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HARBASINS Report:

# Identification of the spatial effect of solid structures on the hydro- and morphodynamics in the Ems-Dollard estuary by applying mathematical modeling

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# 1 Introduction

In coastal areas and particularly in estuaries or areas such as the Wadden Sea, there is a lack of procedures for the identification of ‘Heavily Modified Water Bodies’ (HMWB) according to the water framework directive (WFD) of the European Community. Aim of the investigation is to identify water bodies by comparable standardized methods, e.g. by applying mathematical models.

Currently, the assessment criteria concentrates on the area of impact, but this approach may be insufficient when alterations to current regimes may affect salinity levels and sediment transport in areas outside of the direct impact zone.

Aim of work package 4 “Hydro- and Morphological Pressures and Impacts” in the HARBASINS project is to generate process-based knowledge on these effects by high-resolution mathematical modelling in combination with the analysis of hydro- and morphodynamical parameters. Ultimately, it is intended to establish a modelling strategy to identify the spatial scale of potential HMWBs.

The Ems-Dollard estuary covering the area from the East Frisian Islands as far upstream as the tidal barrier at Herbrum in the Lower Ems is selected as the study area for this purpose.

The preceding HARBASINS reports ‘Set-up of a hydrodynamic model of the Ems-Dollard Estuary’ (HERRLING & NIEMEYER, 2007b) and ‘Set-up of a morphodynamic model of the Ems-Dollard Estuary’ (HERRLING & NIEMEYER, 2008b), respectively describe the set-up of the 2DH hydrodynamic model and the implementation of the morphological module used for the calculation of sediment transport and bottom evolution.

This report focuses on the application of the morphodynamic model identifying the spatial impact of solid structures on the estuarine morphology. The most remarkable solid structure in the Ems-Dollard estuary is the Geise training wall separating the Emder Waterway from the Dollard Bay. It has a total length of about 12 kilometres and was constructed for navigational purposes. The approach is to remove the schematization of the Geise training wall of the model and compare the resulting effect on current velocities and morphology to another model scenario still having included the structure.

The model is run with a continuously updating bathymetry, such as tidal currents affect the movable bottom by sediment transport processes and vice-versa. Bathymetrical changes being the effect of morphological adaptations to the removal of the structure can be identified and highlighted. Mayor interest is not to model the exact quantity of sediment that is relocated due to changes in current regime, but the spatial scale and extension of the morphological alterations that occur. Based on these spatial alterations, the impact of the solid structure can be delimited in space and thus a comparable criterion for the objective identification of a potential HMWB is achieved.

# 2 Area of investigation

The investigation area is located at the Dutch-German North Sea coast and covers the Ems-Dollard estuary as a whole. The seaward limit is close to the 20 meter depth-line in the outer estuary; the landward limit is at the tidal barrier at Herbrum in the Lower Ems. The study area is marked by all geomorphological features characteristic for this type of coastline: deep tidal channels and inlets, inter-tidal flats and the inner estuarine environment (Fig. 1). The morphology in the Ems-Dollard estuary is not stable. Natural and anthropogenic processes induce continuous sedimentation and erosion or the migration of tidal channels and gullies.

The actual mean tidal range in the Ems estuary has a bandwidth between 2.4 m at the island of Borkum increasing to its maximum of 3.5 m at Papenburg and decreasing upstream to 2.7 m at the tidal border at Herbrum (Fig. 2).

The salinity remains nearly constant at Borkum for mean tidal and freshwater conditions. Further upstream it reduces gradually up to Leer (Fig. 3). Contradictory, the concentration of suspended matter increases upstream of Borkum reaching its maximum of about 400 g/m³ between Jemgum and Leer (JONGE, 2000).

The bed sediment composition in the Ems-Dollard estuary varies between very high cohesive sediment contents (> 75%) on the intertidal flats and the margins of the Dollard Bay to very low cohesive sediment contents (< 2%) in the estuarine inlet and the offshore areas. The content of cohesive sediments is strongly dependent on the degree of exposure to currents and waves. The remaining sediment percentage mainly consists of fine to coarse sands, while larger grain sizes are found in the tidal channels and the estuarine inlet.

In the section between Knock and Leerort fluid mud occurs in the near-bottom layer leading to density and viscosity variations over the vertical. The state of aggregation of fluid mud, changing between rather solid and fluid, and thus its viscosity are a function of the shear stresses exerted by the currents.

Bioconsolidation, has an important influence on the stability of the top sediment layer of the intertidal flats. Different biological organisms and their secretions affect the erosion behaviour by binding the top sediment layer.

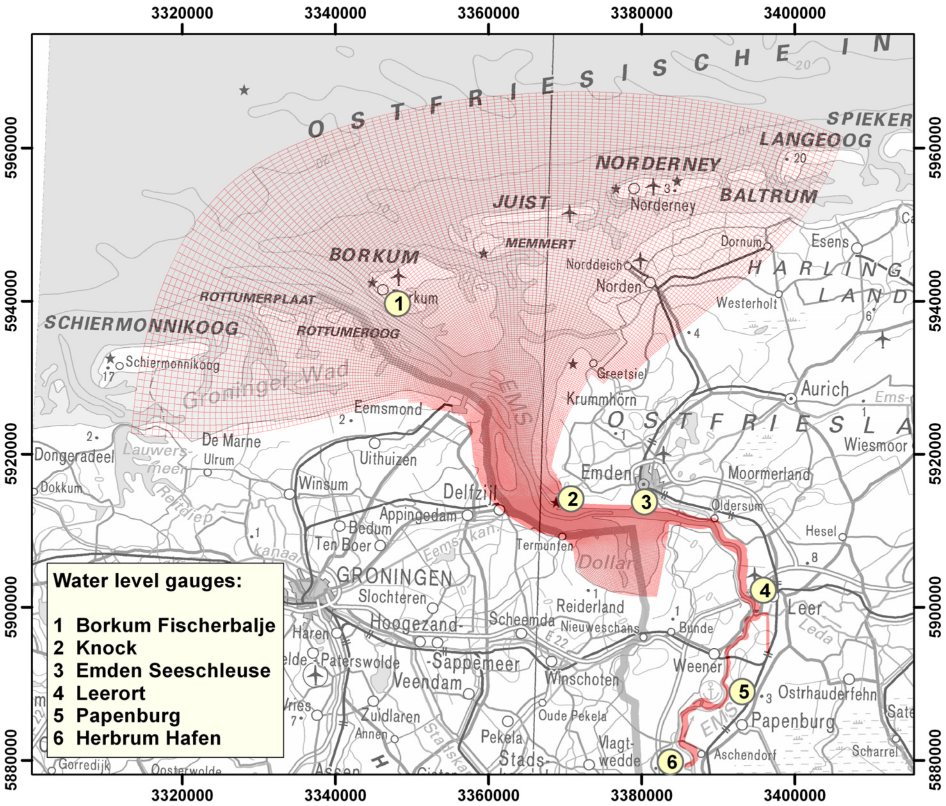


Fig. 1: Investigation area and location of water level gauges

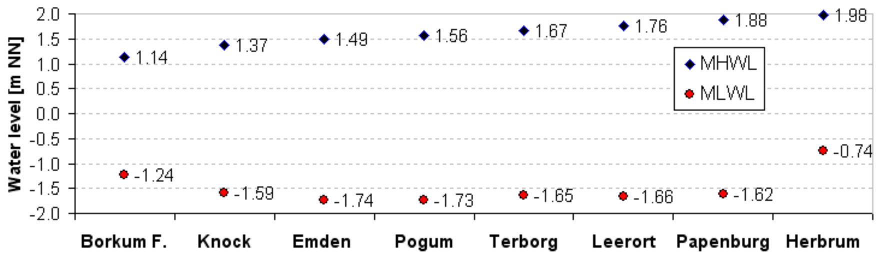


Fig. 2: Mean high water and mean low water levels (MHWL and MLWL) at gauges along the Ems-Dollard estuary for the period from 2001 to 2005

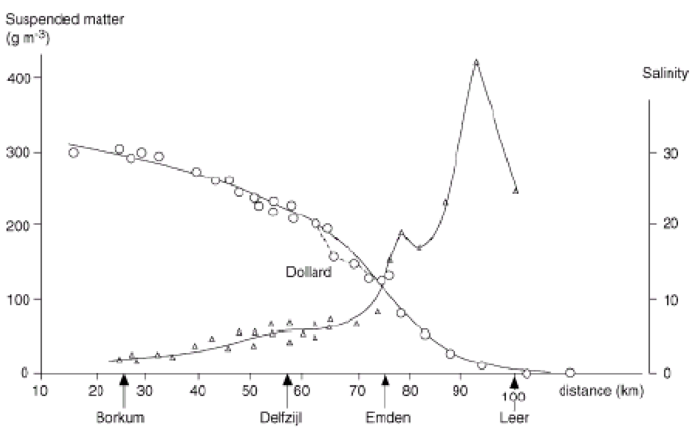


Fig. 3: Longitudinal gradient in suspended matter (mg/l) and salinity (ppt) (JONGE, 2000)

# 3 Geise training wall – solid structure in the Dollard Bay

## 3.1 Description of the structure

The Geise sand bank separates the Waterway of Emden from the Dollard Bay (Fig. 4). In particular the solid constructions as groins, dams and training walls being built to fix the waterway for navigational purposes and to stabilize the elongated Geise sand are responsible for its accretion and extension towards West.

The accretion of sediments in the waterway to the harbor of Emden always led to problems for navigation. Beside the fixation of the waterway against channel migration, the solid structures were intended to concentrate strong downstream flows on the navigational channel in the hope of flushing out the accumulated sediments. But until today, additional maintenance dredging is needed to ensure the required channel depth.

Hydrodynamic measures were built successively starting in 1871 by the construction of 13 groins on the sand bank. By 1900 the groins were connected by rubble-mound dams. From 1900 to 1935 a sheet pile wall was rammed in the sand in North of the old dams suffering from silting up. This training wall with a total length of 5.3 km extended the original construction by additional 2 km to the West and had initially a crest height of about 1.5 meters above Mean Low Water Springs (MLWS). In 1958 to 1969, a training wall of a length of 12 km was built from Pogum to the existing Geiseweststeert at the western point. The crest was at about Mean High Water (MHW). This finally separated the hydrologic systems Dollard and Lower Ems, the latter being elongated until the western end of the Geise sand. (BFG, 1999)

Since then, no maintenance measures have been performed. Over the last decades, the crest of the Geise training wall lowered by 0.6 to 0.7 meters. The construction's subsidence is explained by a combination of circumstances: i.e. construction-conditioned subsidence due to the rotting of the construction's underlayer and base, subsidence of ground due to tectonic effects and the withdrawal of gas as well as the lowering of the relative level of the structure due to the secular sea level rise. The lowered crest of the construction is less resistant against the impact of currents and waves leading to erosion and the formation of small tidal gullies in the eastern part of the construction. (BFG, 1999)

Nowadays, significant parts of the Geise sand and the training wall are flooded at mean high water. Periodically, there is exchange of water over the sand; the amount depends on tide- and wind-induced current velocities and directions. But the solid construction impacts the natural morphological development by preventing possible channel migrations.

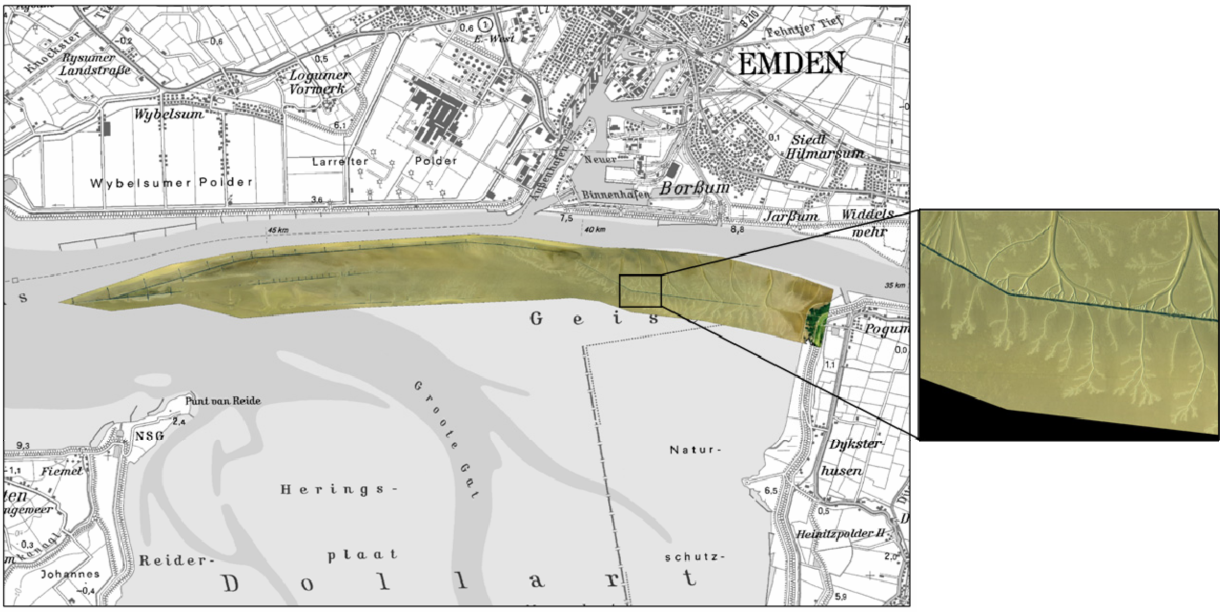


**Fig. 4: Arial photograph of the Geise sand and training wall embedded in the map of the area under consideration. The Geise training wall has a total length of 12 km.**

## 3.2 Schematisation of the structure in the model

Hydraulic structures as groins, weirs, summer dykes or training walls are obstacles for currents generating transitions from flow contradiction to flow expansion and vice versa leading to energy losses and changing flow directions.

In most cases, the size of those hydraulic structures is small compared to the size of a computational grid cell. As a consequence the solid structure cannot be schematized in the model bathymetry. In order to model their impact on the flow, the flow through a computational cell is blocked or an energy loss term is added to the momentum equation. Detailed information about the numerical implementation is given by DELFT HYDRAULICS (2006).

Large parts of the Geise sand and training wall are flooded at mean high water, allowing currents to exchange water over it. For this reason, the training wall is parameterized by “2D-gates” which do not block the flow but generate an energy loss. The energy loss is determined by the relation of the structure’s crest height to the water depth and can optionally be adjusted by a coefficient. The elevation of the training wall is defined according to available data.

# 4 Identification of the spatial effect of the Geise training wall on the hydro- and morphodynamics

Aim of the investigation is to identify the spatial effect of the Geise training wall on the hydro- and morphodynamics in the Ems-Dollard estuary by mathematical modeling. The software suite Delft3D is applied to calculate the sediment transport and bottom evolution due to tide-induced currents.

For details on the set-up of the 2DH hydrodynamic model and the implementation of the morphodynamic module it is referred to preceding HARBASINS reports (HERRLING & NIEMEYER, 2007b and 2008b).

## 4.1 Methodology

The approach being followed is to take out the schematization of the Geise training wall of the model domain and compare the resulting effect on current velocities and morphology to another model scenario having implemented the solid structure.

The initial model bathymetry being set-up for both model scenarios is based on bathymetrical survey-data about the year 2005 (Herrling & Niemeyer 2007b). Thus the schematisation of the estuarine morphology is identical for both settings, except that the Geise training wall is missing in the one model setting.

Both model calculations apply a continuously updating bathymetry. Bed shear stresses exerted by tidal currents affect the movable bed by sediment transport processes. But then bottom evolution and the formation of morphological features affect the tidal currents and vice-versa. It has to be noted that only tidal currents are considered, currents induced by waves or meteorological effects are not incorporated.

One of the complications inherent in carrying out morphological projections on the basis of hydrodynamic flows is that morphological developments take place on a time scale several times longer than typical flow changes. For example, tidal flows change significantly in a period of hours, whereas the morphology will usually take weeks, months, or several years. One technique for approaching this problem is to use a 'morphological time scale factor'. The implementation of the 'morphological time scale factor' is achieved by simply multiplying the erosion and deposition fluxes from the bed to the flow and vice-versa by this scale factor at each computational time-step. This allows accelerated bed-level changes to be incorporated dynamically into the hydrodynamic flow calculations (DELFT HYDRAULICS, 2006).

The mentioned morphodynamical calculations reproduce the period of one month, as long as two complete spring-neap-spring tidal cycles. By applying a 'morphological time scale factor' of twenty, the complete simulation is considered to reproduce the morphological adaptations of about 20 months. Exceeding this period, it turned out to be difficult to distinguish bottom evolutions whether caused by the removal of the structure or by natural transport features like e.g. underwater dunes.

Both model settings induce morphological alterations and adoptions in large parts of the model domain, thus not all bathymetrical changes are exclusively consequences to the removal of the training wall. But in case of the model scenario without the training wall, stronger tidal currents cross-flow the Geise sand and excite sediment movements.

After a simulated period of 20 months the at last updated bathymetry is extracted, respectively for each model scenario and then subtracted from each other. Those changes in bottom depth being not due to the morphological adaptation caused by the removal of the structure are eliminated by subtracting the bathymetries. The difference in bottom depth is highlighted and spatial pattern of erosion and sedimentation can be identified as the effect of the removal of the Geise training wall on the estuarine morphology.

It is not aimed to simulate the exact quantity of sediment being relocated due to changes in current regime, but it is focused on the spatial scale and extension of the morphological alterations. Based on those alterations, the spatial scale of the impact of the solid structure can be identified. Accordingly, the extent of a potential HMWB can be delimited in space.

## 4.2 Spatial effect of the Geise training wall on tide-induced current velocities

States of maximal tidal current velocities over the Geise sand are selected at flood and ebb tide to show the difference between current pattern determined respectively with and without the implementation of the Geise training wall in the mathematical model.

Maximal flood current velocities over the Geise sand occur approximately 1.5 hours before high tide (Figure 5 a, b). Considering the model scenario with the implemented Geise training wall, the sand is flooded at the mentioned state of the tide, but current velocities on the sand are rather insignificant (Fig. 5 a). Cross-currents over the Geise sand are stronger for the state excluding the training wall; in particular in the western and the middle section (Fig. 5 b). Current velocities of up to 0.5 m/s at the margins and about 0.35 m/s on the sand exert shear stresses on the bed. At the eastern part of the sand the cross-currents have similar magnitudes for both model scenarios. High current velocities in the vicinity of the schematized training wall are due to flow constrictions at small tidal gullies having found their way through subsided stretches of the rubble-mound structure.

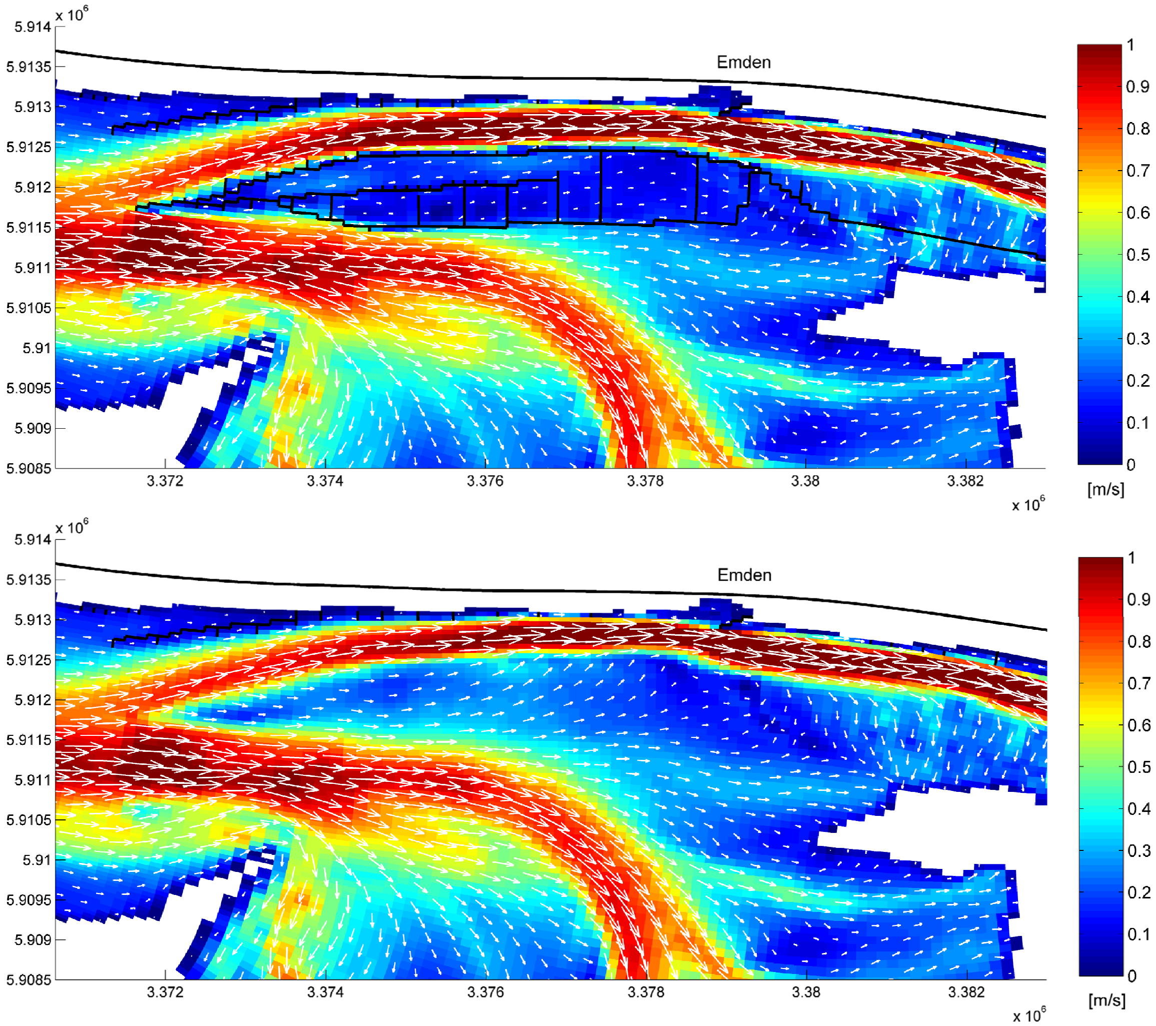


**Fig. 5 a, b: Comparison of flood current velocities [m/s] for the model state a) with and b) without the Geise training wall on July 7th 2005 at 10:30 p.m., approximately 1.5 hours before high tide. Intertidal areas or land are displayed in white colour.**

At about 2.5 hours after high tide (July 8th 2005 at 2:30 a.m.), the ebb current velocities over the western part of the Geise sand reach their maxima (Fig. 6 a, b). Running the model without the training wall, high current velocities of about 0.6 to 0.7 m/s occur at the margins and at the western tip of the sand compared to maximal ebb current velocities of about 0.4 m/s in case of the model with the incorporated structure.

At the eastern part of the Geise sand the intensity of current velocities is generally low for both model scenarios at this state of the tide. Here, the sand is connected to high elevated intertidal areas at the north-eastern side of the Dollard Bay. Large surfaces fall dry or current magnitudes are restricted due to very small water depths.

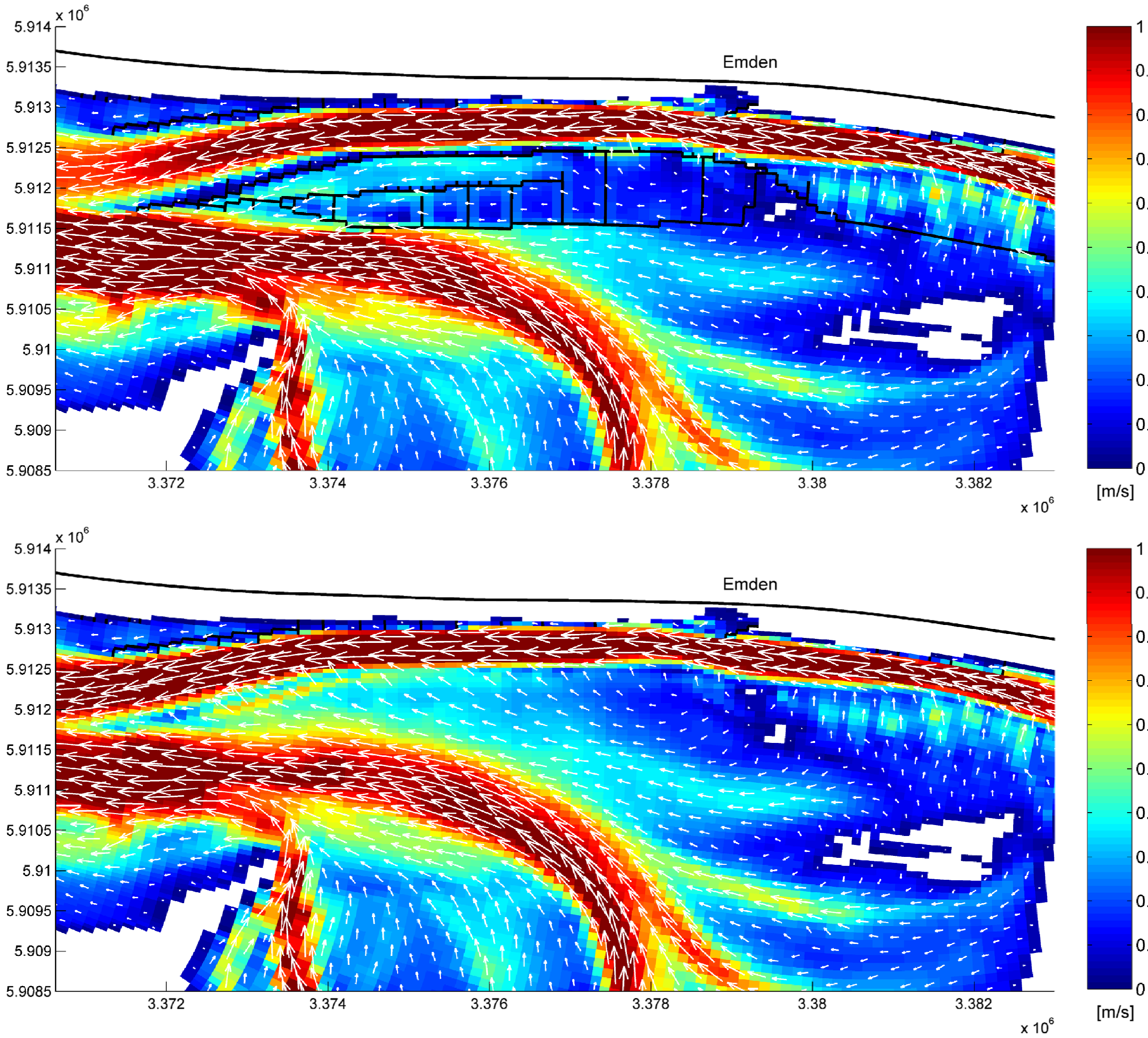


**Fig. 6 a, b: Comparison of ebb current velocities [m/s] for the model state a) with and b) without the Geise training wall on July 8th 2005 at 2:30 a.m., approximately 2.5 hours after high tide. Intertidal areas or land are displayed in white colour.**

## 4.3 Spatial alterations of the morphology due to the removal of the Geise training wall

The previous chapter focused on the differences between the current velocities due to different model settings, respectively with and without the Geise training wall. Hereafter the effect of the changed hydrodynamics is evaluated with respect to its mid-term impacts on the morphology.

When the tide-induced current velocities over the Geise sand and accordingly the bed shear stresses reach a threshold, the bed starts to move and sediment is replaced. By considering only those bottom evolutions that are due to changes in current velocities caused by the removal of the Geise training wall, the spatial effect of the structure on the morphology can be highlighted. The pattern of net erosion and net sedimentation are evaluated after the process of morphodynamical adaptation of respectively 10 and 20 months (Fig. 7 a, b).

The spatial scale of the morphological alterations is similar for the simulation period of 10 months as for the longer period of 20 months. Observed changes over time are mainly due to the quantity of displaced sediments. Within the limits of the investigation it is evaluated that as longer the calculations are performed as more sediment is displaced from one spot to another, but the spatial extent of morphological alterations does evidently not grow.

Twenty months after the removal of the training wall the Geise sand has been eroded at the south-western part in the order of 0.5 to 1.0 meters with single spots of maximal erosion of nearly 2.0 meters at the western tip of the structure. Maximal accretion of sediments is found in the immediate vicinity (Fig. 7b and 8).

The depth of the waterway of Emden tends to decrease due to sedimentation, except for rather small pattern of erosion at its edges. At Knock, the location where the channel is bended towards the estuarine mouth, the waterway slightly migrates. At the northern edge of the channel erosion is dominant, whereas directly downstream in the inner side of the bend the sediment is deposited.

The investigation shows that morphological alterations of more than 0.5 meters being the effect of the removal of the Geise training wall are only found on the Geise sand or at its edges to the flanking tidal channels (Fig. 8). Minor bottom changes in the order of 0.25 meters are noticed more seawards of the structure up to a distance of about 7 km from the western tip of the Geise training wall.

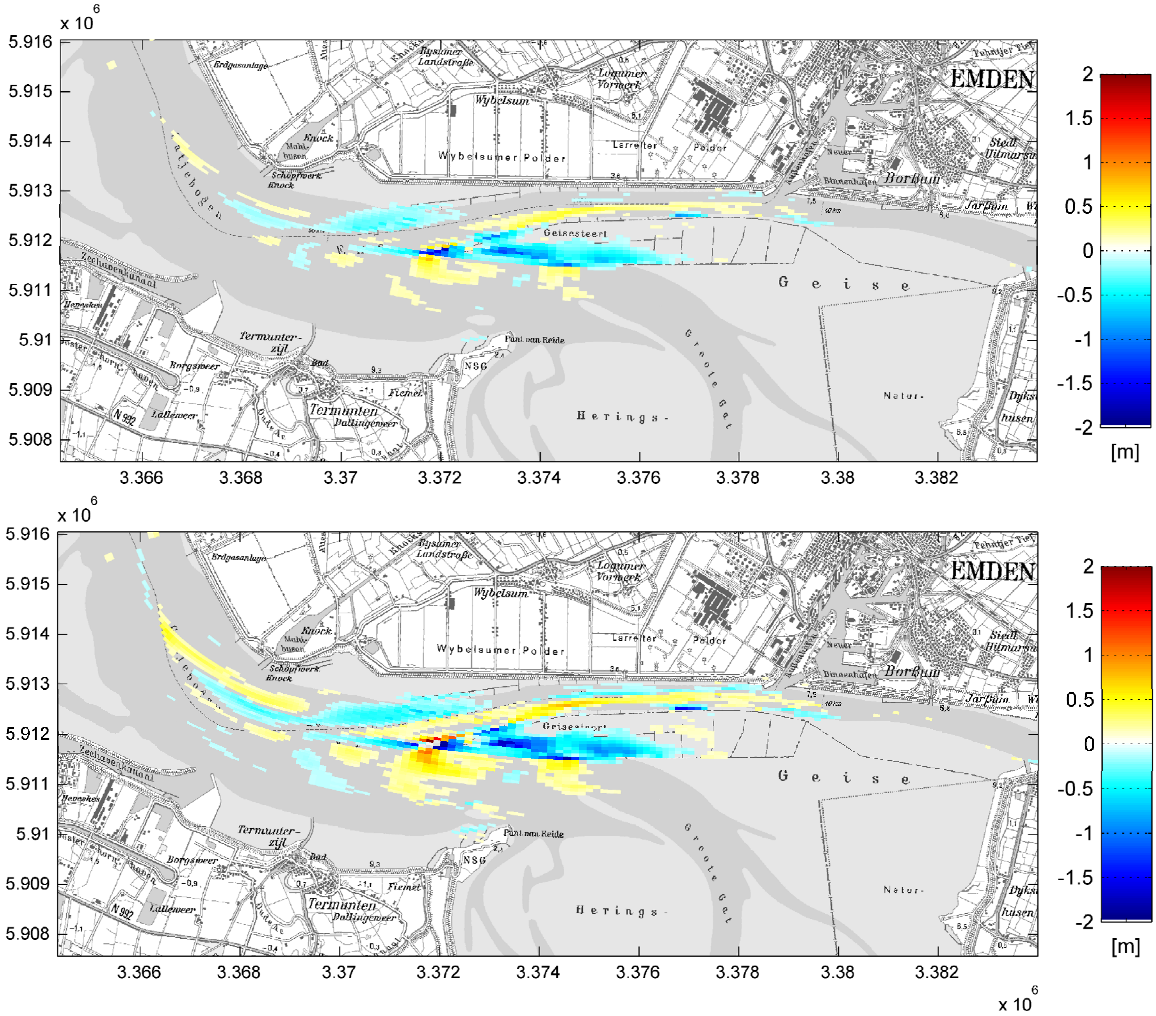


**Fig. 7 a, b: Differences between the bathymetry of the model state without and with the Geise training wall evaluated for morphodynamical adaptation of respectively a) 10 months and b) 20 months. Highlighted are areas of net sedimentation (+) and net erosion (-) as an effect of the removal of the structure.**

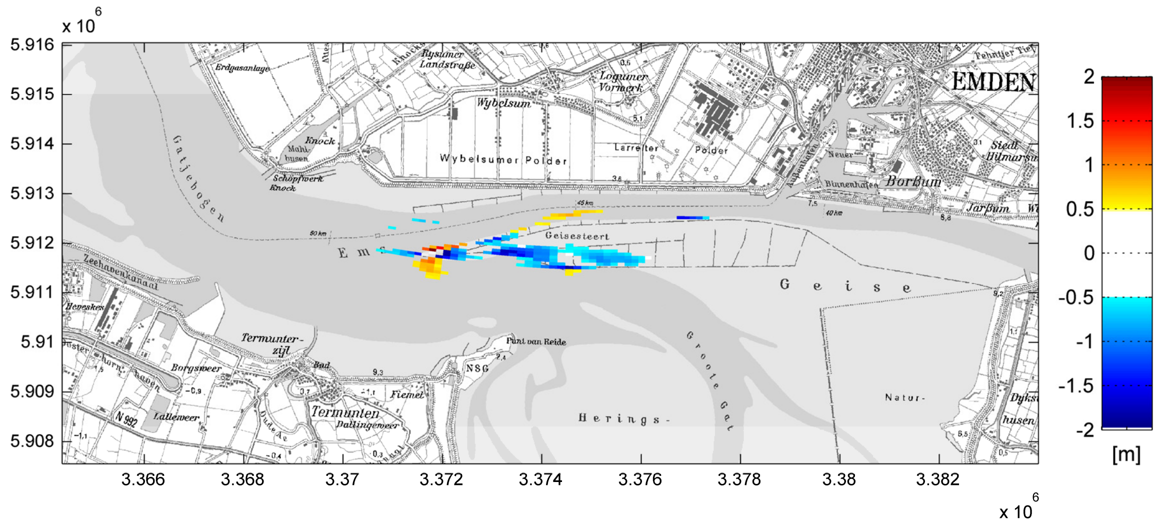


**Fig. 8: Identical to Fig. 7 b, except that areas of net sedimentation (+) and net erosion (-) are only displayed being characterized by morphological changes of more than 0.5 meters.**

# 5 Summary

The hydrodynamic model of the Ems-Dollard estuary incorporating the morphological system-module is applied in the two-dimensional, horizontal mode for the identification of impacts of solid structures on the estuarine morphology. The model area covers the entire estuary, but it is focused on the evaluation of morphological processes in the area of the Dollard Bay and in particular the Geise sand. The spatial impact on current velocities and morphological alterations due to the Geise training wall could be identified and highlighted satisfactorily.

The comparison of maximal current velocities over the Geise sand between the two model scenarios with and without the incorporated Geise training wall, respectively for ebb and flood tide, showed that significant differences in current velocities and directions only emerge at the western part of the Geise sand. In summary, except for spatially very delimited spots where the differences are in the order of 0.5 m/s, it is estimated that the cross-current velocities over and at the edges of the western sand generally double by removing the training wall. Almost no differences between the current velocities occur at the more elevated eastern sand.

Morphological adaptations due to the changes in tidal flow being caused by the removal of the Geise training wall are simulated for the period of 20 months. The model results show reasonable pattern of bottom evolution. The south-western part of the Geise sand is suffering from erosion while the removed sediment is relocated at adjacent spots. The spatial extent of the identified bottom evolutions ranging from about 0.5 to 1.5 meters covers the western Geise sand and the edges to its flanking tidal channels. Minor alterations in the order of 0.25 meters are found at the bed of the waterway of Emden from the harbour entrance as far downstream as 7 kilometers of the most western tip of the Geise training wall.

Based on the spatial extent of bottom evolutions, the impact of the solid structure on the estuarine morphology can be delimited in space and thus a comparable criterion for the objective identification of a potential HMWB is achieved.

# 6 Literature


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