2006.

The bathymetry of the year 2006 serves as reference situation. This bathymetry is modified in the different sandbank scenarios and the results of the model runs are compared to the reference situation. No other parameters are changed, so variations in current velocities and water levels can be clearly referred to the hydraulic measures.

B. Model Validation

The validation of the original model TRIM has already been carried out for San Francisco Bay, California [2]. They found that the model is stable and computationally efficient. As an extended version of the original model TRIM is used, further model validations are implemented. Comparisons between the model outputs and measured values of the applied model for the Elbe Estuary have shown that there is a good agreement in current velocities between modelled and measured values. On the other hand, comparisons of modelled and measured water levels show that the low tide is underestimated. This is caused by the uncertainties of the water level boundary data. For this reason modifications of all input parameters are carried out and re-investigated. Validations resulting from modifications of the input parameters tidal amplitude and bottom friction are discussed in the following sections. Modifications of the wind will be done soon.

In a first step, model outputs of the tidal amplitude of the driving model are set 1.5-times higher and in a second step tidal amplitude is halved. Those two modifications are run for the reference scenario and the scenario 4, including four sandbanks. First model results of the reference scenario with the ‘normal’ amplitude are compared to the reference scenario with the 1.5-times higher amplitude. Results show that the 1.5-times higher amplitude leads to an increase of about 0.6 m in mean maximum high water level at the different monitoring stations (Table 1). Mean minimum low water level decreases on average about 0.39 m, mean maximum flood current velocity increases about 0.23 ms^{-1} and mean minimum ebb current velocity increases about 0.11 ms^{-1} at the different monitoring stations. The same results can be found for scenario 4.

Furthermore effects of scenario 4 with the modified amplitude (difference between scenario four and the reference scenario, in each case with increased amplitude of 1.5) on water level and current velocity are considered. The differences are in the same order of magnitude like those of the scenario 4 with the ‘normal’ amplitude.

The second part of the validation is made up by modifications of the bottom friction. In the reference situation the bottom friction is set in the whole investigation area to the roughness length 10^{-5} m. This constant is firstly modified to a roughness length of 10^{-6} m and secondly to a roughness length of 10^{-4} m. Both modifications are run for the reference situation and scenario 4. A reduction of the friction from 10^{-5} m to 10^{-6} m in the reference scenario leads to an increase in mean maximum high water level of about 0.12 m and a decrease in mean minimum low water level of about 0.14 m at all monitoring stations (Table 1). Maximum flood current velocity increases about 0.12 ms^{-1} and minimum ebb current velocity increases about 0.09 ms^{-1}. For scenario 4 (with modified roughness length) the same values are found.

An increase of the bottom friction from 10^{-5} m to 10^{-4} m in the reference scenario leads to a decrease in mean maximum high water level of about 0.14 m and an increase in mean minimum low water level of about 0.13 m at all monitoring stations. Maximum flood current velocity decreases about 0.13 ms^{-1} and minimum ebb current velocity also decreases about 0.10 ms^{-1} (Table 1). For scenario 4 (with modified roughness length) similar values can be found.

Furthermore effects of scenario 4 with modified friction (difference between scenario 4 and the reference scenario, in each case with increased/decreased friction) on water level and current velocity are considered. Effects on water level as well as effects on current velocity remain in each case almost the same as in the model runs with the ‘normal’ friction.

The results of the model runs with modified amplitude and bottom friction show that the model is sensitive to changes of input parameters. Furthermore it could be demonstrated that - even if some input parameters are changed - the differences between the reference scenario and scenario 4 remain almost the same as in the runs with the original parameters. As for the purpose of this study only differences between the reference situation and the sandbank scenarios are considered it could be shown that simplified assumptions like treating the bottom friction as a constant have no influence on the accuracy of the results.

Table 1 Differences between the modified and the original scenarios. Differences are means of the seven monitoring stations (Reference: authors design).

Scenario	**Modification**	**Mean max. HW level (m)**	**Mean min. LW level (m)**	**Mean max. flood CV (ms^{-1})**	**Mean max. ebb CV (ms^{-1})**
Reference	1.5 Amplitude	0.60	-0.39	0.23	0.11
Scenario 4	1.5 Amplitude	0.59	-0.39	0.22	0.10
Reference	Friction 10^{-6}	0.12	-0.14	0.12	0.09
Scenario 4	Friction 10^{-6}	0.12	-0.14	0.12	0.09
Reference	Friction 10^{-4}	-0.14	0.13	-0.13	-0.10
Scenario 4	Friction 10^{-4}	-0.13	0.13	-0.13	-0.10

V. Results

To investigate the efficiency of the different scenarios differences in water level and current velocity between the reference scenario and the sandbank scenarios are analyzed. As an indication for the effectiveness of the sandbank scenarios the resulting maximum and minimum values are relevant and therefore discussed.

A. Efficiency of sandbank scenario 1-4

First the effects of sandbank scenario 1-3 on maximum high water and minimum low water level at the different monitoring stations are investigated. Results show that on average none of these sandbank scenarios has a significant influence on maximum or minimum values. There is also no change in mean maximum high and mean minimum low water level when all sandbanks are simulated together (scenario 4).

In a second step effects of sandbank scenario 1-3 on current velocity are examined. Sandbank scenario 1 and 2 as well as scenario 3 has on average no significant influence on maximum flood current or ebb current velocity at the different monitoring stations. Scenario 4 also causes no significant change. Summarized even though all sandbanks have a relatively great volume none of them shows a significant influence on water level or current velocity at the different monitoring stations.

To explain this flood and ebb currents are considered. Fig. 2 shows the differences in flood currents between the reference scenario and scenario 4 on October the 1st of the year 2006 at 3 AM. The differences in flood currents are in the whole investigation area relatively small (1 to 4 cms^{-1}). Only in the vicinity of the sandbanks and in the north western part of the Elbe Estuary greater differences can be detected. During the ebb tide two of four sandbanks fall completely dry (sandbanks of scenario 1). Hence, the sandbanks have no influence on the hydrodynamic regime of the Elbe Estuary during the maximum ebb tide (Fig. 3). The remaining two sandbanks lead to modifications of the ebb currents in the surrounding areas. Largest modifications can be detected in the Medemrinne.

This leads to the conclusion that the different sandbanks of sandbank scenario 1-4 cause changes in currents and water levels during the flood tide in the vicinity of the sandbanks in the mouth of the Estuary but show small effects in the further upstream parts of the study site. Hence an attenuation of the incoming tidal energy along the Elbe Estuary cannot be achieved.

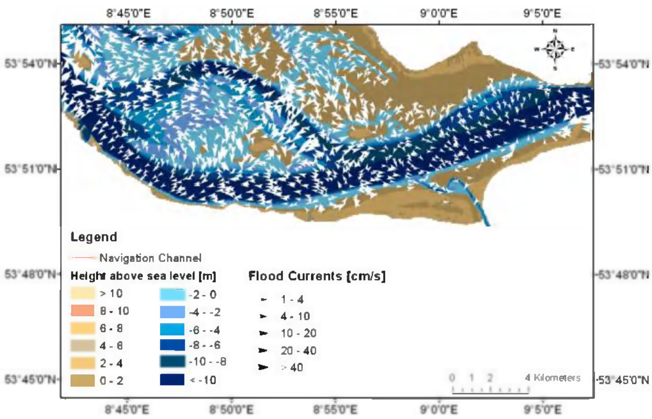

Figure 2. Differences in flood currents [cm/s] between the reference scenario and the scenario 4 on October the 1_{st} in the year 2006 at 3 AM (Reference: Authors design).

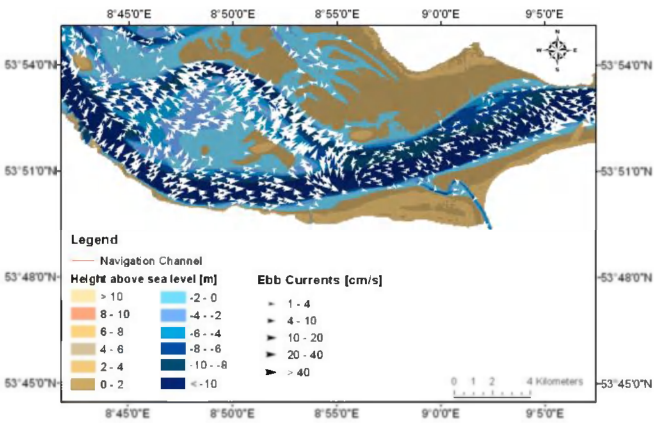

Figure 3. Differences in ebb currents [cm/s] between the reference scenario and the scenario 4 on October the 1_{st} of the year 2006 at 10 AM (Reference: Authors design).

B. *Efficiency of the hypothetical sandbank scenario 5*

As the sandbank scenarios 1-4 show no significant influence on water level and current velocity at the seven monitoring stations a fifth sandbank scenario of larger extend is investigated. This scenario is a hypothetical enhancement of scenario 1 and leads from the northern margin of the Elbe River to the navigation channel (Fig. 1). This scenario is classified as hypothetical as an implementation will be impossible due to nautical, nature conservation and legal feasibility reasons.

Again, differences in water level and current velocity between the reference scenario and the scenario 5 are analyzed. Fig. 4 shows that mean maximum high water level decreases at all monitoring stations about 12 cm. Mean minimum low water level increases at the different monitoring stations between 4 to 16 cm (Table 2). Differences in current velocities could be also found. Mean maximum flood current velocities decrease in the upper part of the Elbe Estuary (monitoring station LZ1, D1-D4) up to 6 cms^{-1}. In the lower part, at the monitoring station LZ3, an increase in mean maximum flood current velocity of about 33 cms^{-1} can be detected. Mean maximum ebb current velocity also increases at the monitoring station LZ3 but experiences in mean a decrease at the other monitoring stations (2 to 7 cms^{-1}).

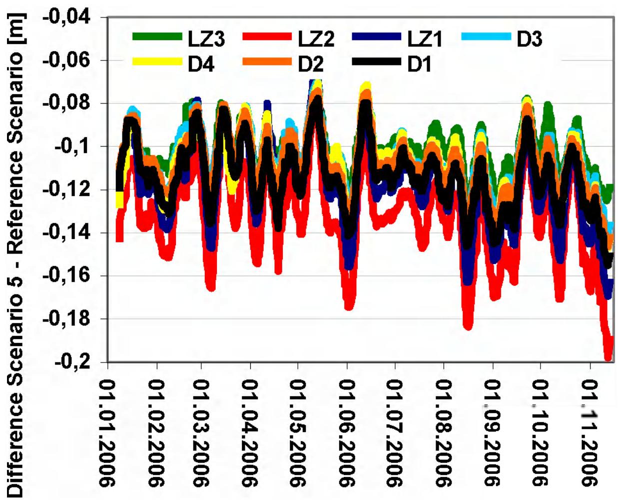

Figure 4. Differences between scenario 5 and the reference scenario: 7-Days moving average of maximum high water level [m] (Reference: Authors design).

Table 2 Differences in water level and current velocity between scenario 5 and the reference scenario at the different monitoring stations (Reference: Authors design).

Variable / Station	LZ3	LZ2	LZ1	D4	D3	D2	D1
Mean Maximum HW Level [m]	-0.10	-0.13	-0.12	-0.11	-0.11	-0.11	-0.11
Mean Mininum LW Level [m]	0.04	0.16	0.16	0.15	0.14	0.14	0.14
Flood Current Velocity [ms^{-1}]	0.33	0.01	-0.02	-0.02	-0.05	-0.06	-0.06
Ebb Current Velocity [ms^{-1}]	0.07	-0.07	-0.05	-0.02	-0.05	-0.05	-0.03

C. Climate change simulations

In the next step the efficiency of the sandbank scenarios under different climate change conditions is investigated. In the framework of this paper three different climate change scenarios were considered. First the year 2025 with a sea level rise of 30 cm in comparison to the reference year 2006 was simulated. In a second and a third step effects of a sea level rise of 50 cm (year 2055) and of 90 cm (year 2085) were investigated (Fig. 5).

To show the effects of the sandbank scenarios under climate change conditions differences in water level and current velocity between the reference scenario and the scenario 4 are analyzed. Fig. 6 shows the effects on mean maximum high water and mean minimum low water level at the monitoring station D1 for the second part of the years 2025, 2055 and 2085. Sandbank scenario 4 leads in the different climate change scenarios to a decrease of mean maximum high water level of 1 cm in comparison to the reference scenario. Mean low water level increases in all scenarios 1 cm in comparison to the reference scenario. Sandbank scenario 4 also has almost no effect under the different climate change conditions on flood and ebb current velocity at the monitoring station D1. The mean maximum flood current velocity remains the same and the mean maximum ebb current velocity shows a mean increase of 1 cms^{-1} (not shown). Considering the other investigated monitoring stations (D2-D4 and LZ1-LZ3) sandbank scenario 4 also has no influence under a rising sea level on water levels and current velocities.

The effects of sandbank scenario 4 on water level and current velocity under varying climate change conditions hence agree with the results of the reference year 2006.

An attenuation of the incoming tidal energy along the Elbe Estuary under rising sea level conditions hence cannot be achieved.

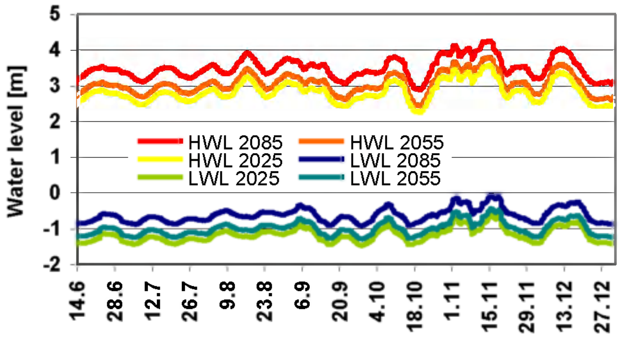

Figure 5. Climate change scenarios: 30 cm SLR (year 2025), 50 cm SLR (year 2055) and 80 cm SLR (year 2085) (Reference: Authors design).

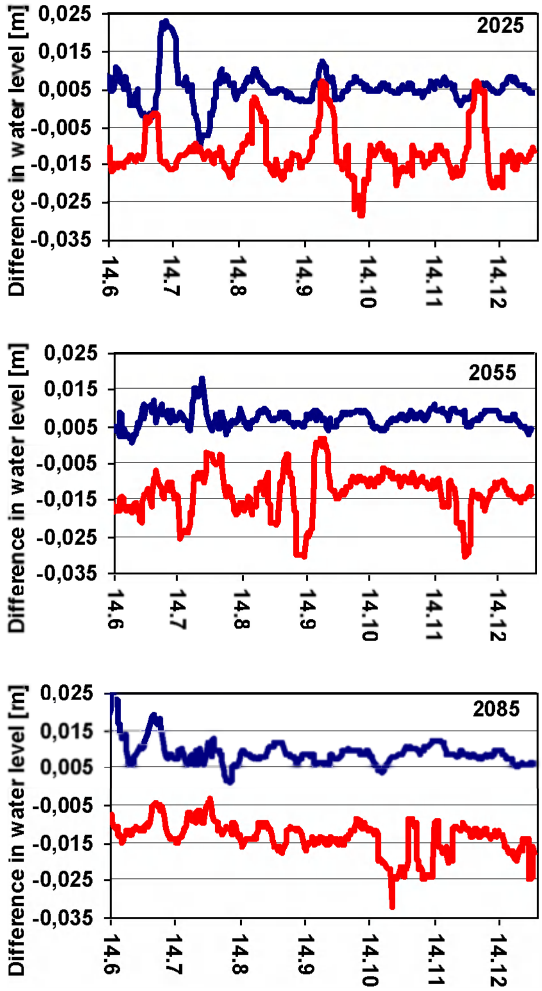

Figure 6. Differences between scenario 4 and the reference scenario at the monitoring station D1: 7-days moving average of maximum high (red) and minimum low (blue) water level for the years 2025, 2055 and 2085 [m] (Reference: Authors design).

VI. Discussion

By engineering works in the past the tidal system of the Elbe has been modified resulting in a higher tidal range and increased current velocities. One possible option to reduce this incoming energy is to reflect it in the mouth of the Estuary. One hydrodynamic measure is the construction of artificial sandbanks. Analysis of the simulations of the first four sandbank scenarios show that they cause modifications of water levels and current velocities in their surroundings in the mouth of the Elbe Estuary. In contrast further upstream those hydrodynamic measures have no significant influence on water level and current velocities. Analysis of ebb and flood currents suggests that the different sandbanks do not sinificantly reflect the tidal wave, but modify the current fields in the vicinity, which leads to a redirection of the tidal energy. In a second step a hypothetical fifth sandbank scenario is carried out. As investigations show this sandbank leads to significantmodifications of the water level and the current velocities. As the fifth sandbank closes the Medemrinne, an important channel for the water body, the incoming tidal energy is partly reflected. In the southern part of the sandbank the water is redirected through the navigation channel. This leads to an increase in current velocities at the nearest located monitoring stations.

VII. Conclusion and outlook

Five different sandbank scenarios in the mouth of the Elbe Estuary have been simulated in the framework of this paper. The aim was to investigate if they could be used to damp the tidal energy along the Elbe River in order to get safer coasts. As results show the first four sandbank scenarios only lead to a redirection of the incoming tidal energy. Water levels and current velocities are only modified in the vicinity of the sandbanks. Only a large reduction of the hydraulic cross-section of the mouth as in scenario 5 produces significant effects in water elevation and currents throughout the estuary.

As the fifth scenario is only a hypothetical one, further investigations of various sandbank scenarios are necessary. Furthermore the efficiency of the sandbank scenarios under storm surge conditions will be analyzed.

Acknowledgments

The support of the European Commission through FP7.2009-1, Contract 244104 - THESEUS ("Innovative technologies for safer European coasts in a changing climate"), is gratefully acknowledged.

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