NUMERICAL SIMULATIONS IN COASTAL HYDRAULICS AND SEDIMENT TRANSPORT

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Abstract

Numerical simulations become more and more important within the analysis of coastal hydraulics and sediment transport. Sediment transport requires the knowledge of the flow profile related to tidal hydrodynamics and wave propagation. The basic sets of equations used in numerical modelling of the mentioned sub-processes as well as concepts of coupled numerical models are discussed within this paper. Additionally, the limits of different modelling concepts are discussed, e.g. three dimensional simulations are favourable in brackish estuarine waters because of the large density gradients caused by the difference in salinity of sea and fresh water. All different modelling concepts are applied to analyse tidal flow, wave propagation and sediment transport within the German estuaries of Jade and Weser. Special focus is placed on the analysis of the effect of climate change on coastal hydraulics.

Introduction

As a consequence of the improvement of computer technology, the capabilities of numerical simulations in coastal hydraulics and sediment transport have significantly increased since 1990.

Figure 1: Overview over the estuaries Jade and Weser (1)

In relation to this improvement more and more problems in coastal hydraulics and sediment transport are now solved not by physical modelling but by numerical modelling, for example, in Germany, studies on the reduction of sediment entrainment into harbours were based on physical modelling until 1992 (Schwarze et al., 1995) and since then have been supplemented by (Ohle et al., 2000) or completely based on (Stoscheck and Matheja 2003) numerical modelling.

While in the beginning of numerical modelling the simulation of water levels and currents, of waves and of sediment transport were treated separately, modelling of the different aspects becomes more integrated nowadays. Nevertheless they are outlined separately in the following chapters. Besides a brief summary of the basic equations, examples of the application of different modelling approaches are given focussing on the estuaries Jade and Weser at the German North Sea. An overview of these estuaries is given in Figure 1.

Modelling of Water Levels and Currents

Modelling of water levels and currents is based on the equations of conservation of mass and momentum assuming water as an incompressible fluid. Simulating processes in the coastal zone, two-dimensional depth-averaged models and three dimensional models are distinguished. In 2D the basic equations are

$$\frac{1}{d}\frac{\partial \zeta}{\partial t} + \sum_{j=1}^{2} \frac{\partial u_j}{\partial x_j} = S_{QQ} \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \sum_{j=1}^{2} \left(\frac{\partial (u_i u_j)}{\partial x_j} + 2\Omega_{ij} u_j \right) = -\frac{g}{d}\frac{\partial \zeta}{\partial x_i} + F_{wind,i} - F_{bottom,i} + F_{turb.,i} \tag{2}$$

with the depth-averaged flow velocity u, the water level ζ, the sinks and sources of water S_{QQ}, the acceleration of gravity *g*, the water depth *d*, the Coriolis parameter Ω, the wind forcing F_{wind}, bottom friction F_{bottom} and turbulent dissipation $F_{turb.}$.

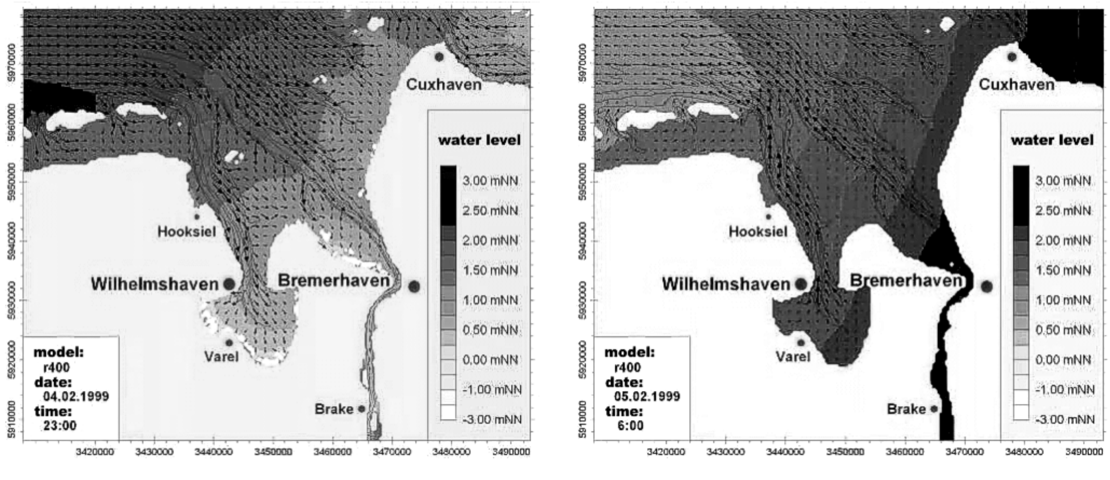

Figure 2: Tidal flow in the estuaries Jade and Weser during a storm surge in 1999, flood current (left) and ebb current (right)

In case of horizontal gradients in temperature and salinity the following conservation equations have to be considered also

$$\frac{\partial S}{\partial t} + \sum_{j=1}^{2} \frac{\partial}{\partial x_j}(S u_j) = \sum_{j=1}^{2} \frac{\partial}{\partial x_j}\left(D_S \frac{\partial S}{\partial x_j} \right) + S_{SS} \tag{3}$$

$$\frac{\partial T}{\partial t} + \sum_{j=1}^{2} \frac{\partial}{\partial x_j}(T u_j) = \sum_{j=1}^{2} \frac{\partial}{\partial x_j}\left(D_T \frac{\partial T}{\partial x_j} \right) + S_{TT} \tag{4}$$

with the depth-average temperature T, the depth-averaged salinity S, the turbulent diffusivities D_S and D_T and the sources or sinks of heat or salinity S_{TT} and S_{SS}.

An example of water levels and depth averaged flow velocities during a storm surge in 1999 calculated by numerical simulation is given for the estuaries of Jade and Weser in Figure 2 revealing a concentration of tidal flow in the fairways. The model is driven by prescription of water levels along the northern and western boundaries, of discharge of the river Weser and of the wind field over the model area. Figure 3 exemplifies the time series of boundary conditions at the north-western corner of the model area.

This model set-up is used to analyze the effect of climate change by altering the boundary conditions (Figure 3). The change in boundary conditions causes a change in the hydrodynamics of the entire coastal zone (Grabemann et al., 2004). For two locations in the fairway (P1+P3) and over the tidal flats (P4+P6) the changes in water levels and flow velocities are displayed in Figures 4 and 5.

In addition to the application of 2D numerical modelling in climate impact assessments the model can also be used to assess the effects of training works within estuaries. Figure 7 presents an example of the effect of the deepening of a fairway (Figure 6) on water levels and flow velocities. While the larger changes in flow velocity are restricted to the direct vicinity of the dredging works, changes in water level occur over much larger areas.

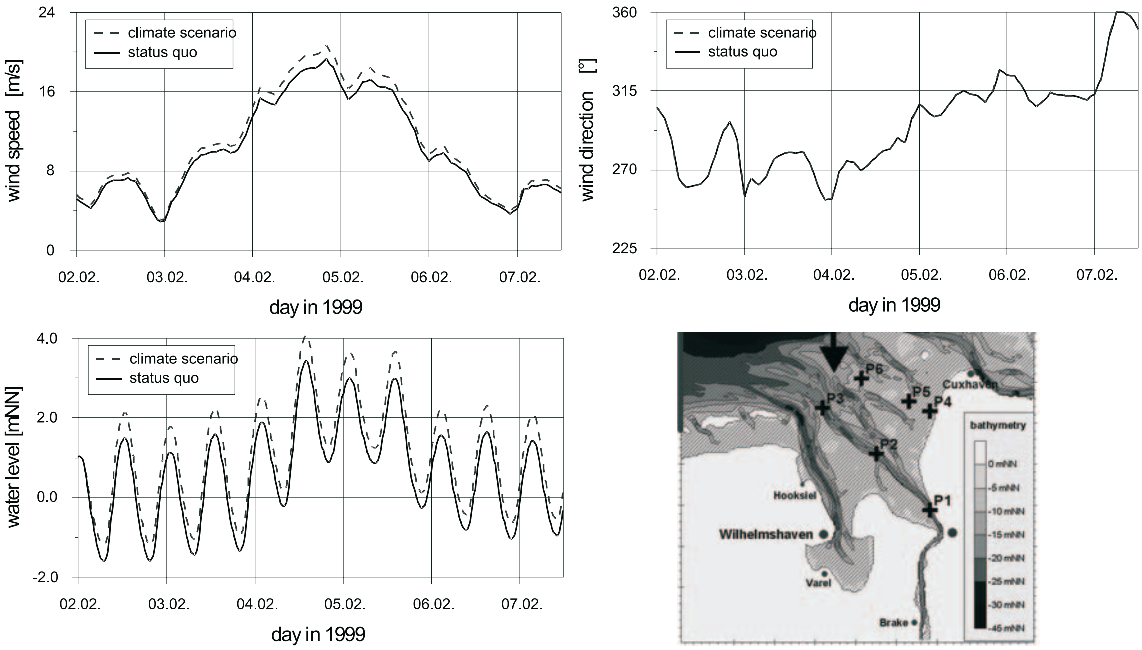

Figure 3: Bathymetry of the model area (bottom right) and scenarios of boundary conditions to analyse the effect of climate change wind speed (top left), wind direction (top right) and water level (bottom left)

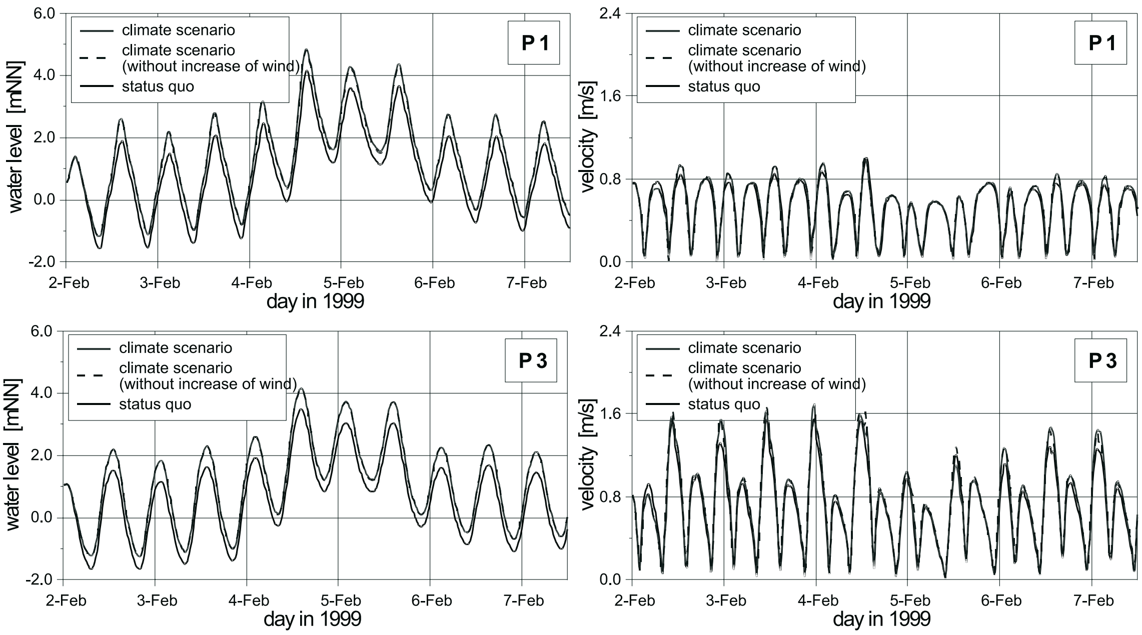

Figure 4: Effect of climate change on water level (right) and flow velocity (left) in the fairway

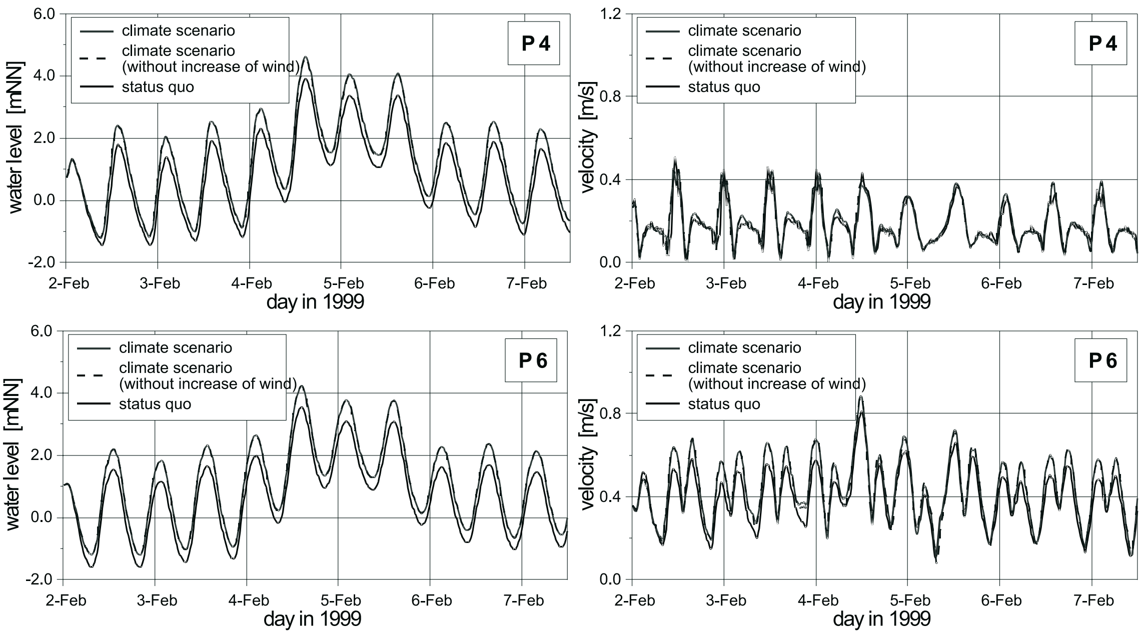

Figure 5: Effect of climate change on water level (right) and flow velocity (left) over the tidal flats

Although depth-averaged modelling gives a first impression of coastal hydraulics it is not sufficient for detailed analysis. This relates to the fact that large vertical gradients in salinity, and therefore in density, are found in coastal waters causing a significant change in the flow profile. A schematization of the flow profile with and without vertical density gradients is given in Figure 8. For this reason the vertical component is introduced into the conservation equations (1) to (4), i.e. the summation is carried out for $i = 1$ to 3. An example of vertical gradients in density or salinity respectively is given in Figure 9 displaying the contours of salinity during ebb and flood current along a cross section outside of the harbour of Bremerhaven located on the river Weser. Fresh water is found at the surface while saline water is found at the sea floor.

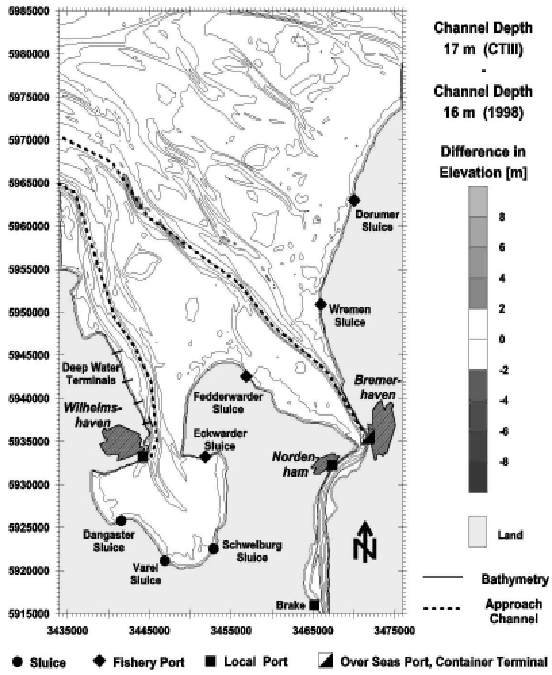

Figure 6: Dredging works within the fairway of the river Weser

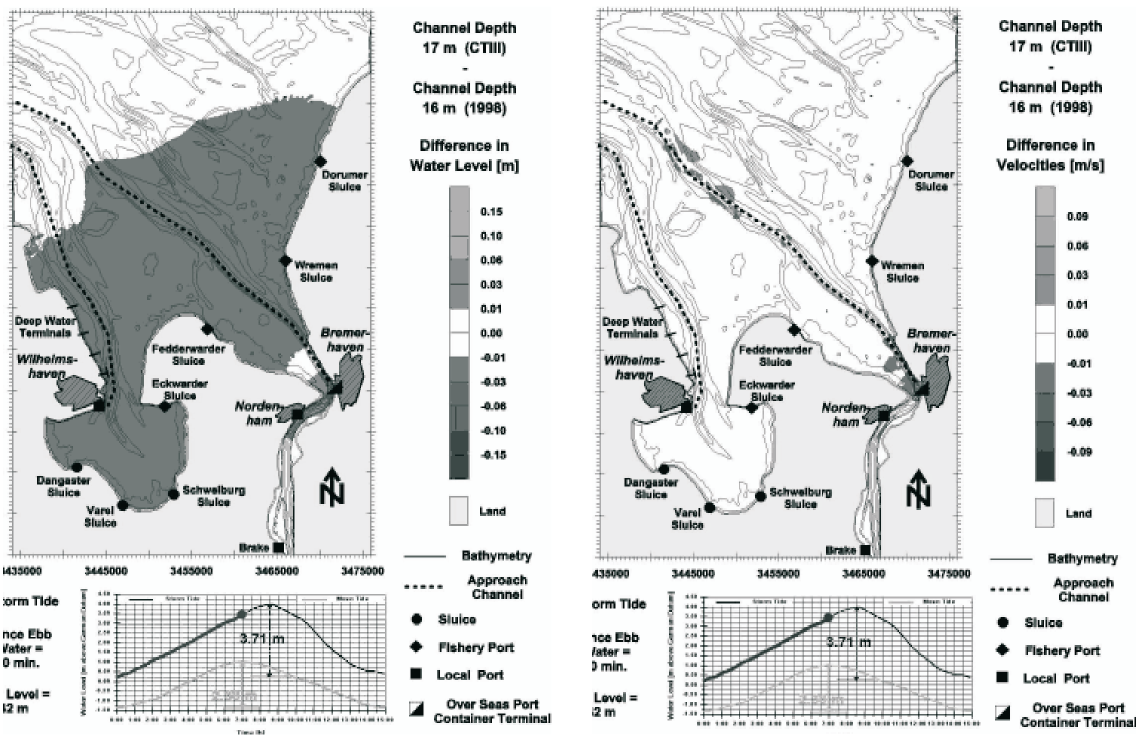

Figure 7: Effect of dredging works in the river changes in water levels (left) and flow velocities (right)

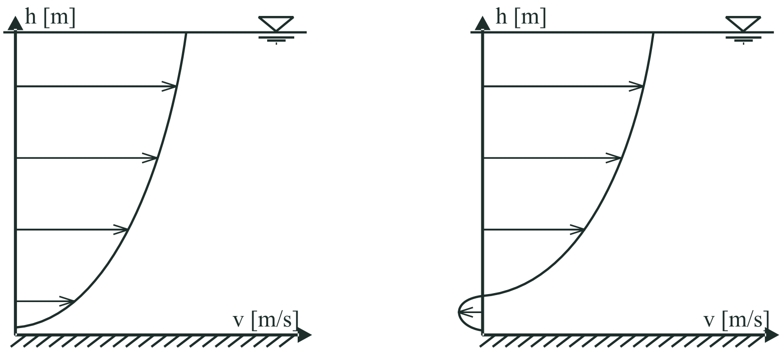

Figure 8: Flow profile with (right) and without (left) vertical gradients in density (Matheja et al., 2003)

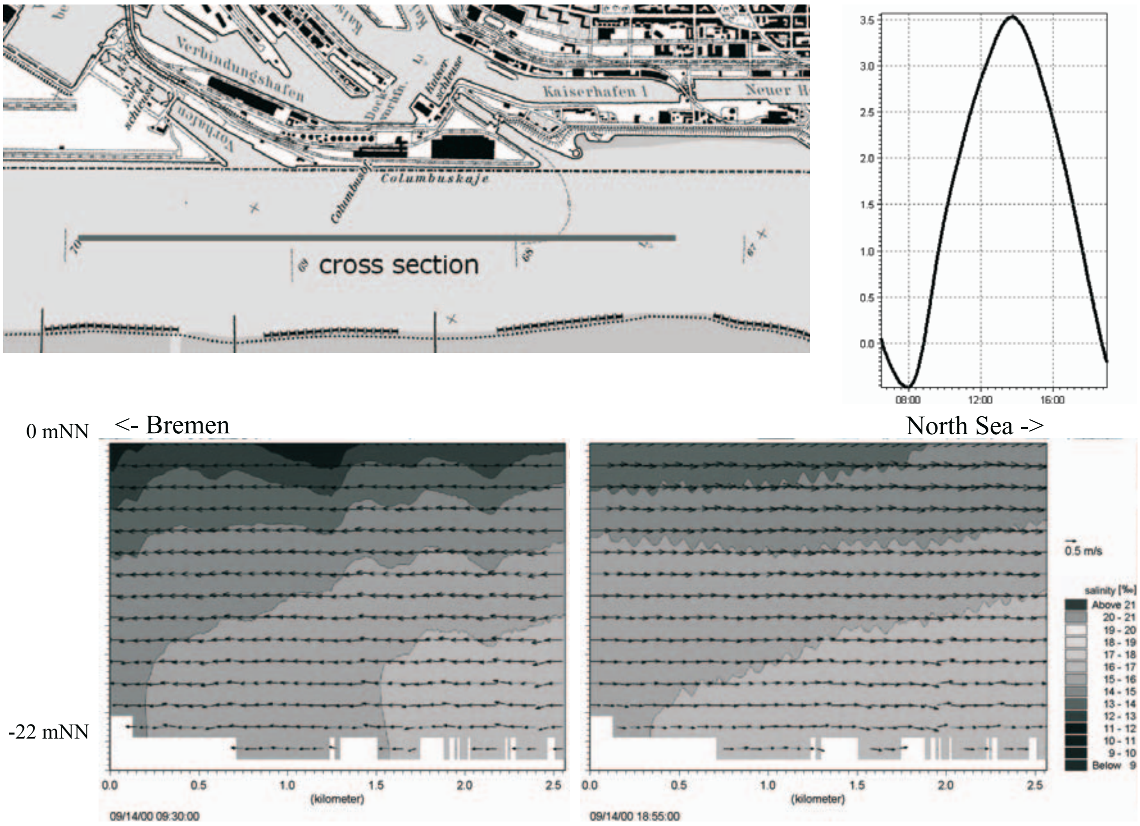

Figure 9: Cross section of the salinity in front of the harbour entrance (top) of Bremerhaven during maximum flood current (bottom left) and ebb current (bottom right)

This stratification can lead to opposite flow directions at surface and sea floor especially in harbour entrances (Figure 8 right). Figure 10 exemplifies this by showing the flow pattern in the harbour entrance called "Vorhafen" during flood current. At the bottom, the maximum inflow of saline water into the harbour is found while fresh water outflow occurs at the surface.

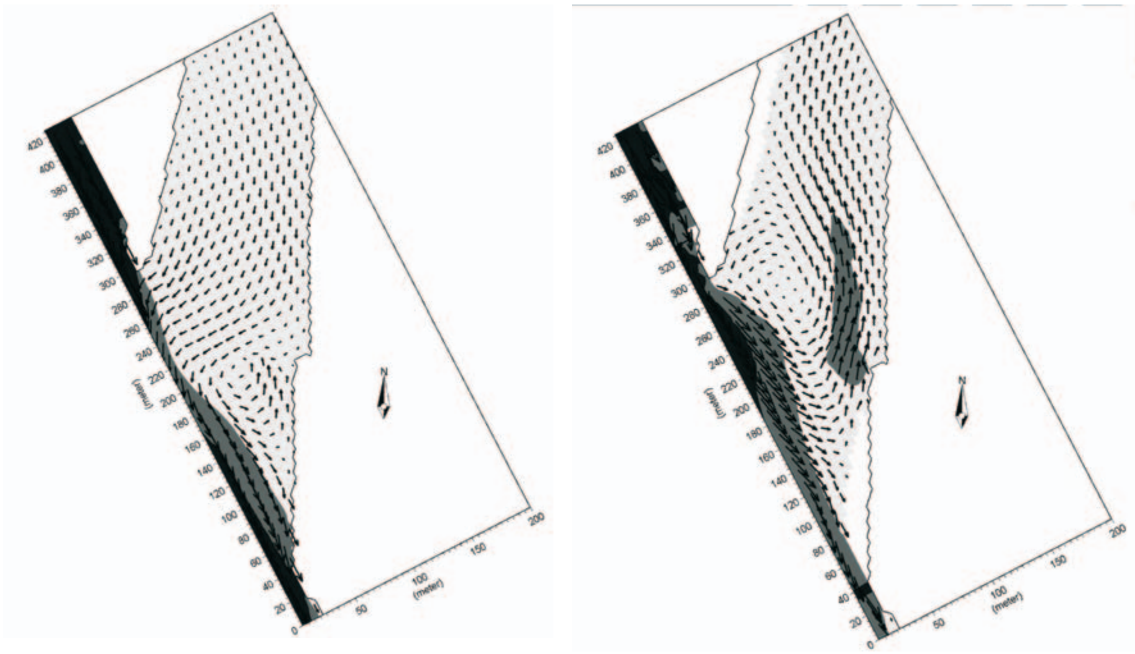

Figure 10: Flow in an entrance of the harbour of Bremerhaven during flood current, surface current (left) and bottom current (right) (Stoschek et al., 2003)

Modelling of Sediment Transport

The knowledge of the vertical profile of flow velocity is essential for the modelling of sediment transport due to the strong vertical gradient in sediment concentration as indicated in Figure 11. The basis to model sediment transport is a conservation equation similar to Eq. (3) and (4). However the settling velocity w_s must be introduced

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x_j}\left(c(u_j - w_{s,j})\right) = \frac{\partial}{\partial x_j}\left(D_c \frac{\partial c}{\partial x_j}\right) + D + E \tag{5}$$

with the deposition rate *D* and the erosion rate *E*. The sub-processes of deposition and erosion are given in Figure 12.

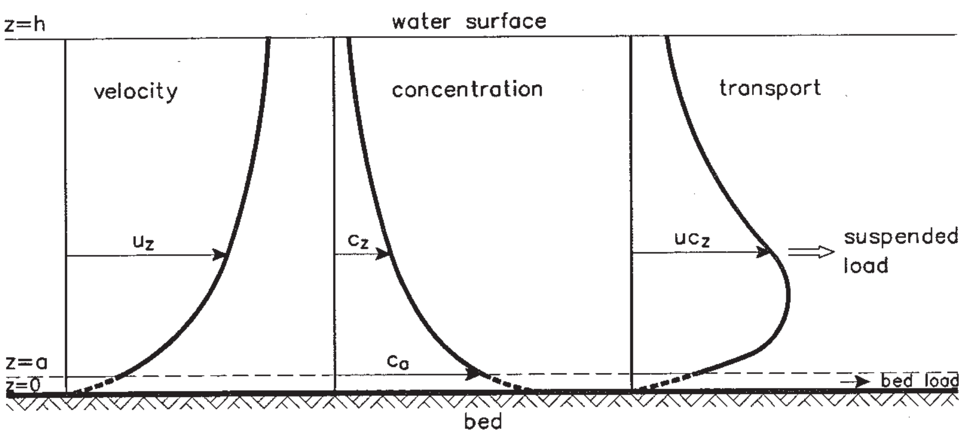

Figure 11: Profile of flow velocity, sediment concentration and sediment transport (Rijn, 1993)

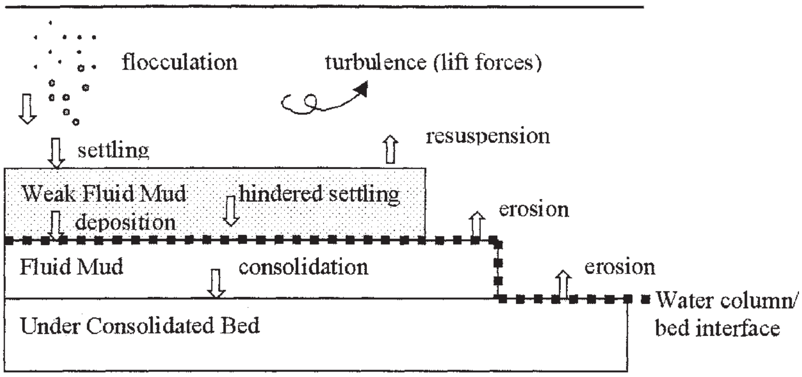

Figure 12: Processes of erosion and sedimentation (Mike3, 2000)

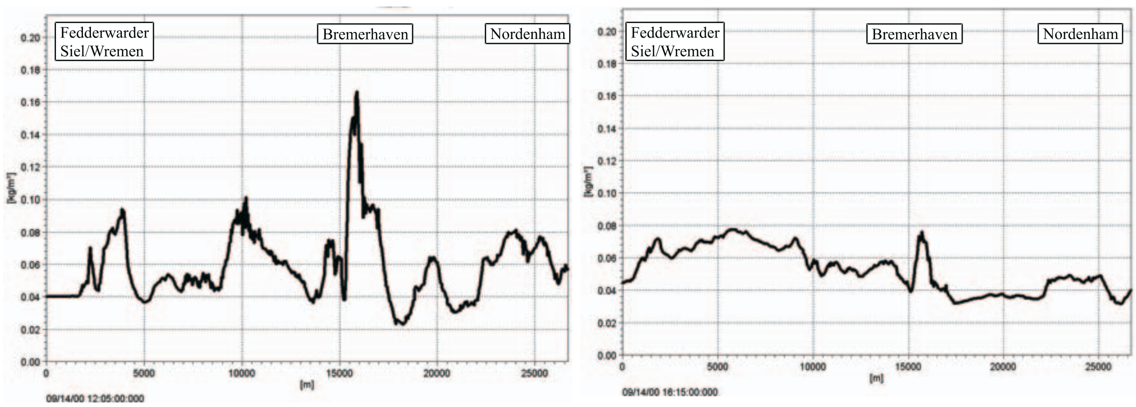

Figure 13: Sediment concentration in the estuary Weser during flood current (left) and ebb current (right)

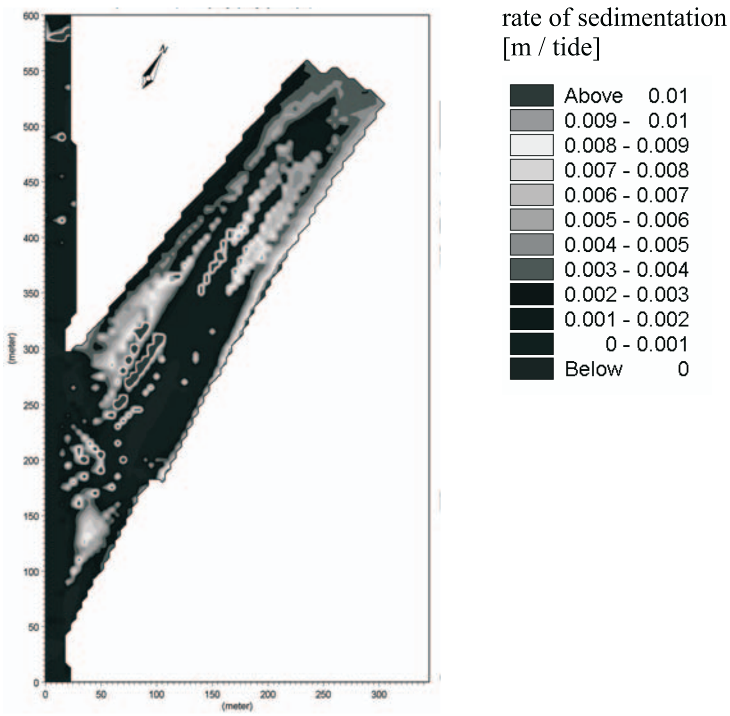

Figure 14: Rate of sedimentation within the harbour entrance of Bremerhaven (Stoschek et al., 2003)

Within the coastal zone, erosion and sedimentation undergo a strong tidal cycle and sediment concentration does as well. In Figure 13 an example of depth-averaged sediment concentration is given along the cross-section. In brackish coastal waters, sediment concentration reaches its maximum during flood current. Integrating the erosion and sedimentation over an entire tidal cycle results in the bathymetric changes to be expected over each tidal cycle. Figure 14 gives an example of this bathymetric change in the entrance to the harbour of Bremerhaven for average tidal conditions. Integrating the change over time will give the equilibrium state of the bathymetry. Changes of tidal conditions as presented in Figure 3 will cause a long-term bathymetric change. For the estuaries of Jade and Weser the bathymetric change relating to a scenario of climate change is given in Figure 15.

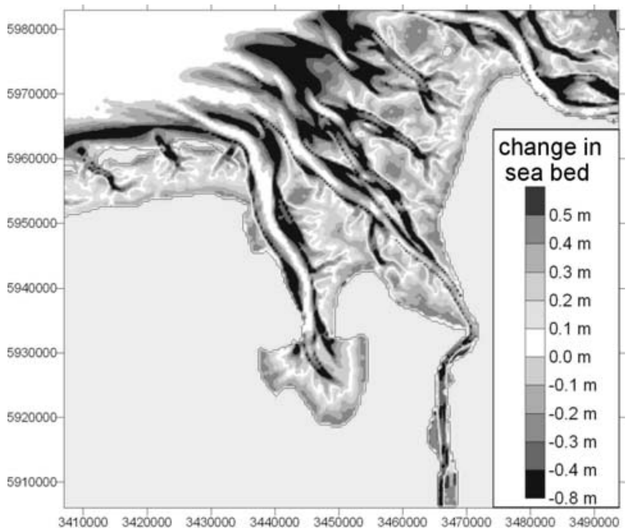

Figure 15: Long-term bathymetric changes as a consequence of climate change

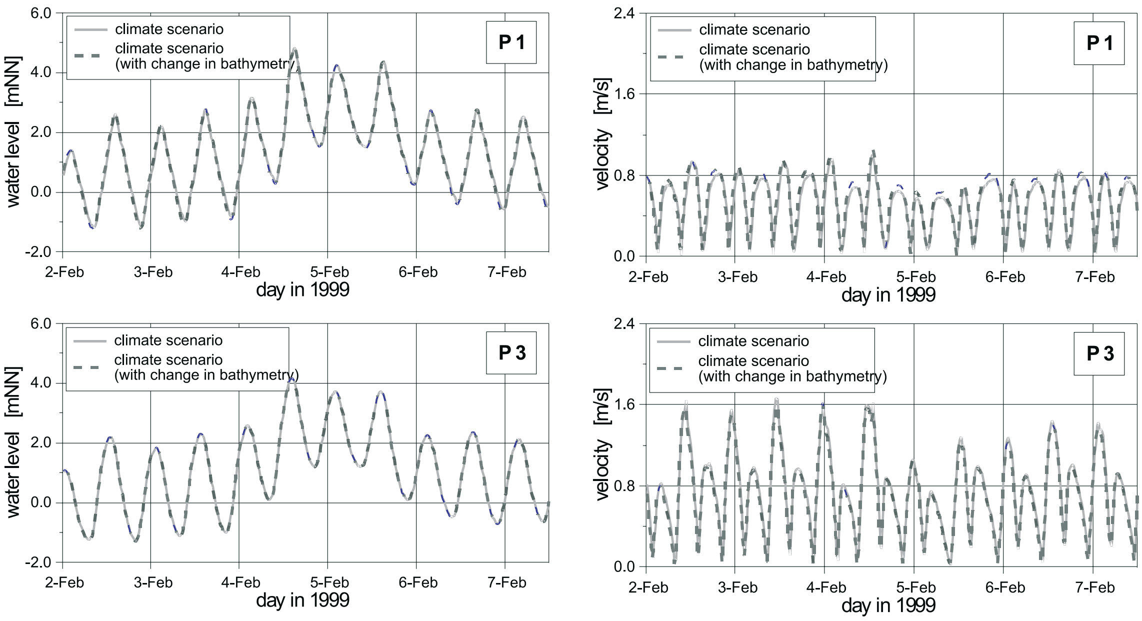

Figure 16: Effect of bathymetric changes on water level and flow velocity in the fairway

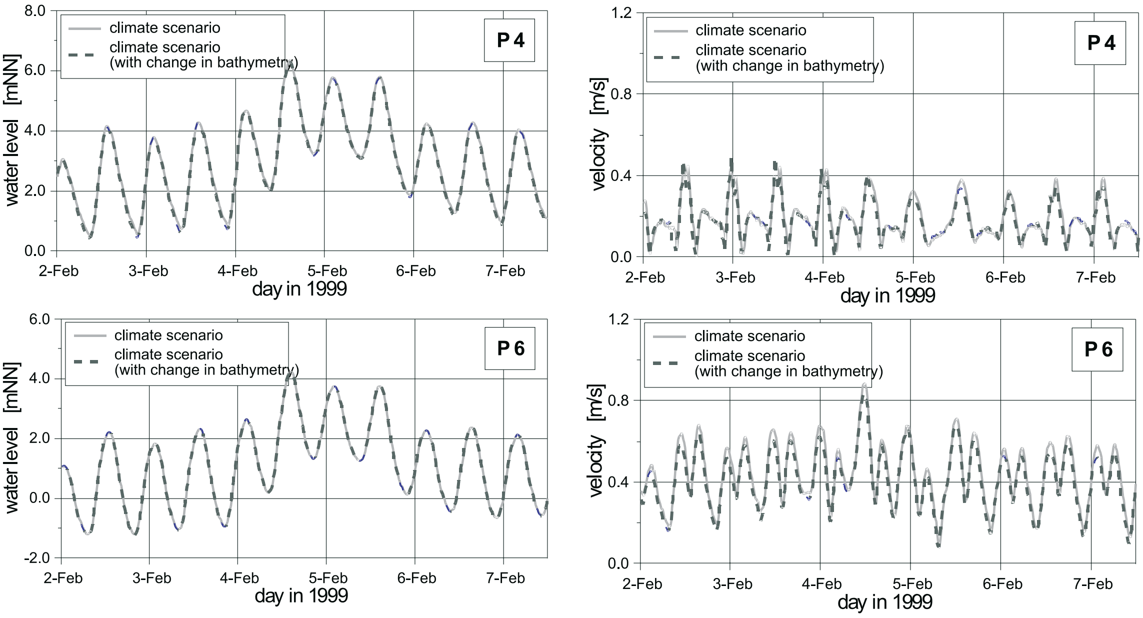

Figure 17: Effect of bathymetric changes on water level and flow velocity over the tidal flats

With the change of bathymetry the coastal hydraulics, i.e. water levels and flow velocities, change significantly. These changes are exemplified in Figure 16 and 17 for two locations in the fairway and over the tidal flats for a scenario of the storm surge of 1999.

Modelling of Wave Propagation

Besides of the influence of vertical density gradients, waves also alter the flow profile. The superposition of wave orbital motion and current velocity is exemplified in Figure 18. In addition to the orbital motion, additional wave induced currents also occur. The driving forces of these currents are typically calculated with phase-average numerical models, like SWAN (9, 10), based on the action balance equation

$$\frac{\partial}{\partial t}N(x,y,\sigma,\theta,t)+\frac{\partial}{\partial x}\left(c_{g,x}+u_x\right)N(x,y,\sigma,\theta,t)+\ldots+\frac{\partial}{\partial y}\left(c_{g,y}+u_y\right)N(x,y,\sigma,\theta,t)+$$
$$+\frac{\partial}{\partial \sigma}c_\sigma\,N(x,y,\sigma,\theta,t)+\frac{\partial}{\partial \theta}c_\theta\,N(x,y,\sigma,\theta,t)=\frac{S(x,y,\sigma,\theta,t)}{\sigma} \quad (6)$$

with the action density N, the current velocity u_x and u_y, the group velocity c_g, the velocities in the spectral domain c_σ and c_θ, the wave direction θ, the relative frequency σ as well as sources and sinks of wave energy, S.

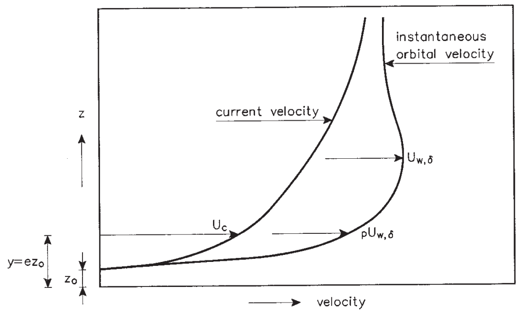

Figure 18: Effects of waves on the profile of flow velocity (Rijn, 1993)

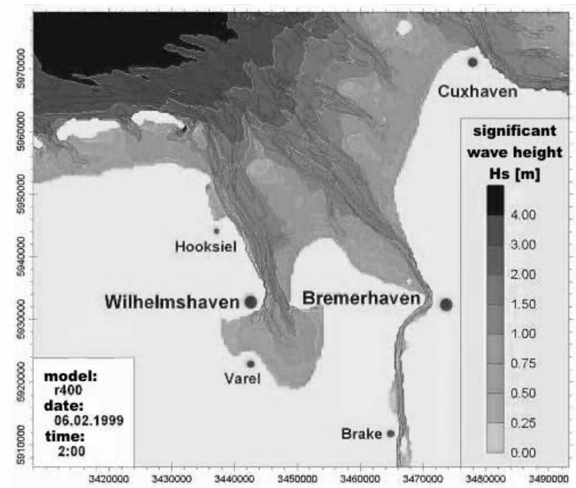

Figure 19: Wave propagation (significant wave height) in the estuaries Jade and Weser during a storm surge in 1999 (Mai and Zimmermann, 2004)

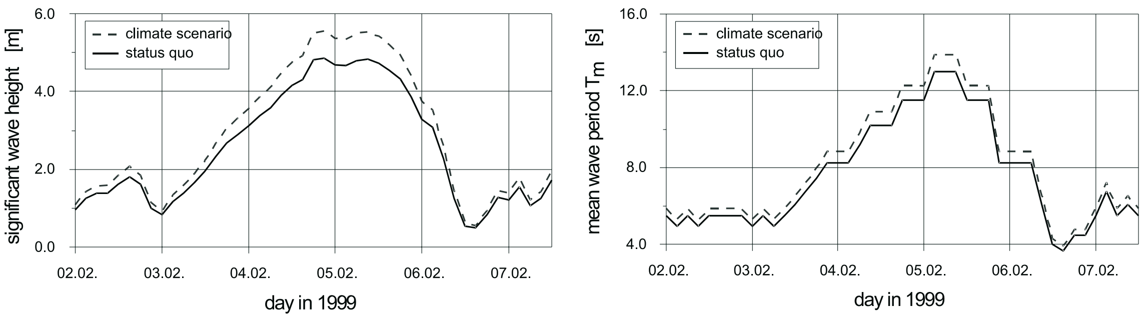

Figure 20: Scenarios of boundary conditions to analyse the effect of climate change in terms of significant wave height (left) and mean wave period (right) of the incoming wave field (Mai and Zimmermann, 2004)

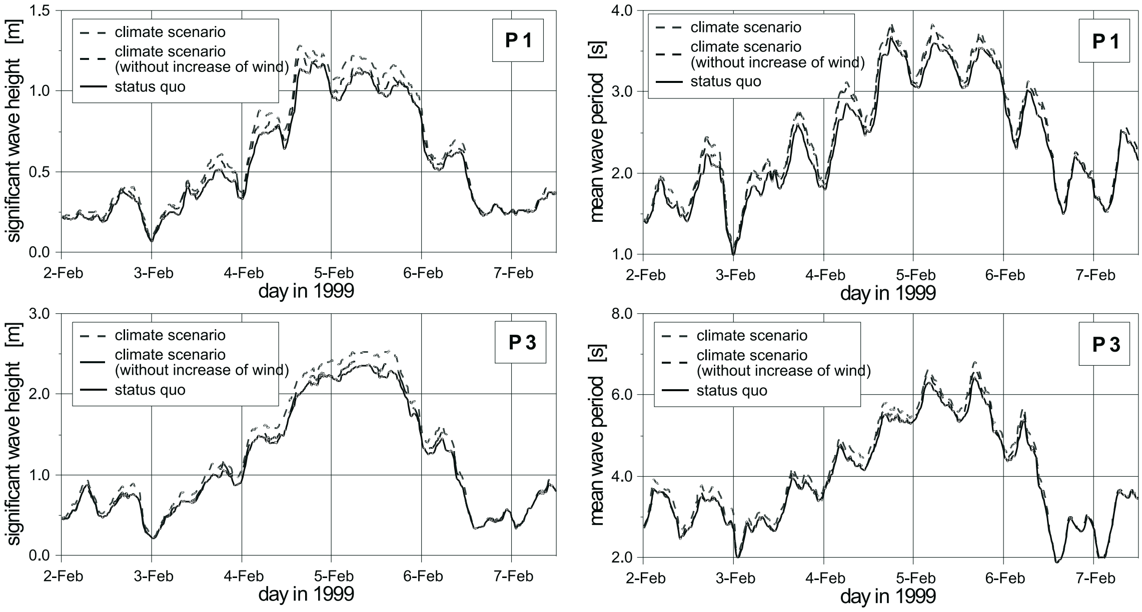

Figure 21: Effect of climate change on significant wave height (left) and mean wave period (right) in the fairway (Mai and Zimmermann, 2004)

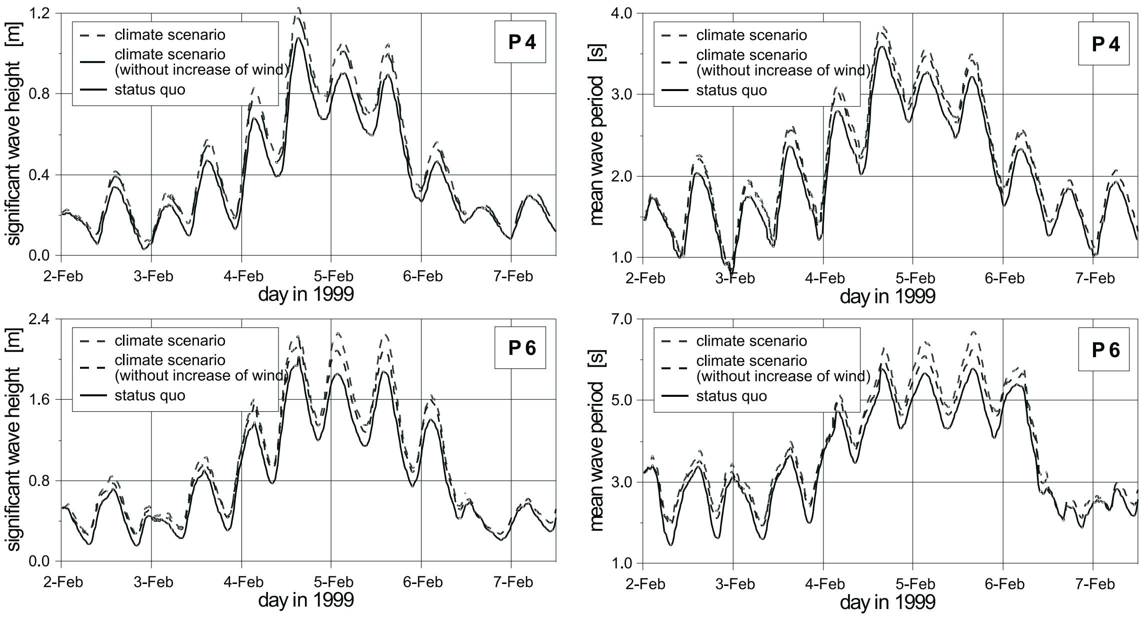

Figure 22: Effect of climate change on significant wave height (left) and mean wave period (right) over the tidal flats (Mai and Zimmermann, 2004)

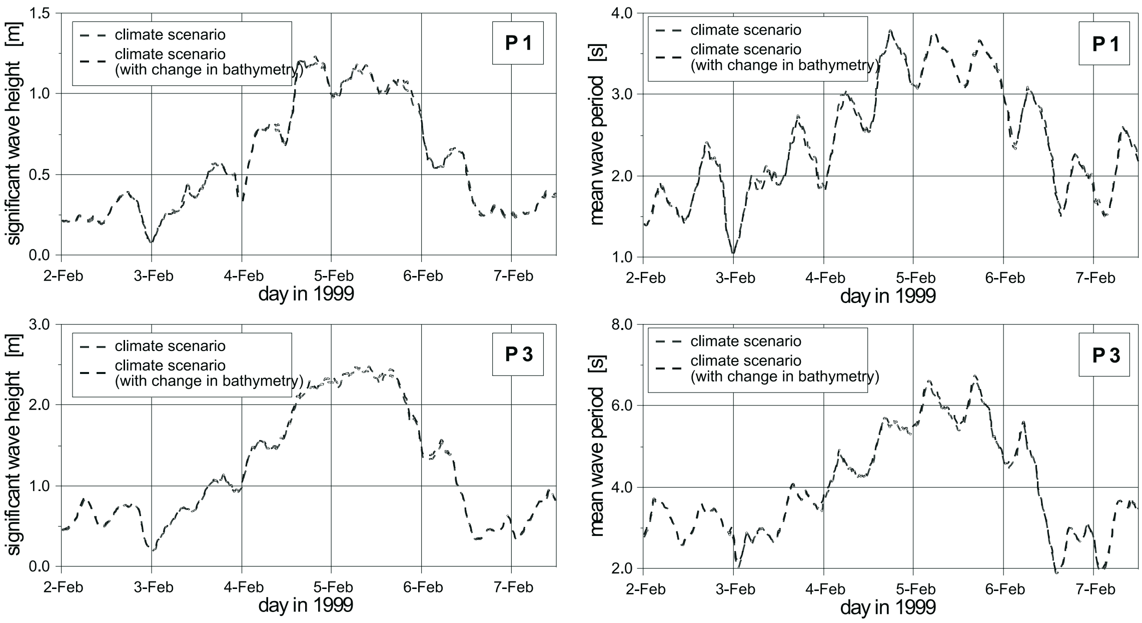

Figure 23: Effect of bathymetric changes on significant wave height (left) and mean wave period (right) in the fairway

Figure 19 presents an example of the wave field within the estuary of Jade and Weser during a storm surge in the year 1999, already given in Figure 3. In addition to the tidal water levels and flow conditions, as given in Figure 2, the incoming wave field was prescribed. The time-series of significant wave height and mean wave period are given in Figure 20. In addition to assumed climate changes, a possible scenario of the boundary conditions is also included to the status-quo. With the change in boundary conditions the wave parameters in the fairway and over the tidal flats also change, as indicated in Figure 21 and 22. The relative change over the tidal flats is approximately twice as great as in the fairways. In the case of the long-term bathymetric changes given in Figure 15, the increase in wave height and wave period is partly compensated. Figure 23 and 24 prove this.

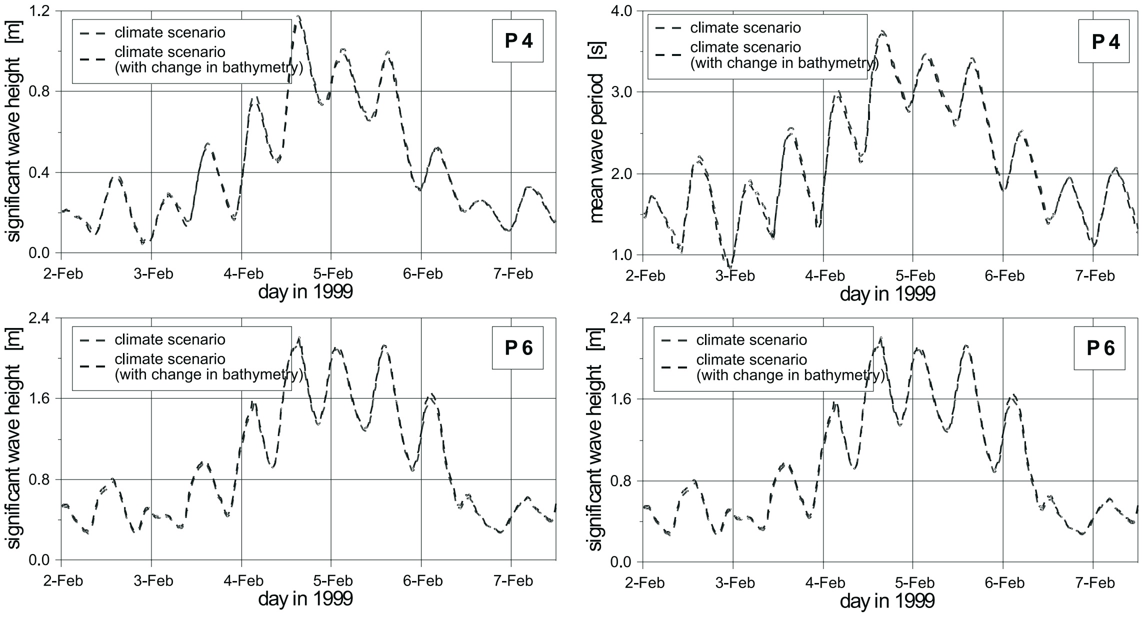

Figure 24: Effect of bathymetric changes on significant wave height (left) and mean wave period (right) over the tidal flats

Summary/Conclusion

The basic concepts of modelling in coastal hydraulics have been illustrated. In these models, the correct representation of the velocity profile, is essential for the correctness of sediment transport modelling. Therefore three-dimensional modelling is needed in brackish coastal waters. In addition to the 3D treatment of tidal flow, the inclusion of wave induced currents as well as wave orbital motion lead to further improvement of the results.

Acknowledgments

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