EFFECTS OF A CURRENT DEFLECTION WALL IN A TIDAL HARBOUR ENTRANCE

by

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ABSTRACT

Siltation as a serious problem in harbours situated on tidal rivers and estuaries causes maintenance dredging or needs other measures, to guarantee safe navigation and is often a large cost factor.

To prevent sedimentation of fine materials entering a harbour, Current Deflecting Wall (CDW) can be used, which passively alters the water exchange.

This paper presents a numerical experiment on the effects of a CDW to reduce siltation in harbours. The experiment was designated to investigate the effects of a CDW on water exchange and turbulent mixing in the transition area between river and harbour basin, and thus reproduce results of previous physical experiments.

The investigated CDW for inhomogeneous conditions covers the top half of the water depth, capturing water during the main part of the flood period in order to slow down outgoing density currents through the upper layer. A sill at the bottom deflects the near-bed density current away from the entrance.

This creates a vertical vortex with its axis across the entrance during rising tide, which reduces near bed water influx coming from the river bed. As a conclusion the exchange during rising tide originates from the upper layer, which is less dense and contains less sediment.

The effect of the Current Deflecting Wall described by VAN LEEUWEN and HOFLAND (1999) were not reproduced. The stated complex and constant eddy structure over the whole entrance (Fig. 9.10, p. 78) was not visible in this experiment.

The experiment showed, that water exchange, and thus sediment input, between river and harbour entrance in an inhomogeneous (brackish) environment can be reduced to a certain extent. CDWs cannot prevent the density driven current. However, a substantial reduction of siltation should be possible.

1. INTRODUCTION

To prevent sedimentation of fine materials entering a harbour, Current Deflecting Wall (CDW) can be used, which passively alters the water exchange (Fig. 1).

VAN LEEUWEN and HOFLAND (1999) described the beneficiary effects of CDWs under tidal conditions with inhomogeneous density as follows:

(a) Reduction of mixing exchange between harbour and river,

(b) Capture of water needed for tidal filling from the top layer of the river and

(c) Diverting away the mixing layer from the harbour basin.

These three main exchange mechanisms were investigated by 3D numerical modelling. Although the magnitudes of the different mechanisms vary continuously over a tidal cycle, and site-specific circumstances are important, a general order of the relative importance in brackish environments is as follows: exchange due to salinity-induced density currents, exchange due to tidal filling and exchange due to turbulent mixing. Density currents due to highly concentrated suspensions were not taken into

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account. Wind driven currents were ignored, due to water depths of more than 10m in most tidal harbours.

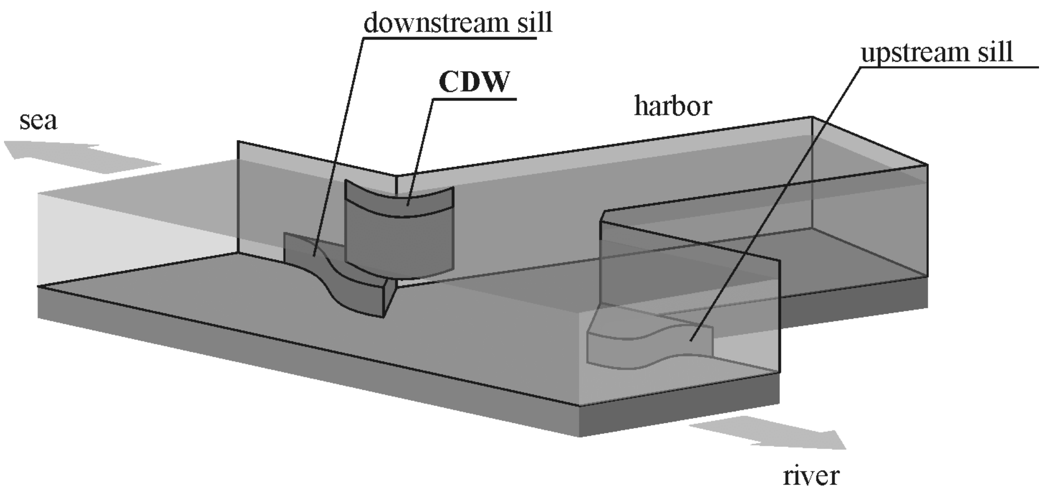

Figure 1: Current Deflecting Wall downstream a Tidal Harbour Entrance

A density difference over the harbour entrance is the driving force behind the density current into the harbour. The velocities have strong changes in direction over time and depth. Flow pattern into the harbour is three-dimensional. The density current causes flow in opposite directions in the upper and lower layers. The resulting in/out boundary layer is varying over the tidal cycle and the entrance. The current is directed into the harbour at the bed from the first half of rising tide to the first half of falling tide.

The investigated CDW for inhomogeneous conditions covers the top half of the water depth, capturing water during the main part of the flood period in order to slow down outgoing density currents through the upper layer. A sill at the bottom deflects the near-bed density current away from the entrance. This creates a vertical vortex near the bed with its axis across the entrance during rising tide, which reduces near bed water influx. As a conclusion the exchange during rising tide originates from the upper layer, which is less dense and contains less sediment.

2. PHENOMENA UNDER INVESTIGATION

A detailed description of flow characteristics in harbour entrances and changes in flow patterns in a tidal brackish environment using a CDW can be found in VAN LEEUWEN and HOFLAND (1999).

Thus, this introduction focuses on critical flow pattern under discussion in research. A density difference along the harbour entrance is the driving force for the density current into the harbour.

Velocities show strong directional changes over time and depth with a three-dimensional flow pattern into the harbour. Strength of this 3D flow structure and intensity of vertical components are under discussion. Density currents cause opposite flows in the upper and lower layers (Fig. 2).

The combined flow mechanisms can be distinguished in the order of influence 1) and 2) changing specific to the site) as follows (LANGEDOEN, 1992):

1) Density driven currents (salinity) between river and harbour,

2) Turbulent mixing in a transition zone between river and harbour and

3) Tidal filling of the harbour.

The resulting horizontal in/out boundary layer is varying in depth over the tidal cycle. Currents are directed into the harbour over the bed from the first half of rising tide to the first half of falling tide, where the largest sediment flux into the harbour takes place.

At present, complete consensus of researchers on the precise function and effects of the CDW does not exist. VAN LEEUWEN and HOFLAND (1999) stated latest for inhomogeneous environments, that CDW function is best during the critical tidal phase of rising tide, where

- CDW directs water from the river top layer into the harbour (tidal filling),
- A downstream sill deflects the near-bed density currents away from the harbour entrance and
- CDW creates a vertical vortex near the bed with its axis across the harbour entrance (Fig. 3).

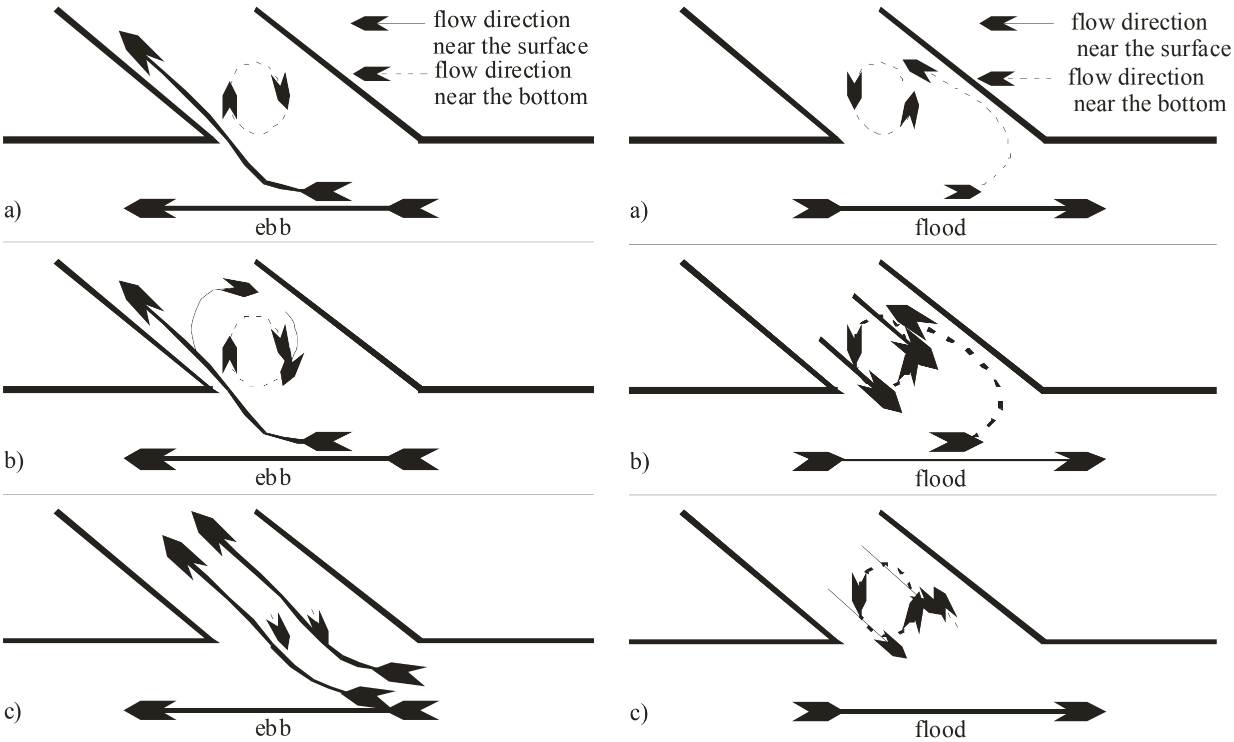

Figure 2: Flow Pattern in the Harbour Entrances during Ebb (left) and Flood (right): (a) Beginning of Ebb/Flood, (b) During Ebb/Flood and (c) End of Ebb/Flood (FRANZIUS-INSTITUT, 2003)

They explained that the vortex is the main cause for the reduction of near bed water influx during rising tide. It is created by a pressure gradient over the vertical behind the CDW. It is stated that this secondary current blocks density currents from the sediment loaded currents from river into the harbour.

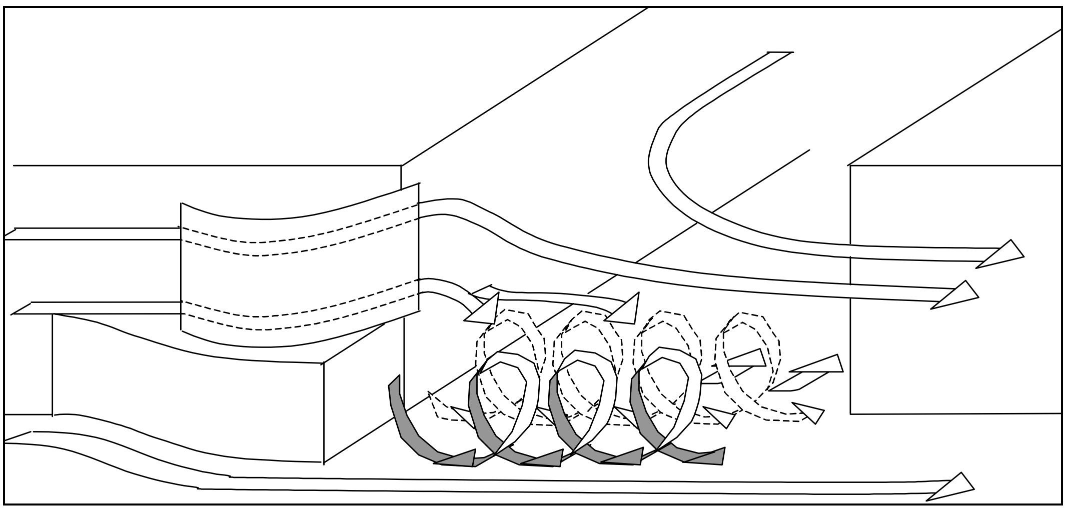

Figure 3: Schematic Flow Pattern in Entrance during Flood with CDW present (VAN LEEUWEN and HOFLAND, 1999).

It can be suspected, that it also fixes the turbulent mixing zone and hinders a turbulent flux into the harbour. For other possible effects, such as "extra pressure against the pressure of the density current", "decrease the effective width of the harbour entrance" and "increase of friction between the layers" they concluded, that these effects cannot have a significant influence.

One of the goals of the numerical experiment described in this paper, was to reproduce this flow pattern in the entrance, to show applicability of CDW.

3. METHODOLOGY OF THE EXPERIMENT

3.1 Application of MIKE 3 Hydrodynamic Module

The theoretical background of MIKE 3 hydrodynamic modelling can be found in VESTED et al. (1992) and EKEBJAERG and JUSTENSEN (1991). Complex Case Studies on the applicability of the described theory were performed during the COSINUS-Project for the Tamar Estuary by PETERSEN et al. (2002) and FRANZIUS-INSTITUT (2003) for the Ems and Weser Estuaries.

Related to these studies we propose the applicability of the chosen modelling technique for the experiment to describe density driven currents in brackish tidal environments.

3.2 Set-Up of the Numerical Experiment

The model set up was developed from physical model tests of VAN LEEUWEN and HOFLAND (1999).

The model topography of physical model tests was scaled up to nature (M 1:50), resulting in an estuary model of 6.500 m length and a width of 54 m.

The grid resolution for the estuarine model (staggered grid with $\Delta x=\Delta y$) was 13.5 m. The model area around the harbour was modelled using a grid resolution of 4.5 m going down to 1.5 m in front of CDW (Fig. 4). CDW and harbour entrance were modelled by a 0.5 m mesh. The vertical resolution was 0.5 m, resulting in 22 layers. Previous investigations showed, that higher grid resolution are not applicable for this problem.

Bathymetry with constant bottom roughness of k = 0.05 m was applied without slope (bottom level of the estuary = 0 mNN), as done for the physical model tests.

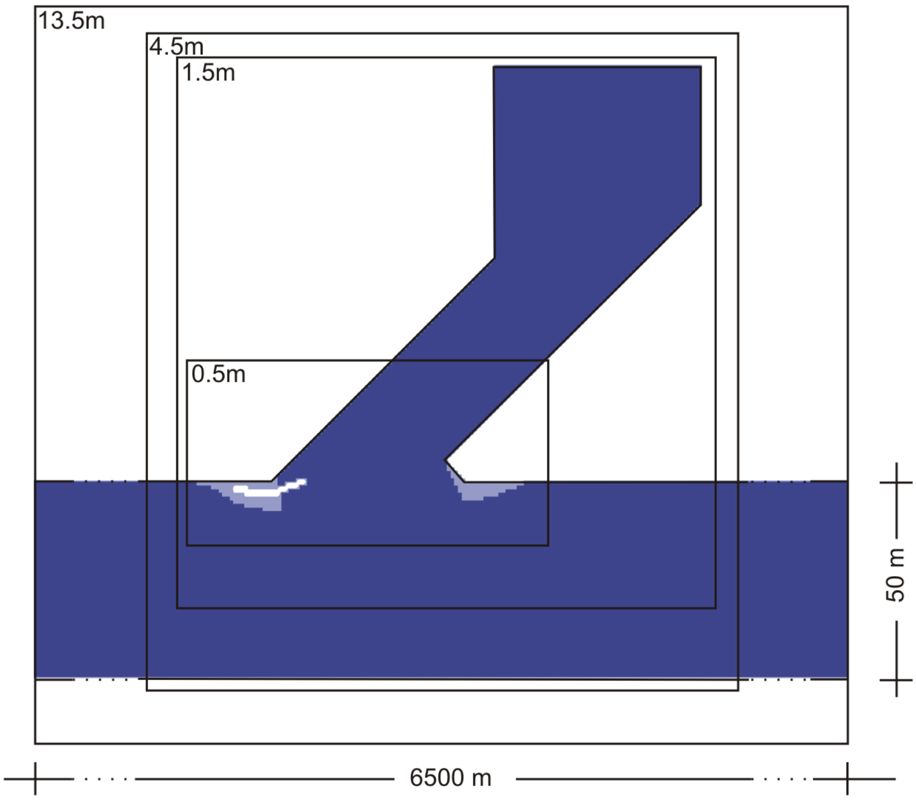

Figure 4: Grid Resolution of different Model Areas

Time step length was $\Delta t = 0.2$ s ($C_R \cong 1$).

A mixed k-ε/Smagorinsky model was used for turbulent modelling (Tab. 1). The k-ε model was used in vertical direction; the Smagorinsky model in the horizontal plane. This approach was tested before by a well known physical model, where field tests and model records were available. It was also used intensively in FRANZIUS-INSTITUT (2003) and found to be the best available alternative.

$k_s = 0.05$ m	$\Delta t = 1$ s	Flood/Dry Check
No. of Layers = 22	$\Delta z = 0.5$ m	0.2 m / 0.3 m
k-ε Model (vertical)	$k = 1e\text{-}007$ [m^2/s^2]	$\varepsilon = 5e\text{-}010$ [m^2/s^3]
$c_\mu=0.09$, $c_{1\varepsilon}=1.44$, $c_{2\varepsilon}=1.92$, $\sigma_k=1$, $\sigma_\varepsilon=1.3$	$c_s = 0.4$	T = 18 [°C]

Table 1: Main Model Parameters

Boundary condition at sea side (h = f(t)) is shown in Fig. 5. On the upper model boundary a constant velocity of v = 1.41 m/s was used.

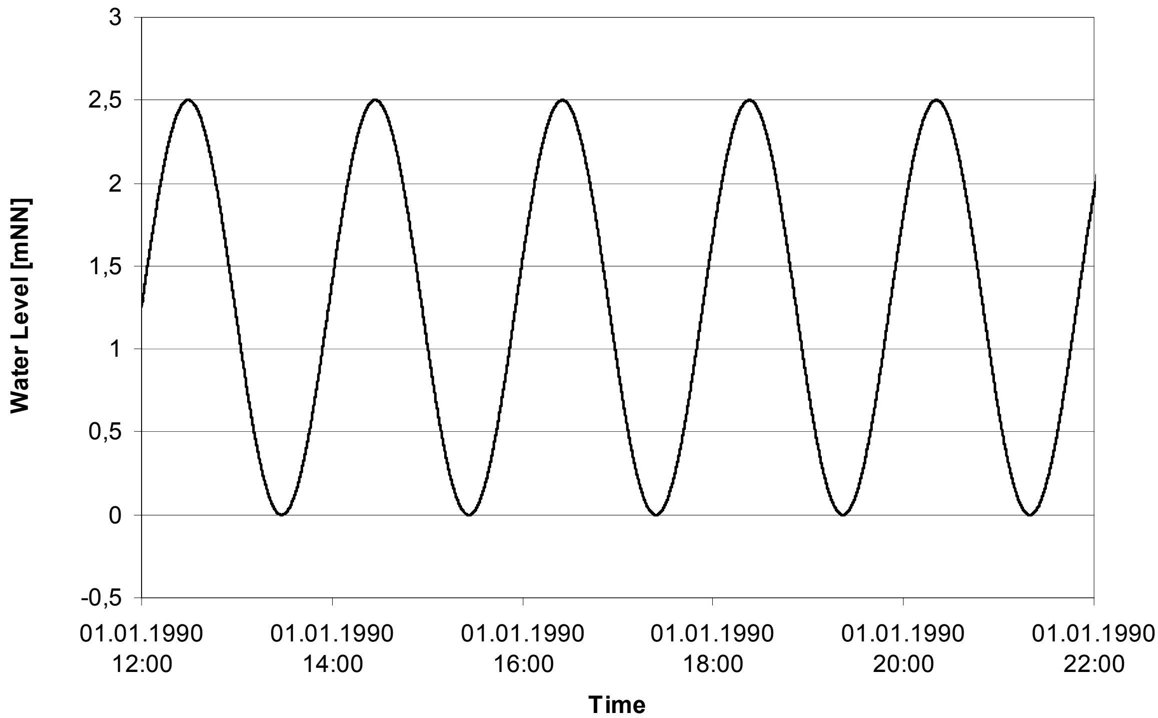

Figure 5: Water Level at Sea Side [mNN]

Salinity (estimated temperature of the water T = 18 °C) was set constant for both model boundaries, suggesting that the sea side (11%) and upper (2%) boundary are fully mixed (no stratification). The model was warmed up for a period of 4 tides to have a stable flow field.

The influence of short surface waves is neglected in this numerical experiment.

4. RESULTS

The period of second half of rising tide was identified in many case studies (FRANZIUS-INSTITUT, 2003 and VAN LEEUWEN and HOFLAND, 1999) as the most important one to be influenced for minimization of sedimentation inside the harbour. Thus, the evaluation of results is restricted to this period (here: 19:20 to 20:00). Results were evaluated for sections shown in Fig. 6.

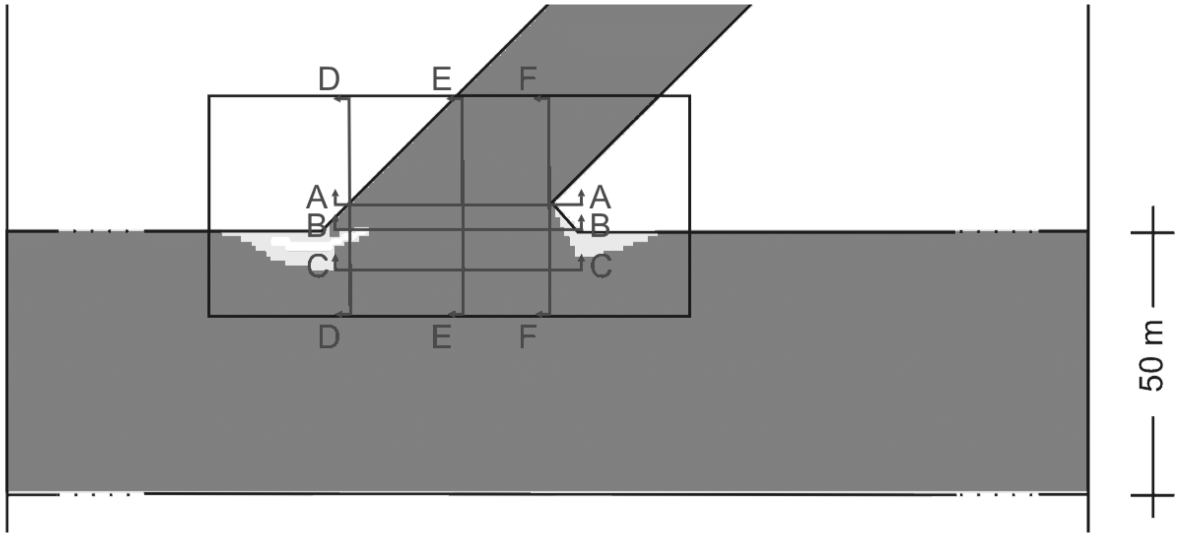

Figure 6: Sections for Evaluation of the Flow Field

Flood starts near the harbour entrance at t = 19:20 (Fig. 7), developing after approximately 20 min a flow field which is constant until 19:55 (Fig. 10). This flow field can be interpreted as fully developed flood current. It is equivalent to measured flow field in nature (Fig. 2). A division of the entrance in several areas of up/down going eddies to produce a flow field as described in Fig. 3 is not visible.

It is shown that after rising tide has started, salinity in the harbour changes slower than in the neighbouring estuary (Fig. 7, Fig. 9), which starts density driven currents between river and harbour.

In section D-D (Fig. 11, Fig. 12) the capture of water needed for tidal filling from the top layer of the river is documented. This is also indicted by Fig. 10, giving an impression how water is falling down after the CDW. The vertical flow velocities between shore and CDW are higher than on the other side of the wall. This indicates, that water is catched, accelerated and thus brought to the entrance to fill the harbour. Flow velocities are higher than outside the wall. Taking water from the upper part with less sediment in it, this is one mechanism of CDW functionality.

From 19:20 to 20:00 an eddy is rotating in section E-E, where it brings in water near the bottom. It is transversal to the opening of the harbour, very stable and compared with eddies shown in Fig. 3 of a huge dimension. The difference is that his water is brought in by the mechanism described before and not directly from the attached part of the river (Fig. 13, Fig. 14).

Section F-F is near the stagnation point and shows an unstable and diffuse flow field of the whole period. A diverting of the stagnation point to the river was not reproduced as mentioned by VAN LEEUWEN and HOFLAND (1999).

The main flow mechanisms of a tidal harbour entrance in brackish tidal environments were found. Having only hydrodynamics available, it is difficult to estimate the impact of the structure to sediment transport.

Due to the fact that results of this numerical experiment are going a little bit contrary to VAN LEEUWEN and HOFLAND (1999), it will be interesting to evaluate if the effects stimulated by CDW can also be available without having the flow field in Fig. 3.This will be tested by introducing sediment transport calculations, which will be one major task in the future.

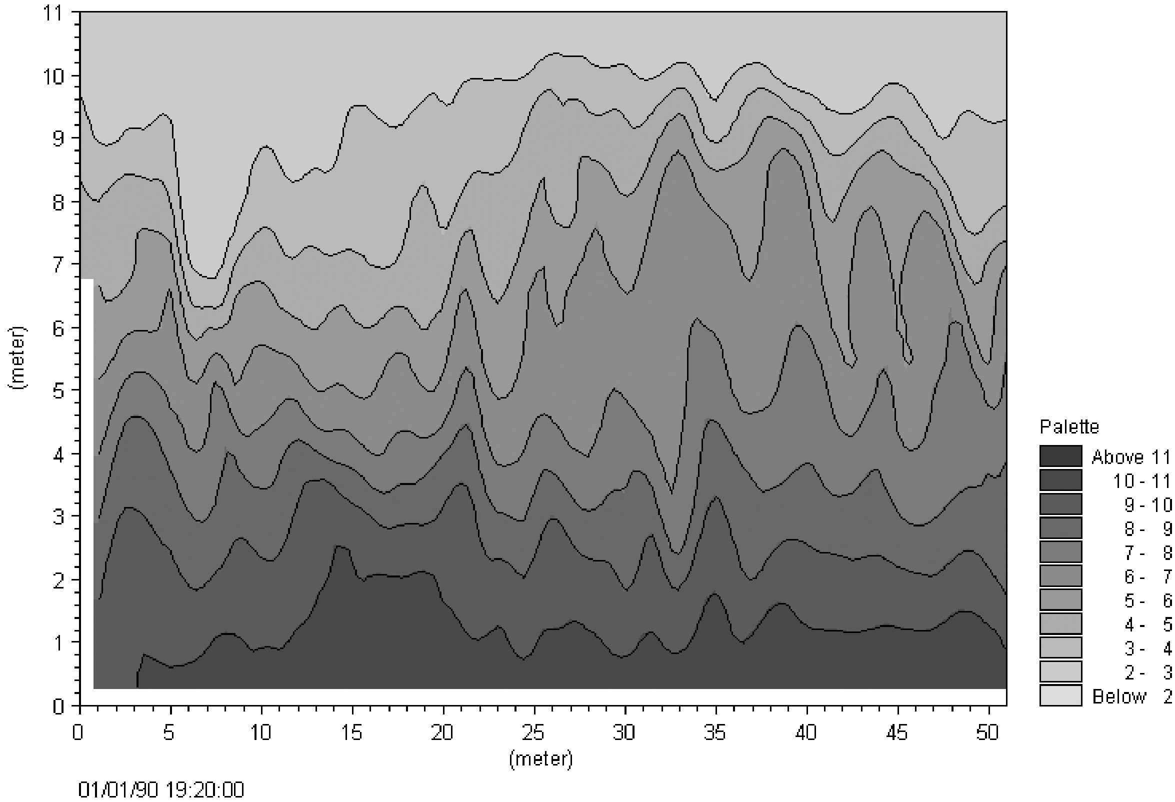

Figure 7: Salinity [‰] in Section C-C at t = 19:20 (start of rising tide)

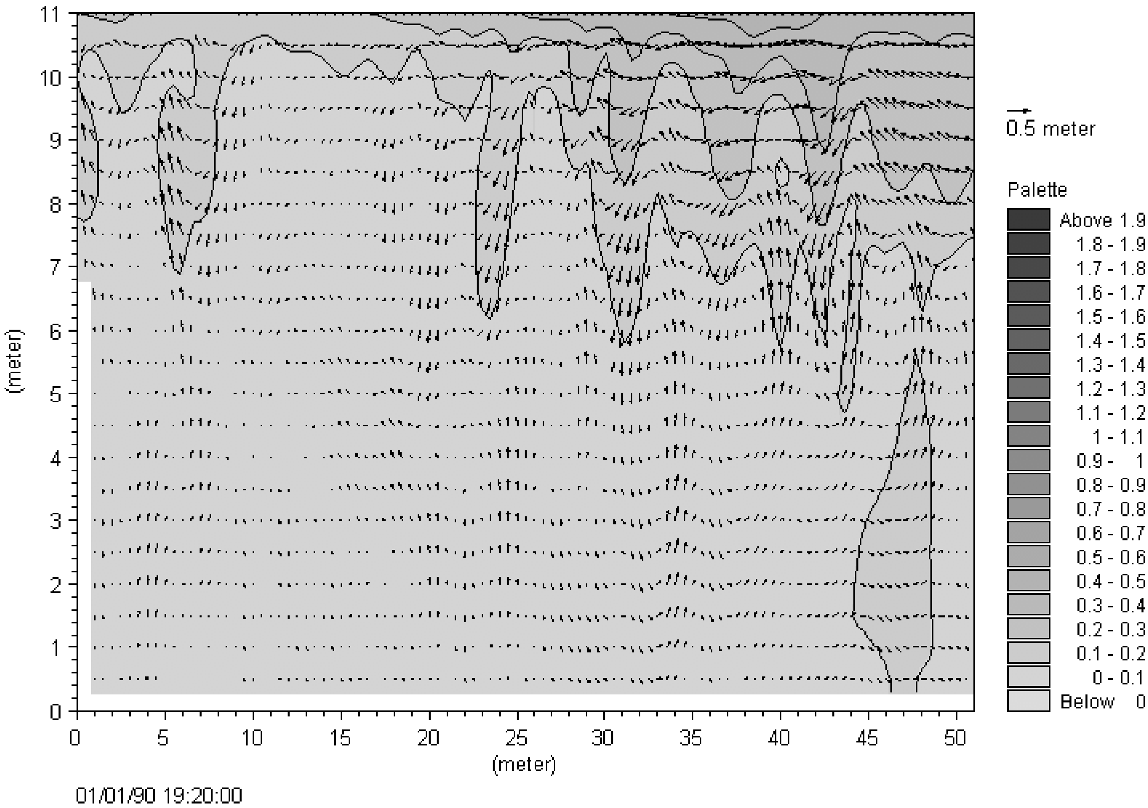

Figure 8: Flow Velocities [m/s] in Section C-C at 19:20 (start of rising tide)

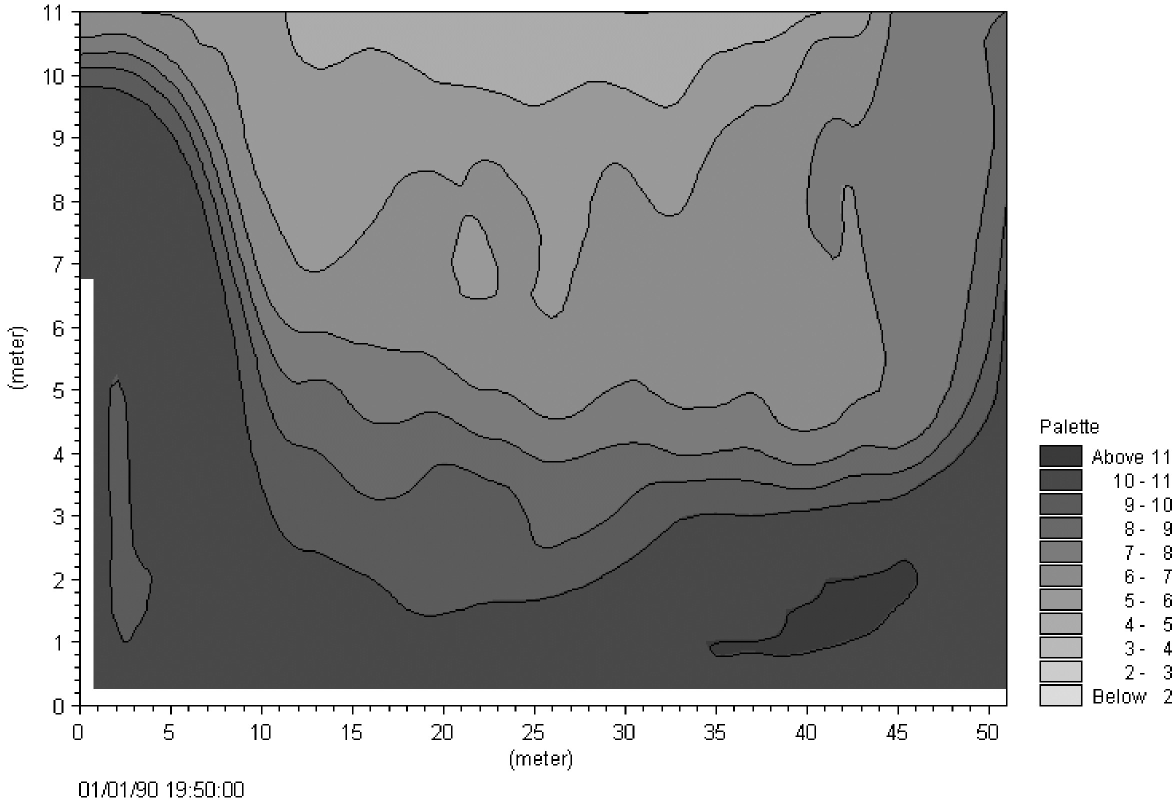

Figure 9: Salinity [‰] in Section C-C at t = 19:55 (fully developed flood)

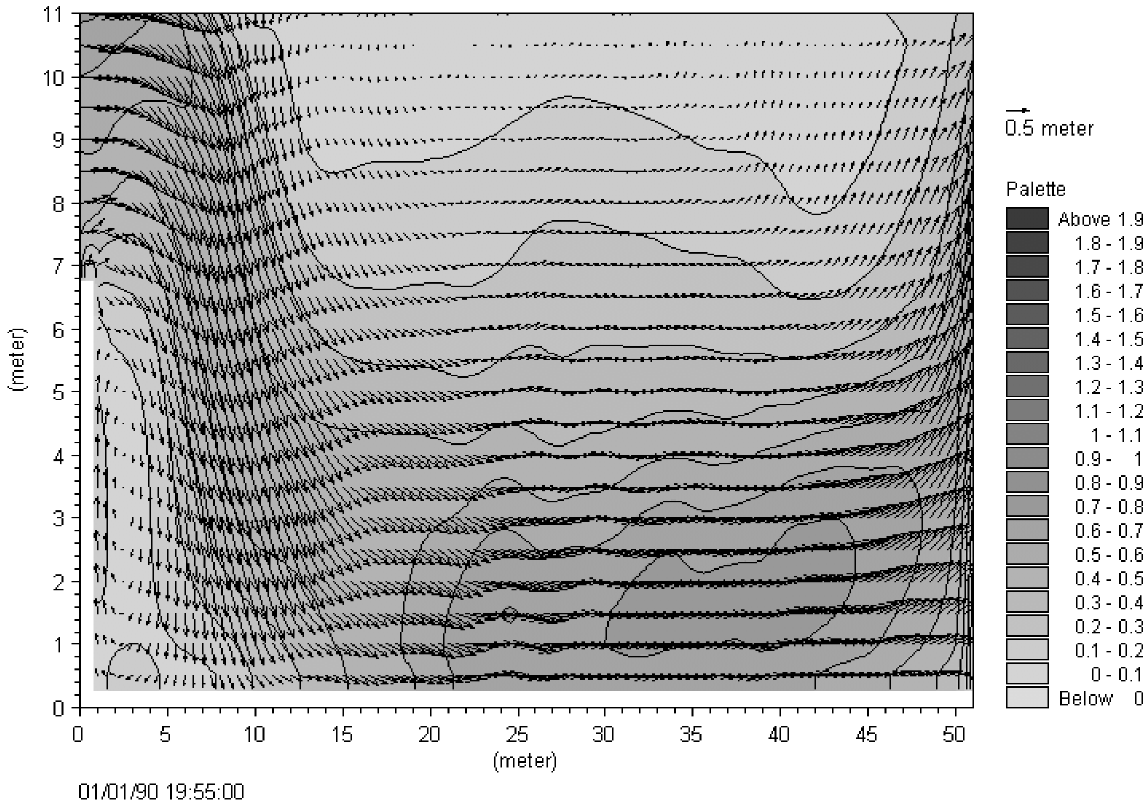

Figure 10: Flow Velocities [m/s] in Section C-C at 19:55 (fully developed flood)

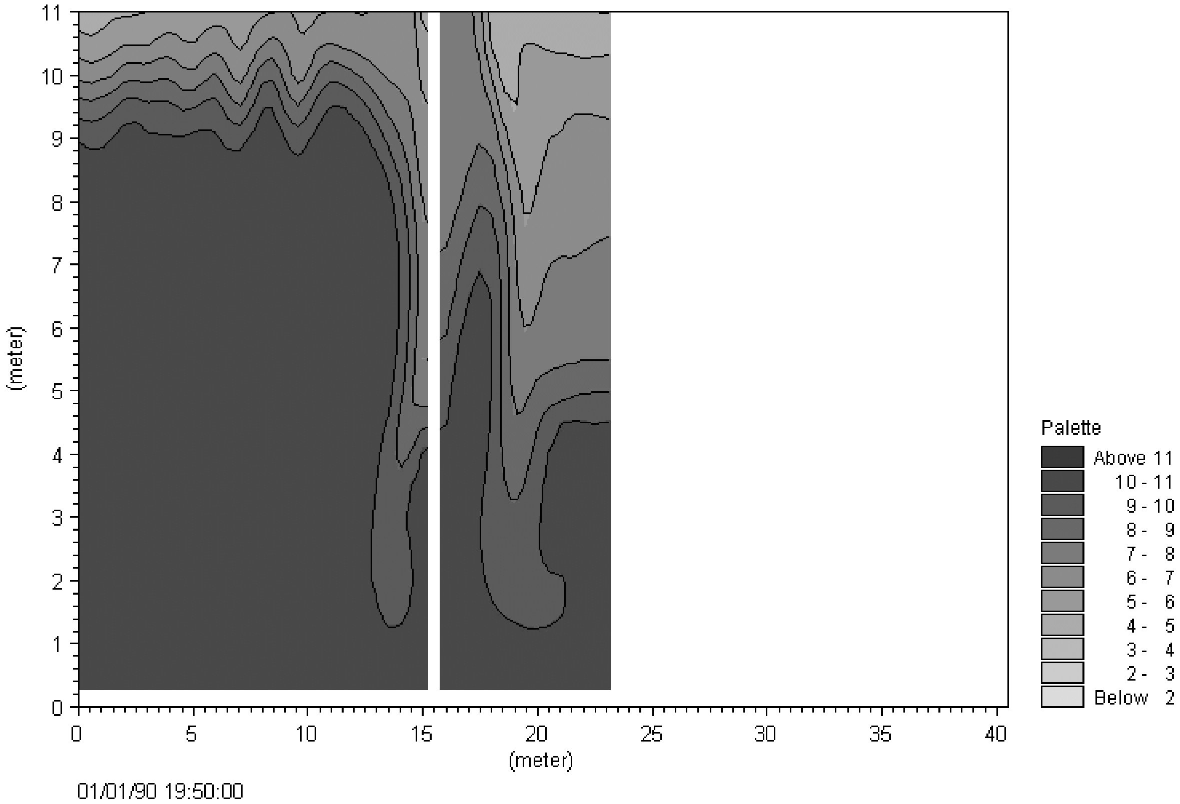

Figure 11: Salinity [‰] in Section D-D at t = 19:55 (fully developed flood)

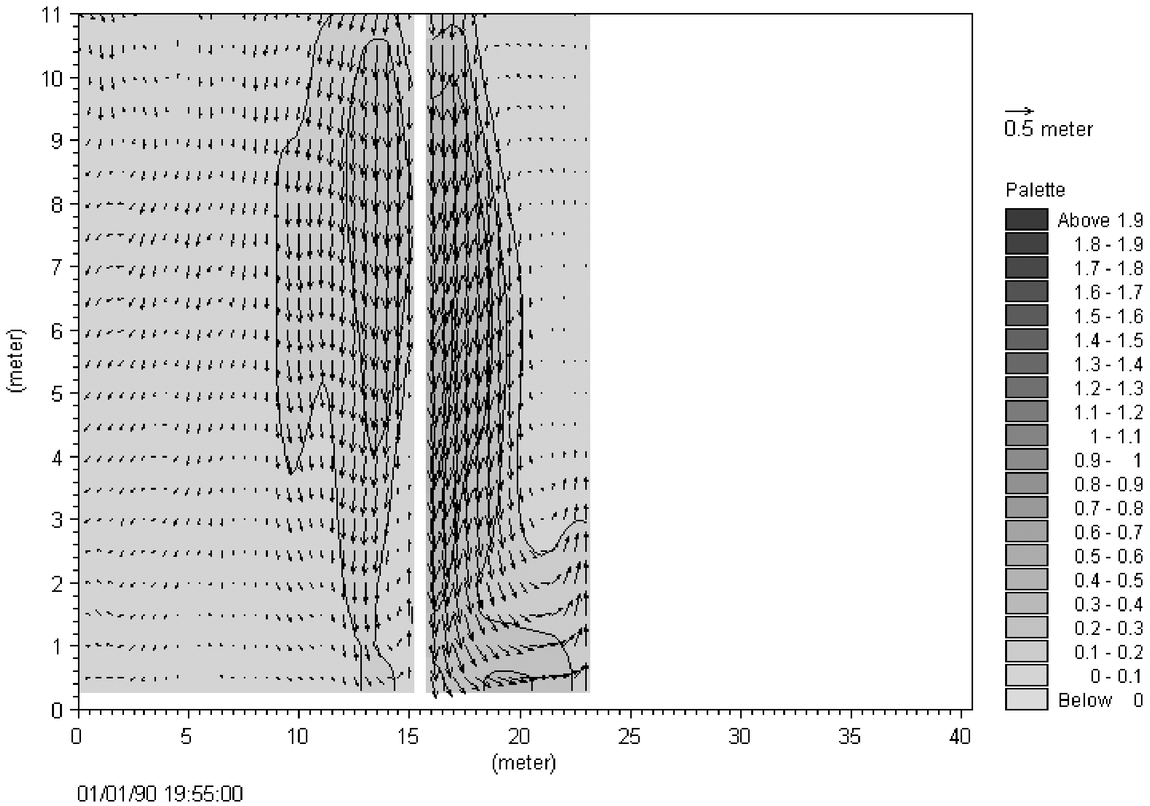

Figure 12: Flow Velocities [m/s] in Section D-D at 19:55 (fully developed flood)

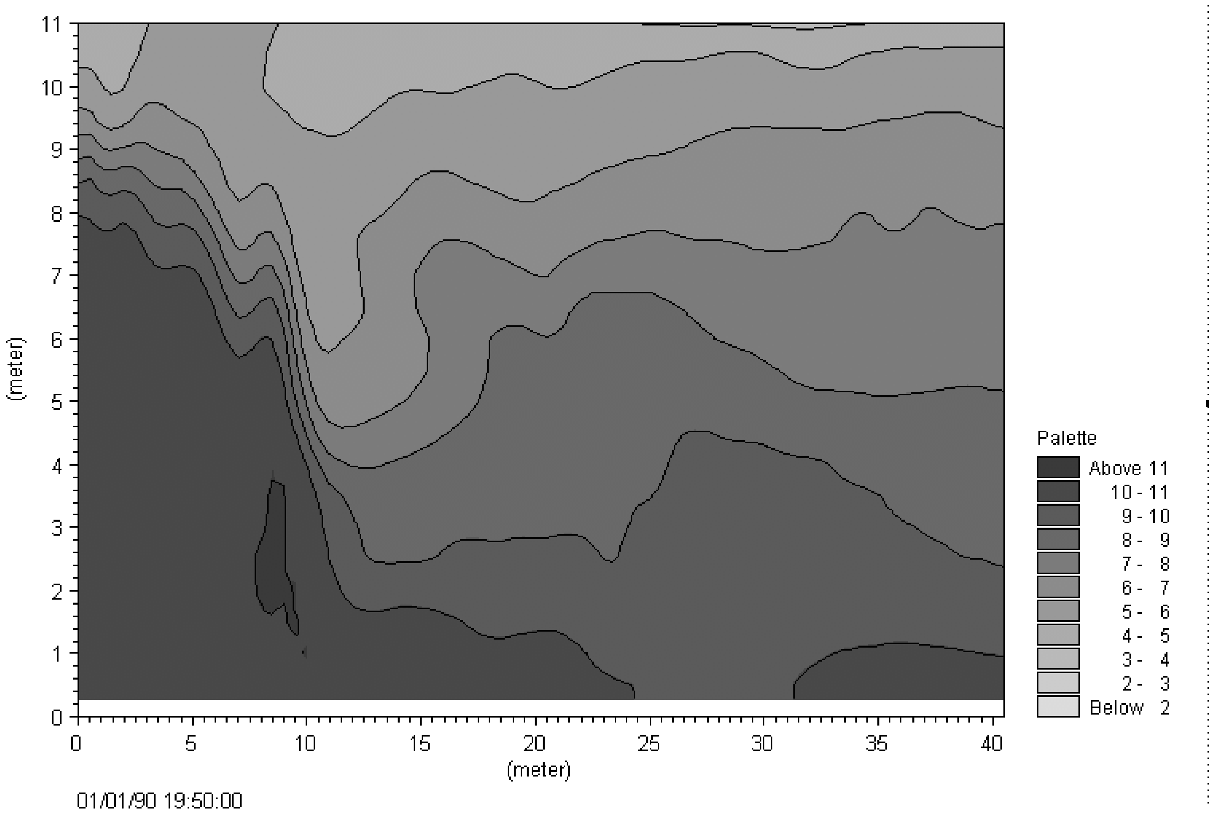

Figure 13: Salinity [‰] in Section E-E at t = 19:55 (fully developed flood)

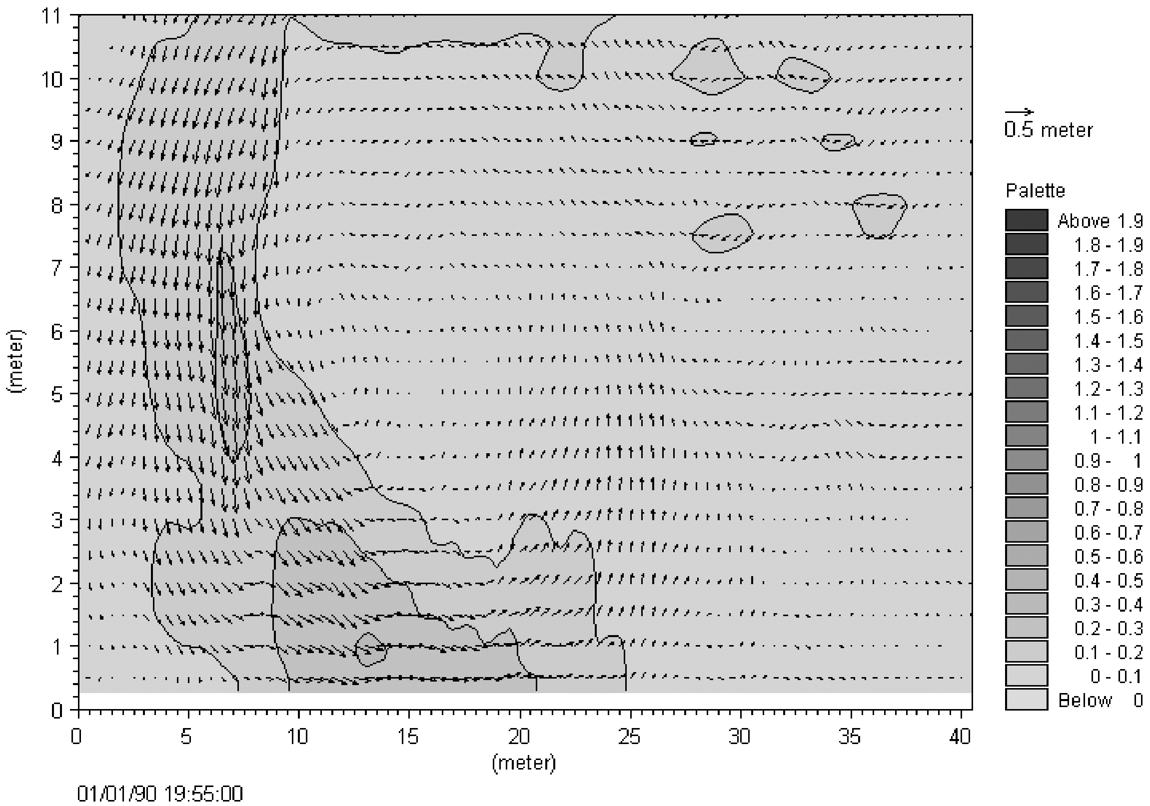

Figure 14: Flow Velocities [m/s] in Section E-E at 19:55 (fully developed flood)

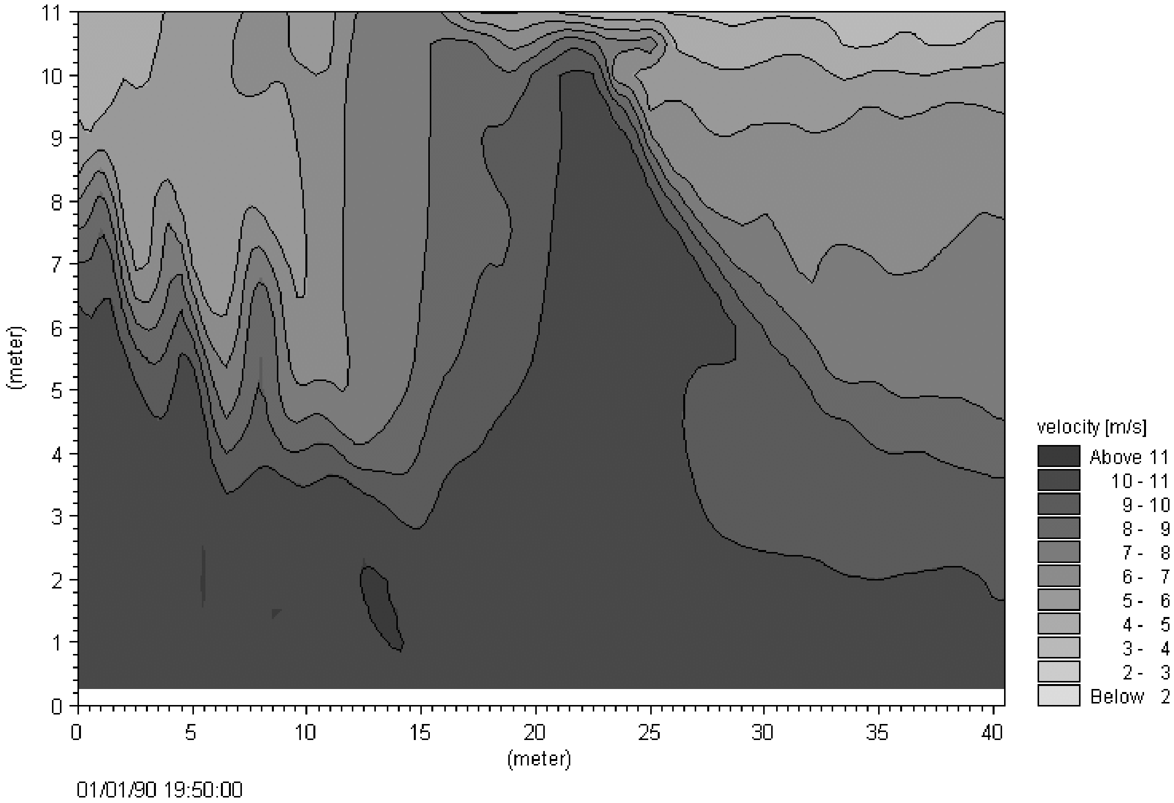

Figure 15: Salinity [‰] in Section F-F at t = 19:55 (fully developed flood)

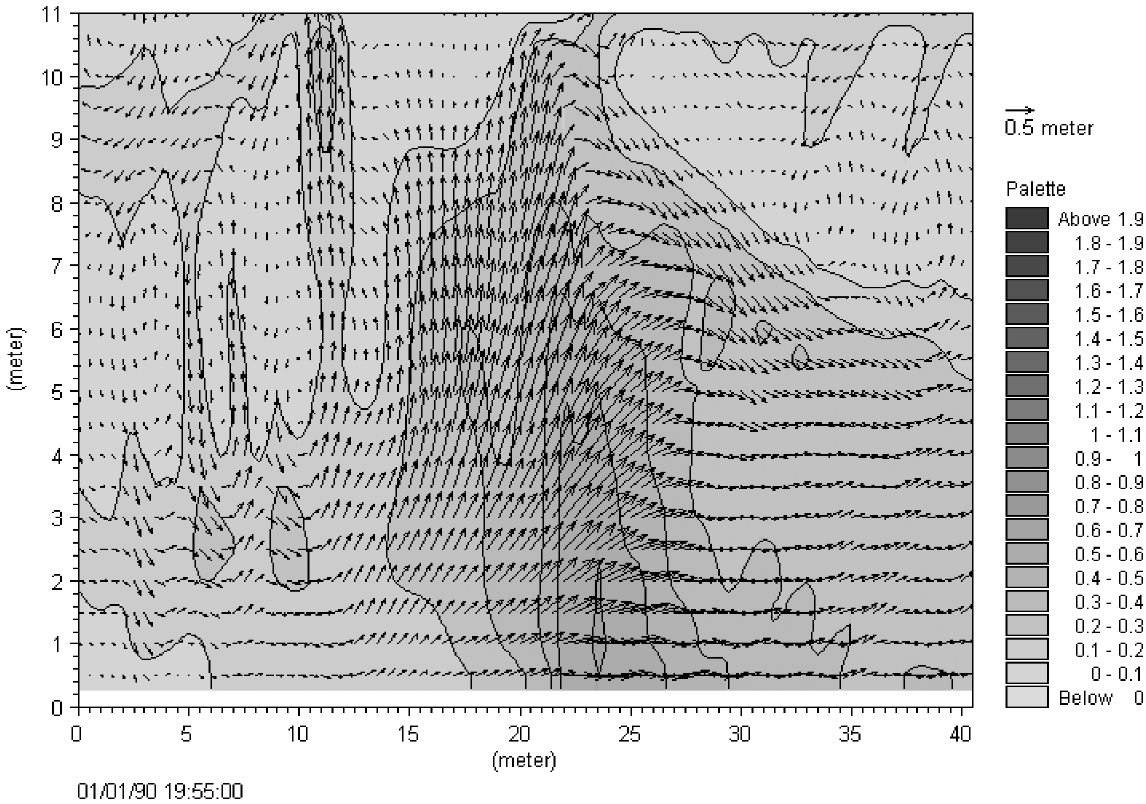

Figure 16: Flow Velocities [m/s] in Section F-F at 19:55 (fully developed flood)

5. SUMMARY

The numerical experiment showed that the hydrodynamic module of MIKE 3 is applicable to model the flow field of density driven currents around complex structures in a brackish tidal environment, if grid resolution is equal or below 0.5 m near the structure. The area of 1.5 m grid resolution should cover the entire harbour entrance. Grid resolution in the estuary is restricted to 13.5 m, due to computational job time.

Nevertheless, the advanced modelling techniques used here are at their limit, indicated by exceptional high job times of more than 6 weeks (Intel® Xeon, 2.2 GHz). Variable and/or internally optimised time step length would be more efficient.

Velocities show strong directional changes over time and depth with a three-dimensional flow pattern into the harbour. Density currents cause opposite flows in an upper and lower layer, who is varying over rising tide. Currents are immediately directed into the harbour over the bed from the beginning to the end of rising tide.

A reduction of the mixing zone and/or a diverting of this zone away from the harbour basin was not found.

Also the complex flow patterns described in Fig. 3 by VAN LEEUWEN and HOFLAND (1999) were not found. Time step length of the experiment should have been short enough (0.02 s) to visualize this flow pattern stated to be constant during rising flood.

The capture of water needed for tidal filling from the top layer of the river was the main identified mechanism of CDW.

The impact of this mechanism to sediment transport will be studied in the future.

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