Impact of Controlled Tidal Barrier Operation on Tidal Dynamics in the Ems Estuary

Dennis Oberrecht and Andreas Wurpts

Summary

River Ems estuary in the NorthWest of Germany is a partially mixed estuary, which exhibits strong accumulation of cohesive fines by means of fluid mud as a result of several deepenings and straightenings that were conducted during the past decades. The driving phenomena are intensified baroclinic circulation which is extended inlands by means of fluid mud induced baroclinic effects. Therefore, the turbidity zone consists of fluid mud deposits of several meters and extends throughout the whole tidally influenced reach up to the most downstream located weir. Strongly increased tidal asymmetry is present and results in short, but strong periods of flood flow in combination with weaker ebb flow over longer durations. The investigation presented here deals with a modelling approach to investigate a modified use of the Ems river barrage in order to influence the tidal wave propagation towards a more symmetric shape, while maintaining the tidal volume as much as possible. The aim is to reduce upstream sediment transport as well as turbidity and increase dissolved oxygen concentration, especially during periods of low fresh water discharge. The investigation shows decreased tidal asymmetry and influences on the baroclinic circulation in both, field measurements and also well reproduced by the numerical model as a result of the barrier operation. Also lower suspended sediment and higher dissolved oxygen concentrations in the lower Ems estuary are observed. The mode of the tidal barrier operation is subject to a hydro- and morphodynamic optimization procedure which is done by the numerical model described here.

Keywords

Ems estuary, tidal asymmetry, baroclinic circulation, tidal control, storm surge barrier, fluid mud

Zusammenfassung

Das Emsästuar im Nordwesten Deutschlands ist teildurchmischt und weist eine starke Ansammlung von kohäsiven Sedimenten in Form von Flüssigschlick auf. Diese ist auf die in der Vergangenheit durchgeführten Vertiefungen und Begradigungen des Flusses zurückzuführen. Im Wesentlichen wurde durch die flussbaulichen Maßnahmen die barokline Zirkulation intensiviert, deren räumliche Ausdehnung vergrößert und die Gezeitenasymmetrie gesteigert. In der Trübungszone des Ästuars bis hin zum Tidewehr findet man Flüssigschlick mit Mächtigkeiten bis zu mehreren Metern in der Wassersäule vor. Als Folge der Ausbauten ist zudem eine starke Asymmetrie entstanden, die eine kurze aber starke Flutströmung und eine lange und schwache Ebbströmung verursacht. Als Folge der verstärkten Ansammlung suspendierter Sedimente weist die Unterems insbesondere über die durch niedrige Oberwasserzuflüsse charakterisierten Sommermonate einen kritischen ökologischen Zustand auf. Die weiteren Nutzungsanforde-

rungen an das Gewässer erlauben jedoch keine Verflachung des Gewässers zur Herstellung der vormaligen Zustände. Die hier vorgestellte Untersuchung befasst sich mit der modelltechnischen Untersuchung einer veränderten Nutzung des Emssperrwerks in Gandersum, um die Gezeitenasymmetrie zu beeinflussen. Durch eine temporäre Dämpfung des extremen Tidestiegs im ersten Drittel der Flut bei gleichzeitig möglichster Beibehaltung des Tidevolumen sollen die in dieser Tidephase sehr ausgeprägten, stromauf gerichteten Sedimenttransporte reduziert werden. Hiervon wird u.a. eine Verbesserung der Gewässergüte während Phasen niedrigen Oberwasserabflusses erwartet. Die numerischen Untersuchungen zeigen eine sehr gute Übereinstimmung im Vergleich mit den Ergebnissen mehrerer Naturversuche unter Einsatz des Emssperrwerks.

Schlagwörter

Ems Ästuar, Tideasymmetrie, barokline Zirkulation, Tidesteuerung, Emssperrwerk, Flüssigschlick

Contents

1 Introduction

In the present study a modified use of the storm surge barrier in Gandersum (GAN) is analyzed by means of hydrodynamic numerical results of estuarine flow behavior of the Ems estuary. A three-dimensional numerical model of the estuary was developed, calibrated and validated by means of data gathered from prototype tests involving the storm surge barrier in the years 2009, 2010 and 2012. This hydrodynamic study is carried out as a part of a hydro- and morphodynamic investigation focusing on changes of sedimentation rates as well as water quality improvements in the lower estuary, due to the modified use of the barrier. The Ems estuary (Fig. 1) is a partially mixed estuary in the NorthWest of Germany which partly also makes up the border to the Netherlands. The tidally influenced part of river Ems extends a total length of 110 km starting from the east Frisian island Borkum to the tidal weir in Herbrum with an average fresh water inflow of 78 m^3/s. Due to deepenings and straightenings in past decades the flow behavior shifted to shorter but strong flood flow and weaker but longer ebb flow. This in turn led to massive accumulation of cohesive sediment, which has fluid mud exhibit complex interactions between suspended sediment and tidal currents like dynamic stratification and a non-Newtonian flow behavior in the lower parts of the water column. Further effects caused by the engineering measures are reduced shear and roughness which implies a less impeded propagation of the tidal wave through the estuary and resulted in higher high water level as well as lower low water levels (HERRLING 2008). The tidal range at the mouth amounts 2.2 meters and increases upstream to 3.2 meters in Papenburg (PAP).

In order to analyze changes of tidal dynamics due to a modified use of the storm surge barrier at Gandersum, the barrage and a gate underflow parameterization have been implemented in the hydrodynamic model. The storm surge barrier was built in 2004 to protect the hinterland against flooding and consists of seven gates, where two gates for crossing vessels are used. Cross-section at the barrier is about 474 meters width, 13 % of which are blocked by piers, which corresponds to a net width of 414 meters. In order to influence the tidal dynamics closure scenarios during the prototype test from 2012 are exemplary considered here. Then up to 67 % of the cross-section was temporarily blocked by means of closing several gates.

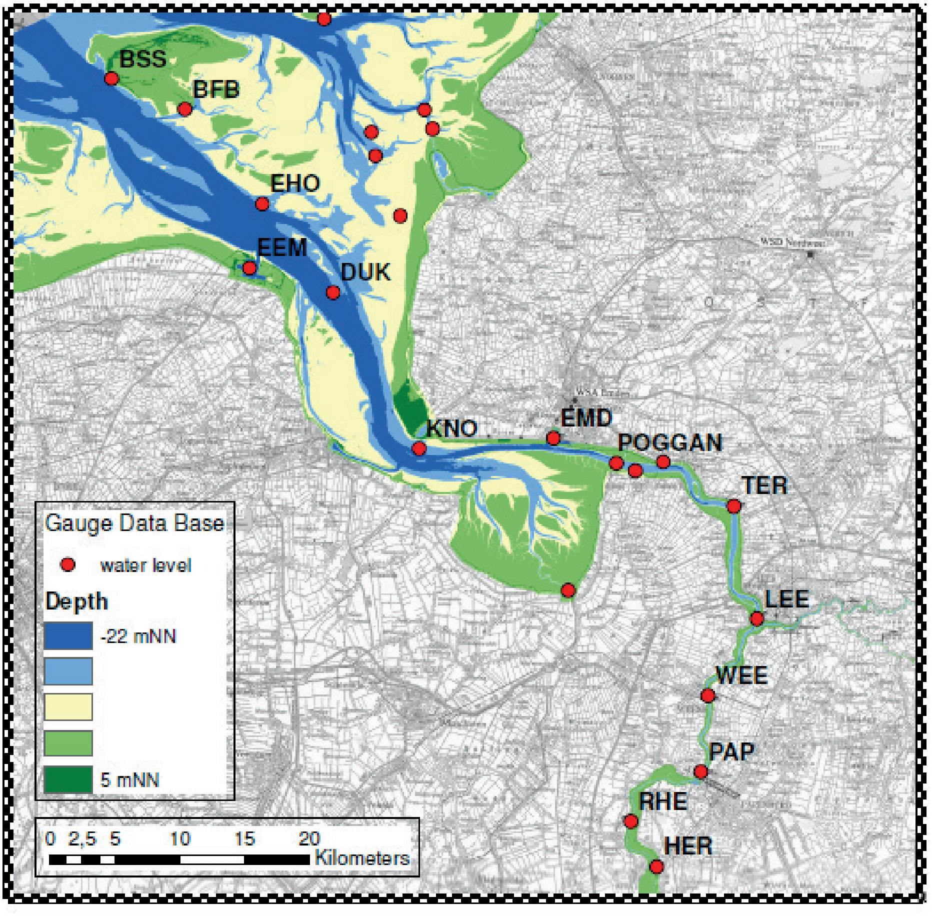

Figure 1: The Ems estuary. Map overlay shows bathymetry and water level and salinity gauge stations.

2 Model approach

A 3D structured grid, finite volume Delft3D model is applied to reproduce the hydrodynamic mechanisms and salt dynamics of the estuary. The specific time dependent mode of the barriers gates operation (cross sectional area is controlled by means of vertical gates with underflow) is implemented as a hydrodynamic energy loss approximation due to gate underflow in the numerical shallow water equation model. To reproduce vertical salinity gradients during slack times and baroclinic circulation pattern as well as turbulence situation of the estuary, a Prandtl-Mixing-Length model with a damping function after PERELS and KARELSE (1982) was implemented to solve the turbulence closure in the diffusion term of the Reynolds-averaged Navier Stokes equation and the vertical diffusivity parameterizations within the coupled advection-diffusion-equations for salt, temperature and suspended sediments.

3 Model calibration and validation

The study area extends from the east Frisian island Borkum up to the tidal barrier 110 km upstream in Herbrum (HER). The tributary river system of Leda and Jümme is also included in the model domain, mounding into the Lower Ems at Leerort. The model domain is represented by 51648 nodes and consists of 10 vertical layers. The lateral model boundaries follow the dike line and are fixed to 8 meters above mean sea level. The open boundary condition at the sea side of the model is implemented by tidal forcing of measured water level time series at station Borkum. Both inland boundaries (Herbrum and Leda) have been implemented as a discharge time series and for the transport of salt and temperature corresponding time series of nearby measurement stations were generated at all boundaries. For saline and temperature initial conditions throughout the model domain, average salinity and temperature values over simulation period were calculated and interpolated to all nodes.

For the investigations a four week simulation period was chosen in 2010. The first two weeks serve as a warm-up period and the remaining two weeks are then used for analysis. The simulation period starting at 10th March 2010 provides freshwater discharge decreasing from relatively high (~200 m^3/s) to lower values of ~100 m^3/s. The calibration of the model and shown figures (2 & 3) of calibration is based on the time period of the prototype test 2012.

Fig. 2 shows a validation of measured and modelled water level differences across the tidal barrier during tidal control operation. The calibrated energy loss approximation enables the shallow water equation based model for sufficient reproduction of the barriers gates influence and hence the damping of the overall tidal dynamics due to the gates operation.

Fig. 3 shows a comparison of measured and calculated salinity differences time series between bottom and surface at location fairway ton 61 (in the "entrance" to lower Ems between Knock (KNO) and Emden (EMD), see Fig. 1). Sufficient reproduction of the flow and salt dynamics at this location is strictly required, since the upstream situation in river Ems is dominantly driven by the dynamics prevailing here, closely upstream of the flow splitting between Ems and Dollart (Fig 1). The large scale baroclinic circulation system is reproduced very well.

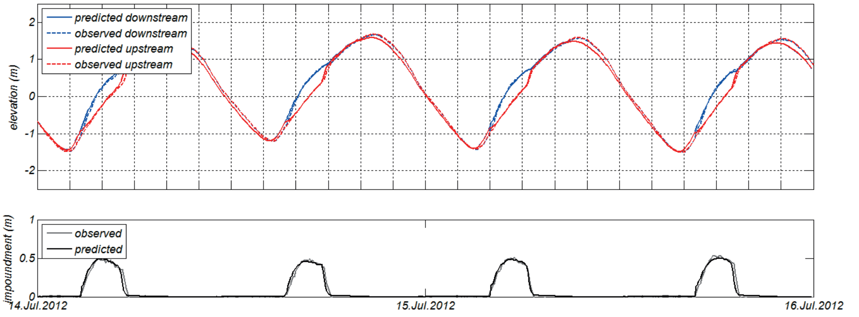

Figure 2: Upper panel shows comparison of measured and modelled water elevation time series during prototype test 2012 at Gandersum. Lower panel shows the corresponding water level differences between upstream and downstream position of the storm surge barrier.

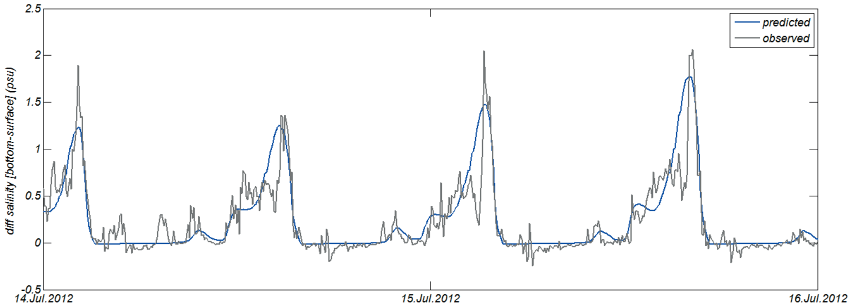

Figure 3: Comparison of vertical salinity difference between surface and bottom at station T61 close to Knock (KNO) during field test 2012.

4 Results and observations

The comparison presented here is based on modeled results of tidal dynamics with and without tidal control (reference state) for the same simulation period and with otherwise all model configuration kept identical. The tidal control scenarios are focused on a prototype test of 2012. During the test in 2012 all gates were closed except the main and secondary traffic gates located at the deepest part of the tidal channel. The other gates were temporarily closed, amounting of a reduction in flow cross-section around 67 %. Closing started at low water and reopening 2.5 hours after slack time before flood.
Fig. 4 shows the effect of the tidal control on the ratio of ebb to flood duration along the estuary. The change in tidal asymmetry is clearly visible from Emden to Weener. The step in Leerort is due to the inflow and outflow of Leda-Jümme River. The reduced tidal asymmetry shows a change to longer flood duration with weaker currents and shorter ebb duration with a stronger ebb flow.

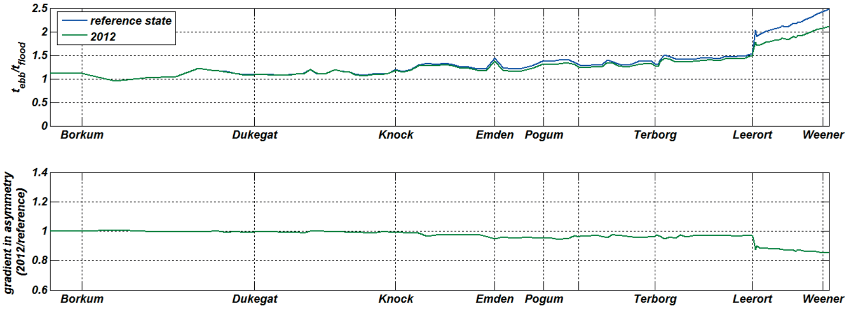

Figure 4: Upper panel shows tidal asymmetry based on modelled velocity measurements along the estuary. Lower panel shows the difference between tidal control and reference state.

Fig. 5 shows vertical salinity gradients as a proxy for baroclinic circulation intensity. Abscises shows time, ordinate shows longitudinal position starting from Eemshaven (EEM) to Oldersum (OLD, see Fig 1 for locations). This range roughly excludes the fluid mud dominated part of lower Ems, since there occur strong interaction phenomena of salinity transport and fluid mud.

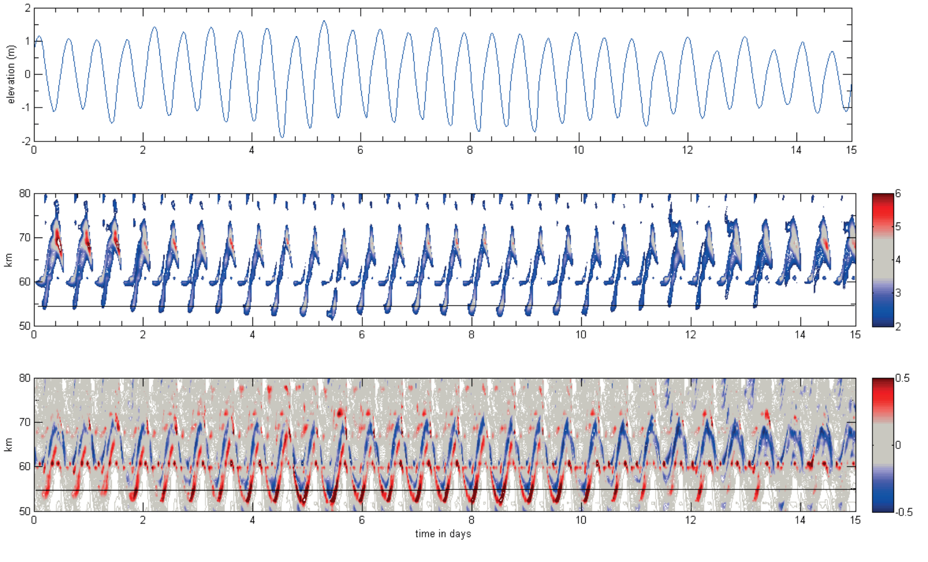

Figure 5: Upper panel shows water level at sea boundary, mid panel shows the vertical salinity gradient at reference model results in a longitudinal section and lower panel shows difference of reference and 2012 tidal control scenario. Black line indicates location of the storm surge barrier.

The location of the storm surge barrier in Gandersum is given by the horizontal black line at km 55. The vertical salinity gradient of reference state in middle panel of Fig 5 is shown. Mid panel of Fig 5 shows a vertical salinity gradient of 5-6 psu during slack time before flood at neap tide (days 0-4 + 11-15) around km 70. At spring tide (days 4-10) a weaker gradient of 4-5 psu during slack before ebb compared to neap tide is observed. At slack time before ebb the strongest vertical salinity gradient appears at Gandersum by 0-2 psu during neap tide while at spring tide a gradient of 3-5 psu arises. Intensity of the vertical salinity gradient is mainly forced by the horizontal salinity gradient along the estuary and local turbulence intensity.

In comparison to reference state lower panel shows the difference with the tidal control scenario. Around Knock an increase of 0.3 psu during spring tide conditions combined with a reduction of stratification during ebb period was calculated. At neap tide occurs a significant reduction of vertical salinity gradient of 0.5 psu upstream of km 70, which causes in smaller baroclinic circulation zone during slack time before flood. During slack time before ebb at spring tide conditions a significant increase of salinity gradient of more than 0.5 psu combined with an upstream area by a clearly pronounced weakening of the gradient downstream. Weaker salinity stratification during ebb period can be observed as well. Calculations of tidal control have shown a reduction of tidal asymmetry at the surface in the baroclinic circulation zone. This statement is confirmed by measured data, which confirms the plausibility of the numerical model.

5 Conclusion

The numerical study which is presented here is part of a larger investigation aiming to improve the ecological situation of the lower Ems. This paper focusses on some hydrodynamic estuarine phenomena and how those are influenced by means of a new approach of tidal control by means of an alternative use of the existing storm surge barrier. The model is carefully adapted to the specific requirements of the physical problem (gate underflow in shallow water equation model, complex baroclinic forcing) and resolves this very well with respect to the relevant driving phenomena. A comparison of modeled tidal control and a reference state without tidal control is shown including changes and intensity of the vertical salinity gradient and baroclinic circulation pattern along the estuary. In comparison to reference state a change in flow behavior is observed due to the modified barrier operation. Tidal control by means of an adapted operation of the storm surge barrier shows to significantly reduce tidal asymmetry and influences the baroclinic mechanism as well. These parameters however are understood as only indicators regarding the major aim of positively influencing the sediment and ecological regime. Therefore in parallel the investigation continues towards an optimization of the operational mode based on sound morphodynamic calculations.

6 References

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