Investigations to reduce sedimentation upstream of a barrage on the river Rhine

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Abstract

Upstream of the last barrage of the river Rhine at Iffezheim sedimentation takes place at a rate of about 150,000 m³ per year leading to severe problems related to flood protection. In the past this material was dredged periodically and was used for the extension of a mole in the upstream part of the barrage. Because of the great amount of material to be dredged and the associated ecological aspects, this is a matter of great economic concern. However, as the measures taken in the past are not applicable any longer and the recurrent accumulations considerably reduce the level of flood protection the responsible authority is urgently looking for an appropriate and environmentally compatible sediment management strategy. The most obvious way to decrease costs for maintenance dredging, transportation and disposal is to reduce the amount of sediments to be dredged, i.e. to prevent the particles transported in suspension from settling above the barrage at that high rate. This may be achieved by changing the hydrodynamic situation close to the barrage e.g. by the installation of flow guiding structures or an appropriate operation of the weir. Periodically flushing of artificially resuspended sediments may support the aspired objective. In this paper results from a two-dimensional hydrodynamic model and from a two-dimensional morphodynamic model are presented to describe the processes close to the barrage. Flow structures at different discharges are analysed and are compared to results from field measurements, in particular with respect to the area of sedimentation. The effectiveness of a flow guiding structure to minimize sedimentation is demonstrated and suggestions are made for further investigations.
Keywords: sedimentation, suspended load, hydrodynamic model, morphodynamic model, eddy, flow guiding structure, barrage, river Rhine, Iffezheim.

1 Introduction

Upstream of the barrage Iffezheim on the upper Rhine river sedimentation takes place at a rate of about 150,000 m³ per year. The accumulations have to be dredged regularly, as the level of flood protection is affected by the water level rising in correspondence to the change of the discharge profile. Huber *et al.* [1] give a thorough description of the situation at this barrage, of the problems related to the quantity and quality aspects of the sediments and of the measures taken in the past to handle this situation. Because of the great amount of material to be dredged and the associated ecological aspects, this is a matter of great economic concern. Thus, the responsible authority is urgently looking for an appropriate and environmentally compatible sediment management strategy.

The most obvious way to minimise the problems in the context of sediment relocation – even if the sediments are not contaminated – is to reduce the amount of sediments to be dredged. Thus, if the sediments transported in suspension could be prevented to settle above the barrage at the rate observed, costs for maintenance dredging, transportation, disposal and treatment could be considerably reduced.

Since the flow structures and the flow velocities are the decisive factors in the context of sedimentation changing the hydrodynamic situation close to the barrage may reduce the settling rate. However, any proposal to improve the situation has to start with a detailed analysis regarding the circumstances of the sedimentation process. The hydrological situation has to be investigated primarily answering the question at which discharges the material dredged afterwards is dominantly transported. The hydrodynamic situation close to the barrage has to be analysed identifying the flow structures and flow velocities that allow the particles to settle. The suspended matter and the accumulated matter have to be examined with respect to their properties determining the sedimentation process.

In this paper some results of investigations to reduce the sedimentation in the upper weir channel of the Iffezheim barrage are reported. Since the level of flood protection is not allowed to decrease, no modifications that significantly reduce the cross section area have been investigated.

2 Modelling system

The hydrodynamic and the morphodynamic simulations have been carried out with modules of the TELEMAC-system developed by Electricité de France - Laboratoire National d'Hydraulique (Hervouet and Bates [2]). TELEMAC-2D solves the shallow water equations for incompressible free surface flow using an unstructured triangular grid, which allows realistic representations of complicated floodplain structures and bathymetries. The simulation of the suspended load and the bottom evolution were calculated using the morphological module SISYPHE that was coupled with TELEMAC-2D. The hydrodynamic parameters were adapted every time step to the actual state of the river bottom.

3 Data

3.1 Geometry

Cross sectional soundings dating from January 2000 performed within the whole reach upstream of the Iffezheim barrage (up to the next barrage) with intervals of 100 metres have been used. Within the last two kilometres upstream of the barrage these soundings have been carried out quarterly with distances of 20 metres.

3.2 Hydrology

Three discharge gauges are situated within the reach upstream of the Iffezheim barrage. Because no water level surveys have been available, the discharge rating curves of two of these gauges – apart from the most downstream one that is strongly influenced by the backwater effect - have been used to calibrate the hydrodynamic model.

3.3 Weir operation

The operation of the weir and the hydropower station is controlled by a regulation curve, which defines a relationship between the discharge and the normal water level elevation at the barrage. The normal water level elevation is held constant at 123.683 m+NN up to a discharge of 3400 m^3/s, and between this discharge and a discharge of 4800 m^3/s it is reduced linearly to 123.083 m+NN. At higher discharges it is held constant again. The design flow of the hydropower station is 1100 m^3/s, i.e. up to this discharge only the power channel is charged.

3.4 Sediment transport

The German Federal Institute of Hydrology (BfG) carries out measurements of suspended matter in numerous cross sections in the free-flowing part of the river Rhine as multipoint-measurements (six to seven verticals, four depths at each vertical) obtaining detailed distributions of stream velocity, concentration, and transport rates of suspended matter for various hydrological conditions (Sauer and Schmidt [3]). For the investigations presented in this paper the results of three multi-point measuring sites located within nine kilometres downstream of the Iffezheim barrage have been used. Concerning the grain size distribution of the dredged material samples taken in April 1998, September 2000, and January 2001 have been used. The properties of the sediment are described with regard to physical, chemical, and ecological aspects in Köthe *et al.* [4].

4 Results

4.1 Analysis of the present situation

The temporal development of the bottom topography was analysed for a period of about three years by means of the cross sectional soundings. Fig. 1 illustrates the recent state of the bottom topography close to the barrage and the differences of this state to the state just after the last dredging action 32 months before. The accumulations in the left part of the weir bay reach a maximum of about 5.3 metres. The total volume of the material accumulated between March 2001 and November 2003 amounts to 335,000 m³. The analysis of the temporal development of the bottom topography allows the assumption that regarding the accumulation process nearly a steady state was reached at the end of 2003 (Huber *et al.* [1]).

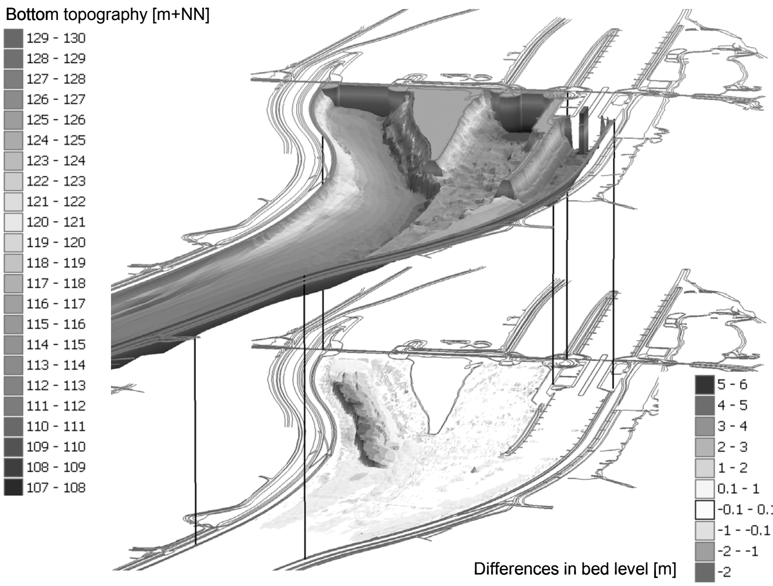

Figure 1: Topography in November 2003 and differences to the state after dredging in March 2001.

4.1.1 Hydrodynamic model

About 54,000 triangular elements (average length of the edges about 15 metres) have been used for the model discretization of the whole reach (km 312.6 to km 334.0) upstream of the Iffezheim barrage. Considering the operation of the weir and the maximum discharge to the hydropower station (1100 m³/s) four different flow conditions are of primary importance: a discharge of 581 m³/s has been chosen to represent low flow conditions without any flow across the weir; a discharge of 1300 m³/s represents the situation with only a little discharge (200 m³/s) across the weir; a discharge of 1800 m³/s represents the situation with a higher discharge across the weir; and a discharge of 4000 m³/s represents a flood situation. The operation of the lock is always neglected, i.e. no discharge through the lock is assumed.

Fig. 2 shows the depth-averaged velocity distribution from the two-dimensional model as contour plots. The flow patterns are illustrated by means of streamlines.

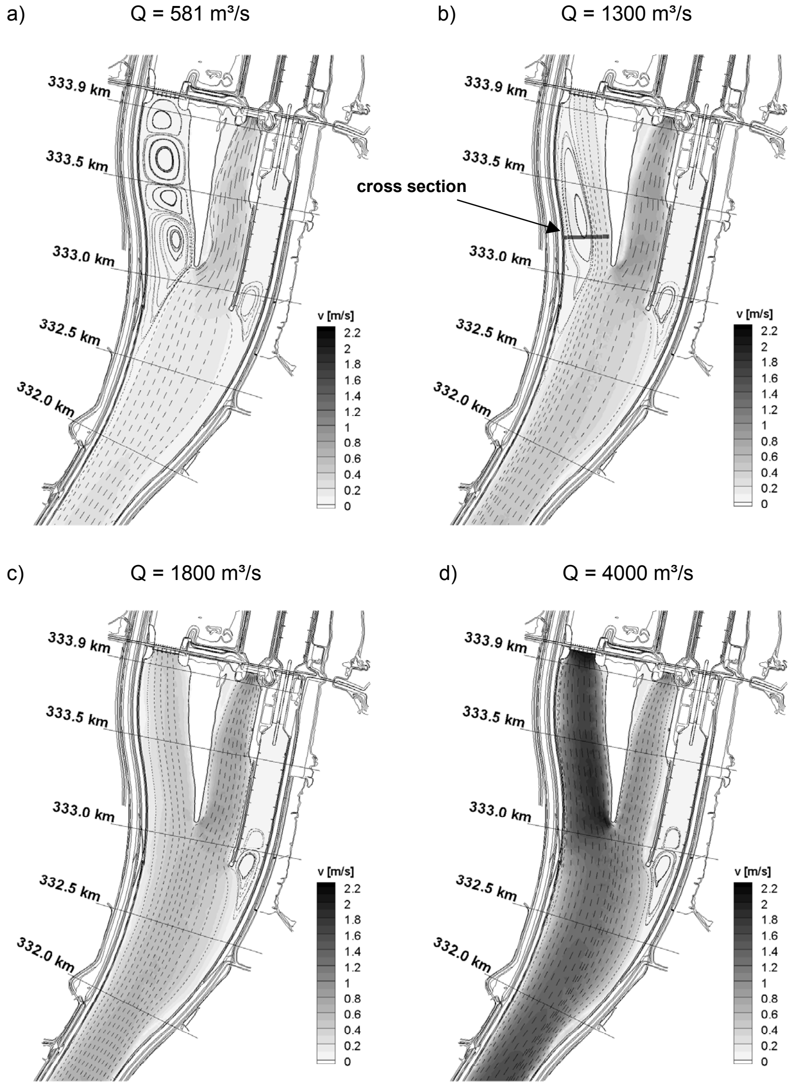

Figure 2: Streamlines and flow velocities at different discharges (present situation).

Up to a discharge of 1100 m^3/s - the design flow of the hydropower station - the power channel is charged exclusively. The discharge of 581 m^3/s, illustrated in fig. 2a, causes the formation of four eddies. With higher discharges the eddies expand and their number becomes less. At a discharge of 1100 m^3/s a pattern with only two eddies is obtained. The circulating water body in the weir channel together with the very small flow velocities (on average 0.015 m/s and not exceeding 0.1 m/s) form a situation that is characteristic for sedimentation areas. At a discharge of 1300 m³/s (fig. 2b) the water turbines operate at the maximum load. The flow velocities in the weir channel are max. about 0.3 m/s. This flow condition is characterized by the appearance of one large eddy that is located exactly above the place of the accumulations (see fig. 1). The extension of this eddy corresponds to the dimensions of the dredging site with flow velocities between 0.02 and 0.15 m/s. With increasing discharges the large eddy in the weir channel becomes smaller and disappears at a discharge of approx. 1700 m³/s. The flow field in fig. 2c (Q = 1800 m³/s) already shows a straight flow against the weir without appearance of any eddy. The flow velocities in the weir channel reach a maximum of 0.5 m/s. Flood conditions with a discharge of 4000 m³/s are illustrated in fig. 2d. The flow velocities in the weir channel increase significantly up to 2 m/s. According to investigations of Westrich and Witt [5] concerning the potential of the settled solids to get in suspension even consolidated material may remobilize above the Iffezheim barrage at such high discharges.

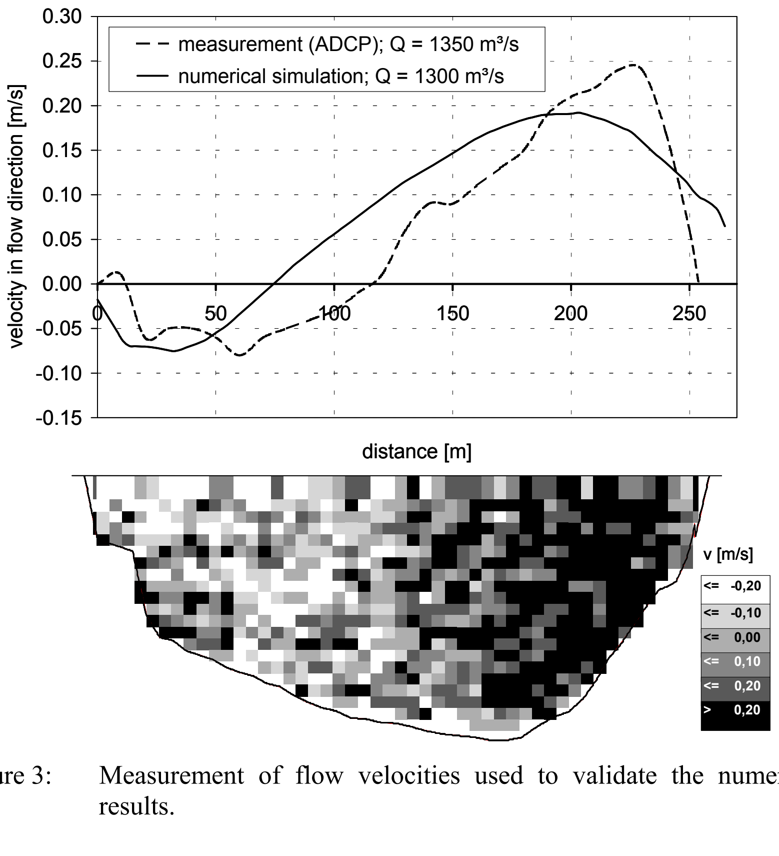

Figure 3: Measurement of flow velocities used to validate the numerical results.

In September 2004 spatially high resolved measurements of flow velocities have been carried out with ADCP to validate the numerical results. The discharge situation with Q = 1350 m³/s corresponds to the situation shown in fig. 2b. In fig 3 results of these measurements are shown together with numerical results for a cross section in the zone of accumulation (see fig. 2b for the location of the cross section). The depth-integrated values resulting from the measurements correspond very well with the depth-integrated values resulting from the numerical calculations.

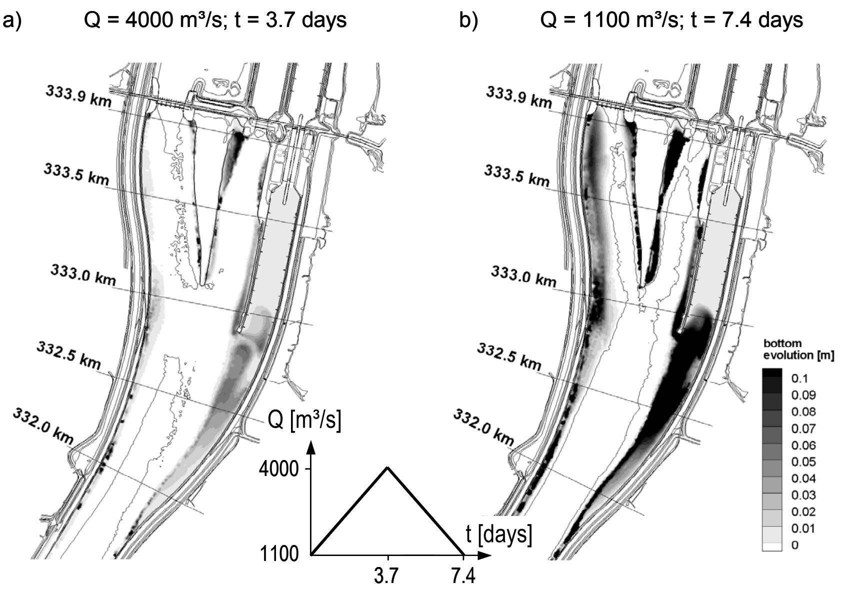

Figure 4: Simulated bottom evolution (present situation).

4.1.2 Morphodynamic model

A schematic hydrograph representing the inclination of natural hydrographs was used to simulate unsteady boundary conditions: starting at 1100 m³/s when the weir just opens, linearly rising to 4000 m³/s and linearly decreasing to 1100 m³/s in 3.7 days respectively. At the upstream boundary the concentration of the suspended sediments was given as a nonlinear function of water discharge derived from field measurements. The grain size of the suspended sediments was chosen to be 0.63 μm, the median diameter of numerous suspended sediments samples.

In fig. 4, the accumulations are shown as contour plots whereas the solid line enclosures the non-scaled areas of erosion. The calculated accumulations in the left part of the weir channel are in good agreement with the observations in nature by cross sectional soundings (see fig.1). The accumulations in the upstream part of the channel towards the locks are not observed in nature to that extent. This discrepancy is explained by the fact that the operation of the locks and the accompanying ship traffic were not simulated in the context of these investigations.

4.2 Modification of the flow pattern by a flow guiding structure

Since the level of flood protection is not allowed to decrease no modifications that significantly reduce the cross section area are applicable. Thus, the main objective of the investigation was to find a solution that destroys the stability of the eddies observed at discharges less than 1700 m³/s without diminishing the flow velocities in the weir channel. Within the scope of the investigation the effects of structural and operational measures have been analysed using the hydrodynamic model.

Most structural measures show the disadvantage of reducing the cross section area considerably. Thus, only the construction of a guiding structure aligned with the direction of flow may yield a success. The investigations show that the best success is obtained by the construction of a narrow training wall in the middle of the weir channel beginning at the diversion between weir channel and power channel and ending just in front of the weir. Because of the restrictions associated with a two-dimensional model the training wall was designed to reach from the bottom up to the water level, i.e. the area of the guiding structure was omitted in the numerical model.

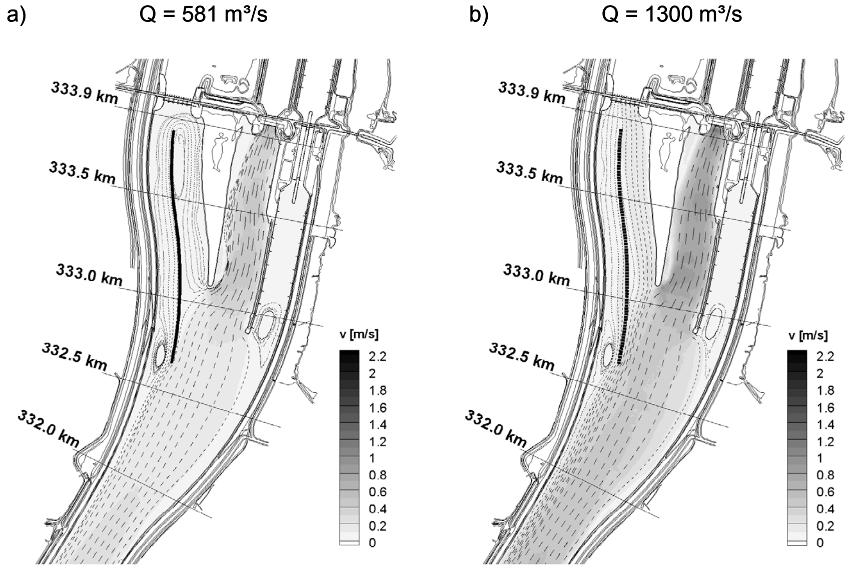

Figure 5: Streamlines and flow velocities at different discharges with flow guiding structure.

4.2.1 Hydrodynamic model

In fig. 5 the steady state flows at discharges of 581 m³/s and 1300 m³/s are illustrated with the flow velocity distribution and streamlines just as in fig. 2. The flow situation in fig. 5a without any flow across the weir shows a totally different pattern compared to the initial state in fig. 2a. The large eddies in the weir channel are destroyed and replaced by a clockwise flow around the new structure. Small eddies remain upstream the guiding structure on the left side and downstream on the right side. However, the flow velocities in the weir channel are still low with on average 0.05 m/s.

At higher discharges with flow across the weir (fig. 5b) the training wall shows also positive effects as the large eddy located above the dredging site has almost disappeared compared to the initial situation. However, the flow velocities do not exceed 0.2 m/s in the weir channel at a discharge of 1300 m³/s. At both discharges the current in the power channel is not significantly influenced by the construction of the training wall.

4.2.2 Morphodynamic model

In fig. 6 the results of the unsteady simulation with the flow guiding structure are shown. At increasing discharges (fig. 6a) the rate of evolution is not significantly affected by this structure. Compared to the bottom evolution without guiding structure the sedimentation on the left side of the training wall - the area of the accumulations to be dredged - is completely prevented (fig. 6b).

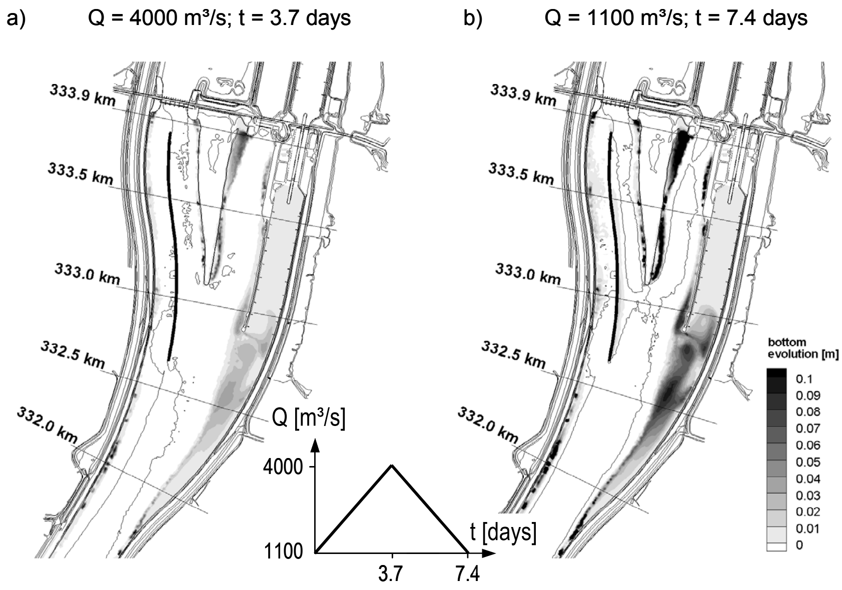

Figure 6: Simulated bottom evolution with flow guiding structure.

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5 Outlook

This paper describes some results of investigations to solve the sedimentation problem in the upper weir bay of the Iffezheim barrage at the river Rhine. In future detailed investigations are required to validate these first findings. Beside the need to optimize the location and the design of the flow guiding structure operational measures, e.g. the modification of the hydropower station control, should be examined as well.
The next step will be to examine the effects of a structure that does not reach up to the water level, e.g. with a height of only two-thirds. This would have the advantages that the cross sectional soundings would not be hampered in future and that the construction costs would be less. Thus, a minimum height has to be found that still assures the destruction of the eddy system. For this, the application of a three-dimensional hydrodynamic model will be applied. Furthermore, the sound analysis of the spatial and temporal development of the bottom topography demands a long-term simulation of the unsteady hydrodynamic and morphodynamic processes.

For a reliable assessment of these phenomena spatially high resolved measurements of flow velocities and sediment concentrations have to be performed in the headwater of the barrage. In addition to this, it has to be revealed by measurements what role bed load transport plays in the context of the sedimentation observed. In particular, the assumption that the accumulations reach a steady state has to be proved.

Acknowledgements

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