# HARBOR-ENTRAINMENT DUE TO COMPLEX TIDAL FLOW PATTERNS

Dr.-Ing. Andreas Wurpts[1]

## ABSTRACT

International seaports accessible for today's big ships are often located at estuaries where the hydrodynamic situation can be strongly influenced by density effects like vertical gravitational circulation. The present paper deals with the hydrodynamic situation of one harbor entrance of the seaport of Bremerhaven. The port is located near the upstream end of the Weser-estuary at the German North Sea coast and suffers from increased sedimentation of fine silty sediment which forms layers of fluid mud in the tidal basin. The sediment is entrained from river Weser by complex flow patterns. Also the fluid mud is entrained into the inner tide-free harbor during lock operation. This contribution deals with the application of a three dimensional morphodynamic numerical simulation model. As a first step the hydrodynamic situation was reproduced in order to do morphodynamic runs later. Due to the influence of density driven flows the transport of dissolved salt was also calculated. Detailed ADCP measurements of flow velocity and direction as well as salinity measurements were available for the port entrance. The local hydrodynamic situation at river Weser is highly transient and dominated by tidal movement and barocline stratification. The flow measurements show distinct interaction of several flow-effects like recirculation, tidal filling and emptying of the harbor basin and density effects at the same time and different depths. This complex situation is taken as a validation case for a three dimensional SMOR3D simulation model, which was extended in order to consider density-depending damping of turbulent momentum exchange. The model can help to improve strategies to minimize the entrainment of sediment into harbor basins under complex hydrodynamic situations in order to reduce dredging–related maintenance costs.

**Keywords**: Numerical modeling, estuary, density stratification, fluid mud

## INTRODUCTION

International seaports accessible for today's big ships are often located at estuaries where the hydrodynamic situation can be strongly influenced by density effects like vertical gravitational circulation. The present paper deals with the hydrodynamic situation of one harbor entrance of the seaport of Bremerhaven. The port is located near the upstream end of the Weser-estuary at the German North Sea coast, Figure 1. The results shown here are a first step towards modeling the entrainment and deposition patterns of fluid mud, which are described within the paper of Nasner et al. also published at WODCON XVIII.

Weser estuary is meso-tidal, which means that the tidal range is between 3 and 4 meters. Regarding its state of stratification the estuary of river Weser can be classified as partially stratified (Cameron and Pritchard 1963) since distinct stratification occurs around slack water times but is not persistent over the complete tidal cycle.

Bremerhaven has major container terminal facilities which are located directly at the tidal stream (see also Figure 4). Additionally there are tide-free harbor basins which are separated from the river and its dynamical situation by several sea locks. The riverside entrance harbors of these locks suffer from increased sedimentation which is a result of sediment entrainment by the river. The sediment to a major amount consists of cohesive fines (silt, fluid mud) which are mainly transported by means of suspended sediment transport. Fluid mud also enters the inner harbor during lock operations. The aforementioned situation causes increased maintenance costs in both the outer lock harbor as well as the inner harbor basin.

[1] Institute for Hydraulic Engineering, Darmstadt University of Technology, Rundeturmstraße 1, 64283 Darmstadt, Germany, Tel.: +49 6151 16-2723, Fax: +49 6151 16-3223, wurpts@wb.tu-darmstadt.de

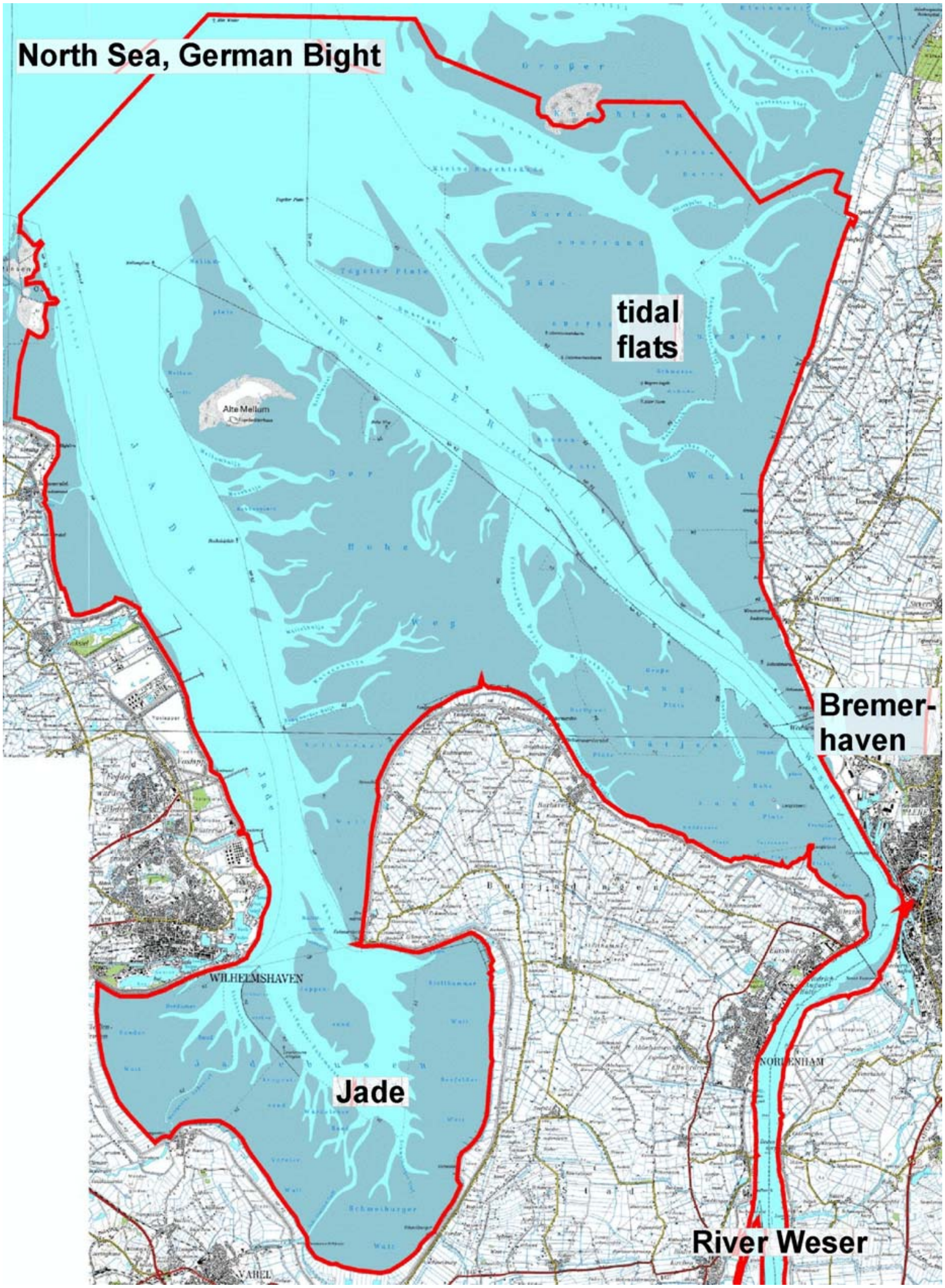


**Figure 1. Overview of Jade-Weser-estuary with estuarine partof the model area, model domain outline and ports of Bremerhaven.**

## METHODOLOGY

### General

The present paper deals with numerical flow and salinity transport simulations in order to reproduce measured flow patterns.

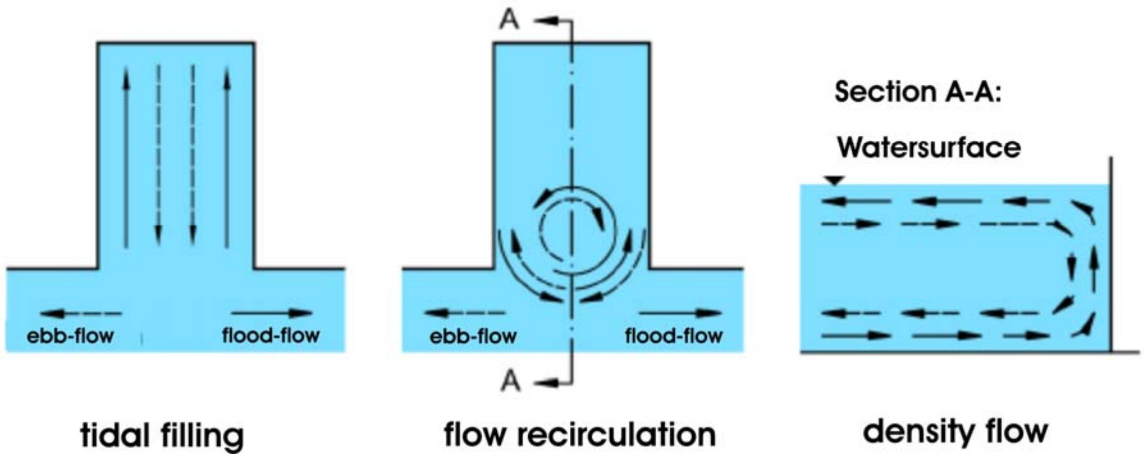


**Figure 2. Different hydrodynamic flow patterns at tidal harbor entrances (Nasner 2003).**

Measurements of flow and salinity distributions in the harbor entrance (Nasner 2003) have discovered complicated flow patterns which result from transient interaction between tidal filling, flow recirculation and density driven flows (see Figure 2). Moreover the situation is strongly varying during the tidal cycle. The flow cases shown here are taken as a complex "real world" validation example for the hydro numerical model. The complex overall situation is a result of the estuarine mixing process of salt and fresh water which is strongly interacting with the tidal flow. For later sediment transport calculations the results are also expected to give deeper insight into the sediment entrainment processes at the harbor entrance observed here. This will allow for the evaluation of sedimentation reduction strategies as well as maintenance strategies.

The impact of density differences forces to consider the damping of turbulent momentum and mass transfer, since density differences contribute to both, barotropic and baroclinic effects. On a local scale the vertical salinity gradient leads to three dimensional hydrodynamic effects like stratification due to decoupling of upper parts of the water column by density gradients, which more or less damp out turbulent exchange. Vertical density gradients which are strong enough compared to vertical shear of flow velocities (which are the "mixing" part of this dynamic equilibrium consideration), affect a suppression of momentum and mass exchange. This causes partial decoupling of the mean flow at a certain depth. The process mentioned above leads to phenomena which are present on very different spatial scales.

Due to its linear dependence of density the additional potential energy of the denser water introduces barotropic currents like the density flow effect sketched at right side of Figure 2. This flow effect is strongly supported by the aforementioned baroclinic suppression of momentum exchange at the density interface.

In the deeper tidal channels which are also impacted by the estuarine salinity differences, the stratified flow can exhibit mean currents, which have opponent flow directions over depth. This especially counts around slack water times. The flood in this stratified case begins near the bottom while at the surface there is still ebb flow and the ebb accordingly starts first at the surface.

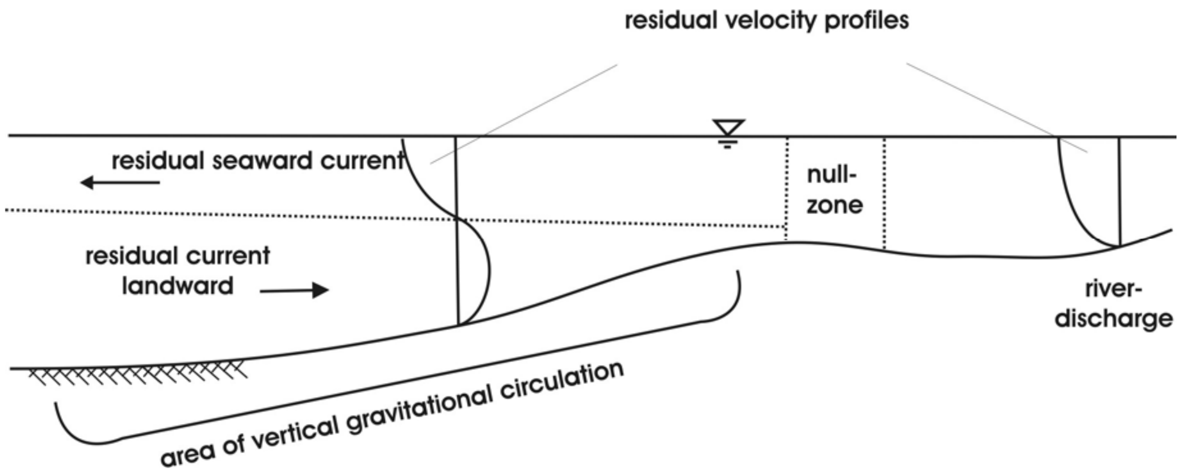


**Figure 3. Sketch of vertical gravitational circulation.**

This mechanism is part of wide area effects like vertical gravitational circulation which is also the case within Weser estuary. The transport-relevant residual flow currents shown in Figure 3 therefore point towards an area called “null zone” which is closely bound to the turbidity zone within the estuary where usually the highest sedimentation rates are found.

**Area of Investigation and Hydrodynamic Situation**

Figure 1 gives an overview of the Jade-Weser-Estuary this paper focuses on. The German North Sea coast consists of mudflats of some 5 – 20 km width. The flats are crossed by deeper tidal channels which provide tidal flooding and drying. River Weser as one of three major rivers disemboguing in the German bight discharges fresh water into the just mentioned area, leading to the estuarine situation. The interaction area of salt and river water at Weser estuary spans from the outer estuary to approximately the point where the river leaves Figure 1 at the lower right corner. Weser estuary is partially stratified and meso-tidal due to its tidal range between 2 and 4 meters and distinct stratification occurs around slack water times.

The local hydrodynamic situation in the main reach of river Weser in front of the locks is therefore dominated by tidal currents and barocline stratification effects due to the presence of salinity gradients which vary in time and space. The sea lock “Nordschleuse” of Bremerhaven, Figure 4, which is focused on here is located at Weser-km 69.2.

The tidal range at the location varies between 3 and 4 meters ($MThb_{1990/99}$=3,72m), local salinity values range 3 ppt to 19 ppt, strongly depending on the tidal phase as well as the amount of fresh water discharge of the river. Variations in tidal range due to spring or neap tide as well as varying fresh water discharge of river Weser also affect the average position of the turbidity zone **(**Wellershaus 1981). The average backwater discharge of river Weser is 326 $m^3/s$ (Gage Intschede, $MQ_{1941/99}$).

The position of the lock is close to the upstream end of the influence of vertical gravitational circulation under average (flow) conditions (i.e. average backwater discharge, average NW-Winds, no storm surge). The average position of the estuarine turbidity zone is also loosely connected to this position, since here the residual currents from the outer estuary and the upstream part of river Weser meet (see Figure 3) and create a “catchment” for sediments from upstream as well as downstream.

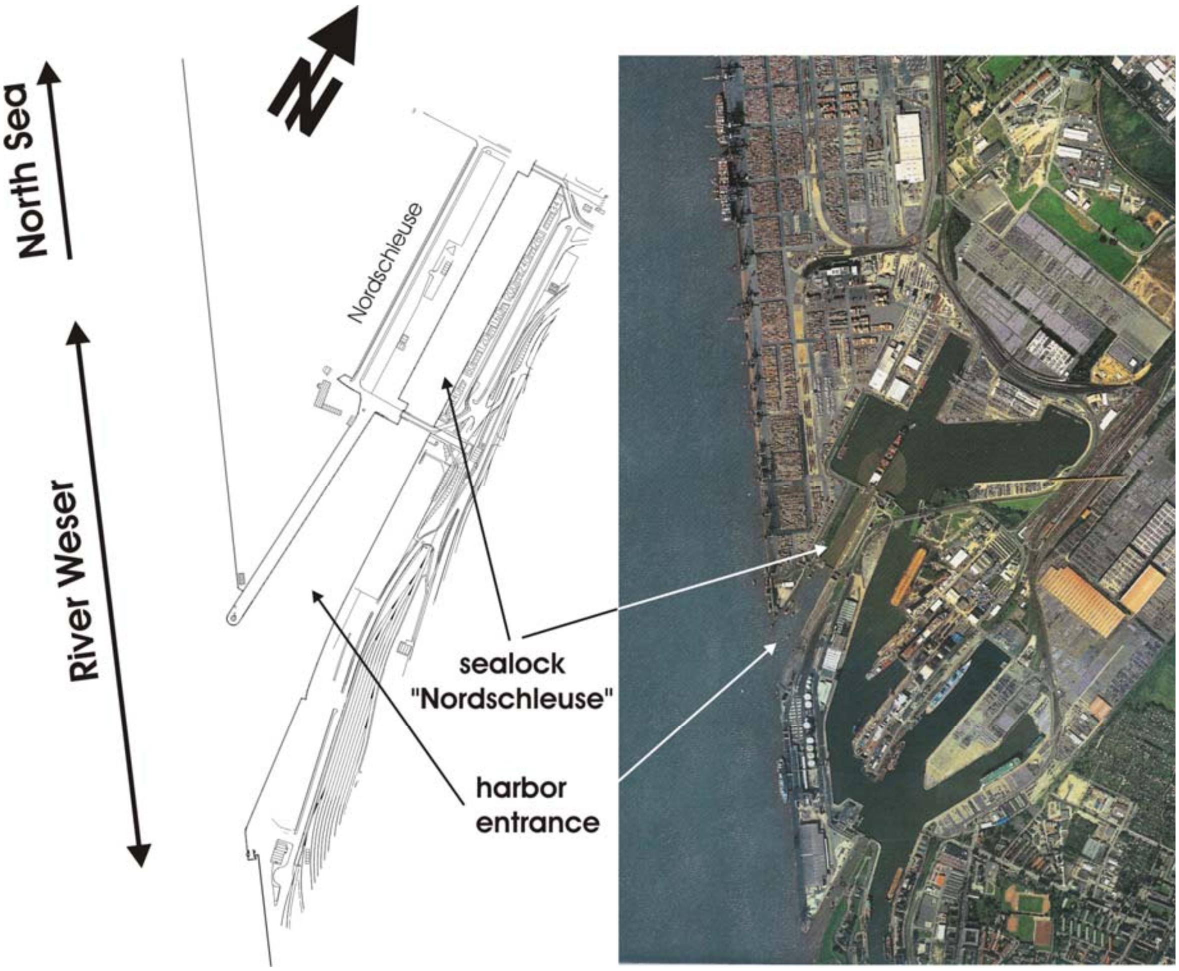


**Figure 4. Bremerhaven sea lock "Nordschleuse" (aerial photograph by bremenports).**

**Numerical Model**

The aforementioned context makes coupled salinity transport simulations necessary, since the salinity distribution strongly affects the density distribution in the water body. In order to consider density effects the transport model for dissolved salt is therefore directly coupled to the flow solver which in turn allows for local barotropic and baroclinic density effects during the flow field calculation.

The model area is bounded by the red line in Figure 1 and spans over approx. 1000 km². Outside the extent shown in the figure at the lower right corner the model domain is continued for approx. 65 kilometers of river reach up to the first weir upstream of the city of Bremen, where the tidal wave is completely reflected.

These dimensions chosen here are necessary in order to account for realistic tidal dynamics as well as the local stratification which also "drives" the local flow situation. Modeling the vertical gravitational circulation, which is also a far field effect, requires modeling its whole spatial extent. Therefore the model domain reaches Lighthouse "Alte Weser" in the very north of Figure 1 at the sea side (where no stratification is present). In order to get reasonable tidal dynamics inside the area, the "Jade"-bay is also included in the model domain due to its significant storage volume.

The numerical model used for the calculations is a time-explicit three dimensional finite-element-code which makes a complete morphodynamic numerical model, Figure 5. For the application shown here only the 3D-hydrodynamic and salinity transport modules were used. All sediment transport modules were switches off for the calculations shown here.

The flow solver works utilizing the hydrostatic pressure approximation. For turbulence closure a modified mixing-length model for turbulent momentum and mass exchange was used. Salinity transport is implemented by a convection-diffusion-formulation. The interaction between density-gradients and momentum exchange is realized by a gradient Richardson number approach according to Wurpts (2006).

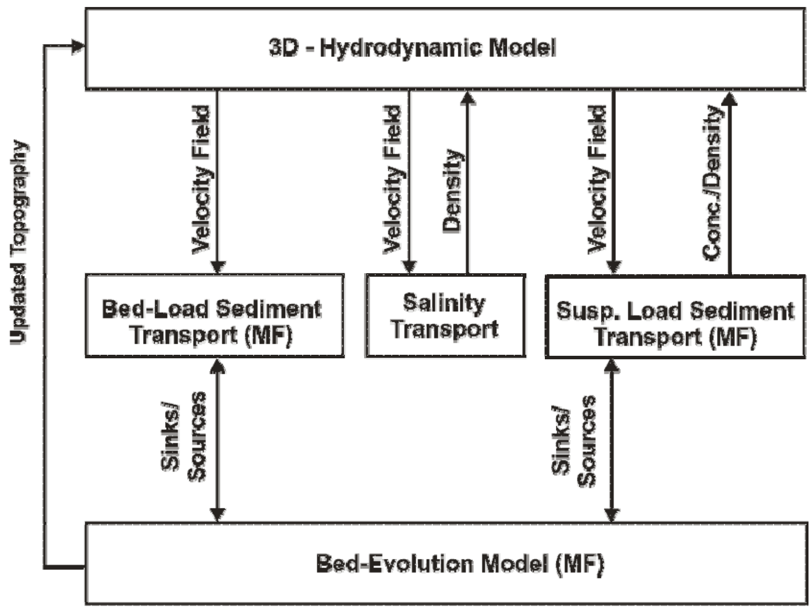


**Figure 5: Numerical coupling scheme of SMOR3D model**

## MEASUREMENTS

Nasner (2003) measured vertical salinity profiles and also used a 600 kHz Broadband ADCP with RTK-DGPS to measure flow velocities along trajectories across river Weser and the harbor entrance mentioned above. The measurements were conducted during periods of different fresh water discharges of river Weser.

### Vertical Salinity Profile

Exemplary results of the Nasner 2003 measurements are shown in Figure 6. Vertical profiles of salinity distribution are given for seven points along the outer tidal harbor of lock Nordschleuse and the deep channel of river Weser during fresh water discharges of 212 $m^3/s$ and 250 $m^3/s$. Profiles are shown for three points of time within each tidal phase (3 Profiles during a flood at 212 $m^3/s$ river discharge, left column and 3 profiles during ebb tide at 250 $m^3/s$, right column). The local baroclinic stratification in river Weser is driving the density effect which contributes to sediment entrainment into the locks forebay harbor. It therefore has to be reproduced by the numerical simulation.

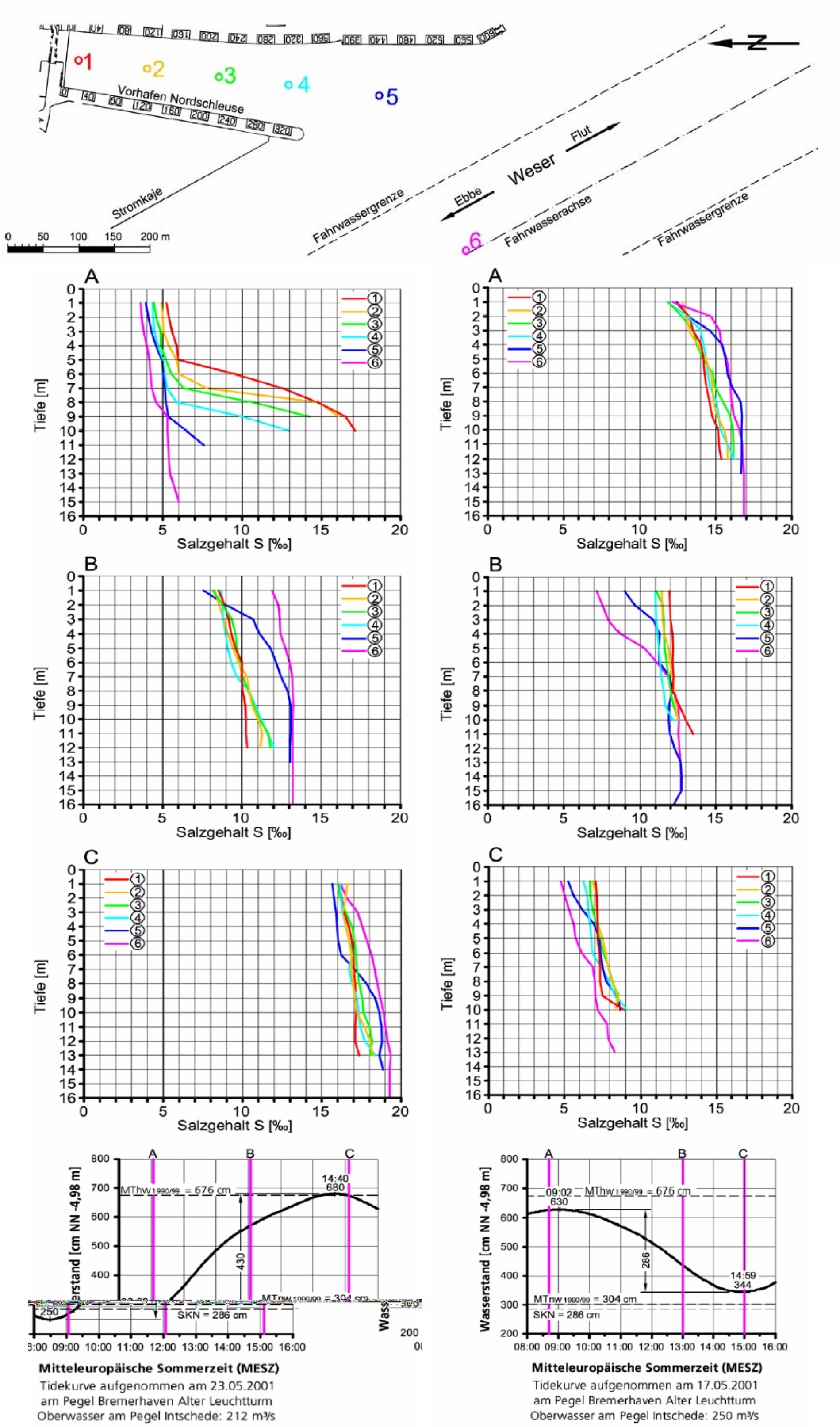


**Figure 6. Vertical salinity profiles measured at river Weser (Position 6) and inside the lock entrance harbour (Positions 1 – 5 in uppermost part of this figure) for 212 m³/s - 250 m³/s river discharge [Nasner 2003].**

As can be seen at position 6 (corresponds to deep channel position, pink profile line) river Weser exhibits weak partial stratification here. This detail is important because the density differences in the deep channel are one of the driving mechanisms regarding in- and outflow of the tidal harbor. The measured salinity profiles show two important things.

Around low water slack time the salinity inside the harbor is higher than in the river. This “storage” of salt water in the tidal harbor basin is increasing with distance to the river and causes a near-bottom outward density flow during the first phase of flood.When salinity values in the river exceed those in the harbor basin, the situation turns to near-bottom inflow and “refills” the “storage.

This density driven flow is interfering with a local recirculation flow in the harbor mouth. The recirculation area is displaced to one of the bounding moles depending on the direction of density in- or outflow as well as the corresponding flow direction in the tidal river.

Figure 7 to Figure 10 show exemplary ADCP measurements, Figure 7 and Figure 8 taken during full flood flow, Figure 9 and Figure 10 during ebb flow. Velocity vectors are given for two different flow depths (near the surface and close to the bottom).

## MODEL RESULTS

The aforementioned figures compare measured values at specific tidal phases and depths with simulated results from the corresponding temporal and spatial calculational domain. The reader should first notify that –according to the given ADCP measurements - the flow directions in the numerical results are given as some kind of ‘flag’ which rotates around the ‘dot’ at one end of each given velocity vector (otherwise one could erroneously assume the velocity vectors are given as ‘arrows’).

As can be seen from Figures 7 and 8, taken at approx. half flood tide, a density driven near-surface outflow occurs, since salinity values in the river are already higher than those inside the tidal harbor (see Figure 6, left column, sketch B). This outflow is driven by a near-bottom inflow as can be seen from Figure 7. In the lower layer shown in Figure 8 the density driven inflow displaces the recirculation zone to the “upstream” (relative to the actual tidal flow direction) jetty. The surface layer shows no distinct recirculation, since it is displaced into the main river flow due to the near-surface outflow, which is dominant at this tidal phase. The resulting situation shows only a “distortion” of the main flow field close to the center of the entrance, which is confined between two major outflowing streams left and right of it.

The calculated results and the measurements are in good agreement regarding as well the spatial distribution of absolute velocities as the corresponding directions. Both plots show maximum near-bottom inflow velocities of about 50 cm/s and the simulation also matches the position of the center of recirculation, which is displaced to the upstream jetty due to the inflow. Maximum flow velocities in the river’s main channel are also calculated in good agreement with the measurements which show values of order of magnitude 1.0 m/s

The ebb flow situation sketched in Figure 9 for the near-surface layer and in Figure 10 for the near bottom layer exhibits different dynamics: Salinity values in the deep channel of the river now are already lower than those remaining in the tidal harbor basin (see Figure 6, right column, sketches B and C). This causes a density driven near bottom outflow. For continuity reasons in the surface layer strong inflow takes place. Recirculating flow exists only in the upper water column since the near-bottom outflow almost completely suppresses recirculation there (at least the recirculation is displaced close to the flow separation point at the upstream mole-head). The upper layer exhibits a recirculating flow. The center of recirculation is displaced to the upstream (again relative to the actual tidal flow direction) jetty, because the continuity-forced inflow concentrates at the opposite side of the basin.

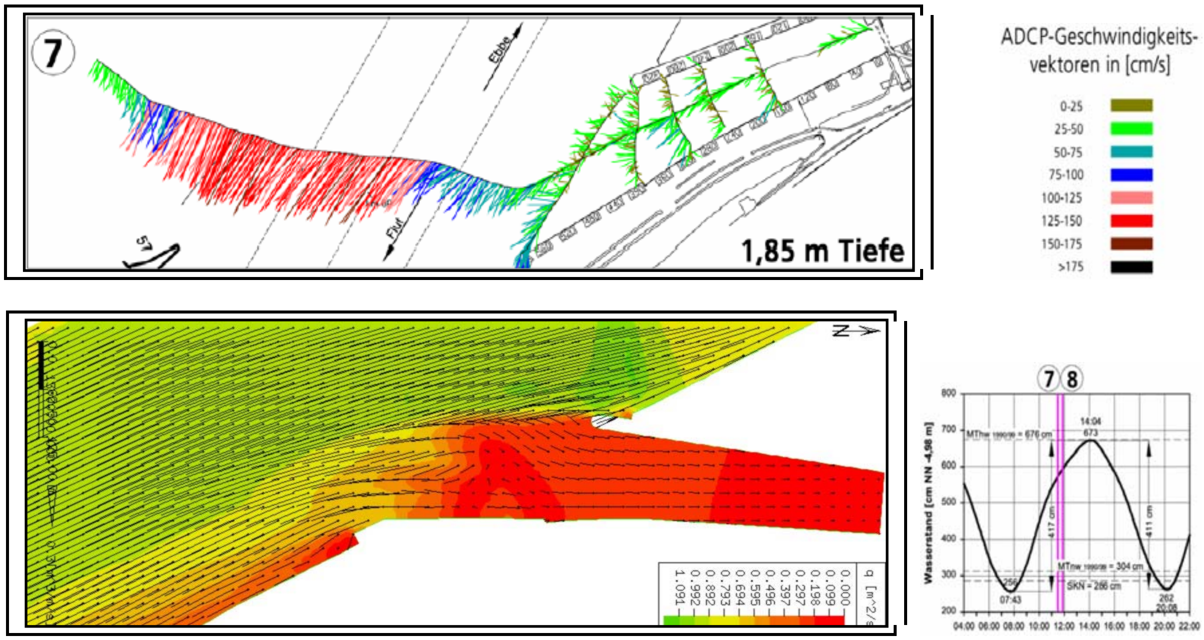


**Figure 7. Flow field in the tidal harbor and river Weser during maximum flood flow. Values are given for layer 2m below water surface. Upper image: measurements [Nasner 2003], lower image: calculated results**

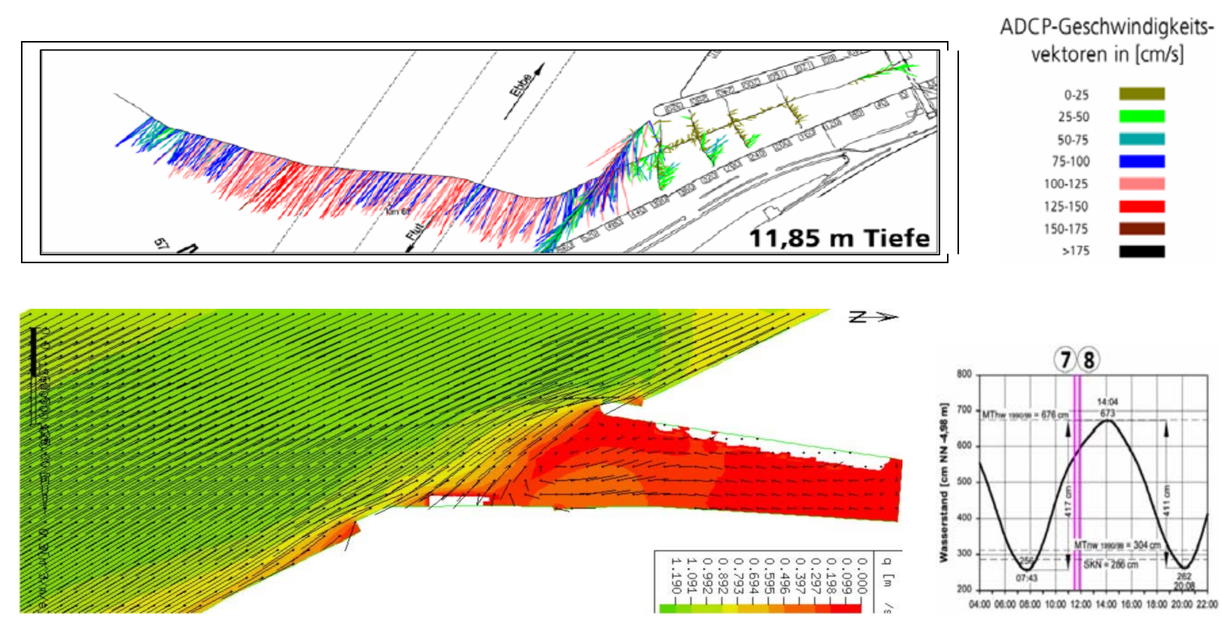


**Figure 8. Flow field in the tidal harbor and river Weser during maximum flood flow. Values are given for layer 12 m below water surface. Upper image: measurements [Nasner 2003], lower image: calculated results.**

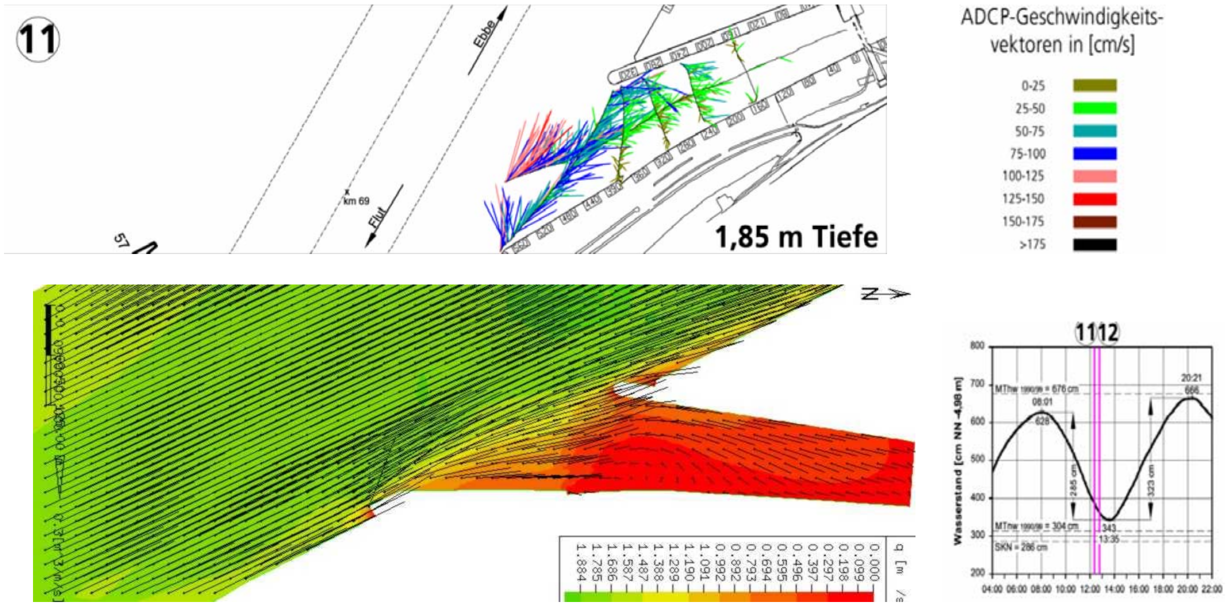


**Figure 9. Flow field in the tidal harbor and river Weser during maximum ebb flow. Values are given for layer 2 m below water surface. Upper image: measurements [Nasner 2003], lower image: calculated results**

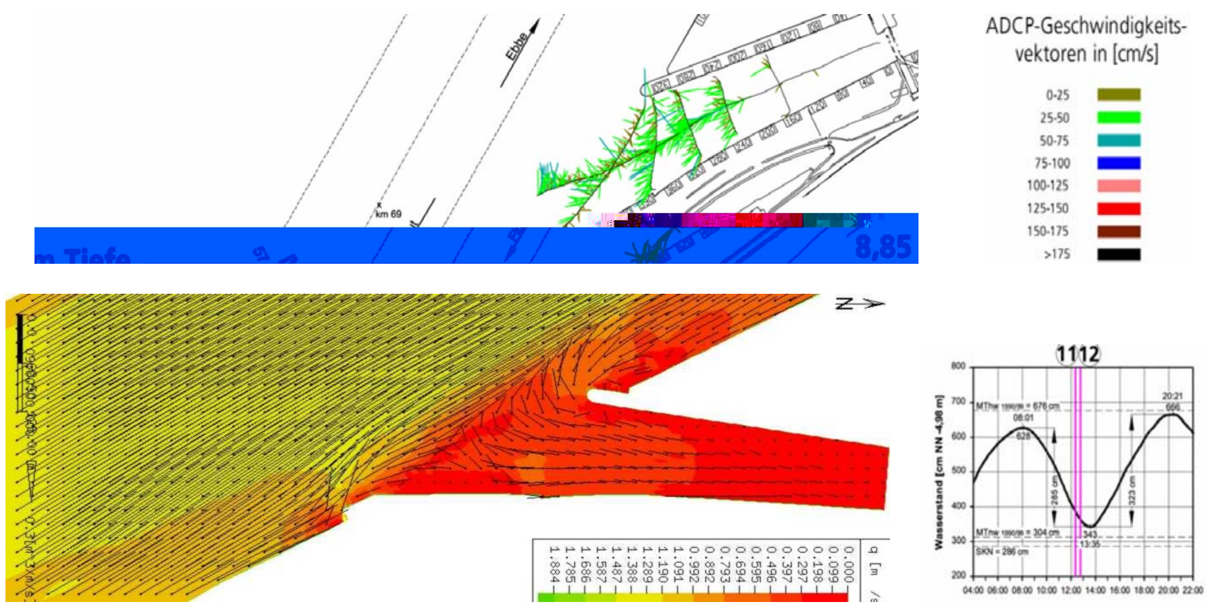


**Figure 10. Flow field in the tidal harbor and river Weser during maximum ebb flow. Values are given for layer 9 m below water surface. Upper image: measurements [Nasner 2003], lower image: calculated results.**

Again the calculated results and the measurements are in good agreement for the ebb flow case shown here, regarding as well the spatial distribution of absolute velocities as the corresponding directions. Both plots show maximum near-bottom outflow velocities of about 50 cm/s and especially the location and absolute value of the peak velocity about 0.75-1.0 m/s is realistically matched by the simulation.

The maximum near-surface inflow velocities occur at the downstream jetty and inside the separation point at the downstream mole head. The absolute values as well as the flow direction fit the measurements.

## CONCLUSION

The present paper shows a application case of a coupled flow and salinity transport simulation. The results shown here are part of a complex "real-world" model validation case in order to show the capabilities of the model. The flow and salinity transport model used here are part of the morphodynamic numerical modeling system SMOR3D. The model results are compared to accurate ADCP measurements which discover a complex hydrodynamic situation consisting of interacting effects like tidal filling, recirculating and density driven flows. The realistic numerical reproduction of this situation is crucial for morphodynamic simulations of harbor sedimentation since the flow field is the driving force for morphodynamic change.

## ACKNOWLEDGEMENT

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