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Artificial sandbanks in the Elbe Estuary mouth: a method for surge mitigation?

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Within the framework of different EU framework research projects (THESEUS and TIDE), investigations of the efficiency of artificial sandbanks in the mouth of the Elbe estuary for the mitigation of tidal energy and a better storm surge protection were carried out. The efficiency of the artificial sandbanks was analysed by means of two- and three-dimensional hydro- and morphodynamic models. The models calculate the water level and current velocities as well as the transport of dissolved constituents under mean and storm surge conditions. To allow the investigation of the effects of the artificial sandbanks on the water level and currents in the inner estuary, a high spatial grid resolution was used. Overall results of the investigations are presented and an outlook on how those measures can contribute to innovative risk mitigation is shown.

Keywords: estuaries; flood protection; numerical simulations; tidal energy; coastal engineering

Introduction

Estuaries and coastal areas are among the most densely populated areas of the world. They play an important role in terms of industry, agriculture, trade, tourism and settlement, to mention some key sectors. Today these areas already suffer from various problems such as erosion, flood risk and long-term habitat deterioration. 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.

The Elbe estuary plays an important role for Northern Germany and functions, for example, as a major federal waterway. The whole Elbe River has undergone several anthropogenic changes since the sixteenth century like diking and river regulations. These modifications led in combination with natural changes in hydrodynamics to an unfavourable hydro-morphological evolution, namely, to an increase in the tidal energy and the tidal pumping further upstream.

Investigation area

The investigation area as a whole comprises the Elbe estuary and the inner part of the German bight. The border in the west is defined by the island of Scharhörn and Trischen at the border to the North Sea (Elbe-km 740) and in the east by the weir Geesthacht (Elbe-km 588). Politically the investigation area comprises many responsibilities, that is, the city of Hamburg and the adjoining federal states Lower Saxony and Schleswig-Holstein. The river Elbe has its source in the Czech republic and reaches the North Sea at Cuxhaven after 1094 km. The entire catchment basin of the Elbe covers 148,268 km². As long as no storm-tide conditions prevail, the tidal influence of the Elbe estuary is limited by the Geesthacht weir (Freitag et al. 2008).

The long-term yearly mean freshwater run-off is ~700 m³/s, in a range from 150 up to 4060 m³/s. The most frequent freshwater run-off is in the range of 300 to 400 m³/s. Tides are semi-diurnal with a marked diurnal asymmetry. The mean tidal range decreases from 3 m at the inlet to 2.7 m 50 km up-estuary, and rises again towards the port of Hamburg, where it attains its maximum of 3.6 m and falls to 2 m at the Geesthacht weir. Spring high tides exceed neap high tides by about 0.7 m from the inlet to Hamburg, while the difference between spring and neap low tides can only be felt up to 50 km from the mouth. The estuary can be classified as a mesotidal and partially mixed coastal plain estuary. The influence of wind during a storm event with winds from a north-westerly direction leads to considerable increases in the tidal high water (HW) levels. While the water level and salinity in an estuary have a uniform large-scale distribution, current velocity is a parameter which varies strongly with space and time. This factor leads to a tidal pumping of sediments from the lower reaches of the Elbe to areas further upstream, resulting in insufficient water depths in the navigation channel and harbour basins (Boehlich & Strotmann 2008).

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Objectives and modelling approach

General approach

The basic idea within the framework of the European projects THESEUS (Monbaliu et al. 2014) and TIDE (Meine & Schultz-Zehden 2013) is to dampen the incoming tidal energy already in the mouth of the estuary. This mitigation approach may allow reducing the water levels along the estuary and in Hamburg by introducing artificial sandbanks in the mouth area of the Elbe. Two different types of artificial sandbanks were investigated:

- Emerged sandbanks (crest above HW).
- Submerged sandbanks (crest below low water (LW)).

In total seven sandbank configurations, which are called scenarios in the following, were tested. The criteria for the selection of the sandbank scenarios (emerged and submerged) were the following:

- Nautical implications.
- Geomorphological aspects.
- Availability of sandy material for the construction.
- Stability and sustainability of the layout.

In the following, the different sandbank layouts are described in terms of location and size. Figure 1 shows the locations of the investigated emerged and submerged sandbank scenarios.

In Table 1 the amounts of sand of the different scenarios are specified, which give an indication of the impact on the hydraulics.

Scenario 1 consists of two artificial sandbanks on wadden areas in the outer estuary separated by a tidal channel. Their influence is confined to the part of the tide when the water level is above the wadden area. Scenario 2 is a dam in the foreland on the southern bank located upstream of scenario 1 at the end of the funnel-shaped part of the outer estuary. The most seaward sandbank is scenario 3, a single sandbank located directly at the margin of the deeper fairway near Cuxhaven. Scenario 4 comprises scenarios 1–3. Scenario 5 is a dam including the sandbanks of scenario 1 blocking the mouth of the estuary excluding the fairway. This scenario is highly hypothetical and was introduced as an extreme test case. Scenarios 6 and 7 are submerged sandbanks. Scenario 6 consists of a partial filling of tidal channel between the sandbanks of scenario 1. Scenario 7 comprises two submerged sandbanks similar to two large groynes in the vicinity of scenario 1.

Hydrodynamic modelling approach

For hydrodynamic modelling, the TRIMNP (Tidal, Residual, Intertidal Mudflat Model Nested Parallel Processing) was applied (Cheng et al. 1993). The depth-averaged 2-d 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 was used (Casulli & Walters 2000). The governing equations include the conservation equations of mass, momentum, conservative scalar variables and an equation of state.

To investigate the effects of the artificial sandbanks on water level and currents, a spatial resolution of 50 m was used. The time domain of the simulations was the year 2006, which includes all water level variations such as mean conditions, spring and neap tides as well as storm surge conditions. The model was driven by outputs (water level and current velocity) of the 3-d operational circulation model of the German Federal Maritime Office (BSH) on the north western open boundary. The BSH model calculates currents, water levels, water temperatures, salinity and ice cover. The grid spacing in the German bight is 1.8 km. Model inputs are current meteorological conditions, tides and river run-off as well as external surges which enter the North Sea from the Atlantic Ocean.

On the upstream boundary of the model, freshwater inflow is another forcing parameter. The input data here are daily values of discharge measured at Neu Darchau (~53 km upstream of the weir Geesthacht). In addition, the meteorological wind forcing was imposed on the whole model domain. The bathymetry of the year 2006 serves as a reference situation. This bathymetry was modified in the different sandbank scenarios and the results of the model runs are compared to the reference situation. No other parameters were changed, so variations in current velocities and water levels can be clearly referred to the hydraulic measures (Sothmann et al. 2011).

Wave modelling approach

For a sustainable design of the artificial sandbanks, not only knowledge of the current fields, but also that of the wave climate in their vicinity is essential. As the wave propagation within the coastal area of the Elbe estuary is strongly influenced by the coastal morphology with its islands, bars, shoals and channels, wave attack on the sandbanks was simulated with numerical model SWAN (Simulation Waves Nearshore, TU Delft). This model solves the predominant processes in the application zone such as shoaling, bottom friction, breaking, refraction, wind generation and, to some extent, diffraction of waves. A comparison of numerical simulations results with SWAN (Ris et al. 1994; Ris 1997) and field data shows good agreements.

The time-dependence of the action balance equation is neglected in this investigation, although SWAN contains a non-stationary mode. The action balance equation was solved in SWAN with a full discrete 2d wave-spectrum

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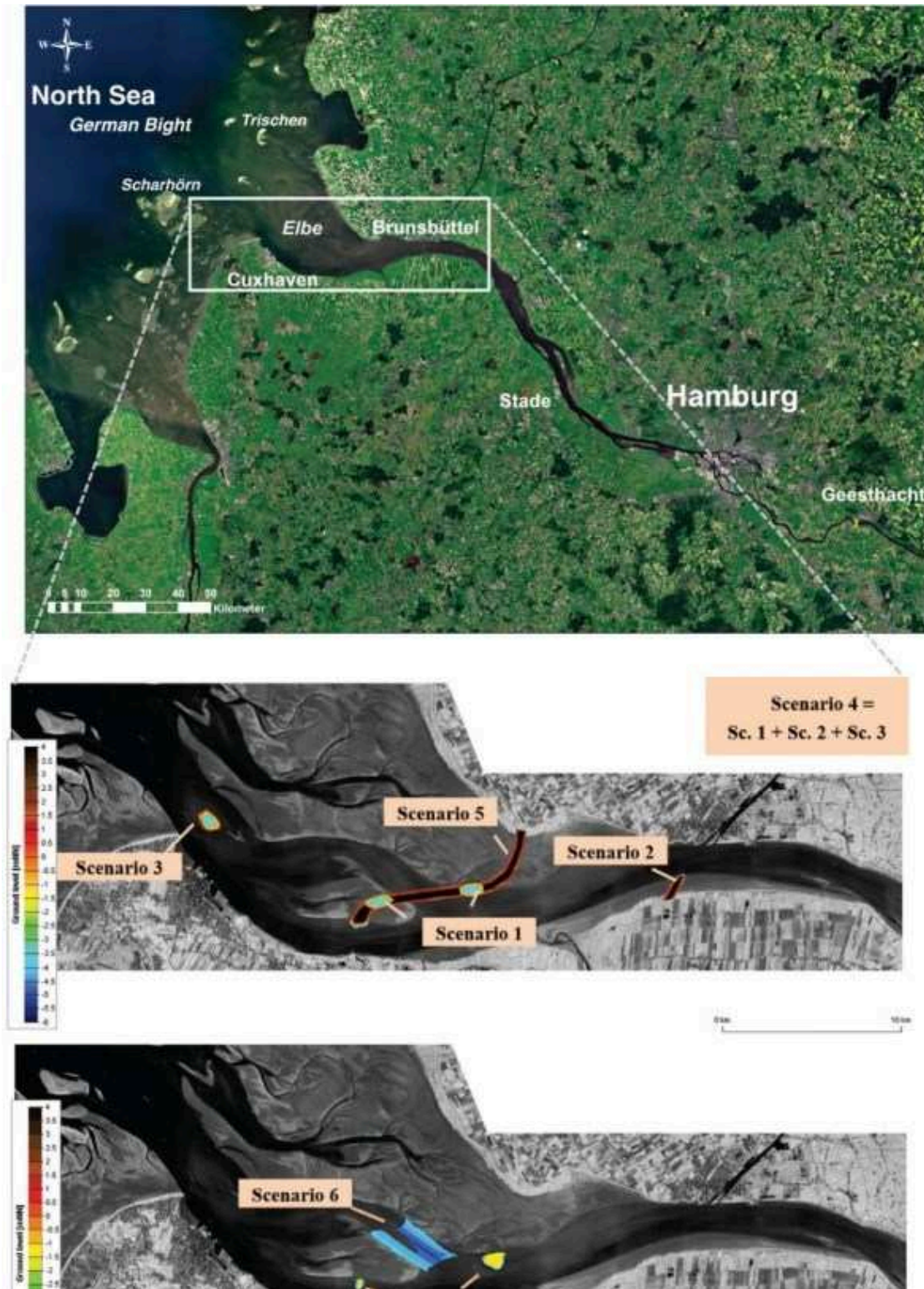


Figure 1. Location of emerged (upper panel) and submerged sandbanks (lower panel) within the mouth of the Elbe estuary.

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#	Scenario name	Volume of sandbanks (Mio. m ³)	Volume above mean LW (Mio. m ³)
1	Medemsand and Neufelder Sand	3.6	3.6
2	Brunsbüttel	2.0	2.0
3	Cuxhaven	3.1	3.0
4	All sandbanks	8.7	8.6
5	Dam	33.9	24.3
6	Medemrinne with UWA	15.8	3.6
7	Submerged sandbanks	6.1	0.1

Table 1. Volume of sand needed for the construction of the investigated scenarios in the mouth of the estuary.

$N(x, y, \sigma, \theta)$ using an iterative four-sweep technique allowing wave propagation in all directions in the entire geographical domain. Using the parametric frequency spectrum, the action balance equation is separated into evolution equations for the zero-order moment and the first-order moment of action-density spectrum. For the numerical simulations with SWAN, boundary conditions for several wind and water level conditions were applied on the open seaward boundary and the model domain to calculate the wave conditions within the model.

Sandbank design criteria

The stability and sustainability of the sandbank layouts are mainly influenced by the wave and current attack in the construction area. Overall, wave heights depend significantly on the individual location with varying water depth, wind speed, wind direction and wind fetch length, respectively, within the model area. The input wave height turns out as little or non-significant, for the wave height within the study area. The bank slopes and bank protections were designed with the above-described wave boundary conditions to be sustainable over a long time period. Nevertheless, for the overall sustainability of the sandbanks, also the active large-scale morphodynamics in the mouth of the Elbe estuary have to be taken into account.

The model results show that the tidal flood currents are generally higher than the ebb currents. The maximum flood currents were, for example, ~ 2 m/s in the investigated scenario 1 for both sandbanks. The calculated ebb currents amount up to ~ 1 m/s (also scenario 1) and vary at different locations. While the flood current field is almost homogenous in space, maximum ebb currents oc-

cur at the southern tips of the sandbanks. Compared to the wave attack, the influence of the tidal currents is of second-order importance for the stability of the sandbanks. The analysis also showed that the orbital velocities are negligible and, therefore, these were not further considered in the analysis.

Results

The efficiency of several artificial sandbank scenarios was investigated by comparing the time series of HW levels and maximum current velocities at four monitoring stations along the Elbe estuary (Figure 2). The height datum NN describes the German geodetic datum and represents today the mean sea level plus approximately 30 cm. Tidal LW levels were also calculated but are not discussed here, because the emphasis of the paper is on flood protection. The effects of the scenarios on LW levels are in the same order as on HW levels.

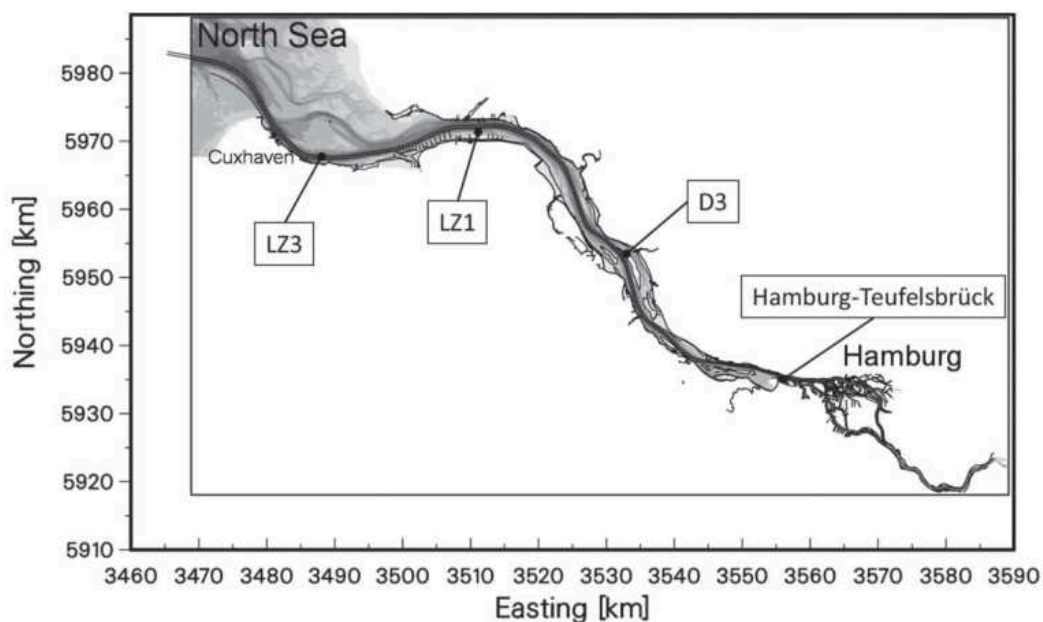


Figure 2. Locations of the monitoring stations along the Elbe estuary.

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Scenario 1: Medemsand and Neufelder sand

The scenario 'Medemsand and Neufelder Sand' (scenario 1) consists of two sandbanks on intertidal areas at both sides of the tidal channel Medemrinne. The crests of the sandbanks are at NN +4.0 m.

The volume of the sandbanks is approx. 3.6 Mio. m³. In Figure 3 the effects of the sandbanks on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe Estuary from the mouth to Hamburg. The time series show differences between the sandbank scenario and the reference situation in 2006, which have been smoothed by a 14 days moving average. Even when applying the moving average, there is a lot of variation in the HW levels at all stations with an amplitude of some 5 cm and no clearly defined offset or trend. There are no effects on maximum current velocities.

Scenario 2: Brunsbüttel

The sandbank for scenario 2 'Brunsbüttel' is a structure like a finger rising from the south bank of the Elbe opposite the town of Brunsbüttel. The crest of the sandbank is at NN +4.0 m. The volume of the sandbank is approx. 2.0 Mio. m³. This sandbank is at the most upstream position of all sandbanks under investigation. In Figure 4 the effects of the sandbank on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe from the mouth to Hamburg.

The time series of the simulation show only small differences between the sandbank scenario and the reference situation in 2006 (smoothed by a 14 days moving average). In this scenario, the fluctuation in HW levels is most pronounced at station D3. There is some hint of a general decrease in HW levels at stations LZ1 and Hamburg-Teufelsbrück, but within the accuracy of the model results the change in HW levels is insignificant at all stations. There is an increase in maximum current velocities of 2 cm/s at station LZ1 some 5 km up-estuary of the sandbank, but there are no changes at the other stations and in the receptor area Hamburg.

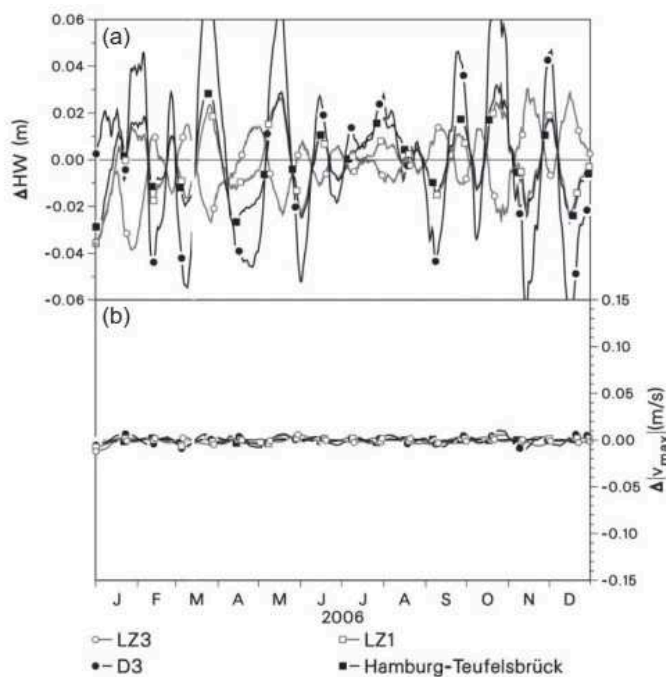


Figure 3. Effects of scenario 1 'Medemsand and Neufelder Sand' on tidal HW level (a) und maximum tidal current velocity (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück.

Curves represent differences between the sandbank scenario and the reference situation in 2006.

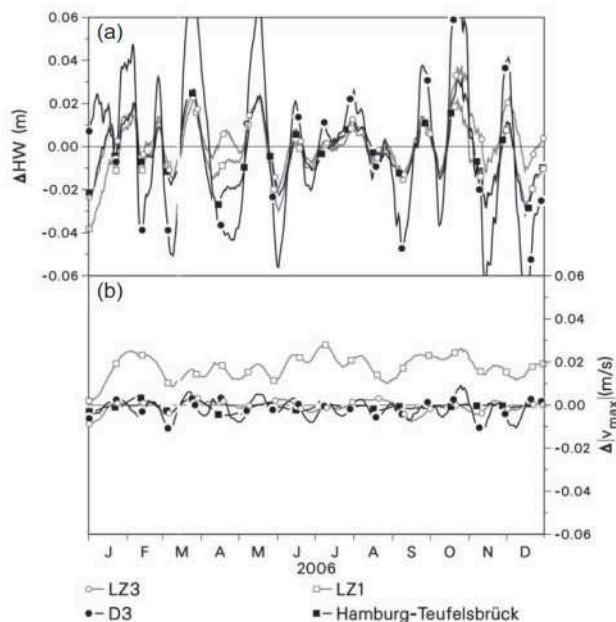


Figure 4. Effects of scenario 2 'Brunsbüttel' on tidal HW level (a) und maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

Scenario 3: Cuxhaven

The sandbank of scenario 'Cuxhaven' (scenario 3) is an island located right at the river mouth on a wadden area opposite of Cuxhaven. The crests of the sandbanks are on NN +4.0 m. The volume of the sandbank is approx. 3.1 Mio. m³ as large as the sandbanks of scenario 1. In Figure 5, the effects of the sandbank on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe Estuary from the mouth to Hamburg.

As in scenario 2, the time series show only small differences between the sandbank scenario and the reference situation in 2006 (again smoothed by a 14 days moving average). In this scenario, the fluctuation in HW levels is mostly pronounced at stations LZ3 and D3. There is a general decrease in HW levels of some 1 cm at all stations and there is a minimal decrease in maximum current

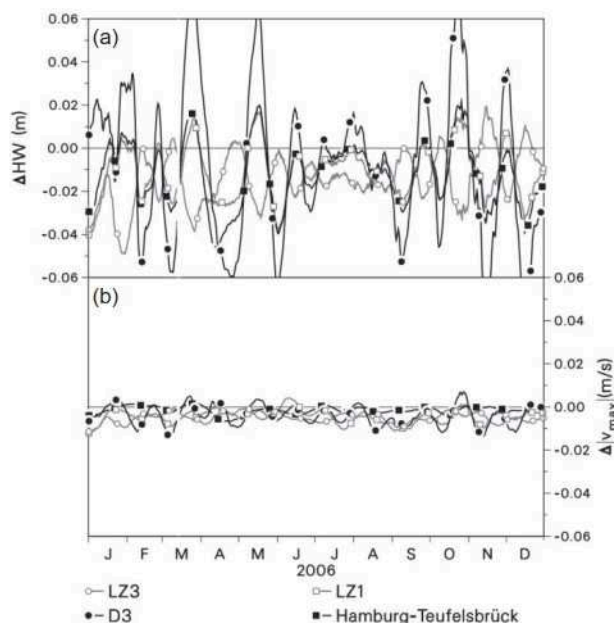


Figure 5. Effects of scenario 3 'Cuxhaven' on tidal HW level (a) and maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

velocities (<1 cm/s) at all stations except the station Hamburg-Teufelsbrück.

Scenario 4: all sandbanks

In scenario 4 all sandbanks of the first three scenarios are combined. The crests of the sandbanks are on the same level (NN +4.0 m). The combined volume of the sandbanks is about 8.7 Mio. m³. In Figure 6, the effects of the combination of all sandbanks on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe from the mouth of the estuary to Hamburg. The time series of this scenario show a change in the differences between all sandbanks and the reference situation in 2006, which was again smoothed by a 14 days moving average. In this scenario, the fluctuation in HW levels is mostly pronounced at the outer stations LZ3 and LZ1. There is a general decrease in HW levels of some 2–3 cm at all stations. This is attended by an increase in maximum current velocities at the outer stations (1–3 cm/s) and a decrease of 1–2 cm/s at the inner stations D3 and Hamburg-Teufelsbrück.

Scenario 5: dam

Scenario 5 is the most extreme and a strongly hypothetical one. The intention of such a scenario is to explore the limits of what can be gained by the construction of artificial sandbanks to affect the tidal energy. The dam scenario closes more or less the mouth of the Elbe with the exception

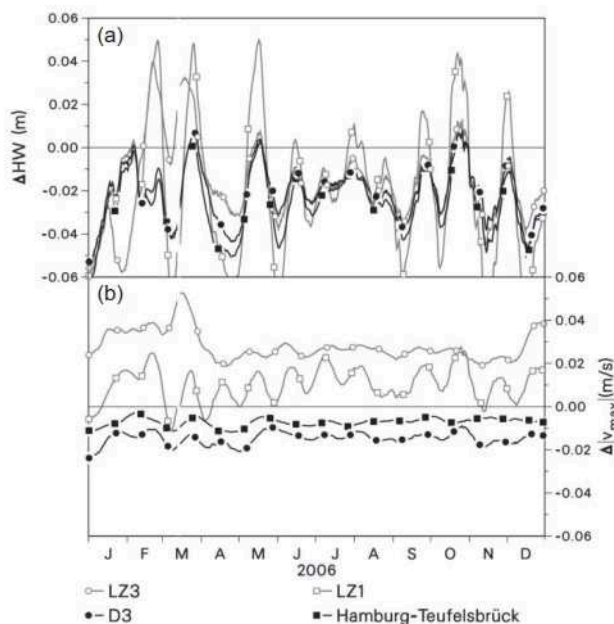


Figure 6. Effects of scenario 4 'All sandbanks' on tidal HW level (a) and maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

of the navigation channel. Starting from a position on Medemgrund just opposite of LZ3, the dam incorporates the sandbanks of scenario 1, obstructs the Medemrinne and ends at the northern bank. The crest of the dam is again at NN +4.0 m and the total volume of the dam is about 33.9 Mio. m³. In Figure 7 the effects of the dam on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe Estuary from the mouth to Hamburg.

The time series show higher differences between the sandbank scenario and the reference situation in 2006 (smoothed by a 14 days moving average). Since in this scenario the effects on HW levels are an order of magnitude greater than that in the previous ones, the scale of Figure 6(a) has been modified. There are large fluctuations in HW levels at all stations and a decrease in HW levels of 10–13 cm. The most significant reduction in HW levels is achieved in the receptor area Hamburg. For the maximum current velocities, there is also a small decrease at all stations up-estuary of the dam, while at station LZ3 an increase of some 3–4 cm/s (e.g. 3%) is observed.

Scenario 6: Medemrinne with UWA

The scenario 'Medemrinne with UWA' (scenario 6) includes the sandbanks of the scenario 'Medesand and Neufelder Sand' (scenario 1) and an underwater deposition area, called UWA in the Medemrinne. The UWA is a planned structure of the next channel adaptation, in which some of the dredged material will be permanently

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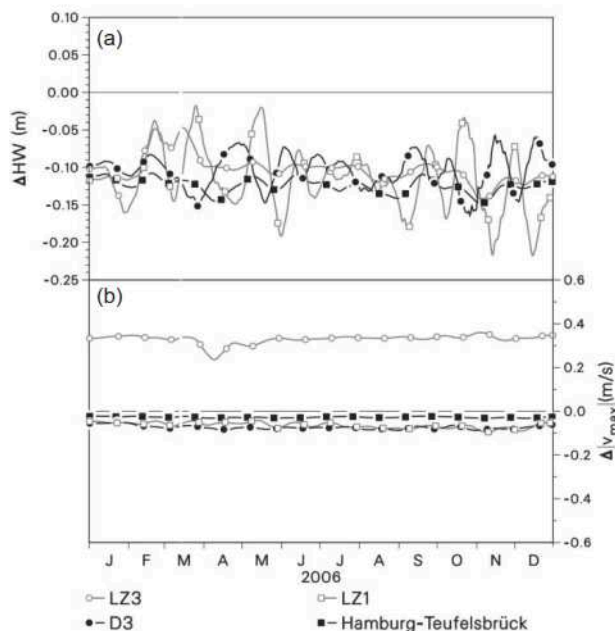


Figure 7. Effects of scenario 5 'Dam' on tidal HW level (a) und maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

deposited. Since the effect of the islands in scenarios 1–4 on HW levels in Hamburg (<3 cm) resulted in a very limited improvement of flood protection, this scenario was also chosen to investigate the possible better performance of submerged sandbanks. The surface of the UWA is at a water depth between NN –3.6 m and NN –5.1 m and its volume is approx. 12 Mio. m³. Together with the 2 sandbanks, this results in some 15.8 Mio. m³ artificial sandbank volume. In Figure 8, the effects of the two sandbanks and the UWA on HW level (a) and maximum current velocity (b) are displayed at four stations along a transect of the Elbe Estuary from the mouth to Hamburg.

The time series show smaller differences than the dam scenario (again smoothed by a 14 days moving average). The results are quite different from scenario 1 (see Figure 3) and indicate that the effect of the UWA considerably outweighs that of the two islands. Again there are large fluctuations in HW levels at the outer stations LZ3 and LZ1, but in contrast to scenario 1 there is a decrease in HW levels of 1–2 cm. The most significant reduction in HW levels is achieved in the receptor area Hamburg. For the maximum current velocities, there is also a small decrease at all stations except LZ3, where an increase of some 4 cm/s is observed.

Scenario 7: submerged sandbanks Neufelder sand and

Glameyer stack In the last scenario, scenario 7, the impact of submerged sandbanks is further analysed. Two single submerged

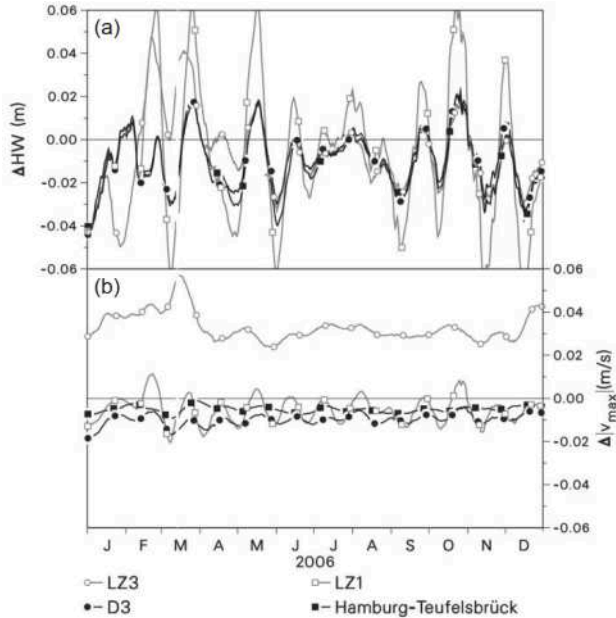


Figure 8. Effects of scenario 6 'Medemrinne with UWA' on tidal HW level (a) and maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

sandbanks are considered, which are attached to wadden areas in the north without impeding navigation in the fairway. The crests of the sandbanks are on NN -1.2 m, which is slightly higher than the mean LW level in this

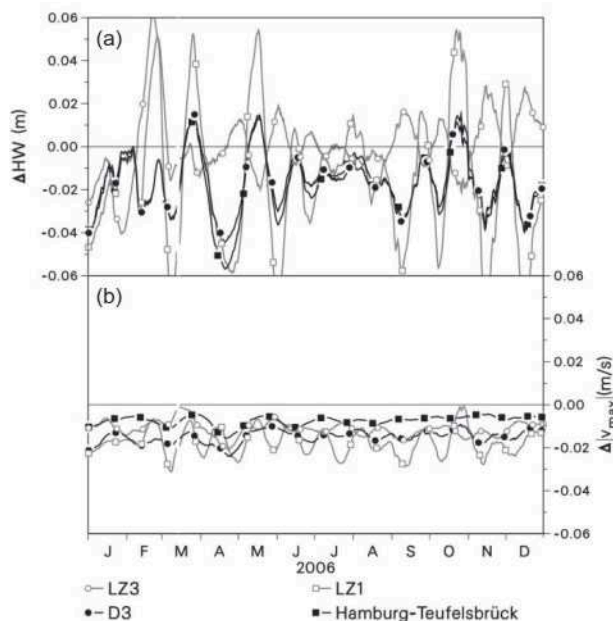


Figure 9. Effects of scenario 7: 'Submerged sandbanks Neufelder Sand & Glameyer Stack' on tidal HW level (a) und maximum tidal current velocity and (b) at stations LZ3, LZ1, D3 and Hamburg-Teufelsbrück. Curves represent differences between the sandbank scenario and the reference situation in 2006.

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area. The volume of the submerged sandbanks is in total nearly 6.1 Mio. m³, 80% of which is contributed by the eastern sandbank (Neufelder Sand). In Figure 9 the effects of the two submerged sandbanks on HW level (a) and max. current velocity (b) are displayed at four stations along a transect of the Elbe estuary from the mouth to Hamburg.

The time series show again only small differences between the sandbank scenario and the reference situation in 2006 (smoothed by a 14 days moving average). The effects of the submerged sandbanks on HW levels are even stronger than in the preceding scenario, although the volume of the sandbanks is only half of the UWA. Again there are large fluctuations in HW levels at the outer stations LZ3 and LZ1 and a general decrease in HW levels of some 2 cm. The most significant reduction in HW levels is also achieved in the receptor area Hamburg. For the maximum current velocities, there is also a small decrease at all stations. There is no increase at LZ3 as in scenario 6, which might be attributed to the reduction in the hydraulic cross section of the Medemrinne.

Summary and conclusions

The effects of the seven different sandbank scenarios (mean year 2006 conditions) in the receptor area Hamburg are summarised in Table 2 in terms of changes in the annual mean and standard deviation. Decreases with respect to the reference situation (no sandbanks) have a positive value; a negative value indicates an increase.

The results of the investigations suggest that artificial sandbanks in the mouth of the Elbe estuary may dampen the tidal energy to some extent. Their effectivity in this respect does not so much depend on their geographical position, but on their elevation. Nor does the effectiveness in general increase with the introduced amount of sand, for example, the volume of the sandbanks. More important for the effects on the hydraulics is how the different scenarios dampen the incoming tidal wave.

For the majority of the investigated scenarios, the reduction in HW level in Hamburg amounts to less than 3 cm compared to a tidal range of 3.6 m. Scenarios 1 and 2 seem to have negligible influence on the HW level in Hamburg, because the sandbanks are located on wadden areas which already dampen the tidal wave to a large extent.

In general the dissipation or redirection of the incoming tidal energy at the river mouth is not achieved to an extent which would be relevant for flood protection in Hamburg. There are local modifications of the current fields and the water elevations in the vicinity of the sandbanks, but the tidal wave in the estuary as a whole is very little affected. Only the highly hypothetical dam scenario produces the desired reflection and damping of the tidal wave and a 10% decrease in HW levels in Hamburg.

Keeping the nautical and environmental constraints in mind, it must be stated that there are narrow margins for constructions in the mouth of the Elbe to influence the HW levels in and near Hamburg. In general, the effects of sandbank scenarios depend on the specific shape and topography of the estuary and have to be investigated individually.

#	Decrease in HW level in area Hamburg (cm: annual mean)	Decrease in HW level in area Hamburg (cm: standard deviation)	Decrease in max. Flow velocity in area Hamburg (cm/s: annual mean)	Decrease in max. Flow velocity in area Hamburg (cm/s: standard deviation)
1	0	2	0	1
2	0	2	0	1
3	1	3	0	1
4	3	3	1–2	1
5	10–13	4	< 1	1
6	1–2	2	0	1
7	2	3	1	1

Table 2. Summary of the effects of the various sandbank scenarios on tidal HW levels and maximum tidal current velocity v_{max} at station Hamburg-Teufelsbrück under current conditions (reference year 2006).

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