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Morphodynamic Evolution in the Mouth of the Elbe Estuary: Effects of the Training Wall Construction "Kugelbake"

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ABSTRACT: The mouth of the Elbe estuary is one of the most morphodynamic active regions in the German Bight. Furthermore, the fairway in the mouth of the Elbe is a major gateway for container ships connecting the harbor of Hamburg to the world. Hence it is important to investigate the effect of man-made measures in terms of the morphodynamic reaction.
Between 1950 - 1973 and 1975 - 1978 the training wall "Kugelbake" was constructed as a dam in the mouth of the Elbe estuary. The reason was to prevent the delta-like opening of the Elbe estuary from developing a naturally formed "three channel" configuration.
After finishing the main dam for a length of about 10 km and several short transverse groins, morphological reactions have been observed in the vicinity. Amongst other reasons, the construction resulted in a deepening of the main channel and the development of many scours around it. Many efforts are needed to sustain the current configuration of the dam and the local bathymetry, which is mainly accomplished by dumping of dredged material near the dam and repairing the rock-fill embankment.

Keywords: Morphodynamics, Training wall, Dam, Construction, Erosion, Sedimentation, Elbe estuary

1 INTRODUCTION

The mouth of the Elbe estuary is one of the most morphodynamic active regions in the German Bight. The large morphological variability can be shown by the bathymetry of 1950 in contrast to 2012. Still in the first half of the 20th century within the mouth of the Elbe estuary a multi trench system could be developed without restrictions. But the requirements of navigation (purposes?) initiating hydraulic engineering constructions in the late 1930 years to stabilize the navigation channels layout in horizontal and vertical alignment. After the 2nd world war the central construction – the training wall "Kugelbake"-, located west of Cuxhaven, could be finished in 1978 in the actual configuration. Since 1968 the hydrodynamic and morphodynamic response was clearly to be seen. The main navigation channel was stabilized, but on the other hand an occurrence of scour systems in the surrounding of the construction was registered. Together with the naturally given high morphodynamic reality in the mouth of the Elbe it is a need to analyze the phenomena of the morphodynamic adaption process after the dam measurement in detail.

The present study compares hydro- and morphodynamic conditions before the construction was done (1948-1950) and the situation after finishing the training wall "Kugelbake" building. Both states are analyzed and modelled with respect to the development of the different bathymetric conditions.

Process-based hydro-morphodynamic model studies have been done to demonstrate cause and consequences of the dam building in the past.

Moreover, as the functionality of the dam is still questioned today, process studies are performed in representing a failure in the dam or the total removal of it at all.

In a *first step* the reasons and the natural consequences of the construction in 1950 are evaluated. Therefore, a bathymetry was implemented which has been reconstructed from historic sea charts. Based on this topography a numerical model is run to obtain the hydro- and morphodynamic conditions at that time. Not least the morphodynamic results in comparison to the measured bathymetry changes over a long adaption time (~ 65 years) are a good basis for validation / calibration purposes.

The *second step* calculates the consequences of a failing of the dam; as a worst-case scenario the whole dam will be removed. Will the adjacent tidal flats retreat and how will small trenches and channels react after that event? A morphodynamic calculation will be carried out and the results will be presented.

The numerical basic concept for both approaches is to set up a morphodynamic-numerical model, which comprises the tidally influenced area of the Elbe estuary and a seaward part of the German Bight which is far away from the construction und investigation.

2 SITUATION IN 1950

2.1 *Reasons for the dam construction*

The reasons to build a training wall / dam in the mouth of the Elbe estuary are manifold. But the strongest one was to concentrate the flood and ebb velocities in one tidal channel (fairway), because at that time (1940 -1950) the bathymetric situation offers two matured channels. The training wall has a length of about 10 kilometers together with several transverse groins.

2.1.1 *Bathymetry situation*

It is clearly to be seen, that at the location of the training wall in 1950 two tidal channels exist in combination with a centered sand bar (Mittelgrund) (Figure 1). This braided channel – bar situation tends to reduce the tidal velocity according to friction. For navigation reasons it is advised to generate and support a single channel configuration which denoted higher velocities in the fairway and therefore a stable channel condition.

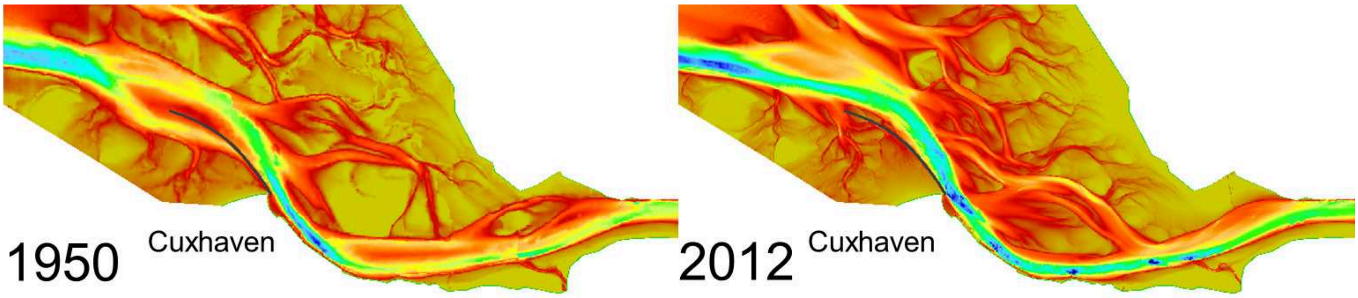

Figure 1. Comparison of the bathymetry 1950 vs. 2012 in the mouth of the Elbe estuary

2.1.2 *Hydrodynamic situation*

The braided flow situation is represented by the maximum flood and ebb velocities in the neighborhood of the dam on Figure 2. The velocities diverge around a centered sand bank in the middle of the fairway (marked with a polygon in the last third of the dam).

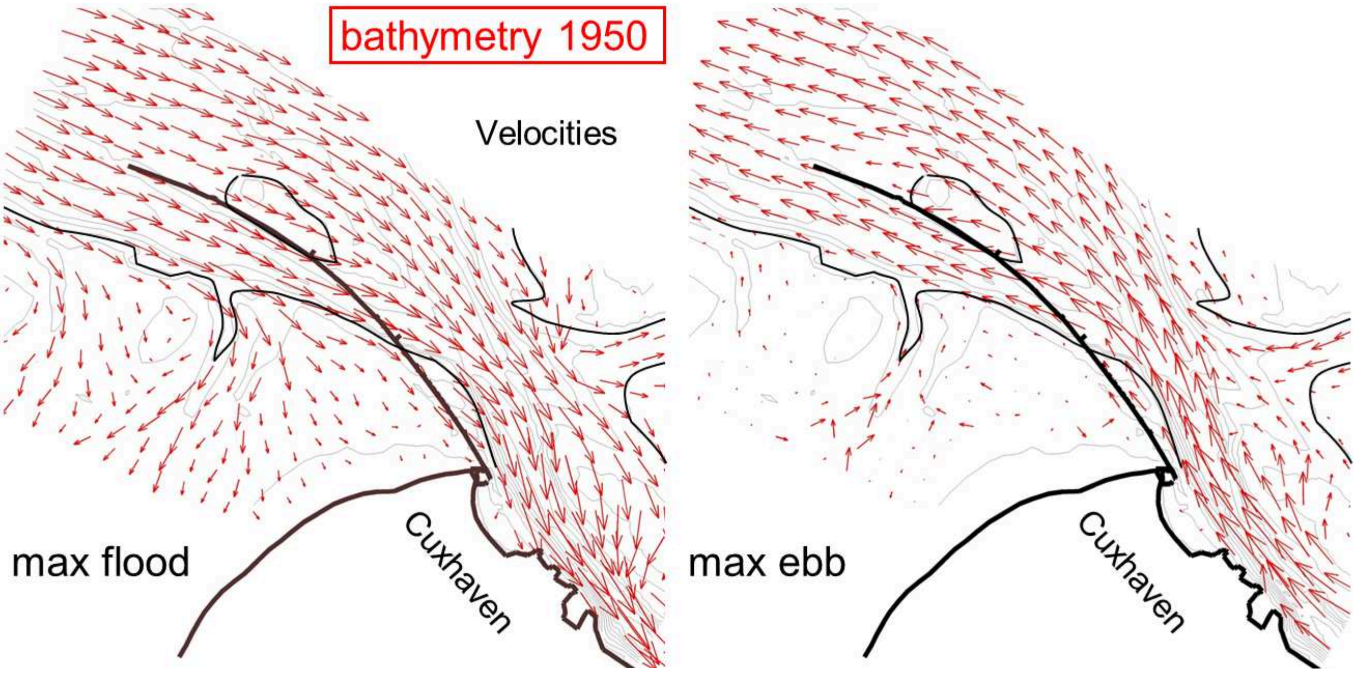

Figure 2. max flood- and ebb velocity around the training wall with the bathymetry of 1950

2.1.3 *Morphological changes after the construction of the training wall*

Between 1950 and 2012 considerable changes of the bathymetry within the opening of the Elbe estuary take place. On Figure 3 it is apparent, that in 1950 there are two branches of the fairway which are cut off by the construction of the training wall “Kugelbake”. In contrast to this, in 2012 the south-westerly part of the two trenches faded away through sedimentation processes after the dam construction. The north-easterly part (in the fairway) expanded and deepened north of the training wall.

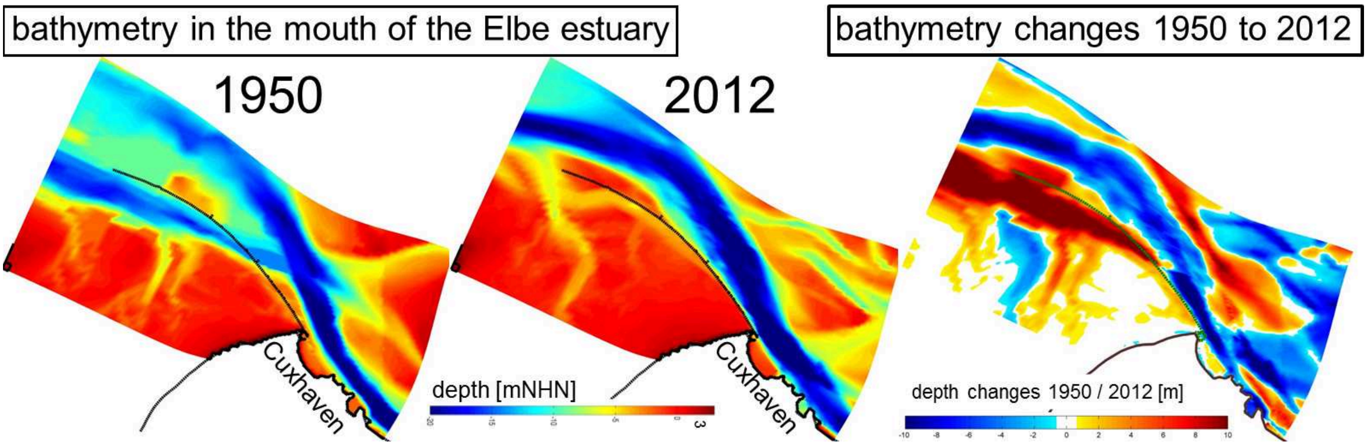

Figure 3. Measured bathymetry 1950 and 2012 and differences between 1950 and 2012

A morphodynamic simulation was done, applying DELFT3D/MOR. This simulation model comprises the whole Elbe estuary from the weir in Geesthacht up to the seaward boundary near Helgoland. Seven sediment fractions are specified for the sediment transport and morphodynamic calculation and the distribution at the bottom. The vertical resolution of the model is represented by 10 layers (σ-layer). This investigation covers a time span of 420 tides.

The calculated sedimentation process south-east of the training wall is in concordance with the measured ones. The south-east tide gully is separated from the main channel in the north after the construction of the training wall and in turn the flood- and ebb currents are minimized. This generates all in all an area of sedimentation – or less erosion (see right panel on Figure 4, highlighted by an ellipsis). So, a basic morphodynamic effect is reproduced by this morphodynamic model simulation.

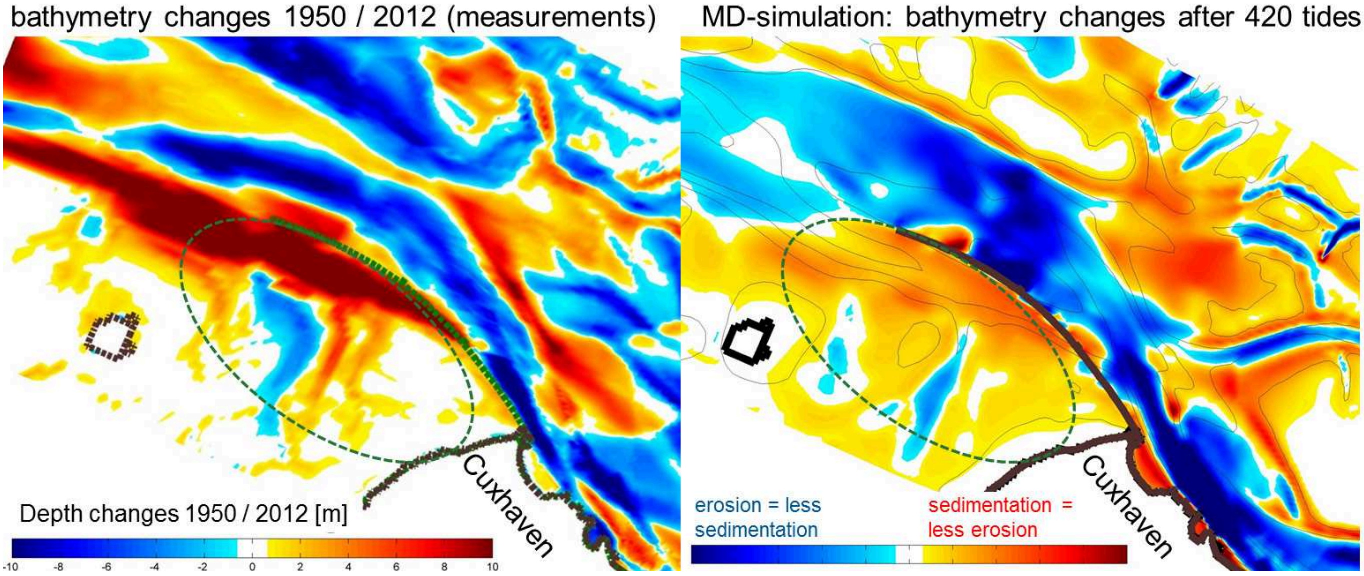

Figure 4. Bathymetry changes 1950/2012 in comparison to a morphodynamic run over 420 tides

3 NOWADAY SITUATION

The present bathymetry (year 2012) offers a total different behavior in contrast to 1950, just before the beginning of the dam construction. So, the effect of removing the training wall is not comparable to the old situation.

For this investigation an actual bathymetry was used in a 3D-hydrodynamic model (DELFT3D-FLOW [Lesser 2004]) and coupled with morphodynamic functionalities (DELFT3D-MOR). The sediment distribution and composition at the bottom was taken from a sedimentological model utilizing a database [Zeiler 2014]. The model simulation compasses 17 tidal cycles, from which the first 3 tides are used as a shake down time for sediment transport and morphodynamic.

3.1 *Bathymetry changes with / without training wall*

In a worst case scenario the total construction of the training wall is removed at all in the numerical model. So, in the surrounding area there are still some changes in the southern trench expected and built into the model (see Figure 5).

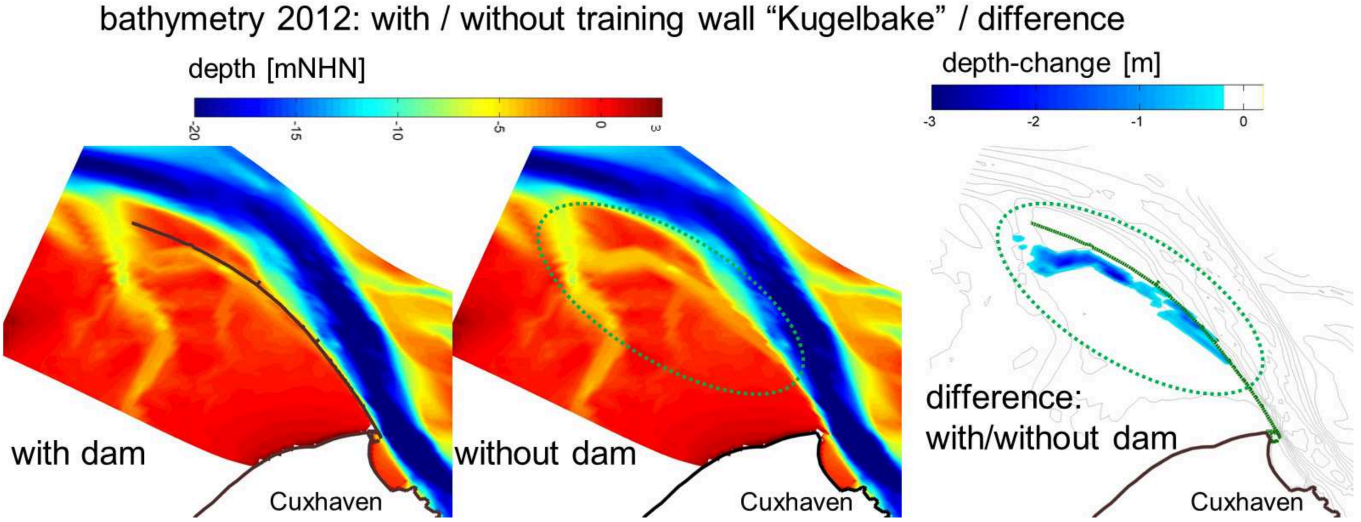

Figure 5. model bathymetry 2012 with / without training wall and difference between both situations

3.2 *Hydrodynamic situation*

In the present bathymetry only one deep fairway beneath the training wall exist; no separate branches cross the dam. Regarding to this, the typical, maximum velocities follow the constraints of the fairway (Figure 6). This is distinctly different to the situation in 1950 (Figure 2).

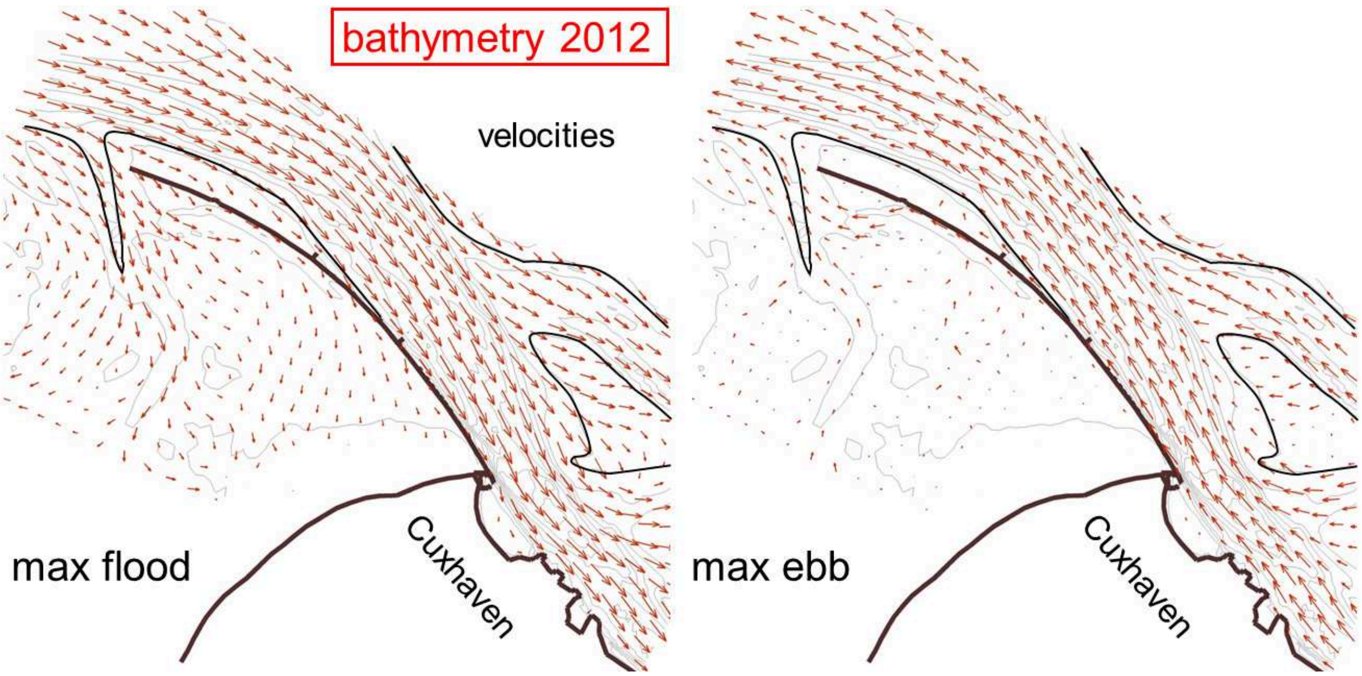

Figure 6. maximum flood and ebb velocities around the training wall with the bathymetry of 2012

3.3 *Morphological reaction after dam failure*

As a worst-case scenario of possible failure of the training wall it was assumed, that the whole construction is removed. Of course this is a strong modification of the bathymetry and as a result of this in the hydro- and morphodynamic. The morphodynamic model results after 140 tidal cycles (14 tides with a morphodynamic acceleration factor of 10) show local / regional changes in the bathymetry in the surrounding of the training wall (Figure 7).

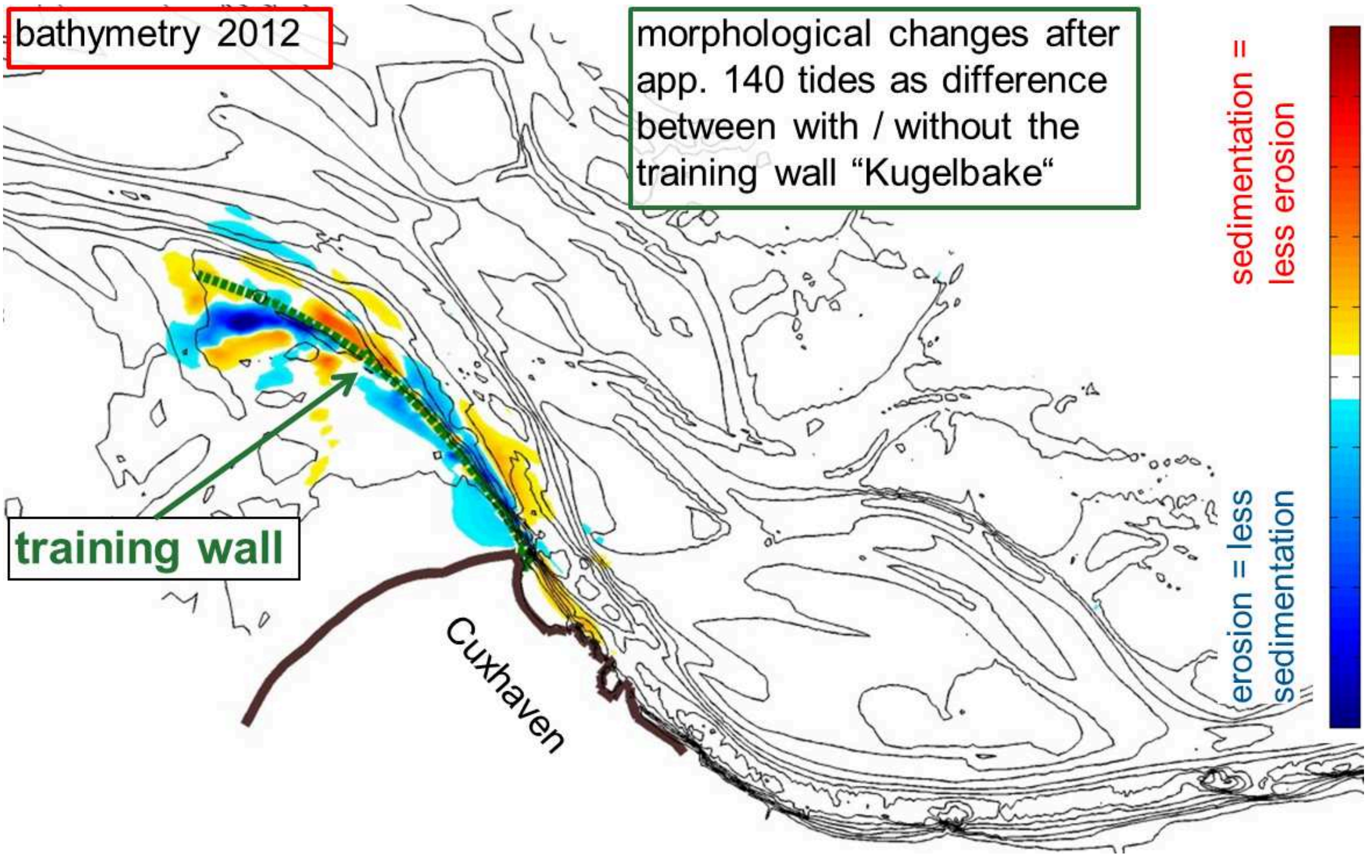

Figure 7. Morphologic changes due to the removal of training wall „Kugelbake" after 140 tides – mouth of Elbe estuary

The southern tidal gully is a connection trench to the main fairway (bathymetry see Figure 4). The reopening of this gully and the assumed deepening will be followed by the so increased tidal velocities. As a result of this the model predicted local erosion in this area (Figure 8). Beside this, sedimentation occurs in the deep fairway in front of the opening of the gully because of releasing the main flux in the fairway towards the gully. The sand bank "Mittelgrund", where the training wall is embedded, remains in the position and some raising of the height (sedimentation).

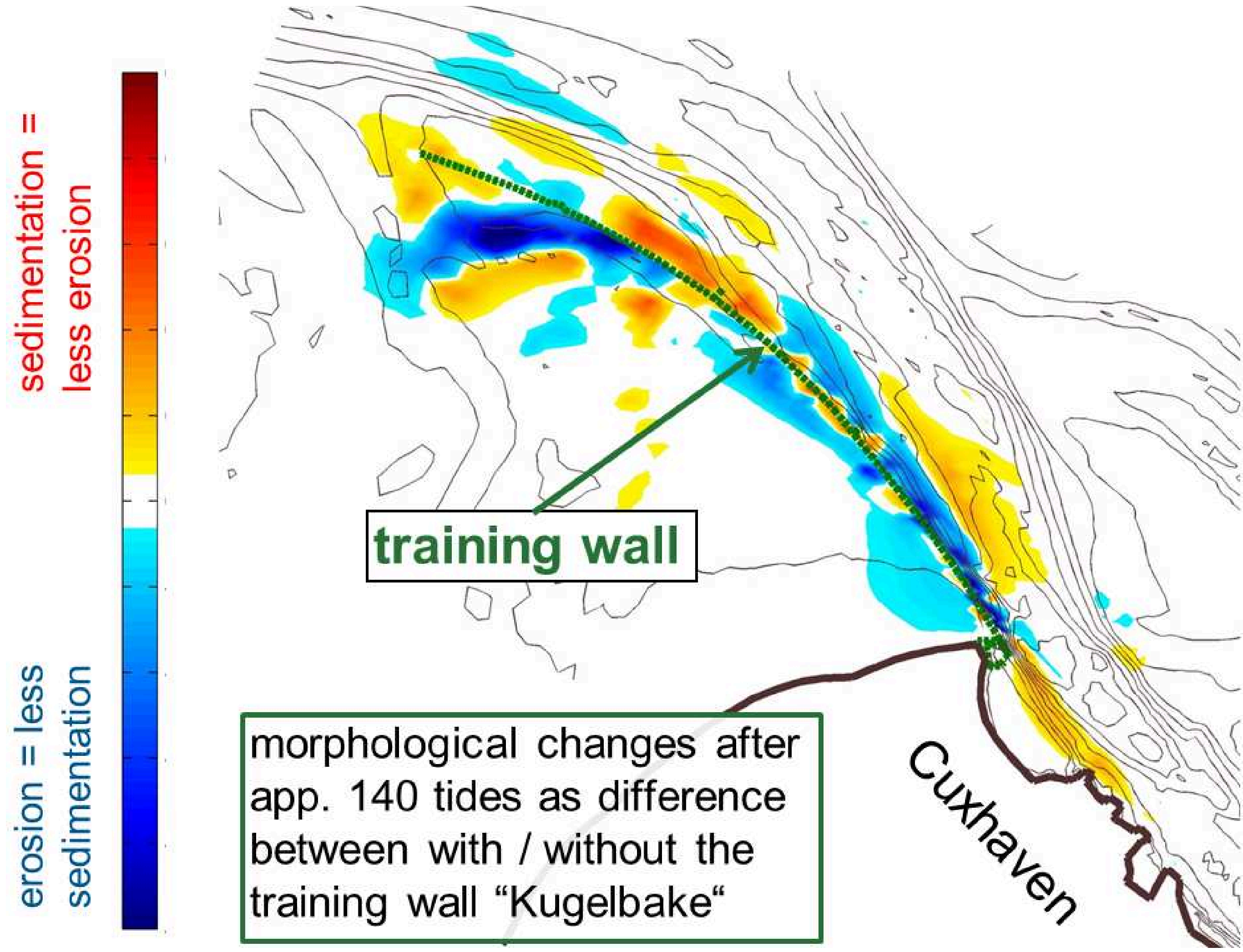

Figure 8. Morphologic changes due to the removal of training wall „Kugelbake“ after 140 tides – detail

4 CONCLUSION

This modelling concept is a first attempt to evaluate the sustainable impact / morphodynamic reactions after constructing a large dam in the branching mouth of an estuary. The dam comprises a length of about 10 km together with several groynes and is located directly beneath the fairway.

The different bathymetries, before and after the construction of the training wall, offers the potential to identify the morphologic reaction in the vicinity of the dam over a long time (app 65 years).

The simulation of the morphological reaction after the construction of the dam, even for a smaller time span than in nature, shows a comparable trend in the sedimentation and erosion patterns. This is a basic step to demonstrate, that the morphodynamic simulation is capable to reproduce such effects, although running for an obviously smaller time span.

Beyond that assuming a total failure of the dam structure the morphological response can be estimated applying the same model strategy as before. One conclusion can be done, that the morphological reaction at first is restricted to the direct surrounding area of the training wall.

Further investigations should focus on longer time spaces and more physical effects. This includes the variation of fresh water discharge, the impact of waves, the influence of storm surges and the dredging and dumping procedure for maintenance of the fairway.

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